Serial No. 285

DEPARTMENT OF COMMERCE

U. S. COAST AND GEODETIC SURVEY

E. LESTER JONES, DIRECTOR

TIDES AND CURRENTS IN NEW YORK HARBOR

By

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Special Publication No. 111

PRICE, 30 CENTS
Sold only by the Superintendent of Documents, Government Printing Office
Washington, D. C.

WASHINGTON
GOVERNMENT PRINTING OFFICE
1925

PREFACE

Altogether apart from their importance in navigation, tides and tidal currents enter as important factors into a number of problems connected with the harbor and port of New York. In the maintenance of a channel for the deep-draft vessels of modern commerce, in harbor improvement, in the disposal of the sewerage of a large industrial center, and in related problems a knowledge of the rise and fall of the tide and of the flood and ebb of the current becomes necessary.

In connection with various projects, tidal and current observations have been made from time to time in the harbor, and the results of some of these observations have appeared in various publications. The greater part of the observational data, however, is still unpublished and, notwithstanding the importance of New York Harbor, no discussion of the detailed observational material has yet appeared.

In the summer of 1922 a comprehensive current survey was carried out jointly by the Coast and Geodetic Survey and the United States Engineer Office, first district, New York. The present publication embodies the results of this survey and also of previous tidal and current surveys made at various times. It is intended here to make available to the mariner, the engineer, the scientist, and the public generally the tidal and current data now in the files of the Coast and Geodetic Survey and the United States Engineer Office, first district, New York.

In connection with this publication, attention is directed to three other Coast and Geodetic Survey publications containing tidal and current data for New York Harbor. These are Tide Tables, Atlantic Coast, North America; Current Tables, Atlantic Coast, North America; and Tidal Bench Marks, State of New York.

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By H. A. Marmer, *Assistant Chief, Division of Tides and Currents, Coast and Geodetic Survey*

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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 1 shows a tide curve for Fort Hamilton, N. Y., for July 4, 1922.

In Figure 1 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.

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

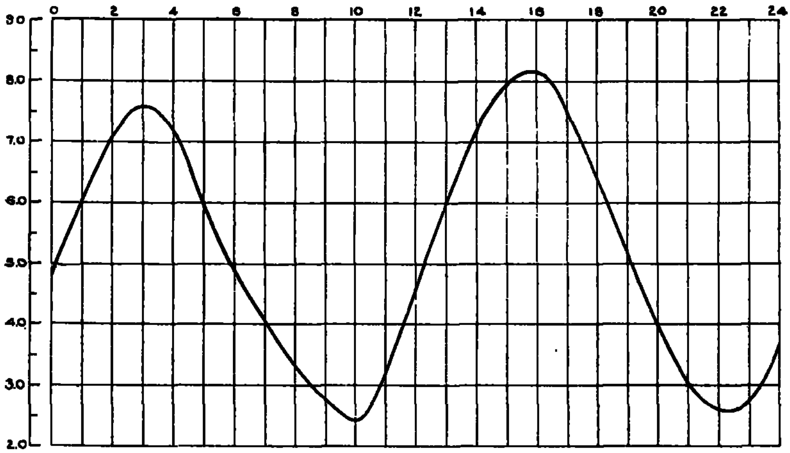

FIG. 1.—Tide curve for Fort Hamilton, N. Y., July 4, 1922

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 response 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 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 2 represents graphically the differences in the tide at San Francisco on October 18 and 24, 1922. On the former date the moon was over the Equator, while on the latter date the moon was at its maximum south declination for the month. The upper diagram thus represents the equatorial tide for San Francisco, while the lower diagram represents the tropic tide.

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

On October 24, when the moon attained its extreme declination for the fortnight, tropic tides occurred. The characteristics of the rise and fall of the tide on that day differ markedly from those on the 18th, when equatorial tides occurred, these differences pertaining both to the time and the height. Instead of an approximately equal duration of rise and of fall of six hours, both morning and afternoon, as was the case on the 18th, we now have the morning rise occupying less time 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

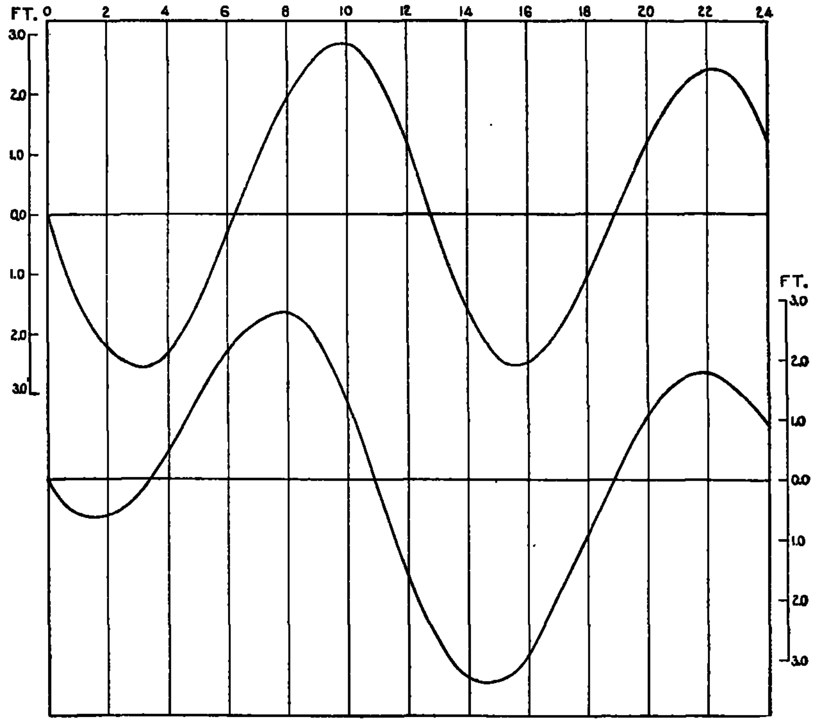

FIG. 2.—Tide curves, San Francisco, Calif., October 18 and 24, 1922

curve shows that there was a difference of a foot in the two high waters of the 24th and a difference of almost 3 feet in the low waters.

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

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

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

TYPES OF TIDE

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

The semidiurnal type of tide is one in which two high and two low waters occur each tidal day with but little diurnal inequality; that is, morning and afternoon tides resemble each other closely. Figure 1 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.

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

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

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

HARMONIC CONSTANTS

Since the tide is periodic in character, it may be regarded as the resultant of a number of simple harmonic movements. In other words, if h be the height of the tide, reckoned from sea level, then for any time t, we may write $h=A\cos(at+\alpha)+B\cos(bt+\beta)+\ldots$. 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 exacty 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 $\frac{180°}{13.78}=13°.06$ per day. Its hourly speed, therefore, is $28°.98-\frac{13°.06}{24}=28°.44$. 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 $\frac{M_2^{\circ}}{28.98}$. The various ages of the tide can likewise be readily determined. Approximately, the ages in hours are: Phase age, $S_2^{\circ}-M_2^{\circ}$; parallax age, $2(M_2^{\circ}-N_2^{\circ})$; diurnal age, $K°_1-O°_1$. 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

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

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 components; 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 component 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 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.

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 current 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 3, which represents the velocity and direction of the current as observed in the Hudson River off Fort Washington on July 22, 1922.

In Figure 3 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.

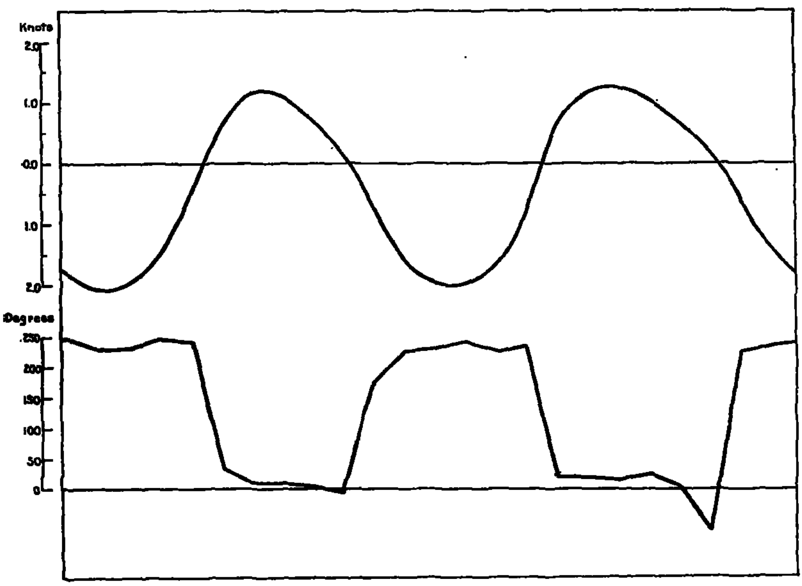

FIG. 3.—Velocity and direction curves for the current, Hudson River, July 22, 1922

The lower curve of Figure 3 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 versing 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 4, 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.

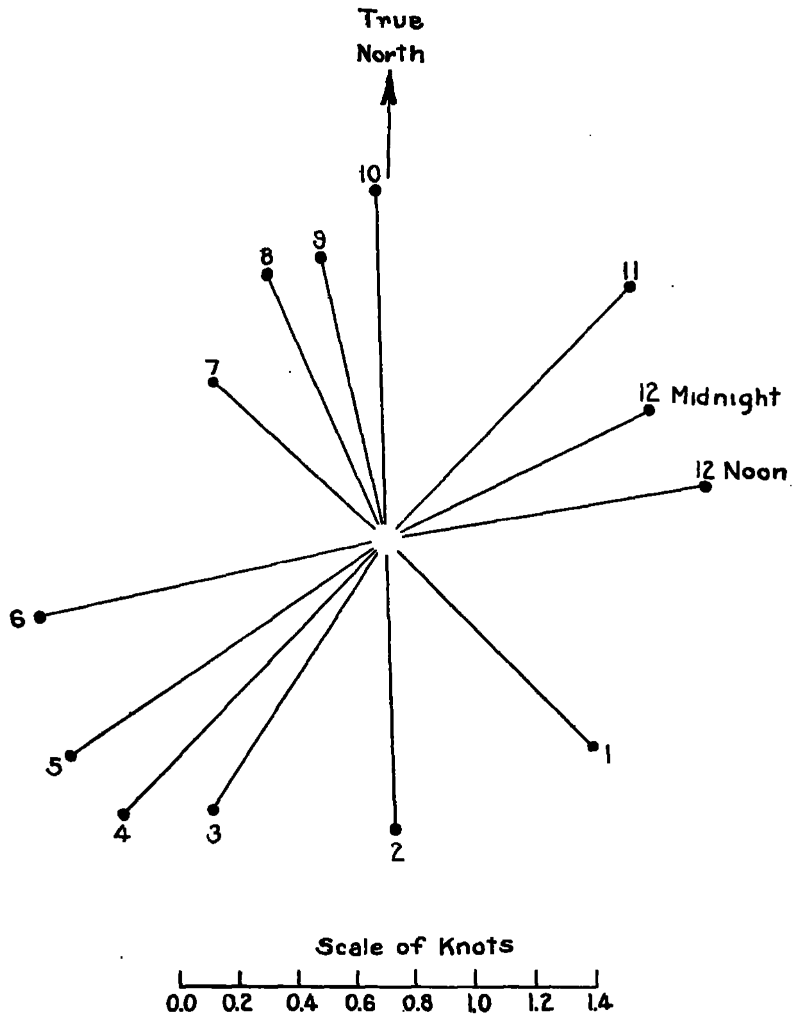

FIG. 4.—Rotary current, Nantucket Shoals Light Vessel, afternoon of September 24, 1919

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.

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 5, 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.

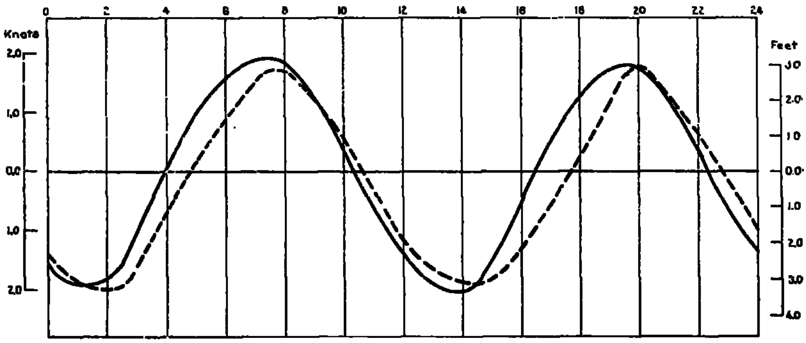

FIG. 5.—Tide and current curves, New York Harbor, October 9, 1919

The diagrams of Figure 5 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 5 it is seen that the corresponding features of tide and current in New York Harbor bear a very nearly constant time relation to each other, and this constancy in time relation of tides and currents is characteristic of tidal waters in which the diurnal inequality is small. This permits the times of slack and of strength of current to be referred to the times of high and low water. Thus, from Figure 5 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

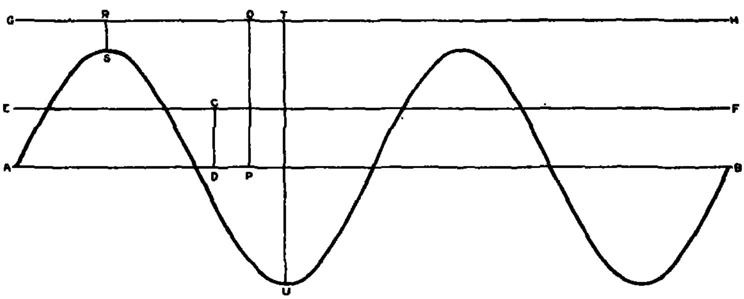

FIG. 6.—Effect of nontidal current on tidal current

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 6, which represents a simple rectilinear tidal current, the time axis of which is the line *A B*, flood velocities being plotted above the line and ebb velocities below.

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

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

Insofar 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, $0.6366 \times 6.2 = 3.95$, 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 tide by primes and of the currents 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 reciprocal of the range of the tide for the same period divided by the mean range of the tide. It is to be noted that in this method of reducing to a mean value, any nontidal currents must first be eliminated and the factor applied to the tidal current alone. This may be done by taking the strengths of the tidal current as the half sum of the flood and ebb strengths for the period in question.

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

III. THE HARBOR OF NEW YORK

COMPONENT PARTS

Most harbors are situated on a tidal river or bay, the harbor proper comprising a portion of the bay or river. New York Harbor differs in this respect from other harbors in that it consists of a number of bays and rivers that communicate with one another, thus forming a system of intercommunicating tidal waterways. And in another hydrographic respect does New York Harbor differ from other harbors; its communication with the sea is through two independent passageways many miles apart. Figure 7 shows that the ocean tide comes to New York Harbor both from the south through Lower Bay and from the east, more than a hundred miles away, through Long Island Sound.

The number of waterways that make up the harbor of New York depends on the limits assigned to the harbor. For the purposes of this publication New York Harbor will be taken to comprise the following waterways: (1) Lower Bay (including Raritan and Sandy Hook Bays), (2) the Narrows, (3) Upper Bay, (4) Newark Bay, (5) Arthur Kill, (6) Kill Van Kull, (7) East River, (8) Hudson River (as far as Mount St. Vincent), (9) Harlem River.

These waterways are all included within the legally constituted port of New York. The relations of the component parts of the harbor to each other are shown in Figure 8.

LOWER BAY

Into Lower Bay the ocean tide sweeps past the gateways of Sandy Hook and Coney Island. If we define the eastern limit of Lower Bay by a line running from the eastern point of Coney Island to the point where Sandy Hook turns west, the entrance to the bay has a width of 8 statute miles. From this eastern limit Lower Bay extends to the Narrows on the north and to the mouth of Raritan River on the west, including thus Gravesend Bay, Raritan Bay, and Sandy Hook Bay. Within these limits Lower Bay covers an area of 118 square statute miles.

Through the bar extending across the entrance to Lower Bay a number of wide and deep channels give access to the bay and to the waterways connecting with it. Ambrose Channel, which leads into the Narrows, is the principal entrance to New York Harbor and has been dredged to a width of 2,000 feet and to a depth of 42½ feet below mean sea level. At its western end Lower Bay shallows considerably, but near its northern end, west of Coney Island, where it leads into the Narrows, the channel shows depths of over 100 feet. For the whole extent of its area within the limits assigned above Lower Bay has an *average depth of 20 feet, reckoned from mean sea* level.

At its northeastern end the tide from Lower Bay passes northward through the Narrows, while at its western end the tide is carried westward into Raritan River and northward into Arthur Kill. Through the Raritan River, Lower Bay receives the drainage waters from an area of about 1,100 square miles, while from the Narrows and Arthur Kill there drains into Lower Bay the waters from a territory having an area of 14,700 square miles.

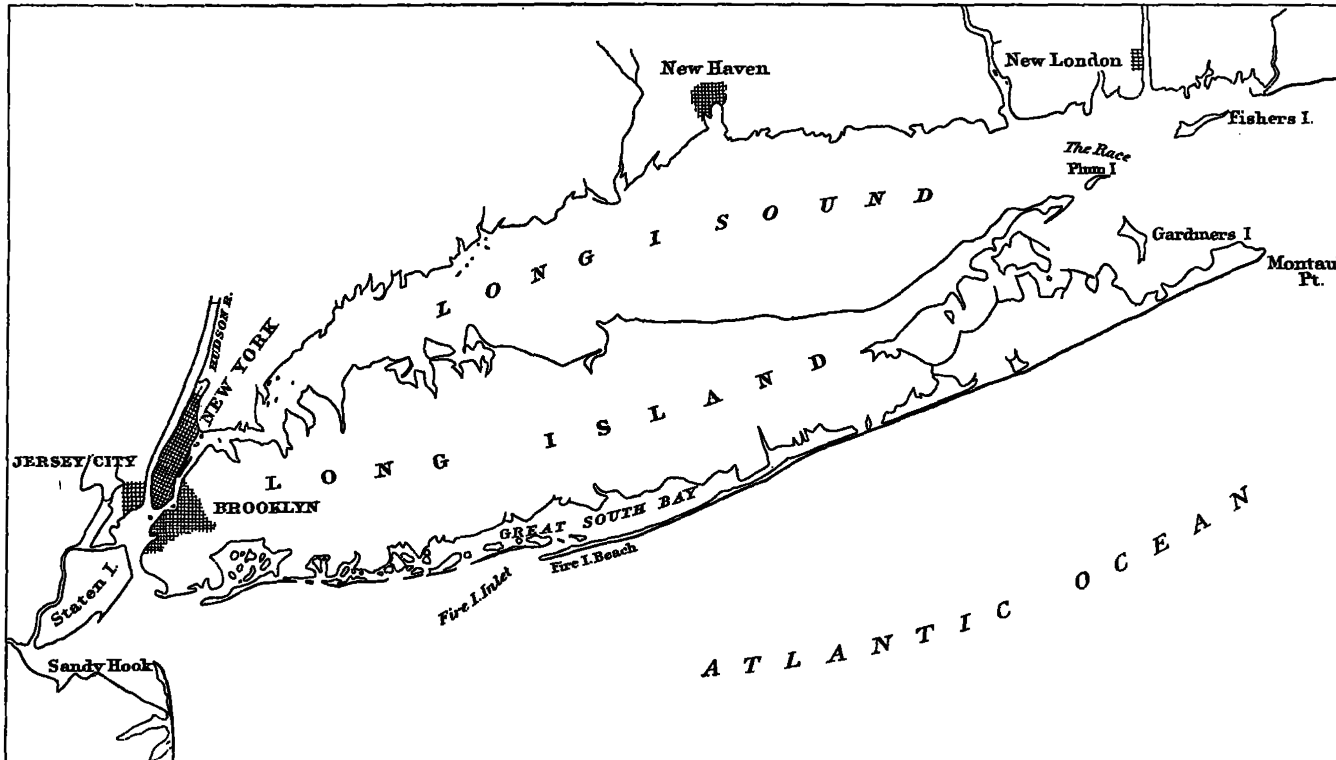

FIG. 7.—New York Harbor, showing the two entrances from the ocean.

THE NARROWS

The Narrows is a short strait leading from Lower Bay into Upper Bay. It is a little more than 3 statute miles long, with a width of 1 mile at its southern end and 2 miles at its northern end. At its southern end where it meets Lower Bay the channel shows depths

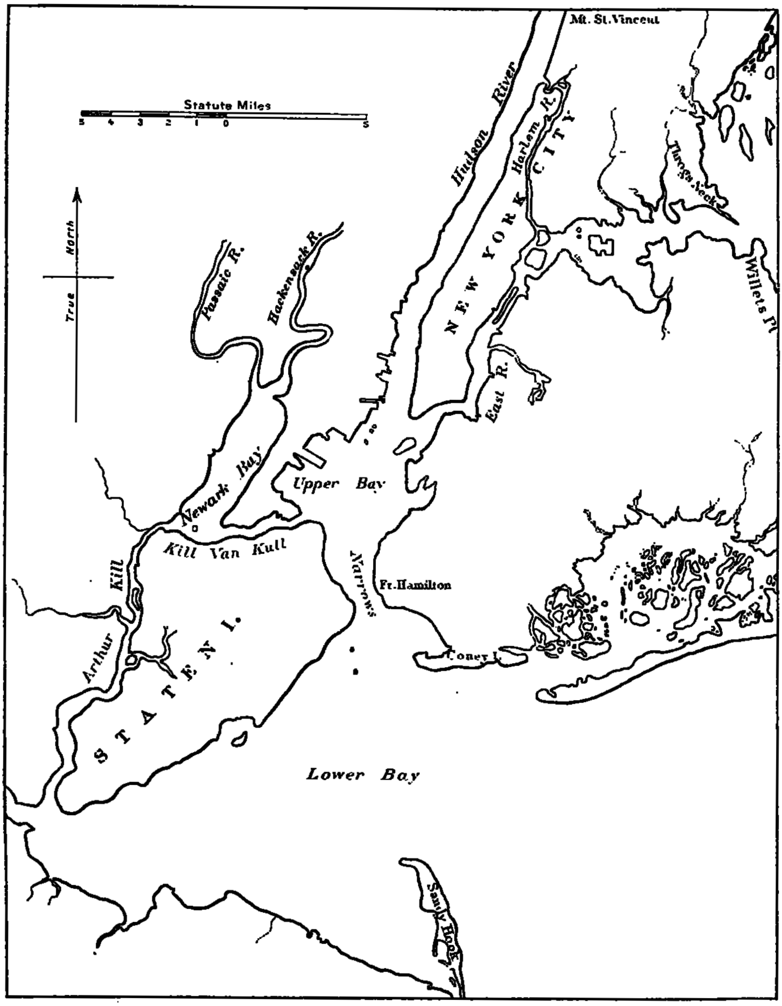

FIG. 8.—New York Harbor, showing the relations of the component waterways

of 100 feet, but as it widens the depth of the channel decreases and at its northern end the greatest depth is 60 feet. At the southern end of the Narrows the deepest part of the channel lies nearer the eastern shore, but after a short distance the deeper part of the channel swings toward the western shore and continues parallel to it into Upper Bay. The area of 4¾ square miles which the Narrows comprises has an average depth of 49 feet, reckoned from mean sea level.

It is through the channel of the Narrows that the greater part of the commerce of New York Harbor passes, and it is through the same channel that the drainage waters of a region approximately 14,500 square miles in area find their way to the sea. For the tides, too, the Narrows is the principal channel to the highways of New York Harbor, affording a deep and commodious passage from Lower Bay.

UPPER BAY

From the Narrows the tide progresses into Upper Bay, a sheet of water a little more than 4 miles long and about 3½ miles wide, having an area of 14½ square miles. The main channel through Upper Bay, leading from the Narrows to the mouth of the Hudson, has a width of about half a mile with depths of 60 feet or more. The western part of the bay is occupied by extensive flats with depths of 8 feet or less, reckoned from mean sea level.

Three islands break the surface of Upper Bay near its northern end. Governors Island, the largest of these, is located near the eastern shore of the bay at the entrance to the East River. Bedloes Island and Ellis Island are situated near the west shore of the bay, and it is on Bedloes Island that the colossal bronze Statue of Liberty stands, the tip of the torch more than 300 feet above sea level.

From Upper Bay three tidal highways radiate—to the west Kill Van Kull leads into Newark Bay, to the northeast East River leads into Long Island Sound, and to the north the Hudson River furnishes a highway into the interior of the State. The channels leading into these three waterways have depths of 40 feet or more, but because of the extensive flats on the western side of the bay the average depth of the 14½ square miles covered by Upper Bay is 25 feet, reckoned from mean sea level.

NEWARK BAY AND THE KILLS

Newark Bay lies to the west of Upper Bay from which it is separated by a narrow tongue of land, less than 1,200 yards wide in some places, on which the city of Bayonne, N. J., is located. It has a length of about 6 miles and an average width of a little more than a mile, comprising an area somewhat in excess of 8 square miles.

Two straits—Arthur Kill and Kill Van Kull—lead the tide into Newark Bay. From the south Arthur Kill brings the tide from the western end of Lower Bay and from the east Kill Van Kull carries the tide from Upper Bay. Arthur Kill has a length measured along its channel of 13 miles and covers an area of 4¼ square miles with an average depth of 17½ feet. Kill Van Kull is shorter than Arthur Kill, having a length of about 3 miles. It is about a third of a mile wide and comprises an area of almost exactly 1 square mile with an average depth, reckoned from mean sea level, of 28 feet. Being shorter, wider, and deeper, Kill Van Kull is the principal tidal inlet into Newark Bay.

Two rivers of considerable size—the Hackensack and the Passaic—empty into Newark Bay at its upper end, and it is principally through these two rivers that Newark Bay drains a territory with an area of nearly a thousand square miles. The Hackensack and the Passaic each carry the tide upstream a distance of about 15 miles. The greater part of Newark Bay is shoal, but a channel obtained partly by dredging leads through the bay to the entrance of the Hackensack and Passaic Rivers. For the 8 square miles comprising its area Newark Bay has an average depth of 9 feet.

EAST RIVER

From Upper Bay East River carries the tide northeastward. Parenthetically, it may be remarked that East River is strictly not a river but a strait connecting Upper Bay and Long Island Sound, so that East River is subject not only to the tide coming northeastward from Upper Bay but also to the tide moving southwestward from Long Island Sound.

From the extreme tip of Manhattan Island on the southwest to Throgs Neck on the northeast East River has a length of 16 miles, but it is not at all uniform in its hydrographic features throughout this length. Hell Gate, which divides East River almost exactly in half, may be taken as separating the waterway into two parts possessing different characteristics. Lower East River, lying southwestward of Hell Gate, is a relatively narrow and deep waterway, comprising an area of 4 square miles with an average depth of 38 feet. Eastward of Hell Gate the river widens and Upper East River covers an area of 9¾ square miles with an average depth of 25 feet.

A number of islands lie scattered near the middle of East River, restricting the width of the waterway and giving rise to swift currents. It is to the stretch of water lying between the northern tip of Blackwells Island and the southern part of Wards Island that the name Hell Gate is applied. While the Dutch words "Helle Gat," from which its name is derived, have a totally different meaning than the English "Hell Gate," the Anglicised form was considered an appropriate designation, especially in the early days when the reefs of rock in the main passage, together with the swift currents and tortuous channel, rendered navigation dangerous at times. Since 1851 a considerable amount of rock has been removed, so that now the channel of Hell Gate is about 850 feet wide and very nearly 29 feet deep from mean sea level.

HUDSON RIVER

The Hudson River is one of the more important rivers of the Atlantic Coast. From its mouth at the Battery, New York City, where it debouches into Upper Bay, it carries the tide from the latter body of water a distance of 150 miles until stopped by the dam at Troy. For a distance of 90 miles above its mouth the Hudson has a deep and unobstructed channel navigable for large vessels. Further upstream the depth lessens, but even for the last 30 miles there is a channel 12 feet deep. The river also serves as a highway for the traffic of the New York State Barge Canal which extends to the Great Lakes.

Near Mount St. Vincent, about 2 miles below Yonkers, runs the northern boundary of the city of New York, and it is the Hudson from the Battery to Mount St. Vincent—a distance of 16 miles—that is here included as forming a part of New York Harbor. For this distance the river has a width of very nearly a mile and covers an area of 14½ square miles, with an average depth, reckoned from mean sea level, of 32½ feet.

It is the Hudson River that brings the greater part of the drainage waters into New York Harbor. Of the 14,500 square miles of territory that drain into the sea through the Narrows the Hudson River contributes over 13,400 square miles, or more than 90 per cent. Computations based on river gaugings and rainfall bring out the fact that, on the average, about 26,000 cubic feet of fresh or nontidal water pass through the Narrows each second, of which the Hudson contributes 24,000 cubic feet. In other words, from the territory it drains, the Hudson pours each day into New York Harbor a volume of water equal to 2,000,000,000 cubic feet.

HARLEM RIVER

Harlem River is the narrow tidal waterway that joins the Hudson with the East River and makes an island of Manhattan by cutting it off from the mainland to the north. Like East River, Harlem River is a strait and not a true river. Its junction with the Hudson is at a point 13½ miles above the mouth of the Hudson, and its junction with the East River is through three channels in the vicinity of Hell Gate, the principal channel lying between Manhattan and Wards Island.

Originally the Hudson River outlet of the Harlem was a tortuous narrow channel through a tidal marsh known as Spuyten Duyvil Creek, the designation "Harlem River" being applied to the rest of the waterway leading into East River. In 1895 a ship canal was completed through the tidal marsh, and now the Harlem is a continuous waterway from the East River to the Hudson, the channel having a length of 7¾ miles. It covers an area of three-quarters of a square mile, with an average depth of 16 feet.

New York Harbor thus forms a system of waterways consisting of 3 bays, 5 straits, and 1 tidal river, through all of which the tide sweeps. From the ocean the tide enters the harbor through two inlets many miles apart, and this, together with the fact that the waterways of New York Harbor are intercommunicating, gives rise to the considerable variety in the rise and fall of the tide and in the flood and ebb of the current.

IV. THE TIDE AT FORT HAMILTON

INTRODUCTORY

Of the tidal observations in New York Harbor those made by the United States Coast and Geodetic Survey at Fort Hamilton, on the east bank of the Narrows, constitute the principal series. These observations cover the period from 1893 to 1920, the record being continuous with but slight interruptions. This record is in the form of a curve drawn to a scale of 1:12 by a three-roller Coast and Geodetic Survey tide gauge. The heights on the paper record are connected with a fixed zero by readings made on a fixed staff, these comparative readings being made several times weekly.

On December 5, 1920, the wharf on which the tide house was located was destroyed by fire. On the reestablishment of the wharf early in 1921 the United States Engineer Office, War Department, installed a Gurley printing gauge which records directly the height of the tide at 15-minute intervals. For the years 1921 and 1922 the data for Fort Hamilton are from the records of the United States Engineer Office.

Care was taken to maintain a fixed datum to which the heights of the tide curve were referred. This was accomplished by leveling with a wye level between the staff and substantial bench marks on the shore whenever it was necessary to renew the staff. In this way the zero of the staff was kept at a constant elevation throughout the period of observation. For the tides of New York Harbor, Fort Hamilton will be taken as the standard station.

THE TIME OF TIDE

The lunitidal intervals at Fort Hamilton, or the intervals by which high and low water follow the moon's meridian passage, vary somewhat from day to day. This variation is due principally to the variation in the positions of sun and moon relative to the earth; but changes in wind and weather also cause variations in the lunitidal intervals. However, when undisturbed by wind or other unusual meteorological conditions, it is only infrequently that these intervals at Fort Hamilton vary by as much as one hour from the mean values.

The change in lunitidal intervals from day to day throughout a summer month is shown by the seventh and eighth columns of Table 1, which list the high-water and low-water intervals for the first 29 days of June, 1919. It is to be noted, however, that for convenience in computation the moon's transits across the meridian of Greenwich are taken, the necessary correction to refer these intervals to the local meridian being made to the average values determined for the month. For Fort Hamilton this correction is −0.11 hour. In the second column the lower transits are inclosed in parentheses, and the values derived from them in the seventh and eighth columns are likewise inclosed in parentheses.

TABLE 1.—*High and low waters, Fort Hamilton, June, 1919*

Date	Moon's transit, meridian of Greenwich	Time of—		Duration of—		Lunitidal interval		Height of—		Range	
		High water	Low water	Rise	Fall	High water	Low water	High water	Low water	Rise	Fall
	Hours	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Feet*	*Feet*	*Feet*	*Feet*
1	(2.5)	10.0	4.1	5.9	------	(7.5)	(1.6)	9.4	3.4	6.0	------
	14.9	22.2	16.1	6.1	6.1	7.3	1.2	10.0	4.1	5.9	5.3
2	(3.4)	10.9	4.9	6.0	6.7	(7.5)	(1.5)	9.2	3.7	5.5	6.3
	15.9	23.1	17.3	5.8	6.4	7.2	1.4	9.6	4.1	5.5	5.1
3	(4.3)	11.8	5.9	5.9	6.8	(7.5)	(1.6)	8.9	3.9	5.0	5.7
	16.7	------	18.0	------	6.2	------	1.3	------	4.2	------	4.7
4	(5.1)	0.1	6.4	6.1	6.3	7.4	(1.3)	8.9	3.8	4.7	5.1
	17.4	12.9	18.8	6.5	5.9	(7.8)	1.4	8.5	4.4	4.7	4.1
5	(5.8)	0.6	7.5	5.8	6.9	7.2	(1.7)	8.3	3.8	3.9	4.5
	18.2	13.7	20.1	6.2	6.4	(7.9)	1.9	8.4	4.5	4.6	3.9
6	(6.5)	1.8	8.4	5.7	6.6	7.6	(1.9)	8.0	4.1	3.5	3.9
	18.9	14.4	21.0	6.0	6.6	(7.9)	2.1	8.5	4.7	4.4	3.8
7	(7.3)	2.7	9.1	5.7	6.4	7.8	(1.8)	7.9	4.0	3.2	3.9
	19.6	15.4	21.8	6.3	6.4	(8.1)	2.2	8.5	4.5	4.5	4.0
8	(8.0)	3.4	10.3	5.6	6.9	7.8	(2.3)	7.9	4.8	3.4	3.1
	20.3	16.3	22.9	6.0	6.6	(8.3)	2.6	9.1	5.3	4.3	3.8
9	(8.7)	4.2	11.2	5.3	7.0	7.9	(2.5)	8.3	4.7	3.0	3.6
	21.1	16.9	23.9	5.7	7.0	(8.2)	2.8	8.9	4.5	4.2	4.4
10	(9.4)	5.2	11.9	5.3	6.7	8.1	(2.5)	7.9	4.3	3.4	3.6
	21.8	17.4	------	5.5	------	(8.0)	------	8.7	------	4.4	------
11	(10.2)	6.2	0.5	5.7	7.1	8.4	2.7	7.6	3.9	3.7	4.8
	22.6	18.5	12.2	6.3	6.0	(8.3)	(2.0)	8.7	4.1	4.6	3.5
12	(11.0)	6.7	1.5	5.2	7.0	8.1	2.9	7.9	4.0	3.9	4.7
	23.4	19.2	13.0	6.2	6.3	(8.2)	(2.0)	8.8	4.1	4.7	3.8
13	(11.8)	7.6	1.7	5.9	6.5	8.2	2.3	7.7	3.7	4.0	5.1
	------	19.5	13.4	6.1	5.8	(7.7)	(1.6)	9.2	4.1	5.1	3.6
14	0.3	8.4	2.4	6.0	6.9	8.1	2.1	8.1	4.0	4.1	5.2
	(12.7)	20.3	13.8	6.5	5.4	(7.6)	(1.1)	9.1	4.3	4.8	3.8
15	1.1	8.6	3.1	5.5	6.8	7.5	2.0	8.2	3.8	4.4	5.3
	(13.5)	21.1	15.1	6.0	6.5	(7.6)	(1.6)	9.1	4.2	4.9	4.0
16	1.9	9.7	3.7	6.0	6.6	7.8	1.8	8.3	3.8	4.5	5.3
	(14.3)	21.6	15.5	6.1	5.8	(7.3)	(1.2)	9.2	4.4	4.8	3.9
17	2.7	10.1	4.3	5.8	6.7	7.4	1.6	8.4	3.9	4.5	5.3
	(15.1)	22.2	16.3	5.9	6.2	(7.1)	(1.2)	8.9	4.5	4.4	3.9
18	3.5	10.9	4.9	6.0	6.7	7.4	1.4	8.5	3.8	4.7	5.1
	(15.9)	23.3	17.3	6.0	6.4	(7.4)	(1.4)	8.8	4.5	4.3	4.0
19	4.3	11.7	5.8	5.9	6.5	7.4	1.5	8.5	3.8	4.7	5.0
	(16.7)	23.9	18.2	5.7	6.5	(7.2)	(1.5)	8.3	4.4	3.9	4.1
20	5.1	12.6	6.5	6.1	6.6	7.5	1.4	8.2	3.3	4.9	5.0
	(17.5)	------	19.0	------	6.4	------	(1.5)	------	4.0	------	4.2
21	5.9	0.6	7.1	5.6	6.5	(7.1)	1.2	8.4	3.9	4.4	4.5
	(18.3)	13.7	19.9	6.6	6.2	7.8	(1.6)	8.9	4.4	5.0	4.5
22	6.8	1.9	8.3	6.0	6.4	(7.6)	1.5	8.2	3.7	3.8	4.5
	(19.2)	14.4	21.3	6.1	6.9	7.6	(2.1)	9.2	4.4	5.5	4.8
23	7.6	2.8	9.3	5.5	6.5	(7.6)	1.7	8.5	3.6	4.1	4.9
	(20.1)	15.4	22.3	6.1	6.9	7.8	(2.2)	9.0	3.7	5.4	5.3
24	8.6	3.8	10.5	5.5	6.7	(7.7)	1.9	8.3	3.3	4.6	5.0
	(21.1)	16.5	23.3	6.0	6.8	7.9	(2.2)	9.3	3.3	6.0	6.0
25	9.6	4.8	11.6	5.5	6.8	(7.7)	2.0	8.3	3.2	5.0	5.1
	(22.1)	17.4	------	5.8	------	7.8	------	9.6	------	6.4	------
26	10.6	5.9	0.3	5.6	6.9	(7.8)	(2.2)	8.7	3.2	5.5	6.4
	(23.1)	18.4	12.4	6.0	6.5	7.8	1.8	9.8	3.3	6.5	5.4
27	11.7	6.9	1.4	5.5	7.0	(7.8)	(2.3)	8.8	3.0	5.8	6.8
	------	19.4	13.4	6.0	6.5	7.7	1.7	9.8	3.1	6.7	5.7
28	(0.2)	7.9	2.3	5.6	6.9	(7.7)	(2.1)	9.1	3.1	6.0	6.7
	12.7	20.4	14.2	6.2	6.3	7.7	1.5	10.4	4.1	6.3	5.0
29	(1.1)	8.8	3.0	5.8	6.6	(7.7)	(1.9)	9.6	3.4	6.2	7.0
	13.6	21.1	15.4	5.7	6.6	7.5	1.8	10.0	4.0	6.0	5.6
Sums				329.4	359.6	431.5	102.1	490.3	222.1	268.2	261.6
Means				5.88	6.54	7.71	1.82	8.76	3.97	4.79	4.76

Since the variation in the lunitidal intervals from day to day is relatively small, the average values for these intervals as determined from a month of observations should not differ much from the values as determined from a considerable period of time. The variation from month to month through two years—1893 and 1922, the first and last years of the observations at hand—is shown in Table 2. In this table the means are for groups covering the first 29 days of each month. To complete a 29-day group for the month of February when it has but 28 days the first day of March is included. The monthly means as given in the table refer to the moon's transit across the meridian of Fort Hamilton.

TABLE 2.—*Lunitidal intervals, Fort Hamilton: Monthly means for 1893 and 1922*

Month	High-water intervals		Low-water intervals	
	1893	1922	1893	1922
	Hours	*Hours*	*Hours*	*Hours*
January	7.73	7.79	1.60	1.71
February	7.80	7.67	1.60	1.66
March	7.60	7.63	1.63	1.52
April	7.62	7.57	1.58	1.52
May	7.64	7.62	1.58	1.67
June	7.71	7.60	1.70	1.59
July	7.69	7.62	1.64	1.54
August	7.68	7.69	1.71	1.69
September	7.70	7.75	1.67	1.66
October	7.74	7.60	1.71	1.58
November	7.77	7.80	1.73	1.71
December	7.81	7.79	1.71	1.78
Sums	92.49	92.13	19.86	19.63
Means	7.71	7.68	1.66	1.64

As determined from a year of observations, the lunitidal intervals give a close approximation to the mean values determined from a period of a number of years. The variation in the high-water and low-water lunitidal intervals from year to year is shown in Table 3 under the headings HWI and LWI, respectively, the intervals being given in hours and decimals. For the years 1893 to 1912, inclusive, the values are from monthly groups, including every day of the month; from 1913 to 1922, inclusive, the values are for monthly groups covering the first 29 days of each month.

TABLE 3.—*Lunitidal intervals, Fort Hamilton: Annual means from 1893 to 1922*

Year	HWI	LWI	Year	HWI	LWI	Year	HWI	LWI
	Hours	*Hours*		*Hours*	*Hours*		*Hours*	*Hours*
1893	7.71	1.65	1903	7.66	1.63	1913	7.62	1.56
1894	7.73	1.69	1904	7.70	1.66	1914	7.56	1.51
1895	7.68	1.61	1905	7.72	1.69	1915	7.56	1.54
1896	7.65	1.58	1906	7.76	1.72	1916	7.57	1.59
1897	7.66	1.57	1907	7.69	1.68	1917	7.62	1.62
1898	7.70	1.62	1908	7.74	1.68	1918	7.61	1.62
1899	7.75	1.68	1909	7.73	1.66	1919	7.67	1.66
1900	7.77	1.73	1910	7.68	1.66	1920	7.69	1.65
1901	7.76	1.70	1911	7.66	1.62	1921	7.77	1.72
1902	7.70	1.68	1912	7.63	1.60	1922	7.68	1.64
Sums	77.11	16.51	Sums	76.97	16.60	Sums	76.35	16.11
Means	7.71	1.65	Means	7.70	1.66	Means	7.64	1.61

If we take a direct mean of the 30 years tabulated in Table 3, we derive for the high-water lunitidal interval 7.68 hours and for the low-water interval 1.64 hours. The values for any one year differ but little from these mean values. For the high-water intervals the greatest deviation in the one direction is represented by 0.09 hour, or 5.4 minutes, in 1900 and again in 1921, and in the other direction by 0.12 hour, or 7.2 minutes, in 1914 and again in 1915. For the low-water intervals these variations are 0.09 hour in 1900 and 0.13 hour in 1914.

In a period of approximately 19 years all of the more important of the moon's motions will have gone through complete cycles. It is therefore customary to regard the values of tidal constants derived from a 19-year series as constituting mean values. The observations from 1893 to 1922 permit two overlapping 19-year groups to be made —1893 to 1911 and 1904 to 1922—the period overlapping being 8 years, 1904 to 1911. From the first 19-year group we derive the high-water interval to be 7.71 hours and the low-water interval 1.66 hours. From the second 19-year group these intervals are, respectively, 7.67 hours and 1.64 hours. There appears thus to have been a change in the time of the tide at Fort Hamilton during the past 30 years. This apparent change is likewise shown by the means of the 10-year groups of Table 3 and may be ascribed to the deepening of the channels leading from the sea. For the mean values of the lunitidal intervals at Fort Hamilton we may therefore take the results of the last 19 years, or 7.67 hours for the high water and 1.64 hours for the low water.

DURATION OF RISE AND FALL

From the mean high and low water intervals at Fort Hamilton of 7.67 hours and 1.64 hours we derive the mean duration of the rise of tide to be 6.03 hours, and since the length of the tidal cycle is 12.42 hours (half the tidal day of 24.84 hours) the duration of fall is 6.39 hours. For individual tides the periods of rise and fall are obviously subject to somewhat greater variation than the lunitidal intervals. In general, however, when undisturbed by wind or weather, these periods at Fort Hamilton do not vary much from their mean values, as shown by the fifth and sixth columns of Table 1, which give the consecutive periods of rise and fall for a typical month.

From Table 2 we may derive the mean durations of rise and fall for each month of 1893 and 1922. These values are given in Table 4 following:

TABLE 4.—*Duration of rise and fall, Fort Hamilton: Monthly means for 1893 and 1922*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Means
1893:													
Rise	6.13	6.20	5.97	6.04	6.06	6.01	6.05	5.97	6.03	6.03	6.04	6.10	6.05
Fall	6.29	6.22	6.45	6.38	6.36	6.41	6.37	6.45	6.39	6.39	6.38	6.32	6.37
1922:													
Rise	6.08	6.01	6.11	6.05	5.95	6.01	6.08	6.00	6.09	6.02	6.09	6.01	6.04
Fall	6.34	6.41	6.31	6.37	6.47	6.41	6.34	6.42	6.33	6.40	6.33	6.41	6.38

If from Table 3 we derive the durations of rise and fall from the means of 10-year groups, we get from the first group 6.06 hours and 6.36 hours, from the second group 6.04 and 6.38, and from the third group 6.03 and 6.39. The differences between these means are small, but they indicate a gradual change in the relative durations of rise and fall. If, as before, we group the whole series of observations into two overlapping 19-year groups, we derive for the first group (1893 to 1911) a duration of rise of 6.05 hours and a duration of fall of 6.37 hours. From the second group (1904 to 1922) we derive, respectively, 6.03 hours and 6.39 hours, and these latter values will be taken as the best determined means for the durations of rise and fall.

MEAN SEA LEVEL

The plane of mean sea level 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. With reference to a bench mark on the shore, the plane of mean sea level may be determined by averaging over a considerable period of time the hourly heights of the tide, as read on a fixed tide staff the zero of which has been connected with the bench mark by spirit levels. This is also accomplished by reading the hourly heights from a tide gauge which is connected with a fixed staff by comparative readings.

For how long a period must the hourly heights of the tide be averaged to give a good determination of mean sea level? This question can best be answered by examining the results derived from observations of varying periods. Obviously, mean sea level determined from tidal observations extending over one day may be in error several feet, due to varying meteorological conditions. But even apart from the effects of wind and weather, it is to be borne in mind that the so-called long period tides, brought about by the tidal forces having periods of half a month or more, introduce a variation in sea level from day to day.

The variation in sea level from day to day is shown in Table 5 for the month of June, 1919, a typical summer month. In this table the values of sea level were derived by averaging the 24 hourly heights of each day which are recorded in feet and tenths and refer to the fixed tide staff to which all the observations at Fort Hamilton are referred.

TABLE 5.—*Daily sea level on staff, Fort Hamilton, June, 1919*

Date	Feet	Date	Feet	Date	Feet
1	6.66	11	6.23	21	6.24
2	6.56	12	6.33	22	6.29
3	6.46	13	6.34	23	6.32
4	6.31	14	6.44	24	6.25
5	6.53	15	6.38	25	6.27
6	6.31	16	6.43	26	6.43
7	6.30	17	6.44	27	6.31
8	6.89	18	6.39	28	6.75
9	6.84	19	6.25	29	6.78
10	6.41	20	6.00	30	6.23
Sum	65.27	Sum	63.23	Sum	63.87
Mean	6.53	Mean	6.32	Mean	6.39

It will be observed that even in a summer month when meteorological conditions do not vary greatly, sea level may vary by as much as 0.9 foot. Table 5 also brings out the fact that mean sea level determined from three consecutive 10-day groups during a month when weather conditions were relatively uniform may differ from each other by 0.2 foot.

Not only is sea level determined from one day of observations subject to serious error, but even when determined from observations covering a period of a month it may not be free from considerable error. In Table 6 the heights of sea level on the tide staff as determined from the first 29 days of each month for the years 1893, 1902, 1911, and 1920 are given.

TABLE 6.—*Monthly sea level on staff, Fort Hamilton, for 1893, 1902, 1911, and 1920*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Means
1893	5.66	5.27	5.73	5.97	6.03	6.17	5.93	6.18	6.01	6.12	5.89	5.42	5.86
1902	5.68	5.81	6.09	6.07	5.96	6.10	6.25	6.30	6.39	6.34	6.34	6.08	6.12
1911	5.60	5.96	5.66	6.02	6.05	6.30	6.04	6.19	6.46	6.45	5.77	5.83	6.03
1920	5.75	5.95	5.52	6.30	6.31	6.46	6.19	6.34	6.30	6.32	6.25	6.07	6.15

From Table 6 it is evident that mean sea level as determined from a series of observations covering a period of a month is subject to considerable variation from month to month. Between the greatest and least values of the monthly means for the four years used in the table the difference is 1.19 feet, and within the period of any one of these years the monthly means may differ by as much as 0.9 foot. Even the mean values determined from 12 months of observations show differences from year to year, as evidenced by the last column of Table 6. This fact is brought out by Table 7, in which the yearly values of sea level from 1893 to 1922 are given.

TABLE 7.—*Sea level on staff, Fort Hamilton: Annual means 1893 to 1922*

Year	Feet	Year	Feet	Year	Feet
1893	5.86	1903	6.05	1913	5.90
1894	5.90	1904	5.90	1914	6.03
1895	5.83	1905	5.86	1915	6.08
1896	5.91	1906	5.97	1916	6.04
1897	5.98	1907	5.92	1917	6.07
1898	6.00	1908	5.89	1918	6.05
1899	5.99	1909	6.02	1919	6.22
1900	5.85	1910	6.08	1920	6.15
1901	6.08	1911	6.03	1921	6.17
1902	6.12	1912	5.85	1922	6.07
Sum	59.52	Sum	59.57	Sum	60.78
Mean	5.95	Mean	5.96	Mean	6.08

A glance at Table 7 shows that sea level from year to year varies by not inconsiderable amounts. For the 30 years from 1893 to 1922 the difference between the greatest and least values of the annual sea level is 0.39 foot. Dividing the observations into 10-year groups, there is a difference of 0.13 foot between the first and last of these groups. For the two overlapping 19-year periods—1893 to 1911 and 1904 to 1922—we derive 5.96 feet for the first period and 6.02 feet for the second period. The mean value for the entire period of observations is 6.00 feet, and this may be taken as the best determined value for sea level at Fort Hamilton, referred to the tide staff used in the observations.

Adopting 6.00 feet on the staff at Fort Hamilton as the value of mean sea level, it is seen that during the first 16 years of the observations sea level was the greater part of the time below the mean value, while during the last 14 years it was above the mean value with but two exceptions. During these years sea level was lowest in 1895 and highest in 1919.

Changes in meteorological conditions are reflected by changes in sea level, and since meteorological conditions vary from year to year the variation in the height of sea level brought out by Table 7 must be ascribed, in large part if not wholly, to variations in meteorological conditions. The apparent rise of sea level since 1909 does not necessarily represent a corresponding subsidence of the land. It is to be noted, too, that from its maximum value in 1919 sea level has been gradually falling, the value for 1922 being 0.15 foot lower. In this connection it is to be noted that tidal observations indicate that within the past 30 years sea level attained its maximum height in 1919 all along the Atlantic coast from Maine to Florida.

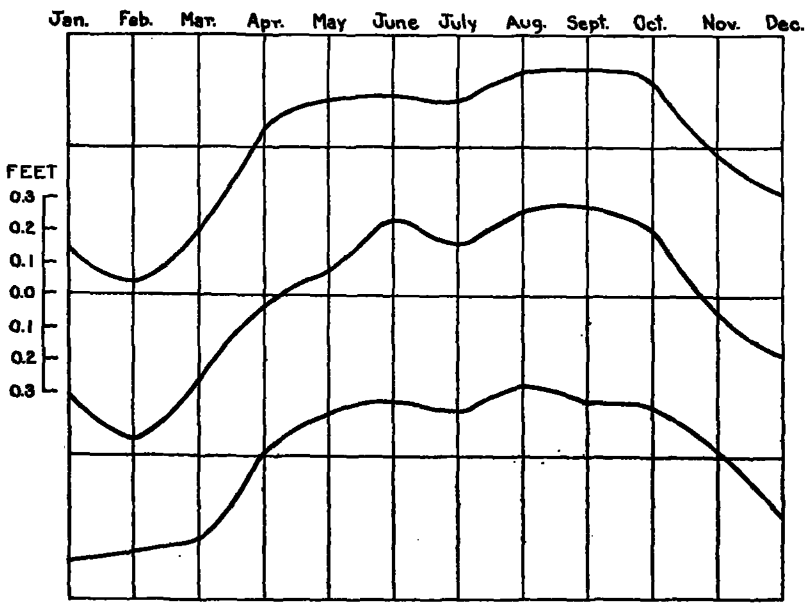

FIG. 9.—Annual variation in sea level at Fort Hamilton, by 10-year periods

It appears, therefore, that sea level varies from day to day, from month to month, and from year to year. Strong winds or sudden changes in atmospheric pressure may bring about very considerable variations in sea level from day to day. The variations from year to year are undoubtedly due to variations in meteorological conditions, but whether these possess any periodicity is not yet evident. The variation in sea level from month to month, however, exhibits very considerable periodicity. A glance at Table 6 brings out the fact that sea level is lowest in winter months, with a minimum generally in January or February, and highest in the summer months, with the maximum generally in August or September. Sea level, then, is subject to an annual variation. For any one year the regularity of this variation may be masked by accidental or unusual meteorological conditions; but if a number of years are averaged the accidental variations will tend to balance out. For purposes of comparison we may divide the observations into three groups of 10 years and derive the average monthly heights of sea level for each of these groups. Figure 9 gives the results in diagrammatic form.

The three curves of Figure 9 exhibit irregularities, but these are of a minor character. The similarities of the curves are so decided that there can be no question of the periodic nature of the variation. If now we group the 30 years of observations into two overlapping 19-year groups—1893 to 1911 and 1904 to 1922—and derive the average monthly means of these two groups these means will furnish the best data for determining the annual variation. This is shown in diagrammatic form in Figure 10.

The curve of Figure 10 shows the height of sea level to be lowest about the middle of February and highest about the beginning of September, the difference being 0.62 foot. The curve also indicates a secondary maximum and minimum in June and July, which is evidence that there are several periods involved. This is brought out by the harmonic constants as will be seen later.

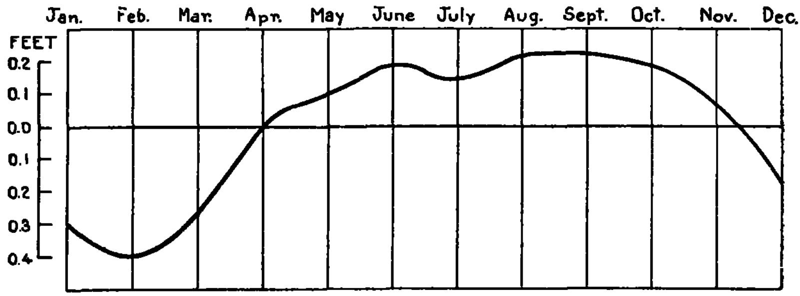

FIG. 10.—Annual variation in sea level, Fort Hamilton, from 30 years of observations

THE PLANES OF HIGH WATER

The height to which high water rises varies from day to day, principally in accordance with the varying positions of the moon relative to earth and sun. At times of new and full moon, when the so-called spring tides occur, high water rises higher than usual; and when the moon is in its first and third quarters the rise of high water is less than usual. Likewise at the times when the moon is in perigee high water rises higher than the average, while at the times of the moon's apogee the rise is lower than the average. Changes in the moon's declination also bring about a difference in the heights of the two high waters of a day. And apart from these variations due to astronomic causes there is also a variation brought about by wind and weather. We may therefore have various planes of high water—spring high water, neap high water, perigean high water, apogean high water, higher high water, lower high water, mean high water, or some arbitrary storm high water. The term "high-water plane" by itself is not precise, for it does not indicate what high-water plane is referred to.

Of all the high-water planes, the one most easily determined is the plane of mean high water. This plane is determined as the average of all the high waters over a considerable period of time. The height to which high water rises varies from day to day; for a typical summer month the daily variation in the height of high water is shown in the ninth column of Table 1. When determined from a month of observations, the plane of high water can not be considered other than approximate, even though undisturbed by storms during this period. During any one year the monthly means of high water may differ from each other by as much as a foot. The monthly means for four years—1893, 1902, 1911, and 1920—are shown in Table 8. The means are for the first 29 days of each month.

TABLE 8.—*Monthly mean high water on staff, Fort Hamilton, for 1893, 1902, 1911, and 1920*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Means
	Feet	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*
1893	7.81	7.42	7.93	8.22	8.24	8.31	8.07	8.35	8.25	8.34	8.10	7.66	8.06
1902	7.96	8.10	8.50	8.44	8.34	8.47	8.64	8.70	8.71	8.73	8.65	8.44	8.47
1911	7.87	8.18	7.92	8.34	8.31	8.64	8.35	8.47	8.67	8.65	8.05	8.15	8.30
1920	8.11	8.30	7.93	8.73	8.71	8.82	8.61	8.72	8.67	8.69	8.58	8.48	8.53

Between the greatest and least values of the monthly means for the four years given in Table 8 the difference is 1.40 feet, and even the mean values determined from a whole year of observations exhibit considerable differences as evidenced by the last column of the table. The height of the plane of high water on staff for each year from 1893 to 1922 is shown in Table 9.

TABLE 9.—*Mean high water on staff, Fort Hamilton: Annual means, 1893 to 1922*

Year	Feet	Year	Feet	Year	Feet
1893	8.06	1903	8.42	1913	8.15
1894	8.10	1904	8.29	1914	8.27
1895	8.03	1905	8.23	1915	8.34
1896	8.15	1906	8.31	1916	8.33
1897	8.23	1907	8.27	1917	8.38
1898	8.26	1908	8.21	1918	8.40
1899	8.27	1909	8.33	1919	8.56
1900	8.17	1910	8.38	1920	8.53
1901	8.39	1911	8.30	1921	8.55
1902	8.47	1912	8.12	1922	8.47
Sum	82.13	Sum	82.86	Sum	83.98
Mean	8.21	Mean	8.29	Mean	8.40

Table 9 shows that the plane of high water varies from one year to the next by as much as 0.22 foot. Several factors conspire to bring about this variation. One of these obviously is the change in sea level from year to year, for it is about the plane of sea level that the tide oscillates. This variation in the plane of high water may be eliminated by referring the height of high water to sea level, which may be done by subtracting the values of Table 7 from the corresponding values of Table 9. The results are shown in Table 10.

TABLE 10.—*Mean high water above sea level, Fort Hamilton: Annual means, 1893 to 1922*

Year	Feet	Year	Feet	Year	Feet
1893	2.20	1903	2.37	1913	2.25
1894	2.20	1904	2.39	1914	2.24
1895	2.20	1905	2.37	1915	2.26
1896	2.24	1906	2.34	1916	2.29
1897	2.25	1907	2.35	1917	2.31
1898	2.26	1908	2.32	1918	2.35
1899	2.28	1909	2.31	1919	2.34
1900	2.32	1910	2.30	1920	2.38
1901	2.31	1911	2.27	1921	2.38
1902	2.35	1912	2.27	1922	2.40
Sum	22.61	Sum	23.29	Sum	23.20
Mean	2.26	Mean	2.33	Mean	2.32

The height of high water above sea level in Table 10 shows a gradual increase till 1904, after which it decreases to 1914 and then begins to increase again. This periodic change, which is seen to occupy a period of about 20 years, is due to the variation in the longitude of the moon's node. This brings about a change in the inclination of the lunar orbit to the plane of the earth's equator which varies from 18°.3 to 28°.6, the average period of this variation being 18.6 years. The tidal forces are less than the average at the time of maximum inclination, and hence the rise of the tide is less than average at such times. Similarly, the tidal forces are greater than the average when the lunar orbit has its minimum inclination, and at such times the rise of the tide is greater than the average.

Corrections to reduce the rise of high water to a mean value have been computed.[3] If we apply these corrections to the annual means in Table 10, we derive the following values given in Table 11:

TABLE 11.—*High water above sea level, Fort Hamilton: Annual means corrected for longitude of moon's node*

Year	Feet	Year	Feet	Year	Feet
1893	2.26	1903	2.30	1913	2.32
1894	2.26	1904	2.32	1914	2.30
1895	2.26	1905	2.31	1915	2.31
1896	2.30	1906	2.29	1916	2.32
1897	2.29	1907	2.32	1917	2.32
1898	2.28	1908	2.32	1918	2.34
1899	2.28	1909	2.33	1919	2.30
1900	2.29	1910	2.34	1920	2.33
1901	2.26	1911	2.32	1921	2.31
1902	2.29	1912	2.33	1922	2.33
Sum	22.77	Sum	23.18	Sum	23.18
Mean	2.28	Mean	2.32	Mean	2.32

It is to be expected that the values given in Table 11 should show some disagreement, since the effects of varying meteorological conditions have not been eliminated. In the last 20 years the variation in the plane of high water from year to year is well within the limits of error, and the means for the last two 10-year periods agree to the second decimal place. In view of this agreement, the difference of 0.04 foot in the mean of the first 10-year period must be regarded as

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

indicating a rise in the level of the plane of high water. Taking the last 19 years—1904 to 1922—the plane of mean high water is determined as 2.32 feet above the plane of mean sea level.

Since sea level is subject to an annual variation, which makes it higher in summer and lower in winter, we may expect to find a like variation in the height to which high water rises. A glance at Table 8 bears this out, and in Figure 11 the annual variation in mean high water, as it appears from the mean of the two 19-year groups of observations—1893 to 1911 and 1904 to 1922—is shown in diagrammatic form.

The annual variation in the plane of high water resembles closely that exhibited by the plane of mean sea level, as a comparison of Figures 10 and 11 shows. High water is lowest about the middle of February and highest about the beginning of September, the difference being 0.66 foot. This compares with a difference of 0.62 foot for sea level for the same months. The secondary maximum and minimum in June and July, to which attention was directed in Figure 10, are also duplicated in Figure 11. We may therefore conclude that the annual variation in the height of high water is due directly to this variation in the plane of mean sea level.

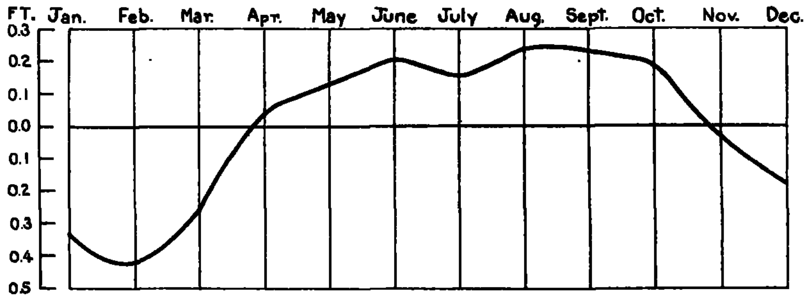

FIG. 11.—Annual variation in high water at Fort Hamilton.

The plane of mean high water being the average height of all the high waters, it follows that we may determine tidal high-water planes above and below the plane of mean high water. The planes of spring high water and neap high waters are such planes. The plane of spring high water is determined as the average over a considerable period of time of all the high waters that come at the time of the spring tides, and these tides, it is to be recalled, are the ones that occur a little after the times when the moon is full or new. The lag in the occurrence of spring tides with reference to new or full moon is known as the phase age of the tide, and the exact determination of this and the other "ages" of the tide will be taken up later. Here it will be sufficient to state that the phase age for Fort Hamilton is about 27 hours; that is, spring tides occur about a day after new or full moon.

For determining the heights of the spring high waters it is customary to take the two consecutive high waters which fall nearest the time given by adding the phase age of the tide to the times of new and full moon. This gives for any month four heights for the spring high water for that month. These heights, too, it is to be recalled, are affected by the moon's parallax, declination, and any accidental meteorological conditions. It is therefore obvious that the heights of the spring high waters, as determined from a month of observations, may differ considerably from that determined from another month. To determine this plane with any degree of precision from high and low water observations requires a series extending over a considerable number of years. From 17 years of observations—1893 to 1909, inclusive—spring high water on the Fort Hamilton staff read 8.68 feet. For this period Table 7 shows the height of mean sea level on staff to have been 5.95 feet; hence, at Fort Hamilton the plane of spring high water is 2.73 feet above the plane of mean sea level.

From the fact that the plane of mean high water exhibits the same annual variations as that of mean sea level we may conclude that the plane of spring high water will do likewise, and a study of the monthly values for this plane brings this out. We may therefore accept this conclusion without detailed consideration.

The plane of spring high water may also be derived from the harmonic constants by means of the formulae developed by Harris.[3] When harmonic constants are at hand, this method is much less time-consuming than the method of direct tabulation, but the results from the harmonic constants generally differ somewhat from the results of direct tabulation. For Fort Hamilton there are at hand harmonic analyses for the years 1900 and 1904. From the 1900 analysis the plane of spring high water is 2.71 feet above mean sea level and from the 1904 analysis it is likewise 2.71 feet. This compares with 2.73 feet derived from the direct tabulation of the spring high waters from 1893 to 1909, and we may therefore take the plane of spring high water at Fort Hamilton as 2.72 feet above mean sea level. On the average, therefore, the rise of spring high water above mean sea level is 17 per cent greater than that of mean high water.

If in the preceding paragraphs relating to spring high water we substitute for new and full moon the moon's first and third quarters, we derive the plane of neap high water. From direct tabulation of the series 1893 to 1909 this plane is found to be 1.87 feet above mean sea level and from the harmonic constants for the two years 1900 and 1904, 1.84 feet. A mean of the two results gives 1.86 feet, which we may take as the height of the plane of neap high water above mean sea level. With respect to mean sea level, therefore, the rise of neap high water is on the average 20 per cent less than that of mean high water.

The periodic variation in the moon's distance from the earth gives rise to another set of tidal planes, namely, the planes of perigean and apogean high water. Perigean and apogean tides come about a day after the corresponding positions of the moon. The direct tabulation of the perigean high waters for the years 1893 to 1909 gives the plane of perigean high water as 2.97 feet above mean sea level, while the harmonic constants for 1900 and 1904 give, through Harris's formulae[4] 2.70 feet. The discrepancy between the two being considerable, it appears best to take a weighted mean, although it is difficult to assign other than arbitrary weights. Giving the result from the direct tabulation a weight twice that assigned to the result from the harmonic constants, we derive for the plane of perigean high water a height of 2.88 feet above mean sea level. For the plane of apogean

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

high water the direct tabulation of the series 1893 to 1909 gives 1.86 feet above mean sea level, while the harmonic constants for 1900 and 1904 give 1.88 feet above. The mean of the two gives for the plane of apogean high water 1.87 feet above mean sea level. With respect to mean sea level, the rise of perigean high water is, on the average, 24 per cent greater and the rise of apogean tides 19 per cent less than that of mean high water.

The periodic fortnightly change in the moon's declination gives rise to four tidal high water planes, namely, the planes of higher high water, lower high water, tropic higher high water, and tropic lower high water. Since these datum planes depend on the moon's declination, they are called declinational planes. Of the two high waters of each day the average height of the higher over a considerable period of time determines the plane of higher high water, while the average height of the lower determines the plane of lower high water. The planes of tropic higher high and lower high water are determined, respectively, as the average heights of the higher high and lower high waters that occur at times of tropic tides; that is, the tides coming at the times of the moon's semimonthly maximum declination.

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. From two years of direct tabulation—1921 and 1922—the plane of higher high water lies 0. 35 foot above the plane of mean high water, or 2. 67 feet above mean sea level, while the harmonic constants from the analyses for two years (1900 and 1904) give 2.63 feet. We may therefore take the plane of higher high water as lying 2.65 feet above mean sea level. The plane of lower high water, it is obvious, lies as much below the plane of mean high water as the plane of higher high water is above. Hence, the plane of lower high water at Fort Hamilton lies 1.99 feet above the plane of mean sea level.

For the tropic higher high water plane there are at hand the direct tabulations of 17 years of observations—1893 to 1909—and the results from the harmonic analyses for two years, 1900 and 1904. The plane of tropic higher high water from the former is 2.74 feet above mean sea level, while from the harmonic constants, it is 2.66 feet. The mean of the two gives 2.70 feet, or a rise for the tropic higher high water of 16 per cent greater than the mean high water. For the plane of tropic lower high water the direct tabulation gives 1.75 feet above mean sea level, while the harmonic constants give 1.67 feet. The mean of the two gives 1.71 feet, or a rise for the tropic lower high water of 26 per cent less than mean high water.

Another high-water plane which is of importance is that of extreme or storm high water. This is not strictly a tidal datum plane, for the highest tides are generally due to storms. It is to be noted, however, that in raising the height of the water the effect of storms at times of spring or perigean tides, when the height of the water is above the average, will be greater than at times of neap or apogean tide. Hence, the datum plane of extreme high water must be somewhat arbitrarily defined. Any high water that is a certain adopted percentage above mean high water may be defined as an extreme high water, but it appears best to adopt a different basis of definition. Here we shall apply the term extreme high water to the highest tide of each month. The plane of extreme high water under this definition will, therefore, for any given year, be determined as the average of the 12 highest tides, one for each month. At first thought it might appear as if this plane would exhibit very considerable variation from year to year, since but 12 heights enter into the determination of this plane for any year. A glance at Table 12, however, shows that this is not the case. For each year the value in the second column is the average height, above mean sea level of the 12 highest tides, one for each month, while the third and fourth columns give the date and height of the highest tide of the year.

TABLE 12.—*Extreme high water above mean sea level, Fort Hamilton: Annual means and highest*

Year	Average	Highest		Year	Average	Highest		Year	Average	Highest	
	Feet	*Date*	*Feet*		*Feet*	*Date*	*Feet*		*Feet*	*Date*	*Feet*
1893	3.92	Aug. 24	5.0	1903	4.26	Oct. 10	5.5	1913	3.96	Dec. 26	5.1
1894	4.20	Dec. 27	5.0	1904	4.13	Mar. 1	4.7	1914	4.25	Feb. 14	[2] 5.1
1895	3.73	Jan. 26	4.6	1905	4.00	Jan. 25	5.0	1915	4.22	Jan. 13	[3] 4.9
1896	4.08	Oct. 12	5.4	1906	4.21	Feb. 9	4.8	1916	3.99	June 16	4.5
1897	4.08	Oct. 25	5.2	1907	3.90	Dec. 2	4.5	1917	4.02	Oct. 24	5.2
1898	4.18	Oct. 19	5.0	1908	4.13	Apr. 30	5.1	1918	4.28	Apr. 11	6.1
1899	4.02	Feb. 8	5.1	1909	4.29	Dec. 26	5.2	1919	4.30	Nov. 8	5.5
1900	3.91	Dec. 4	4.6	1910	4.17	Feb. 12	4.8	1920	4.42	Feb. 5	5.7
1901	4.17	Nov. 24	5.9	1911	3.92	Nov. 7	4.7	1921	4.21	Nov. 29	5.0
1902	4.40	Apr. 8	5.3	1912	4.01	Apr. 2	[1] 4.5	1922	4.27	Jan. 29	5.2
Sums	40.69	----------	51.1	Sums	41.02	----------	48.8	Sums	41.92	----------	52.3
Means	4.07	----------	5.11	Means	4.10	----------	4.88	Means	4.19	----------	5.23

[1] Same height on Nov. 24. [2] Same height on Dec. 7. [3] Same height on Feb. 2.

As determined for periods of 10 years, the plane of extreme high water shows relatively little variation, but it is interesting to note that as in the case of the plane of mean high water an increased elevation is shown for the last 10-year group over the first 10-year group. If, for the best determined plane of extreme high water, we adopt the mean of the 30 years of observations, we derive a value of 4.12 feet above mean sea level. This means that the rise of extreme high water as defined above is 78 per cent greater than that of mean high water.

THE PLANES OF LOW WATER

For each of the high-water datum planes discussed in the previous section there is a corresponding low-water datum plane. It will therefore be unnecessary to go into details of definitions and methods of determination of these datum planes. The plane of mean low water is the most important of the low-water planes. This plane exhibits variations from day to day and from month to month much as the plane of high water. The variation from year to year is shown in Table 13.

TABLE 13.—*Low water on staff, Fort Hamilton: Annual means 1893 to 1922*

Year	Feet	Year	Feet	Year	Feet
1893	3.57	1903	3.59	1913	3.57
1894	3.62	1904	3.45	1914	3.69
1895	3.54	1905	3.42	1915	3.71
1896	3.60	1906	3.55	1916	3.64
1897	3.65	1907	3.49	1917	3.65
1898	3.66	1908	3.48	1918	3.63
1899	3.65	1909	3.66	1919	3.77
1900	3.48	1910	3.71	1920	3.66
1901	3.67	1911	3.66	1921	3.69
1902	3.68	1912	3.49	1922	3.57
Sum	36.12	Sum	35.50	Sum	36.58
Mean	3.61	Mean	3.55	Mean	3.66

The variation from year to year in the plane of mean low water, shown in Table 13, is similar to that of mean high water shown in Table 9, and, like the plane of high water, part of the variation is to be ascribed to the variation in sea level from year to year. By referring the plane of low water to that of sea level, the variations due to changes of sea level will be eliminated. This may be done by subtracting the values of Table 13 from the corresponding values of Table 7. The results are shown below in Table 14.

TABLE 14.—*Low water below sea level, Fort Hamilton: Annual means 1893 to 1922*

Year	Feet	Year	Feet	Year	Feet
1893	2.29	1903	2.46	1913	2.33
1894	2.28	1904	2.45	1914	2.34
1895	2.29	1905	2.44	1915	2.37
1896	2.31	1906	2.42	1916	2.40
1897	2.33	1907	2.43	1917	2.42
1898	2.34	1908	2.41	1918	2.42
1899	2.34	1909	2.36	1919	2.45
1900	2.37	1910	2.37	1920	2.49
1901	2.41	1911	2.37	1921	2.48
1902	2.44	1912	2.36	1922	2.50
Sum	23.40	Sum	24.07	Sum	24.20
Mean	2.34	Mean	2.41	Mean	2.42

The annual means of Table 14 exhibit, from year to year, the variation found in the high waters in Table 10; namely, a regular increase and decrease over a period of about 20 years. In 1894 the plane of low water was 2.28 feet below sea level. For the following nine years the plane fell to an increasingly lower level, reaching in 1903 its minimum value, after which it began rising again. This periodic change in the fall of low water, like the corresponding change in the rise of high water, is brought about by the variation of the longitude of the moon's node, the period of which is 18.6 years. To determine, therefore, whether there has been any change in the plane of mean low water, it is necessary to correct the annual values for the variation in the longitude of the moon's node. Tabular values for this correction may be found in Harris's Manual of Tides.[5] Correcting the values of Table 14 to a mean value we derive the figures shown below in Table 15.

[5] Part III, Coast and Geodetic Survey Report for 1894, p. 247.

TABLE 15.—*Low water below sea level, Fort Hamilton: Annual means corrected for longitude of moon's node*

Year	Feet	Year	Feet	Year	Feet
1893	2.35	1903	2.39	1913	2.40
1894	2.35	1904	2.38	1914	2.41
1895	2.36	1905	2.37	1915	2.42
1896	2.38	1906	2.37	1916	2.44
1897	2.37	1907	2.40	1917	2.43
1898	2.36	1908	2.41	1918	2.41
1899	2.34	1909	2.38	1919	2.41
1900	2.34	1910	2.41	1920	2.44
1901	2.36	1911	2.43	1921	2.41
1902	2.38	1912	2.43	1922	2.43
Sum	23.59	Sum	23.97	Sum	24.20
Mean	2.36	Mean	2.40	Mean	2.42

As in the case of the plane of mean high water, a change in the level of the plane of mean low water appears to have occurred. The difference of 0.06 foot in the mean of the last 10-year group over that of the first 10-year group must be taken to indicate a lowering of the plane of mean low water by approximately that amount. Taking

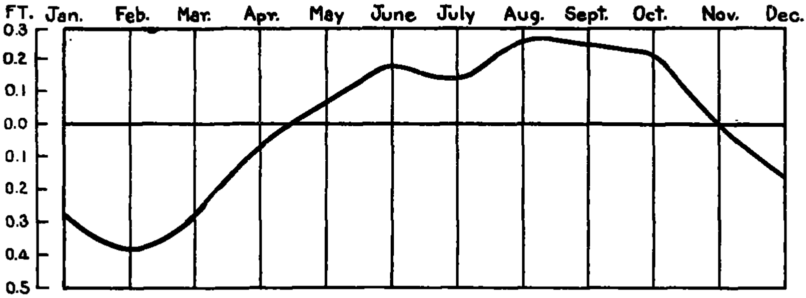

FIG. 12.—Annual variation in low water at Fort Hamilton

the last 19 years—1904 to 1922—the plane of mean low water is determined as 2.41 feet below the plane of mean sea level.

The plane of mean high water for the same period was determined to be 2.32 feet above the plane of mean sea level. We therefore find that high water and low water are not symmetrical with respect to mean sea level, the fall of low water being 0.09 foot greater than the rise of high water. This difference is to be ascribed to the fact that the tide curve is not a symmetrical curve, being made up of a number of simple cosine curves some of which have fixed phase relations with regard to each other.

The annual variation in sea level and in the height of high water is found also in the plane of mean low water. Figure 12 shows the annual variation as it is derived from the mean of two 19-year series of observation—1893 to 1911 and 1904 to 1922. A comparison of Figure 12 with Figures 10 and 11 shows that the annual variation in the plane of mean low water resembles closely the variation in the planes of mean sea level and mean high water. Low water is lowest about the middle of February and highest about the beginning of September, the difference being 0.64 foot. This compares with a difference of 0.62 foot for sea level and 0.66 foot for high water.

The secondary maximum and minimum in June and July, shown by Figures 10 and 11, are also shown in Figure 12.

For the determination of the other tidal low-water planes, we have at hand the results from the direct tabulation of the series 1893 to 1909 and also the results from the harmonic constants for 1900 and 1904. These results and the derived means are shown in Table 16. For comparison the plane of mean low water is included.

TABLE 16.—*Low water planes, Fort Hamilton: Distance below mean sea level*

Datum plane	Direct tabulation	Harmonic constants	Mean
	Feet	*Feet*	*Feet*
Mean low water	2.41		2.41
Spring low water	2.85	2.81	2.83
Neap low water	1.96	1.84	1.90
Perigean low water	2.98	2.80	2.89
Apogean low water	1.98	1.98	1.98
Lower low water [1]	2.64		2.64
Higher low water [1]	2.18		2.18
Tropic lower low water	2.64		2.64
Tropic higher low water	2.02		2.02

[1] These values are derived from three years of direct tabulation (1904, 1921, and 1922), corrected to a mean value.

In consonance with the definition of extreme high water, we may define an extreme low water as the lowest low water of a month. The average height of these extreme low waters will then determine the plane of extreme low water. Table 17 gives the average of the extreme low waters and the date and distance below mean sea level of the lowest low water for each year from 1893 to 1922.

TABLE 17.—*Extreme low water below mean sea level, Fort Hamilton: Annual means and lowest, 1893 to 1922*

Year	Average	Lowest		Year	Average	Lowest		Year	Average	Lowest	
	Feet	*Date*	*Feet*		*Feet*	*Date*	*Feet*		*Feet*	*Date*	*Feet*
1893	3.85	Feb. 21	[1] 5.0	1903	3.94	Jan. 13	5.3	1913	4.12	Jan. 4	6.0
1894	3.88	Feb. 16	4.9	1904	3.96	Feb. 3	5.6	1914	4.09	Jan. 13	6.3
1895	4.14	Feb. 8	6.0	1905	3.98	Feb. 18	5.4	1915	3.83	Dec. 26	5.1
1896	3.91	Feb. 11	5.7	1906	3.96	Mar. 11	5.6	1916	3.87	Dec. 23	5.7
1897	3.81	Dec. 25	4.7	1907	3.96	Oct. 8	4.9	1917	3.88	Dec. 10	5.0
1898	3.92	Feb. 16	5.9	1908	4.22	Feb. 2	6.5	1918	3.84	Jan. 13	4.9
1899	3.81	Feb. 11	5.9	1909	3.76	Feb. 25	5.4	1919	3.74	Mar. 28	5.2
1900	4.18	Jan. 26	5.8	1910	3.92	Dec. 16	6.0	1920	3.62	Mar. 8	4.8
1901	3.71	Feb. 5	5.0	1911	3.92	Mar. 16	5.4	1921	3.60	Jan. 25	4.9
1902	3.75	Feb. 3	4.9	1912	4.18	Jan. 6	[2] 6.3	1922	3.81	Jan. 16	4.7
Sums	38.96		53.8	Sums	39.80		56.4	Sums	38.40		52.6
Means	3.90		5.38	Means	3.98		5.64	Means	3.84		5.26

[1] Same height Mar. 16. [2] Same height Feb. 22.

The plane of extreme low water determined from 10-year groups shows relatively little variation. If we adopt as the best determination of this plane the average of the 30 years of observation, we derive 3.91 feet below mean sea level, which means that the fall of extreme low water is 62 per cent greater than that of mean low water.

For the period 1893 to 1922 the highest tide observed was 6.1 feet above sea level, while the lowest tide observed was 6.5 feet below sea level. As regards time of occurrence, Table 12 shows that the highest tide of the year generally occurs in December, while the lowest tide generally comes in February. The monthly distribution of the highest and lowest tides for the years 1893 to 1922 is shown in Table 18. The figures under the column headed "Number" give the number of times the respective tides occurred during the month, while the figures under the column headed "Per cent" give the monthly occurrence on a percentage basis.

TABLE 18.—*Month of occurrence of highest and lowest tides, 1893 to 1922*

Month	Highest tides		Lowest tides	
	Number	Per cent	Number	Per cent
January	3½	11.7	7½	25.0
February	5	16.7	12	40.0
March	1	3.3	4½	15.0
April	3½	11.7	0	0.0
May	0	0.0	0	0.0
June	1	3.3	0	0.0
July	0	0.0	0	0.0
August	1	3.3	0	0.0
September	0	0.0	0	0.0
October	5	16.7	1	3.3
November	4½	15.0	0	0.0
December	5½	18.3	5	16.7
Sums	30	100.0	30	100.0

THE PLANE OF HALF-TIDE LEVEL

The plane of half-tide level or, as it is sometimes called, the plane of mean-tide level, is the plane lying exactly halfway between the planes of mean high and mean low water. If the rise of mean high water above sea level were exactly equal to the fall of mean low water below sea level, the planes of half-tide level and mean sea level would coincide. But for Fort Hamilton we found the fall of low water to be 0.09 foot greater than the rise of high water. Hence, it follows that the plane of half-tide level lies 0.045 foot below sea level or, to the nearest second decimal, we may take the plane of half-tide level to be 0.05 foot below mean sea level.

From its definition it is obvious that the plane of half-tide level will exhibit the annual variation of the planes of mean high and mean low water. In fact, the curve of annual variation for the plane of half-tide level may be drawn as the mean of the annual variation curves of the two planes shown in Figures 11 and 12. And, since the plane of half-tide level has a constant relation to the plane of mean sea level, the variation from year to year of the former plane will follow that of the latter. For practical purposes the planes of half-tide level and mean sea level are frequently used as if there were no difference between the two; but for the sake of clearness the two must be distinguished.

THE RANGE OF THE TIDE

The extent of rise and fall of the tide or the range of the tide varies from day to day, principally in accordance with the positions of sun and moon relative to the earth. Spring tides and perigean tides bring relatively large ranges, while neap tides and apogean tides bring relatively small ranges of the tide. In fact, the various ranges of the tide may be classified in a manner similar to the datum planes. We thus have mean range, spring range, neap range, perigean range, apogean range, and several kinds of tropic ranges.

The variation in the range of the tide from day to day at Fort Hamilton for a typical summer month is shown in Table 1. The variation from year to year may be derived by subtracting from Table 9 the corresponding values in Table 13, or by adding the values of Table 10 to the corresponding values of Table 14. The results are given below in Table 19.

TABLE 19.—*Range of tide, Fort Hamilton: Annual means 1893 to 1922*

Year	Feet	Year	Feet	Year	Feet
1893	4.49	1903	4.83	1913	4.58
1894	4.48	1904	4.84	1914	4.58
1895	4.49	1905	4.81	1915	4.63
1896	4.55	1906	4.76	1916	4.69
1897	4.58	1907	4.78	1917	4.73
1898	4.60	1908	4.73	1918	4.77
1899	4.62	1909	4.67	1919	4.79
1900	4.69	1910	4.67	1920	4.87
1901	4.72	1911	4.64	1921	4.86
1902	4.79	1912	4.63	1922	4.90
Sum	46.01	Sum	47.36	Sum	47.40
Mean	4.60	Mean	4.74	Mean	4.74

The range of the tide exhibits from year to year the variation discussed in the planes of mean high and mean low water; that is, a variation in a period of 18.6 years, which brings about greater ranges when the inclination of the lunar orbit is small, and smaller ranges when the inclination is large. The corrected mean range for each year is obtained by multiplying the mean range as directly obtained from the tabulations by factors to take account of the variation in the longitude of the moon's node. The corrected mean range may also be obtained by adding the values of Table 11 to the corresponding values of Table 15. The results are shown below in Table 20.

TABLE 20.—*Mean range of tide, Fort Hamilton: Annual means corrected for longitude of moon's node*

Year	Feet	Year	Feet	Year	Feet
1893	4.61	1903	4.69	1913	4.71
1894	4.61	1904	4.70	1914	4.71
1895	4.62	1905	4.68	1915	4.74
1896	4.66	1906	4.66	1916	4.76
1897	4.66	1907	4.72	1917	4.75
1898	4.64	1908	4.72	1918	4.75
1899	4.62	1909	4.70	1919	4.72
1900	4.64	1910	4.74	1920	4.76
1901	4.63	1911	4.75	1921	4.72
1902	4.67	1912	4.76	1922	4.76
Sum	46.36	Sum	47.12	Sum	47.38
Mean	4.64	Mean	4.71	Mean	4.74

The means of the 10-year groups bring out clearly an augmented rise and fall of the tide for the last decade of 0.10 foot. This increase was found reflected in a rise of 0.04 foot in the plane of mean high water and in a lowering by 0.06 foot of the plane of mean low water. Manifestly this increase in the range of the tide is to be ascribed to the deepening of the channels leading from the sea into the Narrows, especially the improvement of Ambrose Channel, which, between 1901 and 1914, was dredged to a width of 2,000 feet and to a depth at mean low water of 40 feet. If for the mean range of the tide at Fort Hamilton we adopt the value determined by the last 19 years of observations, we derive 4.73 feet.

Each of the various ranges of the tide is easily determined as the distance between the corresponding datum planes discussed in the previous sections. The designations given to a number of these ranges are self-evident; as, for example, the mean, spring, neap, perigean, and apogean ranges. Some, however, require definition. Thus, the great diurnal range is the distance between the mean higher high water and mean lower low water, the small diurnal range is the distance between mean lower high water and mean higher low water, the great tropic range is the distance between tropic higher high water and tropic lower low water, the small tropic range is the distance between tropic lower high water and tropic higher low water, the extreme range is the distance between extreme high water and extreme low water, the greatest range is the distance between the highest observed high water and the lowest observed low water. In Table 21 the various ranges for the tide at Fort Hamilton are given.

TABLE 21.—*Tidal ranges, Fort Hamilton, N. Y.*

	Feet		Feet
Mean range	4. 73	Small diurnal range	4. 17
Spring range	5. 55	Great tropic range	5. 34
Neap range	3. 76	Small tropic range	3. 73
Perigean range	5. 77	Extreme range	8. 03
Apogean range	3. 85	Greatest range	12. 6
Great diurnal range	5. 29		

HARMONIC CONSTANTS

Harmonic analyses of the hourly ordinates of the tide at Fort Hamilton have been made for two years—1900 and 1904. The length of the series used in each case was 369 days, beginning with the first of January, the analysis being carried out in the usual manner with the effects of other components eliminated, as explained in the Manual of Tides.[6] The results from these two years are shown in Table 22 below. Several of the lesser components were derived, not from analysis, but by inference from other components. Such inferred values are inclosed in parentheses. The formula used for inferring the amplitudes and epochs are given in the Manual of Tides.[7] In Table 22 the amplitudes of the components are given in the column headed H and the amplitudes in the column headed κ.

[6] Part II, Coast and Geodetic Survey Report for 1897.

[7] Ibid., p. 554.

TABLE 22.—*Harmonic constants, Fort Hamilton*

Component	1900		1904		Component	1900		1904	
	H	*κ*	*H*	*κ*		*H*	*κ*	*H*	*κ*
	Feet	*Degrees*	*Feet*	*Degrees*		*Feet*	*Degrees*	*Feet*	*Degrees*
J_1	(0.018)	(105.6)	(0.018)	(106.5)	Q_1	(0.035)	(95.6)	0.031	87.1
K_1	0.320	103.1	0.324	104.0	2Q	(0.005)	(93.1)	(0.004)	(93.8)
K_2	0.148	244.1	0.132	235.8	R_2	(0.004)	(248.8)	(0.004)	(247.0)
L_2	(0.062)	(238.7)	0.103	231.9	S_1	0.044	68.5	0.036	58.6
M_1	0.008	86.8	0.007	123.0	S_2	0.440	248.8	0.450	247.0
M_2	2.212	221.3	2.208	220.7	S_4	0.035	75.8	0.042	63.9
M_3	0.026	202.1	--------	--------	S_6	--------	--------	0.004	140.8
M_4	0.028	333.4	0.030	345.3	T_2	(0.026)	(248.8)	0.110	156.9
M_6	0.051	35.8	0.053	34.9	λ_2	(0.015)	(234.1)	0.043	197.2
M_8	--------	--------	0.013	80.1	μ_2	(0.053)	(193.8)	0.061	235.2
N_2	0.459	203.9	0.496	204.5	ν_2	(0.089)	(206.2)	0.095	202.7
2N	(0.061)	(186.5)	(0.066)	(188.3)	ρ_1	(0.007)	(96.0)	(0.006)	(96.7)
O_1	0.178	98.1	0.167	98.9	MS	--------	--------	0.046	293.3
OO	(0.010)	(108.1)	(0.010)	(109.1)	Sa	--------	--------	0.303	132.0
P_1	0.102	102.7	0.095	109.1	Ssa	--------	--------	0.138	105.6

To determine the nature of the annual variation in sea level at Fort Hamilton, the monthly means of sea level on staff from 1893 to 1920 were divided into two 14-year groups—namely, 1893 to 1906 and 1907 to 1920—and analyzed harmonically for the following components: Sa, Ssa (or Sa_2), Sa_3, Sa_4 and Sa_6; that is, components having periods respectively of a year, a half year, four months, three months, and two months. The results of these analyses are given below in Table 23.

TABLE 23.—*Harmonic constants, Fort Hamilton, derived from annual variation of sea level*

Component	1893–1906		1907–1920	
	H	*κ*	*H*	*κ*
	Feet	*Degrees*	*Feet*	*Degrees*
Sa	0.309	135.1	0.281	135.8
Sa_2	0.113	78.7	0.085	72.5
Sa_3	0.043	120.3	0.033	158.1
Sa_4	0.053	72.1	0.005	119.5
Sa_6	0.052	143.3	0.053	140.8

The amplitudes of the components in Table 23 are small, and hence the agreement between the amplitudes and epochs of the two groups can not be expected to be as close as in the case of components with larger amplitudes. Nevertheless, with the exception of Sa_4, the agreement between the two groups is so close as to leave no doubt of the existence of these components in the tide at Fort Hamilton. And it is of interest to note that the components, Sa_3 and Sa_6, for which no provision is made in tide-predicting machines, have amplitudes as large or even larger than a number of the components usually taken into account.

The astronomic or true tidal components giving rise to the annual or semiannual variations in mean sea level are very small. As derived from the harmonic analyses of the tidal observations the magnitudes of the components must be due largely to meteorological factors. To determine this the annual variation in barometric pressure at New York City was subjected to the harmonic analysis. Monthly mean barometric pressure was used and two groups—1893 to 1906 and 1907 to 1920—corresponding to the tidal observations were analyzed. The results are shown in Table 24.

TABLE 24.—*Harmonic constants, New York City, derived from annual variation of barometric pressure*

Component	1893–1906		1907–1920	
	H	κ	*H*	κ
	Inches	*Degrees*	*Inches*	*Degrees*
Sa	0.060	254.6	0.056	248.9
Sa_2	0.014	22.3	0.010	332.6
Sa_3	0.008	205.7	0.017	194.9
Sa_4	0.018	185.8	0.009	9.1
Sa_6	0.009	323.3	0.004	320.8

If the annual variation in sea level were due wholly to the variation in local barometric pressure, and if, further, the tidal basin in the vicinity of Fort Hamilton be considered as a negative water barometer, we should expect the corresponding terms of Tables 23 and 24 to bear the following relations to each other: The amplitudes in Table 23 in feet approximately equal to the amplitudes of the corresponding terms in Table 24 in inches, and the epochs of the constants in Table 24 greater by 180° than the corresponding epochs in Table 23. It is obvious, however, that the sea level variation at any point is due, not to local barometric changes, but rather to the variations in the local pressure gradients. Hence, it is not surprising to find the relations of the constants in the two tables differing from the simple relations derived from the above assumptions. However, the existence of like components in the variations of sea level and barometric pressure may be taken as qualitative evidence that the annual variation in sea level is due, in considerable part, to the variations in barometric pressure.

The ages of the tide are most easily derived from the harmonic constants. The formulae for the various ages are as follows:

Phase age, in hours $= 0.984\,(S_2{}^\circ - M_2{}^\circ)$
Parallax age, in hours $= 1.837\,(M_2{}^\circ - N_2{}^\circ)$
Diurnal age, in hours $= 0.911\,(K_1{}^\circ - O_1{}^\circ)$

The phase age of the tide is the interval by which spring tides follow full or new moon, and thus likewise the interval by which neap tide follows the moon's first and third quarters. From the above formulae, substituting the values of the harmonic constants from Table 22, we derive for the phase age of the tide at Fort Hamilton, 26.5 hours.

The parallax age of the tide is the interval by which perigean and apogean tides follow, respectively, the corresponding positions of the moon. From the harmonic constants of Table 22 we derive for the parallax age of the tide at Fort Hamilton, 30.9 hours.

The diurnal age of the tide is the interval by which the tropic tide follows the moon's semimonthly maximum north or south declination. From the harmonic constants of Table 22 we derive for the diurnal age of the tide at Fort Hamilton, 4.6 hours.

The fact that the lunitidal intervals at Fort Hamilton only rarely vary by as much as an hour from the mean, and from the further fact that the diurnal inequality in the heights of high or low water is small, the tide here is of the semidaily type; but from the harmonic constants alone the type of the tide may be inferred, the ratio of K_1+O_1 to M_2+S_2 furnishing the criterion. As stated before, where the ratio is less than 0.25, the tide is of the semidiurnal type. For Fort Hamilton, from the constants of Table 22, the ratio is 0.19.

Another characteristic which may be determined from the harmonic constants is the order of occurrence of the tides. The formulae for that are somewhat involved,[8] and hence need not be reproduced here. These formulae show that at Fort Hamilton the order of the tides is as follows: Higher high water, lower low water, lower high water, higher low water.

EFFECTS OF WIND AND WEATHER

The average rise of extreme high water at Fort Hamilton above mean sea level was found to be 4.12 feet. That this rise is due not alone to tidal causes is evident from the following considerations. The average rise of high water is 2.32 feet; at times of spring tide this is increased 17 per cent, at times of perigean tides it is increased 24 per cent, and tropic higher high water shows an increase of 16 per cent. Hence, the rise of the tide at the time of a tropic higher high water that occurs when the moon is full or new and at the same time is also in perigee should be $17+24+16=57$ per cent greater than the average, or 3.64 feet. This, however, is about half a foot less than the average extreme high water, and we may therefore conclude that these extreme high waters are brought about by wind and weather.

For the extreme low water the average fall below mean sea level was found to be 3.91 feet, while the fall of mean low water is 2.41 feet. From Table 16 we find that spring tides fall 17 per cent below mean low water, perigean tides 20 per cent below, and tropic lower low water 10 per cent below. Hence, the greatest fall below mean sea level due to tidal causes would occur with the tropic lower low water that came when the moon was full or new and also in perigee. At such times the low water should be $17+20+10=47$ per cent lower than mean low water, or 3.54 feet below mean sea level. The average extreme low water, however, falls very nearly half a foot below this; and, as in the case of the extreme high water, we may conclude that extreme low waters are also brought about by wind and weather.

By noting the weather that prevailed on the days during which the highest and lowest tides of the various years occurred, as listed in Tables 12 and 17, we find that the highest high waters generally came with northwesterly winds. Furthermore, the highest high waters almost invariably came with a falling barometer, while the lowest low waters came with a rising barometer.

It is important to note that the extreme tides due to wind and weather are brought about not by an augmented rise or fall of high or low water, but by an unusual rise or fall of sea level. In other words, it is the effect of wind and weather on sea level and not on the rise and fall of the tide that brings an extreme high or low water.

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[8] See Manual of Tides, Part II, Coast and Geodetic Survey Report for 1894, p. 145.

This is evident from a consideration of the highest high water and lowest low water observed at Fort Hamilton during the period of observations.

The highest high water at Fort Hamilton for the period 1893 to 1922 occurred on April 11, 1918, when the tide rose 6.1 feet above mean sea level, or 3.8 feet above the average high water. Insofar as the true or astronomic tide for that day was concerned, it should have been 3.6 feet above sea level, or 50 per cent greater than the average, due to the fact that on April 10 the moon was new and also in perigee. High water should have risen 7.9 feet from the previous low water and fallen 7.0 feet to the succeeding low water. The tide gauge record for Fort Hamilton shows that the high water on April 11 rose 7.1 feet from the previous low water and fell 6.8 feet to the succeeding low water. The exceptional height of the tide, therefore, on that day can not be ascribed to an exceptional rise of high water. If we derive the height of sea level for the day in question, we find that it was 2.4 feet above its mean level. From April 6 sea level gradually rose until the 11th, from which day it fell until the 14th, when it attained its mean value again.

The lowest low water at Fort Hamilton for the period 1893 to 1922 occurred on February 2, 1908, when low water fell 6.5 feet below mean sea level, or 4.1 feet below mean low water. The true or astronomic tide on that day should have fallen 3.3 feet below mean sea level, or 37 per cent more than the average, due to the fact that on February 1 the moon was in perigee and on the 2d the moon was new. The tide in question should have fallen 6.7 feet from the previous high water and risen 6.0 feet to the succeeding high water. The Fort Hamilton tide gauge record for February 2, 1908, shows the tide to have fallen 6.8 feet from the previous high water and then to have risen 6.2 feet to the succeeding high water. The actual rise and fall, therefore, agrees closely with that derived from computation, and hence the abnormal depth to which low water fell must be looked for in an unusual subsidence of sea level. If we derive sea level for February 2, 1908, we find that it was 2.8 feet below its mean level.

In the two instances discussed above wind and weather appear to have had practically no effect at all on the range of the tide, the extreme tides in question appearing to be accounted for wholly by the change in sea level. It is evident, however, that with rapidly varying meteorological conditions changes in sea level between the times of high and low water must bring about changes in the range of tide. In other words, while extreme tides are due to the effect of wind and weather on sea level, rapidly changing weather conditions will be reflected not only in change of sea level but also in a disturbance of the range of the tide.

Apart from the effects on the height of the tide, wind and weather bring about irregularities in the times of high and low water, disturbing the regularity of rise and fall. An example of this is brought out in Figure 13, the upper curve of which represents the mean rise and fall of the tide for Fort Hamilton, while the lower curve represents the rise and fall of the tide at Fort Hamilton for December 13 to 14, 1917, on which days heavy northeast and northwest winds prevailed. To make the tide curves comparable in time, they are referred to the time of the moon's transit over the meridian of Fort Hamilton, zero hours being the instant of the moon's upper meridian passage. For the lower curve zero hours correspond to 11:10 a. m. on December 13, 1917.

Considering, first, the time of tide, it is seen that for the first six hours the two tide curves agree very closely. From that time on the increasing velocity of the wind on December 13, 1917, is reflected in a disturbed condition of the tide, the high water being retarded by an hour and the following low water by four hours. This very considerable disturbance in the time of low water was evidently caused by a rapid rise of sea level between 12^h and 15^h (11 p. m. December 13 and 2 a. m. December 14, 1917). The weather record shows heavy northwesterly winds for the early hours of December 14 between 2 and 4 a. m., a wind velocity of 88 miles per hour being recorded. With less violent winds for the remainder of the day, the following

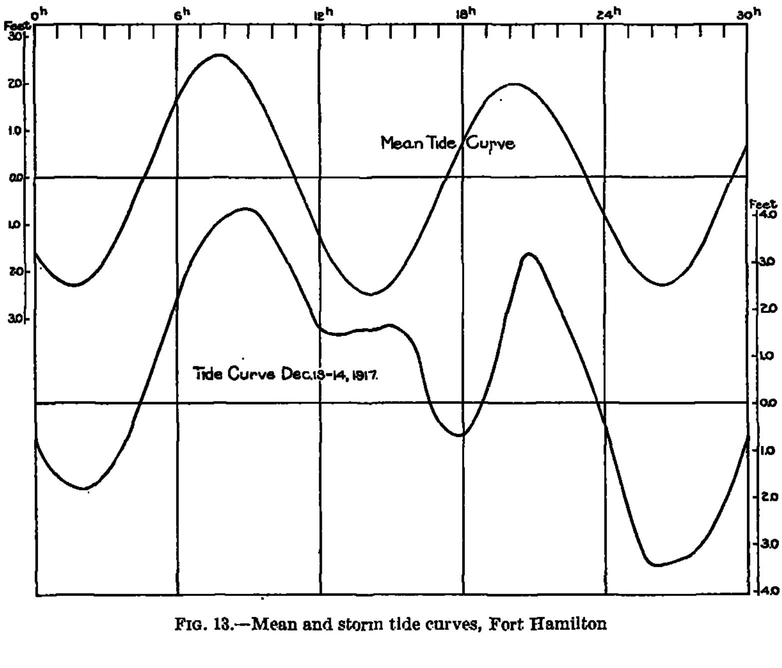

FIG. 13.—Mean and storm tide curves, Fort Hamilton

high and low waters are seen to be much less disturbed in time. The change in time of tide brought about a marked change in the durations of rise and fall. The average duration of rise at Fort Hamilton is 6.03 hours and of fall 6.39 hours. The first rise shown by the tide curve for December 13 to 14, 1917, occupied a period of 6.9 hours. This was followed by a fall of 9.1 hours, then a rise of but 2.9 hours, then a fall of 4.3 hours.

In regard to the height of the tide, it is to be noted that the zero line of heights for each of the tide curves represents mean sea level. A glance at the lower curve shows a very considerable elevation for sea level for the first half of the curve and a subsidence for the second half. For December 13, 1917, sea level stood 1 foot above its mean height, on the 14th it was 0.1 foot below its mean height, and on the 15th it was 1.3 feet below. Coincident with this rapid shifting in the height of sea level we find wide variations in the heights of the tide and consequently in the range of the tide. Beginning with the first low water shown in the curve, the undisturbed tide should have risen 4.3 feet, then fallen 4.1 feet, risen again 5.5 feet, and then fallen 5.9 feet. The effect of wind and weather was to give a rise of 6.0 feet, then a fall of 4.9 feet, followed by a rise of 4.0 feet and a fall of 6.7 feet.

SUMMARY OF TIDAL DATA

Since Fort Hamilton will be taken as the standard station for tides and currents in New York Harbor, it will be convenient to have the data relating to the principal features of the tide at Fort Hamilton assembled in one table, and this is done in Table 25.

TABLE 25.—*Tidal data, Fort Hamilton, N. Y.*

TIME RELATIONS		
High-water interval	hours	7. 67
Low-water interval	do	1. 64
Duration of rise	do	6. 03
Duration of fall	do	6. 39
Phase age	do	26. 5
Parallax age	do	30. 9
Diurnal age	do	4. 6
Sequence of tides is HHW to LLW.		
RANGES		
Mean range	feet	4. 73
Great diurnal range	do	5. 29
Small diurnal range	do	4. 17
Great tropic range	do	5. 34
Small tropic range	do	3. 73
Spring range	do	5. 55
Neap range	do	3. 76
Perigean range	do	5. 77
Apogean range	do	3. 85
Extreme range	do	8. 03
Greatest range	do	12. 6
Spring range÷mean range		1. 17
Neap range÷mean range		0. 79
Perigean range÷mean range		1. 22
Apogean range÷mean range		0. 81
Great diurnal range÷mean range		1. 12
Great tropic range÷mean range		1. 13
HEIGHT RELATIONS		
Mean high water above mean sea level	feet	2. 32
Mean higher high water above mean sea level	do	2. 65
Mean lower high water above mean sea level	do	1. 99
Tropic higher high water above mean sea level	do	2. 70
Tropic lower high water above sea level	do	1. 71
Spring high water above mean sea level	do	2. 72
Neap high water above mean sea level	do	1. 86
Perigean high water above mean sea level	do	2. 88
Apogean high water above mean sea level	do	1. 87
Extreme high water above mean sea level	do	4. 12
Highest high water above mean sea level	do	6. 1
Mean low water below mean sea level	do	2. 41
Mean lower low water below mean sea level	do	2. 64
Mean higher low water below mean sea level	do	2. 18
Tropic lower low water below mean sea level	do	2. 64
Tropic higher low water below mean sea level	do	2. 02
Spring low water below mean sea level	do	2. 83

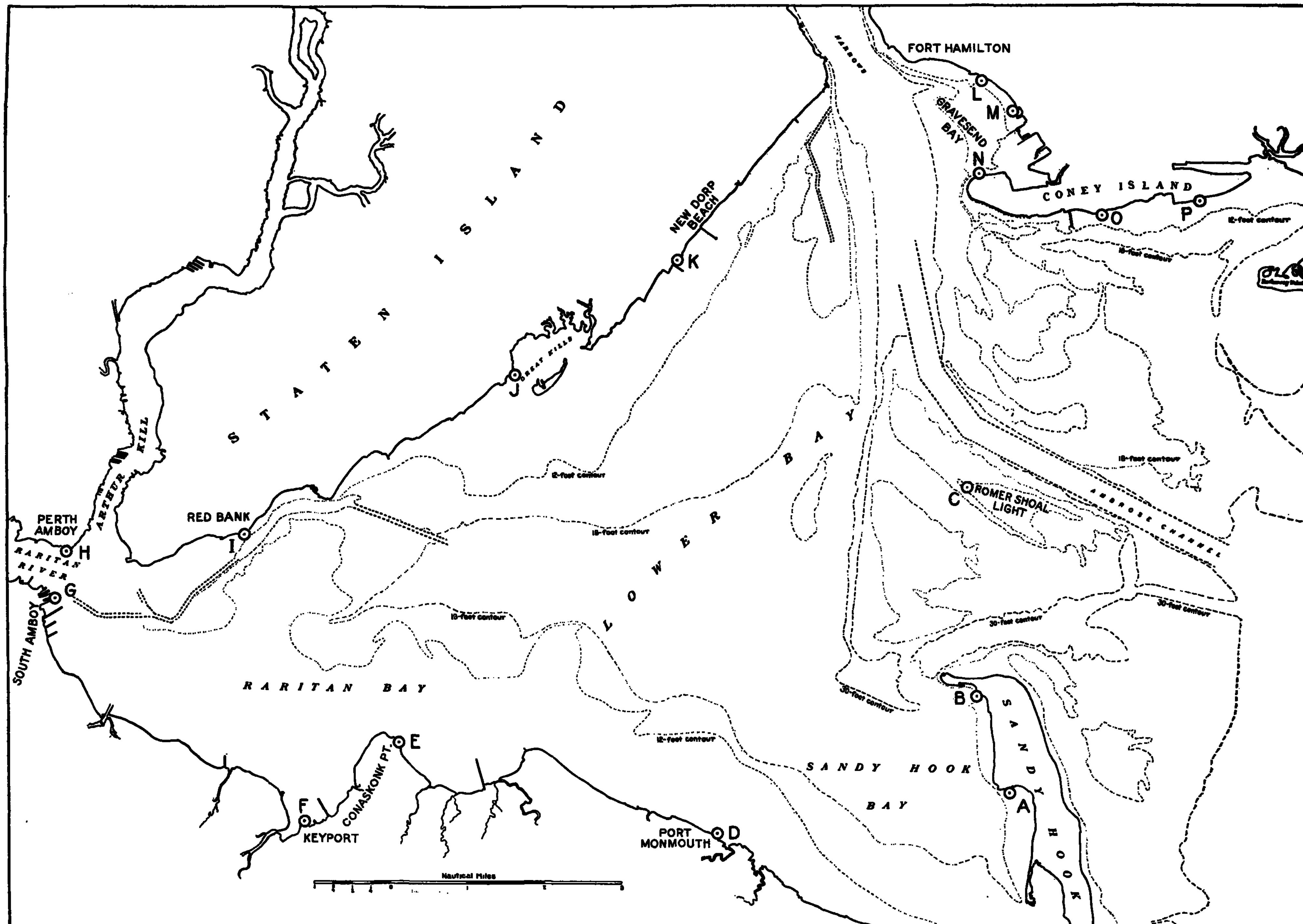

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FIG. 14.—Tide stations, Lower Bay

Neap low water below mean sea level	feet	1.90
Perigean low water below mean sea level	do	2.89
Apogean low water below mean sea level	do	1.98
Extreme low water below mean sea level	do	3.91
Lowest low water below mean sea level	do	6.5
Half-tide level below mean sea level	do	0.05

V. THE TIDE IN LOWER BAY

In connection with various operations tides have been observed in Lower Bay at a number of places at various times. The stations at which the observations have been carried on for periods of sufficient length to determine with reasonable accuracy the time and other characteristics of the tide are shown in Figure 14.

The longest series of observation in Lower Bay is that at station A in the Horse Shoe of Sandy Hook Bay. Short series of observations had been made prior to 1876, but in that year an automatic tide gauge was installed, from the records of which tabulations for the following series are at hand: (*a*) 1876 to 1881, (*b*) 1887 to 1888, (*c*) 1890 to 1892. Each of these series with the exception of (*c*) begins on the 1st of January and runs through to December 31. Series (*c*) begins on February 1 and ends on January 31. The lunitidal intervals and the mean range of the tide from these observations are shown in Table 25. In this table the mean range of the tide has been corrected for the longitude of the moon's node. It is to be noted, too, that for the range the results for the years from 1887 through 1892 are at hand.

TABLE 26.—*Lunitidal intervals and mean range of tide, Station A, Sandy Hook, N. J.*

Series	Length	HWI	LWI	Range
	Years	*Hours*	*Hours*	*Feet*
(*a*) 1876–1881	6	7.58	1.50	4.78
(*b*) 1887–1888	2	7.61	1.48	
(*c*) 1890–1892	2	7.60	1.43	
1887–1892	6			4.68
Weighted means		7.59	1.48	

In view of the difficulties encountered in the operation of tide gauges in the earlier years, we may consider the variations in the lunitidal intervals derived from the three series of observations as coming within the allowable limits of error. For the best determined values we may therefore take the weighted means, but for the mean range of the tide it is difficult to reconcile the values for the series 1876 to 1881 and 1887 to 1892. The probable explanation appears to be that there was an actual decrease in the rise and fall of the tide in the latter period brought about by the continual northward growth of Sandy Hook.

Harmonic analyses have been made of the tidal observations at Sandy Hook for the years 1876 to 1881 and 1887 to 1888. The results of these analyses likewise give evidence of the decrease in the range of the tide for the later years. From the six years—1876 to 1881—the amplitude of M_2 is 2.250 feet, while from the two years—1887 to 1888—the amplitude is 2.188 feet. For the best determined range, therefore, the results from the series 1887 to 1892 will be taken, which give a value of 4.68 feet.

In Table 27 are given the harmonic constants for station A. In deriving the mean values of these constants the results from the series 1887 to 1888 were given the same weight as those from the series 1876 to 1881. The values inclosed in parentheses have been derived not by analysis, but by inference from the values of the principal components.

TABLE 27.—*Harmonic constants, Station A, Sandy Hook, N. J.*

Component	H	κ	Component	H	κ	Component	H	κ
	Feet	*Degrees*		*Feet*	*Degrees*		*Feet*	*Degrees*
J_1	(0.019)	(104)	2N	(0.067)	(184)	T_2	(0.025)	(246)
K_1	0.333	102	O_1	0.172	98	λ_2	(0.016)	(231)
K_2	0.123	243	OO	(0.010)	(105)	μ_2	0.068	226
L_2	0.110	203	P_1	0.105	105	ν_2	0.096	199
M_1	0.016	119	Q_1	0.032	110	ρ_1	(0.005)	(273)
M_2	2.219	218	2Q	(0.004)	(95)	Sa	0.254	143
M_4	0.026	336	R_2	(0.003)	(246)	Ssa	0.101	58
M_6	0.054	353	S_1	0.032	222			
N_2	0.503	201	S_2	0.426	246			

From the harmonic constants given in Table 27, various characteristics of the tide have been determined. These are given in Table 28, in which are included also for the sake of completeness the lunitidal intervals and the mean range of the tide, as determined from direct tabulation of the high and low waters.

TABLE 28.—*Tidal data, Station A, Sandy Hook, N. J.*

High water interval	hours	7.59
Low water interval	do	1.48
Mean range	feet	4.68
Spring range	do	5.57
Neap range	do	3.69
Great diurnal range	do	5.09
Phase age	hours	28.0
Parallax age	do	30.7
Diurnal age	do	3.1
Sequence of tides is HHW to LLW.		
Spring range ÷ mean range		1.19
Neap range ÷ mean range		0.79
Great diurnal range ÷ mean range		1.09

Between 1876 and 1884 the highest tide at station A occurred on January 31, 1878, when high water rose 2.9 feet above mean high water, or 5.2 feet above mean sea level. It is to be noted, however, that on September 12, 1882, a severe storm occurred, during which the height of the water was not recorded as the tide gauge was swept away by the storm. The lowest tide between 1876 and 1884 occurred on January 23, 1828, when low water fell 3.3 feet below mean low water, or 5.6 feet below mean sea level. Between 1887 and 1891 the highest tide occurred on September 10, 1889, high water rising 6.2 feet above mean sea level. During this same period the lowest tide occurred in 1890 on January 22, when low water fell 5.4 feet below mean sea level. The greatest range observed at Sandy Hook is therefore 11.8 feet, which compares with 12.6 feet at Fort Hamilton between the years 1893 to 1922.

For station B, about a mile and a half north of station A, there are at hand the results of two years of observations, 1921 and 1922, made by the United States Engineer office. The direct results from these observations have been reduced to mean values and are given in Table 29 below.

TABLE 29.—*Tidal data, Station B, Sandy Hook, N. J.*

High water interval	hours	7.59
Low water interval	do	1.50
Mean Range	feet	4.66
Great diurnal range	do	5.20
Small diurnal range	do	4.12

The values of Table 29 agree very closely with those of Table 28. These values show that the tide at Sandy Hook resembles closely the tide at Fort Hamilton. As compared with the latter, the tide at Sandy Hook is five minutes earlier for the high waters and nine minutes earlier for the low waters and has a range 1½ per cent less than that of Fort Hamilton.

It is to be noted that, in general, the direct difference between the lunitidal intervals at two stations does not give the difference in time of tide at the two stations. Only if the two stations have the same longitude does the direct difference of the intervals give the difference in time of tide, but when the stations have different longitudes a correction for this difference must be applied. Since the average period of the moon's apparent revolution about the earth is 24.84 hours, the time taken for the moon to travel 1° of longitude is $24.84 \div 360 = 0.069$ hour. Hence, the correction to be applied for the difference in longitude is $0.069\ (L_{,} - L_{,,})$, in which $L_{,}$ and $L_{,,}$ are the longitudes in degrees of the two stations. If both stations are in west longitude, the above correction may be added to the interval of the station having the greater longitude, and the difference in intervals will then give the difference in time of tides.

The tidal data for Lower Bay for the stations shown on Figure 15 are given on Table 30. With the exception of station A, the intervals and ranges given have been reduced to mean values by comparison with simultaneous observations at some stations like Fort Hamilton or Sandy Hook. For the sake of completeness the data for stations A and B are also included.

TABLE 30.—*Tidal data, Lower Bay*

Station	Locality	Lunitidal intervals		Duration of rise	Mean range	Observations	
		High water	Low water			Year	Length
		Hours	*Hours*	*Hours*	*Feet*		
A	Sandy Hook, N. J	7.59	1.48	6.11	4.68	1876–1892	12 years.
B	do	7.59	1.50	6.09	4.66	1921–22	2 years.
C	Romer Shoal Light, N. Y	7.48	1.37	6.11	4.63	1922	3 months.
D	Port Monmouth, N. J	7.53	1.78	5.75	4.65	1886	4 days.
E	Conaskonk Point, N. J	7.57	1.63	5.94	5.02	1886	Do.
F	Keyport, N. J	7.52	1.55	5.97	4.98	1870	14 days.
G	South Amboy, N. J	7.75	1.83	5.92	5.07	1886	10 days.
H	Perth Amboy, N. J	7.95	1.89	6.06	5.28	1873	1 month.
I	Red Bank, N. Y	7.40	1.43	5.97	5.22	1886	Do.
J	Great Kills, N. Y	7.50	1.53	5.97	5.07	1886	5 days.
K	New Dorp Beach, N. Y	7.55	1.62	5.93	4.82	1919	3 days.
L	Gravesend Bay, N. Y	7.52	1.60	5.92	4.64	1886–87	3 months.
M	do	7.67	1.48	6.19	4.53	1881–86	1 month.
N	Norton Point, N. Y	7.45	1.23	6.22	4.87	1919	2 days.
O	Coney Island, N. Y	7.65	1.33	6.32	4.92	1908	1 month.
P	do	7.50	1.15	6.35	4.82	1920	3 months.

From the data of Table 30 it is seen that the time of tide in Lower Bay changes but little, the difference between Romer Shoal Light and the entrance to Raritan River being less than half an hour. Toward the western end of the bay the tide exhibits to a greater degree the characteristics of river tides, as shown by the duration of rise becoming relatively shorter. Toward the western end, also, the range of the tide increases, and this obviously is to be ascribed to the rapidly converging shore lines which concentrate the energy of the tide in a smaller volume, and thus gives a greater rise and fall.

A comparison of the tidal ranges on the north and south shores of Lower Bay brings to light the fact that, relative to the axis of the bay, a point on the northern shore has a greater range than the corresponding point on the southern shore. Thus, stations A and B have ranges less than 4.7 feet, while stations N and O have ranges greater than 4.8 feet; the range at station D is 4.63 feet against 4.82 feet at station J.

This increase in range of tide on the northern shore is brought about by the rotation of the earth, as a consequence of which all moving bodies are impressed with a force deflecting them to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. On the rising tide the water moving into Lower and Raritan Bays is deflected to the right or northern shore. Hence, high water here is raised somewhat higher than on the southern shore. On the falling tide the moving water is again deflected to the right, but now it is the southern shore that is to the right of the moving water, and hence low water is somewhat higher on the southern than on the northern shore. The tide, therefore, rises higher and falls lower on the northern shore, giving a greater range here than on the southern shore.

It will be noted from Tables 25 and 28 that the ratios of the spring, neap, and great diurnal ranges to mean range are practically the same at Fort Hamilton and at Sandy Hook. We may therefore assume that throughout Lower Bay the ratios of the various ranges to mean range are the same as at Fort Hamilton, and these ratios can thus be used for determining the various ranges at any of the stations listed in Table 30. Apart from the range and lunitidal intervals the tide in Lower Bay is much like that at Fort Hamilton, and the features of the tide at the latter place may be taken as characterizing the tide also in Lower Bay.

VI. THE TIDE IN THE NARROWS AND UPPER BAY

On Figure 15 are shown the stations at which tidal observations have been made in the Narrows and Upper Bay. The observations at station A, Fort Hamilton, were discussed in Section IV. At station E, Governors Island, observations were made over a period of 33 years, from 1847 to 1879, an automatic tide gauge being used from 1853; but because of the difficulties encountered in the operation of tide gauges in the earlier years this series does not lend itself to a detailed discussion of the tidal data. From these observations at Governors Island there are at hand the results of the tabulations of high and low water for 19 years, from 1860 to 1879, and also the harmonic analyses of three years of observations. An harmonic analysis has also been made of one year's observations at the Battery, station

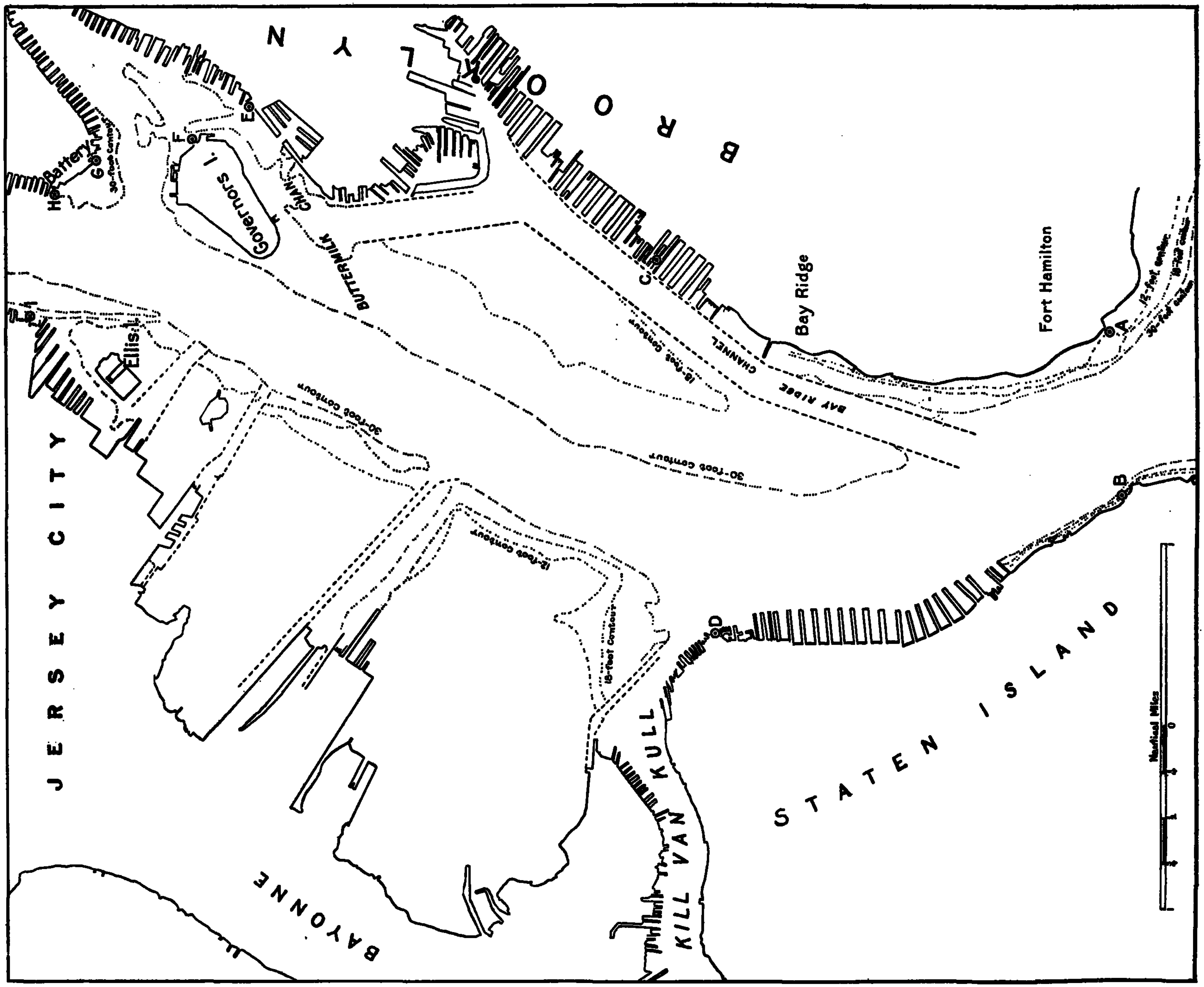

FIG. 15.—Tide stations, the Narrows and Upper Bay

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G. The results from the tabulations of the high and low waters at the various stations in the Narrows and Upper Bay are given in Table 31. With the exception of stations A and F (Fort Hamilton and Governors Island), the lunitidal intervals and ranges given in the table have been corrected to mean values by comparison with simultaneous observations at some near-by standard station, generally Fort Hamilton, Governors Island, or Sandy Hook.

TABLE 31.—*Tidal data, The Narrows and Upper Bay*

Station	Locality	Lunitidal intervals		Duration of rise	Mean range	Observations	
		High water	Low water			Year	Length
		Hours	*Hours*	*Hours*	*Feet*		
A	Fort Hamilton, N. Y.	7.67	1.64	6.03	4.73	1904–1922	19 years.
B	Staten Island, N. Y.	7.77	1.67	6.10	4.46	1886	10 days.
C	Bay Ridge, N. Y.	7.91	1.90	6.01	4.53	1886	3 days.
D	Staten Island, N. Y.	8.07	2.07	6.00	4.34	1917–1918	7 months.
E	Brooklyn, N. Y.	8.07	2.13	5.94	4.40	1856–1865	10 years.
F	Governors Island, N. Y.	8.10	2.25	5.85	4.45	1860–1879	19 years.
G	The Battery, N. Y.	8.23	2.19	6.04	4.43	1921–1922	2 years.
H	do	8.11	2.11	6.00	4.52	1918–1919	1 year.
I	Jersey City, N. J.	8.02	2.13	5.89	4.45	1871	3 days.

Table 31 gives for the difference in time of tide between Fort Hamilton and the mouth of the Hudson (stations A and H) 0.44 hour for the high water and 0.47 hour for the low water, or a mean difference of 0.45 hour. The distance along the channel from Fort Hamilton to the mouth of the Hudson is 6 nautical miles, the waterway between these points having an average depth of 26 feet, reckoned from mean sea level. In the formula for the rate of advance of a progressive wave, $r=\sqrt{gh}$, if we substitute the depth above, we determine r to be 17.1 miles per hour. Hence, if the tidal movement through the Narrows and Upper Bay is of the progressive-wave type, the distance of 6 miles should, from the above value of r be traversed in 0.35 hour. This approximates 0.44 hour given by the tide, and we may therefore conclude that through the Narrows and Upper Bay the tidal movement is of the progressive-wave type.

Table 31 gives in the Narrows a greater range for the eastern shore than for the western shore. This, obviously, was to be expected, as arising from the deflecting force of the earth's rotation. The effect of the diverging shore lines in the Narrows is seen in the decreased range of tide in the upper portion of the Narrows, decreasing from 4.73 feet at Fort Hamilton to 4.53 feet at Bay Ridge. Over the whole of Upper Bay the range of the tide is approximately 4.4 feet. The duration of rise changes but little throughout the Narrows and Upper Bay.

The harmonic constants for Fort Hamilton have already been given in Table 22. For Governors Island and the Battery (stations F and G) the harmonic constants are given in Table 32. For station F the constants are derived from the analysis of three years of observations—1876 to 1879—while the constants for station G are derived from one year of observations, beginning June 1, 1920. The values inclosed in parentheses have been derived by inference from the principal components and not by direct analysis.

TABLE 32.—*Harmonic constants, stations F and G, Upper Bay*

Component	Station F (Governors Island)		Station G (the Battery)		Component	Station F (Governors Island)		Station G (the Battery)	
	H	κ	*H*	κ		*H*	κ	*H*	κ
	Feet	*Degrees*	*Feet*	*Degrees*		*Feet*	*Degrees*	*Feet*	*Degrees*
J_1	(0.018)	(107.3)	(0.018)	(105.8)	Q_1	(0.031)	(103.3)	0.046	137.9
K_1	0.325	106.3	0.327	105.8	2Q	(0.004)	(102.3)	(0.005)	(105.8)
K_2	0.118	255.1	0.107	255.4	R_2	(0.003)	(257.1)	(0.003)	(259.0)
L_2	0.129	248.9	0.077	248.4	S_1	-----	-----	0.049	66.9
M_1	0.016	104.0	0.011	205.4	S_2	0.413	257.1	0.416	259.0
M_2	2.153	231.1	2.112	233.4	S_4	-----	-----	0.043	78.6
M_3	-----	-----	0.033	198.4	S_6	-----	-----	0.005	185.9
M_4	0.087	332.4	0.055	333.3	T_2	0.073	183.1	(0.025)	(259.0)
M_6	0.076	89.1	0.071	80.8	λ_2	0.025	186.0	(0.015)	(245.3)
M_8	-----	-----	0.012	85.6	μ_2	0.063	217.4	(0.051)	(207.8)
N_2	0.496	210.5	0.487	213.4	ν_2	0.093	241.0	(0.094)	(216.1)
2N	(0.066)	(189.9)	(0.065)	(193.4)	ρ_1	(0.006)	(103.4)	(0.007)	(105.8)
O_1	0.161	104.3	0.176	105.8	Sa	0.245	127.0	0.169	108.7
OO	(0.010)	(108.3)	(0.010)	(105.8)	Ssa	0.173	47.4	0.136	92.3
P_1	0.105	104.2	0.102	106.0					

From the harmonic constants above various tidal characteristics may be determined. It is to be noted, however, that ranges determined from harmonic constants are invariably smaller than those determined from high and low waters. Hence, for Table 33 the ranges as derived directly from the harmonic constants have been increased by a factor which is the ratio of the mean range determined from high and low waters to the mean range determined from harmonic constants. This factor is but little greater than unity; for Governors Island it is 1.008 and for the Battery it is 1.015. Table 33 gives the tidal data derived from the harmonic constants with the ranges modified as noted above. For the sake of comparison the results for Fort Hamilton are also included.

TABLE 33.—*Tidal data from harmonic constants, stations A, F, and G, the Narrows, and Upper Bay*

	Station A (Fort Hamilton)	Station F (Governors Island)	Station G (the Battery)
Mean range feet	4.73	4.45	4.43
Great diurnal range do	5.29	4.87	4.86
Small diurnal range do	4.17	4.03	4.00
Great tropic range do	5.34	4.96	4.93
Small tropic range do	3.73	3.66	3.58
Spring range do	5.55	5.34	5.31
Neap range do	3.76	3.47	3.46
Perigean range do	5.77	5.35	5.38
Apogean range do	3.85	3.82	3.65
Phase age hours	26.5	25.6	25.2
Parallax age do	30.9	37.8	36.7
Diurnal age do	4.6	1.8	0.0
Sequence is HHW to LLW	-----	-----	-----
Spring range÷mean range	1.17	1.20	1.20
Neap range÷mean range	0.79	0.78	0.78
Perigean range÷mean range	1.22	1.20	1.21
Apogean range÷mean range	0.81	0.86	0.82
Great diurnal range÷mean range	1.12	1.09	1.10
Great tropic range÷mean range	1.13	1.11	1.11

The data of Table 33 show a very close resemblance between tide at stations F and G and but little difference between the tide at these two stations and station A. It is of interest to note that with the exception of the perigean range at station G the various tidal ranges decrease from Fort Hamilton to the Battery, and that with the exception of the parallax age a similar decrease takes place in the ages of the tide. The ratios of the various ranges to mean range are practically the same at all three stations, and we may therefore use these ratios at Fort Hamilton for determining the various ranges at any of the stations in the Narrows and Upper Bay listed in Table 31.

For the period 1847 to the end of 1878 the highest tide at Governors Island occurred on September 17, 1876, when high water stood 3.3 feet above mean high water, or 5.5 feet above mean sea level. For the same period the lowest tide at Governors Island occurred on December 22, 1876, when low water reached 3.7 feet below mean low water, or 5.9 feet below mean sea level. The greatest range of the tide at Governors Island for this period is therefore 11.4 feet. This compares with 11.8 feet at Sandy Hook for the period 1876 to 1891 and 12.6 feet at Fort Hamilton for the period 1893 to 1922.

VII. THE TIDE IN THE KILLS AND NEWARK BAY

The stations at which tidal observations have been made in Arthur Kill are shown on Figure 16. At no station in this waterway have observations been made for more than a month. To derive mean values, therefore, the observations in Arthur Kill have been compared with simultaneous observations at Sandy Hook, Fort Hamilton, or Governors Island. The data from these observations are given in Table 34.

TABLE 34.—*Tidal data, Arthur Kill*

Station	Locality	Lunitidal intervals		Duration of rise	Mean range	Observations	
		HWI	LWI			Year	Length
		Hours	*Hours*	*Hours*	*Feet*		
A	Perth Amboy, N. J	7.95	1.89	6.06	5.28	1873	1 month.
B	do	7.87	1.73	6.14	5.11	1920	2 months.
C	Tottenville, N. Y	7.93	1.70	6.23	4.98	1:56	1 month.
D	Rossville, N. Y	8.02	2.02	6.00	5.12	1856–1886	2½ days.
E	Carteret, N. J	8.38	2.37	6.01	5.18	1856	1 day.
F	Near Pralls Creek, N. Y	8.52	2.42	6.10	5.25	1856	Do.
G	Elizabeth, N. J	8.22	2.45	5.77	5.00	1855–1886	20 days.
H	do	8.47	2.33	6.14	4.99	1920	2 days.

The data of Table 34 show the tide in Arthur Kill to become later from the Lower Bay entrance to the Newark Bay entrance. From stations A and B we may take the high and low water lunitidal intervals at the southern end as 7.90 hours and 1.80 hours, respectively, while from stations G and H we may take the intervals at the northern end as 8.35 hours and 2.40 hours. This gives a difference of 0.45 hour for high water and 0.60 hour for low water, or a mean difference of 0.52 hour in the time of tide at the two ends of Arthur Kill.

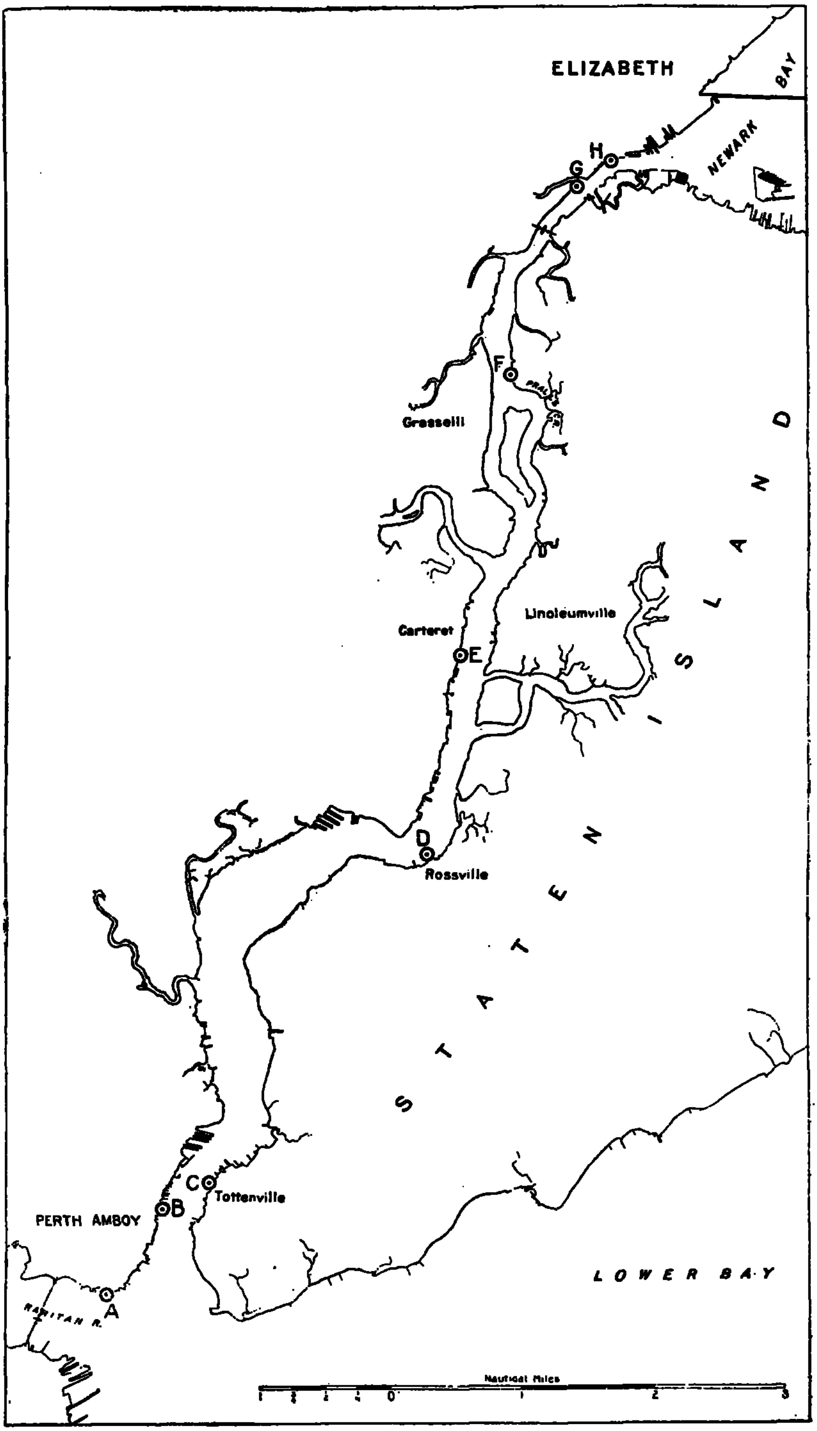

FIG. 16.—Tide stations, Arthur Kill

The length of Arthur Kill, measured along the channel, is about 11½ nautical miles, and its average depth is 17½ feet. Hence, if the tidal movement through Arthur Kill is of the progressive-wave type—that is, progressing in accordance with the formula $r=\sqrt{gh}$—it should traverse this waterway from one end to the other in 0.8 hour. From the data of Table 34 the observations give the difference to be 0.52 hour. Throughout Arthur Kill the range of tide appears to be very nearly the same, namely, 5.1 feet. The duration of the rise likewise appears to be very nearly the same throughout the Kill, approximating 6.1 hours.

KILL VAN KULL

For Kill Van Kull there are at hand observations at six stations, the locations of these being shown on Figure 17. In this waterway, as in Arthur Kill, the observations cover only short periods of time, the longest series being but nine days in length. The tidal data derived from these observations are shown in Table 35. In this table the lunitidal intervals and ranges have been corrected to mean values by comparison with simultaneous observations at some standard tidal station.

TABLE 35.—*Tidal data, Kill Van Kull*

Station	Locality	Lunitidal intervals		Duration of rise	Mean range	Observations	
		HWI	LWI			Year	Length
		Hours	*Hours*	*Hours*	*Feet*		
A	Port Richmond, N. Y.	8.36	2.52	5.84	4.49	1885–86	6 days.
B	Bergen Point, N. J.	8.35	2.13	6.22	4.64	1919	9 days.
C	Port Richmond, N. Y.	8.38	1.87	6.51	4.48	1856	2¼ days.
D	West New Brighton, N. Y.	8.20	2.13	6.07	4.48	1919	2 days.
E	New Brighton, N. Y.	8.03	1.87	6.16	4.48	1919	7 days.
F	Constable Hook, N. J.	8.12	1.95	6.17	4.50	1886	2 days.

For Kill Van Kull the data of Table 35 show that the tide at the eastern end is earlier than at the western end by about one-third of an hour. With a mean depth of 28 feet for Kill Van Kull, a progressive wave would require 0.15 hour to traverse this waterway, which has a length of approximately 2¾ nautical miles. The tidal movement through this Kill, therefore, appears to be not altogether of the progressive-wave type.

As regards the range of the tide for Kill Van Kull the data of Table 35 show it to be practically the same for the entire waterway, with a value of 4.5 feet. For the northern shore, however, the data indicate a greater range than on the southern shore. If this is due to the deflecting force of the earths rotation, the current must be flowing westerly on the rising tide, so that the northern shore is then to the right, and easterly on the falling tide. This, as we shall show later, the current observations show to be the case.

NEWARK BAY

The locations of the tidal stations at which observations have been made in Newark Bay are shown on Figure 18, and the data derived from these observations are given in Table 36. Here, as in the pre-

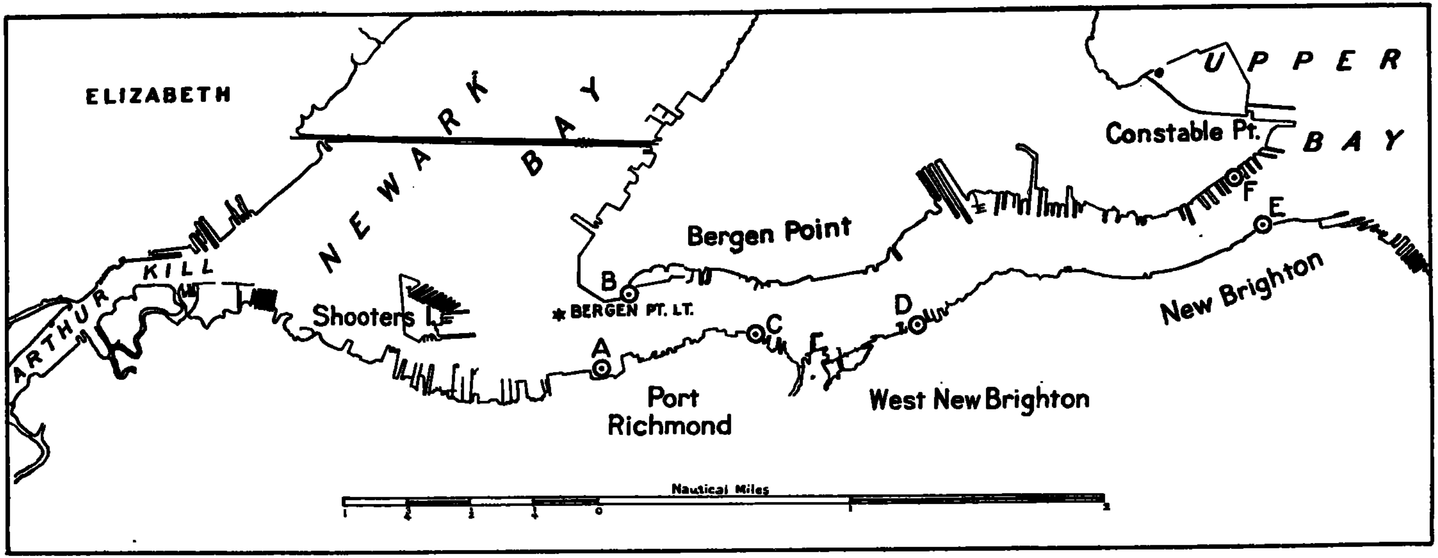

FIG. 17.—Tide stations, Kill van Kull

vious tables, lunitidal intervals and ranges have been corrected to mean values by comparison with simultaneous observations at some

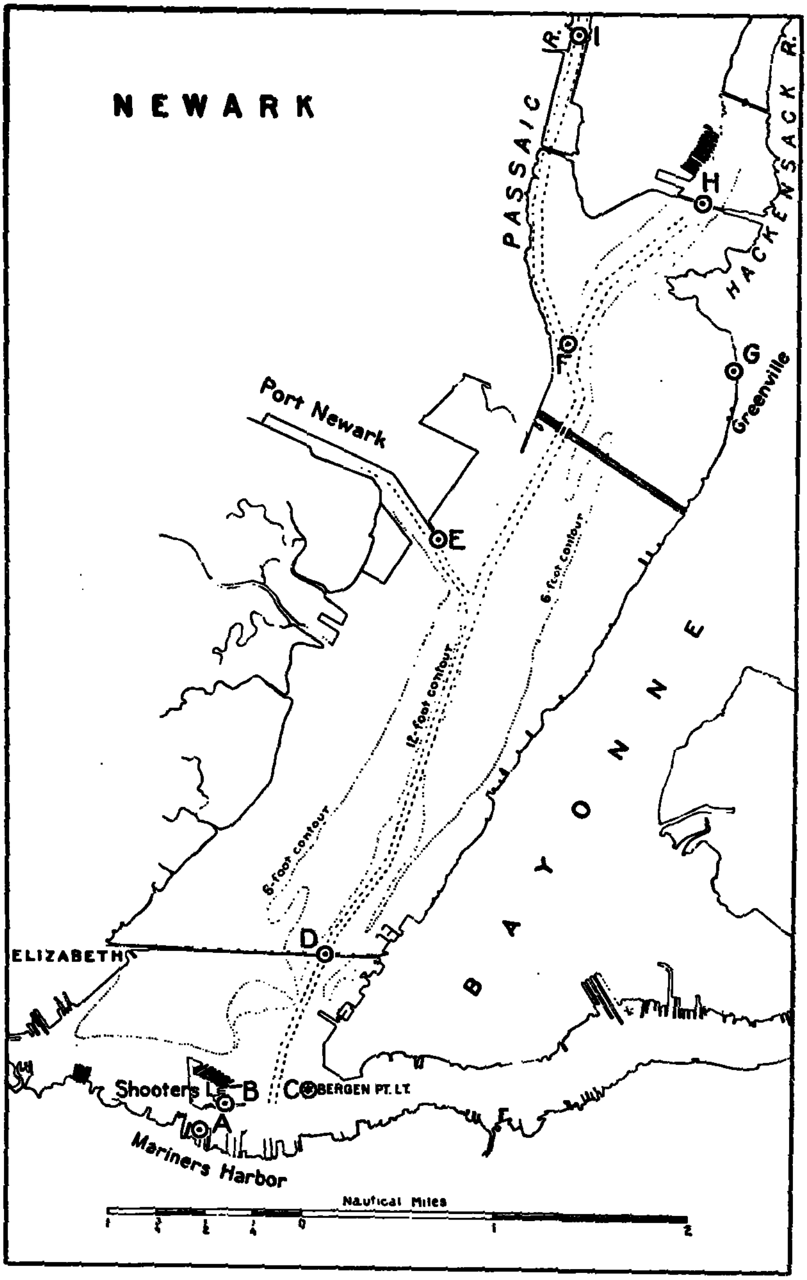

FIG. 18.—Tide stations, Newark Bay

standard tidal station like Sandy Hook, Fort Hamilton, or Governors Island.

TABLE 36.—*Tidal data, Newark Bay*

Station	Locality	Lunitidal intervals		Duration of rise	Mean range	Observations	
		HWI	LWI			Year	Length
		Hours	*Hours*	*Hours*	*Feet*		
A	Mariners Harbor, N. Y	8.45	2.46	5.99	4.76	1920	3 months.
B	Shooters Island, N. Y	8.32	2.43	5.89	4.59	1901	2½ months.
C	Bergen Point Light, N. J	8.70	2.57	6.13	4.41	1856	1 day.
D	Off Bayonne, N. J	8.40	1.83	6.57	4.42	1872	7 days.
E	Port Newark, N. J	8.58	2.84	5.74	4.73	1919	5 months.
F	Off Newark, N. J	8.54	2.71	5.83	4.93	1871–72	3 months.
G	Greenville, N. J	8.70	3.00	5.70	4.58	1920	4 days.
H	Hackensack River, N. J	8.48	3.25	5.23	4.58	1886	3 days.
I	Passaic River, N. J	8.85	3.33	5.52	4.73	1920	2 days.

Into Newark Bay the tide from Kill Van Kull comes with a range of 4.5 feet, while the tide from Arthur Kill comes with a range of 5.0 feet, and the data for stations A to I indicate that for virtually all of the bay the range of the tide lies between these two values. For stations C and D the observations give a range of less than 4.5 feet, but it is to be noted that these observations cover short periods of time and were made many years ago. From the data for station H of Arthur Kill and station A of Newark Bay we may take the lunitidal intervals at the western entrance to Newark Bay as 8.46 hours and 2.40 hours, respectively. The distance from the mouth to station I in the Passaic River is 6½ miles. With a mean depth of 9 feet in Newark Bay, a progressive wave would require 0.56 hour to traverse this distance. From the intervals above we find a difference in the time of tide between the mouth of the bay and station I of 0.39 hour for high water and 0.93 hour for low water, or a mean difference in time of tide of 0.66 hour.

It is to be noted that the difference in time of tide between the mouth and head of Newark Bay, derived in the preceding paragraph, is a little more than twice as great for the low water as for the high water. That the difference for low water should be greater than for high water follows from the fact that the rate of advance depends on the depth. Because of the shallowness of the bay the depth at the time of high water is greater by a very considerable percentage than at the time of low water. For Newark Bay, as a whole, we may take the range of tide as approximately 4¾ feet. The average depth of the bay from mean sea level is 9 feet; at the time of high water the average depth may therefore be taken as approximately 11¼ feet, while at low water we may take it as 6¾ feet. If, now, we regard high water and low water as distinct phases traveling upstream in accordance with the formula $r=\sqrt{gh}$, the rate of advance of high water will be to that of low water as $\sqrt{11\frac{1}{4}}$ is to $\sqrt{6\frac{3}{4}}$; or as 1.3 is to 1. This does not agree well with the ratio of the rates of advance derived above from the observations and goes to show that shallow water and other factors enter into the problem.

VIII. THE TIDE IN THE HUDSON AND HARLEM RIVERS

The stretch of the Hudson that is here considered as forming part of New York Harbor is that from the mouth to Mount St. Vincent, a distance of 14 nautical miles. The stations at which tidal observations have been made in this stretch are shown in Figure 19, and the data derived from these observations are given in Table 37. For each station listed in this Table the intervals and mean range have been reduced to a mean value by comparison with simultaneous observations at some standard tidal station like Fort Hamilton or Governors Island.

TABLE 37.—*Tidal data, Hudson River*

Station	Locality	Lunitidal intervals		Duration of rise	Mean range	Observations	
		HWI	LWI			Year	Length
		Hours	*Hours*	*Hours*	*Feet*		
A	The Battery, N. Y.	8.11	2.11	6.00	4.52	1918–19	1 year.
B	Jersey City, N. J.	8.02	2.13	5.89	4.45	1871	3 days.
C	do	8.19	2.18	6.01	4.30	1860	4 days.
D	do	8.12	2.28	5.84	4.31	1885	1 month.
E	do	8.33	2.40	5.93	4.52	1854	16 days.
F	do	8.28	2.33	5.95	4.26	1874	18 days.
G	New York, N. Y.	7.92	2.10	5.82	4.55	1855	15 days.
H	do	8.28	2.30	5.98	4.16	1919	3½ months.
I	do	8.23	2.17	6.06	4.31	1875	1 day.
J	Weehawken, N. J.	8.28	2.35	5.93	4.13	1872	2 days.
J	do	8.77	2.85	5.92	3.99	1885	22 days.
K	New York, N. Y.	8.27	2.48	5.79	4.11	1871	2 days.
L	do	8.43	2.62	5.81	4.28	1855	13 days.
M	Fort Lee, N. J.	8.52	3.37	5.15	3.83	1837	5 days.
N	Tubby Hook, N. Y.	8.57	3.13	5.44	3.96	1853	1 month.
O	Spuyten Duyvil, N. Y.	9.21	3.06	6.15	3.62	1919–22	2¼ years.
P	Riverdale, N. Y.	9.10	3.23	5.87	3.86	1898	10 days.

In the use of lunitidal intervals for determining the difference in time of tide between two stations the correction to be applied is 0.07 hour for each degree of difference in longitude. But, since the Hudson River runs in an approximately north and south direction, the difference in longitude between any two stations for the stretch of 14 miles under consideration will be very small. Hence, the difference in time of tide for the stations listed in Table 37 may be derived directly by taking the difference of the lunitidal intervals.

Table 37 shows that with the exception of Spuyten Duyvil (station O) the tide becomes later in going up the Hudson in a fairly uniform manner. At stations A and H the time of tide may be considered as well determined, being based on recent observations, in the one case covering a period of a year and in the other a period of 3½ months. The difference in time of tide between the two stations is 0.17 hour for the high water and 0.19 hour for the low water, or a mean difference of 0.18 hour. The distance between stations A and H is 3¾ miles, and the mean depth of the waterway, reckoned from mean sea level, may be taken as 33 feet. In the formula for progressive-wave motion $r=\sqrt{gh}$, the time required to traverse this distance of 3¾ miles is 0.19 hour. The agreement between the observed and calculated values is thus very close, and the tidal movement imme-

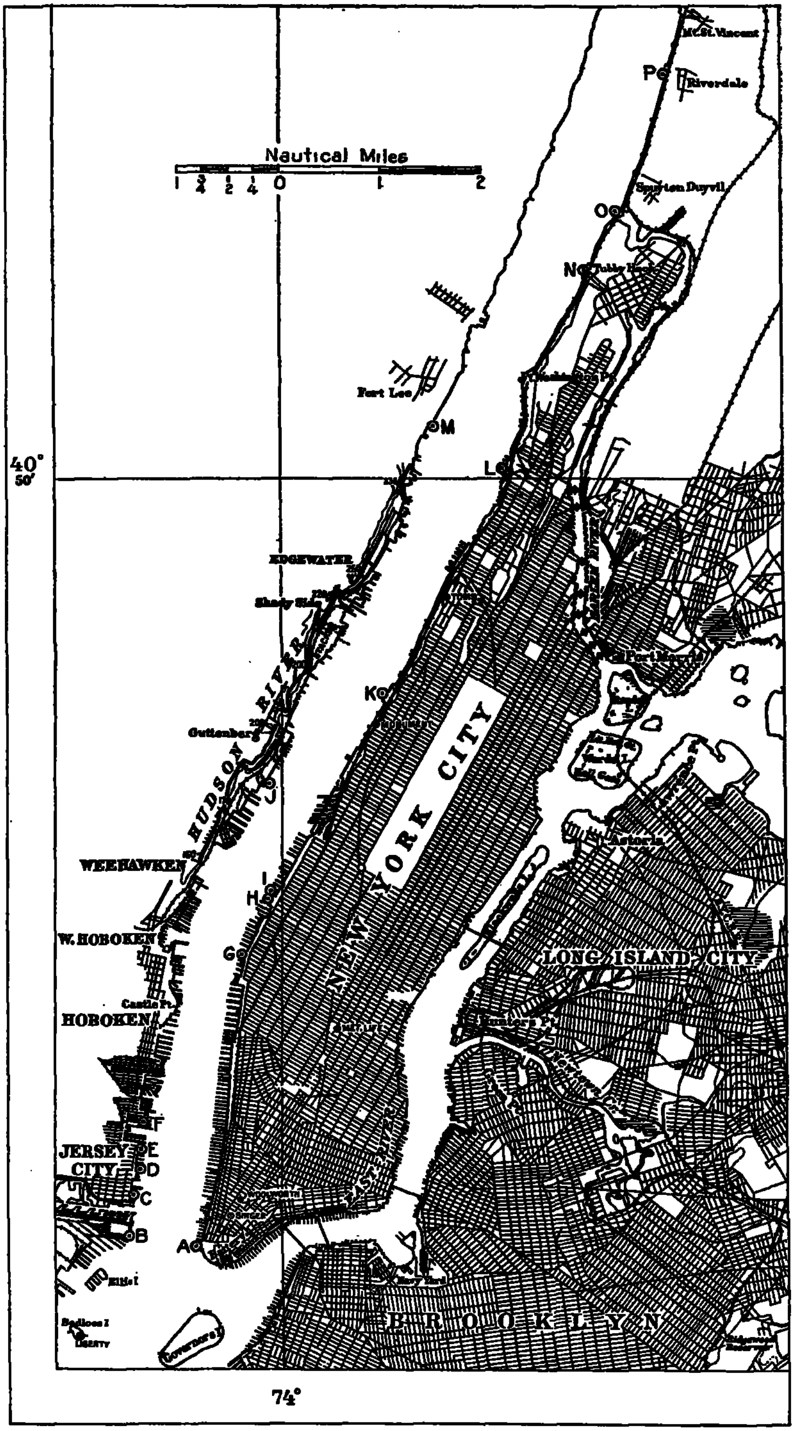

FIG. 19.—Tide stations, Hudson River

diately above the mouth of the Hudson is therefore of the progressive-wave type.

For Spuyten Duyvil (station O) the time of tide is undoubtedly affected by its location at the mouth of the Harlem. The apparent retrogression in the time of tide from Spuyten Duyvil to Riverdale (stations O and P) is therefore to be ascribed to the effect of the Harlem, and 9.10 hours may be considered as an approximately correct high-water interval for station P.

With the exception of Spuyten Duyvil the duration of rise decreases gradually from the mouth of the Hudson upwards, but in every case this duration is less than the duration of fall. At the mouth, since the average duration of rise is 6.0 hours, the duration of fall is 6.4 hours, while at Riverdale the duration of rise and fall are, respectively, 5.9 and 6.5 hours. The data of Table 37 show, too, that in the earlier years the duration of rise was less than now, the durations at station M in 1837 and at station N in 1853 being considerably less than the durations shown at nearby stations in later years.

At Spuyten Duyvil the duration of rise gives evidence of the disturbing effect of the Harlem River. The period of 6.15 hours for the rise is greater than at any other station in the Hudson and it is to be noted that this increase in the duration of rise at Spuyten Duyvil is brought about both by the relative increase in the high-water lunitidal interval and the relative decrease in the low-water interval.

The difference in time of tide between stations H and P is 0.82 hour for the high water and 0.97 hour for the low water, or a mean difference in time of tide of 0.90 hour. The distance between the two stations is 9¾ miles and the mean depth of the waterway 32 feet. From the formula $r=\sqrt{gh}$, the time required for a progressive wave to traverse this distance is 0.51 hour. For this stretch, therefore, the tidal movement is not wholly of the simple progressive-wave type.

The range of the tide is seen to decrease from 4.5 feet at the Battery to 3.9 feet at Riverdale. This decrease takes place in a fairly uniform manner with the exception of Spuyten Duyvil, where the range is less than at the stations above and below it. There can be no question as to the accuracy of the value for the range at Spuyten Duyvil, since it is based on observations covering a period of more than two years. It is evident, therefore, that this decreased range at Spuyten Duyvil is due to the location of the station at the entrance to the Harlem.

A comparison of the ranges on the New York and New Jersey shores brings to light the fact that the range of the tide on the New York shore is the greater. Thus, station A shows a range greater by 0.07 foot than station B and station L a range of 0.45 foot greater than station M. For the latter stations, however, it is to be noted that the ranges are based on short series of observations made many years ago. The New York shore of the Hudson should have a greater range as a consequence of the deflecting force of the earth's rotation, and the Hudson lends itself to a calculation, from theoretical considerations, of the difference in range on the two banks. It will, therefore, be of advantage to compare the observed and calculated differences of range.

DIFFERENCE IN RANGE ON THE TWO BANKS OF A STREAM

If v is the velocity with which a unit mass of water is moving, the deflecting force of the earth's rotation which acts on this unit mass is $2\,\omega\,v\,\sin\,\phi$, where ω is the angular velocity of the earth's rotation and ϕ is the latitude. This force acts to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The transverse slope assumed by the surface of the water in response to this force is $\frac{2\,\omega\,v\,\sin\,\phi}{g}$, where g is the acceleration of gravity. If the strength of current occurs at the times of high and low water, the difference in level at such times between the surface of the water on the two banks of the tidal waterway will be $\frac{2\,\omega\,v\,d\,\sin\,\phi}{g}$, where d is the distance between the banks. Obviously, the difference in range will be twice the difference in level. Hence, since $\omega = 0.0000729$, if v is given in knots and d in nautical miles, the formula for the difference in range on the opposite banks of a tidal stream, expressed in feet, is $\frac{3\,v\,d\,\sin\,\phi}{g}$, approximately.

At its mouth the Hudson has a width of three-quarters of a nautical mile, and the velocity of the current at time of strength is about 1½ knots. For latitude 40° 42′ the sine of the latitude is 0.65, and the value of g is 32.16 feet per second. Hence, the difference in range between the Battery and Jersey City should be, from the above formula, 0.07 foot, with the east bank of the stream showing the greater range. From Table 37 it is found that the range of the tide at station A is well determined, while at station B it is not so well determined, being based on but three days of observations. The difference in range between the two is 0.07 foot, which agrees exactly with the calculated difference. If we adopt for the range of the tide at Jersey City the mean of the ranges at stations A to F, we derive 4.46 feet, or 0.06 foot less than on the New York side.

It may not be amiss here to emphasize the fact that the deflecting force of the earth's rotation is independent of the direction of the movement of the water. At times one still meets with the erroneous assumption that it is only bodies moving in a north and south direction that are subject to the full effect of the deflecting force of the earth's rotation, while bodies moving in an east and west direction are not at all affected by it. It is to be noted that the formula for the deflecting force of the earth's rotation contains no term depending on the direction of the movement.

HARLEM RIVER

The stations at which observations have been made in the Harlem River are shown on Figure 20, and the results derived from these observations, corrected to mean values by comparison with simultaneous observations at some standard station, are given in Table 38.

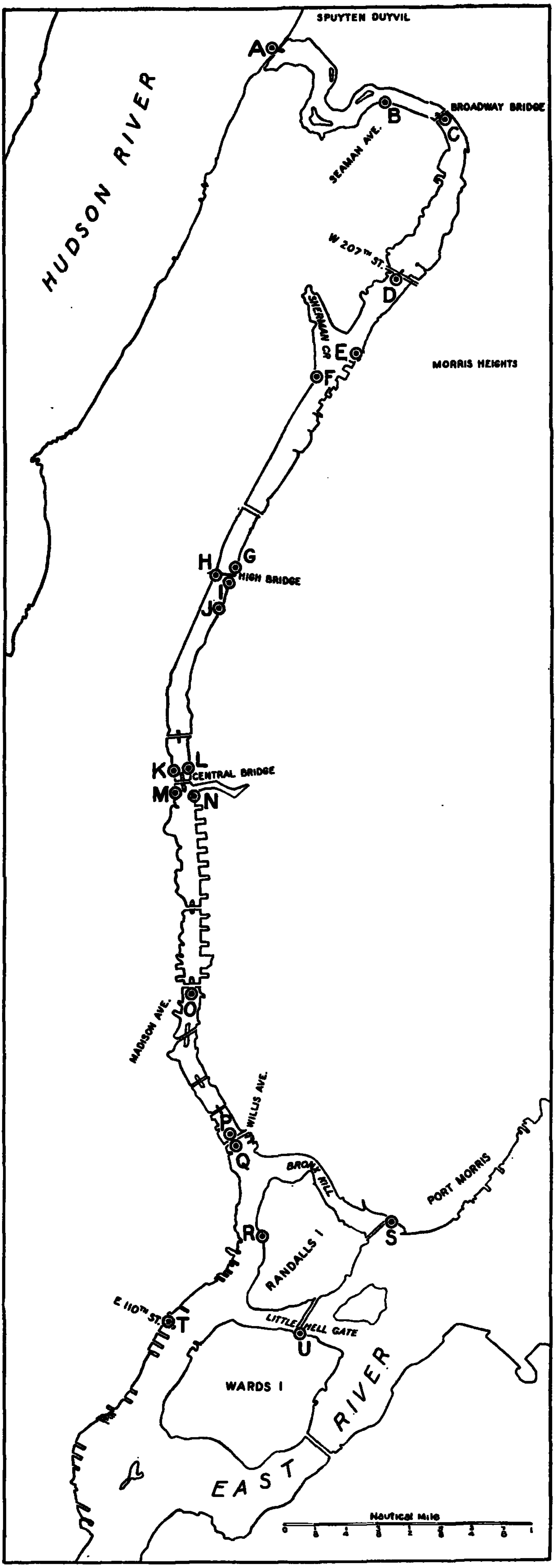

FIG. 20.—Tide stations, Harlem River 3904—24 (Face p. 68.)

TABLE 38.—*Tidal data, Harlem River*

Station	Locality	Lunitidal intervals		Duration of rise	Mean range	Observations	
		HWI	LWI			Year	Length
		Hours	*Hours*	*Hours*	*Feet*		
A	Spuyten Duyvil, N. Y	9.21	3.06	6.15	3.62	1919–1922	2¼ years.
B	Off Seaman Ave	9.66	3.56	6.10	3.66	1919	1 day.
C	Broadway Bridge	9.16	3.60	5.56	3.96	1886	1½ days.
C	do	9.61	3.71	5.90	3.74	1919	1 day.
D	Two hundred and seventh Street Bridge.	9.81	3.81	6.00	3.90	1919	1 day.
E	Off Morris Heights	10.87	5.80	5.07	4.13	1856	1½ days.
F	Sherman Creek	9.91	3.91	6.00	4.21	1919	1 day.
G	North of High Bridge	9.96	3.91	6.05	4.49	1919	1 day.
H	High Bridge	10.46	3.86	6.60	5.84	1886	2½ days.
I	South of High Bridge	10.01	4.01	6.00	4.59	1919	1 day.
J	do	10.97	5.67	5.30	4.45	1856	½ day.
K	North of Central Bridge	10.21	3.96	6.25	4.96	1919	1 day.
L	do	10.11	4.01	6.10	4.86	1919	1 day.
M	South of Central Bridge	10.21	4.11	6.10	4.90	1919	1 day.
N	do	10.01	4.01	6.00	4.95	1919	1 day.
O	Madison Avenue Bridge	10.11	4.11	6.00	5.09	1919	1 day.
P	Willis Avenue Bridge	10.06	3.73	6.33	4.96	1921–1922	2 years.
Q	do	10.21	3.96	6.25	5.27	1919	1 day.
R	Randalls Island	10.19	3.63	6.56	5.24	1886	4 days.
S	Port Morris	11.81	5.61	6.20	6.80	1919	1 day.
T	East One hundred and tenth Street.	10.25	3.73	6.52	4.98	1856–57	2 months.
U	Little Hell Gate	9.79	3.51	6.28	4.74	1849	12 days

For the Harlem River the greatest difference in longitude between any two points is less than 0.2 of a degree. Hence, the difference in time of tide between any two points in the Harlem may be derived directly by taking the difference in the lunitidal intervals. The data of Table 38 show that the tide is earliest at the Hudson River end and latest at the East River end.

Between Spuyten Duyvil and Willis Avenue Bridge (stations A and P) the distance measured along the channel is 5½ nautical miles, and the depth of the waterway measured from mean sea level is 16 feet. The time required for a progressive wave to traverse this distance is 0.56 hour. From Table 38 the difference in time of tide between the two stations is 0.85 hour for the high water and 0.67 hour for the low water, or a mean difference of 0.76 hour. The difference between the calculated and observed values is relatively large and indicates that the tidal movement through the Harlem is not of the simple progressive-wave type.

The range of the tide increases in a fairly uniform manner from the Hudson River end to the East River end. At Spuyten Duyvil the range is 3.6 feet, while at Willis Avenue Bridge it is 5.0 feet. This increase in range of tide shows that the tidal movement through the Harlem is not of the progressive-wave type, for the hydrographic features of the Harlem are relatively uniform throughout its length, and if the tidal movement were of the progressive-wave type, a gradual decrease in the range of tide would be expected from the Hudson to the East River.

In Table 38 the values for stations C, E, H, J, and S stand out strikingly different from the values at stations near by. For the first four of these stations it is to be noted that the observations were made in 1886 or earlier. This was prior to the opening of the ship canal through the tidal marsh at the Hudson River end, which was completed in 1895, and the differences shown by the earlier observations are to be ascribed to this change in the waterway.

Station S is located at Port Morris, and the tide at that point is greatly affected by the tide from the East River, to which it is more nearly related, for the Bronx Kill is a shallow waterway that does not allow free movement for the Harlem River tide; and it is to be noted that station T, which is about the same distance from Willis Avenue Bridge as station S, exhibits tidal characteristics much like those at Willis Avenue Bridge, the channel to the east of Randalls Island being much deeper than Bronx Kill.

For the greater part of the Harlem the duration of rise is slightly less than that of fall. From Spuyten Duyvil to Madison Avenue Bridge (stations A and O) the duration of rise is about 6.1 hours and the duration of fall 6.3 hours. Near the East River end of the Harlem the duration of the rise is the greater, being 6.3 hours against 6.1 for the duration of fall.

The time of tide through the Harlem, the variation in range, and the relative durations of rise and fall show that the tidal movement differs from that in the Hudson and is not of the progressive-wave type. As the discussion of the tidal movement through East River will show, the characteristics of the tide in the Harlem are conditioned chiefly by the fact that it is a short strait connecting two independently tided bodies of water, and that the movement of the water is largely hydraulic.

IX. THE TIDE IN EAST RIVER

East River connects Upper Bay on the west with Long Island Sound on the east. The tide in Upper Bay has a range of about 4½ feet, the lunitidal intervals being approximately 8 hours for the high water and 2 hours for the low water. Toward the western end of Long Island Sound the range of the tide is 7 feet or more, the lunitidal intervals being 11 hours for the high water and 5 hours for the low water. East River, therefore, derives its tide from two bodies of water, the tides in which differ by 3 hours in time and by very nearly 3 feet in range.

This difference in the tides of the two bodies which it connects gives to the tidal movement in East River a character much less uniform than that in rivers with but one tidal entrance. As a result, numerous tidal observations have been made in the East River. It will, therefore, be convenient to divide these observations into two groups, the first covering the stretch of the East River from the Battery through Hell Gate, and the second covering the stretch from Hell Gate to Willets Point. This procedure may be justified, too, by the fact that Hell Gate divides East River into two very nearly equal parts having different hydrographic features—lower East River being a relatively narrow and deep waterway, while upper East River is wider and shallower.

On Figure 21 are shown the locations of the stations at which tidal observations have been made in lower East River. The data derived from these observations are given in Table 39, following. The lunitidal intervals and ranges given in this table have been reduced to mean values by comparison with simultaneous observations at some standard tidal station like Governors Island or Fort Hamilton.

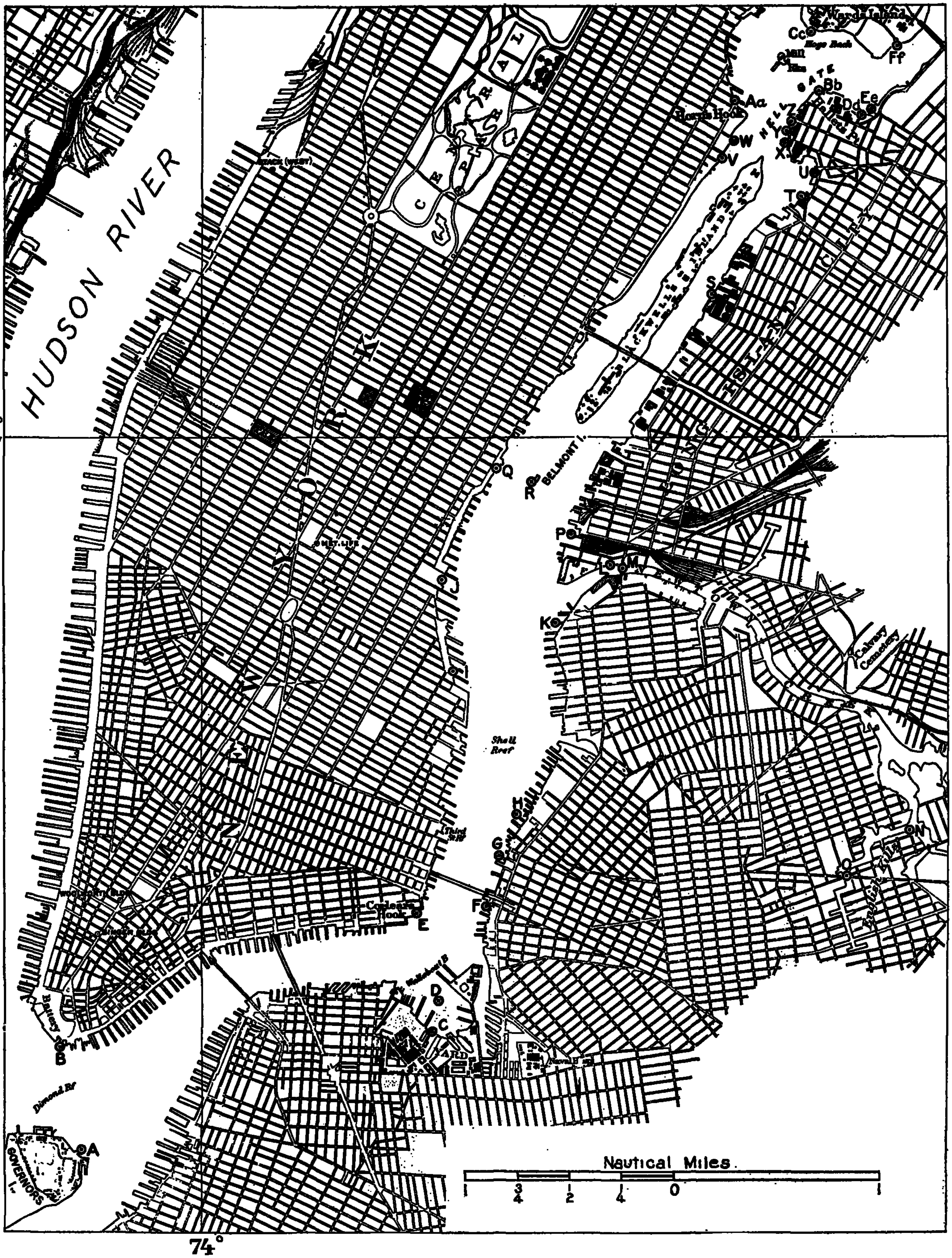

Fig. 21.—Tide stations, lower East River

3904-24. (Face p. 70)

TABLE 39.—*Tidal data, lower East River*

Station	Locality	Lunitidal intervals		Duration of rise	Mean range	Observations	
		HWI	LWI			Year	Length
		Hours	*Hours*	*Hours*	*Feet*		
A	Governors Island	8.10	2.25	5.85	4.45	1860–79	19 years.
B	The Battery	8.23	2.19	6.04	4.43	1921–22	2 years.
C	Navy Yard Basin	8.80	2.70	6.10	4.10	1869	2 months.
D	do	8.95	2.80	6.15	4.16	1855	5 months.
D	do	9.03	2.97	6.06	3.93	1885	16 days.
D	do	8.75	2.77	5.98	4.12	1890	1 month.
E	Corlears Hook	9.33	2.78	6.55	4.01	1886	5 days.
F	South of Williamsburg Bridge	9.02	3.29	5.73	4.02	1837	3 days.
G	North of Williamsburg Bridge	9.41	2.68	6.74	4.09	1920	2 months.
H	do	9.33	2.92	6.41	4.09	1921–22	2 years.
I	South of Bellevue Hospital	9.28	2.97	6.31	4.18	1875	12 days.
J	Off Bellevue Hospital	9.40	3.20	6.20	4.42	1885	8 days.
K	Greenpoint	9.35	3.17	6.18	4.43	1855	2½ months.
L	Newtown Creek	9.86	3.15	6.71	4.07	1915	1½ months.
M	do	9.64	3.61	6.03	3.95	1857	6 days.
N	do	9.92	3.39	6.53	4.16	1915	2½ months.
O	do	9.70	3.48	6.26	4.61	1913	1 month.
P	Hunters Point	9.72	3.31	6.41	4.14	1886	5 days.
Q	West of Belmont Island	9.77	3.33	6.44	4.11	1874	21 days.
R	Belmont Island	9.58	3.12	6.46	4.26	1921–22	2 years.
S	North of Queensboro Bridge	9.88	3.43	6.45	4.53	1886	5 days.
T	Hallets Cove	9.95	3.80	6.15	4.91	1885	10 days.
U	do	8.98	3.08	5.90	5.29	1848	20 days.
U	do	9.73	3.37	6.36	4.75	1868	2 days.
V	South of Horns Hook	10.10	3.87	6.23	4.90	1886	5 days.
W	do	10.27	4.15	6.12	4.73	1857	1 month.
W	do	9.87	3.43	6.44	4.74	1868	4 days.
W	do	9.63	3.47	6.16	4.75	1875	9 days.
W	do	9.96	3.80	6.16	4.81	1920–22	2½ years.
X	Astoria	9.17	3.40	5.77	3.94	1845	9 days.
Y	do	9.90	3.62	6.28	4.80	1868	21 days.
Z	do	8.87	3.12	5.75	4.82	1848	23 days.
Aa	North of Horns Hook	10.08	3.43	6.65	4.77	1868	2 days.
Bb	Astoria	11.27	5.58	5.69	5.64	1857	14 days
Cc	Wards Island	9.97	3.65	6.32	5.11	1866	5 days.
Dd	Pot Cove	11.06	5.01	6.05	5.63	1885–86	20 days.
Ee	do	11.55	5.73	5.82	6.03	1857	1 month
Ee	do	11.35	5.52	5.83	6.07	1868	17 days.
Ee	do	10.58	4.62	5.96	5.51	1875	9 days.
Ff	Wards Island	10.46	5.68	4.78	5.54	1920–22	2½ years.

From the Battery to Hell Gate the greatest difference in longitude between any two points in the East River is about one-tenth of a degree. The difference in time of tide between any two points in East River may therefore be derived directly by taking the difference in the lunitidal intervals of Table 39, since the correction for the difference of longitude of one-tenth of a degree is less than 0.01 hour.

From Table 39 it is seen that the time of tide changes in a somewhat uniform manner from the Battery to the entrance to Hell Gate. In this stretch there are three stations at which observations have been made covering periods of two years or more, so that the times of tides at these stations are quite well determined. These points are station H (north of Williamsburg Bridge), station R (Belmont Island), and station W (south of Horns Hook). From Governors Island these stations are distant, respectively, 3, 4½, and 6½ miles. Between the Battery and each of these stations the time of tide becomes later by approximately a quarter of an hour for each mile, but through Hell Gate the time of tide changes at a much more rapid rate. Between station W and station Ff (Wards Island) the distance is 1 nautical mile. Table 39 shows that the difference in time of tide between these two stations is 0.85 hour, being 0.5 hour for the high water and 1.2 hours for the low water.

The distance between Governors Island and station W is 6½ miles, the waterway between these two points having an average depth of 38 feet, reckoned from mean sea level. For a progressive wave to traverse this distance the formula $r=\sqrt{gh}$ gives 0.31 hour as the time required. The difference in time of tide from Table 39 for this stretch is 1.7 hours. Hence, as regards time of tide through lower East River, the tidal movement is not of the progressive-wave type.

Through the stretch of the East River under consideration the times of high and low water are not retarded by the same amounts, and this causes the durations of rise and fall to vary through this stretch of the river. At the Battery the duration of rise is about 6

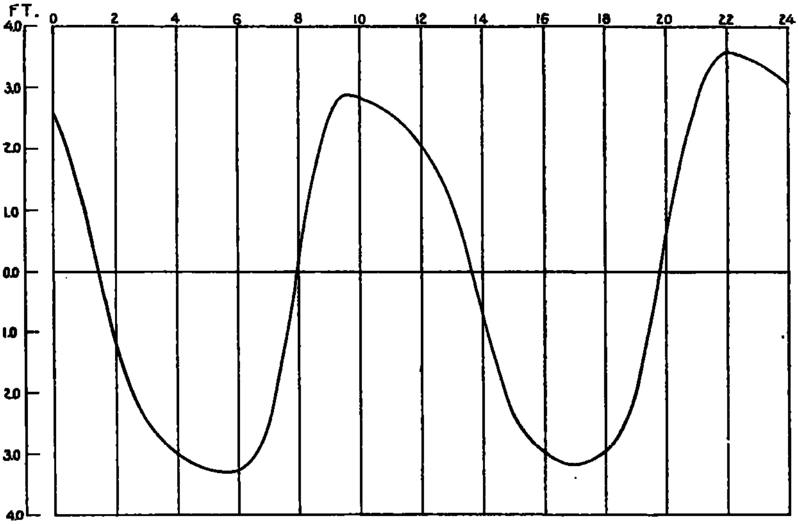

FIG. 22.—Tide curve, Hell Gate, East River

hours and the duration of fall 6.4 hours. Going upstream the duration of rise increases so that at station H it becomes 6.4 hours, while the duration of fall becomes 6 hours. At station R (Belmont Island) the duration of rise attains its greatest value, very nearly 6.5 hours, and from here to the entrance to Hell Gate it gradually decreases to a value of 6.2 hours, so that at the western entrance to Hell Gate the periods of rise and fall are equal. Through Hell Gate the time of low water changes more rapidly than the time of high water, so that at station Ff (Wards Island) the rise occupies a period of but 4.8 hours, while the period of fall is 7.6 hours. The characteristic curve of the tide near the eastern end of Hell Gate is shown in Figure 22, which represents the rise and fall of the tide at station Ff on May 7, 1921.

The range of the tide in the lower East River changes from 4.4 feet at Governors Island to 5.5 feet at Wards Island, but this change does not take place in a uniform manner. For the first 3 miles from

Governors Island the tide decreases at the rate of 0.1 foot per mile, the range at station H being 0.36 foot less than at Governors Island. From here the range increases in going upstream in a somewhat uniform manner as far as Hell Gate and rapidly through Hell Gate. From station H to station W, a distance of 3½ miles, the rate of increase is 0.2 foot per mile. For the mile separating stations W and Ff the difference in range is 0.7 foot. With regard to range, therefore, as well as in regard to time, the tide in the lower East River is not of the progressive-wave type.

For the determination of other ranges at the stations listed in Table 39—as, for example, the spring, neap, and perigean ranges—we may assume that these ranges at any station of Table 39 have the same ratios to the mean range at that station as at Governors Island or at the Battery, given in Table 33.

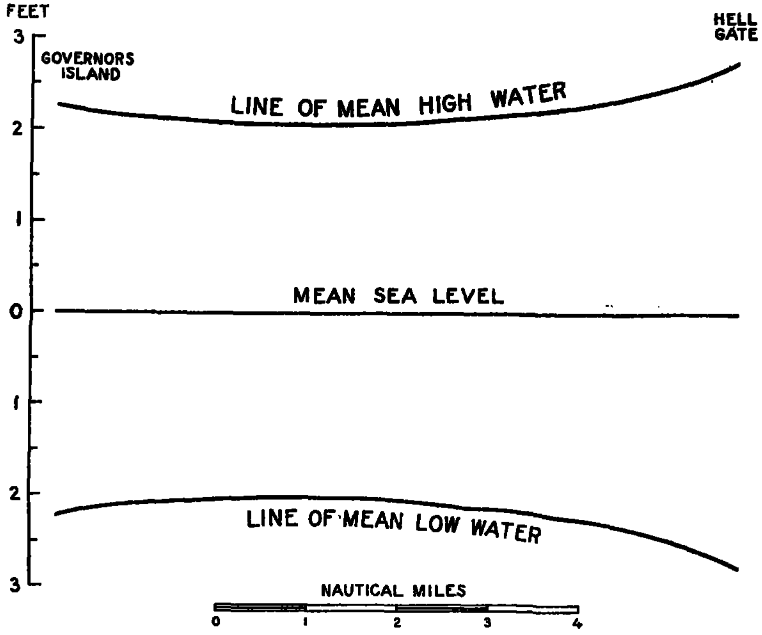

FIG. 23.—Mean high water and low water lines, lower East River

Since the range of the tide in the lower East River does not vary uniformly throughout its length, it follows that with the exception of mean sea level, the line representing the elevation of any given tidal datum plane along the channel will not be a straight line. Figure 23 shows the mean high-water and mean low-water lines through lower East River as derived from the data for stations A, H, W, and Ff. In this figure mean low water is taken the same distance below mean sea level as high water is above it.

As will be seen later, this feature of the tides in lower East River is due to the type of tidal movement that obtains in East River and is characteristic of the tide in a short strait connecting two bodies of water having independent tides. The fact that the line of low water in such a strait is a curved line convex toward the surface has considerable practical importance. In the deepening of such a waterway a considerable saving in excavation may be made; for, instead of dredging the bottom to a uniform depth below mean sea level, advantage may be taken of the fact that the low water line lies above the straight line joining the low-water points at the ends of the waterway.

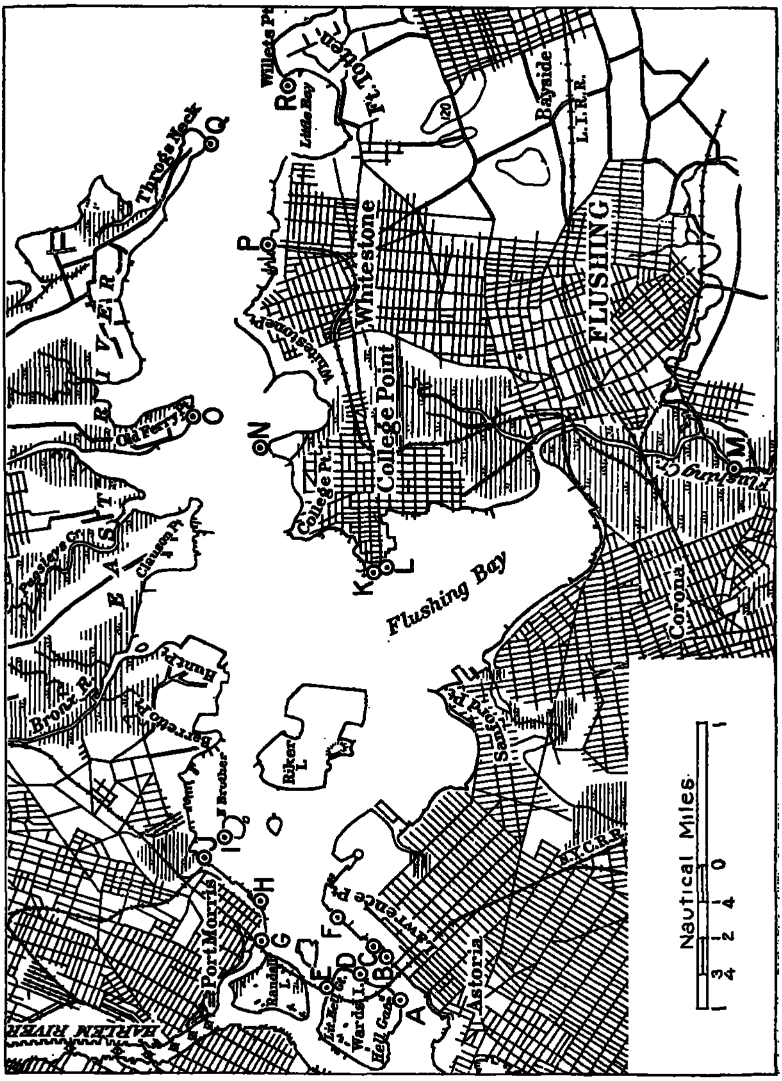

Fig. 24.—Tide stations, upper East River

UPPER EAST RIVER

The stations at which tidal observations have been made in upper East River are shown in Figure 24, and the data derived from these observations are given in Table 40. In this table the lunitidal intervals and ranges have been corrected to mean values by comparison with simultaneous observations at a standard tidal station like Governors Island or Fort Hamilton.

TABLE 40.—*Tidal data, upper East River*

Station	Locality	Lunitidal intervals		Duration of rise	Mean range	Observations	
		HWI	LWI			Year	Length
		Hours	*Hours*	*Hours*	*Feet*		
A	Wards Island	10.46	5.68	4.78	5.54	1920–1922	2½ years.
B	Southeast of Lawrence Point	9.40	3.84	5.56	5.56	1848	5 days.
C	do	11.05	5.33	5.72	6.27	1886	Do.
D	Wards Island	10.51	5.56	4.95	6.35	1845	1 day.
E	Little Hell Gate	9.79	3.51	6.28	4.74	1849	11 days.
F	Lawrence Point	11.40	5.75	5.65	6.55	1868	17 days.
G	Port Morris	11.81	5.61	6.20	6.80	1919	1 day.
H	do	11.59	5.86	5.73	6.32	1921–22	2 years.
I	do	11.71	5.60	6.11	6.84	1886	4 days.
J	North Brother Island	10.33	5.10	5.23	6.27	1847	1¼ months.
J	do	11.56	5.91	5.65	6.06	1883	4 days.
J	do	11.12	5.44	5.68	5.49	1887	2 days.
K	College Point	11.71	6.84	4.87	6.85	1883	3 days.
L	do	11.85	6.17	5.68	7.21	1886	5 days.
L	do	11.72	6.04	5.68	6.64	1922	2 months.
M	Flushing Creek	11.76	5.88	5.88	7.13	1913	1 month.
N	Tallman Island	11.44	5.61	5.83	6.76	1885	2 days.
O	Old Ferry Point	11.91	5.78	6.13	7.41	1886	5 days.
P	Whitestone	10.99	5.54	5.45	7.11	1856–1886	3 days.
Q	Throgs Neck	10.50	5.22	5.28	6.96	1847	2 months.
Q	do	11.26	5.67	5.59	7.10	1920–1922	2 years.
R	Willets Point	11.22	5.75	5.47	6.99	1886	1 month.
R	do	11.30	5.27	6.03	7.17	1891–1894	2½ years.

From station A (Wards Island) the tide becomes later in going eastward as far as station K (College Point). In this stretch of 3½ miles high water becomes later by one and one-fourth hours and low water later by one-third hour. For the stretch of 3½ miles from College Point to Willets Point high water becomes earlier by very nearly half an hour and low water becomes earlier by three-fourths of an hour. With regard to time of tide, therefore, the tidal movement through upper East River is not of the progressive-wave type.

Throughout upper East River the duration of rise is less than that of fall, the period of rise being about five and one-half hours and the period of fall about seven hours. Throughout this stretch the tide curve representing the rise and fall of the tide is much like that in the eastern entrance to Hell Gate, shown in Figure 22.

The range of the tide increases in a fairly uniform manner through upper East River from 5.5 feet in Hell Gate to 7.2 feet at Willets Point. The latter figure likewise represents the range of the tide in the western part of Long Island Sound.

Table 40 shows the range at Willets Point to be somewhat larger than the range at Throgs Neck. If this is due to the deflecting force of the earth's rotation, the current must be setting eastward through upper East River at the time of high water at Willets Point and westward at the time of low water. However, the current observations made at Willets Point show that at the time of high water the current is setting westerly at very nearly its strength. The greater range at Willets Point is therefore not due to the deflecting force of the earth's rotation. It is to be noted that the range of the tide in upper East River increases in going eastward, and that Willets Point is farther east than Throgs Neck, and hence the greater range at the former point is to be ascribed to its more easterly position.

For station R (Willets Point) there are at hand the results of harmonic analyses for two series, each a year in length. The first series begins July 1, 1891, and the second series begins January 1, 1894. The mean results of the two series are given in Table 41. Values inclosed in parentheses have been derived by inference from the principal components and not by direct analysis.

TABLE 41.—*Harmonic constants, station R (Willets Point), East River*

Component	H	κ	Component	H	κ	Component	H	κ
	Feet	*Degrees*		*Feet*	*Degrees*		*Feet*	*Degrees*
J_1	(0.019)	(103.6)	N_2	0.744	304.2	S_2	0.644	352.4
K_1	0.339	118.9	2N	(0.099)	(279.8)	T_2	(0.038)	(352.4)
K_2	0.146	359.0	O_1	0.198	149.7	λ_2	(0.026)	(339.6)
L_2	0.300	2.6	OO	(0.011)	(88.1)	μ_2	(0.088)	(304.8)
M_1	0.020	166.3	P_1	0.091	133.5	ν_2	0.112	312.4
M_2	3.649	328.6	Q_1	(0.038)	(165.0)	ρ_1	(0.008)	(162.9)
M_4	0.096	210.6	2Q	(0.005)	(180.3)			
M_6	0.210	83.8	R_2	(0.005)	(352.4)			

From the harmonic constants given in Table 41 above various characteristics of the tide have been determined. These are given in Table 42, in which are included also for the sake of completeness the lunitidal intervals and the mean range of tide as determined from direct tabulation of high and low water.

TABLE 42.—*Tidal data, station R (Willets Point), East River*

High water interval	hours	11.30
Low water interval	do	5.27
Mean range	feet	7.17
Spring range	do	8.54
Neap range	do	5.68
Great diurnal range	do	7.69
Great tropic range	do	8.21
Phase age	hours	23.4
Parallax age	do	44.8
Diurnal age	do	−28.1
Sequence of tides is HHW to LLW.		
Spring range ÷ mean range		1.19
Neap range ÷ mean range		0.79
Great diurnal range ÷ mean range		1.07
Great tropic range ÷ mean range		1.15

Comparing the data of Table 42 with the data of Tables 28 and 33, it will be seen that the ratios of the various ranges to mean range are practically the same at Sandy Hook, Fort Hamilton, Governors Island, the Battery, and Willets Point. Throughout New York Harbor we may therefore take the ratios of the various ranges at any point to mean range at that point, as follows: Spring range, 1.19; neap range, 0.79; perigean range, 1.21; apogean range, 0.83; great diurnal range, 1.10; great tropic range, 1.12.

It is of interest to note that the data of Tables 28, 33, and 42 show that the phase age and diurnal age of the tide decrease from Sandy Hook to Willets Point, while the parallax age increases. The sequence of the tide at all five stations is from higher high water to lower low water.

THE TIDAL MOVEMENT THROUGH EAST RIVER

It is obvious that in East River the tidal movement is conditioned by the fact that it is open to the tides of Upper Bay and also to the tides of Long Island Sound. It has therefore been customary to ascribe the peculiar characteristics of the tidal movement in East River to the interference of two tide waves—the one entering from Upper Bay and the other from Long Island Sound.

However, the mechanism of the tidal movement in East River can best be understood by regarding the phenomena from the hydraulic point of view; that is, we may regard the changing height

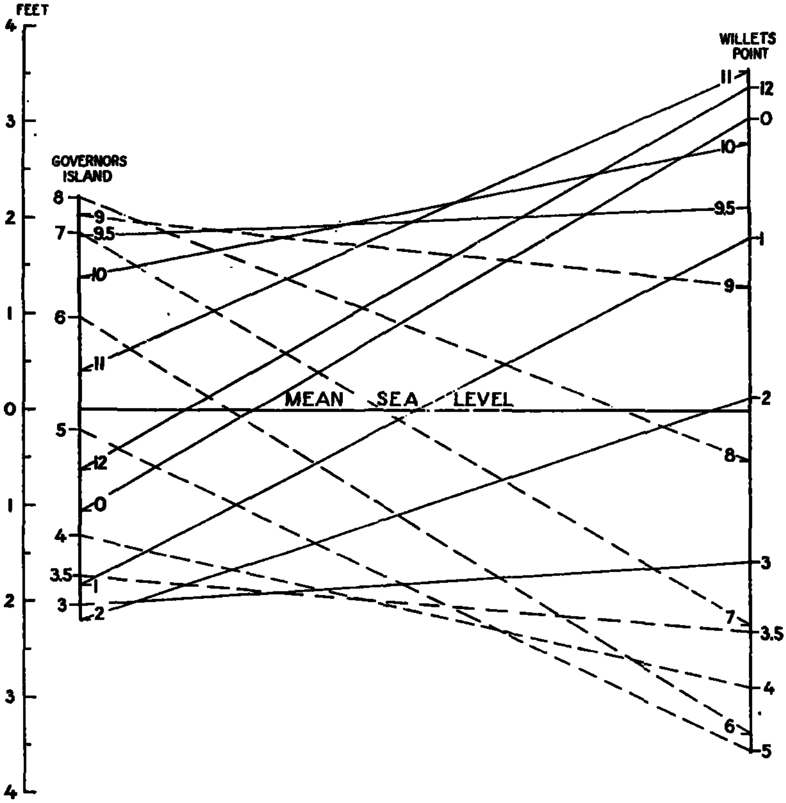

FIG. 25.—Slope lines, East River

of the water in East River as brought about by the fact that part of the time the level of the water in Upper Bay is higher than in Long Island Sound, and part of the time it is lower. In other words, we may regard East River as a channel through which the water flows from the body having temporarily the higher level to the one having the lower level. The height of the water at any point in East River is therefore due to the relative elevations of the water at the two ends.

If we plot the simultaneous heights of the level of the water at the two ends of East River, the lines joining these simultaneous heights will represent the slope of the water surface in the river, and thus the height of the water at those times. These slope lines will then permit the time and range of the tide throughout the river to be determined, since the time and height of the high water at any place will be represented by the highest point in the slope lines passing that place, while the time and height of the low water will be indicated by the lowest point in the slope lines.

In Figure 25 the simultaneous heights of the water at the two ends of East River are represented for each hour of the tidal rise and fall, time being reckoned from the instant of the moon's passage over the meridian of Governors Island. On the vertical line to the left the hourly height of the tide at Governors Island is plotted, while on the vertical line to the right the hourly height of the tide at Willets Point is plotted. In both cases the heights are measured from mean sea level, indicated by the heavy horizontal line, the scale of heights in feet being shown to the left. The figures along the vertical lines denote the hours to which the indicated heights apply, hours and heights being placed to the left of each vertical line for the rising tide and to the right for the falling tide. The slope lines—the lines joining simultaneous heights—are drawn full when the slope is from Long Island Sound to Upper Bay and dashed when the slope is in the reverse direction.

If the tidal movement in the East River is due, primarily, to the difference in elevation of the water at the two ends, then the slope lines of Figure 25 should indicate the approximate high water and low water lunitidal intervals through the river and also the ranges of the tide. In lower East River station H (fig. 21) is 3 miles from Governors Island, or approximately one-fifth the distance between Governors Island and Willets Point. Taking a point on the diagram of Figure 25 one-fifth the distance between the two vertical lines, it is seen that the highest slope line passing that point is approximately the 9.5 line, and hence the high water interval at this point should be about 9.50 hours. Table 39 gives the observed value as 9.33 hours. At this point likewise the lowest slope line is the 3-hour line, and Table 39 gives from observations 2.92 hours. Finally, the slope line diagram gives the height of high water at this point as 1.9 feet above mean sea level and low water as 2.0 feet below mean sea level, or a range of 3.9 feet. The observed value from Table 39 is 4.1 feet.

The slope-line diagram of Figure 25 shows immediately that high water in the river is defined by a curve concave toward the surface and low water by a line convex toward the surface. It shows further that for about one-fourth the distance between Governors Island and Willets Point the tide should decrease in range, which decrease the observations have shown to exist, and it is to be recalled that the fact that the low water line in the river is not a straight line but a curved line convex toward the surface likewise was indicated by observations.

It is obvious that the simple hydraulic considerations upon which Figure 25 is based can give only a first approximation to the tidal conditions existing in the East River. The slope lines are drawn as if the channel from Governors Island to Willets Point ran straight for the stretch of 14 miles with unvarying width and depth. No account has been taken of the varying depths in the waterway, of the differences in width, changes in direction, nor of the effect of the water coming through Harlem River. These factors must obviously bring about modifications; but, notwithstanding this, it is seen that the principal tidal phenomena are easily derived by considering the movement of the water in East River as hydraulic. In the chapter devoted to the currents in the East River it will be seen that the characteristics of the current give further proof of the correctness of the view that the tidal movement in the East River is primarily hydraulic in character.

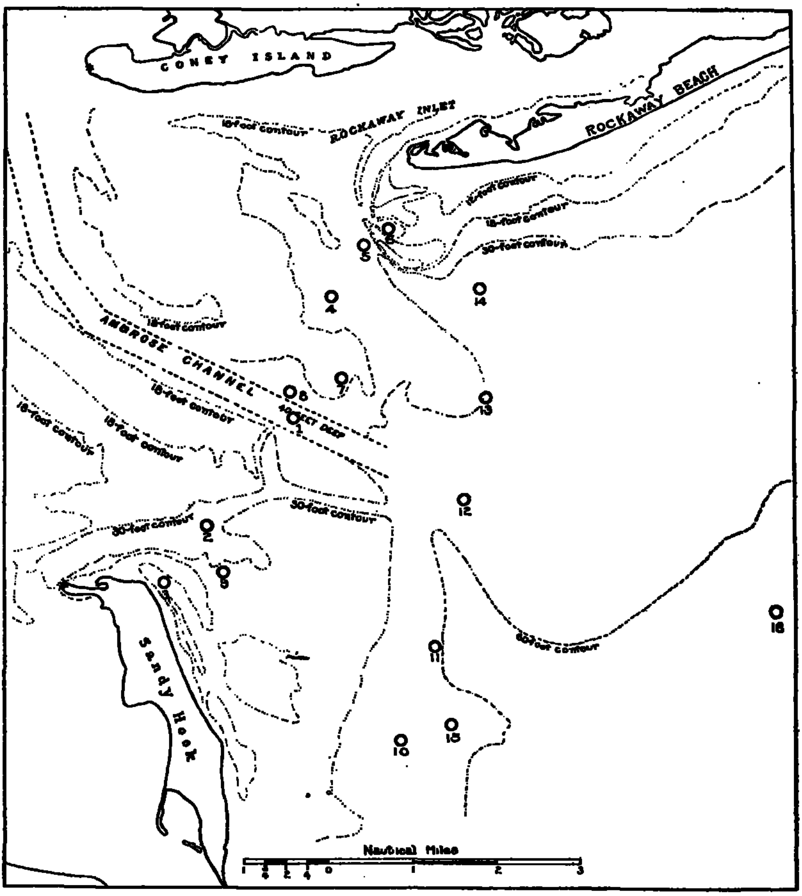

FIG. 26.—Current stations, approaches to Lower Bay

X. THE CURRENT IN THE APPROACHES TO LOWER BAY

On figure 26 are plotted a number of stations in the approaches to Lower Bay at which current observations have been made, the records of which are on file at the office of the Coast and Geodetic Survey. During the current survey of New York Harbor in 1922 by the party of H. C. Denson station 1 in Ambrose Channel was used as a control station. Here continuous observations were made for a period of 4½ days at a depth of 7 feet, and for a period of 2½ days at four different depths, namely, 7 feet, 9 feet, 20 feet, and 32 feet, the latter

3 depths representing, respectively, 0.2, 0.5, and 0.8 of the depth at the station. For the 7-foot depth a log line and current pole was used. This pole was 15 feet long and was weighted with sufficient sheet lead to submerge 14 feet, leaving 1 foot out of water. The log line was graduated for a run of 60 seconds, which was the observation interval used, the observations being made every hour. With the meter the observations were made every half hour, the observation interval likewise being 60 seconds. The meter used was the Price current meter with telephone attachment.

The method employed in reducing the observations consisted in plotting the observed velocities of the current on cross-section paper, flood velocities being plotted above the axis of X and ebb velocities below. A smooth curve was then drawn through these plotted points, and from this curve the times of each slack water and the times and velocities of each strength of flood and ebb were determined and tabulated for each depth separately. Corresponding to the times of flood and ebb strength of the velocities given by the pole, the direction of the current at these times was derived from the hourly readings. In Table 43 is given the tabulation for the 7-foot depth, time being given in hours and decimals, velocities in knots, and directions (magnetic) in degrees, north being 0°; east, 90°; south, 180°; and west, 270°.

TABLE 43.—*Currents at 7-foot depth, station 1, approaches to Lower Bay*

Date	Time of current				Time of tide at Fort Hamilton	
	Slack before flood	Strength of flood	Slack before ebb	Strength of ebb	HW	LW
1922	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*
Aug. 8	2.6	5.4	9.3	-----	8.3	2.4
	15.8	17.8	21.4	12.9	20.5	14.5
Aug. 9	4.4	6.7	9.8	1.4	9.2	2.9
	16.8	18.8	22.0	13.8	20.9	15.0
Aug. 10	5.3	7.3	10.8	2.0	9.6	3.7
	17.0	18.8	23.1	14.0	21.7	15.7
Aug. 11	6.1	8.5	11.0	2.1	10.0	4.4
	17.8	19.6	23.8	14.6	22.6	16.6
Aug. 12	6.0	8.2	-----	3.0	10.8	4.4
	-----	-----	12.1	14.6	23.0	16.0

Date	Time of current with reference to tide at Fort Hamilton				Strength of flood		Strength of ebb	
	Slack before flood	Strength of flood	Slack before ebb	Strength of ebb	Magnetic direction	Velocity	Magnetic direction	Velocity
1922	*Hours*	*Hours*	*Hours*	*Hours*	°	*Knots*	°	*Knots*
Aug. 8	L+0.2	H−2.9	H+1.0	L−2.6	-----	1.7	-----	-----
	1.3	−2.7	0.9	−1.6	318	1.4	151	2.8
Aug. 9	1.5	−2.5	0.6	−1.5	316	2.5	131	2.3
	1.8	−2.1	1.9	−1.2	-----	2.4	-----	2.2
Aug. 10	1.6	−2.3	1.2	−1.7	311	1.5	131	2.4
	1.3	−2.9	1.4	−1.7	313	1.4	131	2.1
Aug. 11	1.7	−1.5	1.0	−2.3	309	1.6	134	2.2
	1.2	−3.0	1.2	−2.0	308	1.5	138	1.9
Aug. 12	1.6	−2.6	-----	−1.4	308	1.4	140	2.4
	-----	-----	1.3	−2.3	-----	-----	135	1.9
Sums	12.2	−22.5	10.5	−18.3	2,178	15.4	1,091	20.2
Means	L+1.36	H−2.50	H+1.17	L−1.83	311	1.71	136	2.27

To make the results of the current observations throughout New York Harbor comparable with each other, the times of current are referred to the times of tide at Fort Hamilton. This, in effect, corrects the times of current to mean values approximately. The velocities of the flood and ebb strengths, however, when derived from a short series must be corrected to a mean value, and since the change in velocity of current may be taken proportional to the change in range of tide the factor for correcting current velocities to a mean value may be taken as the ratio of the mean range of the tide to the range of tide for the period of observations. For the period August 8 to 12, 1922, this ratio of ranges for the tide at Fort Hamilton was 1.02. Hence, the average velocities derived from Table 43 are to be multiplied by 1.02 to reduce them to mean values.

But it is to be noted that it is the tidal current alone that is to be multiplied by this factor. The current as observed is the resultant of the tidal and nontidal currents, but since the effect of the nontidal current is to increase the ebb velocity by the same amount that it decreases the flood velocity we may eliminate the nontidal current by taking as the tidal current the half sum of the observed flood and ebb strengths, and it is this half sum which is multiplied by the correction factor. For the mean values of flood and ebb strengths half the velocity of the nontidal current is then subtracted from the strength of flood and added to the strength of ebb. Table 44 gives the results of the current observations at station 1 for the four depths, reduced to mean values. In this table HW stands for time of high water at Fort Hamilton and LW for time of low water. It is to be noted, too, that the directions given are true, not magnetic.

The period of observations at station 1 is comparatively short. Hence, the differences in the times of slack and also of strength of the current shown for the different depths in Table 44 can not be taken as well determined; but in any event these differences are small, and since the time of tide at Sandy Hook and also at Coney Island is approximately the same as at Fort Hamilton we may take slack before flood as coming 1½ hours after local low water, strength of flood 2½ hours before high water, slack before ebb 1¼ hours after high water, and strength of ebb 1¾ hours before low water. The current, therefore, starts flooding 1½ hours after the water has commenced to rise and continues flooding up to the time of high water and for a period of 1¼ hours thereafter, during which time the water has commenced to fall. Similarly, the current starts ebbing 1¼ hours after the tide has commenced to fall and continues to ebb until the time of low water and 1½ hours beyond, during which time the water has commenced rising. Flood current and rise of tide are therefore not synonymous in this region, neither are ebb and fall of tide. The duration of the flood at station 1 may be taken as 5.81 hours and the duration of ebb as 6.61 hours. At Sandy Hook, it will be recalled, the duration of rise was 6.11 hours and of fall 6.31 hours.

Station 1 is located almost exactly in the axis of Ambrose Channel, which here has a direction of N. 63° W. Table 44 shows that the flood and ebb currents here have directions practically the same as Ambrose Channel. It is to be noted, too, that the duration of flood is less than that of ebb at all four depths.

Table 44.—*Current data, station 1, approaches to Lower Bay*

[Referred to times of HW and LW at Fort Hamilton]

Date	Observations with—	Depth	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
				Time	Direction	Velocity			Time	Direction	Velocity		
1922		*Feet*	*Hours after LW*	*Hours before HW*	*True*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*True*	*Knots*	*Hours*	*Days*
Aug. 8-12	Pole	7	1.36	2.50	N. 60° W.	1.75	5.84	1.17	1.83	S. 55° E.	2.28	6.58	4½
Aug. 10-12	Meter	9	1.70	2.36		1.54	5.76	1.43	1.74		2.50	6.66	2½
Do	do	20	1.60	2.44		1.38	5.78	1.35	1.76		1.86	6.64	2½
Do	do	32	1.54	2.66		1.27	5.84	1.35	2.14		1.41	6.58	2½

TABLE 45.—*Current data, stations 2, 3, 4, 5, and 6, approaches to Lower Bay*

[Referred to times of HW and LW at Fort Hamilton]

Station No.	Date	Observations with—	Depth	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
					Time	Direction	Velocity			Time	Direction	Velocity		
	1922		*Feet*	*Hours after LW*	*Hours before HW*	*True*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*True*	*Knots*	*Hours*	*Days*
2	Aug. 7-9	Pole	7	0.90	1.90	N. 46° W	1.12	6.05	0.92	3.00	S. 83° E	1.86	6.37	2
		Meter	7	0.87	2.10		1.30	6.06	0.90	2.80		1.99	6.36	2
		do	18	0.93	2.27		1.31	6.02	0.92	2.55		1.43	6.40	2
		do	29	0.93	2.33		1.27	6.02	0.92	2.45		1.10	6.40	2
3	Aug. 8-9	Pole	7	0.50	3.90	N. 42° W	1.48	6.03	0.50	2.70	S. 56° E	1.68	6.39	1
		Meter	6	0.40	3.70		1.93	6.18	0.55	2.70		1.70	6.24	1
		do	14	0.40	4.20		1.60	6.23	0.60	2.20		1.55	6.19	1
		do	24	0.40	4.00		1.27	6.23	0.60	2.15		1.20	6.19	1
4	Aug. 7-9	Pole	7	0.20	2.12	N. 78° W	0.90	6.51	0.68	2.80	S. 38° E	1.25	5.91	1¾
		Meter	4	0.50	2.22		0.97	6.21	0.68	2.77		1.05	6.21	1¾
		do	10	0.50	2.30		0.91	6.46	0.93	2.45		0.93	5.96	1¾
		do	16	0.50	2.35		0.88	6.43	0.90	2.40		0.84	5.99	1¾
5	Aug. 7-9	Pole	7	0.77	3.13	N. 51° W	1.41	5.84	0.58	2.70	S. 40° E	1.49	6.58	1¾
		Meter	5	0.45	3.15		1.60	6.08	0.50	2.93		1.53	6.34	1¾
		do	13	0.45	3.35		1.44	6.11	0.53	2.90		1.46	6.31	1¾
		do	21	0.45	3.55		1.38	6.08	0.50	2.97		1.32	6.34	1¾
6	Aug. 7-9	Pole	7	0.40	3.23	N. 66° W	1.07	6.00	0.37	3.17	S. 48° E	1.62	6.42	1½
		Meter	5	0.55	3.40		1.17	5.95	0.47	3.10		1.71	6.47	1¼
		do	13	0.55	3.50		1.27	5.91	0.43	3.05		1.74	6.51	1¼
		do	21	0.55	3.40		1.27	5.91	0.43	3.30		1.54	6.51	1¼

During the period that currents were being observed at station 1 the party of H. C. Denson also observed currents at stations 2, 3, 4, 5, and 6, along a line from Sandy Hook to Rockaway Point, for periods varying from one to two days. The results of these observations, with the velocities corrected to mean values, are given in Table 45. Here, as in Table 44, HW stands for the time of high water at Fort Hamilton and LW for the time of low water.

Table 45 shows that the current turns earliest in the shallow regions near shore and latest in Ambrose Channel. South of Ambrose Channel the currents set almost due northwest on the flood, while to the north of the channel the direction of the flood current is approximately N. 65° W. On the ebb the current in the region of the channel set about S. 70° E., while to the north the direction of ebb current is approximately S. 40° E.

Along the whole line from Sandy Hook to Rockaway Point the ebb current has the greater velocity near the surface; at mid-depth the flood and ebb velocities are approximately equal, while near the bottom the flood current generally has the greater velocity. The data of Table 45, like that of Table 44, also indicate the greater duration for the ebb current throughout this region.

At Scotland and Ambrose Channel Light Vessels hourly current observations have been made with a current pole and log line by the crews of the light vessels for periods covering a month or more at various times. These observations permit a more detailed discussion of the current at these stations and will be taken up later. For the remaining stations shown on Figure 26 the data are given in Table 46, the times of current being referred to the times of tide at Fort Hamilton, HW standing for the time of high water at Fort Hamilton and LW for the time of low water. The velocities of the tidal current have been reduced to a mean value by a factor given by the ratio of the mean range of tide to the range of tide during the period of observations. For these stations the data pertain to the currents near the surface.

The data in Table 46 are given as derived directly from the tabulations of the observations. With the exception of correcting the velocities of the tidal current to mean values, as explained above, no adjustment of the data has been made to derive more concordant results. Since the periods of observation are short, the times and velocities are given to the nearest tenths of hours and knots, respectively, and the direction to the nearest 5°.

For Scotland Light Vessel (station 15) hourly observations with log line and current pole, made by the crew of the light vessel, have been reduced for the following periods: (*a*) November 6, 1912, to January 31, 1913; (*b*) May 1 to 29, 1921; (*c*) July 1 to 29, 1921; (*d*) September 1 to 29, 1922.

The period covered by series (*a*) is 87 days, and for this series an harmonic analysis has been made, and since out in the open the direction of the current varies from hour to hour it is necessary to resolve the hourly observations into two directions perpendicular to each other. The most convenient directions to choose are generally north and south and east and west, and the resolution may be accomplished very expeditiously by the use of a graphic resolution table. The resolved hourly heights for each direction are then analyzed in the same way as the hourly heights of the tide. The results of the harmonic analysis are given in Table 47.

TABLE 46.—*Current data, stations 7 to 14, approaches to Lower Bay*

[Referred to times of HW and LW at Fort Hamilton]

Station No.	Party of—	Date	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
				Time	Direction	Velocity			Time	Direction	Velocity		
			Hours after LW	*Hours before HW*	*True*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*True*	*Knots*	*Hours*	*Days*
7	H. L. Marindin	July, 1887		2.8	N. 75° W	1.2		0.3	2.7	S. 75° E	1.4		3/4
8	do	do	1.2	2.8	N. 65° W	1.4	5.7	0.9	1.4	S. 75° E	1.6	6.7	1/2
9	T. A. Craven	Nov., 1855	1.0	1.5	N. 70° W	1.2	6.8	1.8	2.3	S. 65° E	1.6	5.6	1/2
10	C. G. Hanus	Aug., 1885	1.0	1.8	N. 45° W	0.6	6.4	1.4	1.7	S. 50° E	0.7	6.0	1 1/2
11	do	do	1.3	2.1	N. 45° W	0.7	6.1	1.4	2.1	S. 60° E	0.8	6.3	1 3/4
12	do	do	1.5	1.9	N. 45° W	0.7	5.4	0.9	1.8	S. 70° E	0.8	7.0	1 3/4
13	J. M. Hawley	do	1.5	2.1	N. 50° W	0.6	5.0	0.5	2.2	S. 60° E	1.0	7.4	1 1/4
14	do	do	1.2	2.1	N. 60° W	0.9	5.7	0.9	2.3	S. 55° E	1.3	6.7	1/2

TABLE 47.—*Harmonic constants, station 15 (Scotland Light Vessel)*

[From 87-day series, November 6, 1912, to January 31, 1913]

Component	North and south (magnetic)		East and west (magnetic)	
	H	κ	H	κ
	Knots	*Degrees*	*Knots*	*Degrees*
M_2	0.350	201	0.383	348
M_4	0.068	263	0.034	54
M_6	0.038	316	0.023	152
S_2	0.044	181	0.053	358
S_4	0.009	83	0.018	158

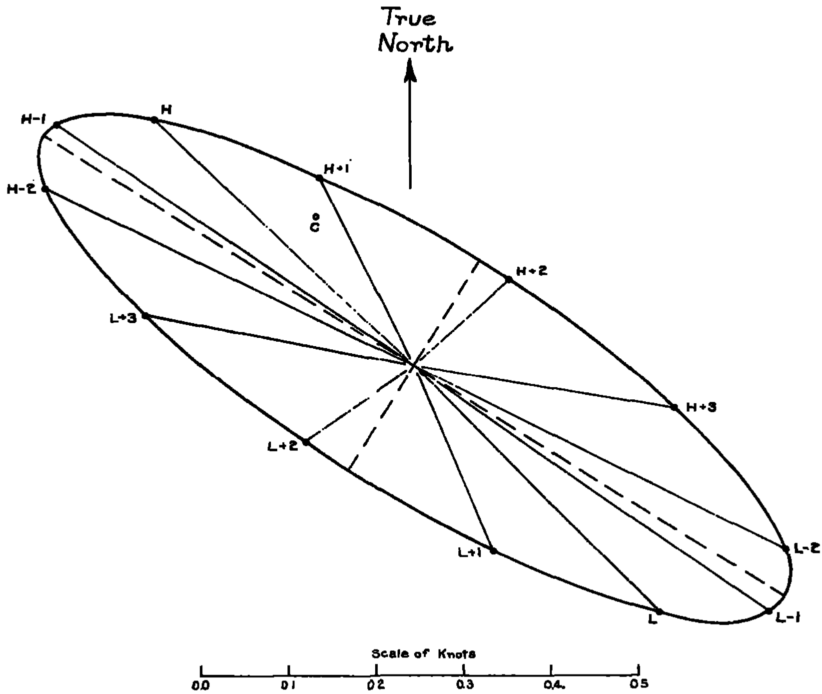

FIG. 27.—Current ellipse for M_2 component, Scotland Light Vessel

Since station 15 is some distance from the coast, we may expect the current here to be of a rotary type. If we plot the hourly velocities of M_2, using the above values for the north and south, and east and west components, we derive an ellipse which gives approximately the curve of the current at station 15. The resultant strength of flood and ebb may be determined from this ellipse, or from the formula,

$$\tan 2\theta = \frac{H_1^2 \sin 2\kappa_1 + H_2^2 \sin 2\kappa_2}{H_1^2 \cos 2\kappa_1 + H_2^2 \cos 2\kappa_2}$$

which is derived by writing the equations of the current in the form $u = H_1 \cos(\theta - \kappa_1)$ for the north and south component and $v = H_2 \cos(\theta - \kappa_2)$ for the east and west component and solving for a maximum.

Figure 27 represents the M_2 current ellipse for station 15 derived from the constants above. The velocities and directions of the tidal current are shown for each hour with reference to the time of tide at Fort Hamilton, H standing for the time of high water and L for the time of low water. From this current ellipse the current at station 15 is seen to rotate in the direction of the hands of a clock. The strength of the flood comes 1.35 hours before the time of high water at Fort Hamilton and sets N. 57° W. with a velocity of 0.50 knot, while the minimum current before ebb comes 3.10 hours later, or 1.65 hours after the time of high water at Fort Hamilton and sets N. 33° E. with a velocity of 0.15 knot. Since M_2 alone is taken into account in the current ellipse above, the strength of ebb has the same velocity as that of flood and sets in a direction exactly opposite, and this is likewise the relation of slack before flood to slack before ebb.

It is to be noted that the velocities and directions of the current derived from the current ellipse of Figure 27 refer to the tidal current alone, for the harmonic analysis eliminates the nontidal current. To derive the mean currents actually prevailing for the period covered by the observations of series (*a*), it is necessary to take account of the nontidal current, which during this time had a velocity averaging 0.21 knot, setting S. 32° E. This nontidal current may be combined with the tidal current, graphically, by shifting the origin of coordinates to the point *C*, lying 0.21 knot N. 32° W. from the center of the figure. For the strength of flood we now get 0.32 knot, setting N. 75° W., and for the strength of ebb 0.69 knot, setting S. 50° E.

The velocity and direction of the nontidal current at any station are determined from the following considerations. If the current at the station is wholly tidal, then in a period of $24^h\ 50^m$ the hourly velocities resolved into north and south, and east and west directions should sum up to zero for each of these directions; that is, since the tidal current is periodic, its average north velocity will equal its average south velocity, and likewise its average east velocity will equal its average west velocity. The nontidal current, however, is not periodic and will therefore make itself evident in the sums of the resolved directions to the extent of its components in these directions, which thus furnish the data for its determination. The tidal current from whatever period determined should show approximately constant characteristics, but the nontidal current may be expected to exhibit variable velocity and different directions, depending on the season of the year.

For short series the current ellipse may be more easily determined nonharmonically by tabulating the resolved hourly velocities and directions of the current with respect to the time of tide at some nearby point, and this method has been employed in reducing the observations for series (*b*), (*c*) and (*d*). The current ellipse derived by this method does not possess the regularity of the M_2 ellipse, nor can the velocity and direction of the strength of flood and ebb be determined with as great precision. It has, however, the advantage of giving results that take account of the effects of the other components besides M_2. The curve for series (*b*) is shown in Figure 28.

It is obvious that in tabulating the hourly velocities of the current the nontidal current is not eliminated, and this is brought out by

Figure 28, the lines representing the hourly velocity and direction of the current radiating from a point some distance from the center of the figure. For the period covered by these observations, May 1 to 29, 1921, the nontidal current is determined as setting S. 1° E. with a velocity of 0.19 knot. The tidal current alone may be determined approximately by drawing major and minor axes for the ellipse, which will then represent the velocities and directions of the strength and of the minimum of the tidal current. From Figure 28 the strength

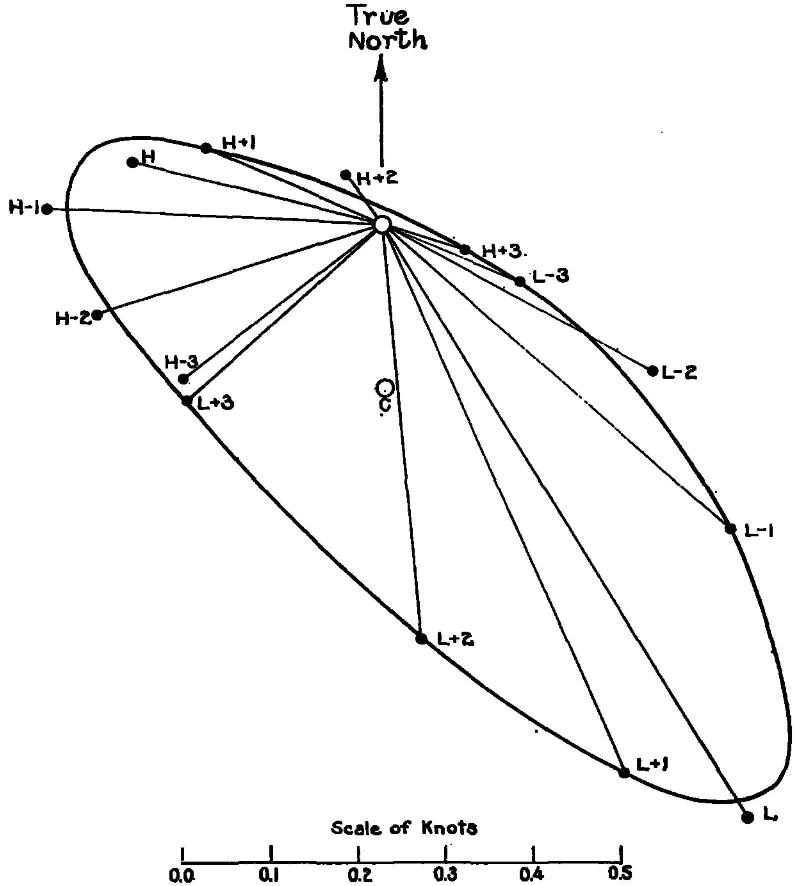

FIG. 28.—Current ellipse from nonharmonic tabulation, Scotland Light Vessel

of flood is determined to be 0.54 knot, setting N. 49° W., and the minimum current before ebb 0.20 knot, setting N. 41° E.

Table 48 gives the current data at station 15 for the four series of current observations. For the tidal current the data are given for the strength of flood and minimum before ebb, since the strength of ebb and minimum before flood will be the same, respectively, but with directions reversed. The time is given with reference to the time of tide at Fort Hamilton, HW standing for the time of high water and LW for the time of low water. It is to be noted, too, that for the minimum before ebb the time given in every case is a quarter tidal period or 3.1 hours after the strength of flood, and the direction of the minimum before ebb is given at right angles to the direction of strength of flood.

TABLE 48.—*Current data, station 15 (Scotland Light Vessel)*

[Referred to times of HW at Fort Hamilton]

Series	Date of observations	Tidal current						Nontidal current	
		Strength of flood			Minimum before ebb				
		Time	Velocity	Direction	Time	Velocity	Direction	Velocity	Direction
		Hours before HW	*Knots*	*True*	*Hours after HW*	*Knots*	*True*	*Knots*	*True*
(a)	Nov. 6, 1912–Jan. 31, 1913.	1.35	0.50	N. 57° W.	1.75	0.15	N. 33° E.	0.21	S. 32° E.
(b)	May 1–29, 1921	1.4	0.54	N. 49° W.	1.7	0.20	N. 41° E.	0.19	S. 1° E.
(c)	July 1–29, 1921	0.7	0.49	N. 55° W.	2.4	0.14	N. 35° E.	0.16	S. 4° W.
(d)	Sept. 1–29, 1922	1.2	0.43	N. 54° W.	1.9	0.15	N. 36° E.	0.22	S. 8° W.
	Weighted mean	1.22	0.51	N. 55° W.	1.88	0.16	N. 35° E.	0.19	S. 15° E.

For the best determined value at station 15, we may take a weighted mean of the values given in Table 48, weighting the different series in accordance with the length of the observations. Strictly, the velocities of the current from the four different series should be resolved to derive the mean velocity, but the differences in the directions for the strength of current are so small as to make no appreciable difference in the result. For the nontidal current, however, the difference in the directions is considerable, and the mean has been derived by resolving the velocities.

For Ambrose Channel Light Vessel (station 16) a series 87 days in length—November 5, 1912, to January 31, 1913—has been analyzed harmonically, and a series 29 days in length has been tabulated nonharmonically. The results from the harmonic analysis are given in Table 49, and the current ellipse for M_2, based on the data of Table 49, is shown in Figure 29.

TABLE 49.—*Harmonic constants, station 16 (Ambrose Channel Light Vessel)*

[From 87-day series, November 5, 1912, to January 30, 1913]

Component	North-and-south (magnetic)		East-and-west (magnetic)	
	H	κ	H	κ
	Knots	*Degrees*	*Knots*	*Degrees*
M_2	0.045	157	0.197	2
M_4	0.007	58	0.012	147
M_6	0.008	135	0.106	318
S_2	0.039	188	0.044	8
S_4	0.009	314	0.011	196

Figure 29 shows the current at station 16 to be relatively weak and only slightly rotary. The strength of the flood current comes 1.2

hours before the time of high water at Fort Hamilton and sets N. 88° W., with a velocity of 0.20 knot. Minimum current before ebb comes 1.7 hours after low water at Fort Hamilton and sets N. 2° E. with a velocity of 0.02 knot. Practically, therefore, the current at Ambrose Channel Light Vessel is of the rectilinear type, but it is of interest to note that what little rotary current there is rotates counterclockwise, or in a sense opposite to that found at Scotland Light Vessel. This is also brought out by the observations for September 1 to 29, 1922, which have been tabulated nonharmonically. The results from this tabulation give for the tidal current as follows: Strength of flood comes about 1.8 hours before time of high water at Fort Hamilton and sets N. 83° W., with a velocity of 0.23 knot. Minimum current before ebb comes about 1.1 hours after time of low water and sets N. 7° E., with a velocity of 0.02 knot. The 87-day series—November 5, 1912, to January 30, 1913—gave a nontidal current of 0.20 knot, setting due east, while the 29-day series—

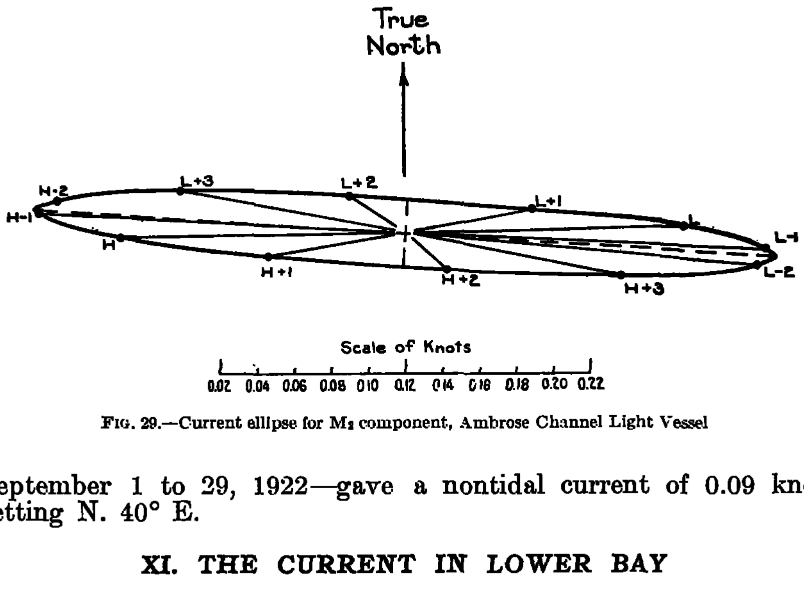

FIG. 29.—Current ellipse for M_2 component, Ambrose Channel Light Vessel

September 1 to 29, 1922—gave a nontidal current of 0.09 knot setting N. 40° E.

XI. THE CURRENT IN LOWER BAY

Under Lower Bay is here understood the whole body of water lying westward of a line drawn from the eastern tip of Coney Island to Sandy Hook and bounded on the north by the Narrows, on the northwest by Arthur Kill, and on the west by Raritan River. For this body of water Figure 30 shows the locations of 35 stations at which observations have been made at various times. The data derived from these observations are given in Table 50, and for each station these data refer to the current near the surface. Different methods of observation were employed at different times, but, in general, it may be taken that the data given in this table are based on observations made with a current pole and pertain to the currents at a depth of about 7 feet.

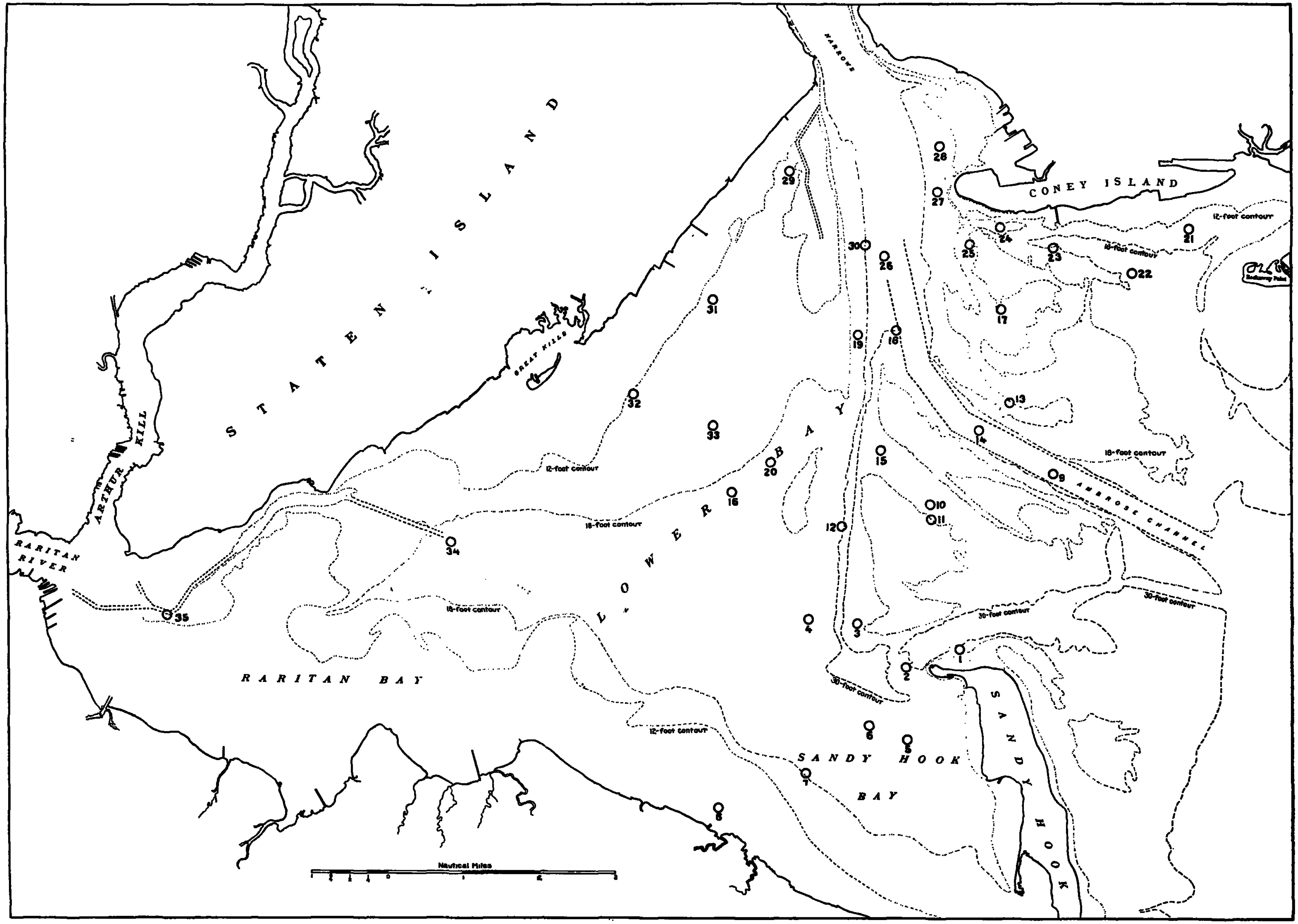

FIG. 30.—Current stations, Lower Bay

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Table 50.—*Current data, Lower Bay*

[Referred to times of HW and LW at Fort Hamilton]

Station No.	Location	Party of—	Date	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
					Time	Direction	Velocity			Time	Direction	Velocity		
				Hours after LW	*Hours before HW*	*True*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*True*	*Knots*	*Hours*	*Days*
1	Off Sandy Hook	H. L. Marindin	July, 1887	0.9	3.1	----------	1.6	4.9	−0.2	4.0	----------	2.2	7.5	1
2	do	H. C. Denson	Aug., 1922	0.7	2.2	S. 50° W	1.2	5.7	0.4	3.0	N. 10° E	1.4	6.7	1½
3	do	J. M. Hawley	Aug., 1885	1.6	3.1	S. 65° W	0.7	4.8	0.4	2.5	S. 85° E	0.9	7.6	½
4	do	T. A. Craven	Oct., 1855	0.9	2.1	N. 70° W	0.5	5.0	−0.1	3.1	S. 65° E	1.0	7.4	½
5	Sandy Hook Bay	H. Mitchell	July, 1856	0.5	3.3	S. 40° E	0.5	3.5	−2.0	4.1	North	0.7	7.9	½
6	do	do	do	0.7	3.2	S. 65° W	0.4	3.8	−1.5	5.0	N. 70° E	0.7	7.6	1½
7	do	do	do	−0.3	1.5	N. 80° W	0.5	6.5	0.2	3.8	S. 80° E	0.3	5.9	½
8	do	do	do	−0.3	2.7	S. 85° W	0.5	6.3	0.0	4.0	N. 25° E	0.3	6.1	½
9	Middle of bay	H. L. Marindin	July, 1887	1.3	2.3	N. 70° W	1.3	5.6	0.9	1.8	S. 60° E	1.8	6.8	1¾
10	do	do	do	1.1	2.1	N. 50° W	1.6	5.9	1.0	1.2	S. 50° E	1.5	6.5	1
11	do	T. A. Craven	Aug., 1855	1.1	2.1	N. 50° W	0.8	6.3	1.4	1.9	S. 60° E	1.4	6.1	½
12	do	J. M. Hawley	do	0.4	3.1	S. 80° W	0.7	6.0	0.4	2.6	East	0.6	6.4	1½
13	do	H. L. Marindin	June, 1887	0.9	2.4	N. 70° W	1.5	6.1	1.0	1.5	S. 60° E	1.6	6.3	2
14	do	do	do	1.8	1.8	N. 60° W	1.5	5.5	1.3	1.3	S. 50° E	1.6	6.9	2
15	do	T. A. Craven	Sept., 1855	1.6	1.4	N. 45° W	0.8	6.1	1.7	1.9	S. 40° E	0.8	6.3	½
16	do	J. M. Hawley	Aug., 1885	0.5	3.3	S. 70° W	0.9	6.2	0.7	2.2	S. 80° E	0.8	6.2	½
17	do	W. G. Cutter	do	0.9	2.6	N. 75° W	1.2	6.2	1.1	1.7	S. 75° E	1.6	6.2	1
18	do	do	do	2.3	1.8	N. 30° W	1.0	4.7	1.0	0.5	South	1.7	7.7	1
19	do	H. C. Denson	Aug., 1922	3.5	0.2	North	0.9	5.0	2.5	0.0	S. 10° W	1.3	7.4	1½
20	do	do	do	−0.2	3.2	S. 70° W	1.0	6.3	0.1	2.9	S. 80° E	0.6	6.1	1½
21	Off Coney Island	E. B. Thomas	Sept., 1881	−0.5	3.5	N. 40° W	0.4	6.0	−0.5	4.2	S. 85° E	0.3	6.4	½
22	do	W. P. Elliot	May, 1889	0.8	2.2	N. 70° W	1.1	6.9	1.7	2.0	S. 70° E	1.2	5.5	1
23	do	do	do	0.2	2.8	N. 85° W	2.0	7.2	1.4	2.5	S. 85° E	1.8	5.2	2½
24	do	H. Mitchell	Aug., 1858	0.8	2.4	N. 85° W	2.0	6.6	1.4	2.3	N. 85° E	1.9	5.8	½
25	do	W. P. Elliot	May, 1889	1.0	2.4	N. 75° W	1.9	6.2	1.2	2.2	S. 70° E	1.7	6.2	1
26	do	H. Mitchell	Aug., 1858	3.2	0.5	N. 10° W	0.9	5.0	2.2	0.2	S. 10° E	2.0	7.4	9
27	do	H. C. Denson	Aug., 1922	2.0	2.2	N. 30° W	1.1	4.8	0.8	1.0	South	1.8	7.6	1
28	do	do	do	3.4	0.9	N. 75° W	0.5	3.5	0.9	0.8	S. 26° E	1.7	8.9	1
29	Off Staten Island	do	do	0.7	2.4	N. 20° E	0.9	7.1	1.8	1.9	S. 30° W	0.8	5.3	1
30	do	T. A. Craven	Aug., 1855	2.6	0.6	N. 10° E	1.2	5.8	2.4	0.1	S. 15° W	2.2	6.6	½
31	do	H. Mitchell	June, 1859	1.6	0.8	N. 20° E	0.4	7.2	2.8	0.3	S. 45° W	0.3	5.2	1
32	do	do	July, 1872	−2.0	4.6	S. 55° W	0.4	5.9	−2.1	4.6	N. 70° E	0.5	6.5	½
33	do	do	do	−1.2	2.0	S. 60° W	0.3	7.3	0.1	3.0	N. 80° E	0.4	5.1	½
34	Raritan Bay	H. C. Denson	Aug., 1922	0.2	3.0	West	0.6	6.8	1.0	2.7	S. 85° E	0.4	5.6	2
35	do	do	do	0.7	3.0	N. 80° W	0.7	6.5	1.2	2.1	East	1.2	5.9	1

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In Table 50 above the times of slack and strength of current are given in hours and tenths and are referred to the times of tide at Fort Hamilton, N. Y., HW representing the time of high water and LW the time of low water. The velocity of the current is given in knots and tenths and the direction is given to the nearest 5°.

It will be noted that, in general, the current turns earliest in the shallow regions near the shores and latest in the deeper central parts of the bay. Thus, at station 1, near Sandy Hook, the current turns earlier by about an hour than at stations 9 and 14 in the center of the channel; at stations 24 and 25, near Coney Island, the current is earlier by about two hours than in the deeper central part in the vicinity of stations 18, 19, 26, and 30.

From the entrance to Lower Bay the current becomes later in going northward to the Narrows, station 30 showing the current later than station 9 by somewhat more than an hour; but going westward toward Arthur Kill and Raritan River the current apparently becomes earlier for a short distance and then is very nearly simultaneous over the greater portion of Lower Bay and Raritan Bay. Thus, at stations 12, 16, and 20 the current is earlier by about three-quarters of an hour than at stations 9, 10, 11, and 14, and at stations 34 and 35 the current is but little later than at stations 12, 16, and 20.

This difference in time of current is brought about by the fact that in the central part of Lower Bay the current is somewhat rotary in character, rotating in the direction of the hands of a clock. The current, therefore, sets westward earlier than northward. It is to be noted that for stations lying westward of Sandy Hook the direction of the flood current is about S. 75° W., while at the stations lying in the region between the entrance and the Narrows the flood current sets more nearly N. 60° W., on the strength.

Between stations 31 and 32, off Staten Island, the flood and ebb currents change directions. At station 31 and in the region northward the flood sets northeasterly and the ebb southwesterly, while at station 32 and in the region southwestward the flood sets southwesterly and the ebb northeasterly. As the terms "flood" and "ebb" are ordinarily used, the flood current is the one that sets inland or upstream and the ebb current the one that sets seaward or downstream. In tidal rivers there can generally be no question as to which direction is upstream and which downstream; but in a case like that of the region in the vicinity of stations 31 and 32 the terms upstream and downstream or inland and seaward are no longer precise, and it therefore becomes necessary to define flood and ebb in terms other than that of direction.

From a consideration of the relation of current to tide both in the progressive-wave and stationary-wave types of tidal movement the flood current may be defined as the one that attains its strength on a rising tide, while the ebb current may be defined as the one that attains its strength on a falling tide. And it is to be noted that these definitions of flood and ebb, based on time relations of current to tide, agree with the ordinary use of these terms in cases where no ambiguity arises from the definition based on direction.

From Table 30 it is evident that the time of tide in the vicinity of stations 31 and 32 is practically the same as that at Fort Hamilton. Hence HW and LW in Table 50 may be taken as representing not only the times of high and low water at Fort Hamilton but also the times of local high and low water in the vicinity of stations 31 and 32, and the data of Table 50 show that the strength of the northeasterly current comes on a rising tide at station 31 and on a falling tide at station 32. At the former station, therefore, the northeasterly current is the flood current, while at the latter station it is the ebb current.

Since the time of tide throughout Lower Bay differs but little from that at Fort Hamilton, Table 50 may be taken as giving directly the relations of the current at the various stations to local tide. For more accurate determinations use may be made of the data in Table 30.

In general, the velocity of the current in the channels of Lower Bay is between 1 and 1½ knots, with the ebb velocity greater than the flood by a quarter of a knot; the greater ebb velocity obviously brought about by the considerable amount of fresh water draining into Lower Bay. Where variations from the general conditions noted above are shown by the data of Table 50, these generally find explanation in the hydrographic features at the station. Thus, at station 28 the strength of the ebb current is greater than the flood by more than a knot. A glance at the location of the station shows that the western point of Coney Island prevents the main stream of the flood current, which sets toward the Narrows, from embracing station 28 in its sweep; but on the ebb this station lies in the direct path of the main stream from the Narrows, and hence shows the current velocity belonging to that main stream. Stations 34 and 35 likewise exhibit wide variations from the general conditions prevailing in Lower Bay. While the flood velocities at the two stations differ by but 0.1 knot, the ebb velocities differ by 0.8 knot. Here, again, the location of the station with respect to the main flood and ebb streams explains the difference. With respect to the flood stream they are located very much alike, but the main stream of the ebb current setting from Raritan River and Arthur Kill sweeps directly over station 35 but to one side of station 34.

As regards the durations of flood and ebb in Lower Bay, Table 50 shows that almost without exception the ebb has the greater duration, and this was to be expected because of the fresh-water discharge through Lower Bay. Stations 22, 23, and 24, near Coney Island, stand out markedly different with flood durations greater than the ebb. Here, too, it would appear that the location of the stations with respect to the main stream of the current explains this departure from the general conditions prevailing in Lower Bay. On the flood these stations are in the path of the main stream of the current, while on the ebb Coney Island cuts them off from the main stream issuing through the Narrows. A similar explanation probably accounts for the greater flood duration at stations 29, 31, and 34; but the greater duration of flood at station 35 is contrary to what would be expected in view of the fresh-water discharge through Raritan River and Arthur Kill.

TABLE 51.—*Current data for various depths, Lower Bay*

[Referred to times of HW and LW at Fort Hamilton]

Station No.	Location	Date	Depth	Slack	Flood strength		Flood duration	Slack	Ebb strength		Ebb duration	Length of observations
					Time	Velocity			Time	Velocity		
		1922	*Feet*	*Hours after LW*	*Hours before HW*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*Knots*	*Hours*	*Days*
2	Off Sandy Hook	Aug. 9–11	11	0.8	2.2	1.42	5.6	0.4	3.4	1.43	6.8	1½
			26	0.7	2.7	1.25	5.9	0.6	3.0	1.35	6.5	1½
			42	0.7	2.8	1.10	6.0	0.7	3.4	1.27	6.4	1½
19	Middle of Bay	do.	5	3.9	0.0	0.83	4.4	2.3	0.2	1.28	8.0	1½
			12	3.8	0.4	0.65	4.4	2.2	0.5	1.05	8.0	1½
			19	3.7	0.6	0.55	4.3	2.0	1.0	0.77	8.1	1½
20	do.	do.	5	−0.2	3.4	1.15	6.8	0.6	3.5	0.73	5.6	1½
			12	−0.2	3.4	0.98	6.8	0.6	3.5	1.00	5.6	1½
			19	−0.2	3.4	0.80	6.8	0.6	3.6	0.95	5.6	1½
27	Off Coney Island	Aug. 11–12	5	2.0	2.8	0.97	4.8	0.8	0.5	1.97	7.6	1
			12	2.0	2.3	1.33	5.0	1.0	1.2	1.75	7.4	1
			19	1.8	2.4	1.29	5.2	1.0	1.6	1.49	7.2	1
28	do.	do.	6	3.4	0.8	0.69	3.6	1.0	−0.7	1.61	8.8	1
			15	3.4	0.8	0.68	3.6	1.0	0.2	1.30	8.8	1
			22	3.3	0.8	0.74	3.8	1.1	0.4	1.01	8.6	1
29	Off Staten Island	do.	4	1.0	2.6	0.88	6.7	1.7	1.9	0.80	5.7	1
			9	0.9	2.7	1.00	6.8	1.7	1.9	0.70	5.6	1
			14	0.6	2.6	0.89	7.0	1.6	2.0	0.62	5.4	1
34	Raritan Bay	do.	5	0.4	3.1	0.74	6.2	0.6	2.8	0.62	6.2	2
		Aug. 21–22	12	0.3	3.2	0.70	6.3	0.6	3.0	0.56	6.1	2
			19	0.2	3.4	0.62	6.4	0.6	3.0	0.44	6.0	2
35	do.	Aug. 19–20	4	1.0	2.9	0.91	6.1	1.1	2.6	1.06	6.3	1
			13	0.5	3.0	0.91	6.6	1.1	2.9	0.76	5.8	1
			20	0.7	3.1	0.83	6.0	0.7	3.3	0.66	6.4	1

At the eight stations occupied by the party of H. C. Denson observations on the subsurface currents were also made, a current meter being used for this purpose. These observations were made at three depths—two-tenths, five-tenths, and eight-tenths of the depth at the station. The results of these observations, with velocities reduced to mean values, are given in Table 51. In this table HW and LW represent, respectively, the times of high and low water at Fort Hamilton, times being given to the nearest tenth of an hour and velocities to the nearest hundredth of a knot.

The observations on which the data of Table 51 are based are from one to two days in length. In a day there are but two floods and two ebbs, so that slight differences in the results for the various depths derived from observations covering but a day or two may be due to accidental variations. In general, however, the data of Table 51 indicate but little difference in the time of strength or of slack at the various depths. For the velocities, however, the differences between various depths are unmistakable.

The stations which are located outside the path of the current passing through the Narrows show, in general, a decrease in velocity with increase in depth, both on the flood and on the ebb. This is in accordance with the distribution of velocity in ordinary hydraulic flow and is evidenced by the data for station 2 off Sandy Hook, station 19 in the middle of the bay, and station 34 off Staten Island. For these stations, too, it will be noted that the durations of the flood or ebb periods do not vary much for the different depths.

The stations located in the path of the current from the Narrows show a different vertical velocity distribution for flood and ebb. Station 27 is a good illustration of this. On the ebb the current at the different depths varies in accordance with the vertical velocity distribution of ordinary hydraulic motion, the velocity decreasing with increasing depth; but on the flood the velocity shows an increase from the surface downward for a considerable depth. At station 27 the flood strength at the two-tenths depth is less than at mid-depth or at the eight-tenths depth and at the latter depth is but little less than at mid-depth.

This difference in the vertical distribution of the current velocity evidently is due to the nontidal or fresh-water discharge from the Narrows. 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 water 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 increasing depth. And while the data for station 27 are based on but one day of observations this increase in the flood period with increasing depth is shown unmistakably. The data for station 28, located similarly with regard to the current from the Narrows, give evidence of features similar to those for station 27.

XII. THE CURRENT IN THE NARROWS AND UPPER BAY

For the Narrows there are at hand current observations at 24 stations, the locations of these being shown on Figure 31. The data derived from these observations, with the velocities reduced to mean values, are given in Table 52 and may be taken to pertain to the current at a depth of about 7 feet. The times of current are referred to the times of tide at Fort Hamilton, N. Y., HW standing for the time of high water and LW for the time of low water.

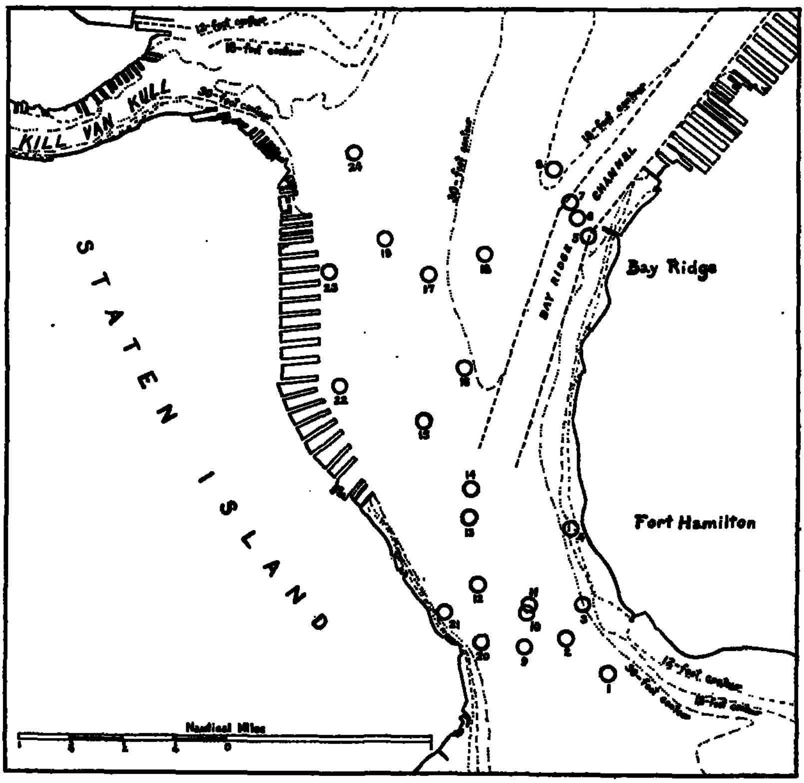


FIG. 31.—Current stations, the Narrows

From the data of Table 52 it appears that through the Narrows slack before flood comes about 2½ hours after local low water, strength of flood half an hour before high water, slack before ebb 2 hours after high water, and strength of ebb 1 hour before low water. These time relations of current to tide are approximately those obtaining in progressive-wave motion, and the tidal movement through the Narrows deduced from the relation of current to tide is therefore of the progressive-wave type; and it is to be recalled that this conclusion likewise was indicated by the behavior of the tides in the Narrows discussed in Section VI.

TABLE 52.—*Current data, the Narrows*

[Referred to times of HW and LW at Fort Hamilton]

Station No.	Location	Party of—	Date	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
					Time	Direction	Velocity			Time	Direction	Velocity		
				Hours after LW	*Hours before HW*	*True*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*True*	*Knots*	*Hours*	*Days*
1	Off Brooklyn	H. Mitchell	Aug., 1858	3.1	0.2	N. 40° W.	1.1	4.4	1.5	0.8	S. 35° E.	1.9	8.0	4
2	do	T. A. Craven	Aug., 1855	2.7	0.9	N. 35° W.	1.2	5.3	2.0	1.3	S. 20° E.	2.3	7.1	½
3	do	H. C. Denson	Aug., 1922	3.0	0.3	N. 10° W.	1.5	5.0	2.0	1.0	S. 45° E.	1.9	7.4	2½
4	do	H. L. Marindin	Sept., 1885	3.3	0.5	----------	1.7	4.5	1.8	1.2	----------	2.1	7.9	1½
5	do	H. Mitchell	Aug., 1858	3.3	0.1	N. 10° E.	1.3	5.1	2.4	0.1	S. 40° W.	1.5	7.3	½
6	do	H. C. Denson	Aug., 1922	2.2	1.0	N. 20° E.	1.4	6.1	2.3	1.6	S. 10° W.	1.6	6.3	1
7	do	I. Winston	Oct., 1919	1.8	0.3	N. 15° E.	1.5	6.1	1.9	1.7	S. 25° W.	1.5	6.3	2
8	do	H. Mitchell	Aug., 1872	1.7	2.0	N. 30° E.	1.2	5.8	1.5	2.1	S. 50° W.	1.3	6.6	1
9	Mid-channel	H. C. Denson	Aug., 1922	3.1	0.8	N. 20° W.	1.1	4.8	1.9	−0.1	S. 20° E.	1.9	7.6	11
10	do	I. Winston	Oct., Nov., 1919.	2.8	1.1	N. 25° W.	1.3	4.8	1.6	1.1	S. 20° E.	1.8	7.6	2
11	do	H. C. Denson	Sept., 1922	2.5	0.8	N. 20° W.	1.4	5.3	1.8	1.2	S. 15° E.	1.5	7.1	1½
12	do	H. L. Marindin	Sept., 1885	2.9	1.1	----------	2.1	4.9	1.8	1.1	----------	2.4	7.5	1½
13	do	C. G Hanus	Oct., 1886	2.9	0.5	N. 45° W.	1.5	5.3	2.2	1.0	S. 5° E.	1.8	7.1	2
14	do	U. S. S. Amphitrite	Aug.–Oct., 1917.	2.2	0.8	N. 5° W.	1.1	5.9	2.1	1.2	S. 5° E.	1.4	6.5	87
15	do	H. Mitchell	Aug., 1858	2.4	0.5	N. 10° W.	1.7	5.5	1.9	0.6	S. 5° E.	2.1	6.9	1
16	do	I. Winston	Sept., 1919	2.5	0.3	N. 5° W.	1.9	5.9	2.4	1.4	S. 10° W.	2.0	6.5	2½
17	do	H. Mitchell	July, 1859	2.5	0.3	N. 5° E.	1.4	5.5	2.0	0.8	S. 5° W.	1.5	6.9	1
18	do	T. A. Craven	Aug., 1855	2.2	0.7	N. 20° E.	1.1	5.4	1.6	0.5	South	2.0	7.0	½
19	do	I. Winston	Sept., 1919	2.3	0.2	N. 5° E.	1.6	5.8	2.1	0.6	S. 15° E.	2.4	6.6	2
20	Off Staten Island	H. C. Denson	Aug., 1922	3.4	0.6	N. 25° W.	1.5	4.6	2.0	0.1	S. 15° E.	2.3	7.8	2½
21	do	H. L. Marindin	Sept., 1885	2.8	1.0	----------	1.6	4.7	1.5	1.7	----------	2.0	7.7	1
22	do	H. C. Denson	Sept., 1922	2.1	0.8	N. 5° W.	0.9	5.3	1.4	1.1	S. 15° W.	1.5	7.1	½
23	do	do	do	1.8	0.2	N. 15° E.	0.9	5.6	1.4	1.4	S. 10° W.	1.3	6.8	½
24	do	do	Aug., Sept., 1922.	1.5	−0.1	N. 5° W.	1.2	6.4	1.9	1.7	S. 35° E.	1.6	6.0	1½

In the Narrows the duration of rise of tide is 6 hours and the duration of fall is 6.4 hours; and since for the currents near the surface in the Narrows slack before flood comes 2½ hours after low water and slack before ebb 2 hours after high water the duration of flood is about 5½ hours and the duration of ebb is about 7 hours. This excess of 1½ hours in the duration of ebb over the duration of flood obviously is due to the fresh water draining into Upper Bay which finds its outlet to the sea through the Narrows. In consequence of this fresh or nontidal water it is to be expected that near the surface the ebb current would at strength have a considerably greater velocity than the flood current. Table 52 shows this to be the case, the strength of ebb being on the average about 30 per cent greater than the strength of flood. Through the Narrows the strength of flood is about 1.4 knots and the strength of ebb 1.8 knots. Near the surface, therefore, the tidal current through the Narrows has a velocity at strength of about 1.6 knots.

The greatest current velocity will obviously be found in mid-channel where the effects of friction are least. For the mid-channel stations Table 52 gives a flood length of 1.5 knots and an ebb strength of 1.9 knots or a velocity for the tidal current of 1.7 knots. For the stations near the Brooklyn shore the flood strength is 1.4 knots and the ebb strength is 1.8 knots; while for the Staten Island shore the flood strength is 1.2 knots and the ebb strength 1.7 knots. The stations in the vicinity of Buttermilk Channel above Bay Ridge (stations 5, 6, 7, and 8) show ebb velocities but little greater than the flood velocities. The flood strengths at these stations are not greater than for the rest of the Narrows, but the ebb velocities are less than the average. This departure from the average conditions is due to the location of these stations outside the sweep of the main stream of the ebb current, which from Upper Bay sets southwesterly toward the Staten Island shore.

At the southern entrance to the Narrows the channel runs approximately N. 20° W., while at the northern entrance the direction of the channel is about S. 15° W. It is therefore to be expected that, in general, the directions of the flood and ebb currents at any given station will not be exactly opposite each other, for the momentum of the moving mass of water will cause the direction of the flood current to be modified by the direction of the channel south of the station and the direction of the ebb current by the direction of the channel north of the station.

At a number of the stations shown on Figure 31 subsurface current observations were also made by use of a current meter. Generally these observations were made at three depths—two-tenths, five-tenths, and eight-tenths of the depth at the station; and in addition to velocity observations the party of H. C. Denson also determined the directions of the subsurface currents at the depths to which the meter was suspended. These directions were determined by means of a device called the bifilar direction indicator.

Essentially the bifilar direction indicator consists of a pipe with a rudder attached at one end, which is suspended horizontally at the desired depth by two fine wires, these wires connecting with an upper horizontal bar that journals at its center in a ball-bearing joint which permits it to move in azimuth. The ball-bearing joint is fixed on an outrigger or davit of the observing vessel, and as the lower bar with its attached rudder takes the direction of the current at the depth to which it is lowered the upper bar takes the same direction.

Table 53 gives the results of the subsurface current observations made in Lower Bay in recent years. For comparison the observations made near the surface with log line and pole, which are given in Table 52, are also included. To bring out the differences in the currents at the various depths, the times in Table 53 are given to the second decimal of an hour, velocities to the second decimal of a knot and directions to the nearest whole degree.

At station 9 the current observations were continued uninterruptedly for 11 days, so that the data at this station may be considered as relatively well determined. The slack before flood is seen to become earlier toward the bottom, the difference between the first and last depths being 2.2 hours. This acceleration of the time of slack before flood obviously finds explanation in the nontidal water discharging through the Narrows, since this fresh water is less dense than the salt water of the ocean, and therefore tends to remain near the surface.

The time of strength of flood does not vary much from the surface to the bottom, though there appears to be a well-defined acceleration in the tide for the first three depths, being latest at the middle. The direction of flood likewise does not vary much for the different depths, although a slight westward deflection toward the bottom is unmistakable. The direction of the current at the 7-foot depth is that of the channel, while the direction of the current near the bottom is 10° to the westward. Figure 31 is too small to show detailed soundings, but on examining a large-scale chart of the Narrows it will be seen that toward the bottom the contour lines run more nearly northwest and southeast than near the surface, so that the current at any depth may be taken as running parallel to the direction of the channel at that depth.

Because of the fresh water flowing through the Narrows the strength of the flood current should be least near the surface and become greater toward the bottom, and this is borne out by the results for station 9. The increase in the velocity at strength is approximately at the rate of 0.01 knot per foot of depth.

The duration of flood at station 9 varies from 4.9 hours at the 7-foot depth to 7.1 hours at the 70-foot depth, or a difference of 2.2 hours. This likewise was the difference in the times of turning of the current from ebb to flood as between the 7 and 70 foot depths. It follows, therefore, that the turn of the current from flood to ebb must occur about the same time at all depths, and this the data for slack before ebb at station 9 show to be the case, there being but little difference in the time of this slack for the four depths given.

For the time of strength of ebb the data for station 9 indicate an acceleration from the surface to the bottom, the difference between the 7 and 70 foot depths being 1.7 hours. For the strength of flood the acceleration appears to take place to mid-depth only, and from that depth to the bottom there was a retardation in the time of strength. The direction of the ebb current at the time of strength shows a slight eastward deflection toward the bottom which corresponds to the westward shift found on the flood current discussed above.

3904—25†——8

TABLE 53.—*Current data for various depths, the Narrows*

[Referred to times of HW and LW at Fort Hamilton]

Station No.	Location	Date	Party of—	Observations with—	Depth	Slack	Flood strength: Time	Flood strength: Direction	Flood strength: Velocity	Flood duration	Slack	Ebb strength: Time	Ebb strength: Direction	Ebb strength: Velocity	Ebb duration	Length of observations
					Feet	*Hours after LW*	*Hours before HW*	*True*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*True*	*Knots*	*Hours*	*Days*
3	Off Brooklyn	Aug. 14–17, 1922	H. C. Denson	Pole	7	3.02	0.30	N. 11° W.	1.49	4.96	1.95	1.00	S. 45° E.	1.89	7.46	2½
				Meter	14	3.30	0.32	N. 26° W.	1.41	4.85	2.12	0.72	S. 40° E.	1.65	7.57	2½
				do	36	3.26	0.68	N. 21° W.	1.24	4.89	2.12	0.75	S. 55° E.	0.94	7.53	2½
				do	58	3.08	0.52	N. 40° W.	0.88	5.11	2.16	0.78	S. 53° E.	0.78	7.31	2½
6	do	Aug. 17–18, 1922	do	Pole	7	2.25	0.95	N. 20° E.	1.39	6.13	2.35	1.65	S. 10° W.	1.64	6.29	1
				Meter	8	2.00	0.80	N. 22° E.	1.26	6.53	2.50	1.35	S. 18° W.	1.41	5.89	1
				do	21	1.85	0.85	N. 30° E.	1.41	6.33	2.15	0.80	S. 22° W.	1.31	6.09	1
				do	33	1.50	1.40	N. 30° E.	1.34	6.53	2.00	1.15	S. 20° W.	1.19	5.89	1
7	do	Oct. 1–3, 1919	I. Winston	Pole	7	1.78	0.33	N. 15° E.	1.51	6.13	1.88	1.73	S. 26° W.	1.51	6.29	1
				Meter	9	2.15	0.72		1.49	6.01	2.13	1.16		1.65	6.41	1
				do	22	2.08	0.78		1.56	5.87	1.92	1.16		1.40	6.55	1
				do	35	2.05	1.38		1.32	5.83	1.85	1.04		1.26	6.59	1
9	Mid-channel	Aug. 7–18, 1922	H. C. Denson	Pole	7	3.08	0.82	N. 20° W.	1.09	4.89	1.94	−0.14	S. 19° E.	1.86	7.53	11
				Meter	17	2.65	1.12	N. 17° W.	1.25	5.31	1.93	0.02	S. 18° E.	1.81	7.11	11
				do	44	1.82	1.59	N. 27° W.	1.53	6.44	2.23	0.36	S. 23° E.	1.81	5.98	11
				do	70	0.89	0.48	N. 30° W.	1.75	7.11	1.97	1.57	S. 23° E.	1.27	5.31	11
10	do	Oct. 13–14, Nov. 12–13, 1919.	I. Winston	Pole	7	2.78	1.12	N. 25° W.	1.32	4.83	1.58	1.10	S. 20° E.	1.82	7.59	2
				Meter	18	2.38	1.28		1.18	5.51	1.86	1.30		1.57	6.91	2
				do	42	2.08	1.22		1.38	6.09	2.14	1.04		1.43	6.33	2
				do	60	1.65	1.20		1.60	6.38	2.00	1.12		1.53	6.04	2
11	do	Sept. 5–6, 1922	H. C. Denson	Pole	7	2.53	0.83	N. 22° W.	1.46	5.32	1.82	1.17	S. 13° E.	1.54	7.10	1½
				Meter	18	2.53	0.87	N. 29° W.	1.37	5.80	2.30	0.90	S. 19° E.	1.49	6.62	1½
				do	45	1.63	1.20	N. 24° W.	1.67	6.75	2.35	0.83	S. 47° E.	1.51	5.67	1½
				do	72	1.17	1.37	N. 26° W.	1.66	7.21	2.35	0.60	S. 42° E.	1.42	5.21	1½
16	do	Sept. 17–18, 1919	I. Winston	Pole	7	2.54	0.30	N. 6° W.	1.85	5.87	2.38	1.44	S. 10° W.	1.97	6.55	2½
				Meter	8	2.34	0.30		1.83	5.81	2.12	1.58		1.91	6.61	2½
				do	21	2.00	1.06		1.64	6.15	2.12	1.48		1.56	6.27	2½
				do	36	2.06	1.16		0.98	6.05	2.08	1.22		1.00	6.37	2½
19	do	Sept. 24–26, 1919	do	Pole	7	2.28	0.15	N. 6° E.	1.59	5.90	2.15	0.65	S. 17° E.	2.35	6.52	2
				Meter	12	2.60	0.50		1.55	5.38	1.95	0.65		1.97	7.04	2
				do	30	2.18	1.72		1.61	5.95	2.10	0.53		2.00	6.47	2
				do	48	1.88	2.52		1.30	6.12	1.97	0.43		1.64	6.30	2
20	Off Staten Island.	Aug. 14–17, 1922	H. C. Denson	Pole	7	3.36	0.60	N. 23° W.	1.52	4.67	2.00	−0.10	S. 17° E.	2.26	7.75	2½
				Meter	17	3.06	1.06		1.63	5.21	2.24	−0.20		2.41	7.21	2½
				do	42	1.84	1.28		1.47	5.77	1.58	1.16		1.89	6.65	2½
				do	67	1.32	2.80		0.92	6.13	1.42	1.78		1.55	6.29	2½
22	do	Sept. 6, 1922	do	Pole	7	2.10	0.80	N. 7° W.	0.94	5.33	1.40	1.10	S. 13° W.	1.54	7.09	½
				Meter	10	2.20	0.40	N. 12° W.	1.18	5.43	1.60	1.20	S. 13° W.	1.63	6.99	½
				do	24	2.00	1.20	N. 25° W.	1.39	5.93	1.90	1.60	S. 2° E.	1.09	6.49	½
				do	38	1.00	0.60	N. 20° W.	0.62	6.93	1.90	1.80	S. 24° E.	0.62	5.49	½
23	do	do	do	Pole	7	1.80	0.20	N. 15° E.	0.94	5.63	1.40	1.40	S. 8° W.	1.34	6.79	½
				Meter	8	1.50	0.00	N. 15° E.	1.08	6.03	1.50	1.70	S. 11° W.	1.73	5.99	½
				do	21	1.50	0.50	N. 2° E.	1.53	6.23	1.70	1.50	S. 8° W.	1.28	6.19	½
				do	34	1.50	0.70	N. 5° E.	1.34	6.23	1.70	1.20	South	0.79	6.19	½
24	do	Aug. 17–18, Sept. 6, 1922.	do	Pole	7	1.47	−0.13	N. 4° W.	1.19	6.46	1.90	1.73	S. 37° E.	1.59	5.96	1½
				Meter	10	1.33	0.10	N. 17° W.[1]	1.55	6.85	2.15	2.13	S. 23° E.[1]	1.48	5.57	1½
				do	24	1.80	1.23	N. 48° W.[1]	1.77	6.58	2.35	0.87	S. 10° E.[1]	1.34	5.84	1½
				do	38	1.63	1.57	N. 23 W.[1]	0.98	6.62	2.22	0.67	S. 4° E.[1]	1.01	5.80	1½

[1] These directions from observations on Sept. 6, only.

Since the effect of the fresh water was manifested in an increase in the strength of flood at the rate of 0.01 knot per foot of depth, a like decrease in the strength of ebb might be expected. But curiously, at station 9, the strength of ebb does not differ much from the 7 to 44 foot depths—that is, from near the surface to mid-depth—though near the bottom the velocity shows a considerable decrease from the velocity at mid-depth.

The decrease in the duration of ebb from the surface downward, shown by the data for station 9, corresponds to the increase in the duration of flood discussed above.

The features of the current found at station 9 may be taken as characteristic of the mid-channel current in the Narrows. Thus the data for stations 10 and 11 present much the same features as at station 9, but nearer shore variations appear. At station 3 the current turns from ebb to flood at practically the same time at all four depths, and as a consequence the durations of flood at all depths are the same. This means, therefore, that but little of the nontidal water passes station 3, and this conclusion is borne out by the velocities of the current, which show a decrease from the surface to the bottom both on the flood and on the ebb, though it is to be noted that on the ebb this decrease takes place more rapidly than on the flood, indicating some influence of the fresh-water discharge.

Since in mid-channel the current does not turn from ebb to flood at the same instant from the surface to the bottom, it is evident that there will be times when the current near the bottom will be flowing in a direction opposite to the current near the surface; but since the difference in time of turning is less than three hours, the current at the time of strength, from surface to bottom, will be setting in the same direction.

For the purpose of deriving harmonic constants for the prediction of the current in the Narrows the observations made with the pole at station 9 were submitted to harmonic analysis. To provide a 15-day series, 1½ days were extrapolated at the beginning and 2½ days at the end of the 11 days of observations. These observations were analyzed in the usual manner. A simultaneous series of tidal observations at Fort Hamilton was also analyzed and the amplitude ratios and epoch differences between the components at Fort Hamilton, derived from this short series, and those determined from the analysis of the series for the year 1904, were applied as corrections to the current amplitudes and epochs derived from the short series. The analysis was carried out for the five principal components, namely, M_2 and harmonics, S_2, N_2, K_1 and O_1. The values of other components were then inferred from these principal components. The results are given in Table 54, inferred values being inclosed in parentheses.

TABLE 54.—*Harmonic constants, station 9, the Narrows*

Component	H	κ	Component	H	κ	Component	H	κ
	Knots	*Degrees*		*Knots*	*Degrees*		*Knots*	*Degrees*
K_1	0.20	78	M_6	0.12	133	Q_1	(0.20)	(54)
K_2	(0.05)	(279)	N_2	0.25	177	S_2	0.19	279
L_2	(0.04)	(223)	2N	(0.03)	(154)	T_2	(0.01)	(279)
M_2	1.338	200	O_1	0.09	29	μ_2	(0.03)	(121)
M_4	0.04	240	P_1	(0.07)	(78)	ν^2	(0.05)	(180)

The epoch for M_2 refers to the time of flood strength, and since the epoch for the M_2 tide at Fort Hamilton is 221° the harmonic constants show the strength of flood in the Narrows to come 21°, or about three-quarters of an hour before high water at Fort Hamilton, which agrees with the value of HW–0.8 hours derived in Table 52.

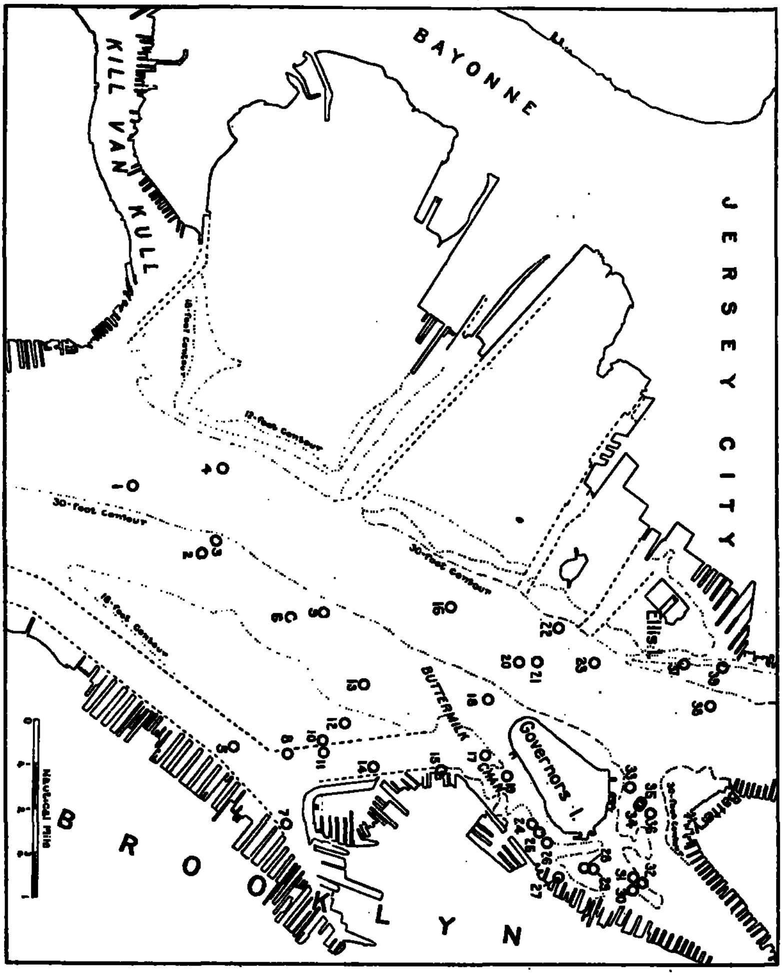


FIG. 32.—Current Stations, Upper Bay.

UPPER BAY

Figure 32 shows the locations of 39 stations at which current observations in Upper Bay have been made. The data derived from these observations are given in Table 55. These data pertain to the current at a depth of about 7 feet from the surface. The times of slack and strength of current are referred to the times of high and low water at Fort Hamilton, HW standing for the time of high water and LW for the time of low water.

TABLE 55.—*Current data, Upper Bay*

[Referred to times of HW and LW at Fort Hamilton, N. Y.

Station No.	Location	Party of—	Date	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Lngth of observations
					Time	Direction	Velocity			Time	Direction	Velocity		
				Hours after LW	*Hours before HW*	*True*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*True*	*Knots*	*Hours*	*Days*
1	In channel	H. Mitchell	Aug., 1872	2.8	−0.2	N. 10° E.	1.5	5.8	2.6	−0.1	S. 25° W.	1.5	6.6	1
2	do	T. A. Craven	Aug., 1855	3.5	−0.6	N. 25° E.	1.1	5.8	3.3	−0.0	S. 10° W.	2.0	6.6	½
3	do	H. Mitchell	July, 1859	3.7	−1.0	N. 5° E.	1.1	5.3	3.0	−0.9	S. 25° W.	1.4	7.1	¾
4	do	I. Winston	Oct., 1919	2.7	0.4	N. 15° E.	1.3	5.3	2.0	0.7	S. 25° W.	1.8	7.1	2
5	Off Brooklyn	H. Mitchell	Aug., 1872	1.8	1.6	N. 30° E.	0.9	6.0	1.8	1.2	S. 25° W.	0.7	6.4	¾
6	In channel	do	do	3.7	0.0	N. 35° E.	0.8	4.3	2.0	0.4	S. 35° W.	1.4	8.1	1
7	Off Brooklyn	H. C. Denson	Sept., 1922	−0.5	3.5	N. 45° E.	0.1	5.4	−1.1	4.0	S. 70° W.	0.1	7.0	½
8	do	do	do	1.6	1.2	N. 30° E.	1.0	6.4	2.0	1.5	S. 5° E.	1.0	6.0	½
9	In channel	do	Aug., 1922	3.8	−0.5	N. 25° E.	1.2	4.8	2.6	−0.4	S. 15° W.	1.9	7.6	1
10	Off Brooklyn	H. L. Marindin	Aug., 1872	2.2	1.7	N. 15° E.	1.4	6.1	2.3	1.1	South	1.0	6.3	1
11	do	I. Winston	Oct., 1919	1.5	1.2	N. 15° E.	0.8	6.3	1.8	1.7	S. 5° E.	1.3	6.1	2
12	do	H. Mitchell	Aug., 1872	2.8	1.0	N. 15° E.	1.3	5.8	2.6	0.4	South	1.1	6.6	1
13	In channel	do	do	3.3	0.3	N. 30° E.	0.9	4.8	2.1	0.5	S. 5° W.	1.3	7.6	¾
14	Off Brooklyn	do	do	3.4	1.0	N. 10° W.	1.3	4.7	2.1	1.6	S. 10° E.	0.8	7.7	¾
15	do	H. C. Denson	Sept., 1922	1.6	2.2	N. 25° E.	0.8	6.6	2.2				5.8	½
16	In channel	I. Winston	Oct., 1919	3.2	−0.8	N. 25° E.	1.2	5.6	2.8	0.2	S. 25° W.	2.2	6.8	2
17	Buttermilk Channel	do	do	1.3	1.7	N. 45° E.	1.1	6.5	1.8	1.8	S. 55° W.	1.6	5.9	1½
18	Off Governors Island.	H. C. Denson	Sept., 1922	3.3	0.6	N. 5° W.	1.2	5.9	3.2	−1.3	N. 75° W.	0.4	6.5	½
19	Buttermilk Channel	H. Mitchell	Sept., 1872	2.1	0.6	N. 50° E.	1.5	6.3	2.4	1.3	S. 55° W.	2.4	6.1	½
20	Off Governors Island.	T. A. Craven	July, 1855	3.6	−1.3	N. 10° E.	1.5	4.9	2.5	0.1	S. 25° W.	2.8	7.5	½
21	do	H. Mitchell	Sept., 1858	3.6	−0.2	N. 30° E.	1.0	5.3	2.9	0.0	S. 25° W.	1.9	7.1	3½
22	do	H. C. Denson	Aug., 1922	3.6	0.1	N. 35° E.	1.5	5.2	2.8	−0.2	S. 25° W.	2.4	7.2	1¼
23	do	I. Winston	Oct., 1919	3.6	−0.4	N. 20° E.	2.0	5.6	3.2	−0.2	S. 25° W.	2.6	6.8	2
24	Buttermilk Channel	H. C. Denson	July, 1922	2.0	1.8	N. 50° E.	1.8	6.0	2.0	1.1	S. 45° W.	2.6	6.4	3¾
25	do	R. J. Auld	Sept., 1920	2.0	1.8	N. 45° E.	1.6	6.3	2.3	1.7	S. 40° W.	2.6	6.1	¾
26	do	T. A. Craven	July, 1855	1.8	0.8	N. 80° E.	1.7	6.9	2.7	1.3	S. 45° W.	2.4	5.5	½
27	do	H. C. Denson	Sept., 1922	1.4	1.6	N. 40° E.	0.6	7.1	2.5	0.9	S. 35° W.	0.4	5.3	½
28	do	M. Woodhull	July, 1854	1.7	1.3	N. 45° E.	1.4	6.9	2.6	1.9	S. 45° W.	1.3	5.5	½
29	do	H. L. Marindin	Aug., 1872	1.4	0.9	N. 25° E.	1.6	6.7	2.1	1.6	South	1.2	5.7	½
30	Off Brooklyn	H. Mitchell	do	1.4	1.3	N. 45° E.	1.5	6.2	1.6	2.1	S. 15° W.	1.1	6.2	½
31	do	H. L. Marindin	do	1.8	0.8	N. 60° E.	1.3	6.5	2.3	1.9	S. 25° W.	1.8	5.9	1
32	do	T. A. Craven	July, 1855	1.5	0.8	N. 60° E.	2.5	7.0	2.5	1.1	S. 50° W.	2.6	5.4	½
33	Off Governors Island.	R. J. Auld	Oct., 1920	1.7	1.2	N. 80° E.	1.2	6.2	1.9	0.5	S. 75° W.	2.4	6.2	1
34	do	H. C. Denson	July, 1922	2.0	0.8	S. 85° E.	1.2	6.0	2.0	0.8	West	1.7	6.4	3½
35	do	H. Mitchell	Sept., 1858	1.4	0.4	N. 85° E.	1.4	6.9	2.3	0.5	S. 70° W.	1.9	5.5	½
36	do	do	Aug., 1872	1.6	0.4	N. 75° E.	1.5	6.9	2.5	0.8	S. 40° W.	1.8	5.5	½
37	Off Ellis Island	do	do	3.9	−0.6	N. 20° E.	0.9	5.5	3.4	−0.2	S. 10° W.	1.8	6.9	½
38	Off Jersey City	I. Winston	Oct., 1919	3.9	−0.2	N. 20° E.	1.6	5.3	3.2	−0.6	S. 20° W.	2.4	7.1	2¼
39	do	H. Mitchell	Sept., 1872	4.2	0.4	N. 10° E.	1.2	5.4	3.6	−0.3	S. 20° W.	1.3	7.0	½

The data of Table 55 show that along the main channel of Upper Bay the current becomes later by about three-quarters of an hour from the lower end to the upper end. There appears also a slight change in the relative durations of flood and ebb. At the lower end the durations of flood and ebb are, respectively, 5.5 hours and 6.9 hours, while at the upper end they are 5.4 hours and 7.0 hours.

Along the main channel the ebb current has the greater velocity, the strength of ebb being 1¾ knots against 1¼ knots for the flood strength. This excess of the ebb strength over the flood strength is brought about by the same causes as in the Narrows discussed previously. The velocity of the flood current in the main channel is approximately the same throughout the length of Upper Bay, but for the ebb current the upper end shows a somewhat greater velocity than the lower end.

For the stations along the Brooklyn shore Table 55 shows a diminished velocity for both flood and ebb as compared with the main channel. Furthermore, the velocity of the current at flood strength is generally greater than that of ebb strength, and the duration of flood and ebb are approximately equal. These features undoubtedly find explanation in the fact that the flood coming in through the Narrows, being deflected to the right by the deflecting force of the earth's rotation, is directed somewhat toward the Brooklyn shore. On the ebb, however, the main stream of the current sets away from the Brooklyn shore because of the direction of the channel, and the deflecting force of the earth's rotation now acts to deflect the current still farther away from the Brooklyn shore. Hence the Brooklyn shore lies in the path of the main stream of the flood current, but to one side of the main stream of the ebb current.

Throughout Upper Bay the time of tide is about one-third of an hour later than at Fort Hamilton. Table 55, therefore, shows that with respect to the time of local tide, slack water in Upper Bay comes about three hours after the times of high and low water, while the strength of the current comes about the times of high and low water. These relations of current to tide in Upper Bay prove the tidal movement to be of the progressive-wave type, and this, it is to be recalled, was also indicated by the progress of the tide through Upper Bay discussed in Section VI.

In Table 55 the times of slack and strength of current at station 7 stand out markedly different from the values for the other stations. Instead of slack coming about three hours after the times of local tide, slack at station 7 comes near the times of high and low water; and the strength of the current instead of coming at the times of high and low water comes approximately midway between high and low water. The location of station 7 explains these differences, for it is situated at the entrance to Gowanus Bay, which is of such limited extent that there can be little progression of the tide. Hence, strength of flood and ebb must come when this restricted waterway is being filled most rapidly, namely, midway between high and low water, when the tide is rising or falling most rapidly. Similarly, the tidal movement should cease at the times of high and low water, when the rise or fall of the tide has ceased.

For Buttermilk Channel, too, the data of Table 55 show decided differences from the data for stations in the main channel of Upper

Bay. The time of current is considerably earlier in Buttermilk Channel, slack before flood coming about two hours earlier than in the main channel of Uppr Bay and slack before ebb about half an hour earlier. This makes the duration of flood in Buttermilk Channel greater than in the rest of Upper Bay and changes the relative magnitude of the periods of flood and ebb. In the main channel of Upper Bay the ebb period is the greater, having a duration of 7 hours against 5½ hours for the flood; in Buttermilk Channel the flood period is the greater, having a duration of 6½ hours, while the duration of ebb is a little less than 6 hours.

These differences of the current in Buttermilk Channel must be ascribed to the influence of the East River, into which Buttermilk Channel furnishes the principal inlet for the flood current. The stretch of water between Governors Island and the Battery, which likewise is under the influence of East River, shows similar current characteristics. The current here is considerably earlier than in the channel of Upper Bay directly to the west and the period of flood here is 6½ hours against the flood period of 5½ hours in the main channel of Upper Bay.

The direction of the current in Upper Bay, as shown by Table 55, is generally in the direction of the channel. Where the direction of the channel changes, the direction of the flood and ebb currents are generally not directly opposite each other, the direction of the channel above and below then exerting an influence on the directions of the flood and ebb currents.

At 16 of the stations listed in Table 55 observations of the subsurface current were also made by use of a current meter, and for several of these stations the party of H. C. Denson determined the direction of the subsurface currents by the use of the bifilar direction indicator. The data for the various depths at these stations are given in Table 56 following.

The relations of the current at different depths in Upper Bay are much like those found in the Narrows. In the main channel the slack before ebb generally becomes earlier from the surface downward. If for convenience we speak of the 7-foot depth as the surface and the eight-tenths depth as the bottom, it may be said that from the surface to the bottom the slack before flood in Upper Bay becomes earlier by about an hour, as evidenced by the data for stations 9, 16, 22, and 23; and as in the case of the current in the Narrows this acceleration in time with increase of depth is to be ascribed to the effect of the fresh or nontidal water from the Hudson.

In the main channel of Upper Bay the difference in the vertical velocity distribution between flood and ebb strengths stands out markedly. The strength of ebb, without exception, decreases in velocity from the surface downward, the rate of decrease being about 0.03 knot per foot of depth. The strength of flood, however, generally increases somewhat to mid-depth and then decreases slowly to the bottom. As a consequence the flood strength from mid-depth to bottom is generally greater than the ebb strength, notwithstanding the fact that near the surface the ebb strength has considerably greater velocity. The data for station 23 brings this out well. At the 7-foot depth the flood strength is 1.96 knots and the ebb strength 2.60 knots; at mid-depth they are, respectively, 2.02 knots and 1.82 knots, and at the eight-tenths depth 2.02 knots and 1.04 knots.

TABLE 56.—*Current data for various depths, Upper Bay*

[Referred to times of HW and LW at Fort Hamilton, N. Y.]

Station No.	Location	Date	Party of—	Observations with—	Depth	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
							Time	Direction	Velocity			Time	Direction	Velocity		
					Feet	*Hours after LW*	*Hours before HW*	*True*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*True*	*Knots*	*Hours*	*Days*
4	In channel	Oct. 8-10, 1919	I. Winston	Pole	7	2.75	0.35	N. 16° E.	1.32	5.28	2.00	0.70	S. 24° W.	1.76	7.14	2
				Meter	15	2.95	0.65		1.20	5.17	2.09	0.62		1.52	7.25	2
				do	38	2.85	1.52		1.13	5.27	2.09	0.52		1.09	7.15	2
				do	60	2.75	1.62		0.95	5.37	2.09	0.68		0.55	7.05	2
8	Off Brooklyn	Sept. 5, 1922	H. C. Denson	Pole	7	1.60	1.20	N. 32° E.	0.96	6.43	2.00	1.50	S. 6° E.	0.96	5.99	½
				Meter	9	1.80	1.30	N. 8° E.	1.10	6.23	2.00	1.90	S. 5° W.	1 5	6.19	½
				do	23	1.30	1.60	N. 51° E.	1.01	6.73	2.00	1.90	S. 15° W.	0.71	5.69	½
				do	36	1.20	1.80	N. 12° E.	0.93	6.83	2.00	1.70	S. 1° W.	0.28	5.59	½
9	In channel	Aug. 15-16, 1922	do	Pole	7	3.83	−0.50	N. 27° E.	1.17	4.75	2.55	−0.35	S. 16° W.	1.87	7.67	1
				Meter	6	3.88	−0.25		0.94	4.65	2.50	−0.35		1.84	7.77	1
				do	15	3.38	0.05		1.20	5.02	2.37	−0.15		1.65	7.40	1
				do	24	2.88	0.80		0.95	5.52	2.37	−0.00		1.10	6.90	1
11	Off Brooklyn	Oct. 15-17, 1919	I. Winston	Pole	7	1.52	1.22	N. 15° E.	0.82	6.26	1.75	1.72	S. 6° E.	1.26	6.16	2
				Meter	[illegible]	1.72	1.22		0.80	6.41	2.10	1.35		1.24	6.01	2
				do	21	1.55	1.27		0.89	6.58	2.10	1.58		0.83	5.84	2
				do	33	1.28	1.60		1.03	7.00	2.25	1.48		0.48	5.42	2
15	do	Sept. 3, 1922	H. C. Denson	Pole	7	1.60	2.20	N. 24° E.	0.80	6.63	2.20				5.79	½
				Meter	5	2.30	2.00	N. 20° E.	1.20	5.43	1.70				6.99	½
				do	12	2.20	1.60	N. 20° E.	1.05	5.43	1.60				6.99	½
				do	18	2.30	1.50	N. 24° E.	1.00	5.33	1.60				7.09	½
16	In channel	Oct. 22-24, 1919	I. Winston	Pole	7	3.20	−0.85	N. 24° E.	1.23	5.68	2.85	0.23	S. 27° W.	2.22	6.74	2
				Meter	12	2.98	−0.45		1.34	5.87	2.82	0.52		1.99	6.55	2
				do	30	2.52	−0.20		1.62	6.36	2.85	0.52		1.45	6.06	2
				do	48	2.25	0.22		1.60	7.00	3.22	0.10		1.00	5.42	2
17	Buttermilk Channel.	Oct. 27-28, Nov. 10-11, 1919.	do	Pole	7	1.30	1.70	N. 44° E.	1.10	6.50	1.77	1.83	S. 53° W.	1.64	5.92	1½
				Meter	8	1.33	1.42		1.15	6.58	1.88	1.90		1.50	5.84	1¾
				do	21	1.33	1.38		1.20	6.60	1.90	1.83		1.20	5.82	1¾
				do	34	1.20	1.10		0.85	6.78	1.95	1.80		0.90	5.64	1¾
18	Off Governors Island.	Sept. 3, 1922	H. C. Denson	Pole	7	3.30	0.60	N. 6° W.	1.20	5.93	3.20	−1.30	N. 75° W.	0.40	6.49	½
				Meter	5	2.40	0.80	N. 22° W.	1.30			2.40	S. 27° E.	0.60		½
				do	13	2.40	0.80	N. 31° W.	1.25			2.10	S. 43° E.	0.75		½
				do	21	2.20	1.00	N. 39° W.	1.15			2.30	S. 30° E.	0.65		½
22	do	Aug. 15-16, 1922	do	Pole	7	3.60	0.10	N. 35° E.	1.46	5.23	2.80	−0.23	S. 27° W.	2.36	7.19	1¼
				Meter	14	3.45	−0.30		1.39	5.35	2.77	−0.10		2.24	7.07	1¼
				do	35	3.00	−0.20		1.77	6.13	3.10	−0.10		1.67	6.29	1¼
				do	56	2.56	−0.35		2.09	6.61	3.13	−0.40		1.14	5.81	1¼
23	do	Oct. 29-31, 1919	I. Winston	Pole	7	3.70	−0.40	N. 20° E.	1.96	5.58	3.25	−0.22	S. 24° W.	2.60	6.84	2
				Meter	15	2.98	0.20		1.69	6.55	3.50	0.18		2.24	5.87	2
				do	38	2.58	−0.10		2.02	6.90	3.45	0.08		1.82	5.52	2
				do	60	2.18	0.20		2.02	7.33	3.48	−0.12		1.04	5.09	2
24	Buttermilk Channel.	July 23-25, Aug. 13-15, 1922.	H. C. Denson	Pole	7	2.00	1.80	N. 52° E.	1.80	6.00	1.97	1.08	S. 44° W.	2.60	6.42	3¾
				Meter	8	2.08	2.08		1.72	5.92	1.97	1.13		2.46	6.50	3¾
				do	20	2.13	2.12		1.73	5.87	1.97	1.03		2.43	6.55	3¾
				do	32	2.15	2.03		1.50	5.85	1.97	0.97		2.16	6.57	3¾
25	do	Sept. 29-30, 1920	R. J. Auld	Pole	7	1.95	1.80	N. 44° E.	1.63	6.38	2.30	1.70	S. 40° W.	2.58	6.04	¾
				Meter	8	1.88	1.42		1.52	6.23	2.08	0.92		2.32	6.19	¾
				do	21	1.85	1.50		1.44	6.23	2.05	1.15		2.24	6.19	¾
				do	34	1.82	1.68		1.21	6.23	2.02	1.18		1.91	6.19	¾
27	do	Sept. 2, 1922	H. C. Denson	Pole	7	1.40	1.60	N. 41° E.	0.55	7.13	2.50	0.90	S. 35° W.	0.40	5.29	½
				Meter	9	2.00	1.60	N. 43° E.	1.25	6.73	2.70	0.70	S. 41° W.	0.75	5.69	½
				do	22	2.00	2.20	N. 38° E.	1.25	6.63	2.60	1.50	S. 41° W.	0.40	5.79	½
				do	35	2.20	2.20	N. 28° E.	1.05	6.43	2.60	2.30	S. 37° W.	0.60	5.99	½
33	Off Governors Island.	Oct. 8-9, 1920	R. J. Auld	Pole	7	1.70	1.20	N. 82° E.	1.18	6.23	1.90	0.50	S 74° W.	2.43	6.19	1
				Meter	12	1.98	0.62		1.15	5.58	1.53	0.62		2.05	6.84	1
				do	30	2.00	2.25		0.68	5.48	1.45	0.50		2.08	6.94	1
				do	48	2.02	2.28		0.59	5.43	1.42	0.58		2.09	6.99	1
34	do	July 23-24, Aug. 13-15, 1922.	H. C. Denson	Pole	7	2.03	0.83	S. 86° E.	1.20	6.00	2.00	0.83	S. 89° W.	1.73	6.42	3½
				Meter	10	2.02	0.43		1.20	5.91	1.90	0.90		1.72	6.51	3½
				do	25	2.03	0.93		1.25	5.92	1.92	0.98		1.58	6.50	3½
				do	40	2.00	1.37		1.06	6.00	1.97	0.90		1.55	6.42	3½
38	Off Jersey City	Sept. 30, Oct. 20-21, Nov. 3-4, 1919.	I. Winston	Pole	7	3.93	−0.15	N. 21° E.	1.59	5.28	3.18	−0.57	S. 19° W.	2.37	7.14	2¼
				Meter	8	3.92	−0.42		1.56	5.49	3.38	−0.47		2.11	6.93	2½
				do	20	3.25	−0.42		1.92	6.41	3.63	−0.37		1.46	6.01	2½
				do	32	3.12	−0.10		1.58	6.33	3.42	−0.38		1.04	6.09	2½

The increase in duration of flood and corresponding decrease of duration of ebb from the surface downward is especially marked at the stations in the main channel near the upper end of Upper Bay. Stations 23 and 38 give an average increase in the duration of flood from the surface to the bottom of about one hour. In Upper Bay, as in the Narrows, this increase in the duration of flood is brought about by the acceleration in the time of slack before flood, the slack before ebb occurring at practically the same time from surface to bottom.

The ebb current in the main channel of Upper Bay has the greater duration at the surface throughout the whole of its length; at the lower end the data for stations 4 and 9 show the ebb to have the greater duration from the surface to bottom, but at its upper end the influence of the drainage waters of the Hudson River is shown in a greater duration for the flood than for the ebb from mid-depth to the bottom.

In Buttermilk Channel the data of Table 56 show the current to differ considerably from the current in the main channel of Upper Bay. For both the slack before flood and slack before ebb there is little difference in time from surface to bottom. The durations of flood and of ebb are therefore practically the same at all depths. This makes it appear that through Buttermilk Channel very little nontidal water passes.

The vertical velocity distribution in Buttermilk Channel, likewise, differs from the velocity distribution in the main channel of Upper Bay. The velocities of both the flood and ebb strengths in Buttermilk Channel generally decrease from the surface to the bottom. Stations 24 and 25 bring this out well.

For the region lying between Governors Island and the Battery the data for stations 33 and 34 show that the current here is similar to that in Buttermilk Channel. But little change in the duration of flood or of ebb takes place from the surface to the bottom and the velocity both of the flood and of the ebb decreases from surface to bottom.

XIII. THE CURRENT IN THE KILLS AND NEWARK BAY

Figure 33 shows the location of 11 current stations in Arthur Kill, the data for these being given in Table 57. In this table the times of current are referred to the times of tide at Fort Hamilton, N. Y., HW standing for time of high water and LW for time of low water. The data may be taken to refer to the current at a depth 7 feet from the surface.

At station 1, near the southern entrance to Arthur Kill, and at station 9, near the northern entrance, the observations are for simultaneous periods of very nearly five days. These observations, therefore, furnish data relatively well determined for purposes of comparison. These data, as given in Table 57, show that the current in the southern entrance to Arthur Kill turns earlier than at the northern entrance by 1.4 hours. At station 5 the observations were simultaneous with observations at stations 1 and 9, and at station 5 the current is later than at station 1 by 0.75 hour and earlier than at station 9 by 0.65 hour. Station 5 is 6 nautical miles from station 1 and 4 miles from station 9. The differences in the time of current between

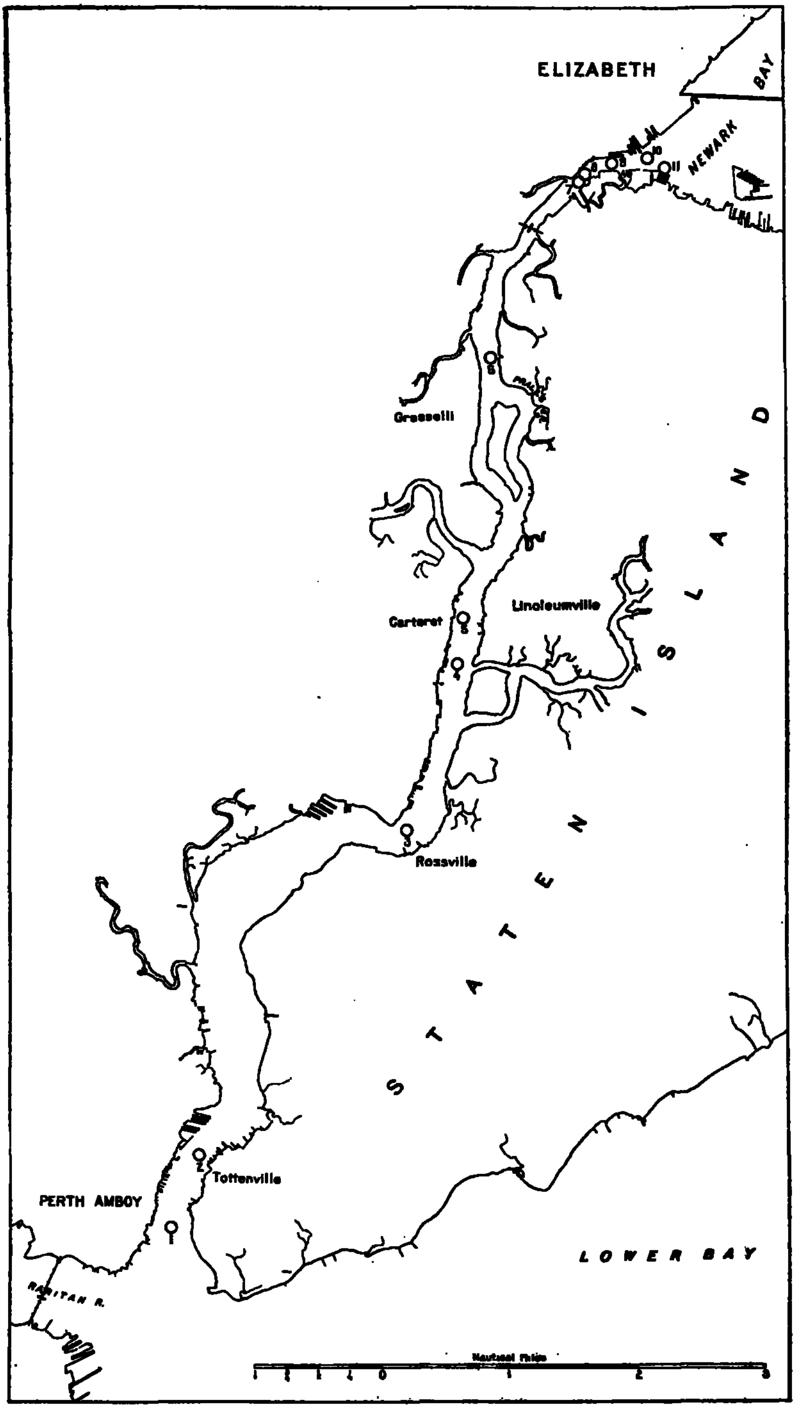


FIG. 33.—Current stations, Arthur Kill

TABLE 57.—*Current data, Arthur Kill*

[Referred to times of HW and LW at Fort Hamilton, N. Y.]

Station No.	Location	Party of—	Date	Slack	Flood strength: Time	Flood strength: Direction	Flood strength: Velocity	Flood duration	Slack	Ebb strength: Time	Ebb strength: Direction	Ebb strength: Velocity	Ebb duration	Length of observations
				Hours after LW	*Hours before HW*	*True*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*True*	*Knots*	*Hours*	*Days*
1	Off Perth Amboy, N. J.	H. C. Denson	Aug., 1922	1.2	2.0	N. 10° E.	0.9	6.0	1.2	2.6	S. 10° W.	0.9	6.4	5¼
2	Off Tottenville, N. Y.	H. Mitchell	Aug., 1856	0.7	2.4	N. 60° E.	0.5	6.3	1.0	2.5	S. 35° W.	0.5	6.1	1
3	Off Rossville, N. Y.	do	do	0.9	2.2	N. 65° E.	0.5	6.3	1.2	2.3	S. 45° W.	0.4	6.1	½
4	Off Cartaret, N. J.	do	do	1.5	1.8	N. 55° E.	0.7	5.7	1.2	2.3	S. 30° W.	1.1	6.7	½
5	Off Linoleumville, N. Y.	H. C. Denson	Aug., 1922	2.0	1.5	N. 15° E.	1.0	5.9	1.9	1.9	S. 15° E.	1.0	6.5	1¾
6	Off Grasselli, N. J.	H. Mitchell	Aug., 1856	2.3	1.2	N. 5° W.	1.3	5.5	1.8	2.1	S. 5° E.	1.0	6.9	½
7	Off Elizabeth, N. J.	do	Sept., 1856	2.9	0.5	N. 5° W.	1.6	5.7	2.6	1.2	S. 5° E.	1.4	6.7	½
8	do	H. L. Marindin	July, 1885	2.5	1.1		1.8	5.4	1.9	0.9		1.7	7.0	1
9	do	H. C. Denson	Aug., 1922	2.6	1.0	East	1.2	6.0	2.6	0.3	West	0.8	6.4	4¾
10	do	R. J. Auld	Nov., 1920	2.2	0.8	N. 60° E.	1.0	6.2	2.4	0.8	S. 75° W.	0.5	6.2	2
11	do	H. Mitchell	Aug., 1856	2.4	1.0	East	1.2	5.9	2.3	0.7	S. 85° W.	1.0	6.5	1

stations 1 and 5 and between stations 5 and 9 are very nearly proportional to their distances from each other. We may therefore conclude that through Arthur Kill the current becomes uniformly later from the southern to the northern entrance.

Table 57 shows that in Arthur Kill the slacks occur about two hours after the time of tide at Fort Hamilton and the strengths about one and one-half hours before the time of tide. From the tidal data of Table 30 it is found that the tide in Arthur Kill is approximately one-half hour later than at Fort Hamilton. It follows, therefore, that with regard to the local tide the slacks in Arthur Kill occur about one and one-half hours after high and low water and the strengths about two hours before high and low water. The tidal movement in Arthur Kill is therefore not of the simple progressive-wave type, being modified to a considerable extent by the fact that it connects two independent bodies of water—Raritan Bay and Newark Bay.

Through Arthur Kill the velocity of the current at strength is approximately 1 knot. At the southern entrance and for the greater part of the Kill the flood and ebb strengths appear to be equal, but at the northern end the flood current is greater by very nearly half a knot.

The results for the more recent observations of Table 57 show that in Arthur Kill the ebb period is somewhat greater than the flood period. A duration of 6.4 hours for the ebb and of 6.0 hours for the flood appear to be the most probable values.

At four of the stations shown on Figure 33 observations of the subsurface current were made with the current meter, and at station 5 the party of H. C. Denson determined the direction of the subsurface current by the use of the bifilar direction indicator. The results from these observations are given in Table 58.

At stations 1 and 9 the data of Table 58 show the current to have features similar to those found in the Narrows and in the main channel of Upper Bay, these features being conditioned by the movement of fresh or nontidal water. The slack before flood becomes earlier from the surface to the bottom, while the slack before ebb occurs at practically the same time at all depths, this resulting in an increased duration of the flood with increasing depth. The ebb strength decreases in velocity from the surface to the bottom at a relatively rapid rate, while the flood strength decreases much more slowly.

At station 1 these features are well marked. From the 5-foot depth to the 21-foot depth the slack before flood becomes earlier by very nearly half an hour, while the slack before ebb occurs at practically the same time at all four depths. For the 5-foot depth the duration of flood is 5.97 hours, and this duration increases regularly in going downward, attaining at the 21-foot depth the value of 6.41 hours. At the surface the strength of ebb has a greater duration than the strength of flood; at mid depth the two periods are about equal, and near the bottom the flood has the greater duration.

The velocity of the current at station 1 likewise gives evidence of fresh-water flow. The ebb strength decreases from 1.08 knots at the 5-foot depth to 0.71 knot at the 21-foot depth, while the flood current shows a decrease for the same depths from 0.95 knot to 0.82 knot.

TABLE 58.—*Current data for various depths, Arthur Kill*

[Referred to times of HW and LW at Fort Hamilton]

Station No.	Location	Date	Party of—	Observations with—	Depth	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
							Time	Direction	Velocity			Time	Direction	Velocity		
					Feet	*Hours after LW*	*Hours before HW*	*True*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*True*	*Knots*	*Hours*	*Days*
1	Off Perth Amboy, N. J.	Aug. 19-24, 1922	H. C. Denson	Pole	7	1.17	2.03	N. 12° E	0.88	6.08	1.22	2.63	S. 10° W	0.92	6.34	5¼
				Meter	5	1.33	1.97		0.95	5.97	1.27	3.07		1.08	6.45	5¼
				do	14	1.07	2.13		0.91	6.19	1.23	3.05		0.92	6.23	5¼
				do	21	0.87	1.98		0.82	6.41	1.25	2.93		0.71	6.01	5¼
5	Off Lincoleumville, N. Y.	Aug. 22-24, 1922	do	Pole	7	1.97	1.53	N. 16° E	0.97	5.96	1.90	1.87	S. 15° E	0.97	6.46	1¾
				Meter	6	2.03	1.60	N. 19° E	1.03	5.88	1.88	1.77	S. 6° W	0.95	6.54	1¾
				do	15	2.07	1.38	N. 17° E	0.94	5.91	1.95	1.93	South	0.86	6.51	1¾
				do	24	2.07	1.45	N. 18° E	0.84	5.86	1.90	1.40	S. 3° W	0.74	6.56	1¾
9	Off Elizabeth, N. J.	Aug. 19-24, 1922	do	Pole	7	2.57	0.98	N. 88° E	1.22	6.03	2.57	0.32	West	0.84	6.39	4¾
				Meter	6	2.65	0.77		1.38	6.00	2.62	0.23		0.94	6.42	5
				do	15	2.63	0.77		1.36	6.02	2.62	0.43		1.00	6.40	5
				do	24	2.48	1.08		1.25	6.17	2.62	0.70		0.87	6.25	5
10	do	Nov. 5-7, 1920	R. J. Auld	Pole	7	2.20	0.77	N. 61° E	0.98	6.25	2.42	0.82	S. 76° W	0.54	6.17	2
				Meter	5	2.47	0.23		0.93	6.24	2.68	0.92		0.41	6.18	2
				do	12	2.47	0.60		1.01	6.28	2.72	0.43		0.56	6.14	2
				do	19	2.43	0.53		0.94	6.28	2.68	0.60		0.50	6.14	2

Station 9, at the northern entrance to Arthur Kill, exhibits the features due to nontidal water in a much less marked manner. This may be taken to indicate that of the fresh water passing through Arthur Kill a very considerable percentage is brought in by the streams tributary to the Kill itself, and that but a small percentage of the drainage waters of Newark Bay pass into Arthur Kill.

KILL VAN KULL

For Kill Van Kull there are at hand current observations for 10 stations, the locations of these being shown in Figure 34. The results of these observations for the current at a depth of about 7 feet from the surface are given in Table 59.

Kill Van Kull being a short strait, the time of current changes but little through the strait. At station 2, near the eastern entrance, and at station 10, near the western entrance, simultaneous observations for a period of one day are at hand, and these bring to light the fact that the different phases of the current have different time relations at the two ends. Table 59 shows that slack before flood at the eastern entrance comes 0.3 hour earlier than at the western entrance, strength of flood 0.9 hour earlier, slack before ebb 0.1 hour earlier, and strength of ebb 1.6 hours earlier.

From the tidal data of Table 35 the time of tide in Kill Van Kull is found to be half an hour later than at Fort Hamilton. Applying this difference to the values in Table 59 the slacks in Kill Van Kull are found to come about half an hour after local high or low water and the strengths about three hours before high or low water. The tidal movement through Kill Van Kull is therefore not of the progressive-wave type. As in Arthur Kill, the tidal movement through Kill Van Kull is conditioned by the fact that it is a short strait connecting two large tidal bodies of water.

The ebb current through Kill Van Kull has a greater velocity than the flood current except at points that are in the path of the main stream of the flood current but outside the path of the main stream of the ebb current. Thus, from the data for stations 1, 2, 3, 7, 9, and 10, the strength of flood is 1.4 knots and strength of ebb 1.8 knots. Stations 4 and 5 show greater velocities for the flood than for the ebb, but the locations of these stations show them to be outside the main stream of the ebb current but directly in the path of the main stream of the flood current. The greater flood strength at station 8 appears anomalous, for stations 9 and 10 both show greater ebb velocities.

Throughout Kill Van Kull Table 59 shows the ebb current to have the greater duration, with a value of 6.8 hours against 5.4 hours for the flood. This, together with the greater ebb velocity, would indicate the existence of fresh water flow. It is to be recalled that in Arthur Kill the durations of ebb and flood were, respectively, 6.4 hours and 6.0 hours. A relatively greater percentage of fresh water is therefore indicated for Kill Van Kull.

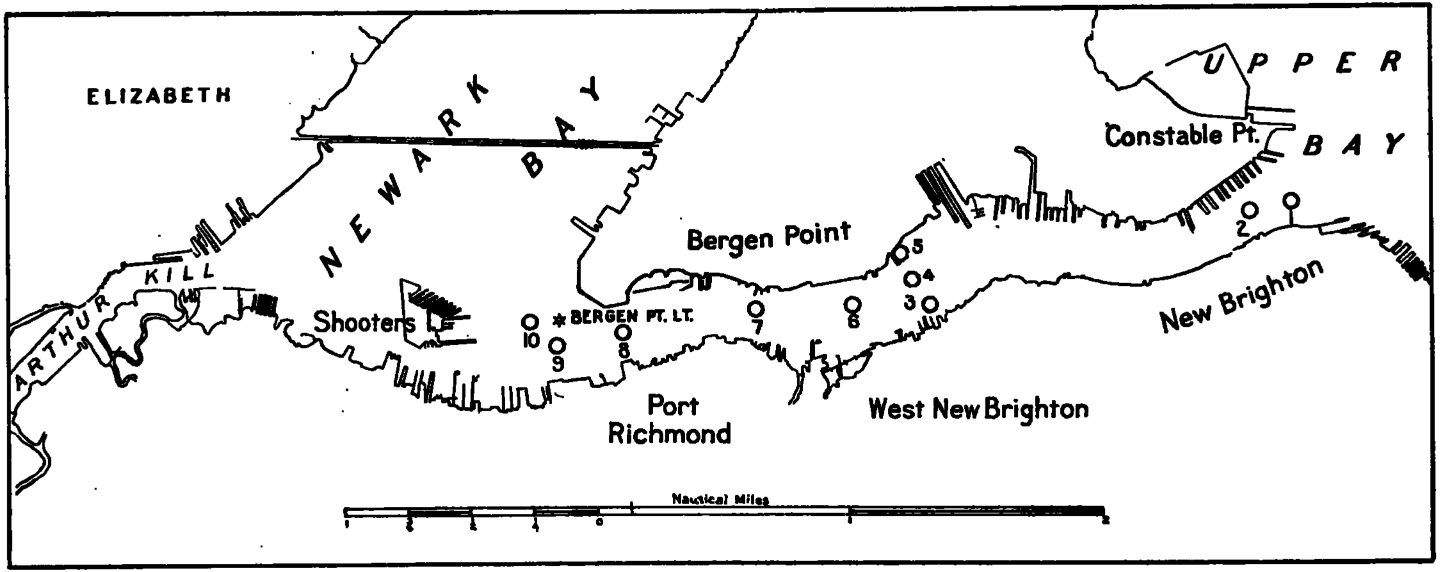


FIG. 34.—Current stations, Kill van Kull

TABLE 59.—*Current data, Kill Van Kull*

[Referred to times of HW and LW at Fort Hamilton, N. Y.]

Station No.	Location	Party of—	Date	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
					Time	Direction	Velocity			Time	Direction	Velocity		
				Hours after LW	*Hours before HW*	*True*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*True*	*Knots*	*Hours*	*Days*
1	Off New Brighton, N. Y.	I. Winston	Nov., 1919	1.4	2.4	S. 15° W.	1.4	5.1	0.5	3.0	N. 75° E.	1.9	7.3	1¾
2	Do	H. C. Denson	Aug., 1922	1.1	2.5	S. 30° W.	1.7	5.7	0.8	3.0	N. 40° E.	1.8	6.7	10¾
3	Off West New Brighton, N. Y.	H. L. Marinden	July, 1885	1.6	3.1		1.2	4.6	0.2	2.2		1.4	7.8	¾
4	Off Bergen Point, N. J.	do	do	1.8	2.1		1.9	5.0	0.8	2.0		1.5	7.4	¾
5	Do	do	do	1.6	2.8		1.9	5.3	0.9	2.2		1.5	7.1	¾
6	Do	I. Winston	Nov., 1919	1.2	1.8	S. 65° W.	2.2	5.6	0.8	2.5	N. 80° E.	2.1	6.8	1¼
7	Do	H. Mitchell	Aug., 1856	1.7	1.4	S. 85° W.	1.4	5.3	1.0	2.2	S. 85° E.	2.2	7.1	1¼
8	Off Port Richmond, N. Y.	I. Winston	Nov., 1919	1.1	2.1	S. 80° W.	2.3	5.7	0.8	2.8	N. 85° E.	1.9	6.7	1¾
9	Off Bergen Point Light.	H. Mitchell	Aug., 1856	1.7	1.6	N. 85° W.	1.8	5.9	1.6	1.5	S. 50° E.	2.0	6.5	1¼
10	Do	H. C. Denson	Aug., 1922	1.4	1.5	N. 50° W.	1.2	5.5	0.9	1.4	S. 15° E.	1.7	6.9	1

TABLE 60.—*Current data for various depth, Kill Van Kull*

[Referred to times of HW and LW at Fort Hamilton, N. Y.]

Station No.	Location	Date	Party of—	Observations with—	Depth	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
							Time	Direction	Velocity			Time	Direction	Velocity		
					Feet	*Hours after LW*	*Hours before HW*	*True*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*True*	*Knots*	*Hours*	*Days*
1	Off New Brighton, N. Y.	Nov. 18–19, Dec. 2–3, 1919.	I. Winston	Pole	7	1.35	2.37	S. 75° W	1.39	5.21	0.53	3.05	N. 75° E	1.90	7.21	1¾
				Meter	8	1.12	2.32		1.16	5.51	0.60	2.90		1.83	6.91	1¾
				do	21	0.82	2.55		1.15	6.14	0.93	2.35		1.00	6.28	1¾
				do	34	0.35	2.18		1.12	6.75	1.07	2.30		0.37	5.67	1¾
2	do	Aug. 13–24, 1922	H. C. Denson	Pole	7	1.13	2.47	S. 30° W	1.72	5.69	0.79	3.02	N. 41° E	1.80	6.73	10¾
				Meter	10	1.20	2.55	S. 24° W	1.73	5.75	0.92	3.23	N. 36° E	1.73	6.67	10¾
				do	24	0.88	2.52	S. 24° W	1.49	6.28	1.13	2.98	N. 32° E	1.43	6.14	10¾
				do	38	0.43	2.27	S. 19° W	1.30	6.63	1.03	2.65	N. 39° E	0.89	5.79	10¾
6	Off Bergen Point, N. J.	Nov. 25–26, Dec. 10–11, 1919.	I. Winston	Pole	7	1.20	1.80	S. 63° W	2.24	5.58	0.75	2.47	N. 80° E	2.14	6.84	1¼
				Meter	7	1.40	1.80		1.81	5.55	0.92	2.50		2.23	6.87	1¾
				do	16	1.40	1.80		1.62	5.55	0.92	2.42		1.99	6.87	1¾
				do	24	1.20	1.80		1.26	5.73	0.90	2.23		1.66	6.69	1¾
8	Off Port Richmond, N. Y.	Nov. 21–22, Dec. 5–6, 1919.	do	Pole	7	1.10	2.08	S. 82° W	2.30	5.76	0.83	2.83	N. 86° E	1.93	6.66	1¾
				Meter	7	1.22	2.30		2.24	5.91	1.10	2.62		1.66	6.51	2
				do	16	1.12	2.30		2.18	5.96	1.05	2.55		1.72	6.46	2
				do	24	1.08	2.38		1.93	6.05	1.10	2.38		1.63	6.37	2
10	Off Bergen Point, Light, N. J.	Aug. 20–21, 1922	H. C. Denson	Pole	7	1.40	1.50	N. 49° W	1.15	5.53	0.90	1.35	S. 13° E	1.72	6.89	1
				Meter	5	1.40	1.80	N. 53° W	1.35	5.58	0.95	1.20	S. 8° E	1.55	6.84	1
				do	12	1.35	1.55	N. 49° W	1.33	5.73	1.05	1.45	S. 9° E	1.39	6.69	1
				do	20	1.30	1.65	N. 49° W	1.21	5.78	1.05	2.00	S. 9° E	1.25	6.64	1

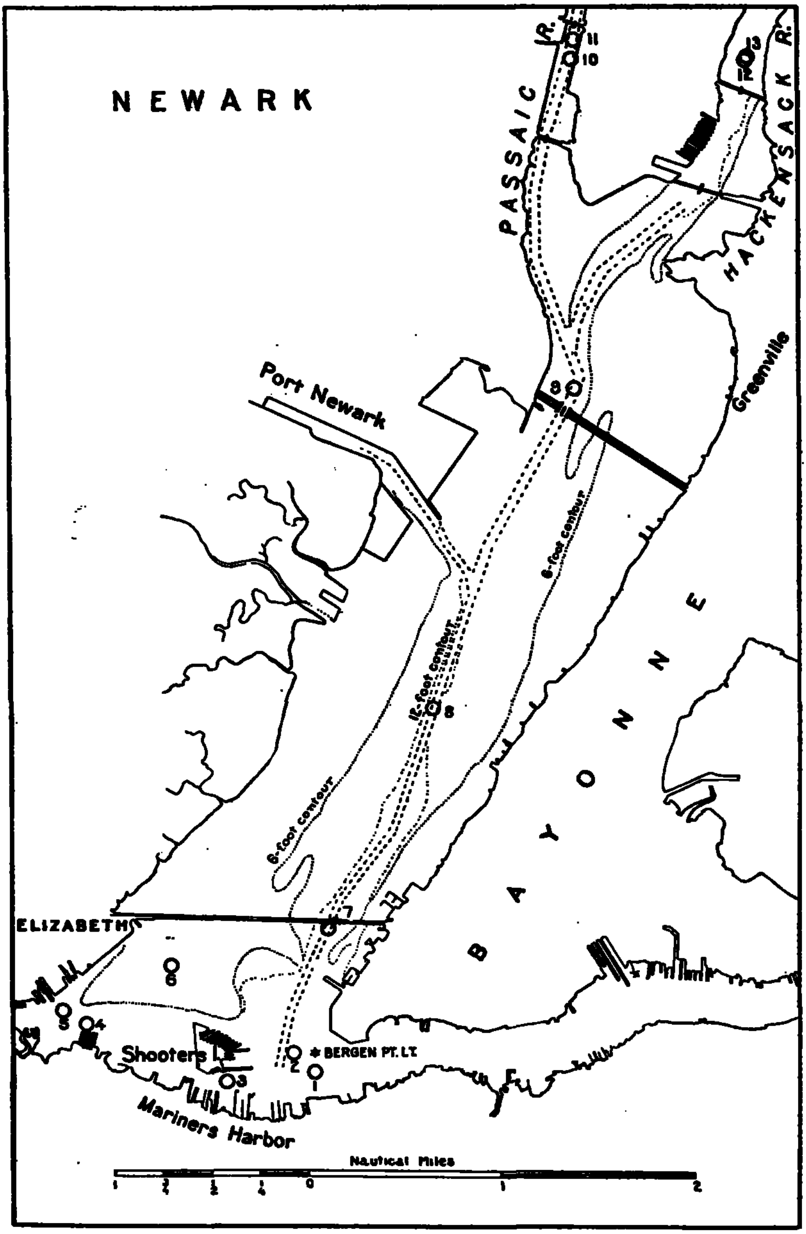


FIG. 35.—Current stations, Newark Bay

At five of the stations listed in Table 59 subsurface current observations were also made by means of a current meter. These observations, like the subsurface observations in the other waterways of New York Harbor, were made at three depths—two-tenths, five-tenths, and eight-tenths of the depth at each station. In addition, observations on the direction of the subsurface current with the bifilar direction indicator were made at two stations. The results of these observations are given in Table 60. For comparison there is included also the observations made with the current pole which pertain to the current at a depth of 7 feet. In Table 60 the direction of the current is given to the nearest whole degree, while in Table 59 the directions are given to the nearest 5°. For any given stations, therefore, there will be a slight difference in direction between the values of Tables 59 and 60.

The data of Table 60 for stations 1 and 2 indicate the existence of considerable fresh water flow in Kill Van Kull. The slack before ebb becomes earlier from the surface to the bottom by very nearly an hour; the duration of flood increases from the surface to the bottom; the strength of flood decreases slowly with increasing depth, while the strength of ebb decreases at a much more rapid rate; and although near the surface the strength of ebb has the greater velocity, from mid-depth to bottom the strength of flood has the greater velocity. The current in Kill Van Kull also shows a retardation in time of slack before ebb with increasing depth—shown without exception by the data for each station listed in Table 60.

NEWARK BAY

Figure 35 shows the locations of 13 current stations in Newark Bay and in the lower reaches of the Passaic and Hackensack Rivers. The current data derived from these observations, with the velocities corrected to mean values, are given in Table 61. These data may be taken to pertain to the current at a depth of about 7 feet from the surface.

The current into Newark Bay from Kill Van Kull comes about an hour earlier than the current from Arthur Kill, as a comparison of the times of the turning of the current at stations 1 and 2 and at stations 4 and 5 shows. Furthermore, both on the flood and on the ebb the data of Table 61 show that the current from Kill Van Kull has the greater strength, and it is to be noted that at the stations in the upper part of Newark Bay the current turns earlier than at stations 4 and 5 in the entrance to Arthur Kill but later than at stations 1 and 2 in the entrance to Kill Van Kull.

The tidal data of Table 36 show that the tide in Newark Bay is about an hour later than at Fort Hamilton. Applying this difference to the data of Table 61, it is found that the slack of the current in Newark Bay comes about an hour after the time of local high or low water and the strength of the current about two hours before high or low water.

For station 3, between Mariners Harbor and Shooters Island, the data of Table 61 indicate that the current here differs considerably from the current in the rest of Newark Bay. The current here is earlier than at the Kill Van Kull entrance by 2 hours and earlier than at the Arthur Kill entrance by more than 2½ hours. The duration of flood at this station is considerably greater than the duration of ebb, the flood current having also the greater strength.

Table 61.—*Current data, Newark Bay*

[Referred to times of HW and LW at Fort Hamilton, N. Y.]

Station No.	Location	Party of—	Date	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
					Time	Direction	Velocity			Time	Direction	Velocity		
				Hours after LW	*Hours before HW*	*True*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*True*	*Knots*	*Hours*	*Days*
1	Off Bergen Point Light, N. J.	H. Mitchell	Aug., 1856	1.7	1.6	N. 85° W	1.8	5.9	1.5	1.5	S. 50° E	2.0	6.5	1¼
2	do	H. C. Denson	Aug., 1922	1.4	1.5	N. 50° W	1.2	5.5	0.9	1.4	S. 15° E	1.7	6.9	1
3	Off Mariners Harbor, N. Y.	do	do	−1.2	3.5	N. 80° W	0.7	7.8	0.6	4.0	N. 85° E	0.5	4.6	1
4	Off Elizabeth, N. J.	H. Mitchell	Aug., 1856	2.4	1.0	East	1.2	5.9	2.3	0.7	S. 85° W	1.0	6.5	1
5	do	R. J. Auld	Nov., 1920	2.2	0.8	N. 60° E	1.0	6.2	2.4	0.8	S. 75° W	0.5	6.2	2
6	do	H. Mitchell	Aug., 1856	2.9	1.2	N. 5° W	0.7	4.9	1.8	0.6	S. 20° W	0.7	7.5	½
7	Off Bergen Point, N. J.	R. J. Auld	Nov., 1920	1.6	1.9	N. 40° E	1.2	5.9	1.5	1.4	S. 30° W	1.2	6.5	2
8	Off Bayonne, N. J.	H. C. Denson	Aug., 1922	1.9	2.2	N. 45° E	0.9	6.1	2.0	−0.4	S. 45° W	1.4	6.3	1
9	Off Port Newark, N. J.	R. J. Auld	Oct., 1920	1.5	1.8	N. 5° E	1.5	6.0	1.5	1.5	South	1.4	6.4	2
10	Off Passaic River	H. C. Denson	Aug., 1922	2.2	0.6	North	0.8	5.7	1.9	2.9	S. 10° E	0.7	6.7	1
11	do	R. J. Auld	Oct., 1920	1.9	1.2	N. 15° E	0.6	6.2	2.1	2.0	S. 5° W	0.4	6.2	2
12	Off Hackensack River.	do	do	2.4	0.5	N. 15° E	1.1	6.2	2.6	1.0	South	0.9	6.2	2
13	do	H. C. Denson	Aug., 1922	2.3	0.5	North	0.7	6.2	2.5	0.4	South	0.8	6.2	½

TABLE 62.—*Current data for various depths, Newark Bay*

[Referred to times of HW and LW at Fort Hamilton, N. Y.]

Station No.	Location	Date	Party of—	Observations with—	Depth	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
							Time	Direction	Velocity			Time	Direction	Velocity		
					Feet	*Hours after LW*	*Hours before HW*	*True*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*True*	*Knots*	*Hours*	*Days*
2	Off Bergen Point Light.	Aug. 20-21, 1922.	H. C. Denson.	Pole	7	1.40	1.50	N. 49° W.	1.15	5.53	0.90	1.35	S. 13° E.	1.72	6.89	1
				Meter	5	1.40	1.80	N. 53° W.	1.35	5.58	0.95	1.20	S. 8° E.	1.55	6.84	1
				do	12	1.35	1.55	N. 49° W.	1.33	5.73	1.05	1.45	S. 9° E.	1.39	6.69	1
				do	20	1.30	1.65	N. 49° W.	1.21	5.78	1.05	2.00	S. 9° E.	1.25	6.64	1
4	Off Mariners Harbor.	Aug. 19-20, 1922.	do	Pole	7	−1.25	3.50	N. 79° W.	0.69	7.88	0.60	4.05	N. 83° E.	0.46	4.54	1
				Meter	6	−1.30	4.00	N. 86° W.	0.66	8.43	1.10	3.75	N. 84° E.	0.56	3.99	1
				do	15	−1.45	2.30	N. 85° W.	0.79	8.63	1.15	3.40	N. 85° E.	0.26	3.79	1
				do	24	−1.15	2.05	S. 89° W.	0.86	8.38	1.20	1.60	N. 85° E.	0.26	4.04	1
5	Off Elizabeth, N. J.	Nov. 5-7, 1920.	R. J. Auld.	Pole	7	2.20	0.77	N. 61° E.	0.98	6.25	2.42	0.82	S. 76° W.	0.54	6.17	2
				Meter	5	2.47	0.23		0.93	6.24	2.68	0.92		0.41	6.18	2
				do	12	2.47	0.60		1.01	6.28	2.72	0.43		0.56	6.14	2
				do	19	2.43	0.53		0.94	6.28	2.68	0.60		0.50	6.14	2
7	Off Bergen Point, N. J.	Nov. 3-5, 1920.	do	Pole	7	1.60	1.90	N. 42° E.	1.25	5.90	1.47	1.40	S. 32° W.	1.19	6.52	2
				Meter	7	1.73	2.00		1.15	5.93	1.63	1.23		1.08	6.49	2
				do	18	1.60	2.00		1.18	6.00	1.57	1.57		0.93	6.42	2
				do	29	1.52	2.08		1.04	6.01	1.50	2.08		0.82	6.41	2
8	Off Bayonne, N. J.	Aug. 21-22, 1922.	H. C. Denson.	Pole	7	1.90	2.15	N. 46° E.	0.94	6.13	2.00	−0.35	S. 45° W.	1.41	6.29	1
				Meter	6	2.05	1.65	N. 54° E.	0.85	5.83	1.85	1.10	S. 37° W.	1.35	6.59	1
				do	16	1.95	2.30	N. 29° E.	0.90	5.93	1.85	1.15	S. 38° W.	1.30	6.49	1
				do	26	1.60	1.85	N. 27° E.	0.96	6.28	1.85	0.95	S. 41° W.	1.13	6.14	1
9	Off Port Newark, N. J.	Oct. 21-23, 1920.	R. J. Auld.	Pole	7	1.52	1.77	N. 5° E.	1.53	6.03	1.52	1.52	South	1.43	6.39	2
				Meter	5	1.88	1.62		1.53	5.62	1.47	1.10		1.35	6.80	2
				do	12	1.85	1.88		1.50	5.71	1.53	1.17		1.07	6.71	2
				do	20	1.72	2.03		1.45	5.98	1.67	1.40		0.88	6.44	2
10	Passaic River	Aug. 23-24, 1922.	H. C. Denson.	Pole	7	2.15	0.63	N. 1° W.	0.33	5.78	1.90	2.90	S. 8° E.	0.71	6.64	1
				Meter	5	2.30	1.00	N. 10° W.	0.42	5.28	1.55	3.10	S. 8° E.	0.62	7.14	1
				do	13	1.95	1.45	N. 2° W.	0.67	5.98	1.90	2.85	S. 4° E.	0.29	6.44	1
				do	21	0.80	0.97	N. 2° W.	0.74	7.33	2.10	3.75	S. 18° E.	0.07	5.09	1
11	do	Oct. 28-30, 1920.	R. J. Auld.	Pole	7	1.92	1.20	N. 16° E.	0.64	6.21	2.10	2.02	S. 4° W.	0.42	6.21	2
				Meter	5	2.18	0.97		0.57	5.43	1.58	2.33		0.59	6.99	2
				do	10	1.97	1.20		0.82	5.85	1.79	1.97		0.32	6.57	2
				do	20	1.42	0.79		0.72	6.56	1.95	1.93		0.12	5.86	2
12	Hackensack River.	Oct. 25-27, 1920.	do	Pole	7	2.45	0.52	N. 17° E.	1.07	6.13	2.55	0.98	S. 1° W.	0.88	6.29	2
				Meter	5	2.53	0.63		0.87	6.38	2.88	1.43		0.80	6.04	2
				do	13	2.47	0.55		0.88	6.49	2.93	1.53		0.71	5.93	2
				do	21	2.43	0.47		0.86	6.50	2.90	1.68		0.59	5.92	2
13	do	Aug. 23, 1922.	H. C. Denson.	Pole	7	2.30	0.60	North	0.67	6.23	2.50	0.40	South	0.79	6.19	½
				Meter	7	2.50	1.00		0.59	6.23	2.70	1.20		0.96	6.19	½
				do	18	2.40	0.80		0.73	6.33	2.70	1.20		0.78	6.09	½
				do	29	2.30	0.30		0.81	6.43	2.70	1.10		0.66	5.99	½

Throughout Newark Bay, for the current near the surface, the duration of ebb is somewhat greater than that of flood, though near the upper end they become equal. In general, the ebb current has the greater velocity at strength.

At the greater number of the stations listed in Table 61 subsurface current observations were also made, the current meter being used for this purpose. The depths at which these observations were made were approximately two-tenths, five-tenths, and eight-tenths of the depth at each station. For some of these stations the direction of the subsurface currents was determined by means of the bifilar direction indicator. Table 62 gives the results of these observations, together with the observations made with the current pole, which refer to the 7-foot depth. As in all the previous current tables, the velocity of the flood and ebb strengths have been reduced to mean values.

The data of Table 62 show that the characteristics of the subsurface current in Newark Bay are conditioned by fresh water flow from the Passaic and Hackensack Rivers. The ebb current decreases rapidly in velocity with increase of depth, while the flood current decreases much more slowly. Generally, the ebb current has a considerably greater velocity near the surface, but toward the bottom the flood and ebb strengths are approximately equal, and at the stations in the two rivers the flood current from mid-depth downward has the greater velocity.

XIV. THE CURRENT IN THE HUDSON AND HARLEM RIVERS

For the 14-mile stretch of the Hudson, from the Battery to Mount St. Vincent, Figure 36, shows the locations of 67 stations at which current observations have been made, the records of which are on file in the office of the Coast and Geodetic Survey. These observations were made between the years 1855 and 1922, generally in the summer or early autumn months when weather conditions are most favorable.

In Table 63 are given the results of the observations made near the surface. For the earlier observations it is difficult to specify a definite depth, since various methods were employed in observing the currents. For the later observations the data of Table 63 may be taken to refer to a depth about 7 feet below the surface. In general, greater weight is to be given the results of the later observations because of the use of standard time and also because of the greater uniformity in the apparatus and the methods of observation.

The times of slack and strength of the current are given in hours and tenths with reference to the time of tide at Fort Hamilton, N. Y., HW referring to high water and LW to low water. The times are given to the nearest tenth of an hour, since short series of observations can not be considered as giving results of greater accuracy. For the same reason the velocities are given to one decimal of a knot and directions to the nearest 5°, these directions being true and not magnetic. The durations of flood and ebb, likewise, are given in hours and tenths. The strength of flood and ebb given in Table 63 have been corrected to mean values by the ratio of ranges.

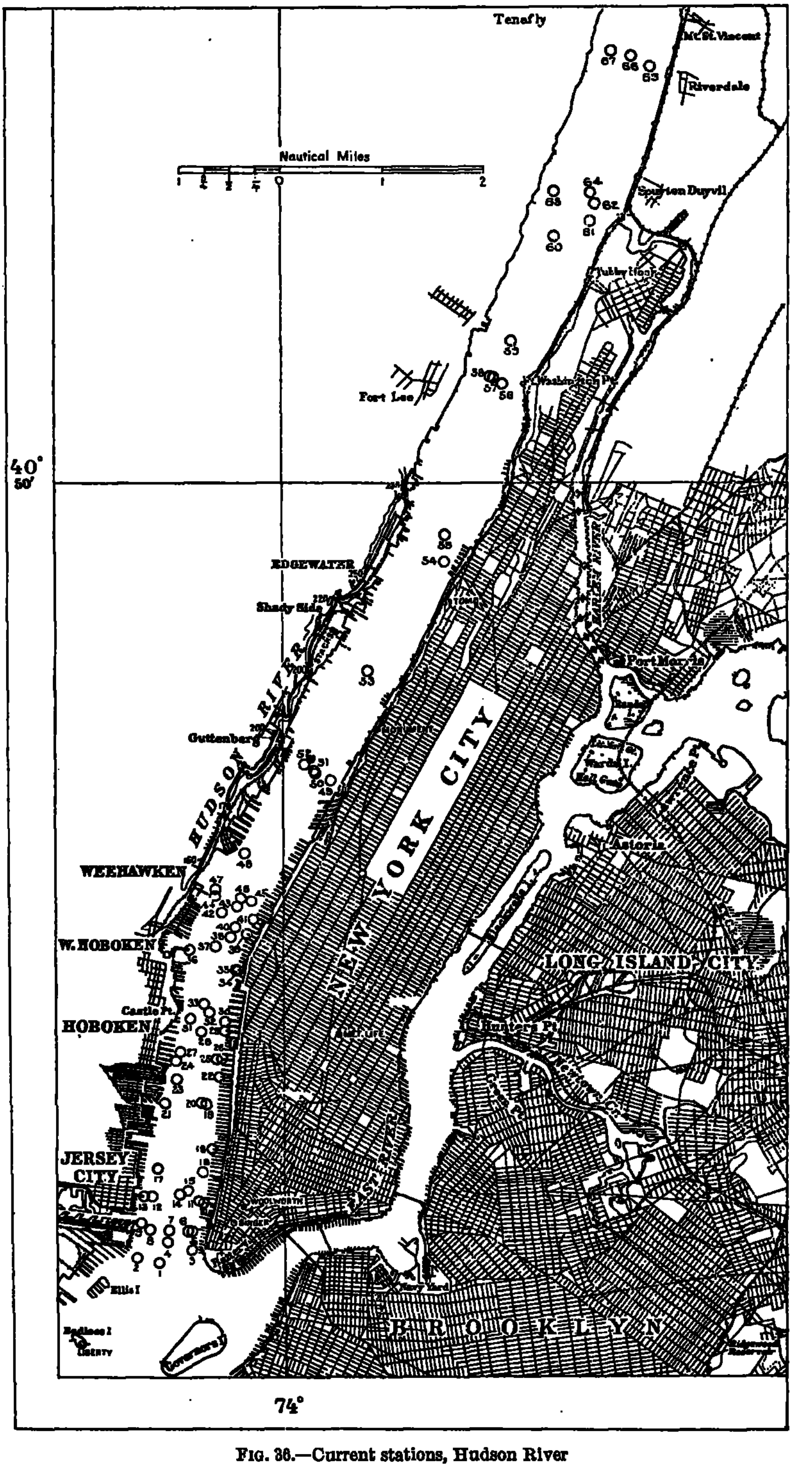


FIG. 36.—Current stations, Hudson River

TABLE 63.—*Current data, Hudson River*

[Referred to times of HW and LW at Fort Hamilton, N. Y.]

Station No.	Location	Party of—	Date	Slack	Flood strength: Time	Flood strength: Direction	Flood strength: Velocity	Flood duration	Slack	Ebb strength: Time	Ebb strength: Direction	Ebb strength: Velocity	Ebb duration	Length of observations
				Hours before HW	*Hours after HW*	*True*	*Knots*	*Hours*	*Hours before LW*	*Hours after LW*	*True*	*Knots*	*Hours*	*Days*
1	Midstream	I. Winston	Oct., 1919	2.1	0.2	N. 20° E.	1.6	5.3	3.2	0.6	S. 20° W.	2.4	7.1	2¼
2	Off Jersey City, N. J.	H. Mitchell	Sept., 1872	1.8	−0.4	N. 10° E.	1.2	5.4	2.8	0.3	S. 20° W.	1.3	7.0	½
3	Off Battery, N. Y.	H. L. Marindin	July, 1872		0.6	North	1.4		3.6	0.3	S. 5° W.	1.8		½
4	Midstream	F. F. Ness	Sept., 1872		0.8	N. 10° E.	1.5		2.1	−0.2	S. 15° W.	1.9		½
5	Off New York City	H. L. Marindin	Sept., 1873	2.0	−0.6	N. 20° E.	1.4	4.1	4.3	−0.1	S. 10° W.	1.7	8.3	½
6	do.	H. C. Denson	July, 1922	2.4	0.6	North	1.4	5.5	3.3	0.3	S. 5° W.	2.2	6.9	3
7	Midstream	do.	do.	1.8	0.6	N. 15° E.	1.2	5.1	3.1	0.7	S. 15° W.	2.2	7.3	32
8	Off Jersey City, N. J.	do.	do.	2.8	−0.3	N. 15° E.	0.7	5.2	4.0	−0.2	S. 10° W.	1.8	7.2	4¼
9	do.	H. L. Marindin	Aug., 1873	1.8	0.4	N. 15° E.	0.8	4.8	3.4	1.0	S. 15° W.	1.4	7.6	1
10	Off New York City	H. C. Denson	Aug., 1922	2.2	0.4	N. 15° E.	0.4	4.8	3.8					½
11	do.	R. Wainright	Sept., 1855	2.6	0.0	N. 30° E.	1.3	5.3	3.7	0.1	S. 10° W.	1.6	7.1	½
12	Off Jersey City, N. J.	do.	do.	3.1	−0.3	N. 20° E.	1.4	5.7	3.8	0.2	S. 10° E.	1.8	6.7	½
13	Off Jersey City	H. C. Denson	Aug., 1922	2.4	0.2		0.1	5.8	3.0				6.6	½
14	Midstream	I. Winston	Sept., 1919	2.4				4.7	3.1	0.2	S. 5° W.	2.3	7.7	1¾
15	do.	Schooner Madison	June, 1854	2.2	0.4	N. 25° E.	1.6	6.2	2.4	1.2		2.1	6.2	1
16	Off New York City	H. Mitchell	Sept., 1873	2.9	0.4	N. 15° E.	1.9	6.2	3.1	0.7	S. 10° W.	1.5	6.2	1
17	Off Jersey City	do.	Aug., 1873	2.6	0.4	N. 15° E.	1.2	5.2	3.8	0.1	S. 10° W.	1.9	7.2	1
18	Off New York City	H. C. Denson	Aug., 1922	2.2	−0.2	N. 25° W.	0.8	5.8	2.8	1.5	S. 10° W.	1.0	6.6	½
19	do.	H. L. Marindin	Aug., 1873	2.2	0.6	N. 10° E.	1.4	6.0	2.6	1.4	S. 5° W.	1.0	6.4	1
20	Midstream	Schooner Madison	June, 1854	1.9	0.6	N. 20° E.	1.6	6.1	2.2	0.6	S. 10° W.	2.1	6.3	1
21	Off Jersey City	H. L. Marindin	Aug., 1873	2.5	0.4	N. 5° E.	0.9	5.0	3.9	0.5	S. 10° W.	1.6	7.4	1
22	Off New York City	R. Wainright	Sept., 1855	1.9	−0.1	N. 20° E.	0.8	4.5	3.8	−1.0	S. 5° W.	1.6	7.9	½
23	Off Jersey City	do.	do.	1.2	0.3	N. 15° E.	0.8	3.3	4.3	0.2	S. 5° W.	2.0	9.1	1
24	Off Hoboken, N. J.	H. C. Denson	Aug., 1922	1.8				4.8	3.4	0.8	S. 10° W.	1.2	7.6	½
25	Off New York City	H. Mitchell	Aug., 1873	1.5	0.8	N. 10° E.	1.6	5.4	2.5	1.1	S. 5° E.	1.7	7.0	½
26	do.	H. C. Denson	Aug., 1922						4.7	−0.3	S. 25° W.	1.6		½
27	Off Hoboken, N. J.	H. Mitchell	Aug., 1873	2.0	0.7	N. 20° E.	1.0	4.5	3.9	1.0	S. 20° W.	1.9	7.9	½
28	Midstream	I. Winston	Sept., 1919	2.5	−0.3	N. 15° E.	1.2	5.2	3.7				7.2	½
29	Off New York City	H. C. Denson	Aug., 1922	2.8	−0.4	N. 15° E.	0.4	4.5	4.7	−0.2	S. 5° W.	1.2	7.9	½
30	do.	R. Wainright	Sept., 1855	2.4	1.0	N. 25° E.	1.0	5.3	3.5	−0.1	S. 5° W.	1.4	7.1	½
31	Off Hoboken, N. J.	do.	do.	1.7	0.8	N. 5° W.	1.8	6.3	2.8	1.0	South	2.0	6.1	¾
32	Midstream	H. C. Denson	July, 1922	0.4	1.4	North	0.7	3.6	3.2	1.4	South	2.6	8.8	1
33	do.	Schooner Madison	July, 1854	2.0	0.5	N. 20° E.	1.7	5.8	2.6	0.1	S. 20° W.	2.3	6.6	1
34	Off New York City	H. C. Denson	Aug., 1922	1.4	−0.1	N. 15° E.	0.6	4.0	3.8	1.9	S. 15° W.	0.9	8.4	½
35	do.	R. Wainright	Sept., 1855	1.9	−1.0	N. 30° E.	1.0	4.3	4.0	1.6	S. 15° W.	1.3	8.1	½
36	Off Hoboken, N. J.	H. C. Denson	Aug., 1922	1.7	0.5	North	0.5	4.1	4.0	0.4	S. 25° E.	1.8	8.3	½
37	Midstream	I. Winston	Sept., 1919	2.2	0.8	N. 15° E.	1.6	5.7	2.9	0.2	S. 25° W.	2.3	6.7	2
38	Off New York City	Schooner Madison	July, 1854	0.8	1.6	N. 20° E.	1.9	4.5	2.7	1.3	S. 45° W.	2.7	7.9	1
39	do.	H. C. Denson	Aug., 1922	1.4	0.4	N. 15° E.	0.3	4.1	3.7	−0.3	S. 35° W.	1.2	8.3	½
40	Midstream	do.	July, 1922	1.4	1.1	N. 15° E.	1.5	4.9	2.9	0.8	S. 25° W.	2.4	7.5	1¾
41	Off New York City	H. L. Marindin	Aug., 1885						4.1	0.4		1.8		½
42	Midstream	H. C. Denson	July, 1922	1.7	0.9	N. 10° E.	1.3	5.3	2.8	0.9	S. 25° W.	2.5	7.1	1¾
43	do.	H. L. Marindin	Aug., 1885	1.7	0.6	N. 30° E.	1.7	5.2	2.9	0.6	S. 35° W.	2.8	7.2	2¾
44	Off Weehawken, N. J.	do.	do.	2.6				5.8	3.2	−0.4		1.9	6.6	½
45	Off New York City	H. Mitchell	Sept., 1858	2.1	0.4	N. 25° E.	1.3	5.9	2.6	0.6	S. 30° W.	2.1	6.5	1
46	Midstream	F. F. Ness	Sept., 1872	2.0	0.8	N. 40° E.	1.4	5.6	2.8	0.6	S. 35° W.	2.7	6.8	1¼
47	Off Weehawken, N. J.	H. Mitchell	do.	2.6	0.5	N. 30° E.	1.1	5.7	3.3	0.1	S. 30° W.	1.4	6.7	1¼
48	do.	R. Wainright	Sept., 1855	2.8	0.9	N. 30° E.	1.5	6.3	2.9	0.0	S. 15° W.	1.7	6.1	½
49	Off New York City	H. C. Denson	Aug., 1922	1.9	0.4	N. 40° E.	1.0	4.9	3.4	0.1	S. 25° W.	1.8	7.5	½
50	Midstream	do.	do.	1.5	0.5	N. 30° E.	1.7	4.9	3.0	0.6	S. 25° W.	2.6	7.5	½
51	do.	do.	July, 1922	1.3	1.2	N. 25° E.	1.8	5.1	2.6	1.4	S. 30° W.	2.5	7.3	2¾
52	Off Guttenberg, N. J.	do.	Aug., 1922	1.5	0.9	N. 35° E.	1.5	4.6	3.3	−0.2	S. 35° W.	2.2	7.8	½
53	Off New York City	H. Mitchell	Sept., 1871	2.3	1.1	N. 20° E.	1.3	5.6	3.1	0.6	S. 40° W.	1.5	6.8	1
54	do.	R. Wainright	Aug., 1855	0.4	2.6	N. 40° E.	0.7	4.0	2.8	1.9	S. 20° W.	2.2	8.4	1
55	Midstream	I. Winston	Sept., 1919	1.9	0.6	N. 15° E.	2.0	5.3	3.0	0.5	S. 15° W.	2.0	7.1	2
56	Off New York City	R. Wainright	Aug., 1855	1.6	1.1	N. 25° E.	1.8	5.2	2.8	1.1	S. 20° W.	2.3	7.2	¾
57	Midstream	H. C. Denson	July, 1922	1.6	0.9	N. 5° E.	1.2	5.4	2.6	1.2	S. 40° W.	1.9	7.0	1¾
58	do.	I. Winston	Sept., 1919	0.6	1.4	N. 15° E.	2.1	4.5	2.5	1.0	S. 25° W.	3.1	7.9	2
59	do.	H. C. Denson	July, 1922	1.7	1.0	N. 30° E.	1.7	5.7	2.4	1.1	S. 35° W.	2.0	6.7	2
60	do.	I. Winston	Aug., 1919	2.3	0.5	N. 30° E.	1.8	6.2	2.5	0.9	S. 25° W.	2.0	6.2	2
61	Off Harlem River entrance.	R. Wainright	Aug., 1855	1.2	1.6	N. 15° E.	1.5	4.9	2.7	1.0	S. 5° W.	2.4	7.5	½
62	do.	H. C. Denson	July, 1922	0.3	1.8	N. 30° E.	1.7	4.8	1.9	2.3	S. 15° W.	2.1	7.6	¾
63	Off Englewood, N. J.	do.	do.	1.0	1.5	N. 20° E.	1.2	5.3	2.1	1.8	S. 35° W.	1.8	7.1	1½
64	Off Spuyten Duyvil	I. Winston	Aug., 1919	1.5	1.1	N. 30° E.	1.6	5.2	2.7	0.9	S. 20° W.	2.2	7.2	2
65	Off Riverdale, N. Y	H. C. Denson	Aug., 1922	1.3	1.9	N. 10° E.	1.6	5.5	2.2	1.4	S. 30° W.	2.1	6.9	3¾
66	Midstream	do.	do.	0.8	2.0	N. 15° E.	1.3	5.2	2.0	1.8	S. 10° W.	1.9	7.2	6¼
67	Off Tenafly, N. J.	do.	do.	1.3	1.0	N. 5° E.	1.1	4.7	3.0	1.2	S. 25° W.	1.8	7.7	3¾

At the mouth of the Hudson the tide is 0.45 hour later than at Fort Hamilton. From Table 63 the midstream current at the mouth of the Hudson is at its strength about half an hour after the time of high or low water at Fort Hamilton, and slack occurs about two and one-half hours before high or low water at Fort Hamilton. With respect to the local tide, therefore, the strength of the midstream current at the mouth of the Hudson comes about the times of high and low water and slack about three hours before high and low water. The tidal movement at the mouth of the Hudson, as deduced from the relation of the time of current to the time of tide, is therefore of the progressive-wave type.

From the mouth of the Hudson to Riverdale the current becomes later by one hour. For this same stretch the tide likewise becomes later by about an hour. Throughout this stretch of the Hudson, therefore, the relation of time of current to time of the local tide is the same as that at the mouth.

Along the axis of the channel the velocity of the current at strength of flood is approximately 1½ knots from the Battery to Riverdale. Flood velocities of 2 knots or more are shown at only two stations, numbers 55 and 58. For station 55 the flood velocity of 2 knots is probably correct, since station 56, which is near it, shows a flood velocity of 1.8 knots. The flood velocity of 2.1 knots at station 58 is probably too large. Four flood strengths were observed at this station, the average of these being 1.12 knots. Unusually small ranges of the tide prevailed on the days of these observations, so that the correction factor for the ratio of ranges was 1.58. Apparently the velocity of the current at this station does not vary in simple proportion to the range of the tide.

The ebb current in the channel has a velocity of approximately 2¼ knots at strength. The difference of three-quarters of a knot in the velocities of flood and ebb strengths is due to the fresh water draining into the Hudson. Since, in general, the effect of this nontidal water is to increase the ebb velocity by the same amount as it decreases the flood velocity, the nontidal current (or permanent current, as it is sometimes called) in the lower Hudson has a velocity near the surface of three-eighths of a knot.

Through the stretch of the Hudson under consideration the velocity of the ebb current is practically the same. The single value of over 3 knots at station 58 is due to the large correction factor for the ratio of ranges, mention of which was made above, and is undoubtedly too large.

A comparison of the time of current at the stations located in the axis of the channel with those located near the shores shows that the current turns earlier near the shore. Stations 6, 7, and 8 illustrate this well, the current at stations 6 and 8 being earlier, both at slack and at strength, than at station 7 by somewhat more than half an hour. The data for stations 49, 50, and 52 give the current earlier near the shore by about a quarter of an hour, and from the data for stations 65, 66, and 67 the current near the shore is a little more than half an hour earlier than along the axis of the channel.

With the exception of a stretch of about 3 miles from Hoboken to Weehawken, N. J., the axis of the channel of the Hudson from the Battery to Riverdale lies near the New York shore. It is therefore to be expected that the current in the Hudson as far as Riverdale should turn earlier near the New Jersey shore. The data of Table 63 bear this out. At station 8 the current is more than half an hour earlier than at station 6; at station 13 the current is a little less than half an hour earlier than at station 10. The observations made in 1855 at stations 11 and 12 give a difference of a quarter of an hour between the current on the New Jersey and New York shores, being earlier on the New Jersey shore. The 1873 observations at stations 16 and 17 and at stations 19 and 21 likewise show the current on the New Jersey shore to be earlier. For stations 65 and 67, off Riverdale, the data of Table 63 show the current on the New Jersey shore to be earlier by almost exactly half an hour.

The greatest velocity of the current is obviously to be found midstream, or along the axis of the channel, where the effects of friction are least. Table 63 shows this to be the case. The greatest velocities shown are almost without exception those for stations located in midstream. This is especially well shown by stations located on a section across the river. Thus, in the section off Guttenberg, N. J., at stations 49, 50, 51, and 52, the strength of the tidal current—that is, the strength of the current freed from the effects of nontidal water, or the half sum of the flood and ebb strengths—is 2.2 knots for the midstream stations, against 1.4 knots for the station near the New York shore and 1.8 knots for the station near the New Jersey shore.

Similarly, in the section off Jersey City, stations, 10, 11, 12, 13, and 14, the strength of the tidal current is over 2 knots at the midstream station and considerably less than 2 knots near the New York and New Jersey shores. This section also shows that the nearer the station is to the shore the less is the velocity, stations 11 and 12 having velocities greater than a knot, while at stations 10 and 13 it is less than a knot. In the section off Weehawken, N. J., stations 41, 43, and 44, the tidal current at the midstream station has a velocity at strength of more than 2 knots, while the stations near the New York and New Jersey shores have velocities less than 2 knots.

The section near the mouth of the Hudson, consisting of stations 5, 6, 7, 8, and 9, appears to give results that do not agree with the statements above, for the velocity is greatest, not at station 7 in midstream, but at station 6 near the New York shore. At station 7 the strength of the tidal current is 1.7 knots, while at station 6 it is 1.8 knots. A glance at a chart of the Hudson on which soundings are plotted—as, for example, Coast and Geodetic Survey Chart No 369—shows that the axis of the channel near the mouth lies close to the New York shore, and that the depth at station 6 is greater than at station 7 in midstream. The greatest velocity is therefore at the stations along the axis of the channel, as distinguished from midstream.

A similar condition obtains in the section off Riverdale, comprising stations 65, 66, and 67. Here the strength of the tidal current a station 66, in midstream, is 1.6 knots, while at station 65, near the New York shore, it is 1.8 knots. The axis of the channel off Riverdale lies close to the New York shore, the depth at station 65 being greater than at station 66, and hence the velocity at station 66 is the greater.

Since the axis of the channel in the lower Hudson generally lies near the New York shore, the velocity of the current should be greater near that shore than near the New Jersey shore. Taking the data for the sections discussed in the three previous paragraphs, we find this generally the case. Near the mouth, at station 5, the strength of the tidal current is 1.6 knots against 1.1 knots at station 9 on the New Jersey shore; at station 6 it is 1.8 knots against 1.2 knots at station 8; at station 10 it is 0.4 knot against 0.1 knot at station 13; at station 65 it is 1.8 knots against 1.4 knots at station 67.

The relative durations of the flood and ebb periods are obviously dependent to some degree on the amount of fresh water coming down the Hudson. Hence, altogether apart from other factors that may be involved, these periods as determined at different times may be expected to differ. In general, it may be stated that the data of Table 63 show that in the stretch of the Hudson from the Battery to Riverdale the period of ebb for the current near the surface is on the average about 2 hours greater than the period of flood, the duration of ebb being 7.2 hours and the duration of flood 5.2 hours.

The direction of the channel of the Hudson from the mouth to West Hoboken is N. 10° E., and the data of Table 63 show that for this stretch of the river the direction of the current is approximately that of the channel. In general, the direction of the current on the flood is directly opposite that on the ebb.

Off West Hoboken the channel swings further eastward, the direction from that point to a point midway between Edgewater and Fort Lee, N. J., being N. 25° E. The direction of the current through this stretch changes to conform to the direction of the channel, as the data of Table 63 show, and for the greater part of this stretch the flood and ebb currents are very nearly opposite in direction, but off West Hoboken, where the channel begins to turn, the deviation in the flood and ebb directions from a straight line is quite pronounced. On the flood the direction continues to be that of the lower stretch of the river and approximately N. 15° E., while on the ebb the influence of the stretch above is evident and the direction approximates S. 25° W.

Between Edgewater and Fort Lee the channel swings about 10° to the north, continuing in a practically unchanged direction of N. 15° E. as far as Riverdale, where it makes a further swing to the north of a little more than 5°. Through this stretch the relation of the direction of the current to that of the channel is similar to that discussed in the preceding paragraph.

At 34 of the stations listed in Table 63 subsurface current observations with current meters were also made. Generally these observations were made at three depths—two-tenths, five-tenths, and eight-tenths of the depth at the station—and for several of these stations the direction of the subsurface current was determined by means of a bifilar direction indicator.

The data derived from these observations are given in Table 64. To bring out differences in the current at the different depths, times and velocities are given to the second decimal place and directions to the nearest degree. For comparison there are given also for the stations listed in Table 64 the data derived from the pole observations which pertain to the 7-foot depth and which have been given in Table 63. The velocities in Table 64 for the strengths of flood and ebb have been reduced to mean values.

The subsurface current in the Hudson presents the features found in the subsurface current in the Narrows and Upper Bay. The slack before flood becomes earlier from the surface downward, while the slack before ebb occurs about the same time from surface to bottom. The velocity of the flood strength decreases very slowly with increasing depth, or may even increase, while strength of ebb decreases at a relatively rapid rate. At the surface the ebb has the greater duration, but with increasing depth the duration of flood increases while the duration of ebb decreases, so that near the bottom the duration of flood may become the greater.

Taking up these features of the subsurface current in the Hudson in detail, the data of Table 64 indicate that for the stretch of the Hudson here under consideration the acceleration in the time of slack before flood from the surface downward is approximately at the rate of 0.04 hour per foot. At station 7, where the observations cover a period of 31 days, the results may be considered as well determined; and here we find the rate of acceleration in the time of slack before flood to be 0.05 hour per foot. At stations 65, 66, and 67, near Mount St. Vincent, the rate of acceleration in the time of slack before flood is 0.06 hour per foot. For the slack before ebb there is generally but little difference in time from the surface to the bottom, although it is to be noted that the data for station 7 indicate a retardation at the rate of 0.01 hour per foot, while for station 66 the data indicate an acceleration at the rate of about 0.01 hour per foot.

For the strength of flood it appears that there is, in general, a slight acceleration in time from the surface downward. For station 7 this is at the rate of 0.01 hour per foot, while for stations 65, 66, and 67 it is at the rate of 0.06 hour per foot. The strength of ebb shows a slight acceleration from the surface downward. At station 7 and at stations 65, 66, and 67 it is at the rate of about 0.03 hour per foot.

The ebb strength at all of the stations listed in Table 64 has a greater velocity at the surface than the flood strength. From the surface the ebb strength decreases in velocity in a fairly uniform manner. At station 7 this decrease is at the rate of 0.04 knot per foot, and at stations 65, 66, and 67 the rate is likewise 0.04 knot per foot. This value at the other stations approximates 0.04 knot per foot, and it may therefore be taken as the rate of decrease in the velocity of ebb strength for the whole stretch from the Battery to Mount St. Vincent.

For the flood strength the data of Table 64 show that the greatest velocity is found, in general, at mid-depth. For station 7 the strength of flood increases from the surface to mid-depth at the rate of 0.02 knot per foot, and from mid-depth downward it decreases at the same rate. Station 1 shows an increase to mid-depth of a little more than 0.02 knot per foot and a decrease from mid-depth of very nearly 0.03 knot per foot; for station 37 these rates are, respectively, 0.03 knot and 0.04 knot, and for stations 65, 66, and 67 they average respectively 0.01 knot and 0.03 knot per foot.

TABLE 64.—*Current data for various depths, Hudson River*

[Referred to times of HW. and LW. at Fort Hamilton, N. Y.]

Station No.	Location	Date	Party of—	Observations with—	Depth	Slack	Flood strength: Time	Flood strength: Direction	Flood strength: Velocity	Flood duration	Slack	Ebb strength: Time	Ebb strength: Direction	Ebb strength: Velocity	Ebb duration	Length of observations
					Feet	*Hours before HW*	*Hours after HW*	*True*	*Knots*	*Hours*	*Hours before LW*	*Hours after LW*	*True*	*Knots*	*Hours*	*Days*
1	Midstream	Sept. 30, Oct. 20-21, Nov. 3-4, 1919.	I. Winston	Pole	7	2.10	0.15	N. 21° E.	1.59	5.28	3.19	0.57	S. 19° W.	2.37	7.14	2¼
				Meter	8	2.11	0.42		1.56	5.49	2.99	0.47		2.11	6.93	2½
				do	20	2.78	0.42		1.92	6.41	2.74	0.37		1.46	6.01	2½
				do	32	2.91	0.10		1.58	6.33	2.95	0.38		1.04	6.09	2½
6	Off New York City.	July 23-25, Aug. 25-26, 1922.	H. C. Denson	Pole	7	2.42	0.63	N. 1° W.	1.42	5.49	3.30	0.27	S. 3° W.	2.20	6.93	3
				Meter	11	2.47	0.30		1.56	5.59	3.25	0.27		1.93	6.83	3
				do	27	2.90	0.30		1.57	6.15	3.12	0.27		1.50	6.27	3
				do	43	3.37	0.08		1.35	6.71	3.03	0.13		1.11	5.71	3
7	Midstream	July 15-Aug. 6, Aug. 11-18, Aug. 25-31, 1922.	do	Pole	7	1.79	0.58	N. 17° E.	1.19	5.03	3.13	0.73	S. 14° W.	2.22	7.39	32
				Meter	9	1.82	0.58		1.20	5.26	3.03	0.70		2.13	7.16	31
				do	24	2.62	0.52		1.56	6.20	2.79	0.33		1.52	6.22	31
				do	38	3.33	0.15		1.30	6.87	2.83	−0.08		1.05	5.55	31
8	Off Jersey City	July 23-27, Aug. 25-26, 1922.	do	Pole	7	2.77	−0.33	N. 14° E.	0.66	5.16	3.98	−0.23	S. 12° W.	1.76	7.26	4¼
				Meter	6	2.73	−0.79		0.72	4.88	4.22	−0.58		1.82	7.54	2¾
				do	15	2.82	−0.65		0.72	5.29	3.90	−0.27		1.47	7.13	2¾
				do	24	2.92	0.48		0.72	5.69	3.60	−0.22		1.11	6.73	2¾
10	Off New York City.	Aug. 30, 1922	do	Pole	7	2.20	0.40	N. 14° E.	0.44	4.77	3.80				7.65	½
				Meter	9	2.30	0.40	N. 29° E.	1.15	5.57	3.10	−0.50	S. 47° W.	1.20	6.85	½
				do	22	2.70	−0.20	N. 20° E.	1.38	5.97	3.10	−0.30	S. 57° W.	0.63	6.45	½
				do	35	3.70	−1.20	N. 24° E.	1.28	6.97	3.10	−0.50	S. 37° W.	0.58	5.45	½
13	Off Jersey City	do	do	Pole	7	2.40	0.20		0.11	5.77	3.00				6.65	¼
				Meter	8	2.50	0.20	N. 70° E.	0.41	4.97	3.90	0.10	S. 15° E.	1.11	7.45	½
				do	20	2.80	−0.40	N. 28° E.	0.51	5.47	3.70	0.10	S. 45° E.	1.01	6.95	½
				do	32	3.10	−0.50	N. 5° E.	0.93	5.77	3.70	0.10	S. 55° E.	0.93	6.65	½
14	Midstream	Sept. 22-23, Oct. 6-7, 1919.	I. Winston	Pole	7	2.42				5.72	3.07	0.18	S. 3° W.	2.26	6.70	1¾
				Meter	9	2.38	0.17		1.73	5.55	3.20	0.07		2.36	6.87	2
				do	22	2.58	0.20		1.73	6.02	2.93	−0.02		1.69	6.40	2
				do	35	2.70	0.17		1.37	6.05	3.02	0.13		1.10	6.37	2
18	Off New York City.	Aug. 30, 1922	H. C. Denson	Pole	7	2.20	−0.20	N. 23° W.	0.83	5.72	2.85	1.50	S. 9° W.	1.03	6.70	½
				Meter	7	2.10	1.00	North	0.84	5.47	3.00	0.60	S. 26° W.	1.29	6.95	½
				do	18	2.40	0.80	N. 9° E.	1.18	5.97	2.80	0.60	S. 44° W.	0.73	6.45	½
				do	28	2.70	−0.40	N. 7° E.	0.96	6.27	2.80	0.50	S. 11° W.	0.51	6.15	½
24	Off Hoboken, N. J.	Aug. 29, 1922	do	Pole	7	1.80				4.77	3.40	0.80	S. 11° W.	1.19	7.65	½
				Meter	9	1.80	0.10	N. 6° E.	0.58	4.47	3.70	0.30	S. 7° E.	1.58	7.95	½
				do	22	2.60	0.10	N. 34° E.	0.76	5.37	3.60	−0.60	S. 30° E.	0.86	7.05	½
				do	35	2.90	0.40	N. 13° E.	1.06	5.77	3.50	−1.10	S. 10° E.	0.66	6.65	½
26	Off New York City.	do	do	Pole	7						4.70	−0.30	S. 24° W.	1.62		½
				Meter	7	1.70	0.50	N. 16° E.	0.85	4.27	3.80	1.12	S. 22° W.	1.75	8.15	½
				do	18	2.50	0.50	N. 20° E.	1.03	5.37	3.50	0.90	S. 34° W.	1.13	7.05	½
				do	28	3.70	0.10	N. 13° E.	1.07	6.57	3.50	0.60	S. 12° W.	0.82	5.85	½
28	Midstream	Sept. 10-11, 1919.	I. Winston	Pole	7	2.50	−0.30	N. 14° E.	1.16	5.17	3.70				7.25	½
				Meter	12	2.30	−0.30		1.16	5.17	3.50				7.25	½
				do	30	2.40	−0.10		1.54	5.47	3.30				6.95	½
				do	48	2.60	−0.10		1.38	5.57	3.40				6.85	½
29	Off New York City.	Aug. 29, 1922	H. C. Denson	Pole	7	2.80	−0.40	N. 15° E.	0.41	4.47	4.70	−0.25	S. 7° W.	1.21	7.95	½
				Meter	9	2.40	0.10	N. 4° E.	1.01	5.37	3.40	−0.20	S. 27° W.	1.29	7.05	½
				do	22	2.80	−0.40	N. 9° W.	1.01	5.77	3.40	−0.10	S. 24° W.	0.96	6.65	½
				do	35	3.20	−1.10	N. 30° W.	0.96	6.27	3.30	−0.30	S. 23° W.	0.76	6.15	½
32	Midstream	July 19-21, 1922	do	Pole	7	0.40	1.45	N. 2° W.	0.67	3.60	3.17	1.40	S. 2° E.	2.64	8.82	1
				Meter	14	0.70	1.75		0.92	4.04	3.03	1.10		2.70	8.38	1
				do	36	1.95	1.55		1.38	5.75	2.57	0.40		1.43	6.67	1
				do	50	3.00	1.10		0.87	6.37	3.00	0.10		1.22	6.05	1
34	Off New York City.	Aug. 28-29, 1922.	do	Pole	7	1.40	−0.10	N. 17° E.	0.57	3.97	3.80	1.90	S. 17° W.	0.87	8.45	½
				Meter	7	1.30	0.60	N. 29° E.	0.57	3.87	3.80	1.00	S. 24° W.	0.67	8.55	½
				do	18	1.80	−0.20	N. 18° E.	0.87	4.37	3.80	0.50	S. 24° W.	0.37	8.05	½
				do	29	1.90	−0.50	N. 4° E.	0.92	4.47	3.80	0.10	S. 54° W.	0.47	7.95	½
36	Off Hoboken, N. J.	do	do	do	7	1.70	0.50	N. 1° E.	0.50	4.07	4.00	0.40	S. 26° E.	1.75	8.35	½
				do	18	2.10	0.50	N. 11° E.	1.05	4.97	3.50	0.50	S. 22° E.	1.30	7.45	½
				do	28	2.60	−0.30	N. 10° E.	0.90	5.37	3.60	0.50	S. 47° E.	1.35	7.05	½
37	Midstream	Sept. 15-17, 1919.	I. Winston	Pole	7	2.17	0.80	N. 16° E.	1.60	5.64	2.90	0.22	S. 24° W.	2.26	6.78	2
				Meter	10	1.82	0.80		1.96	5.40	2.79	0.35		2.30	7.02	2
				do	24	2.15	0.79		2.14	5.59	2.93	0.38		1.92	6.83	2
				do	38	2.17	0.68		1.60	5.56	2.98	0.52		1.42	6.86	2
39	Off New York City.	Aug. 28-29, 1922.	H. C. Denson	Pole	7	1.40	0.40	N. 13° E.	0.27	4.07	3.70	−0.30	S. 37° W.	1.22	8.35	½
				Meter	9	1.60	−0.30	N. 39° W.	0.47	4.27	3.70	−0.40	S. 34° W.	1.17	8.15	½
				do	23	2.30	−0.40	N. 27° E.	0.62			−0.30	S. 33° W.	0.72		½
				do	37	2.40	0.10	N. 36° E.	0.72			−0.20	S. 32° W.	0.62		½
40	Midstream	July 21-23, 1922	do	Pole	7	1.43	1.13	N. 16° E.	1.46	4.93	2.87	0.83	S. 25° W.	2.36	7.49	1¾
				Meter	10	0.80	1.35		1.44	4.57	2.60	0.50		2.36	7.85	¾
				do	25	1.60	1.35		1.39	5.27	2.70	0.50		1.52	7.15	¾
				do	40	2.10	1.25		1.30	5.62	2.85	0.10		0.98	6.80	¾

TABLE 64.—*Current data for various depths, Hudson River*—Continued

Station No.	Location	Date	Party of—	Observations with—	Depth	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
							Time	Direction	Velocity			Time	Direction	Velocity		
					Feet	*Hours before HW*	*Hours after HW*	*True*	*Knots*	*Hours*	*Hours before LW*	*Hours after LW*	*True*	*Knots*	*Hours*	*Days*
42	Midstream	July 21-23, 1922	H. C. Denson	Pole	7	1.72	0.93	N. 11° E.	1.26	5.29	2.80	0.87	S. 27° W.	2.51	7.13	1¾
				Meter	9	2.08	1.10		1.25	5.62	2.83	0.70		2.10	6.80	1¾
				do	23	2.38	1.10		1.55	6.08	2.67	0.60		1.98	6.34	1¾
				do	37	2.53	0.05		1.19	6.00	2.90	0.70		1.72	6.42	1¾
49	Off New York City	Aug. 26-27, 1922	do	Pole	7	1.90						0.10	S. 27° W.	1.80		¼
				Meter	7	1.90	0.40	N. 41° E.	1.00	4.87	3.40	0.00	S. 27° W.	2.13	7.55	½
				do	17	2.70	−0.10	N. 36° E.	1.10	5.67	3.40	−0.15	S. 33° W.	1.68	6.75	½
				do	27	3.00	−0.40	N. 27° E.	1.12	6.17	3.20	−0.45	S. 36° W.	0.99	6.25	⅓
50	Midstream	do	do	Pole	7	1.50	0.50	N. 32° E.	1.72	4.87	3.00	0.60	S. 27° W.	2.62	7.55	½
				Meter	12	1.80	0.90	N. 27° E.	1.62	5.32	2.85	0.70	S. 29° W.	2.74	7.10	½
				do	29	2.40	0.00	N. 28° E.	1.30	5.67	3.10	0.65	S. 29° W.	2.38	6.75	½
				do	46	2.90	−0.30	N. 20° E.	1.24	6.12	3.15	0.65	S. 29° W.	1.64	6.30	½
51	do	July 16-19, 1922	do	Pole	7	1.32	1.20	N. 26° E.	1.75	5.06	2.63	1.35	S. 32° W.	2.52	7.36	2¾
				Meter	11	1.32	1.27		1.84	5.09	2.60	1.28		2.55	7.33	2¾
				do	27	2.05	0.93		2.25	6.02	2.40	0.85		2.13	6.40	2¾
				do	43	3.10	0.18		1.68	6.60	2.87	0.60		1.63	5.82	2¾
52	Off Gutenberg, N. J.	Aug. 26-27, 1922	do	Pole	7	1.50	0.90	N. 37° E.	1.49	4.57	3.30	−0.15	S. 35° W.	2.21	7.85	½
				Meter	10	1.90	0.90	N. 38° E.	1.76	5.37	2.90	−0.30	S. 36° W.	2.24	7.05	½
				do	24	2.40	0.80	N. 29° E.	1.95	5.97	2.80	−0.55	S. 38° W.	1.72	6.45	½
				do	38	2.80	0.70	N. 36° E.	1.24	6.37	2.80	−0.55	S. 33° W.	1.12	6.05	½
55	Midstream	Sept. 8-10, 1919	I. Winston	Pole	7	1.88	0.65	N. 16° E.	2.03	5.23	3.02	0.47	S. 13° W.	2.04	7.19	2
				Meter	10	2.20	0.83		2.09	5.64	2.93	0.48		2.07	6.78	2
				do	24	2.62	0.45		1.90	6.14	2.85	0.43		1.53	6.28	2
				do	39	2.79	0.55		1.50	6.24	2.92	0.10		0.95	6.18	2
57	do	July 21-23, 1922	H. C. Denson	Pole	7	1.42	0.92	N. 5° E.	1.16	5.19	2.60	1.20	S. 39° W.	1.94	7.23	1¾
				Meter	7	1.62	0.58		1.36	5.39	2.60	0.97		2.07	7.03	1¾
				do	18	2.00	0.30		1.37	5.49	2.88	0.67		1.83	6.93	1¾
				do	29	2.25	0.12		0.88	5.44	3.18	0.47		0.93	6.98	1¾
58	do	Sept. 2-4, 1919	I. Winston	Pole	7	0.63	1.42	N. 17° E.	2.07	4.52	2.48	0.98	S. 26° W.	3.11	7.90	2
				Meter	8	1.10	1.40		1.84	4.72	2.75	1.02		2.74	7.70	2¼
				do	21	1.23	1.73		1.52	4.88	2.72	1.42		2.40	7.54	2¼
				do	33	1.50	1.62		0.89	5.07	2.80	0.57		1.61	7.35	2¼
59	do	July 21-23, 1922	H. C. Denson	Pole	7	1.72	0.95	N. 30° E.	1.70	5.74	2.35	1.08	S. 34° W.	2.02	6.68	2
				Meter	9	1.82	0.88		1.81	6.04	2.15	1.08		2.05	6.38	2
				do	22	2.32	0.50		1.62	6.31	2.38	0.85		1.52	6.11	2
				do	35	2.70	0.38		1.34	6.35	2.72	0.38		1.11	6.07	2
60	do	Aug. 28-30, 1919	I. Winston	Pole	7	2.34	0.48	N. 30° E.	1.75	6.17	2.48	0.87	S. 26° W.	2.04	6.25	2
				Meter	7	2.23	0.42		1.67	6.13	2.47	0.85		1.97	6.29	2
				do	17	2.62	0.23		1.53	6.52	2.47	0.37		1.50	5.90	2
				do	27	2.60	−0.03		1.00	6.54	2.43	−0.02		1.07	5.88	2
62	Off Harlem River entrance.	July 20-21, 1922	H. C. Denson	Pole	7	0.30	1.85	N. 31° E.	1.74	4.77	1.90	2.13	S. 14° W.	2.09	7.65	¾
				Meter	10	0.90						1.80		2.24		¼
				do	24	1.50										¼
63	Off Englewood, N. J.	July 19-20, 1922	do	Pole	7	1.05	1.47	N. 18° E.	1.17	5.32	2.10	1.80	S. 33° W.	1.79	7.10	1½
				Meter	4	0.95	1.53		1.49	4.95	2.37	1.40		2.30	7.47	1½
				do	11	1.65	0.77		1.42	5.55	2.47	1.10		1.52	6.87	1½
				do	18	2.75	0.33		1.09	6.49	2.63	0.65		0.94	5.93	1½
64	Off Spuyten Duyvil, N. Y.	Aug. 25-27, 1919	I. Winston	Pole	7	1.47	1.08	N. 32° E.	1.64	5.16	2.68	0.88	S. 21° W.	2.17	7.26	2
				Meter	8	1.63	0.95		1.63	5.28	2.72	1.18		2.07	7.14	2
				do	20	1.92	0.67		1.48	5.47	2.82	0.95		1.38	6.95	2
				do	32	2.62	0.67		1.12	6.17	2.82	0.55		0.83	6.25	2
65	Off Riverdale, N. Y.	July 16-19, Aug. 27-28, 1922	H. C. Denson	Pole	7	1.32	1.92	N. 11° E.	1.59	5.49	2.20	1.43	S. 30° W.	2.06	6.93	3¾
				Meter	10	1.40	1.83		1.63	5.54	2.23	1.30		1.89	6.88	3¾
				do	26	2.02	1.48		1.78	6.56	1.83	1.18		1.50	5.86	3¾
				do	42	2.62	0.33		1.31	6.91	2.08	0.68		1.05	5.51	3¾
66	Midstream	July 15-21, Aug. 27-28, 1922	do	Pole	7	0.82	2.02	N. 15° E.	1.32	5.19	2.00	1.75	S. 13° W.	1.89	7.23	6¼
				Meter	8	0.73	2.00		1.56	5.15	1.95	1.82		2.07	7.27	6¼
				do	20	1.72	1.02		1.52	6.16	1.93	1.32		1.57	6.26	6¼
				do	32	2.67	0.27		1.12	6.66	2.38	0.48		1.05	5.76	6¼
67	Off Tenafly, N. J.	July 16-19, Aug. 27-28, 1922	do	Pole	7	1.30	1.03	N. 6° E.	1.09	4.67	3.00	1.18	S. 26° W.	1.85	7.75	3¾
				Meter	4	1.23	1.17		1.45	4.97	2.63	1.27		2.22	7.45	3¾
				do	11	1.67	0.97		1.49	5.25	2.79	1.07		1.96	7.17	3¾
				do	18	2.17	0.27		1.18	5.51	3.03	0.73		1.24	6.91	3¾

The data of Table 63 for the current near the surface show that the duration of ebb in the stretch of the Hudson here under consideration was about 2 hours greater than the duration of flood, the values being respectively 7.2 hours and 5.2 hours. For the subsurface current, Table 64 shows that almost without exception the duration of ebb decreases from the surface downward, so that toward the bottom the periods of floods and ebb become approximately equal. At station 7 this decrease of the duration of ebb and consequent increase in the duration of flood is at the rate of about 0.06 hour per foot; at stations 1 and 6 it averages 0.05 hour per foot; for the section off Guttenberg, comprising stations 49, 50, 51, and 52, it is 0.05, and for the section off Riverdale, stations 65, 66, and 67, it likewise averages 0.05 hour per foot.

At stations where the flood and ebb currents have, near the surface, the average durations of 5.2 and 7.2 hours, respectively, it follows that in consequence of the increase in duration of flood at the rate of about 0.05 hour per foot, the durations of flood and ebb will be equal at a depth of about 20 feet, and this the data for stations 1, 6, 7, 55, 59, 60, 65, and 66 show to be the case.

The characteristic features of the subsurface current in the Hudson discussed above are obviously brought about by the fresh water that flows into the Hudson from the large area that it drains. The effect of such nontidal flow on the tidal current has been discussed in the previous sections, more particularly in the paragraphs devoted to the subsurface current in the Narrows, to which reference is here made.

THE CURRENT IN THE HARLEM RIVER

For the Harlem River Figure 37 shows the locations of 14 stations at which observations on the current near the surface have been made. The data derived from these observations are given in Table 65 and may be taken to pertain to the current at a depth of about 7 feet. Here, as in the previous tables, the times of current are referred to the times of tide at Fort Hamilton, HW representing the time of high water and LW the time of low water. The velocities of the flood and ebb strengths given in this table have been reduced to mean values.

Harlem River has two entrances, one from the Hudson and the other from East River. Upstream and downstream, therefore, have no precise meanings here, and the determination of which stream is the flood current and which the ebb current must therefore be made with reference to time relations between current and tide, as discussed in Section XI.

From the tidal data of Table 38 the tide in the Harlem River is about 2 hours later than at Fort Hamilton. Applying this difference to the data of Table 65, we find that at the Hudson River entrance to the Harlem River the current that sets eastward attains its strength about two and one-half hours before high water; that is, on a rising tide. Hence, the current setting into the Harlem from the Hudson is the flood current. At Willis Avenue Bridge, likewise, it is the current from the Hudson that attains its strength on a rising tide, so that in the Harlem from Spuyten Duyvil to Willis Avenue Bridge the flood current is the one that sets toward East River, while the ebb current is the one that sets toward the Hudson.

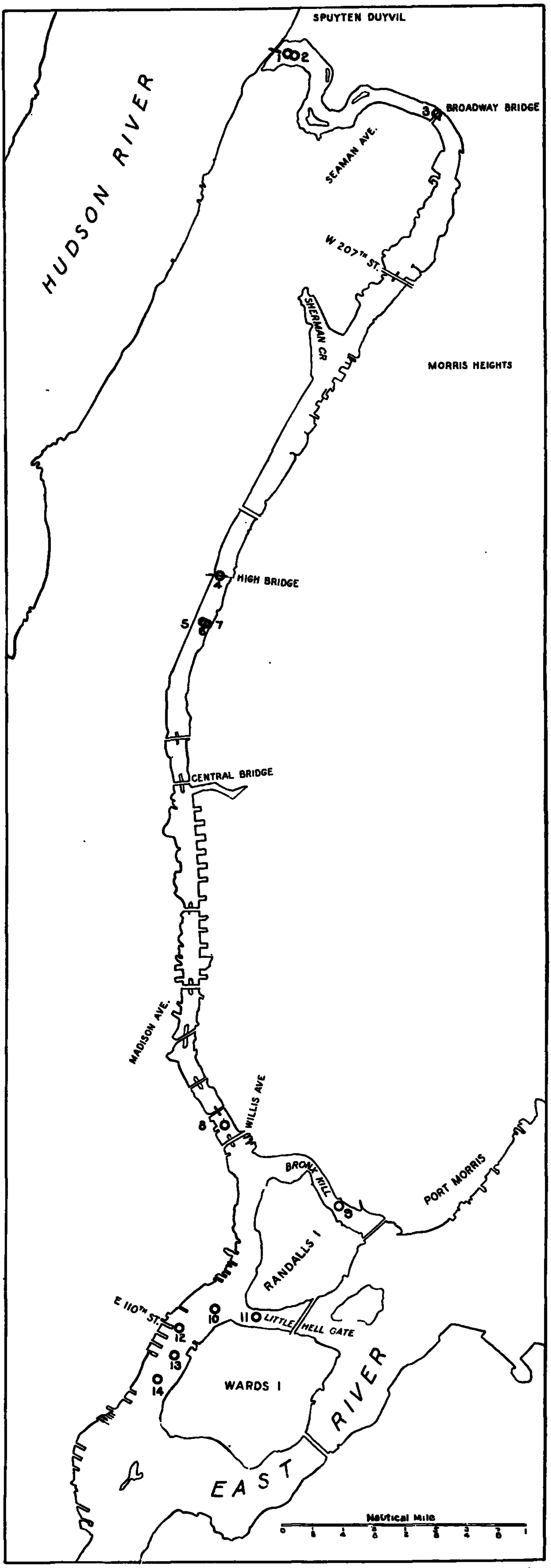


FIG. 37.—Current stations, Harlem River 3904-24. (Face p. 136.)

TABLE 65.—*Current data, Harlem River*

[Referred to times of HW and LW at Fort Hamilton, N. Y.]

Station No.	Location	Party of—	Date	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
					Time	Direction	Velocity			Time	Direction	Velocity		
				Hours after LW	*Hours before HW*	*True*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*True*	*Knots*	*Hours*	*Days*
1	Off Spuyten Duyvil	R. J. Auld	Nov., 1920	1.9	1.1	S. 75° E.	1.6	5.8	1.7	0.9	N. 75° W.	2.0	6.6	2
2	do	H. C. Denson	July, 1922	1.7	0.6	S. 70° E.	1.3	6.2	1.9	0.9	N. 70° W.	1.8	6.2	22
3	Broadway Bridge	R. J. Auld	Nov., 1920	1.9	0.6	S. 65° E.	2.1	5.8	1.7	1.6	N. 60° W.	2.4	6.6	2
4	Off High Bridge	do	do	1.8	1.0	S. 10° W.	3.0	5.8	1.6	1.7	N. 15° E.	2.8	6.6	2
5	do	H. C. Denson	Aug., 1922	1.5	0.9	S. 35° W.	1.2	6.4	1.9	1.3		1.3	6.0	3/4
6	do	do	do	1.7	1.0	S. 30° W.	1.4	6.2	1.9	1.5	N. 30° E.	1.5	6.2	1 1/2
7	do	do	do	1.6	0.7	S. 25° W.	1.5	6.3	1.9	1.2	N. 20° E.	1.3	6.1	3/4
8	Off Willis Avenue Bridge.	do	do	1.3	1.2	S. 35° E.	0.9	6.6	1.9	1.9	N. 40° W.	1.0	5.8	1 3/4
9	Bronx Kill	do	do	1.5	0.6	N. 35° W.	1.6	6.4	1.9	1.8	S. 50° W.	1.9	6.0	1
10	North of Wards Island.	T. A. Craven	Aug., 1856	1.9	0.4	N. 55° E.	0.5	6.3	2.2	2.0	S. 50° W.	0.6	6.1	1/2
11	Little Hell Gate	H. C. Denson	Aug., 1922	1.6	1.0	East	2.3	6.0	1.6	2.2	S. 85° W.	2.3	6.4	1
12	West of Wards Island.	C. H. Davis	June, 1845	1.5	1.6	N. 40° E.	0.9	5.7	1.2	1.0	S. 5° W.	1.0	6.7	1/2
13	do	T. A. Craven	Aug., 1856	2.3	−0.3	N. 45° E.	0.7	6.4	2.7	1.4	S. 20° W.	0.8	6.0	1/2
14	do	H. C. Denson	Aug., 1922	2.4	−0.5	N. 35° E.	0.6	5.9	2.3	1.8	S. 40° W.	0.8	6.5	2 1/2

TABLE 66.—*Current data for various depths, Harlem River*

[Referred to times of HW and LW at Fort Hamilton, N. Y.]

Station No.	Location	Date	Party of—	Observations with—	Depth	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
							Time	Direction	Velocity			Time	Direction	Velocity		
					Feet	*Hours after LW*	*Hours before HW*	*True*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*True*	*Knots*	*Hours*	*Days*
1	Off Spuyten Duyvil.	Nov. 14-16, 1920	R. J. Auld	Pole	7	1.92	1.08	S. 75° E.	1.57	5.83	1.72	0.88	N. 76° W.	2.00	6.59	2
				Meter	4	1.97	1.03		1.43	5.74	1.68	0.83		1.93	6.68	2
				do	10	2.05	1.20		1.31	5.65	1.67	0.57		1.84	6.77	2
				do	17	2.02	1.03		1.23	5.66	1.65	0.68		1.70	6.76	2
2	do	July 15-Aug. 7, 1922.	H. C. Denson.	Pole	7	1.72	0.58	S. 69° E.	1.28	6.23	1.92	0.88	N. 72° W.	1.76	6.19	22
				Meter	4	1.68	0.58		1.41	6.30	1.95	1.03		1.82	6.12	22
				do	11	1.79	0.63		1.25	6.17	1.93	0.75		1.85	6.25	22
				do	18	1.87	0.57		1.18	6.08	1.92	0.70		1.61	6.34	22
3	Broadway Bridge.	Nov. 18-20, 1920	R. J. Auld	Pole	7	1.90	0.60	S. 64° E.	2.14	5.85	1.72	1.62	N. 61° W.	2.38	6.57	2
				Meter	4	1.82	0.63		2.18	6.11	1.90	1.37		2.28	6.31	2
				do	10	1.83	0.45		2.07	6.07	1.87	1.50		2.23	6.35	2
				do	16	1.82	0.63		1.82	6.04	1.83	1.70		2.04	6.38	2
4	High Bridge	Nov. 22-24, 1920	do	Pole	7	1.79	1.05	S. 9° W.	3.05	5.79	1.55	1.70	N. 15° E.	2.85	6.63	2
				Meter	4	1.87	0.83		2.75	5.56	1.40	1.80		2.59	6.86	2
				do	10	1.85	0.87		2.62	5.55	1.37	1.95		2.79	6.87	2
				do	16	1.77	0.97		2.23	5.66	1.40	2.00		2.30	6.76	2
5	Off High Bridge.	Aug. 3, 1922	H. C. Denson.	Meter	3	1.40	0.30		1.25	6.53	1.90	0.90		1.25	5.89	¾
				do	7	1.50	0.90		1.25	6.43	1.90	1.30		1.34	5.99	¾
				do	10	1.60	0.40		1.16	6.33	1.90	1.10		1.16	6.09	¾
6	do	Aug. 2-4, 1922	do	Pole	1½	1.70	0.87	S. 30° W.	1.36	6.25	1.92	1.23	N. 29° E.	1.36	6.17	1½
				Meter	4	1.77	0.97		1.40	6.13	1.87	1.60		1.48	6.29	1½
				do	11	1.70	1.13		1.33	6.20	1.87	1.35		1.48	6.22	1½
				do	17	1.70	1.17		1.19	6.20	1.87	1.28		1.30	6.22	1½
7	do	Aug. 3-4, 1922	do	Pole	1½	1.60	0.40	S. 26° W.	1.12	6.38	1.95	1.40	N. 20° E.	1.12	6.04	¾
				Meter	4	1.70	0.90		1.53	6.23	1.90	0.90		1.23	6.19	¾
				do	10	1.60	0.60		1.43	6.33	1.90	1.60		1.43	6.09	¾
				do	16	1.60	1.00		1.12	6.33	1.90	1.10		1.12	6.09	¾
8	Off Willis Avenue Bridge.	Aug. 2-4, 1922	do	Pole	7	1.27	1.20	S. 33° E.	0.88	6.69	1.93	1.90	N. 41° W.	0.97	5.73	1¾
				Meter	4	1.33	0.67		0.80	6.70	2.00	2.10		1.07	5.72	1¾
				do	11	1.43	0.83		0.85	6.30	1.70	2.15		0.97	6.12	1¾
				do	17	1.43	1.00		0.73	6.03	1.43	1.95		0.87	6.39	1¾
9	Bronx Kill	Aug. 1-2, 1922	do	Pole	7	1.50	0.60	N. 35° W.	1.58	6.43	1.90	1.85	S. 49° E.	1.93	5.99	1
				Meter	4	1.40	0.80		1.83	6.63	2.00	2.00		1.78	5.79	1
				do	10	1.50	0.70		1.58	6.43	1.90	1.75		1.78	5.99	1
				do	15	1.65	1.05		0.93	6.08	1.70	1.70		1.68	6.34	1
11	Little Hell Gate	do	do	Pole	7	1.60	0.95	N. 89° E.	2.32	6.03	1.60	2.25	S. 87° W.	2.32	6.39	1
				Meter	4	1.55	0.75		2.12	6.28	1.80	1.85		2.72	6.14	1
				do	9	1.55	0.75		2.02	6.28	1.80	1.95		2.47	6.14	1
				do	15	1.45	0.60		1.73	6.48	1.90	2.35		1.93	5.94	1
14	West of Wards Island.	Aug. 4-7, 1922	do	Pole	7	2.43	−0.48	N. 35° E.	0.55	5.88	2.28	1.79	S. 39° W.	0.79	6.54	2½
				Meter	6	2.27	−0.87		0.65	5.99	2.23	2.32		0.89	6.43	2¾
				do	15	2.33	−0.52		0.57	5.68	1.98	2.02		1.03	6.74	2¾
				do	24	2.12	−0.38		0.43	5.79	1.88	1.50		1.05	6.63	2¾

In the stretch of the river lying westward of Wards Island the data for stations 13 and 14 show the strength of the northeasterly stream to come about one-half hour after high water at Fort Hamilton or about one and one-half hours before local high water. Hence in this stretch it is the current coming from the East River that is the flood current. In a tidal sense, therefore, the southern entrance to the Harlem River is at the southern tip of Randalls Island.

The tide in the Harlem being two hours later than at Fort Hamilton, the data of Table 65 show that the slack of the current in the Harlem comes a little before local high or low water and the strength of the current about midway between high and low water. As in Arthur Kill and in Kill Van Kull, the tidal movement of the Harlem is not of the progressive-wave type, but is conditioned by the fact that it is a short strait connecting two larger tidal bodies of water.

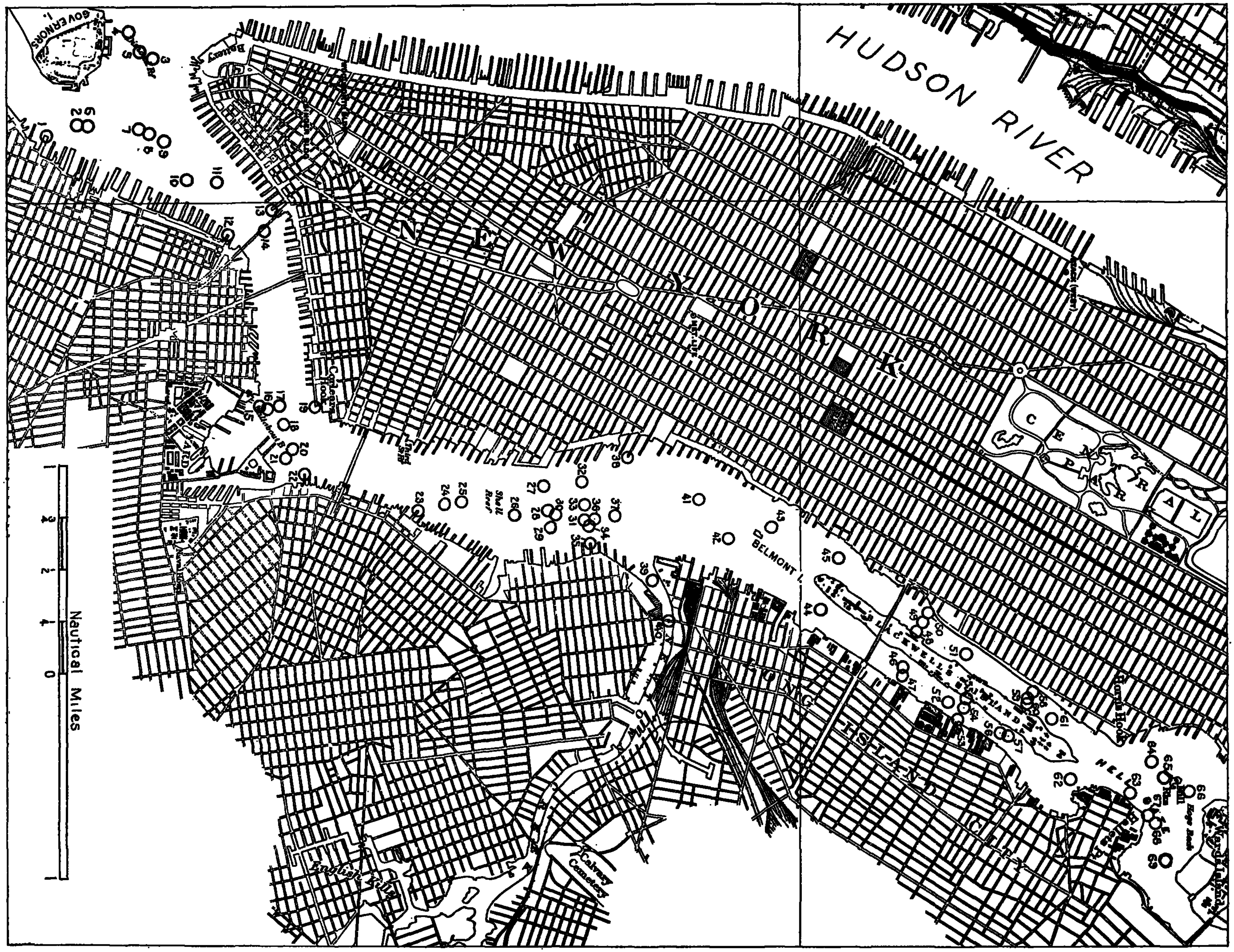
From Spuyten Duyvil to Willis Avenue Bridge the slack before flood becomes earlier by 0.4 hour, while the slack before ebb in this stretch occurs simultaneously. In consequence of this the duration of flood increases by 0.4 hour from Spuyten Duyvil to Willis Avenue Bridge. At the Hudson River entrance the durations of flood and ebb are equal, but near the East River entrance the flood has the greater duration.

The ebb current in the Harlem has the greater velocity at strength, averaging 1.8 knots against 1.6 knots for the flood. In constricted passages between bridge piers the current attains its greatest velocity; under High Bridge the current has a velocity of about 3 knots.

At all stations listed in Table 65, with the exception of stations 10, 12, and 13, subsurface current observations were made with current meters at depths representing approximately two-tenths, five-tenths, and eight-tenths of the depth at each station. The data derived from these observations, with the flood and ebb strengths reduced to mean values, are given in Table 66. For comparison the results of the observations made with the current pole, which pertain to the current at a depth of 7 feet, are also included. It is to be noted, however, that at stations 6 and 7 the current pole used was submerged to a depth of 3 feet, so that the data derived refer to a depth of 1½ feet.

At station 2, off Spuyten Duyvil, the current observations were carried on uninterruptedly for a period of 22 days; the results for this station may therefore be considered as well determined. The slack before flood appears to become somewhat later from surface to bottom, while the slack before ebb occurs about the same time at all depths. This feature causes the duration of flood to decrease with increasing depth. At the 4-foot depth the duration of flood is 6.3 hours, while at the 18-foot depth it is 6.1 hours. In this respect, therefore, the current in the Harlem reverses the conditions found in the Hudson, where it was the duration of ebb that decreased with increasing depth.

The vertical velocity distribution in the Ha lem likewise differs from that in the Hudson. In the latter river it was the ebb strength that decreased rapidly in velocity with increasing depth, while the flood strength decreased more slowly. In the Harlem, from the data of station 2, it is the flood strength that decreases at a relatively rapid



3904—24. (Face p. 141.)

FIG. 38.—Current stations, lower East River

rate with increasing depth, while the ebb strength increases from surface to mid-depth and then decreases toward the bottom. The decrease of flood strength at station 2 is at the rate of very nearly 0.02 knot per foot, while the ebb strength at first shows an increase in velocity from the two-tenths depth to mid-depth and then a decrease toward the bottom.

This difference in the behavior of the current in the Hudson and Harlem Rivers is brought about by the fact that any considerable amount of fresh or nontidal water can come into the Harlem only from the Hudson. And it is on the flood current that the Hudson is discharging into the Harlem. That is, in the Harlem the nontidal water is flowing in the same direction as the tidal water on the flood, while in the Hudson this takes place on the ebb. As regards features dependent on fresh-water flow, the Harlem should exhibit these on the flood in the same way that the Hudson does on the ebb. This we find to be the case, as evidenced by the increase of duration of ebb with increasing depth and by the vertical velocity distribution of the flood and ebb strengths.

XV. THE CURRENT IN EAST RIVER

In the discussion of the current in East River it will be convenient to divide the river into two parts—lower East River, stretching from Governors Island to Hell Gate, and upper East River, stretching from Hell Gate to Willets Point. Lower East River, it is to be recalled, is a relatively narrow and deep waterway, while upper East River is wider and shallower.

On Figure 38 are shown the locations of 69 stations at which current observations have been made in lower East River between the years 1845 and 1922. The results derived from these observations pertaining to the current near the surface are given in Table 67. For the more recent years these results are derived from observations made with a 15-foot pole submerged a distance of 14 feet, so that but 1 foot floated out of water. In general, the data of Table 67 may be taken to refer to the current at a depth of about 7 feet.

The times of slack and strength of the current in Table 67 are given in hours and tenths with reference to time of tide at Fort Hamilton, N. Y., HW standing for the time of high water and LW for the time of low water. For the flood and ebb strengths the directions are given to the nearest 5° and the velocities in knots and tenths. These velocities have been corrected to mean values by a factor derived from the range of tide. This correction factor for the current in East River is not the ratio of the mean range of tide divided by the range for the period of observation, as in the case of the Hudson River, but the square root of this ratio. This difference is due to the fact that the tidal movement in the East River is primarily hydraulic in character, as shown in Section XI and as will appear farther in this chapter; and in hydraulic motion the velocity varies as the square root of the head or the difference in the height of water at the two ends of the channel.

TABLE 67.—*Current data, Lower East River*

[Referred to times of HW and LW at Fort Hamilton, N.Y.]

Station No.	Location	Party of—	Date	Slack	Flood strength: Time	Flood strength: Direction	Flood strength: Velocity	Flood duration	Slack	Ebb strength: Time	Ebb strength: Direction	Ebb strength: Velocity	Ebb duration	Length of observations
				Hours after LW	*Hours before HW*	*True*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*True*	*Knots*	*Hours*	*Days*
1	Off Brooklyn	H. C. Denson	Sept., 1922	1.4	1.6	N. 40° E.	0.6	7.1	2.5	0.9	S. 35° W.	0.4	5.3	½
2	Off Governors Island.	M. Woodhull	July, 1854	1.7	1.3	N. 45° E.	1.3	6.9	2.6	1.9	S. 45° W.	1.4	5.5	½
3	do	H. Mitchell	Aug., 1872	1.6	0.4	N. 75° E.	1.5	6.9	2.5	0.8	S. 40° W.	1.8	5.5	½
4	do	R. J. Auld	Oct., 1920	1.7	1.2	N. 80° E.	1.2	6.2	1.9	0.5	S. 75° W.	2.4	6.2	1
5	do	H. C. Denson	Aug., 1922	2.1	0.8	S. 85° E.	1.2	5.9	2.0	0.8	West	1.7	6.5	3½
6	do	H. Marindin	Aug., 1872	1.4	0.9	N. 25° E.	1.6	6.8	2.2	2.5	South	1.2	5.6	½
7	Off Brooklyn	do	do	1.8	0.8	N. 60° E.	1.3	6.5	2.3	1.9	S. 25° W.	1.8	5.9	1
8	do	T. A. Craven	July, 1855	1.5	0.8	N. 60° E.	2.5	7.0	2.5	1.1	S. 50° W.	2.6	5.4	½
9	do	H. Marindin	Aug., 1872	1.4	1.9	N. 70° E.	1.2	7.0	2.4	1.2	S. 25° W.	1.7	5.4	½
10	do	H. Mitchell	July, 1872	1.4	0.9	N. 50° E.	1.6	6.5	1.9	1.5	S. 30° W.	1.5	5.9	1
11	Midchannel	M. Woodhull	July, 1854	1.9	1.2	N. 20° E.	2.2	6.4	2.3	1.2	S. 35° W.	3.4	6.0	½
11	do	H. C. Denson	Aug., 1922	2.0	0.9	N. 45° E.	2.3	6.1	2.1	1.0	S. 40° W.	3.2	6.3	13
12	Off Brooklyn	do	Sept., 1922	0.8	0.1	N. 40° E.	1.8	7.5	2.3	1.6	S. 55° W.	0.3	4.9	½
13	Off New York	do	do	1.9	1.7	N. 45° E.	2.0	6.4	2.3	1.3	S. 40° W.	1.5	6.0	½
14	Brooklyn Bridge	R. J. Auld	Sept., 1920	1.9	0.3	N. 50° E.	3.2	6.7	2.6	0.6	S. 65° W.	3.8	5.7	¾
15	Off navy yard	H. C. Denson	Sept., 1922	1.7	1.1	N. 75° E.	0.8	6.2	1.9				6.2	½
16	do	M. Woodhull	July, 1854	2.1	1.2	N. 80° E.	3.2	5.9	2.0	0.8	West	3.5	6.5	1
17	do	T. A. Craven	July, 1855	2.2	0.9	S. 85° E.	5.3	5.7	1.9	1.1	S. 80° W.	4.2	6.7	½
18	do	R. J. Auld	Sept., 1920	2.2	0.8	N. 55° E.	3.9	6.0	2.2	1.2	S. 60° W.	3.3	6.4	1
19	Off Corlears Hook	H. C. Denson	Sept., 1922	2.5	0.9	N. 75° E.	0.4	5.4	1.9	1.3	S. 25° W.	2.2	7.0	½
20	Midchannel	T. A. Craven	July, 1855	2.1	0.9	N. 65° E.	4.5	6.1	2.2	1.3	S. 45° W.	3.9	6.3	1
21	Off Brooklyn	M. Woodhull	July, 1854	1.7	0.2	N. 35° E.	2.9	6.8	2.5	1.6	S. 40° W.	2.9	5.6	1
22	do	H. C. Denson	Sept., 1922	1.7	0.4	N. 25° E.	1.6	6.2	1.9				6.2	½
23	do	do	do	3.2	−0.3	N. 15° W.	0.1	5.6	2.8	1.7	S. 45° W.	0.6	6.8	½
24	Midchannel	T. A. Craven	July, 1855	2.3	0.5	N. 35° E.	4.8	5.7	2.0	0.8	S. 40° W.	3.9	6.7	½
25	do	M. Woodhull	July, 1854	2.2	0.1	N. 25° E.	2.1	6.4	2.6	0.9	S. 20° W.	3.2	6.0	1
26	do	H. Mitchell	July, 1859	2.1	0.1	N. 25° E.	2.5	6.2	2.3	1.2	S. 5° W.	1.3	6.2	1
27	Off New York	H. C. Denson	July, 1922	1.8	1.2	N. 10° W.	1.4	6.0	1.8	1.3	S. 10° E.	2.2	6.4	4¾
28	Midchannel	do	do	1.8	0.8	N. 5° W.	1.5	6.1	1.9	1.5	South	2.0	6.3	4¾
29	Off Brooklyn	do	do	1.7	0.7	North	1.9	6.1	1.8	1.8	S. 10° W.	1.8	6.3	4¾
30	Midchannel	H. Mitchell	July, 1858	2.1	1.1		2.5	6.3	2.4	1.6	S. 20° E.	1.8	6.1	¾
31	do	H. L. Marindin	Oct., 1886	2.2	0.9	N. 15° W.	2.1	6.2	2.4	1.3	S. 10° E.	2.3	6.2	3¼
32	Off New York	do	Aug., 1885	1.9				6.0	1.9	1.1		2.5	6.4	¼
33	Midchannel	do	do	2.1	0.9		2.0	6.1	2.2	1.6		2.3	6.3	1½
34	Off Brooklyn	do	do	1.9				6.0	1.9	1.4		2.1	6.4	¼
35	do	H. C. Denson	Sept., 1922	1.7	1.2	N. 10° W.	1.1	7.0	2.7	0.2	S. 10° E.	0.5	5.4	½
36	do	R. J. Auld	Aug., 1920	1.9	1.0	North	2.1	6.2	2.1	1.4	S. 15° E.	1.8	6.2	¾
37	Midchannel	M. Woodhull	July, 1854	2.3	0.6	N. 5° W.	2.3	6.6	2.9	1.9	S. 15° W.	1.6	5.8	1
38	Off New York	H. C. Denson	Sept., 1922	2.1	1.5	North	1.4	5.7	1.8	1.6	South	1.7	6.7	½
39	Newton Creek	R. J. Auld	Oct., 1920	2.5	0.0	N. 60° E.	0.3	5.6	2.1	1.4	S. 50° W.	0.3	6.8	1
40	do	H. C. Denson	Sept., 1922	2.0	1.3		0.4	6.3	2.3	0.8		0.3	6.1	½
41	Midchannel	do	do	2.3	1.0	N. 25° E.	1.6	5.8	2.1	0.8	S. 35° W.	2.1	6.6	3¼
42	do	T. A. Craven	July, 1855	1.9	1.2	N. 15° E.	2.3	5.4	1.3	0.4	S. 35° W.	1.5	7.0	½
43	do	do	do	2.6	0.8	N. 20° E.	2.5	6.0	2.6	0.8	S. 25° W.	4.1	6.4	½
44	Off Blackwells Island.	H. Mitchell	July, 1858		0.8	N. 45° E.	1.6			0.7	S. 40° W.	2.5		½
45	do	do	do	2.0	0.7	N. 25° E.	2.7	6.1	2.1	1.6	S. 30° W.	3.2	6.3	2¾
46	do	H. L. Marindin	July, 1874		1.1	N. 35° E.	2.7			0.6	S. 40° W.	2.7		¼
47	do	R. J. Auld	Sept., 1920	1.6	0.5	N. 30° E.	2.6	6.6	2.2	1.4	S. 30° W.	1.9	5.8	1
48	do	H. L. Marindin	July, 1874		0.6	N. 40° E.	3.7			0.7	S. 40° W.	2.3		¼
49	do	do	do		0.3	N. 40° E.	4.1			0.6	S. 40° W.	4.9		¼
50	do	do	do		0.6	N. 35° E.	4.0			0.6	S. 25° W.	3.1		¼
51	do	H. C. Denson	Aug., 1922	2.1	1.1	N. 35° E.	3.6	5.9	2.0	1.2	S. 45° W.	4.7	6.5	2¾
52	do	do	do	1.8	0.8	N. 25° E.	3.5	6.3	2.1	1.6	S. 30° W.	3.3	6.1	2¾
53	do	H. L. Marindin	July, 1874		1.3	N. 20° E.	2.9			1.4	S. 40° W.	1.6		¼
54	do	do	do		1.3	N. 30° E.	4.0			1.4	S. 45° W.	3.9		¼
55	do	do	do		0.8	N. 35° E.	3.5			1.2	S. 35° W.	3.5		¼
56	do	H. Mitchell	May, 1857	2.0	1.0	N. 35° E.	4.3	6.1	2.1	1.5	S. 35° W.	4.0	6.3	8¾
57	do	C. H. Davis	June, 1845	2.3	0.6	N. 30° E.	3.0	6.3	2.6				6.1	½
58	do	H. L. Marindin	July, 1874		0.5	N. 35° E.	3.9			0.8		2.8		¼
59	do	R. J. Auld	Aug., 1920	1.9	1.2		4.8	6.3	2.2	1.6		5.0	6.1	1
60	do	C. H. Davis	June, 1845	1.7	1.3	N. 35° E.	4.2	6.3	2.0	1.3	S. 40° W.	4.8	6.1	½
61	do	H. Mitchell	May, 1857	2.4	0.9	N. 40° E.	4.7	5.8	2.2	1.0	S. 40° W.	4.9	6.6	7½
62	do	R. J. Auld	Sept., 1920	2.5	0.8	N. 10° W.	3.4	5.9	2.4	1.8	S. 15° E.	1.6	6.5	1
63	Hell Gate	C. H. Davis	June, 1845	2.0	1.3	N. 20° E.	4.2	6.2	2.2	2.0	S. 60° W.	3.0	6.2	½
64	do	do	do	1.3	2.1	N. 25° W.	1.2	6.1	1.4	1.4	S. 20° E.	2.6	6.3	½
65	do	do	do	1.9	1.4	N. 35° E.	2.4	5.5	1.4	2.1	S. 70° W.	4.2	6.9	½
66	do	do	do	1.4	2.2	S. 85° E.	2.3	5.8	1.2	1.9	N. 55° W.	2.7	6.6	½
67	do	R. J. Auld	Oct., 1920	2.5	0.0	N. 60° E.	0.3	5.6	2.1	1.4	S. 50° W.	0.3	6.8	1
68	do	H. C. Denson	Aug., 1922	1.9	1.2		3.9	6.0	1.9	1.6		3.6	6.4	1½
69	do	C. H. Davis	June, 1845	1.3	1.5	S. 85° E.	5.7	6.0	1.3	1.7	N. 80° W.	4.6	6.4	½

In entering East River from Upper Bay it is natural to regard the current setting from Upper Bay into East River as the flood current; but East River may also be entered from Long Island Sound, from which body of water it is just as natural to regard the westerly setting current as the flood current. In East River, manifestly, upstream and downstream can not be used for specifying the flood and ebb currents, and recourse must be had to the time relations between current and tide. From the tidal data of Table 39 the tide in lower East River, from Governors Island to Hell Gate, is seen to be about two hours later than at Fort Hamilton. Applying this difference to the data of Table 67, the strength of the current setting into East River from Upper Bay is found to occur about three hours before local high water; that is, on a rising tide. Hence, the flood current in lower East River, and as we shall find later the flood current throughout the whole of East River, is the one setting from Upper Bay toward Long Island Sound, while the ebb current is the one that sets from Long Island Sound toward Upper Bay.

From Upper Bay there are two entrances to East River, one through Buttermilk Channel, south of Governors Island, and the other between Governors Island and the Battery. In both these entrances the current turns about the same time. Indeed, throughout the entire stretch of lower East River the current is very nearly simultaneous. The observations made by the party of H. C. Denson in 1922 show that the slack before flood throughout the stretch from the Battery to Hell Gate comes two hours after low water at Fort Hamilton, and the slack before ebb two hours after high water.

It is to be noted that since the current in East River is dependent on the relative heights of the water in Upper Bay and Long Island Sound short series of observations will not give as concordant results in this waterway as in a tidal river that has but one entrance for the tide. This may be taken to explain some of the comparatively wide divergences in the results for the different stations listed in Table 67.

Although lower East River is a relatively narrow stream with a very nearly rectangular channel, the current is seen to turn earlier near shore and latest in mid-channel. The section comprising stations 32, 33, and 34 serves to illustrate this.

Since the channel of East River changes direction frequently, the flood and ebb directions are generally not directly opposite each other, the direction at any point being influenced by the direction of the channel below and above that point. This is well illustrated by station 14, for which Table 67 gives the flood direction as N. 50° E. and the ebb direction as S. 65° W. The direction of the channel below this station is N. 45° E., and the flood current approximated this direction closely. Above the station the channel runs S. 80° W., and on the ebb the direction of the current is 20° farther westward than on the flood, thus indicating the influence of the direction of the channel above the station.

The frequent changes in direction of the channel of lower East River have another consequence. In a straight stretch of the river the swiftest thread of the current lies in mid-channel; but when the direction of the channel changes the swiftest thread of the current will be found not in mid-channel but to one side. Thus, for stations 27, 28, and 29 it is obvious from the locations of these stations on Figure 38 that on the flood station 29 will be in the path of the main stream of the flood current, although it is not in mid-channel; and on the flood Table 67 shows a greater velocity for station 29 than either for stations 27 or 28, notwithstanding the fact that the latter is a midstream station. On the ebb the turn of the channel southward in the vicinity of Newton Creek makes the momentum of the moving stream continue its more westerly direction, and station 27 is now in the path of the main ebb stream, and the ebb velocities of Table 67 show that the ebb strength at station 27 is now greater than either at stations 28 or 29.

The swiftest current in lower East River is found in the constricted passages of Blackwells Island and in Hell Gate, where the mean velocity of the current is 4 knots or more. In this connection it is to be noted that the more recent observations, in which improved methods and instruments were used, give lesser velocities than the observations made in 1855. For this reason the velocity of 5.3 knots on the flood listed in Table 67 for station 17 is undoubtedly too great, as appears to be the case also for the observations made in that same year at stations 8, 20, and 24.

Through lower East River the ebb current has the greater velocity. This general rule is subject to modification by the location of the station, whether in the direct path of the ebb and flood current or not. This was illustrated in the previous paragraph by the currents at stations 27, 28, and 29 and is also illustrated by station 62, which shows a flood velocity of 3.4 knots and an ebb velocity of 1.6 knots, whereas from the general rule above the ebb velocity should be the greater. The location of this station is seen to be in the direct path of the flood current through the eastern channel of Blackwells Island but to one side of the main stream of the ebb current which sets from Hell Gate directly into the west channel of Blackwells Island.

The two channels of Blackwells Island show considerable differences. The data for stations 51 and 52 may be considered as fairly well determined, being based on recent observations extending over a period of very nearly three days. The velocity at station 51 in the western channel is somewhat greater on the flood and considerably greater on the ebb than at station 52 in the eastern channel. The observations at stations 44 and 45 were made in 1858, and these show the same differences between the two channels, the velocity in the western channel being the greater, and the observations in 1874 at stations 46 and 49 likewise show the greater velocity for the western channel. A glance at a hydrographic chart of this region shows that the western channel of Blackwells Island is considerably deeper than the eastern channel and therefore offers a freer passage for the water. The direction of the channels likewise tends to bring the main flood and ebb streams through the western channel, and this is particularly the case on the ebb.

Table 39, giving the tidal data for lower East River, shows that the time of tide from Governors Island to Hell Gate changes in a more or less uniform manner by about 3 hours. The current through this stretch, however, is practically simultaneous. It follows, therefore, that with regard to local tide, the current becomes earlier from Governors Island to Hell Gate. Thus, from Tables 31, 39, and 67 the slack of the current at station 5 in the entrance to lower East River is found to come 1½ hours after local high or low water, while in Hell Gate, at station 68, the slack of the current comes about 1½ hours before local high or low water.

TABLE 68.—*Current data for various depths, Lower East River*

[Referred to times of HW and LW at Fort Hamilton, N. Y.]

Station No.	Location	Date	Party of—	Observations with—	Depth	Slack	Flood strength: Time	Flood strength: Direction	Flood strength: Velocity	Flood duration	Slack	Ebb strength: Time	Ebb strength: Direction	Ebb strength: Velocity	Ebb duration	Length of observations
					Feet	*Hours after LW*	*Hours before HW*	*True*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*True*	*Knots*	*Hours*	*Days*
1	Off Brooklyn	Sept. 3, 1922	H. C. Denson	Pole	7	1.40	1.60	N. 41° E.	0.55	7.13	2.50	0.90	S. 35° W.	0.40	5.29	½
				Meter	9	2.00	1.60	N. 43° E.	1.25	6.73	2.70	0.70	S. 41° W.	0.75	5.69	½
				do	22	2.00	2.20	N. 38° E.	1.25	6.63	2.60	1.50	S. 41° W.	0.40	5.79	½
				do	35	2.20	2.20	N. 28° E.	1.05	6.43	2.60	2.30	S. 37° W.	0.60	5.99	½
4	Off Governors Island.	Sept. 29–30, 1920	R. J. Auld	Pole	7	1.70	1.20	N. 82° E.	1.18	6.23	1.90	0.50	S. 74° W.	2.43	6.19	1
				Meter	12	1.98	0.62		1.15	5.58	1.53	0.62		2.05	6.84	1
				do	30	2.00	2.25		0.68	5.48	1.45	0.50		2.08	6.94	1
				do	48	2.02	2.28		0.59	5.43	1.42	0.58		2.09	6.99	1
5	do	July 23–24, Aug. 13–15, 1922.	H. C. Denson	Pole	7	2.08	0.83	S. 86° E.	1.20	5.92	1.97	0.83	S. 89° W.	1.73	6.50	3½
				Meter	10	2.02	0.43		1.20	5.91	1.90	0.90		1.72	6.51	3½
				do	25	2.03	0.93		1.25	5.92	1.92	0.98		1.58	6.50	3½
				do	40	2.00	1.37		1.06	6.00	1.97	0.90		1.55	6.42	3½
11	Mid-channel	July 23–Aug. 16, 1922.	do	Pole	7	2.01	0.86	N. 46° E.	2.28	6.13	2.11	1.04	S. 42° W.	3.22	6.29	13
				Meter	10	1.97	0.73		2.30	6.16	2.10	1.20		3.25	6.26	12½
				do	25	1.97	0.71		2.09	6.15	2.09	1.21		3.03	6.27	12½
				do	40	1.99	0.66		1.81	6.13	2.09	1.08		2.77	6.29	12½
12	Off Brooklyn	Sept. 2, 1922	do	Pole	7	0.80	0.10	N. 42° E.	1.77	7.53	2.30	1.60	S. 55° W.	0.27	4.89	½
				Meter	10	1.50	1.70	N. 39° E.	2.18	6.93	2.40	1.90	S. 59° W.	0.48	5.49	½
				do	24	1.50	0.40	N. 41° E.	1.92	6.93	2.40	1.70	S. 36° W.	0.37	5.49	½
				do	38	1.50	0.40	N. 38° E.	1.97	7.03	2.50	1.70	S. 41° W.	0.37	5.39	½
13	Off New York	do	do	Pole	7	1.90	1.70	N. 43° E.	2.03	6.43	2.30	1.30	S. 42° W.	1.53	5.99	½
				Meter	9	2.10	1.50	N. 36° E.	2.14	5.73	1.80	2.00	S. 42° W.	1.94	6.69	½
				do	23	2.00	1.40	N. 37° E.	1.13	5.83	1.80	1.90	S. 42° W.	1.73	6.59	½
				do	36	2.00	1.00	N. 41° E.	1.08	5.73	1.70	1.70	S. 21° W.	1.58	6.69	½
14	Brooklyn Bridge	Sept. 24–25, 1920	R. J. Auld	Pole	7	1.95	0.30	N. 50° E.	3.20	6.68	2.60	0.55	S. 64° W.	3.75	5.74	¾
				Meter	13	1.98	0.92		3.19	6.53	2.48	0.82		3.64	5.89	¾
				do	33	2.00	1.25		2.77	6.48	2.45	0.85		3.27	5.94	¾
				do	53	2.02	0.79		2.55	6.23	2.22	0.23		2.80	6.19	¾
15	Off navy yard	Sept. 1, 1922	H. C. Denson	Pole	7	1.70	1.10	N. 75° E.	0.83	6.23	1.90				6.19	½
				Meter	10	1.90	0.70	N. 74° E.	0.75	6.33	2.20	1.80	S. 78° W.	1.75	6.09	½
				do	24	2.00	1.00	N. 60° E.	1.00	6.23	2.20	2.10	S. 79° W.	1.45	6.19	½
				do	38	2.00	1.00	N. 72° E.	1.05	6.23	2.20	1.90	S. 74° W.	1.50	6.19	½
18	do	Sept. 21–22, 1920	R. J. Auld	Pole	7	2.15	0.80	N. 55° E.	3.87	6.13	2.25	1.20	S. 62° W.	3.32	6.29	1
				Meter	8	2.18	0.72		3.73	6.18	2.33	1.17		2.98	6.24	1
				do	25	2.15	0.60		3.44	6.18	2.30	1.35		2.84	6.24	1
				do	40	2.12	0.23		2.98	6.28	2.37	1.33		2.68	6.14	1
19	Off Corlears Hook.	Sept. 1, 1922	H. C. Denson	do	7	2.50	0.90	N. 77° E.	0.40	5.43	1.90	1.35	S. 26° W.	2.23	6.99	½
				do	17	2.50	1.60	N. 50° E.	0.35	5.43	1.90	1.20	S. 25° W.	2.25	6.99	½
				do	27	2.50	1.80		0.35	5.43	1.90	1.30	S. 25° W.	2.25	6.99	½
22	Off Brooklyn	do	do	Pole	7	1.70	0.40	N. 24° E.	1.61	6.23	1.90				6.19	½
				Meter	10	0.90	0.90	N. 31° E.	1.14	7.83	2.70				4.59	½
				do	25	1.40	1.10	N. 45° E.	1.35	7.33	2.70				5.09	½
				do	40	1.50	1.10	N. 33° E.	1.30	7.23	2.70				5.19	½
23	do	Aug. 31–Sept. 1, 1922.	do	Pole	7	3.20	0.95		0.10	5.63	2.80	1.70	S. 44° W.	0.62	6.79	½
				Meter	7	3.00	0.95	N. 17° W.	0.35	5.23	2.20	1.70	S. 39° W.	1.03	7.19	½
				do	18	3.05	0.85	N. 24° W.	0.34	5.18	2.20	1.30	S. 26° W.	1.19	7.24	½
				do	29	3.00	1.10	N. 22° W.	0.35	5.33	2.30	0.80	S. 23° W.	1.08	7.09	½
27	Off New York	July 25–30, 1922	do	Pole	7	1.80	0.80	N. 12° W.	1.45	6.00	1.77	1.27	S. 12° E.	2.22	6.42	4¾
				Meter	6	1.88	0.53		1.59	5.89	1.74	1.07		2.54	6.53	4¾
				do	16	1.88	0.49		1.49	5.93	1.78	1.02		2.44	6.49	4¾
				do	26	1.87	0.52		1.36	6.02	1.86	1.17		2.12	6.40	4¾
28	Mid-channel	do	do	Pole	7	1.78	0.69	N. 6° W.	1.48	6.15	1.90	1.52	S. 1° W.	1.97	6.27	4¾
				Meter	10	1.73	0.43		1.52	6.34	2.04	1.44		1.93	6.08	4¾
				do	25	1.87	0.32		1.35	6.22	2.06	1.13		1.79	6.20	4¾
				do	40	1.87	0.18		1.25	6.25	2.09	1.08		1.54	6.17	4¾
29	Off Brooklyn	do	do	Pole	7	1.71	0.66	N. 2° E.	1.87	6.16	1.84	1.76	S. 9° W.	1.75	6.26	4¾
				Meter	11	1.70	0.23		1.96	6.34	2.01	1.69		1.75	6.08	4¾
				do	27	1.85	0.00		1.90	6.29	2.11	1.44		1.70	6.13	4¾
				do	44	1.96	−0.21		1.69	6.27	2.20	1.26		1.58	6.15	4¾
35	do	Aug. 31–Sept. 1, 1922.	do	do	8	1.70	1.25	N. 11° W.	1.10	7.03	2.70	0.20	S. 9° E.	0.54	5.39	½
				do	19	1.70	0.30	N. 9° W.	1.35	7.03	2.70	0.20	S. 9° E.	0.75	5.39	½
				do	30	1.70	0.30	N. 25° W.	1.45	6.83	2.50	0.60	S. 1° W.	0.80	5.59	½
36	do	Aug. 27–28, 1920	R. J. Auld	Pole	7	1.90	1.05	N. 2° E.	2.12	6.23	2.10	1.40	S. 14° E.	1.82	6.19	¾
				Meter	7	1.80	0.60		1.82	6.23	2.00	2.10		1.62	6.19	¾
				do	18	1.83	0.68		2.07	6.28	2.08	2.03		1.72	6.14	¾
				do	28	1.87	1.07		2.12	6.38	2.22	1.67		1.82	6.04	¾
38	Off New York	Aug. 31–Sept. 1, 1922.	H. C. Denson	Pole	7	2.10			----	5.73	1.80	1.60	S. 2° W.	1.73	6.69	½
				Meter	8	2.00	1.50	N. 2° W.	1.43	5.83	1.80	1.60	S. 5° W.	1.88	6.59	½
				do	21	2.00	1.60	N. 2° W.	1.17	5.83	1.80	1.60	S. 11° W.	1.87	6.59	½
				do	33	2.00	1.90	N. 2° W.	1.02	5.83	1.80	1.50	S. 11° W.	1.77	6.59	½

TABLE 68.—*Current data for various depths, Lower East River*—Continued

Station No.	Location	Date	Party of—	Observations with—	Depth	Slack	Flood strength: Time	Flood strength: Direction	Flood strength: Velocity	Flood duration	Slack	Ebb strength: Time	Ebb strength: Direction	Ebb strength: Velocity	Ebb duration	Length of observations
					Feet	*Hours after LW*	*Hours before HW*	*True*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*True*	*Knots*	*Hours*	*Days*
39	Newton Creek	Oct. 14-15, 1920	R. J. Auld	Pole	7	2.00	−0.05	N. 58° E.	0.34	6.16	2.13	1.40	S. 49° W.	0.29	6.26	1
				Meter	4	1.98	0.02		0.35	6.38	2.33	0.97		0.20	6.04	1
				do	9	2.05	0.25		0.25	6.13	2.15	0.55		0.20	6.29	1
				do	15	2.22	0.03		0.30	5.93	2.12	0.88		0.25	6.49	1
40	do	Oct. 2, 1922	H. C. Denson	do	5	2.00	1.30		0.41	6.33	2.30	0.80		0.31	6.09	½
				do	13	2.10	1.50		0.31	6.03	2.10	0.30		0.21	6.39	½
				do	21	1.90	1.80		0.31	6.13	2.00	0.00		0.31	6.29	½
41	Midchannel	Aug. 31-Sept. 3, 1922.	do	Pole	7	2.25	1.02	N. 27° E.	1.55	5.85	2.07	0.75	S. 34° W.	2.11	6.57	3¼
				Meter	8	2.38	1.15	N. 29° E.	1.76	5.72	2.07	0.80	S. 33° W.	2.32	6.70	3¼
				do	21	2.40	1.03	N. 33° E.	1.62	5.76	2.13	0.72	S. 32° W.	2.37	6.66	3¼
				do	34	2.40	0.67	N. 37° E.	1.47	5.80	2.17	0.75	S. 33° W.	2.22	6.62	3¼
47	Off Blackwells Island.	Sept. 28-29, 1920	R. J. Auld	Pole	7	1.60	0.45	N. 32° E.	2.62	6.60	2.17	1.35	S. 32° W.	1.87	5.82	1
				Meter	6	1.63	0.52		2.52	6.62	2.22	1.92		1.92	5.80	1
				do	15	1.55	0.50		2.21	6.66	2.18	1.65		1.76	5.76	1
				do	24	1.52	0.43		2.17	6.66	2.15	1.68		1.47	5.76	1
51	do	Aug. 4-7, 1922	H. C. Denson	Pole	7	2.10	1.08	N. 35° E.	3.64	5.95	2.02	1.20	S. 43° W.	4.70	6.47	2¾
				Meter	15	1.93	1.38		3.58	6.07	1.97	1.52		4.52	6.35	2¾
				do	37	1.92	1.33		3.39	6.09	1.98	1.43		4.15	6.33	2¾
				do	58	1.93	1.13		3.08	6.03	1.93	1.60		3.72	6.39	2¾
52	do	do	do	Pole	7	1.82	0.75	N. 26° E.	3.50	6.33	2.12	1.60	S. 32° W.	3.30	6.09	2¾
				Meter	6	1.82	0.80		3.17	6.14	1.93	1.50		3.17	6.28	2¾
				do	16	1.80	0.97		3.13	6.16	1.93	1.80		2.98	6.26	2¾
				do	26	1.80	0.85		2.73	6.16	1.93	1.58		2.47	6.26	2¾
59	do	Aug. 27-28, 1920	R. J. Auld	Pole	7	1.85				6.38	2.20				6.04	½
				Meter	10	1.93	1.22		4.78	6.18	2.08	1.62		5.03	6.24	1
				do	25	1.80	1.20		4.64	6.33	2.10	1.50		5.24	6.09	1
				do	40	1.82	1.43		4.69	6.28	2.07	1.98		5.44	6.14	1
62	do	Sept. 19-20, 1920	do	Pole	7	1.85	0.75	N. 11° W.	3.35	6.53	2.35	1.75	S. 17° E.	1.65	5.89	1
				Meter	10	2.08	0.82		2.95	6.38	2.43	1.82		1.65	6.04	1
				do	18	2.05	0.85		2.65	6.33	2.35	1.65		1.50	6.09	1
				do	40	2.02	0.58		2.41	6.38	2.37	1.23		1.31	6.04	1
67	Hell Gate	Oct .6-7, 1920	do	Pole	7	2.15	0.50	N. 70° E.	4.53	6.05	2.17	1.15	S. 86° W.	4.31	6.37	1
				Meter	9	2.13	0.77		4.14	6.03	2.13	1.32		3.29	6.39	1
				do	22	2.15	0.85		4.04	5.98	2.10	1.25		3.49	6.44	1
68	do	Aug. 5-7, 1922	H. C. Denson	Pole	7	1.90	1.20		3.85	6.03	1.90	1.65		3.55	6.39	1½
				Meter	9	2.10	1.10		4.40	6.00	2.07	1.47		4.20	6.42	1½
				do	22	2.15	1.13		3.85	6.01	2.13	1.50		3.85	6.41	1½
				do	34	2.10	1.10		3.59	6.03	2.10	1.53		3.49	6.39	1½

At stations 5, 11, 27, 28, 29, 31, 41, 45, 51, 52, and 56 the current observations were carried on for periods of more than two days. Taking the data from these stations as constituting the best determined data, we find that the flood current in lower East River has duration of 6.1 hours, while the ebb current has a duration of 6.3 hours. This, together with the fact that the velocity of the ebb current is the greater, might be taken to indicate the presence of fresh-water flow toward Upper Bay; but the subsurface-current observations, to be discussed presently, do not bear this out. The reason for the greater velocity and duration of the ebb current must be sought in the character of the tidal movement in the East River.

An examination of Figure 25 shows that on the assumption of hydraulic motion through East River the slope lines would be horizontal at about 3.3 hours and 9.3 hours, and that from 3.3 hours to 9.3 hours, or for a period of 6 hours, the current would be setting toward Willets Point, or flooding, while for a period of 6.4 hours it would be ebbing. These values deduced from the slope-line diagram agree very closely with the values of 6.1 hours and 6.2 hours derived directly from the observations. It is therefore due to the hydraulic character of the flow through East River that the ebb current has the greater duration.

Since the flow through East River is primarily hydraulic in character, Figure 25 shows that the current should be simultaneous throughout the river, the slack of the current coming when the slope lines are horizontal and the strength of the current coming when the slope lines have their maximum slope. From Figure 25 it is seen that the slope lines show a change in direction from ebb to flood at about 9.3 hours and a change from flood to ebb at about 3.3 hours; the maximum slope is shown by the 6-hour line in the one direction and by the 0-hour line in the other direction. In this connection it is to be recalled that the hours of the slope lines are reckoned from the time of transit of the moon over the meridian of Governors Island. It follows, therefore, that the slack of the current should come about 1.6 hours after the time of tide at Fort Hamilton and the strength of the current about 1.6 hours before the time of tide. Table 67 shows that slack of the current comes 2 hours after the time of tide at Fort Hamilton and the strength comes 1.1 hours before the time of tide. It is to be noted that the times deduced from the slope-line diagram are earlier than observed by about half an hour. Part of this discrepancy is to be ascribed to the fact that in the slope-line diagram no allowance is made for the momentum of the moving mass of water, for obviously, in consequence of the momentum of the water, slack water must occur somewhat after the time the water at both ends of East River has attained the same level.

For 28 of the stations listed in Table 67 subsurface-current observations were made with a current meter during the surveys of 1920 and 1922, and during the 1922 survey the direction of the subsurface current was determined at a number of stations by means of a bifilar direction indicator. The results derived from these observations with the velocities of the flood and ebb strengths reduced to mean values, are given in Table 68. The observations with the current pole at these stations, which pertain to the current at a depth of 7 feet and which have been given in slightly different form in Table 67, are also included for purposes of comparison.

At station 11, near the entrance to lower East River, the observations were carried on for about 13 days, and the results may therefore be considered relatively well determined. Table 68 shows that at this station the slack before flood, and also the slack before ebb, occurs at the same time at all depths, so that the flood and ebb durations remain constant from the surface to the bottom. The velocities of both the flood and ebb strengths decrease from the surface to the bottom at the same rate, though it is to be noted that the pole velocity at the 7-foot depth is somewhat less than the meter velocity at the 10-foot depth. The ebb strength from surface to bottom has the greater velocity.

The features of the subsurface current derived from the data for station 11 appear to be the characteristic features of the subsurface currents in lower East River, as indicated by the data for the other stations of Table 68. Throughout lower East River, therefore, the current is running flood, or ebb, from one end to the other and from the surface to the bottom at the same time, and there are none of the differences in the vertical distribution of velocity at strength or in the duration of the flood and ebb currents found in the Hudson River and also in Upper Bay and in the Narrows.

At stations 27 and 29 it will be recalled that, although located in the same cross section of the river, the current near the surface at the former station shows the greater ebb velocity, while at the latter station it was the flood current that had the greater velocity; and for the subsurface currents we find this difference to persist at all four depths

UPPER EAST RIVER

For upper East River there are at hand current observations for 24 stations, the locations of which are shown on Figure 39. These observations may be taken to pertain to the current at a depth of about 7 feet. The results derived from these observations, with the velocities of the flood and ebb strengths corrected to mean values, are given in Table 69.

The tide in upper East River is about 3¾ hours later than at Fort Hamilton. Applying this difference to the times given in Table 69, it is seen that the easterly current in upper East River attains its strength about 5 hours before local high water and hence on a rising tide. The easterly current here is therefore the flood current and the westerly current the ebb current. This likewise was the case in lower East River, so that throughout the whole length of East River the current setting from Upper Bay toward Long Island Sound is the flood current, while the one setting from Long Island Sound toward Upper Bay is the ebb current.

In upper East River the time of slack before flood becomes earlier from Hell Gate to Willets Point by 1½ hours, while the time of slack before ebb becomes earlier by half an hour. In consequence of this the duration of flood changes from 6 hours at Hell Gate to 7.2 hours off Willets Point. For upper East River as a whole, therefore, the flood current has the greater duration, which reverses the conditions found in lower East River.

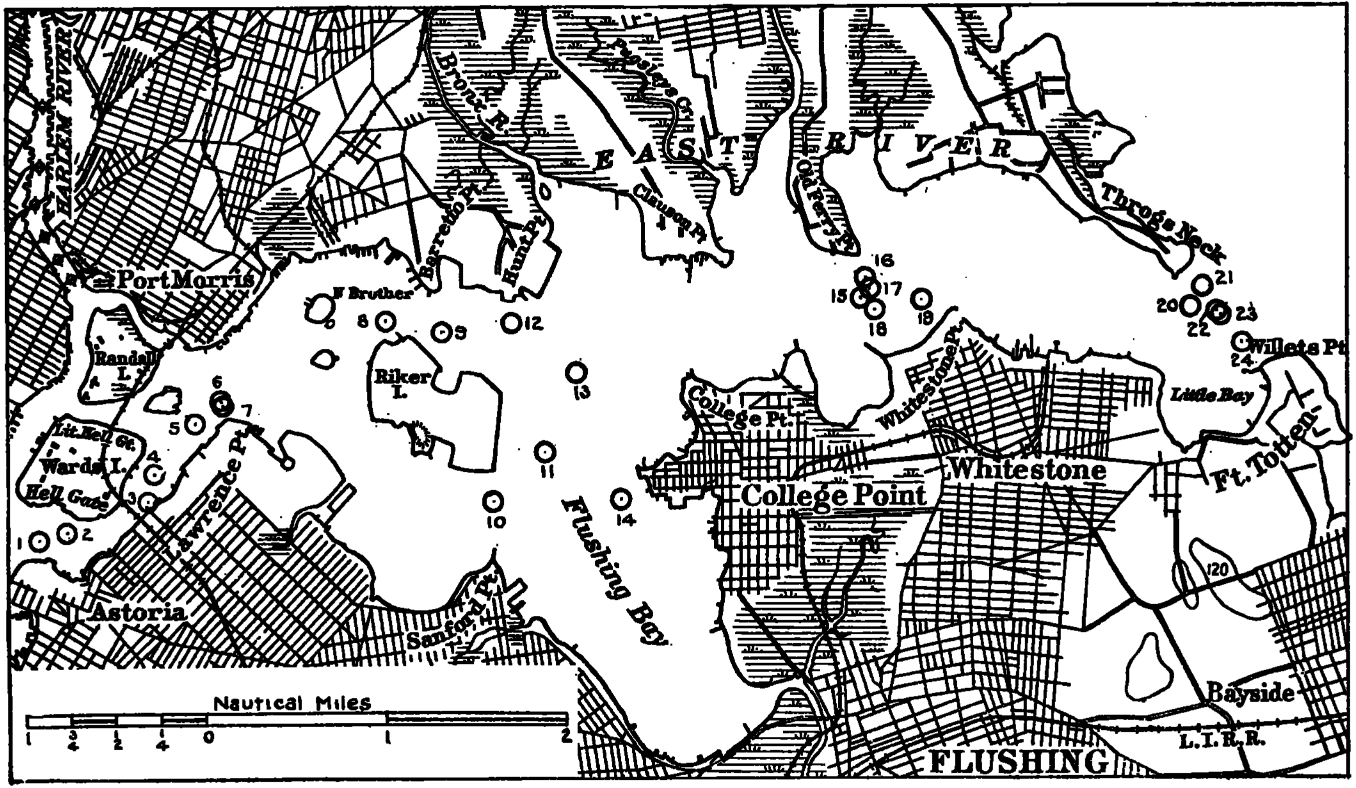


FIG. 39.—Current stations, Upper East River

TABLE 69.—*Current data, Upper East River*

[Referred to times of HW and LW at Fort Hamilton]

Station No.	Location	Party of	Date	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
					Time	Direction	Velocity			Time	Direction	Velocity		
				Hours after LW	*Hours before HW*	*True*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*True*	*Knots*	*Hours*	*Days*
1	Hell Gate	H. C. Denson	Aug., 1922	1.9	1.2		3.9	6.0	1.9	1.6		3.6	6.4	1½
2	do	C. H. Davis	June, 1845	1.3	1.5	S. 85° E.	5.7	6.0	1.3	1.7	N. 80° W.	4.6	6.4	½
3	Off Wards Island	do	do	1.3	2.2	N. 35° E.	3.7	5.7	1.0	2.4	S. 40° W.	2.1	6.7	½
4	do	H. Mitchell	June, 1857	2.3	0.9	N. 45° E.	3.2	6.3	2.6	1.5	S. 35° W.	2.3	6.1	7¾
5	Off Lawrence Point	J. R. Goldsborough.	Oct., 1846	2.2	0.6	N. 60° E.	2.6	6.2	2.4	0.8	S. 20° W.	2.4	6.2	½
6	do	H. C. Denson	Aug., 1922	1.9	0.9	N. 45° E.	2.4	6.2	2.1	2.0	S. 40° W.	2.0	6.2	2
7	do	H. Mitchell	July, 1858	2.1	0.9	N. 40° E.	3.1	6.2	2.3	1.6	S. 50° W.	2.4	6.2	5½
8	Off Barretto Point	J. R. Goldsborough.	Oct., 1846	2.5	0.3	S. 30° E.	1.0	6.5	3.0	1.7	N. 50° W.	0.6	5.9	½
9	do	R. J. Auld	Sept., 1920	1.5	0.9	S. 70° E.	1.9	6.8	2.3	1.6	N. 80° W.	0.9	5.6	1
10	Off Riker Island	H. C. Denson	July, 1922	1.7	1.6	N. 70° E.	1.1	6.1	1.8	1.8	S. 85° W.	1.0	6.3	¾
11	do	J. R. Goldsborough.	Oct., 1846	2.6	1.5	N. 50° E.	0.5	6.3	2.9	1.7	N. 45° W.	1.0	6.1	1
12	Off Hunts Point	H. C. Denson	July, 1922	1.5	1.8	N. 80° E.	1.1	7.1	2.6	1.6	N. 85° W.	1.6	5.3	¾
13	do	J. R. Goldsborough.	Oct., 1846	2.0	0.7	East	1.3	6.2	2.2	1.3	N. 60° W.	1.1	6.2	1
14	Off College Point	R. J. Auld	Sept., 1920	4.7	−1.6	S. 45° E.	0.6	5.8	4.1	−0.8	N. 25° W.	0.5	6.6	1
15	Off Old Ferry Point	H. C. Denson	July, 1922	1.1	2.1	N. 65° E.	1.0	6.3	1.4	2.4	S. 80° W.	1.3	6.1	1
16	do	H. L. Marindin	Aug., 1885	0.4	1.6		2.0	6.8	1.2	2.4		1.5	5.6	1
17	do	do	do	0.7	1.7		1.5	6.8	1.5	1.9		1.3	5.6	1½
18	do	do	do	0.6	1.8		0.9	6.6	1.2	2.4		1.1	5.8	¾
19	Off Whitestone Point.	J. R. Goldsborough.	Oct., 1846	0.8	1.7	S. 65° E.	1.4	6.9	1.7	1.8	N. 50° W.	1.1	5.5	1
20	Off Throgs Neck	H. Mitchell	July, 1858	0.4	1.0	East	1.0	7.4	1.8	1.8	S. 85° W.	0.8	5.0	6
21	do	H. C. Denson	July, 1922	−0.2	2.9	N. 55° E.	0.9	5.9	−0.3	2.0	S. 85° W.	0.6	6.5	1
22	do	do	do	0.3	1.4	East	1.2	7.2	1.5	2.5	S. 70° W.	0.5	5.2	11½
23	do	R. J. Auld	Sept., 1920	0.7	1.4	S. 85° E.	1.2	6.7	1.4	2.4	S. 80° W.	0.7	5.7	1
24	Off Willets Point	H. C. Denson	July, 1922	0.2	1.4	N. 80° E.	1.0	7.6	1.8	2.2	S. 70° W.	0.4	4.8	1

TABLE 70.—*Current data for various depths, Upper East River*

[Referred to times of HW and LW, at Fort Hamilton, N. Y.]

Station No.	Location	Date	Party of—	Observations with—	Depth	Slack	Flood strength			Flood duration	Slack	Ebb strength			Ebb duration	Length of observations
							Time	Direction	Velocity			Time	Direction	Velocity		
					Feet	*Hours after LW*	*Hours before HW*	*True*	*Knots*	*Hours*	*Hours after HW*	*Hours before LW*	*True*	*Knots*	*Hours*	*Days*
1	-------	Aug. 5-7, 1922	H. C. Denson	Pole	7	1.90	1.20		3.85	6.03	1.90	1.65		3.55	6.39	1½
				Meter	9	2.10	1.10		4.40	6.00	2.07	1.47		4.20	6.42	1½
				do	22	2.15	1.13		3.85	6.01	2.13	1.50		3.85	6.41	1½
				do	34	2.10	1.10		3.59	6.03	2.10	1.53		3.49	6.39	1½
6	Off Lawrence Point.	Aug. 1-2, 1922	do	Pole	7	1.85	0.95	N. 45° E.	2.43	6.25	2.07	1.97	S. 41° W.	1.97	6.17	2
				Meter	7	1.95	0.85		2.50	6.28	2.20	2.00		1.67	6.14	2
				do	18	1.98	0.90		2.15	6.25	2.20	1.77		1.60	6.17	2
				do	30	2.00	0.68		1.53	6.23	2.20	1.30		1.53	6.19	2
9	Off Barretto Point.	Sept. 14-15, 1920	R. J. Auld	Pole	7	1.50	0.90	S. 71° E.	1.86	6.83	2.30	1.60	N. 78° W.	0.90	5.59	1
				Meter	10	1.73	1.12		1.88	6.38	2.08	1.67		0.98	6.04	1
				do	25	1.75	1.40		1.48	6.28	2.00	1.85		1.18	6.14	1
				do	40	1.62	1.53		1.11	6.33	1.92	2.28		1.06	6.09	1
10	Off Rikers I.	July 31-Aug. 1, 1922.	H. C. Denson	Pole	7	1.70	1.60	N. 71° E.	1.09	6.13	1.80	1.80	S. 87° W.	1.04	6.29	¾
				Meter	9	1.80	1.30		1.09	6.13	1.90	1.40		0.99	6.29	¾
				do	22	1.85	1.50		0.99	5.88	1.70	1.90		0.89	6.54	¾
				do	35	1.95	1.30		0.89	5.58	1.50	1.70		0.69	6.84	¾
12	Off Hunt Point.	July 31-Aug. 1, 1922.	do	Pole	7	1.50	1.85	N. 80° E.	1.09	7.13	2.60	1.60	N. 84° W.	1.59	5.29	¾
				Meter	11	1.95	1.45		0.99	6.48	2.40	1.70		1.34	5.94	¾
				do	29	2.10	1.10		0.89	6.23	2.30	2.00		1.24	6.19	¾
				do	45	2.00	1.05		0.69	6.23	2.20	1.70		1.09	6.19	¾
15	Off Old Ferry Point.	July 30-31, 1922	do	Pole	7	1.10	2.10	N. 67° E.	1.01	6.30	1.37	2.45	S. 79° W.	1.31	6.12	1
				Meter	21	1.15	1.90		1.11	6.28	1.40	2.15		1.46	6.14	1
				do	53	1.25	2.30		1.17	6.05	1.27	2.10		1.07	6.37	1
				do	84	1.50	2.20		1.17	5.60	1.07	2.05		0.67	6.82	1
21	Off Throgs Neck	do	do	Pole	7	−0.20	2.90	N. 53° E.	0.93	5.93	−0.30	2.00	S. 83° W.	0.58	6.49	1
				Meter	14	−0.05	3.20		0.93	6.18	0.10	2.60		0.73	6.24	1
				do	35	0.15	2.75		0.78	5.38	−0.50	2.65		0.68	7.04	1
				do	58	0.30	2.05		0.72	5.18	−0.55	2.75		[illegible]	[illegible]	
22	do	July 26-Aug. 7, 1922.	do	Pole	7	0.30	1.43	S. 88° E.	1.20	7.21	1.48	2.52	S. 68° W.	0.53	5.21	11½
				Meter	22	0.53	1.20		1.19	7.05	1.55	2.27		0.63	5.37	11½
				do	55	0.48	1.30		0.91	7.02	1.47	2.12		0.76	5.40	11½
				do	88	0.60	1.48		0.82	6.68	1.25	2.27		0.73	5.74	11½
23	do	Sept. 10-11, 1920	R. J. Auld	Pole	7	0.70	1.35	S. 87° E.	1.24	6.73	1.40	2.40	S. 80° W.	0.68	5.69	1
				Meter	4	0.53	1.57		1.50	6.93	1.43	2.72		0.50	5.49	¾
				do	20	0.50	1.55		1.02	6.93	1.40	2.60		0.67	5.49	1
				do	50	0.57	1.73		0.79	6.68	1.22	2.43		0.74	5.74	1
				do	80	0.63	1.67		0.70	6.48	1.08	2.77		0.70	5.94	1
24	Off Willets Point	July 30-31, 1922	H. C. Denson	Pole	7	−0.25	1.40	N. 78° E.	1.03	8.03	1.75	2.15	S. 69° W.	0.38	4.39	1
				Meter	8	0.15	1.60		1.18	7.88	2.00	2.45		0.38	4.54	1
				do	20	0.25	1.50		0.98	7.63	1.85	1.70		0.48	4.79	1
				do	30	0.15	1.55		0.93	7.58	1.70	1.75		0.53	4.84	1

With the exception of the small stretch west of Lawrence Point, the current in upper East River has a velocity much less than in lower East River; and whereas in the lower East River the ebb current has the greater velocity, it is the flood current that has the greater velocity in upper East River.

For station 14 the times of slack and strength of current stand out strikingly different from the values at the other stations in upper East River. A glance at Figure 39 shows that station 14 is located at the entrance to Flushing Bay. This bay is of a relatively restricted area and therefore there can be but little progression of the tide. Hence, the time of high and low water in Flushing Bay must occur but little later than in upper East River, and this is shown by the tidal observations listed in Table 40. But the strength of the current in the entrance to Flushing Bay obviously must occur when the tide is rising or falling most rapidly—that is, about 3 hours before local high or low water—while the slack must come about the times of high and low water. In upper East River proper the current attains its strength 5 hours before local tide, hence, from the reasoning above, the current at station 14 should be about 2 hours later than in upper East River. The data in Table 69 show the current at station 14 to be later by 2¾ hours.

The fact that the velocities of the current in upper East River are less than in lower East River is obviously due to the greater width of the channel in upper East River; but the reversal of the relative magnitudes of the durations of flood and ebb and of the flood and ebb strengths can not be accounted for on this ground. If we compare the current data for the Harlem River given in Table 65 with the data of Table 69, we find that the current in the Harlem is very nearly simultaneous with the current in upper East River. On the flood the Harlem is carrying the waters from the Hudson into East River, at which time the current is setting from lower East River into upper East River. There should, therefore, be evidence in the current phenomena of upper East River of the effect of fresh-water flow both on account of the fresh water from the Hudson and also on account of the fresh water from the various streams tributary to upper East River. This evidence is found in the greater duration of the flood period and also in the greater velocity of the flood strength. We may also expect to find the vertical velocity distribution and the relative durations of flood and ebb from surface to bottom showing the effects of fresh-water flow, which effects, it is to be recalled, were absent in lower East River.

Subsurface current observations are at hand for 10 of the stations listed in Table 69. These observations were made with the current meter at three depths representing approximately two-tenths, five-tenths, and eight-tenths of the depth at each station. In addition observations at a depth of 4 feet were made at station 23. The results derived from these observations, with the velocities of the flood and ebb strengths corrected to mean values, are given in Table 70. For comparison the observations made with the current pole, which pertain to the current at a depth of 7 feet, are also included.

The characteristic effects of fresh-water flow in tidal streams are exemplified in the current of the Hudson and were discussed in Section XIV. The slack before flood becomes earlier from the surface downward, while the slack before ebb occurs about the same time at all depths, this feature causing the duration of flood to increase from the surface to the bottom. Furthermore, the velocity of the flood strength decreases very slowly with increasing depth and may even increase, while the strength of ebb decreases at a relatively rapid rate. It is to be noted that in tidal streams like the Hudson the ebb current is the one that carries the fresh or nontidal water down to the sea; but in upper East River it is the flood current that carries the fresh water from the Harlem and from its own tributaries out toward the sea. Hence, the effects of fresh-water flow enumerated above should, in upper East River, reverse flood for ebb.

At station 22 the subsurface current observations were carried on uninterruptedly for 11½ days. The results of these observations may therefore be considered as relatively well determined. Table 70 shows that the slack before flood at this station becomes somewhat later from the surface downward while the slack before ebb becomes earlier. Hence, the duration of flood decreases with increasing depth, while the duration of ebb increases. At the 7-foot depth the durations of flood and ebb are, respectively, 7.2 hours and 5.2 hours, while at the 88-foot depth these become 6.7 hours and 5.7 hours.

The vertical distribution of the velocities of the flood and ebb strengths at station 22 shows the flood strength to decrease in velocity at a relatively rapid rate, while the ebb strength increases in velocity to mid-depth and then decreases slowly toward the bottom. At the 7-foot depth the flood strength has a velocity more than 125 per cent greater than the ebb, but at the eight-tenths depth the ebb strength is only 12 per cent greater. In upper East River, therefore, the effects of fresh-water flow are clearly evident in the current, while in lower East River it is to be recalled the current was free from such effects.

XVI. THE TIDAL MOVEMENT IN THE HARBOR

The tables in the foregoing sections, which give in detail the results of the tidal and current observations in the component waterways of New York Harbor, furnish the data for a comprehensive view of the tidal movement, including under this term both the rise and fall of the tide and the flood and ebb of the current, in the harbor. At any given instant the tidal movement may be represented in diagrammatic form by an arrow pointing in the direction of the current and by the letter R or F to indicate, respectively, a rising or a falling tide; but it is obvious that within the compass of a small diagram any schematic representation of the tidal movement over a large area, in which the times of tide and of current differ as much as in New York Harbor, can give only a generalized view without reference to details in the smaller bays and inlets fringing the main waterways of the harbor.

In the present section the tidal movement in New York Harbor is represented schematically for each hour of the tide. Since the times of both tide and current in the tables of tidal and current data have been given with reference to the time of tide at Fort Hamilton, it will obviously be of advantage to refer the tidal movement to the time of tide at Fort Hamilton. The current arrows are to be taken as representing the general direction of the current near the surface.

At the time of low water at Fort Hamilton, Figure 40 represents the tidal movement in the harbor. Excepting a few small indentations like Gowanus Bay, the current throughout the harbor is ebbing, the water flowing toward Lower Bay. And with the exception of Lower Bay, the tide over the whole harbor is falling. In the Hudson the current is very nearly at its strength, while the

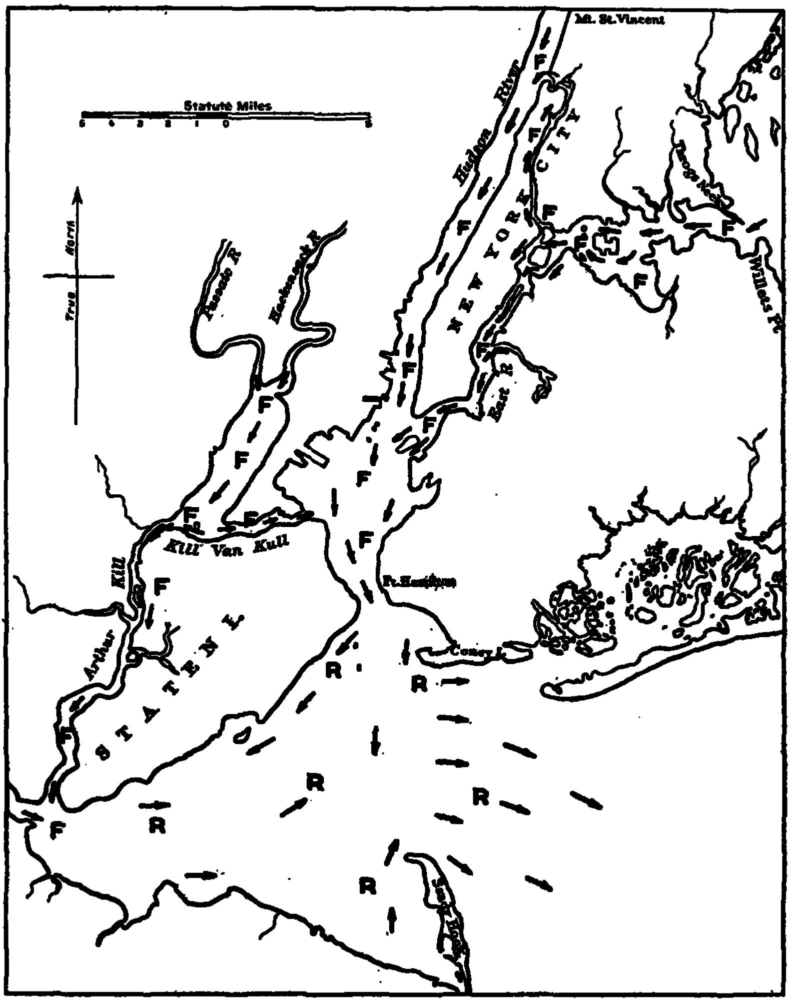


FIG 40.—The tidal movement at the time of low water at Fort Hamilton

tide is near low water, which is still 1 hour away. The Harlem is now carrying the water from East River toward the Hudson, the tide being below mean sea level and about 2 hours from its low water. Upper East River is bringing the water from Long Island Sound toward Hell Gate, while its level is falling rapidly, being now 2 hours after high water. Through Hell Gate and lower East River the water is flowing toward Upper Bay at very nearly its strength, which was passed an hour ago, the level of the water being a little below mean sea level and falling rapidly.

At the time of low water at Fort Hamilton the current in Newark Bay has not yet attained its strength. The waters from Newark Bay are now pouring partly into Arthur Kill, but principally into Kill van Kull, which is carrying them into Upper Bay. In Upper

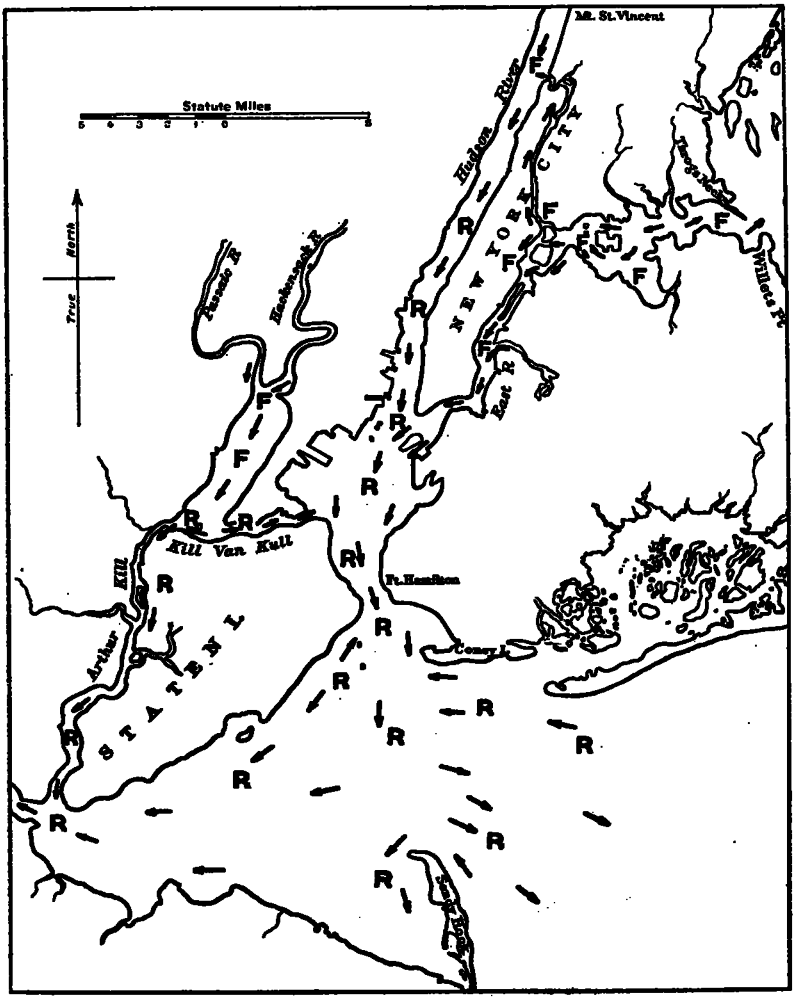


FIG. 41.—The tidal movement one hour after low water at Fort Hamilton

Bay the current has passed its strength about half an hour previously, but it is still running with a velocity not far from strength and passing on the waters from the Hudson River, East River, and Kill van Kull into the Narrows. The level of the water in Newark Bay, Kill van Kull, and Upper Bay is still falling, but rather slowly, for low water is less than an hour away.

Low water at Fort Hamilton is coincident with the strength of the ebb current in the Narrows. The tidal waters which are flowing into Upper Bay through Hudson River, East River, and Kill van Kull, together with the nontidal waters from a territory having an area of very nearly 15,000 square miles, are now pouring through the Narrows into Lower Bay at the rate of more than three-quarters

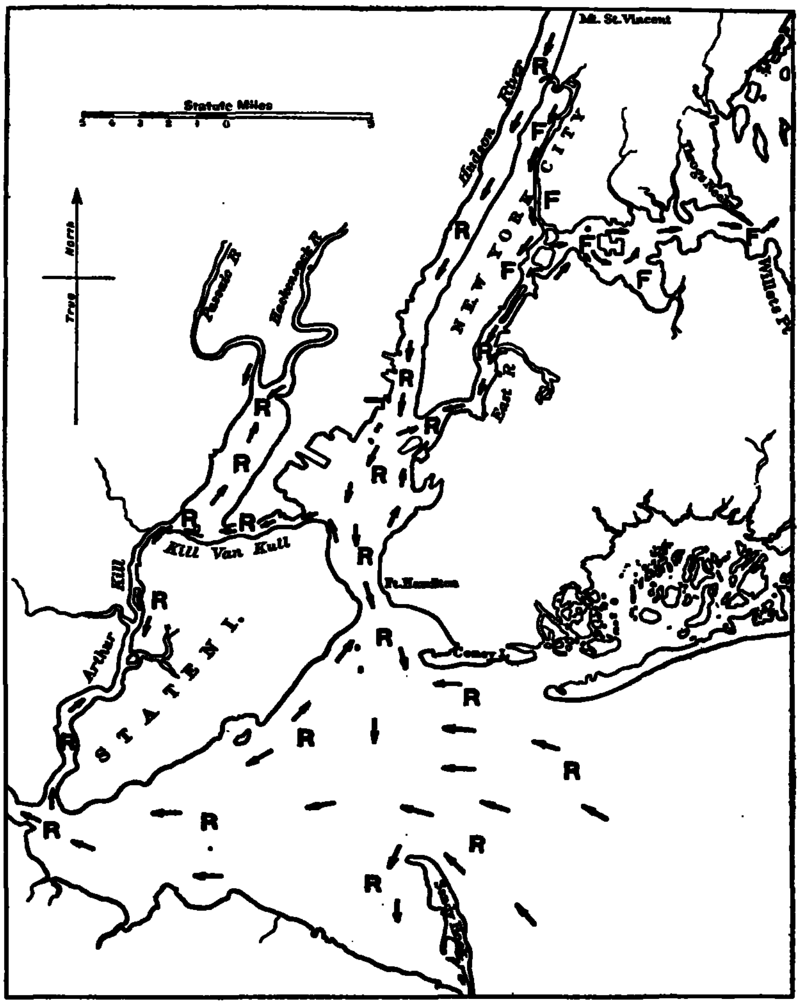


FIG. 42.—The tidal movement two hours after low water at Fort Hamilton

of a million cubic feet per second. Arthur Kill, too, is flowing toward Lower Bay, and from Lower Bay the waters now are passing out to sea, although the strength of the current has already passed. In Arthur Kill the level of the water is falling slowly, low water being half an hour away, but in Lower Bay the water is beginning to rise very slowly, the low water here having occurred a few minutes before this time.

One hour later, or one hour after low water at Fort Hamilton, the tidal movement is represented by Figure 41. Through the greater part of the harbor the current is still ebbing, but here and there the flood is beginning to make itself felt. The current in the Hudson is now ebbing at its strength, the tide being about low water. For the lower half of the stretch from the Battery to Mount St. Vincent

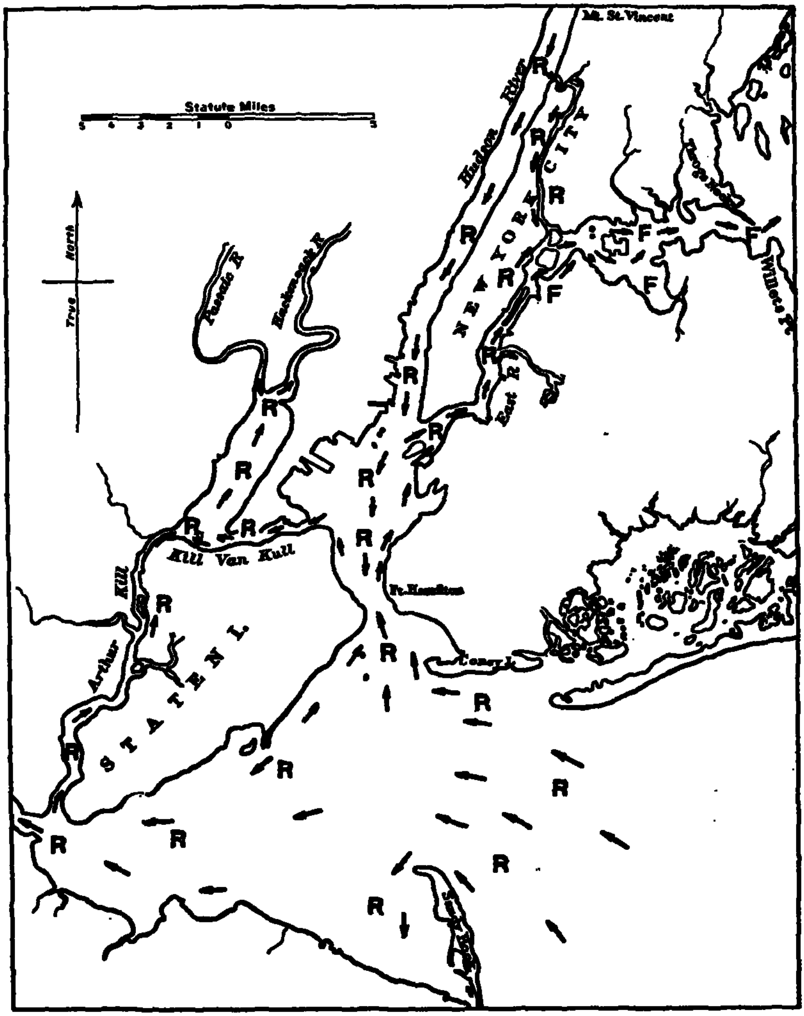


FIG. 43.—The tidal movement three hours after low water at Fort Hamilton

the water is beginning to rise slowly, while in the upper half of this stretch the level is still falling, but very slowly. The Harlem with a falling tide is still discharging into the Hudson, but in upper East River the current has turned flood from Old Ferry Point to Willets Point and is now setting toward Long Island Sound. The greater part of upper East River, however, is still ebbing, the water flowing toward Hell Gate, and over the whole of its area the water is falling.

In lower East River, 1 hour after low water at Fort Hamilton, the tide is still falling from Hell Gate as far as the navy yard, but from here to the Battery the tide is beginning to rise, low water having been passed a few minutes before. Through all of lower East River the current is still setting toward Upper Bay. Through Upper Bay, Kill van Kull, the Narrows, and Arthur Kill the current is

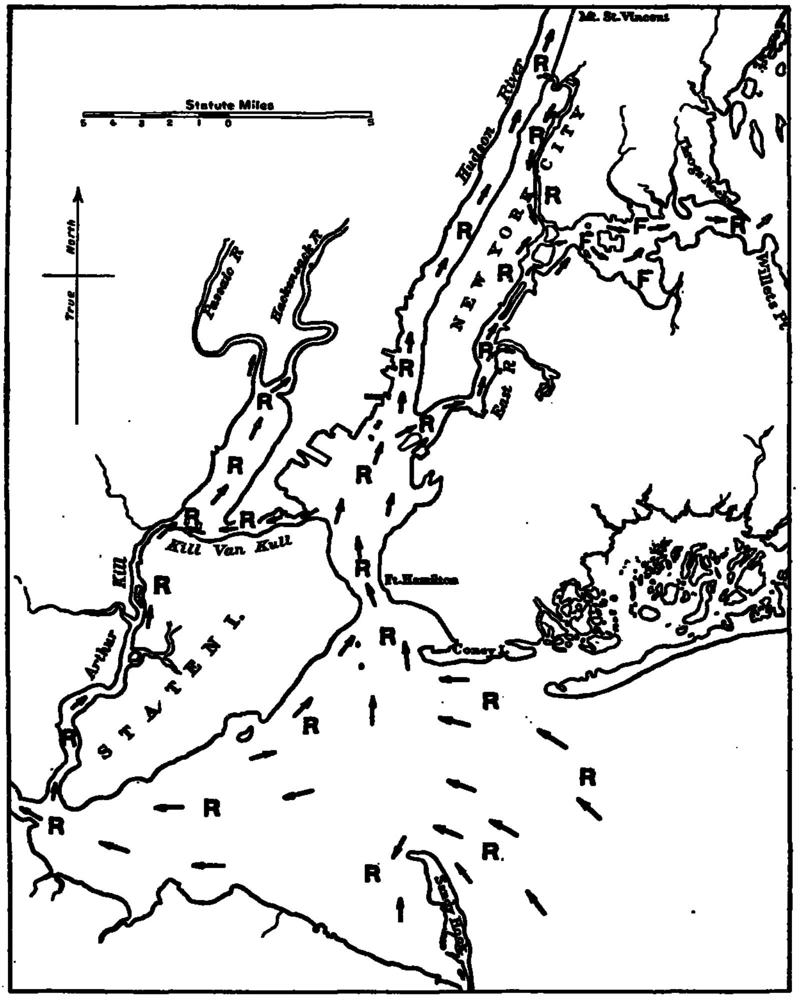


FIG. 44.—The tidal movement four hours after low water at Fort Hamilton

ebbing, while the tide is rising slowly, but in Newark Bay, while the current is also ebbing, the tide is still falling, low water being about half an hour away. Throughout Lower Bay the tide is rising and over the greater part of its area the current has commenced to flood; but in the channel leading from the Narrows the waters of the ebbing current from the Hudson and East Rivers and from Kill van Kull overcome the feeble flood and still set seaward. It is to be noted, however, that on both sides of the main channel leading out to the sea the current is flooding.

Two hours after low water at Fort Hamilton the tidal and current conditions in the harbor are represented in Figure 42. In the Hudson the tide is rising while the current is ebbing. Less than half an hour before, the current in the Harlem turned from ebb to flood

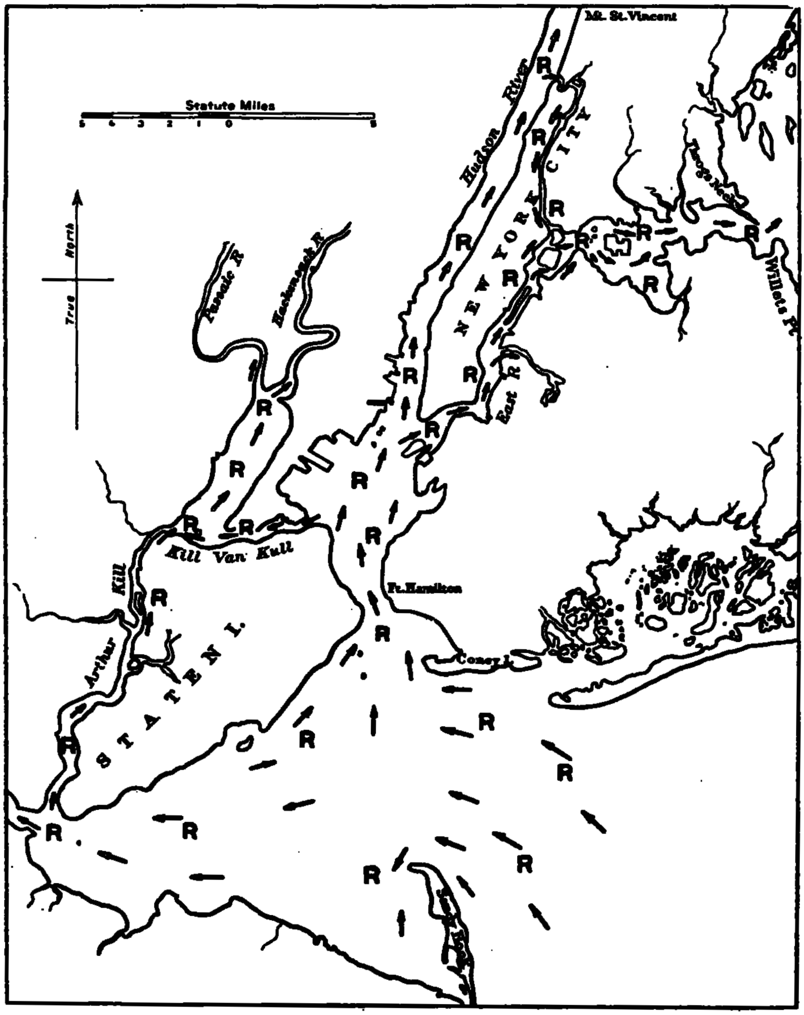


FIG. 45.—The tidal movement five hours after low water at Fort Hamilton

and now it is carrying the waters from the Hudson toward East River. Near the Hudson River entrance to the Harlem the tide has commenced to rise, but over the greater part of its area the tide is still falling. In upper East River the tide is still falling but the current is now flooding throughout its length from Hell Gate to Willets Point. In lower East River the water has commenced flooding at its entrance off Governors Island, but for the greater part it is still ebbing, with the water rising from the Battery to Hell Gate. In Upper Bay the current in the main channel is still under control of the waters from the Hudson and is ebbing; but through Buttermilk Channel it is flooding, the tide over the whole of Upper Bay now rising. In the Narrows similar conditions prevail, the deeper central portion ebbing, while in the shallow areas near the shores the flood current has begun, the level of the water rising over the whole area.

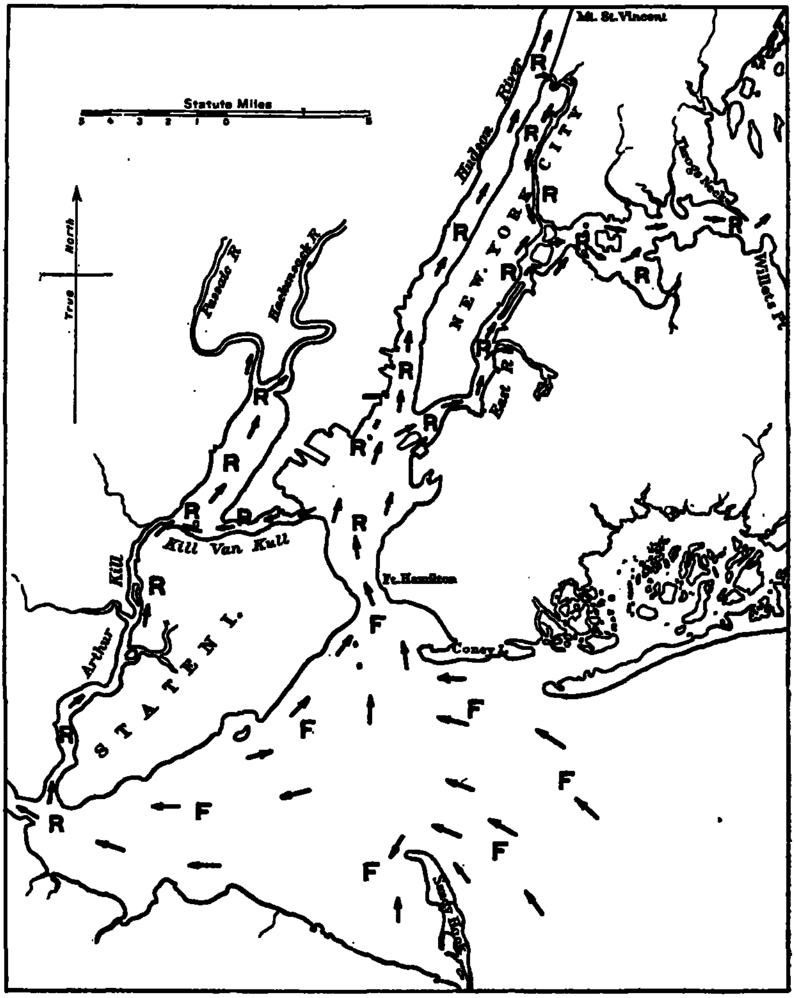


FIG. 46.—The tidal movement at the time of high water at Fort Hamilton

In Kill van Kull at this time—two hours after low water at Fort Hamilton—the tide is rising and the current has begun to flood, the turn from ebb to flood having occurred half an hour previously. In Newark Bay proper the current likewise has turned flood, but the Hackensack and Passaic Rivers are still ebbing, the tide over the whole region, however, now rising. In Arthur Kill the current at this time is very weak, the upper part continuing a weak ebb current, while in the lower part the current has turned to flood less than an hour before; the tide throughout the Kill is continuing its rise. Over all of Lower Bay the tide is rising, and over nearly all of the bay the current is flooding, the only exception being a short stretch of the channel leading from the Narrows, where it is ebbing weakly.

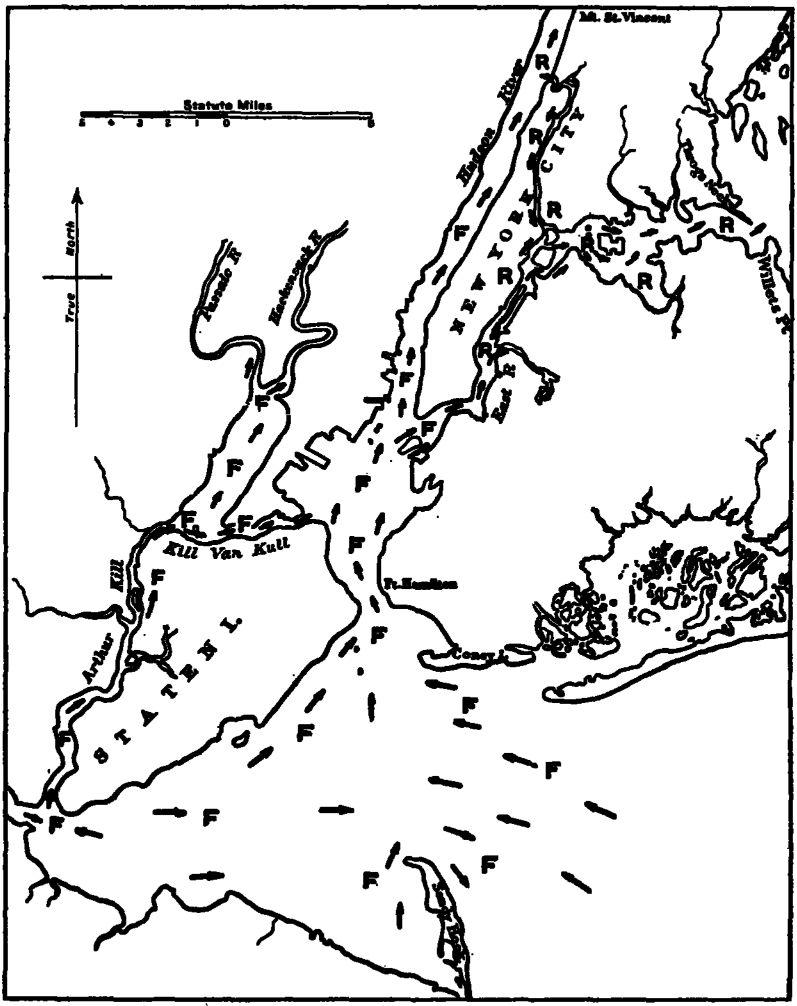


Fig. 47.—The tidal movement one hour after high water at Fort Hamilton

Figure 43 represents the tidal movement in the harbor three hours after low water at Fort Hamilton. In the Hudson and Harlem Rivers the tide is still below sea level but is now beginning to rise rapidly, the current in the Hudson ebbing while in the Harlem it is flooding. Throughout East River the current is flooding, accompanied by a rising tide in lower East River and by a falling tide in upper East River. Through Upper Bay, Kill van Kull, Newark Bay, Arthur

Kill, and Lower Bay the tide is rising rapidly and through all these waterways, with the exception of Upper Bay, the current is flooding. In Upper Bay the main channel leading from the Hudson to the Narrows is still ebbing, but in the regions near the shores the current is flooding.

Four hours after low water at Fort Hamilton the current is flooding throughout New York Harbor, and with the exception of upper East

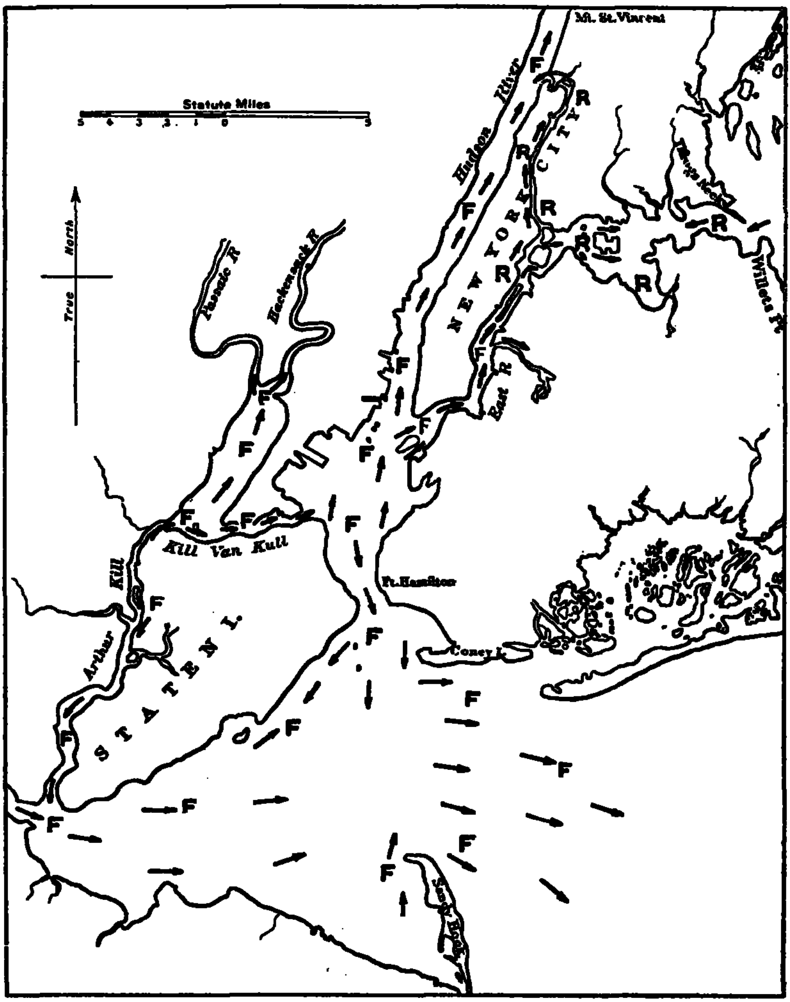


Fig. 43.—The tidal movement two hours after high water at Fort Hamilton

River the tide throughout the harbor is rising. Figure 44 represents the conditions of the tide and current at this time. In the Hudson the current turns later than in the other waterways of the harbor, and the turn from ebb to flood has just taken place. The level of the water in the Hudson has now reached mean sea level and is rising very rapidly. In lower East River the tide has been rising for about half an hour, in Hell Gate it is now low water, and in upper East River the tide is falling slowly except in the region between Old Ferry Point and Willets Point, where the water is at its low-water stand, and at the entrance to Long Island Sound, where the tide has begun to rise.

Figure 45 represents the tidal movement in the harbor five hours after low water at Fort Hamilton. The current is still flooding

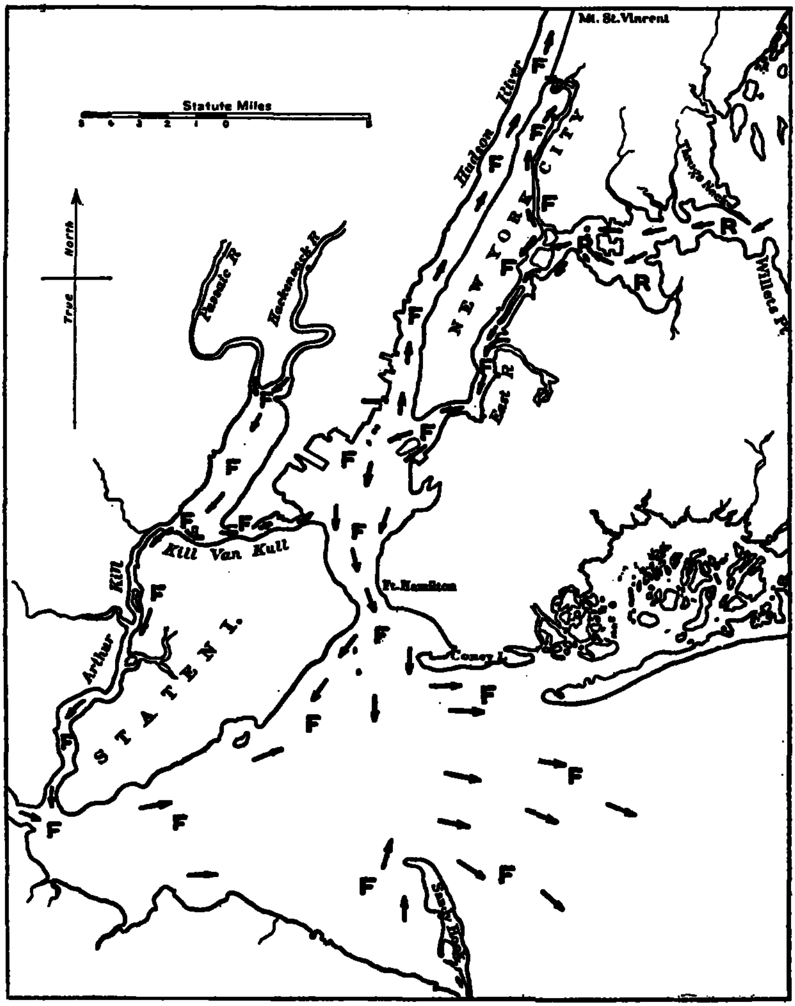


FIG. 49.—The tidal movement three hours after high water at Fort Hamilton

through all the waterways of the harbor, and the tide now likewise is in the same phase over the whole harbor. In upper East River low water comes later than in the other waterways of the harbor, but now the water is rising all over its area.

At this time—five hours after low water at Fort Hamilton—the flood current throughout New York Harbor is very nearly at its strength. In the Hudson the strength comes latest, and it is still one and one-half hours away. But through the Harlem, upper East River, and lower East River the current is now running at its full strength. In Upper Bay the current is running at very nearly its full strength, which will come half an hour later; in Kill van Kull the strength occurred one and one-half hours previously, and in

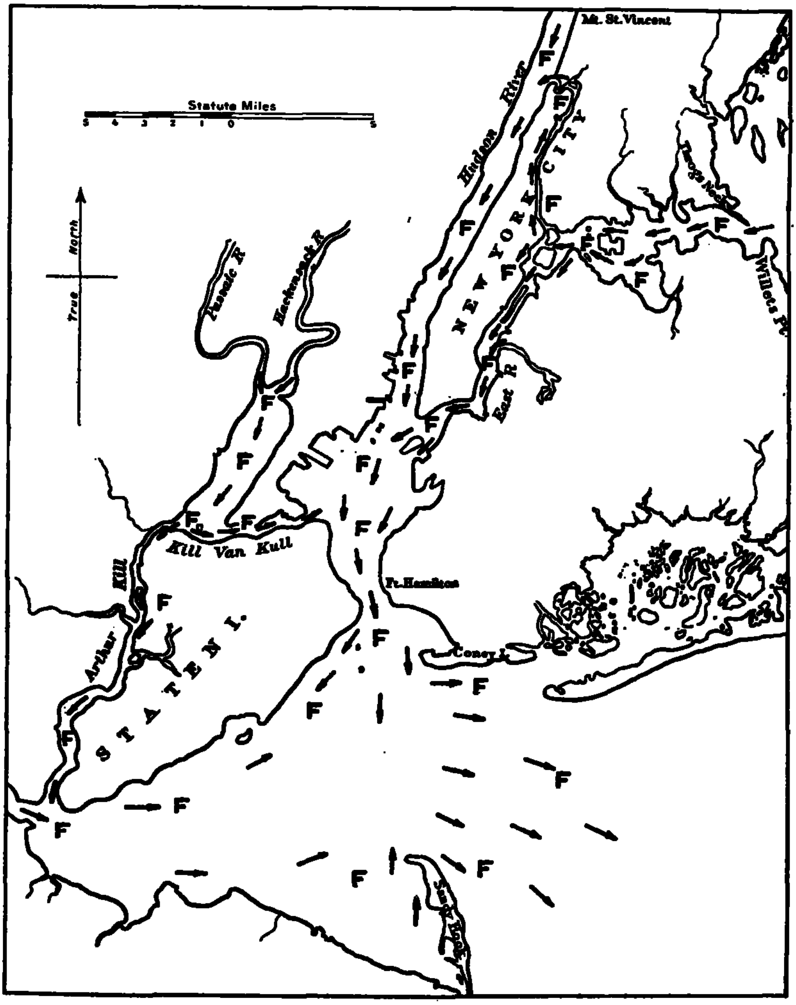


FIG. 50.—The tidal movement four hours after high water at Fort Hamilton

Newark Bay it occurred somewhat less than an hour previously. Through the Narrows the current is practically at its strength, which will come a few minutes later, and the waters from Lower Bay are now pouring in through the Narrows at the rate of nearly three-quarters of a million cubic feet per second.

Six hours after low water at Fort Hamilton is coincident with the time of high water. The current at this time is still flooding through the whole harbor and, with the exception of Lower Bay, the tide is still rising. In the latter waterway the tide is earliest and high water occurred a few minutes previously, so that now the level of the water is falling. The tidal and current conditions in the harbor at this time are represented in Figure 46.

One hour after high water at Fort Hamilton the condition of tide and current in the harbor is represented in Figure 47. The current

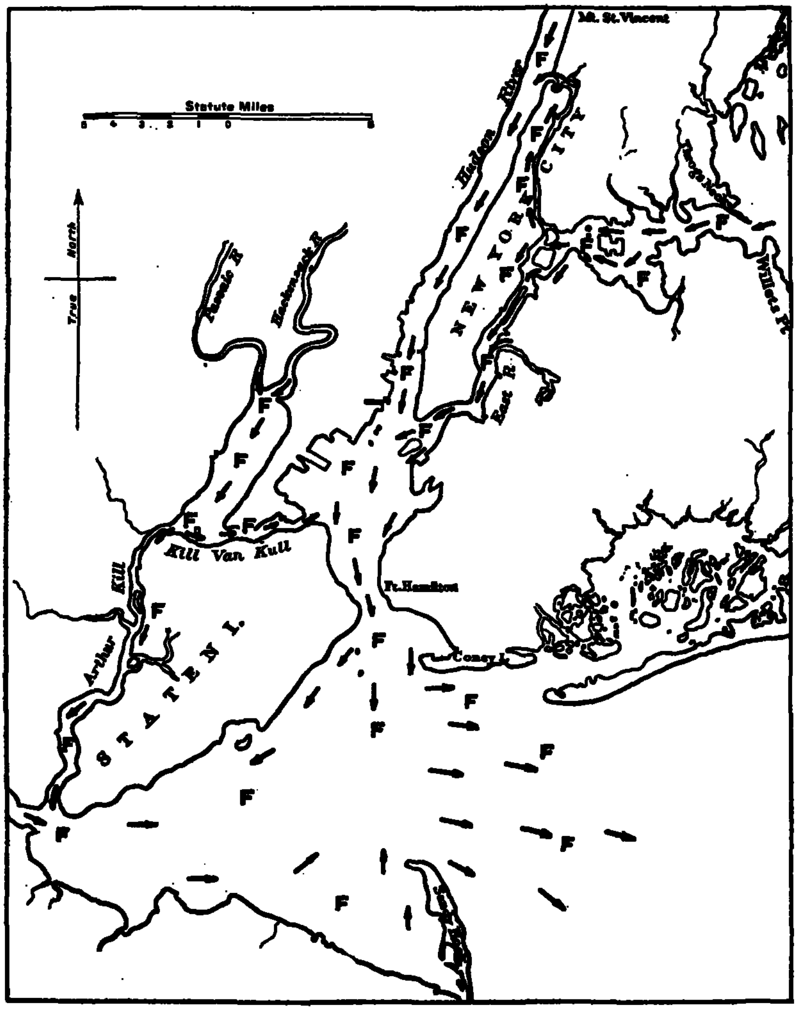


FIG. 51.—The tidal movement five hours after high water at Fort Hamilton

is now no longer in the same phase throughout the harbor, for about a quarter of an hour before this time the current in Kill van Kull turned from flood to ebb, and around Sandy Hook too the current has turned seawards; but through the other waterways of the harbor the current is still flooding. The tide is rising in the East and Harlem Rivers and in the Hudson above the Harlem, but in the rest of the harbor it is falling.

Figure 48 represents the tidal and current conditions in the harbor two hours after high water at Fort Hamilton. The current is running ebb through all of Lower Bay, the Narrows, Kill van Kull, the lower reach of Arthur Kill, Harlem River, and the western portion of upper East River. In Newark Bay and in the entrance from Arthur Kill, in Upper Bay, Hudson River, lower East River, and in upper East

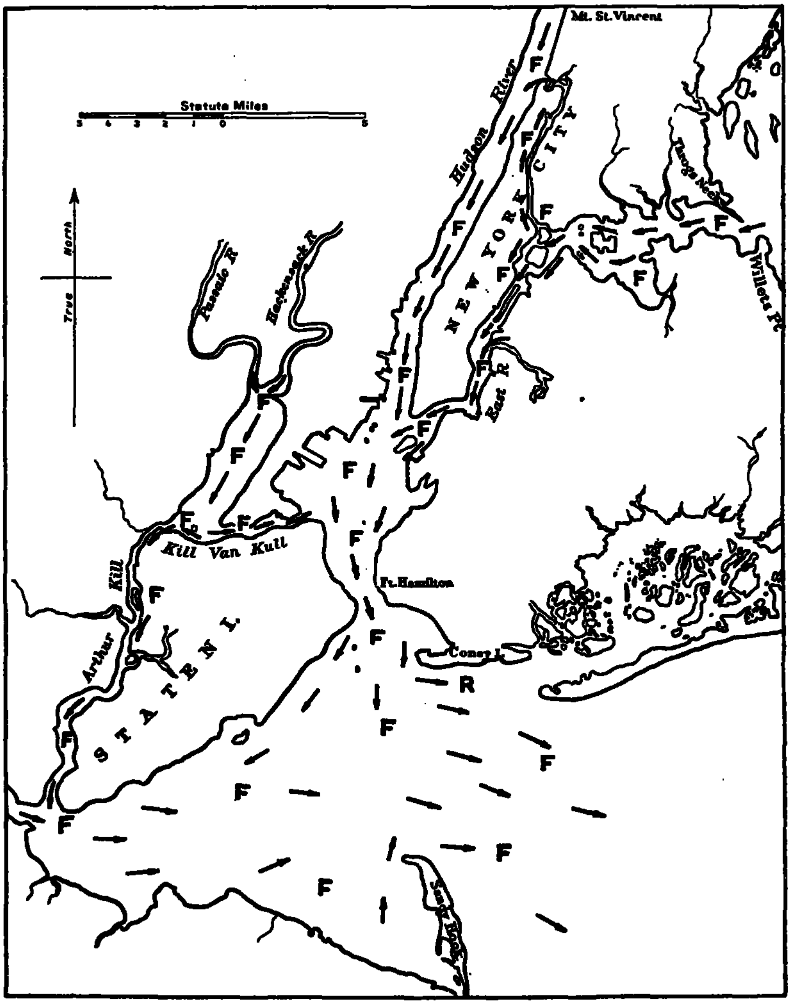


FIG. 52.—The tidal movement six hours after high water at Fort Hamilton

River from Hell Gate to Old Ferry Point the current is flooding. The tide in the harbor is now falling everywhere except in the East River from Blackwells Island to Willets Point, and in the Harlem from the East River as far as Broadway Bridge.

Three hours after high water at Fort Hamilton the tidal movement in the harbor is represented in Figure 49. The tide throughout the harbor, with the exception of upper East River, is now falling. In the latter waterway the tide is rising very slowly, being only a few minutes away from high water. In the Hudson the current is still running flood, but very weakly, the turn to ebb coming about a quarter of an hour later. Through the rest of the harbor, however, the current is ebbing, and in Kill van Kull the current is very nearly at its strength.

Four hours after high water at Fort Hamilton the current is ebbing throughout New York Harbor, the last waterway to turn ebb being the Hudson River. The phase of the tide too is now the same throughout the harbor, the water falling in all the waterways. The tidal and current conditions at this time are represented in Figure 50.

Five hours after high water at Fort Hamilton the tidal movement in the harbor is represented in Figure 51. Through all the waterways of the harbor the current is still ebbing and the tide falling, as was the case an hour previously. However, now the current has a greater velocity through the various waterways, with the exception of Kill van Kull, in which the strength of ebb occurs about four hours after high water at Fort Hamilton; and since the water has been falling the level of the water throughout the harbor now is lower than it was an hour previous.

Six hours after high water at Fort Hamilton the conditions of tide and current in New York Harbor are represented in Figure 52. The tide throughout the harbor is falling, but in Lower Bay it is very near low water, and near the western end of Coney Island low water has actually occurred, and the tide here is beginning to rise, although very slowly. The current is still ebbing throughout the harbor and running nearly at its strength in Upper Bay and in the Narrows.

Six hours after high water at Fort Hamilton is equivalent to four-tenths of an hour before low water. The tidal and current conditions in the harbor at this time should, therefore, be very nearly similar to the conditions at the time of low water, as represented in Figure 40, and a comparison of the latter figure with Figure 52 shows that with the exception of the tide in Lower Bay the two figures are alike. In Lower Bay at the time of low water at Fort Hamilton the tide has just passed low water and is therefore rising, while six hours after high water at Fort Hamilton the tide in Lower Bay is still falling, low water being still about a quarter of an hour away. The 13 diagrams of Figures 40 to 52, therefore, represent the tidal movement in New York Harbor for each hour of the tidal cycle.

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