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CHART DATUMS

By

H. A. MARMER
Assistant Chief, Division of Tides and Currents

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INTRODUCTORY

NEED FOR DATUM PLANES

Heights and depths, whether on land or sea, must be reckoned from some fixed level which is adopted as a reference plane. Technically this adopted reference plane is known as a datum plane or datum. The datums used in connection with nautical or hydrographic charts belong to the class known as hydrographic datum planes. As the name implies, hydrographic datum planes are datums used in hydrographic work.

The need for hydrographic datum planes arises in connection with all hydrographic work that involves either the depths of the water or the heights along the shore. Thus, in the improvement of harbors to meet the demands of the deep-draft vessels of modern commerce, the depths to which channels are dredged must be referred to some fixed datum. In the construction of wharves and of marine structures of all kinds, the basic elevations refer to some fixed hydrographic datum.

But it is especially in connection with the construction of hydrographic or nautical charts that hydrographic datum planes become important. To determine the depths in the region covered by the chart, depth measurements, or soundings as they are usually called, are made. But these depths as actually measured do not correctly represent the depths in the region; for the soundings are made from the surface of the sea, the level of which is constantly changing under the influence of the rise and fall of the tide and of the disturbing effects of wind and weather. To determine the correct depths from the soundings they must be reduced to some uniform level or fixed datum plane.

Again, the delineation of the shore line on the chart is possible only with reference to some datum. For the boundary between land and sea is shifting continually—landward with the rising tide and seaward with the falling tide. Only with reference to some hydrographic datum plane can this boundary be fixed on the chart.

Nautical charts are issued primarily for the use of the navigator and may be considered as serving three purposes. In the first place, a nautical chart indicates the depth of water in the region which it covers, and thus permits the navigator to choose safe lanes of travel. Secondly, it reveals the hidden topography of the sea bottom, which is of use in locating the position of a ship, especially in thick weather. Thirdly, by representing coastal features it makes for ease in identifying locations along the coast.

Now it is to be noted that the topography of the sea bottom, as depicted on a chart, remains the same whatever the datum used. For example, a submarine ridge or valley as it appears on a chart bears exactly the same relation to the surrounding submarine features whether the datum used in plotting the area be a low-water datum, a high-water datum, or any other datum. In other words, as regards nautical charts, the topography of the sea bottom is independent of the datum.

As regards coastal features represented on a chart, it is clear that the appearance of these features will vary somewhat with the datum adopted. A rock or shoal area which becomes uncovered at low water will appear as a visible object on a chart that makes use of a low-water datum, while on a chart that makes use of a high-water datum the same feature will be shown as under water. The appearance of the shore line and of coastal features on a chart depends, therefore, somewhat on the datum adopted.

The depths shown on a chart, however, depend wholly on the datum used. Different charts of the same region will show different depths unless the same datum plane is used by all the charts. Thus a chart of a given region will show depths two feet greater than another chart of the same region if the datum used in the former is two feet higher than the datum used in the latter.

KINDS OF DATUM PLANES

In some hydrographic work the immediate purposes involved make it of little moment whether one datum plane or another is used. In such work it is merely necessary that the heights or depths involved be referred to some definite datum plane. Thus, in the delineation of the topography of the bottom of the sea of a given region, it is frequently immaterial whether a high-water datum, a low-water datum or some arbitrary datum, like that defined by the top of a certain rock, be used.

Arbitrary datum planes, however, are subject to a number of objections as hydrographic datums. In the first place, any depths shown with reference to an arbitrary datum plane have no meaning in themselves. For example, a depth at a given point of 20 feet below the level defined by some mark on shore gives no information of the actual depth of the water at that point. For it all depends on the relation of the adopted mark to some phase of the tide. If, however, the depth at the given point is stated as 10 feet below mean low water, it is immediately clear that the greater part of the time 10 feet of water or more will be found at that point.

Another and even more serious disadvantage of arbitrary datum planes for hydrographic purposes arises from the fact that such datums can not be recovered if lost. Take the case of a harbor chart on which the depths are shown with reference to some well-defined point on a given wharf. In the course of time the particular wharf may be destroyed by one cause or another. And then, when a survey is made to determine whether any changes in depth have taken place in the harbor, there are no means for accurately determining this, because the datum used on the previous chart is lost.

It is clear, therefore, that with regard to the two features discussed above, a rational datum plane should define depths with regard to some well-defined phase of the level of the sea, and should moreover be capable of recovery even though all bench mark connections be lost. These advantages are possessed in marked degree by datums dependent on the rise and fall of the tide. Specifically, hydrographic datum planes based on the rise and fall of the tide possess the advantages of simplicity of definition, accuracy of determination and certainty of recovery. For these reasons tidal datum planes are made use of as hydrographic datums.

But even when restricted to the use of datum planes based on the tide, the hydrographer is confronted by a bewildering variety of such datum planes from which he must choose. For convenience, however, they may all be grouped into three classes; namely, high-water datums, mean sea-level datums, and low-water datums. A brief consideration of each of these classes will bring out the distinctions between them.

A high-water datum is one determined by some high-water phase of the tide, and for some purposes such datums are very desirable. Lands fronting the seashore frequently are delimited by the high-water line, which makes some high-water datums (mean high water or mean higher high water) basic datums in connection with the title to such lands. An important consideration in connection with bridges spanning navigable tidal waters is the clearance under the bridge. This clearance is least at high water. Hence the clearance allowed for is specified with respect to some high-water datum, generally mean high water. In warehouse construction along the water front, the height to which high water may rise determines the height below which storage is unsafe for certain commodities; and here some high-water datum like spring high water or storm high water is the most satisfactory reference datum.

As a datum for nautical charts, however, a high-water datum has many disadvantages. When referred to a high-water datum the depths shown on the chart are maximum depths which obtain only for short periods once or twice a day. Such depths give a false sense of security; for shoal places, which constitute dangers in navigation, will be shown with the maximum depth of water over them. Rocks which most of the time are uncovered, and thus constitute land marks for location of position, will appear on nautical charts as covered with water when referred to a high-water datum. High-water datums are therefore rarely used as datums for charting depths on nautical charts.

Mean sea-level datums are those which approximate the mean level of the sea, as for example the datum of mean sea level or that of half-tide level. These latter datums, for hydrographic purposes, are free from a number of disadvantages inherent in high-water datums. Indeed, at first thought mean sea level suggests itself as the most suitable datum, since in a true sense the depth of water at any point is its depth at mean sea level; for it is clear that while the actual depth at the point is constantly changing, being sometimes more and sometimes less than the mean sea level depth, its average depth is that reckoned from mean sea level. For many purposes mean sea level is the most satisfactory datum from which to reckon depths in the sea.

For the purposes of the navigator, however, mean sea level is not the most satisfactory datum. For the mariner is interested not so much in the absolute depth of the water as in a depth sufficient for his vessel. The critical depths are therefore in shoal areas at the time of low water when there may not be sufficient depth for the draft of his vessel. With mean sea level used as the datum, such critical areas will still show depths greater than those found at the time of low water.

Coming now to a consideration of low-water datums for use on nautical charts, it becomes evident at once that these are free from the disadvantages inherent in the other two classes of datums. The approximate minimum depth at any point obviously occurs when the tide is at low water. The use of a low-water datum as the chart datum, therefore gives immediately the approximate minimum depths at all points.

Another advantage low-water datums possess, comes to light in connection with the use of tide tables for determining the actual depth of water at a given time. As a general rule it is a simpler matter to add a correction to a depth than to subtract it. With the use of a low-water datum the corrections for the rise and fall of the tide are predominantly additive. With a mean sea-level datum half of these corrections are positive and half negative; and with a high-water datum they are predominantly negative.

The purposes of the mariner are thus best served by the use of some low-water datum on nautical charts. If the tide fell to the same depth at each low water, the problem of hydrographic datum planes would be a simple one. Under such conditions there would be but one low-water datum and a single low-water observation would be sufficient to determine it. But unfortunately the fall of low water at any place varies continually, this variation being in large part in response to the periodic changes in the tide. This means not only that different low-water datums may be defined, but also that the accurate determination of a low-water datum is not a simple matter. These two aspects of the problem, namely, the choice of the most suitable low-water datum for a given region, and the accurate determination of this plane, will be considered in some detail later. As a preliminary, a brief discussion of the tide will be of advantage.

THE TIDE

GENERAL CHARACTERISTICS

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 moon. Both in the times of occurrence of high and low water and in the extent of rise and fall does the tide exhibit its close relation to the movement of the moon.

The characteristics of the rise and fall of the tide at any place are most clearly exhibited in the form of a tide curve, that is by a graphic representation of the changing level of the water at that place. A tide curve may be made by plotting, to a suitable scale on cross section paper, the heights of the water as observed at regular intervals on a fixed vertical staff graduated to feet and decimals, 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.

In Figure 1 is shown the tide curve for the first two days of June, 1920, at Fort Hamilton in New York Harbor. The figures at the top, from 0 to 24, represent the hours of the day beginning with midnight. Numbering the hours consecutively to 24 eliminates all uncertainty as to whether a given hour is in the morning or in the afternoon; in addition there is the further advantage of great convenience in computations. The figures at the left increasing upward from 0 to 6 represent the height of the tide as referred to a vertical tide staff.

It is seen that in its rise and fall the tide does not move at a uniform rate. Starting for example at low water, the tide is seen to rise very slowly at first but at a constantly increasing rate for

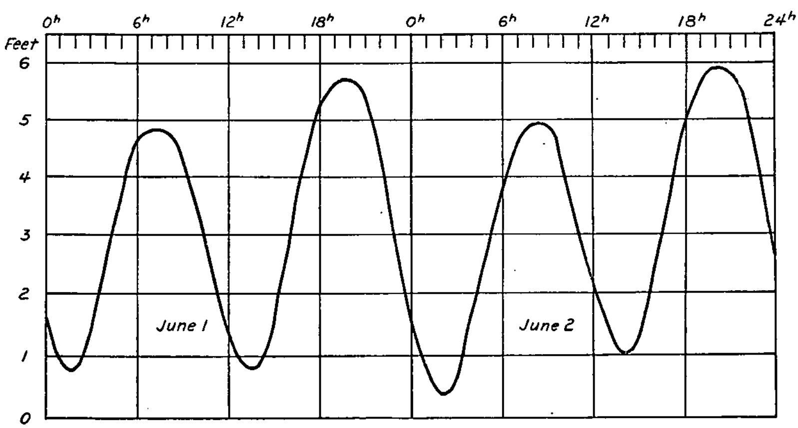

FIGURE 1.—Tide curve, Fort Hamilton, N. Y., June 1–2, 1920

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 fall of the tide occurs in a similar manner, the rate of fall being least immediately after high water but increasing continually for about three hours when it is at a maximum, and then decreasing for the following three hours, when low water is reached.

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

It is important to note that in the use of the terms high water and low water in reference to the tide, the absolute height of the water is not in question. It is not at all infrequent at many places to have the high water of one day lower than the low water of another day. Whatever the height of the water, when the rise of the water ceases and the fall is to begin, the tide is at high water; and when the fall of the water ceases and the rise is to begin the

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tide is at low water. 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 height of high and low water at any given place is called the "mean range."

Figure 1 shows further that high water and low water in New York Harbor follow each other by intervals of a little over six hours, which means that the interval separating two high or two low waters is somewhat more than 12 hours. This interval varies somewhat from day to day but on the average is 12 hours 25 minutes. This means that from day to day the tide becomes later by 50 minutes. In other words the tidal day, like the lunar day, has a length of 24 hours 50 minutes on the average. This is true not only for New York Harbor but for the whole world.

VARIATIONS IN RISE AND FALL

If the rise and fall of the tide at any place is studied, it is found to vary from day to day. In part this variation reflects changing meteorological conditions. But in greater part the variations in rise and fall of the tide are due to astronomic causes, being brought about by variations in the position of the moon relative to earth and sun.

In the following section it will be necessary to consider in detail the variations to which the fall of low water is subject. Here it will be sufficient to consider briefly the principal variations in the rise and fall of the tide. These are three in number and are related respectively to the moon's phases, parallax, and declination.

At the time of new moon or full moon the tidal forces of sun and moon are in the same phase and so strengthen each other. As a result, high water at such times rises higher and low water falls lower than at other times. The tides that occur at the times of new or full moon 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 in opposite phase, and the tide therefore does not rise as high nor fall as low as on the average. At such times the tides are called "neap tides," and the range of the tide then is known as the "neap range."

The period of the moon's phases (the synodic month) is approximately 29½ days in length. Within this period therefore, there will be two cycles of increasing and decreasing rise and fall of the tide, each cycle having a period of about two weeks. Beginning at new moon there is a week of decreasing rise and fall to the time of the moon's first quarter. This is followed by a week of increasing rise and fall to full moon, when a week of decreasing rise and fall ensues to the time of the moon's third quarter. The full cycle is then completed by a week of increasing rise and fall to the time of new moon.

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 second of the three principal variations in the rise and fall of the tide is that dependent on the varying parallax of the moon or its distance from the earth. 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 time exhibiting a decreased rise and fall. These tides are called "apogean tides" and the corresponding range the "apogean range."

Now, while the period of the moon's distance, the so-called anomalistic month, has a length approximating that of the moon's phases, only one cycle of increasing and decreasing rise and fall of the tide takes place in response to the moon's varying distance. But 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 third variation in the rise and fall of the tide arises from the fact that 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 as between morning and afternoon tides. When the moon is on or close to the Equator—that is, when its declination is small—morning and afternoon tides are very much alike. As the declination increases, morning and afternoon tides begin to show decided differences; and at the time of the moon's maximum semimonthly declination these differences are very nearly at a maximum.

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. 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"; and, 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.

The period of the moon's declination, known as the tropic month, is approximately 27⅓ days in length. Like the periods of the phase and parallax variations the length of the tropic period is approximately four weeks. And within this period there are two full cycles of variation as between morning and afternoon tides.

The three variations in the rise and fall of the tide considered above are exhibited by the tide the world over; but the degree to which response is made to each of the variations differs considerably. 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 synodic month) is approximately $29\frac{1}{2}$ days in length; the month of the moon's distance (the anomalistic month) is approximately $27\frac{1}{2}$ days in length; the month of the moon's declination (the tropic month) is approximately $27\frac{1}{3}$

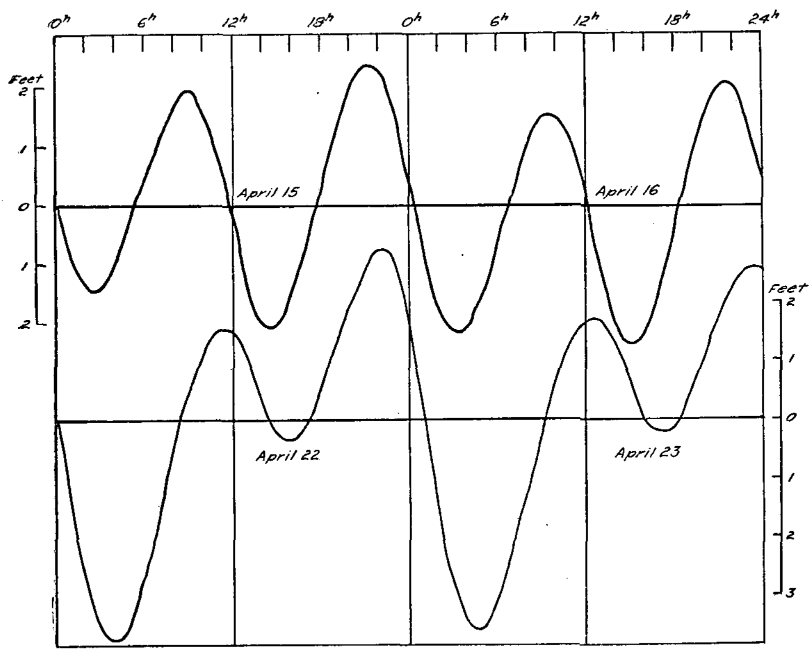

FIGURE 2.—Tide curves, San Francisco, Calif., April 15–16 and 22–23, 1920

days in length. It follows, therefore, that very considerable variation in the rise and fall 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 arising from 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 April 15–16 and April 22–23, 1920. To make the tide curves for the two periods easily comparable, 0 hours was taken to be the time, both on April 15 and on April 22, when the tide had reached the mean level of the sea, which is represented by the horizontal line associated with each of the tide curves.

In the second half of April, 1920, the moon was over the Equator on the 15th, and at its greatest north declination on the 22d. The upper curve of Figure 2 thus typifies the equatorial tides at San Francisco while the lower curve typifies the tropic tides. For the two days of April 15–16, morning and afternoon tides are seen to resemble each other closely; that is, morning and afternoon high waters resemble each other, and likewise morning and afternoon low waters.

For the two days of April 22–23, however, as the lower curve shows, morning and afternoon tides do not resemble each other. The morning high waters are lower than the afternoon high waters, while the morning low waters are very considerably lower than the afternoon low waters. In other words, for these two days the tide exhibited considerable diurnal inequality.

The existence of diurnal inequality makes necessary the distinction between the two high waters as well as between the two low waters of a day. Distinctive names have been given to each. Of the two high waters of a day, 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."

TYPES OF TIDE

From one place to another the tide exhibits differences in regard to time, range, and characteristics of rise and fall. As regards differences in time and range of tide at different places, it is unnecessary here to consider the matter except to note that these differences exist and may be very marked. Thus, within the tidal waters of Chesapeake Bay the tide at different places differs in time by as much as 12 hours. In the body of water that embraces the Gulf of Maine and the Bay of Fundy, the tide on a given day will be found to rise and fall but a foot on the southern shore of Nantucket Island, and 40 feet or more in Noel Bay.

The differences in the characteristics of rise and fall of the tide, however, it is necessary to consider in some detail, since these differences are of importance in connection with hydrographic datum planes. While the differences in characteristics of rise and fall of tide are of great variety, it is found possible to group the various kinds of tides under three types, namely, semidaily, daily, and mixed. Instead of semidaily and daily the more technical terms of semidiurnal and diurnal are frequently used.

The semidaily type of tide is one in which two high and two low waters occur each tidal day, with but little diurnal inequality. In this type of tide the cycle of rise and fall occupies half a day, both cycles of the day resembling each other closely. Figure 1, which represents the rise and fall of the tide in New York Harbor for a period of two days, illustrates this type of tide. The semidaily is the predominant type of tide along the Atlantic coast of the United States.

In the daily type of tide, as the name implies, there is but one cycle of rise and fall in a day; that is, high water and low water follow each other by intervals of a little over 12 hours. This type of tide is not widely distributed. Do Son, in French Indo-China, may be cited as a place where the tide is always of the daily type. At Pensacola, Fla., the tide is almost always of the daily type. At St. Michael, Alaska, the tide is very largely daily. At Galveston, Tex., and at Manila, P. I., the tide is frequently of the daily type. Figure 3, which illustrates this type of tide, is the tide curve for Pensacola, Fla., for the first two days of June, 1926. The horizontal line of the curve represents mean sea level.

The mixed type of tide is one in which two high and two low waters occur during the tidal day, but with marked diurnal inequality. Like the semidaily type of tide there are in the mixed type two cycles of rise and fall in a tidal day, the distinguishing feature being the existence of marked diurnal inequality. This type of tide is the predominant type on the Pacific coast of the United States. The lower curve of Figure 2, which represents the rise and fall of the tide at San Francisco at the time of the moon's maximum semimonthly declination, may be taken as illustrating one form of the mixed type of tide.

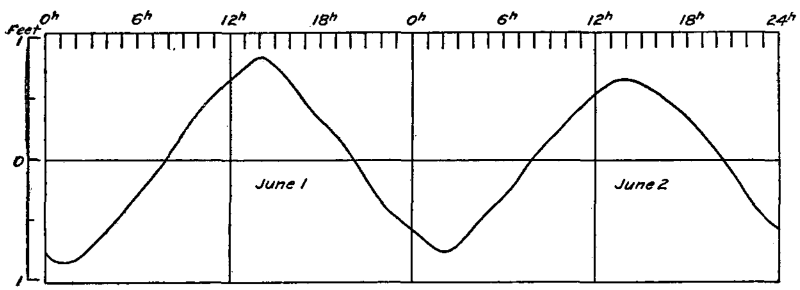

FIGURE 3.—Tide curve, Pensacola, Fla., June 1–2, 1926

It can be shown that the mixed type of tide results from a mixture or combination of the daily and semidaily types of tide. The principal tide-producing forces of sun and moon are those having periods of half a day and a day, respectively. In responding to these forces, different bodies of water behave differently, depending on their lengths and depths. Those bodies of water that respond best to the semidaily forces will have semidaily tides; those that respond best to the daily forces will have daily tides; while those that respond in approximately equal degree to both kinds of tide-producing forces will have the mixed type of tide.

Several forms of the mixed type of tide occur. In one form the diurnal inequality is exhibited principally by the low waters. This is exemplified by Figure 2, but more strikingly by the tide curves for the same days at Seattle, Wash., shown in Figure 4. For the two days shown, the average rise and fall of the tide at Seattle was 9 feet. The greatest difference between morning and afternoon high waters during these two days was less than a foot, but morning and afternoon low waters differed by 8 feet.

The second form of the mixed type of tide is that in which the difference between morning and afternoon tides is exhibited principally by the high waters. As an example of this type, the tide at Honolulu, T. H., may be instanced. In Figure 5 the tide curve at Honolulu for April 22–23, 1920—the same days as shown in Figure 4—is represented. Here the range of the tide for the two days shown averaged 1.2 feet. Morning and afternoon low waters on these days were practically of the same height, differing by but one-tenth of a foot. Morning and afternoon high waters, however,

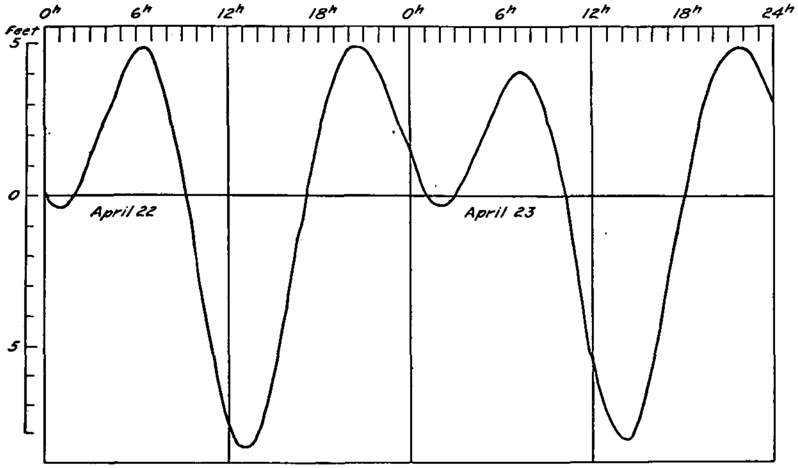

FIGURE 4.—Tide curve, Seattle, Wash., April 22–23, 1920

differed by 1.3 feet. It is of interest to note, too, that the lower high waters for each of the two days did not rise as high as mean sea level, which is represented by the horizontal line of the figure.

A third form of the mixed type of tide lies midway between the two forms discussed above. In this third form the diurnal inequality

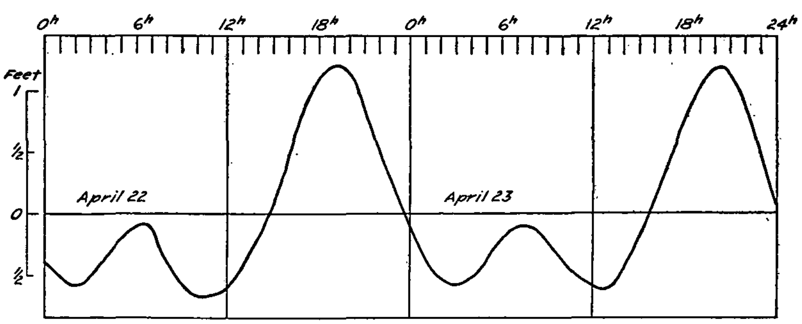

FIGURE 5.—Tide curve, Honolulu, Hawaii, April 22–23, 1920

is exhibited in equal degree by the high and low waters. This form is typified by the tide curve for San Diego, Calif., for April 22–23, 1920, shown in Figure 6. This tide curve, it is to be noted, is for the same two days as shown in Figures 4 and 5. The diurnal inequality in Figure 6 is seen to be very nearly the same in both the high and low waters. For the two days shown, morning and afternoon high waters differed by about 2 feet, while morning and afternoon low waters differed by about 2½ feet.

The different forms of the mixed type of tide can be shown to result from different combinations of the daily and semidaily tides. As an example, suppose that at a given place the daily and semidaily tide-producing forces give rise to daily and semidaily tides of equal range and that the phases of these are such that the high water of the semidaily occurs at the same time as the high water of the daily. This is shown graphically in Figure 7 in which the dotted curve represents the semidaily tide and the dashed curve the daily tide. The height of the resultant tide at any moment will obviously be the sum of the heights of the semidaily and daily tides at that moment. In Figure 7 the resultant tide is shown by the full-line curve.

In the particular case illustrated by Figure 7 it is seen that the tide resulting from the combination of the daily and semidaily tides is a mixed tide with the inequality featured wholly in the high

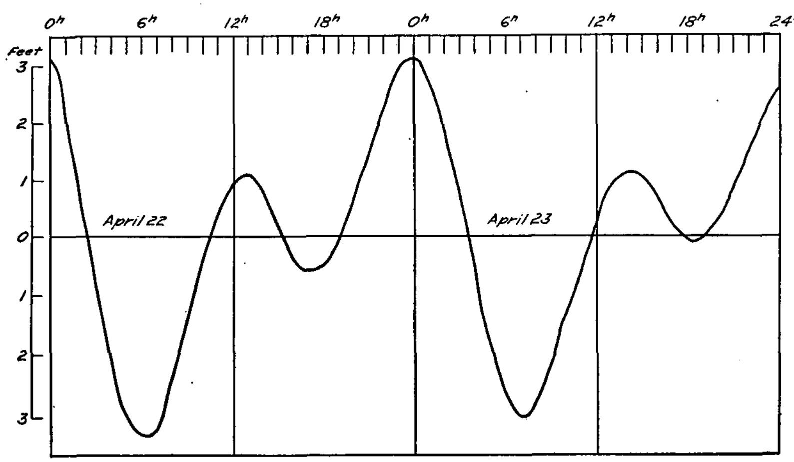

FIGURE 6.—Tide curve, San Diego, Calif., April 22–23, 1920

waters, resembling closely the tide curve for Honolulu in Figure 5. If the semidaily and daily constituents of the tide have such phases that their low waters coincide, the resultant tide will be of the mixed type with the inequality wholly in the low waters. Graphically this would be represented by turning Figure 7 upside down and bearing in mind that time is now reckoned from right to left. This case resembles the tide curve for Seattle shown in Figure 4. Finally if the daily and semidaily constituents of the tide have such phases that they are at mean sea level at the same instant, the resultant tide will be of the mixed type with the inequality featured in equal degree by both high waters and low waters. In the latter case the resultant tide curve resembles the tide curve for San Diego shown in Figure 6.

The illustrative examples discussed in the two preceding paragraphs were limited to three cases in which the phases of the daily and semidaily constituents of the tide were different but their ranges equal. If now we take combinations of daily and semidaily constituents of different ranges and also of different phases it is clear that a very great variety in the forms of the mixed type of tide will result. And as a matter of fact a very great variety of forms of the mixed type of tide is illustrated by the tides actually observed in the seven seas.

The diurnal inequality in the tide at any place varies throughout the month in accordance with the moon's declination. When this declination is small—that is, when the moon is on or close to the Equator—the diurnal inequality is least; while, when the declination is large, near the times of the moon's maximum semimonthly north or south declination, the diurnal inequality is greatest. This gives rise to several features which require consideration here.

In the first place, as a result of the varying diurnal inequality, tides of the mixed type resemble the semidaily type during those times of the month when the moon is close to the Equator. The upper curve of Figure 2, representing the tide curve for San Francisco on April 15–16, 1920, illustrates this nicely. Likewise at times when the declination of the moon is large, the semidaily type of tide will

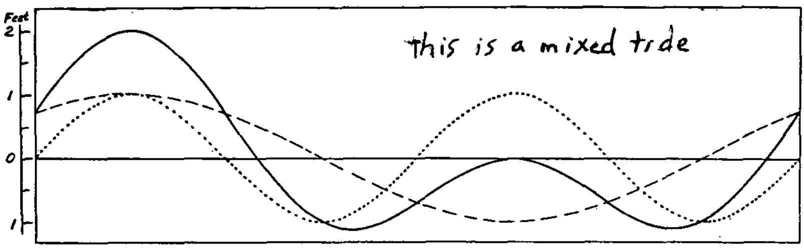

FIGURE 7.—Combination of a daily and semidaily tide

exhibit relatively large inequality, resembling the mixed type of tide at such times. Hence in assigning the tide at any place to a particular type, reference is made to the predominating characteristics of the tide at that place. If for the greater part of the month the tide at a given place exhibits little inequality, it is classed as of the semidaily type. If during the greater part of the month the tide exhibits considerable inequality, it is classed with the mixed type.

It follows, too, that no sharp line of demarcation can be drawn between the semidaily type of tide on the one hand, and the mixed type on the other. For technical purposes the tidal mathematician, by means of the harmonic constants, defines the type of tide with reference to definite ratios between the semidaily and daily constituents of the tide. But here it is unnecessary to enter into that phase of the subject.

Not only is it difficult to draw a sharp line of demarcation between the semidaily and mixed types of tide, but it is also difficult to draw one between the mixed and the daily types. For it is clear that as the inequality in the tide at any place increases, the difference between the lower high water and the higher low water becomes less and less, until finally the two merge so that but one high and one low water occur; that is, giving rise to a daily tide. This is exemplified by the tide curves for Galveston, Tex., for the period June 22–29, 1920, shown in Figure 8.

Referring to a table of the moon's phases it is found that in the latter part of June, 1920, the moon was on the equator on the 22d, and at its maximum southern declination on the 29th. On the 22d, Figure 8 shows that there was but little diurnal inequality in the rise and

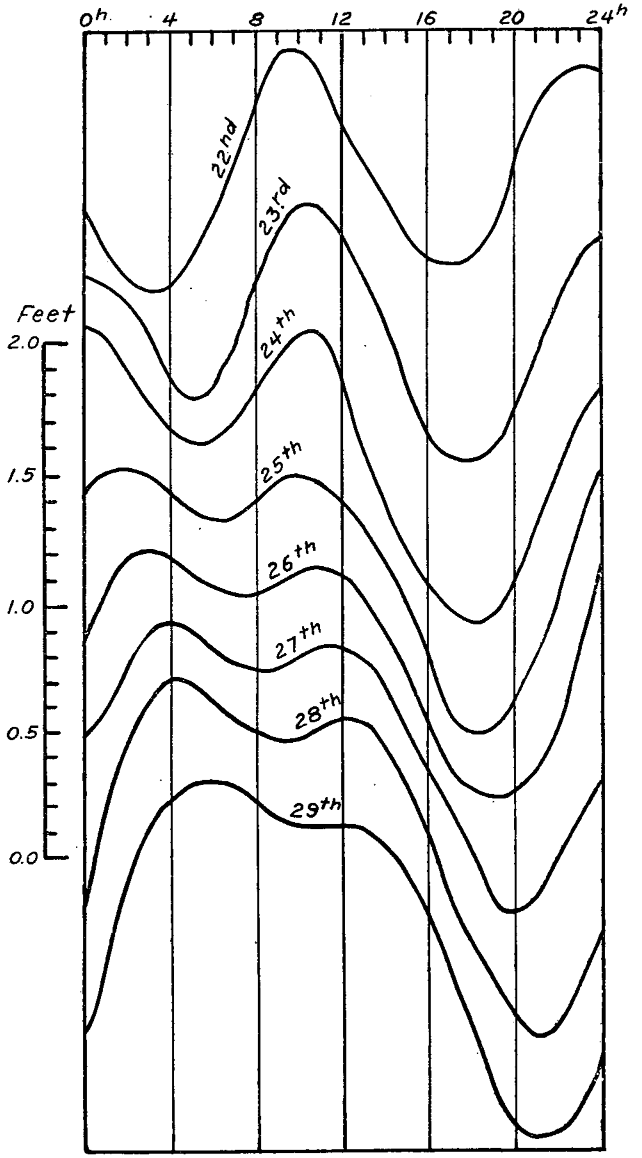

FIGURE 8.—Tide curves, Galveston, Tex., June 22–29, 1920

fall of the tide at Galveston. Thereafter, however, with the increasing declination of the moon the inequality in the tide increased, the higher low water approaching in height the lower high water. On the 28th, there was but 0.1 foot difference between the higher low water and the immediately succeeding lower high water, and on the 29th they merged giving but one high and one low water on that day.

Obviously the existence of different types of tide introduces a complicating factor in the matter of hydrographic datum planes. A datum suitable for one type of tide is clearly not suitable for another. For example, in New York Harbor, where the tide is of the semidaily type, mean low water is a very satisfactory datum, since consecutive low waters do not, as a rule, differ much. But for Seattle this datum is not satisfactory since consecutive low waters may differ by 8 feet or more.

Not only in the choice of the most suitable datum, but also in the accurate determination of the datum plane chosen, does the existence of diurnal inequality complicate matters. For this adds another fluctuation to which the fall of low water is subject and all these different fluctuations must be taken into account in the determination of any desired plane of low water.

IRREGULARITIES IN TIDES

In the consideration of the various features of the tide, thus far, it has been tacitly assumed that the rise and fall of the tide takes place in a regular manner, resulting in a tide curve characterized by regularity of outline as illustrated for the various types of tide. In protected waters during calm weather the tide curve drawn by an automatic tide gauge is a smooth curve wholly free from irregularities.

There are various agencies at work, however, that tend to bring about irregularities in tides. Such irregularities manifest themselves not only in visible irregularities in the tide curve for any one day but also in irregularities in the progression of the times and heights of high and low water.

The chief agency disturbing the regularity of the tide is the wind. The waves, due to the wind, mask the regular rise and fall of the tide by superimposing upon it the rapid change in level of short-period waves. On the record of an automatic tide gauge such waves manifest themselves as numerous small "saw teeth," as illustrated in the bottom curve of Figure 9, which is a reproduction, on a reduced scale, of the tide gauge record at Atlantic City for January 3, 1925. On that day and also on the preceding day there had been heavy winds which gave rise to heavy seas. The waves left their record on the tide curve in the form of "saw teeth"; that is, of rapid changes in the elevation of the surface of the sea.

A more pronounced effect of the wind is seen in the middle curve of Figure 9. A little after 11 o'clock movements of greater amplitude and longer period are seen to have taken place, culminating in the very sharp rise of 1½ feet, a little after 1 p. m. On that day the wind at Atlantic City attained a velocity of 78 miles per hour, this occuring a little before 1 p. m.

These oscillations of relatively large amplitude and period, are not due to ordinary wind waves, but to stationary wave oscillations known as seiches. These are usually most pronounced within a bay or harbor. In Figure 10 are shown the tide curves at Honolulu, T. H., for the period February 2–6, 1923, during which very large seiche movements took place.

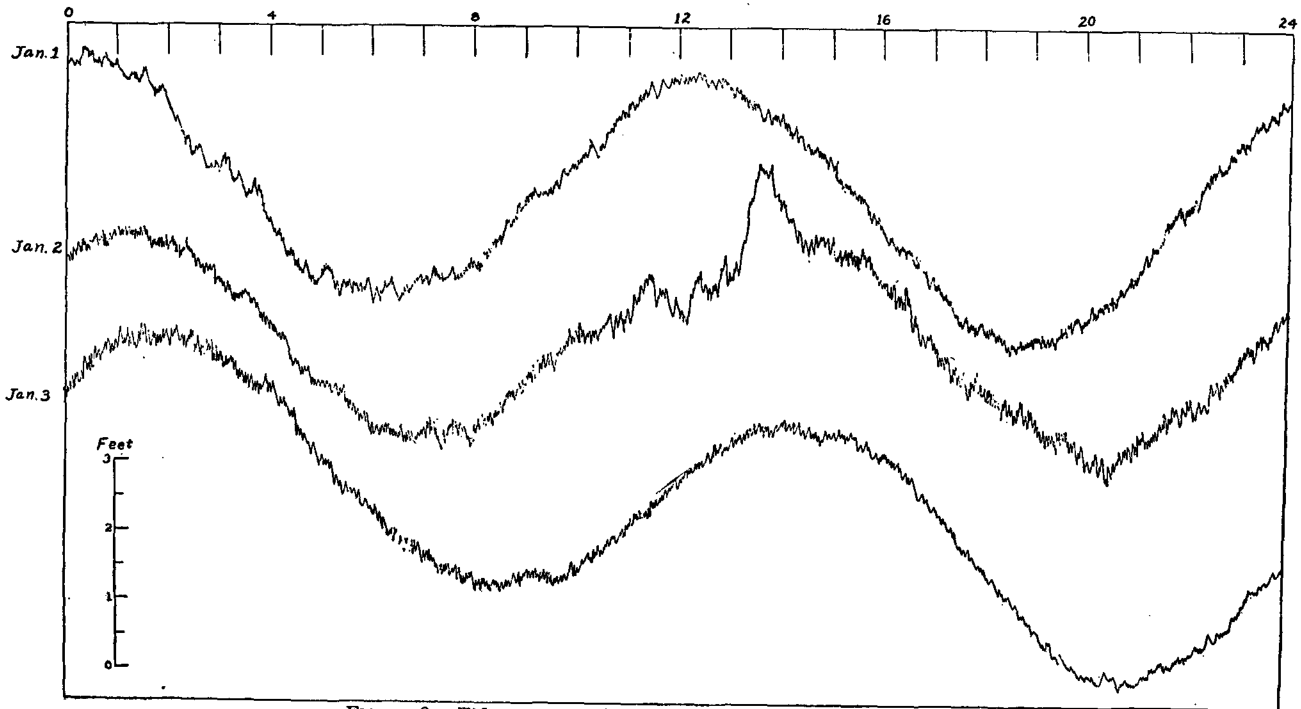

FIGURE 9.—Tide curves, Atlantic City, N. J., January 1–3, 1925

The upper curve of Figure 10 represents the tide curve for Honolulu for February 2, 1923, and exemplifies the normal tide curve for that place. The second curve, for the first half of February 3, likewise is the normal tide curve; but a little before noon, the regularity of the rise and fall is disturbed by a rapid oscillation of the water with a period of about a third of an hour. This seiche, it is of interest to note, has an oscillation of very nearly 3 feet or considerably more than the normal range of the tide.

Seiches may arise from winds, sudden changes in barometric pressure or from seismic waves. The seiches in the middle curve of Figure 9 were due to heavy winds, while those illustrated in Figure 10 were due to seismic waves arising from a quake which occurred on February 3, 1923, off the coast of Kamchatka, about 2,500 miles from Honolulu.

Wind and barometric pressure are also instrumental in changing the level of the sea and thus in changing the heights of high and low water. Onshore winds as a rule raise sea level and thus the heights of high and low water, while offshore winds lower these heights. In the same way decreasing barometric pressure as a rule raises the heights of high and low water while increasing pressure lowers these heights.

In changing the level of the water, winds also bring about irregularities in the progression of the times and heights of high and low water. An example of this is shown in Figure 11, which represents the tide curves at Philadelphia, Pa., for the 5-day period February 28 to March 4, 1914.

For February 28, the tide curve is a normal tide curve for Philadelphia, as is also the tide curve for the greater part of March 1. On that day heavy northwesterly winds began to blow and the water began to recede from the river, so that the low water which would normally have occurred about midnight is completely masked. The recession of the water continued until 14 o'clock on March 2, obliterating the high water that would have occurred a little after 5 o'clock, so that on March 2 but one high water and one low water occurred. On March 3, the tide became more nearly normal and on the 4th the curve is that of the normal Philadelphia tide.

The disturbance in the times of high and low water for March 2 is obvious from the tide curve. The heights, too, were greatly disturbed. The low water which occurred a little after 14 o'clock registered 2 feet below mean low water, whereas the undisturbed low water for that afternoon should have registered half a foot above mean low water.

In the upper reaches of tidal rivers irregularities in the rise and fall of the tide arise also in consequence of the variation of freshwater run-off. During freshet conditions not only are the heights of high and low water raised above their normal heights, but the tidal fluctuation may be completely obliterated.

FLUCTUATIONS OF LOW WATER

NATURE OF THE FLUCTUATIONS

If the depths to which the low waters at any place fall are measured, it is found that they vary within relatively wide limits. In New York Harbor, for example, where the tide is of the semidaily

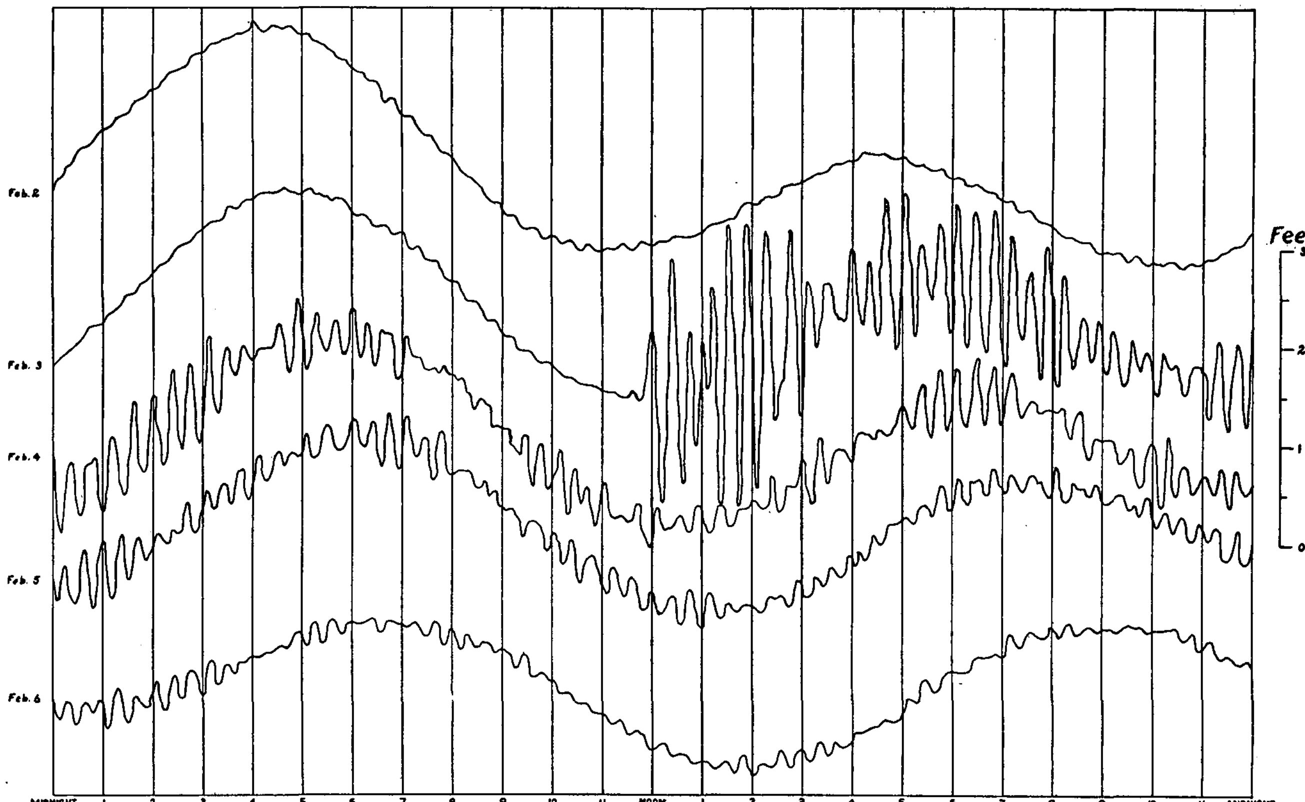

FIGURE 10.—Tide curves, Honolulu, Hawaii, February 2–6, 1923

type, that is, morning and afternoon tides not differing much, it is not at all uncommon for the low water of one day to differ by several feet from the low water of another day during the same month. And within a year the low waters of two different days may differ by more than 5 feet.

In the harbor of Seattle, Wash., even greater differences between low waters occur. Here the tide is of the mixed type and there are several days during each month when successive low waters differ by as much as 8 feet. Within a year the difference in height of two low waters may be as much as 13 feet or even more.

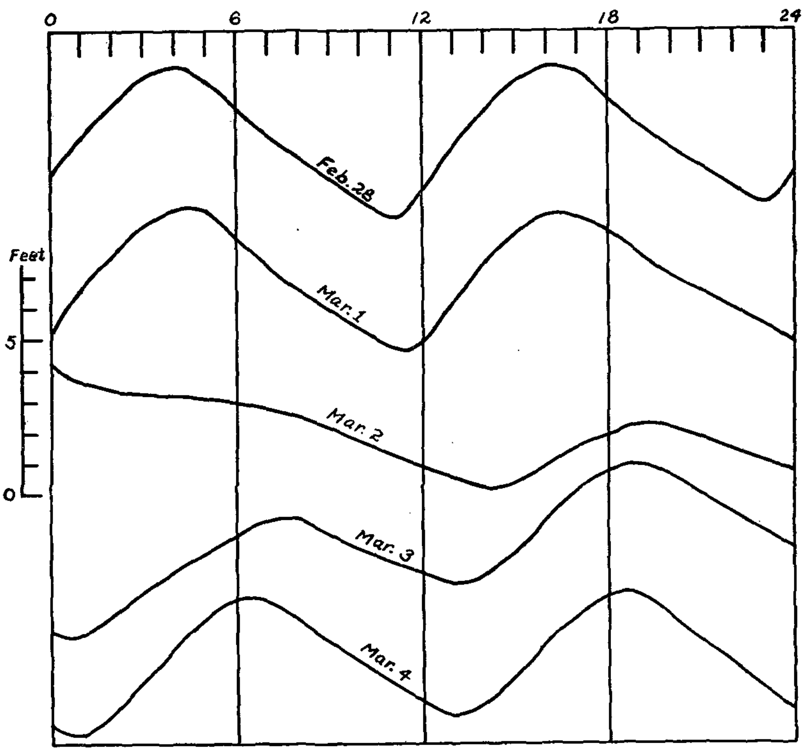

FIGURE 11.—Tide curves, Philadelphia, Pa., February 28–March 4, 1914

On investigation it is found that the fluctuations to which low water is subject are of two kinds, periodic and nonperiodic. The periodic fluctuations are principally those arising from periodic variations of the tide-producing forces, due to the changing positions of the moon, relative to earth and sun. The nonperiodic fluctuations are those arising from variations in wind and weather.

The principal periodic fluctuations in low water were discussed briefly in the previous section under the topical heading of "Variations in Rise and Fall." It was there shown that at the times of new and full moon and also at the time of the moon's perigee, the fall of the tide was greater than usual, while at the times of the moon's first and third quarters, and also when the moon is in apogee, the fall of low water is less than usual. Other periodic fluctuations of longer period have been found, and they will be considered later.

As regards the nonperiodic fluctuations, arising from changes in wind and weather, it is clear that an offshore wind tends to lower the level to which low water falls, while an onshore wind tends to raise the level. The effect of the wind is different at different places, depending on the hydrographic features of the body of water. In general the effect of the wind is greater on shallow bodies of water than on deep bodies.

Variations in barometric pressure likewise bring about fluctuations in the height of the water. This follows from general considerations, for any arm of the sea may be regarded as constituting a huge inverted water barometer. When the atmospheric pressure over this arm of the sea rises, the level of the water will be lowered and when the pressure decreases the level of the water will rise.

The first approximation to the theoretical relation between changes in barometric pressure and the resultant changes in the height of the water may be easily derived. The barometric pressure is measured in inches (or millimeters) of mercury. And since mercury is about 13 times as heavy as sea water, it follows that a change in barometric pressure of 1 inch should be reflected by an inverse change of 13 inches in the level of the water. Approximately this may be stated as follows: The fluctuation in low water in feet should be inversely as the change in barometric pressure in inches.

Actually, the relationship between change in low water and change in barometric pressure is not so simple as derived above. Local hydrographic features enter into this relationship. Moreover, it is the variation in the barometric gradient rather than in local barometric pressure that is the controlling factor. But as an approximate rule the above relationship may be taken to hold.

The various fluctuations to which low water is subject may be most conveniently considered under the headings of daily fluctuations, monthly fluctuations, annual fluctuations, and long-period fluctuations.

DAILY FLUCTUATIONS

The daily fluctuation in low water manifests itself as a difference between the two low waters of the day; that is, between morning and afternoon low waters. For the semidaily type of tide such differences are generally small; only during periods of rapid changes in wind and weather will these differences amount to more than a foot.

The daily fluctuations of low water for a tide of the semidaily type are illustrated in Figure 12, which represents in graphic form the depths to which the successive low waters fell during the month of June, 1920, at Fort Hamilton in New York Harbor. The small circles give the depth of each low water below mean sea level, which is represented by the horizontal line. To indicate the successive low waters clearly, each low water is joined by a straight line to the preceding and succeeding low waters.

June is a month of relatively uniform wind and weather conditions along the Atlantic coast of the United States, and from Figure 12 it appears clearly that during the month shown, morning and afternoon low waters generally differed but several tenths of a foot.

Only twice during the month did the two low waters of a day differ by as much as a foot, and part of this difference is to be ascribed to changes in meteorological conditions. In general the daily fluctuations of low water in tides of the semidaily type are small, except as they may arise from rapid changes in meteorological conditions.

In the mixed type of tide, however, the daily fluctuations due to the moon's declination may be relatively very large, as was found in the discussion of types of tide. In this connection distinction must be made between the different forms of the mixed type of tide. The form in which the inequality is exhibited principally in the high waters will, with regard to the low waters, behave much as the semidaily type of tide; that is, in that form there will be but little daily variation between the two low waters. This is exemplified by the tide at Honolulu illustrated in Figure 5.

In the second form of the mixed type of tide, that in which the inequality is exhibited in about equal degree by both high and low waters, relatively large daily fluctuations of a periodic nature may

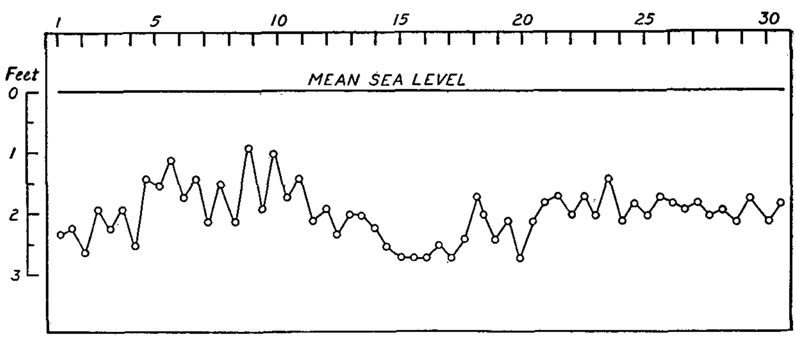

FIGURE 12.—Low water, Fort Hamilton, N. Y., June, 1920

be expected. This is exemplified by the tide at San Francisco for the month of June, 1920, shown in Figure 13. The low waters in this figure were plotted in a similar manner to that employed in Figure 12. To bring out clearly the relationship of the daily fluctuation of low water to the position of the moon, these positions are indicated by symbols explained in the figure.

On the 1st, 15th, and 29th of the month the moon was alternately at its maximum south and north declinations. And Figure 13 shows that the tides about these dates were responding to the moon's high declination by exhibiting relatively large inequality, the difference between morning and afternoon low waters amounting to as much as 4 feet. On the 9th and 22d the moon was over the Equator and the tides on these and the immediately following days show but little inequality. It is of interest to note, too, that at certain times during the month, low water did not fall below mean sea level.

A comparison of Figure 13 with Figure 12 brings out clearly the difference in the daily fluctuation of low water as between the semidaily and the mixed types of tide. This difference becomes even more striking if comparison is made with the mixed type of tide at a place like Seattle where the range of tide is relatively large and

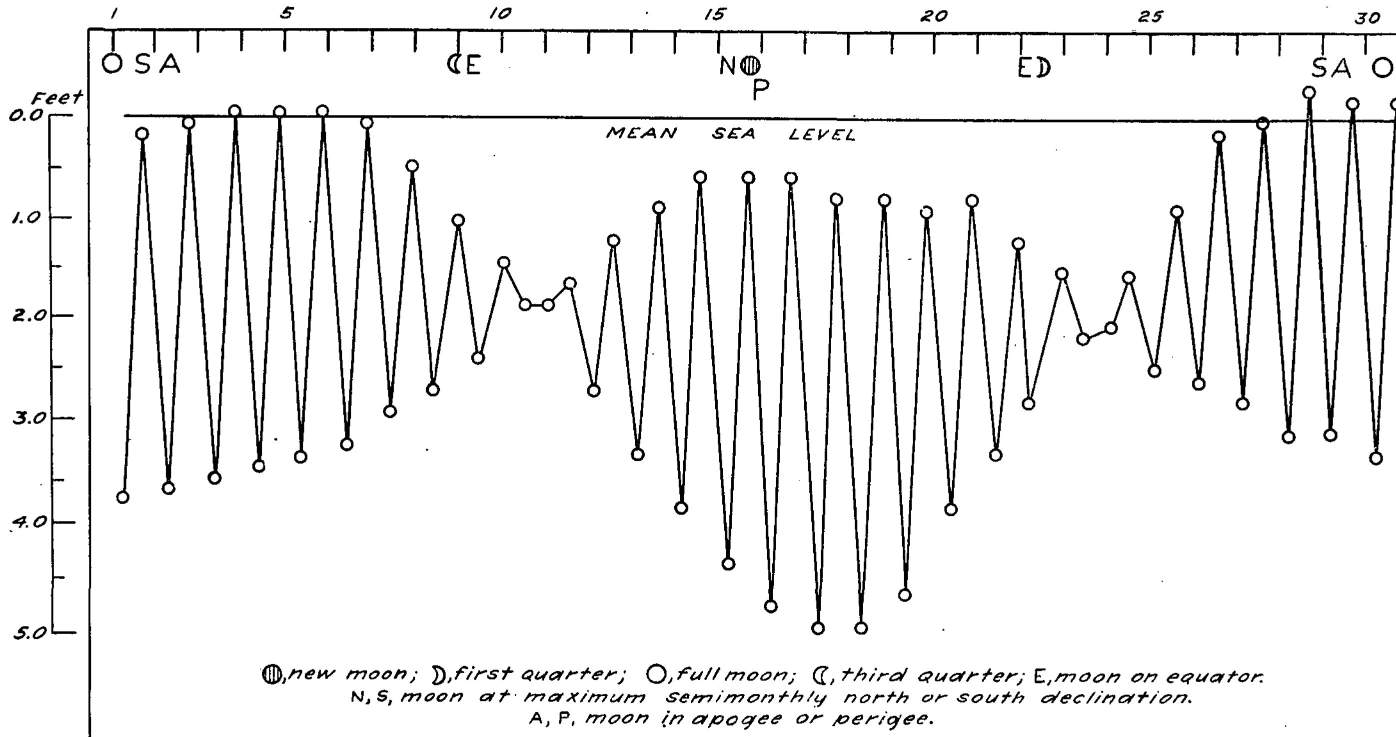

FIGURE 13.—Low water, San Francisco, Calif., June, 1920

where the diurnal inequality is exhibited principally in the low waters. During the same month as shown in Figures 12 and 13, the daily fluctuation in low water at Seattle was as follows: Starting with a difference of 8.3 feet in the two low waters on the 1st, the inequality gradually decreased until the 9th, when it amounted to 1 foot. From this date it increased to 10.3 feet on the 16th, then decreased to 1.1 feet on the 23d, and then again increased to 8.4 feet on the 30th.

MONTHLY FLUCTUATIONS

Within a month much larger fluctuations in low water may be expected than within a day. Figures 12 and 13 may be taken as typifying the periodic monthly fluctuation of low water in the semidaily and mixed types of tide respectively. In New York Harbor, during the month represented in Figure 12, the difference between the highest and lowest values of low water was 1.8 feet. In San Francisco Bay during the same month this difference was 5 feet and at Seattle it was 10.5 feet.

June being a month of relatively uniform conditions of wind and weather on both the Atlantic and Pacific coasts of the United States, the monthly fluctuations considered above are primarily periodic fluctuations. Superimposed on these periodic fluctuations are fluctuations arising from variations in wind and weather. Thus, in New York Harbor during the month of January, 1914, the difference between the highest and lowest values of low water was 8.1 feet; in San Francisco Bay this difference was 5.4 feet in December, 1923, and at Seattle it was 13.5 feet in January, 1916.

In the semidaily type of tide, the periodic monthly fluctuation in low water is primarily that depending on the phase or parallax of the moon. In the mixed type of tide, however, the primary periodic monthly fluctuation depends on the declination of the moon. In the daily type of tide the periodic monthly fluctuation likewise depends primarily on the declination of the moon, but generally it is small.

ANNUAL FLUCTUATIONS

If low water were subject only to daily and monthly fluctuations, it is clear that by averaging the varying heights of low water at any given place for a period of a month, an average value of low water would be derived which would remain constant from month to month. On investigation, however, it is found that monthly values of low water differ, sometimes by relatively large amounts. In Figure 14 are plotted the average monthly heights of low water for the four-year period, 1925–1928, at Atlantic City, N. J., and Seattle, Wash.

In Figure 14 the small solid circles give the relative heights of the monthly low waters, the upper diagram being for Atlantic City and the lower for Seattle. The change from month to month is seen to vary from less than a tenth of a foot to more than three-quarters of a foot. At first glance the fluctuation from month to month appears to be haphazard, being sometimes higher and sometimes lower. But on more careful examination, a large element of periodicity appears. At Atlantic City low water is seen to be low in the winter months and high in the summer and fall months. At Seattle, on the other hand, low water is seen to be high in the winter months and low in the summer months.

Detailed investigation of the matter brings to light the fact that the fluctuation of low water from month to month at any place is in part periodic and in part nonperiodic, the periodic part being primarily of a seasonal character; that is, having a period of a year.

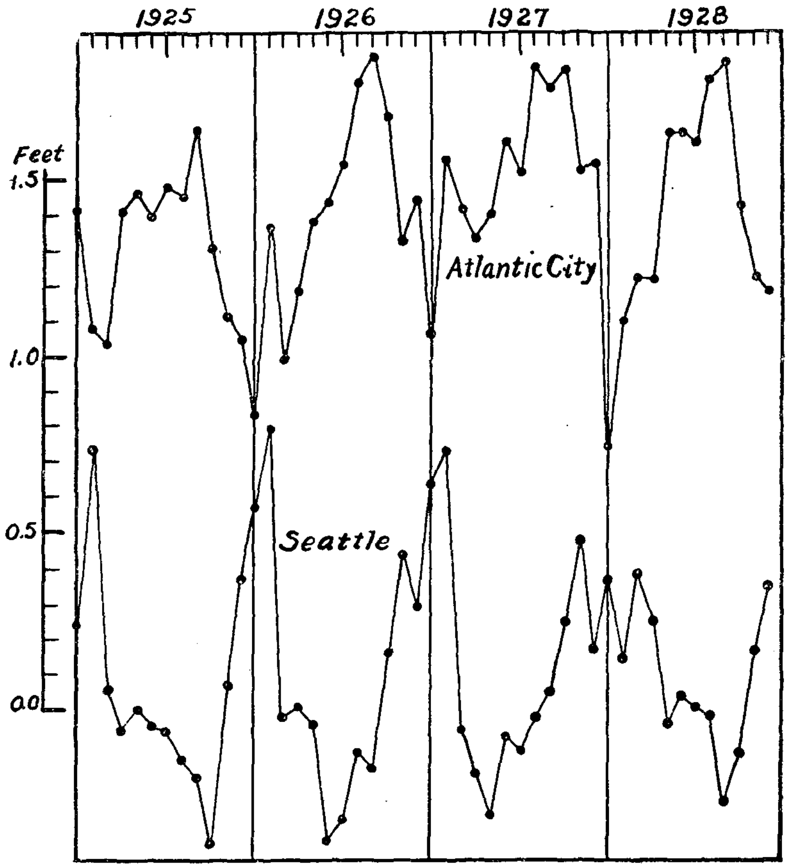

FIGURE 14.—Monthly low water, Atlantic City, N. J. and Seattle, Wash., 1925–1928

The nonperiodic part arises as a result of differences in wind and weather for corresponding months of different years.

To derive the periodic annual variation in low water at any place we need only average, over a number of years, the heights of low water for corresponding months. In this way the nonperiodic fluctuations will be very largely eliminated. Obviously, the greater number of years of observations used, the more nearly are the nonperiodic fluctuations eliminated. But even three or four years are sufficient to bring out the characteristic features of the annual fluctuation of low water at any given place.

In Figure 15 are shown the curves of annual variation in low water at three stations, one each on the Atlantic, Gulf, and Pacific coasts of the United States, each curve being based on a number of years of observations. The annual variation is seen to be different at each of these stations. Indeed, observations made at different places bring out the fact that at any given place the curve of annual variation in low water is distinguished by characteristic features. It is to be noted, however, that for any given body of water, or portion of such body, over which climatic and meteorologic conditions do not differ much, the annual variation in low water likewise does not differ much.

In connection with the fluctuations of low water, distinction must be made between those due to the tide and those due to other causes,

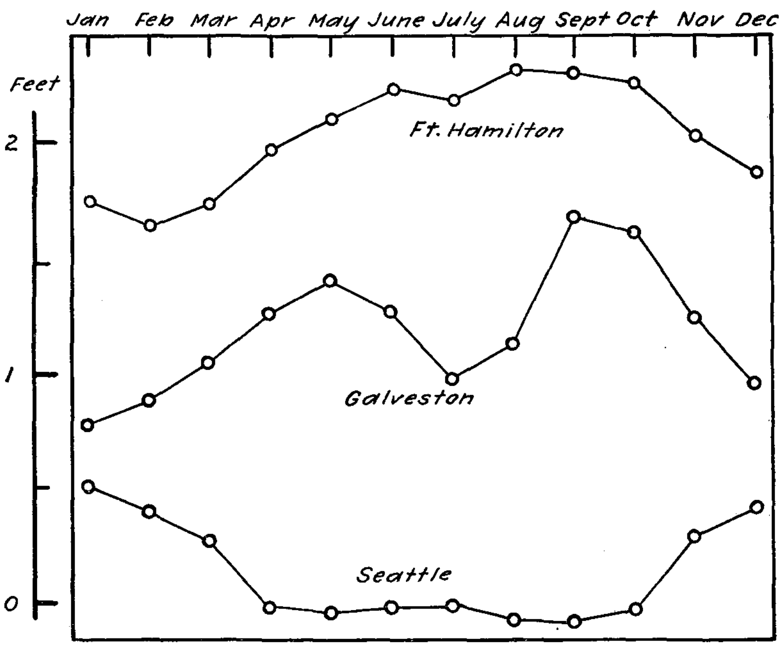

FIGURE 15.—Annual variation in low water, Fort Hamilton, N. Y., Galveston, Tex., and Seattle, Wash.

which have been grouped under the general name of wind and weather. To distinguish these two classes of fluctuations, it is most convenient to regard the nontidal fluctuations in low water as arising from fluctuations in sea level. This makes it a simple matter to separate the two kinds of fluctuations. For it is clear that if we average the varying height of the surface of the sea over a day, the tidal fluctuation for that day is very largely eliminated. In this way fluctuations in sea level as between two days or longer periods are derived.

The periodic fluctuations in low water which were discussed under the headings of daily and monthly fluctuations are brought about by tidal causes, but the annual variation is brought about primarily by an annual variation in sea level. This becomes evident by comparing the monthly heights of sea level with the corresponding monthly heights of low water. In Figure 16 the monthly heights of sea level as derived from a number of years of observations at Fort Hamilton, N. Y., Galveston, Tex., and Seattle, Wash., are shown. Comparing these diagrams with the corresponding diagrams of Figure 15 brings out clearly the fact that the annual variation in low water at any place follows the annual variation in sea level at that place closely.

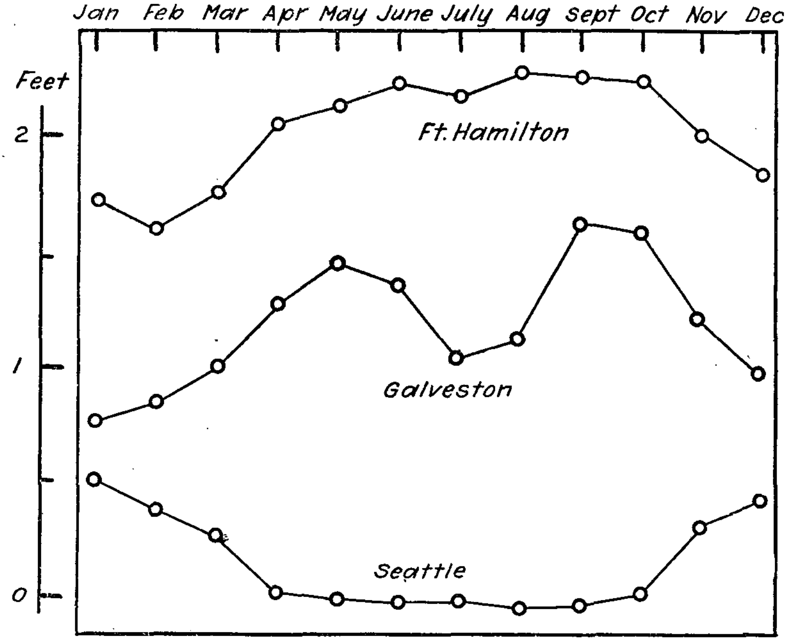

FIGURE 16.—Annual variation in sea level, Fort Hamilton, N. Y., Galveston, Tex., and Seattle, Wash.

LONG-PERIOD FLUCTUATIONS

If the varying heights of low water at any place are averaged over the period of a year the annual fluctuation will be eliminated. If, therefore, there were no fluctuations in low water other than the daily, monthly, and annual fluctuations which have been discussed, yearly heights of low water at any place would remain constant. In Figure 17 the yearly heights of low water are plotted for a number of years, for three stations, one each on the Atlantic, Gulf, and Pacific coasts of the United States.

That differences in the height of low water from one year to another occur is clear at a glance of Figure 17. It is equally clear, however, that these differences are much smaller than the differences in low water from month to month represented in Figure 14. From month to month changes of half a foot or more are not at all uncommon. But from year to year the changes are generally but one or two tenths of a foot and only rarely do they exceed a quarter of a foot.

An inspection of Figure 17 fails to disclose any very clear evidences of periodicity in the fluctuations of low water from year to year. In this connection, however, it is to be remembered that in the change of low water from year to year two different kinds of fluctuations may be present. In the first place, there may be long-period fluctuations due to purely tidal causes. In the second place, there may be fluctuations due to changes in sea level. Because of the mobility of its waters, the sea responds to all forces that tend to

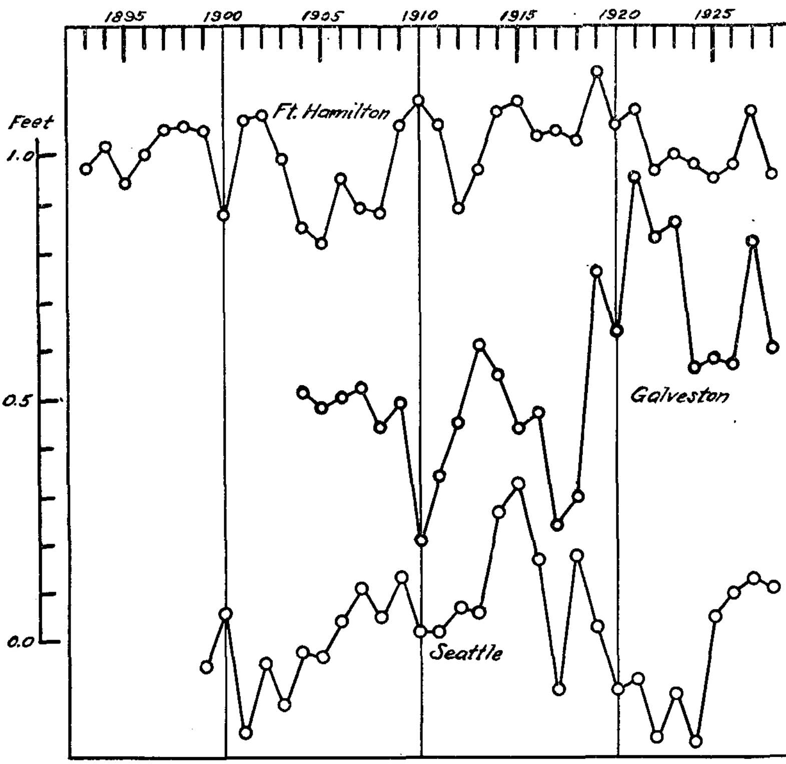

FIGURE 17.—Yearly low water, Fort Hamilton, N. Y., Galveston, Tex., and Seattle, Wash.

disturb it. Hence long-period fluctuations in sea level may arise from long-period fluctuations in such agencies as wind and weather.

Since changes in sea level are reflected by corresponding changes in low water, we may eliminate from the fluctuations in low water shown in Figure 17 the fluctuations due to changes in sea level. This is easily done by subtracting the heights of low water for each year from the corresponding yearly heights of sea level. This will give the fall of low water below sea level due to tidal causes alone. In Figure 18 is shown the fall of low water below sea level for each of the three stations represented in Figure 17.

The open circles of the diagrams in Figure 18 represent the yearly heights of low water below yearly sea level at each of the three stations, the scale of heights being indicated by the scale to the left. The horizontal line associated with each of the diagrams represents the average fall of low water below sea level derived from the series of observations at each station. This average fall in feet is indicated for each station. Thus at Fort Hamilton the average fall of low water below sea level, as derived from the observations from 1893 to 1928, inclusive, is 2.40 feet. At Galveston the average fall is 0.51 foot and at Seattle it is 3.82 feet.

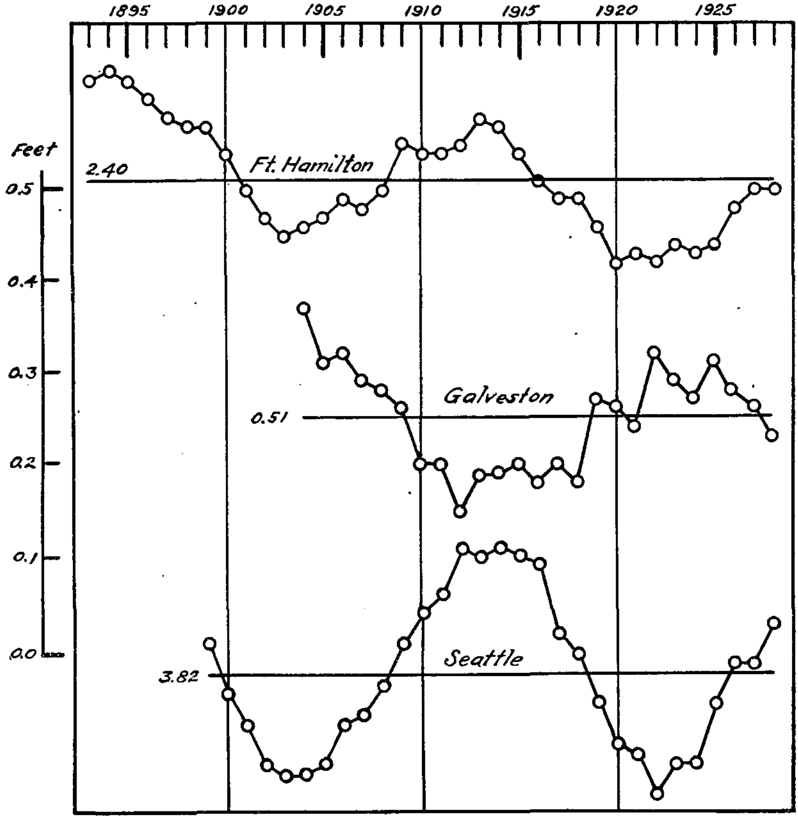

FIGURE 18.—Yearly low water below sea level, Fort Hamilton, N. Y., Galveston, Tex., and Seattle, Wash.

While the yearly heights of low water as shown in Figure 17 gave no clear evidence of the existence of periodicity in the fluctuation of low water from year to year, the evidence in Figure 18 is positive. A fluctuation with a period of about 19 years is clearly indicated, and from the theory of tides such a fluctuation is to be expected. The inclination of the lunar orbit to the plane of the Equator varies within a period of 18.6 years and this is reflected in a variation in the fall of low water below sea level.

The periodic variation in the inclination of the lunar orbit has different effects on the daily and semidaily constituents of the tide. When this inclination is greatest the daily constituent of the tide has its maximum rise and fall, while the semidaily has its minimum. Similarly, when the inclination is least the semidaily constituent has its maximum rise and fall and the daily its minimum. This explains why in Figure 18 the curve of fluctuation in yearly low water below sea level for Fort Hamilton is opposite in phase to that for Seattle.

It now remains to consider whether there are any long-period fluctuations in low water which arise from fluctuations in sea level. This resolves itself into the consideration of the question of the

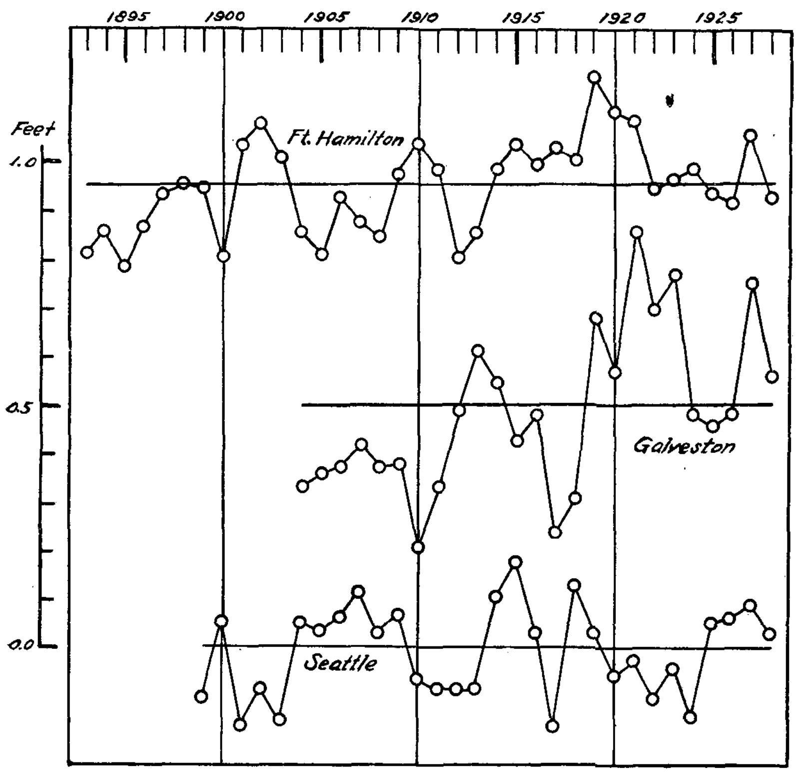

FIGURE 19.—Yearly sea level, Fort Hamilton, N. Y., Galveston, Tex., and Seattle, Wash.

long-period fluctuations in sea level. In Figure 19 the yearly heights of sea level for Fort Hamilton, Galveston, and Seattle are shown. The open circles in the figure give the yearly heights of sea level, while the horizontal line associated with each diagram represents the average or mean sea level for each station derived from the series of observations.

Each of the three diagrams of Figure 19 gives evidence of a fluctuation in sea level with a period of something like eight or nine years. Whether these are true periodic fluctuations or not is at the present time not known. Nor is it known to what agencies such periodic fluctuations are due. In general, fluctuations in sea level from year to year are ascribed to the effects of wind and weather. In the present instance it is sufficient to note that in addition to long-period fluctuations in low water due to tidal causes there are evidences also of long-period fluctuations arising from fluctuations in sea level.

PRINCIPAL CHART DATUMS

VARIETY OF LOW-WATER DATUMS

The existence of periodic fluctuations of various kinds in the fall of low water makes possible the choice of a great variety of low-water datums at any given place. Thus we may take the datum determined by the average value of low water at that place, or the datum of mean low water. Or we may use the average of only the lower low waters; that is, the datum of lower low water. Other low-water datums may be defined by averaging the low waters that occur at specified times, as, for example, at spring, neap, perigean, apogean, or tropic tides. The list can be further extended by datums defined by such combinations as perigean spring low water, or tropic perigean lower low water, etc.

For the practical purposes of datum planes for nautical charts, however, it has been found unnecessary to make use of more than half a dozen different datums. The more important that have been so used are mean low water, lower low water, spring low water, monthly lowest low water, and the so-called harmonic tide plane. Before discussing these in detail it will be of advantage to take up at this point the considerations that govern the choice of a datum.

CONSIDERATIONS GOVERNING CHOICE OF DATUM

There are four chief considerations that must be taken into account in choosing the datum for the chart of a given region. These are: (1) that the depths shown will be the least depths that normally prevail; (2) that the datum represent some natural and easily understood phase of the tide; (3) that it admit of easy and accurate determination; and (4) that it make necessary the use of only small negative corrections for the rise and fall of the tide, and only relatively few of these in number. The most suitable datum for any given region is that which most satisfactorily fulfills the above four conditions.

In the consideration of the relative merits of high-water, sea-level, and low-water datums for chart use, it was found that the superiority of low-water datums lay in the fact that such datums gave at a glance the approximate least depths throughout the region covered. It might, therefore, appear that the datum of lowest low water would be the most suitable datum for chart use since the charted depths would then show the least depths that might be found at any time. However, several objections to such a datum may be urged.

In the first place, what precisely is lowest low water and how can it be determined practically? For it is to be kept in mind that in the hydrographic survey of any given locality a tide gauge is kept in operation for but a relatively short period of time, generally not exceeding several months. And the lowest low water occurring during this period of observation, which almost without exception corresponds with the period of least variable weather conditions, may be several feet higher than the lowest low water during an exceptionally severe storm. The very term "lowest low water" is so vague and indefinite as to preclude its use as a hydrographic datum plane if any pretence to precision is to be made.

But even if it were possible from a relatively short period of observation to determine with precision the lowest low water that may occur in a given locality, are there not serious disadvantages in the use of a datum which makes the depths shown on the chart such as occur only at very rare intervals during the periods of exceptional storms? At the present time, with the draft of vessels approximating the normal low water depths in the channels of many of the most important harbors, the datum of lowest low water would make the depths shown on the chart so shallow as to give a totally false idea of the navigability of these channels.

There is still another objection to the adoption of an extremely low low-water datum. Banks and rocks, which at normal low water are very nearly uncovered, will be shown as visible on charts making use of an extremely low low-water datum. Being shown as visible on the chart, the navigator would attempt to use them as aids in navigation with the resulting danger of very serious mistakes. It is clear therefore that the most suitable datum is not that defining the lowest low water, but one that will show the least depths that ordinarily occur.

The second condition to be fulfilled by a satisfactory datum plane, that the datum represent some natural and easily understood phase of the tide, requires little discussion. The tide is the principal cause of the continually changing depth of water. It is, however, a complex subject and the mariner's purposes are fully served by an acquaintance with the general features of the tide. Hence the importance of using a datum based on an easily understood phase of the tide.

The third condition, namely, that the datum admit of easy and accurate determination, is almost axiomatic. For the immediate purposes of navigation, to be sure, great accuracy in the determination of datum planes may appear unnecessary, since the depths on a chart are generally given only to whole feet. But accurate datum planes permit the determination of any changes in depth that are taking place in a given region. Such changes are generally slow, but clearly of great importance. And only accurate determinations of datum planes permit definite conclusions where such changes are slow.

The fourth condition to be fulfilled by a suitable datum, that it make necessary the use of only small negative corrections for the rise and fall of the tide, and only relatively few of these in number, is so nearly self-evident as to require but little discussion. In general, negative heights in tide tables are troublesome both in the preparation of the tide tables and in their use by the mariner. But if these negative heights are small they may, as a rule, be disregarded by the mariner; for he realizes that since it is impossible to make advance predictions of the weather in connection with the prediction of the tide as given in the tide tables, the predicted heights are to be regarded as approximations to the heights which will actually occur, because of the disturbing effects of wind and weather.

The principal chart datums may now be considered in the light of the conditions to be fulfilled by satisfactory datum planes.

MEAN LOW WATER

The datum of mean low water at any place is defined by the average or mean height of low water at that place. In other words, it is the average height of all the low waters at that place over a considerable period of time. From its definition it is clear that it is the simplest low-water datum and the one most readily derived.

The plane of mean low water also possesses the advantage that from a given series of tide observations it can be determined with a greater degree of precision than any other of the low-water datums. For the best determined mean values will be for those phases of the tide for which the greatest number of observations are at hand. And since mean low water is the average of all the low waters, a greater number of observed values will be at hand for determining this datum than any datum defined by certain selected low waters.

The advantages possessed by the plane of mean low water clearly makes it the datum to be used wherever it is applicable. In regions where the fluctuations in low water are relatively small this datum is a most satisfactory one for use on charts. It is, therefore, adapted to the semidaily tide except in regions where very large tides obtain. It is also suitable for that form of the mixed type of tide in which the inequality is exhibited principally in the high waters. The Coast and Geodetic Survey makes use of the datum of mean low water for its charts covering the Atlantic coast of the United States.

In regions with large range of tide of the semidaily type the datum of mean low water may give relatively large negative corrections for the tide. In such cases it is possible to retain all the advantages inherent in the plane of mean low water by choosing as the chart datum a plane one or more feet below mean low water.

LOWER LOW WATER

In contradistinction to the datum of mean low water, the datum of lower low water is determined by the mean value of the lower low waters alone. From any given series of tide observations, therefore, there will be half as many observed lower low waters for the determination of this datum as for the determination of the datum of mean low water. In regard to ease as well as accuracy of determination the datum of lower low water ranks immediately below mean low water but ahead of the other low-water datums.

From its name it is clear that the datum of lower low water is the most suitable one for that form of the mixed type of tide in which the diurnal quality is featured by the low waters. This datum is used on the Coast and Geodetic Survey charts covering the Pacific coast of the United States. It is also suitable for regions in which the tide frequently becomes of the daily type; for when a high water and a low water merge to give rise to a daily tide, it is clear that the single low water of the day is the lower low water.

SPRING LOW WATER

The datum of spring low water, or mean low water springs as it is sometimes called, is defined as the average value of the low waters that occur at spring tides, that is the large tides following new and full moon. Since these occur fortnightly, it is clear that a relatively long series of observations is required to determine this datum with any degree of precision.

The datum of spring low water has been used in various countries, especially for tides of the semidaily type which have a large range of tide and which are characterized by large monthly fluctuations depending on the phase of the moon. Because of the relatively long series of observations necessary for an accurate determination of the plane, it has not been, as a rule, as well determined as is now desirable. This makes it difficult to correlate charts of contiguous areas using this datum, unless the relations of the datums to mean sea level are expressly stated.

MONTHLY LOWEST LOW WATER

The datum of monthly lowest low water is defined by the average value of the lowest of the monthly low waters; that is, if from a given series of tide observations the lowest tide of each month is picked out and the average value of these lowest tides determined, the result will be the datum of monthly lowest low water.

The datum of monthly lowest low water has not been used very much. It is clearly a datum lower than the three datums previously discussed, but it can not be as accurately determined from a given series of observations. It is, however, especially suitable for use in regions characterized by small range of tide subject to considerable irregularity in rise and fall because of variable wind and weather conditions.

THE HARMONIC TIDE PLANE

The harmonic tide plane or the Indian tide plane, as it is frequently called, has been used for a number of ports in India. It is defined as the datum that lies below mean sea level a distance given by adding the amplitudes of the following components of the tide: Principal lunar semidiurnal, principal solar semidiurnal, principal lunisolar diurnal, and principal lunar diurnal components. In the notation used in the harmonic analysis, it may be written as follows: $MSL-(M_2+S_2+K_1+O_1)$. This datum plane is sometimes called also the plane of Indian spring low water. From its definition in terms of the harmonic constants, it corresponds approximately to tropic spring lower low water.

For the purposes of the tidal mathematician, the harmonic analysis provides the most satisfactory and the most powerful method for the analysis and prediction of tides. Harmonic analysis, however, is a highly specialized mathematical process and necessitates a very considerable amount of time-consuming computations. Moreover, datums defined by harmonic constants are not nearly so well understood by the mariner and hydrographic surveyor as are datums based on easily observed phases of the tide.

In this connection, too, it is to be observed that from a given series of tide observations, the precision with which a datum plane can be determined is the same whether derived from an harmonic analysis or from a low water tabulation. It is, however, a much simpler matter to tabulate tide observations with regard to some low water phase than to subject them to an harmonic analysis. As a rule, therefore, a chart datum based on some observed phase of the tide is to be preferred to a datum defined by harmonic constants.

DETERMINATION OF DATUM PLANES

PRINCIPLES INVOLVED

The accurate determination of datum planes is a problem that falls within the province of the subject of tides. For the details of methods employed in the determination of datum planes, reference must be made to manuals dealing with this phase of the subject of tides.[1] Here it is necessary to consider only the principles involved in the determination of datum planes.

In the section devoted to the fluctations of low water, it was found that the fall of low water was subject to fluctations both periodic and nonperiodic in character. The periodic fluctations have periods varying in length from a fortnight to approximately 19 years. The nonperiodic fluctations, arising from variations in wind and weather, may be assumed to balance out in a period of 19 years. Hence, a period of 19 years is taken to give a primary determination of a tidal datum plane. That is, if nothing occurred over a period of years to change the datum planes at any given place, we should expect two 19-year series to give determinations differing perhaps by not more than a hundredth of a foot.

For chart purposes it is clearly impractical to make primary determinations of datum planes. In connection with other tidal work methods have been developed by means of which sufficiently accurate determinations may be derived from short series of observations. By means of these methods the results derived from a short series of observations are reduced to mean values.

In reducing the results from a short series of tide observations to mean values, advantage is taken of the fact that the fluctuations in low water are much the same over relatively large areas subject to like climatic and meteorologic conditions. By comparing the results of a short series of observations with simultaneous observations at a station where a long series of observations is at hand, corrections may be derived both for the periodic and nonperiodic fluctuations. It is in large part for this purpose that the Coast and Geodetic Survey maintains a number of primary tide stations at carefully selected places along the Atlantic, Gulf, and Pacific coasts of the United States. At these primary tide stations, which are functioning continuously, a number of years of observations are at hand and these are used to reduce to mean values the results derived from short series of observations.

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[1] See, for example, Tidal Datum Planes, U. S. Coast and Geodetic Survey Special Publication No. 135.

ACCURACY OF SECONDARY DETERMINATIONS

Since a primary determination of a datum plane has been defined as that derived directly from a 19-year series of tide observations, datum planes determined from shorter series of observations may be designated as secondary determinations. The precision with which a secondary determination may be derived depends both on the length of the series and on the suitability of the primary station chosen for correcting the results to mean values.

In regard to this latter factor, it is to be observed that as a rule the nearer the primary and secondary stations are to each other the better. But it is not nearness of itself that is important, but the closeness with which the low water fluctuations at the primary station approximate those at the secondary station. It may well happen, therefore, that a more distant primary station is more suitable than a nearer one.

Mean low water.—From any given series of observations the datum of mean low water can be determined with greater precision than any other of the low-water datums since all the low waters are used in determining mean low water. The accuracy with which mean low water may be derived from series of various lengths is best exemplified by illustrative examples.

The shortest series of tide observations that may be used to derive mean low water with any pretense at precision is one day. In the case of such a short series it is important to choose a day of calm weather and to use a fairly close primary station for correction to mean values. To illustrate the accuracy with which mean low water may be derived from one day of observations, we may use the tides observed at Atlantic City during the first 10 days of May, 1919. As primary station for correcting the results of these observations to mean values, Fort Hamilton, at the entrance to New York Harbor, will be used. Fort Hamilton is about 100 miles distant from Atlantic City. The latter fronts directly on the open sea, while Fort Hamilton lies within a protected waterway which may be considered as a continuation of the Hudson River.

In Table 1, columns 2 and 3 give the tide data for Fort Hamilton and columns 7 and 8 the corresponding data at Atlantic City for the days in question. Columns 4 and 9 give, respectively, the fall of low water below sea level at each place, the value for each being clearly the corresponding daily values of low water on staff subtracted from the value of sea level on staff. These six columns of figures constitute the observed data.

The first correction necessary is that for the variation in sea level from day to day. From a long series of observations at Fort Hamilton the value of mean sea level on the staff at that place is 6.00 feet. The difference therefore between the value of sea level on each of the days in Table 1 and 6.00 feet gives the correction necessary to reduce the daily value of sea level to mean sea level, this correction being shown in column 5 and the corrected values of sea level at Atlantic City, or mean sea level at that place from each day of observation, in column 10.

The second correction necessary is for the periodic fluctuations in low water. This is determined by deriving the factor necessary to correct the daily fall of low water below sea level to a mean value.

At Fort Hamilton a long series of observations gives the value of mean low water on the staff as 3.59 feet; hence the fall of mean low water below mean sea level at Fort Hamilton is 6.00−3.59=2.41 feet. The factor to correct the daily fall of low water to mean value is therefore given by dividing the figures in column 4 into 2.41, these factors being given in column 6.

Now by multiplying the daily fall of low water below sea level at Atlantic City by the corresponding factors given in column 6, the corrected or mean fall of low water is derived, the results being shown in column 11. Mean low water on staff at Atlantic City for each day is now derived by subtracting the corrected fall of low water from the corrected sea level, the values being given in column 12.

It should be noted that for the 10 days of May, 1919, of Table 1, the daily low water at Atlantic City varied from a minimum value of 3.70 on the 3d to a maximum value of 6.15 feet on the 10th, a difference of approximately 2½ feet. In other words, had the low-water datums been taken directly as derived from each of these two days, a difference of 2½ feet would have resulted. However, after correction to mean values the difference between the datums derived from each of these days of observations is less than a quarter of a foot.

From a long series of observations at Atlantic City, the value of mean low water at this place has been determined as 4.51 feet on the tide staff. For the first five days therefore, low water at Atlantic City, as shown in column 7, was below mean low water, while for the following five days it was above mean low water. It is of interest to note that the derived values of mean low water from each of the 10 days of observations are closer to the well-determined value of 4.51 than the uncorrected values. In every case the corrected values are within half a foot of the best determined value. It may, therefore, be taken in general that from one day of tide observations the datum of mean low water can be derived correct to within half a foot, when corrected by simultaneous observations at a suitable primary station.

TABLE 1.—*Mean low water from one day of observations*

1919	Fort Hamilton, N. Y. MLW=3.59; MSL=6.00					Atlantic City, N. J.					
	Low water on staff	Sea level on staff	Low water below sea level	Correction to sea level	Factor for fall of low water	Low water on staff	Sea level on staff	Low water below sea level	Corrected sea level	Corrected fall of low water	Mean low water
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	Feet	*Feet*	*Feet*	*Feet*		*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*
May 1	2.95	6.37	3.42	−0.37	0.705	4.00	6.98	2.98	6.61	2.10	4.51
May 2	3.15	6.34	3.19	−.34	.755	3.85	6.68	2.83	6.34	2.14	4.20
May 3	3.00	5.90	2.90	+.10	.831	3.70	6.30	2.60	6.40	2.16	4.24
May 4	3.30	6.00	2.70	.00	.893	4.00	6.20	2.20	6.20	1.96	4.24
May 5	3.35	5.78	2.43	+.22	.992	4.05	5.99	1.94	6.21	1.92	4.29
May 6	3.75	5.96	2.21	+.04	1.090	4.75	6.60	1.85	6.64	2.02	4.62
May 7	4.20	6.23	2.03	−.23	1.187	5.00	6.67	1.67	6.4[illegible]	1.98	4.46
May 8	3.90	6.05	2.15	−.05	1.121	4.75	6.48	1.73	6.43	1.94	4.49
May 9	4.35	6.47	2.12	−.47	1.137	5.40	7.00	1.60	6.53	1.82	4.71
May 10	5.65	7.42	1.77	−1.42	1.362	6.15	7.99	1.84	6.57	2.51	4.06

To exemplify the accuracy with which the datum of mean low water may be determined from one week of observations, the observations at Los Angeles Harbor, Calif., for the month of April, 1927, may be used. As primary tide station for correcting these observations to mean value, San Diego, Calif., is suitable. The distance between the two places is about 100 miles.

In passing, it may be noted that the figures in Table 1 exemplify to a limited extent the accuracy with which mean low water can be derived from a week of observations. Thus, from column 7 it is found that the first seven days give low water on staff at Atlantic City as 4.19 feet, while the last seven days give it as 4.87 feet. From the last column of the same table mean low water from the first seven days is derived as 4.37 feet and from the last seven days as 4.41 feet. From a long series of observations mean low water was determined as 4.51 feet. Hence each of the two weeks of observations gives a direct value of low water which differs from the best determined mean low water by 0.32 and 0.36 feet, while the corrected values differ from the best determined mean low water by 0.14 and 0.10 feet, respectively. From each of these weeks of observations, therefore, mean low water is derived correct to within about a quarter of a foot.

In Table 2 are given the data for deriving mean low water from a week of observations at Los Angeles Harbor for the first four weeks of April, 1927, San Diego being used as primary station. The data are arranged in a manner similar to that in Table 1, explained above. Column 7 gives the value of low water for each week at Los Angeles Harbor derived directly from the observations while column 12 gives the value of mean low water derived after correction by comparison with San Diego.

TABLE 2.—*Mean low water from one week of observations*

	San Diego, Calif. MLW=4.62: MSL=6.54					Los Angeles, Calif.					
1927	Low water on staff	Sea level on staff	Low water below sea level	Correction to sea level	Factor for fall of low water	Low water on staff	Sea level on staff	Low water below sea level	Corrected sea level	Corrected fall of low water	Mean low water
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	Feet	*Feet*	*Feet*	*Feet*		*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*
Apr. 1–7	3.64	6.17	2.53	+0.37	0.759	3.75	6.01	2.26	6.38	1.72	4.66
Apr. 8–14	4.45	6.34	1.89	+.20	1.016	4.39	6.13	1.74	6.33	1.76	4.57
Apr. 15–21	4.21	6.26	2.05	+.28	.937	4.29	6.15	1.86	6.43	1.74	4.69
Apr. 22–28	4.55	6.39	1.84	+.15	1.043	4.56	6.23	1.67	6.38	1.74	4.64

An inspection of column 7 of Table 2 shows that the direct values of low water for the first and last weeks differ by 0.81 foot, while the corresponding values after correction, as shown in column 12, differ by 0.02 foot. Furthermore, the maximum difference between the corrected values for the four weeks is but 0.12 foot. From a series of observations covering several years, mean low water at Los Angeles Harbor has been determined as 4.63 feet on the staff of that place. Hence the values of mean low water from each of the four weeks is correct to within one-tenth of a foot. In general, it may therefore be taken that from a week of observations, when corrected by simultaneous observations at a suitable primary station, mean low water can be derived correct to within a quarter of a foot.

From the last column in Table 2 the average value of mean low water as derived from the four weeks of observations is 4.64 feet, which compares with the best determined value of 4.63 feet. From that particular month of observations at Los Angeles, therefore, mean low water is derived very close to its best determined value. Further illustrative examples covering a number of individual months will be of advantage and for this purpose we may take the tide observations at Atlantic City for the year 1919 and derive mean low water for each of the months of that year, using Fort Hamilton, as before, for correcting to mean values. The data are given in Table 3, the arrangement of the table being analagous to that of Tables 1 and 2.

TABLE 3.—*Mean low water from one month of observations*

1919	Fort Hamilton, N. Y. MLW=3.59: MSL=6.00					Atlantic City, N. J.					
	Low water on staff	Sea level on staff	Low water below sea level	Correction to sea level	Factor for fall of low water	Low water on staff	Sea level on staff	Low water below sea level	Corrected sea level	Corrected fall of low water	Mean low water
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	Feet	*Feet*	*Feet*	*Feet*		*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*
January	3.33	5.72	2.39	+0.28	1.008	4.19	6.19	2.00	6.47	2.02	4.45
February	3.43	5.88	2.45	+.12	.984	4.50	6.53	2.03	6.65	2.00	4.65
March	3.58	6.04	2.46	−.04	.980	4.48	6.58	2.10	6.54	2.06	4.48
April	3.62	6.10	2.48	−.10	.972	4.47	6.56	2.09	6.46	2.03	4.43
May	3.93	6.43	2.50	−.43	.964	4.80	6.88	2.08	6.45	2.01	4.44
June	3.97	6.41	2.44	−.41	.988	4.85	6.94	2.09	6.53	2.06	4.47
July	3.83	6.28	2.45	−.28	.984	4.69	6.78	2.09	6.50	2.06	4.44
August	4.10	6.53	2.43	−.53	.992	4.96	7.06	2.10	6.53	2.08	4.45
September	3.96	6.37	2.41	−.37	1.000	4.84	6.87	2.03	6.50	2.03	4.47
October	4.05	6.45	2.40	−.45	1.004	4.94	7.02	2.08	6.57	2.09	4.48
November	4.02	6.49	2.47	−.49	.976	4.96	7.04	2.08	6.55	2.03	4.52
December	3.47	5.93	2.46	+.07	.980	4.50	6.57	2.07	6.64	2.03	4.61

The direct values of low water from a month of observations at Atlantic City during the year 1919 are seen to vary from 4.19 feet in January to 4.96 feet in November, a difference of 0.77 foot. When corrected by comparison with the simultaneous observations at Fort Hamilton the values of mean low water for these two months differ by 0.07 foot.

The best determined value of mean low water at Atlantic City is 4.51 feet. With the exception of the value for February the figures in the last column of Figure 3 show differences from the best determined value of not over one-tenth of a foot. For February the difference is 0.14 foot. But on the Atlantic coast of the United States February is a month of relatively severe weather conditions, so that the greater difference for this month may reasonably be ascribed to that fact. In general, it may be taken that from a month of tide observations mean low water may be obtained correct to within a tenth of a foot.

The value of mean low water from the observations for the year 1919 at Atlantic City, derived by averaging the values in the last column of Table 3, is 4.49 feet, which differs by 0.02 foot from the best determined value. To further exemplify the accuracy with which mean low water may be derived from a year of observations, we may take the observations at Boston, Mass., for the 8-year period 1922 to 1929. As primary station for correcting these observations to mean values, Portland, Me., will be used. The distance between the two places is 100 miles. In Table 4 are given the data and the results derived.

TABLE 4.—*Mean low water from one year of observations*

Year	Portland, Me. MLW=8.62: MSL=13.09					Boston, Mass.					
	Low water on staff	Sea level on staff	Low water below sea level	Correction to sea level	Factor for fall of low water	Low water on staff	Sea level on staff	Low water below sea level	Corrected sea level	Corrected fall of low water	Mean low water
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	Feet	*Feet*	*Feet*	*Feet*		*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*
1922	8.43	13.02	4.59	+0.07	0.974	3.12	8.09	4.97	8.16	4.84	3.32
1923	8.49	13.07	4.58	+.02	.976	3.11	8.08	4.97	8.10	4.85	3.25
1924	8.50	13.08	4.58	+.01	.976	3.14	8.10	4.96	8.11	4.84	3.27
1925	8.47	13.00	4.53	+.09	.987	3.11	8.03	4.92	8.12	4.86	3.26
1926	8.46	12.98	4.52	+.11	.989	3.18	8.06	4.88	8.17	4.83	3.34
1927	8.62	13.10	4.48	−.01	.998	3.30	8.17	4.87	8.16	4.86	3.30
1928	8.59	13.02	4.43	+.07	1.009	3.25	8.07	4.82	8.14	4.86	3.28
1929	8.62	13.00	4.38	+.09	1.021	3.33	8.09	4.76	8.18	4.86	3.32

For the eight years given in Table 4, the yearly values of low water at Boston, as derived directly from the observations, varied from a minimum of 3.11 feet to a maximum of 3.33 feet, or a difference of 0.22 foot. After correcting to mean values by comparison with simultaneous observations at Portland, the greatest difference between the yearly values of mean low water was 0.09 foot. The average of the eight yearly values of mean low water at Boston is 3.29 feet, and this may be accepted as a well determined value of the datum of mean low water at that place. Each of the yearly determinations of mean low water is therefore within 0.05 foot of the well-determined value. In general it may be taken that a year of observations will give the datum of mean low water correct to within half a tenth of a foot, if observations at a suitable primary station are at hand for reducing to mean values.

The eight years of observations listed in Table 4 permit grouping into two 4-year series. The first four years give the direct value of low water as 3.12 feet and the second group gives 3.26 feet. These values compare with the well-determined value of mean low water of 3.29 feet and show that even so long a series as four years is not sufficient to give a direct determination of mean low water.

From the last column of Table 4, the value of mean low water from the first 4-year series is 3.28 feet, while from the second 4-year series, it is 3.31 feet. These values differ from the best determined value of mean low water by only 0.01 and 0.02 foot respectively. By comparison with a properly situated primary station, therefore, the datum of mean low water may be derived correct to within several hundredths of a foot from a 4-year series.

In the discussion of the determination of the datum of mean low water from series of various lengths, it has been tacitly assumed that no changes in the datum had taken place. Where such changes occur, it is clear that a series of observations prior to the change will give a different datum from a series of observations made after the change has taken place. This question of change of datum is of importance and will be considered in greater detail later.

Lower low water.—Like the mean low water, a primary determination of the datum of lower low water may be derived directly by averaging all the lower low waters from a series of observations 19 years in length. Secondary determinations, derived from shorter series of observations, necessitate the correction to mean values by comparison with simultaneous observations at some suitable primary station.

The computations required in deriving a secondary determination of lower low water are somewhat more complicated than is the case with mean low water.[2] The accuracy of such determinations may be briefly summarized as follows: When compared with observations at a suitable primary station, the datum of lower low water may be derived correct within a foot from one day of observation, within half a foot from a week of observations, within a quarter of a foot from a month of observations, within a tenth of a foot from a year of observations and within half a tenth of a foot from four years of observations. In general, therefore, the accuracy with which the datum of lower low water can be derived from a series of equal length is about half that of the datum of mean low water.

Other datums.—To derive datums like spring low water, monthly lowest low water or the harmonic tide plane with any degree of precision requires relatively long series of observations. From a series of given length these planes can not be determined with anything like the precision of mean low water and lower low water. Moreover, the computations to reduce the results from short series of observations to mean values are quite involved. As a rule there is no attempt to determine such datums with great precision, reliance being placed on the correlation of these datums with such well-determined datums as mean sea level.

CORRELATION OF DATUMS

If two charts of the same region make use of different datums, the depths shown on these charts will be different. For example, if on one chart the datum used is spring low water while on the other the datum is mean low water the depths on the two charts may differ by a foot or more.

Ordinarily, it is assumed that these differences in depths represent the difference in the datums used. Suppose, however, that the charts are based on different surveys made a number of years apart, the differences in depth between the two charts then represent not only

[2] See Tidal Datum Planes, Special Publication No. 125, pp. 117–124.

the difference between the two datums, but also actual changes in depth due to erosion or silting. To determine whether such actual changes have taken place, it is necessary to correlate the two datums; that is, to determine the relation of the two datums to each other.

A similar problem arises when charts of contiguous areas make use of different datums, for the depths on the one chart are not directly comparable with the depths on the other chart. If, however, the relation of the one datum to the other is known, the depths on the two charts become comparable. Thus, if the difference between the two datums is 1 foot, like depths will be shown as 1 foot greater on the chart using the higher datum than on the chart using the lower datum.

If the information on a chart relative to the datum used merely designates the datum, this will not permit a correlation between different charts when different datums are used. But if, in addition, the relation of the datum to mean sea level is given, this additional information permits the correlation of different datums. For example, suppose one chart makes use of the datum of lower low water while the other makes use of the datum of mean low water. This information of itself permits no correlation of the two datums. But if in addition the one chart states that lower low water is 3.3 feet below mean sea level, while the other chart states that mean low water is 2.1 feet below mean sea level, then obviously the one datum is 1.2 feet below the other and the depths on the two charts become immediately comparable.

In the correlation of datums, therefore, the relation of the datum used to mean sea level is the basic information. So soon as this relation is known, different datums can be immediately correlated. It is to be observed that in the determination of datum planes it is always necessary to determine mean sea level; so that this basic relation of a datum to mean sea level is obtained at the same time that the datum is determined.

CHANGES IN DATUMS

ASSUMPTION OF CONSTANCY

In the use of the various tidal datums for chart purposes, it is generally taken for granted that such datums remain constant over relatively long periods of time; that is, it is taken for granted that the plane of mean low water, lower low water, or other tidal datum plane, when accurately determined at any place at one time, will correspond exactly with the same plane accurately determined at another time.

This constancy of tidal datums, however, is based on two tacit assumptions. It involves in the first place the assumption of coastal stability and in the second place the assumption of tidal constancy. In a region in which the coast is stable—that is, one which is neither subsiding nor emerging, and in which no change in tidal régime is taking place—datum planes determined at different times will correspond exactly. But if changes in coastal stability or in tidal régime take place, changes in datums are bound to follow. These matters, therefore, merit detailed consideration.

COASTAL STABILITY

The determination of a datum plane involves the determination of the elevation of this plane with respect to some fixed point on shore; that is, the datum is determined as corresponding to some definite reading on a fixed tide staff or as a certain number of feet below a bench mark on shore.

Now, suppose that after a datum plane has been determined at a given place, the coast in the vicinity subsides, whether suddenly or gradually over a number of years, is for the present discussion immaterial. After a number of years, during which this subsidence amounts to *A* feet, another determination of the datum plane with respect to the same tide staff or bench mark is made. Clearly this second determination of the datum plane will not correspond to the same reading on the tide staff, nor be the same number of feet below the bench mark as the first determination, but will be *A* feet higher. In other words there will be a change in the datum of *A* feet.

If the subsidence of the coast in question has been uniform over a considerable area, the change in datum will be accompanied by a corresponding increase of *A* feet in the depth of the water in the vicinity. But an increase in depth can not of itself be taken to indicate a change in datum; for obviously change in depth may arise also from erosion of the sea bottom. As a matter of fact changes in topography of sea bottom take place more frequently than changes in datum.

Changes in datum planes, with corresponding changes in depth, arise also in connection with an emerging coast. In this case the changes in both datums and in depths are of a reverse character from those discussed above.

With regard to periods of time measured in thousands of years, there is indubitable evidence that changes in relative elevation of land to sea have taken place in many regions. For the lesser periods of time involved in everyday affairs, however, such changes are generally so small that they have been disregarded and coastal stability taken for granted, in so far as datum planes for charts are concerned. It is clear, however, that in the course of time coastal stability can not be taken for granted, but must be definitely determined.

It is to be observed in this connection that the accurate determination of datum planes, when related to bench marks, furnishes a ready means for determining with precision changes in the relative elevation of land to sea. If a change in datum as determined at two different times is found, it is evident that the coast has changed in elevation by the amount indicated, provided no part of this change in datum is due to change in tidal régime.

TIDAL CONSTANCY

The determination of a datum plane involves the derivation of the mean value of some continually varying phase of the tide. The variations are both periodic and nonperiodic. The latter variations may be assumed to balance out in a number of years; but the former are assumed to be of a strictly periodic nature; that is, it is assumed that after given periods of time these variations recur in exactly the same way.

Now it is to be noted that the assumption of tidal constancy for any given place is valid only so long as nothing occurs to change permanently the tidal régime at that place. Any change in régime of the tide obviously brings in its train changes in the various high-water and low-water datums. If the range is increased, the high-water datums are raised and the low-water datums are lowered. With a decrease in range the high-water datums are lowered, and the low-water datums raised.

Changes in tidal régime generally take place when changes in the hydrographic features of a region occur. On the open coast it is clear that only profound changes in the hydrographic features can bring about changes in the range of the tide. But in inland tidal waters, because of the relatively limited areas and depths involved, changes in hydrographic features of lesser magnitude, whether due to natural or artificial causes, are sufficient to bring about changes in the range of the tide and thus produce changes in datums.

The quantitative relations subsisting between changes in the hydrographic features of a given body of water and changes in datums are difficult to establish in advance. Qualitatively, however, the direction of the change in datum that will follow given changes in hydrographic features can be determined from general considerations. Tidal rivers furnish illustrative examples.

The tides in rivers are due to the tides sweeping into them from the seas with which they connect, the tide traveling upstream until stopped by falls or rapids, as a rule. The wider and deeper the channel of a river, the freer is the movement of the tide from the open sea, and therefore the greater the rise and fall. With the stabilization of the hydrographic features of the river, a stable tidal régime ensues, and this means a stabilization of datum planes in the river.

Tidal rivers that carry the drainage waters from large areas are subject to influences that tend to change rather than to stability of hydrographic features. During freshet conditions, the channel in some parts may become deeper or wider, while in other parts deposition may take place, making the channel narrower or shallower. In those sections, therefore, a change in the tidal régime will result which frequently is reflected in a change of range of tide and therefore in a change of the low-water and high-water datums.

The channel leading into the river from the open sea likewise is subject to influences that make for change of hydrographic features. During periods of storms the entrance may become wider or narrower, deeper or shallower. In this way the tide sweeping into the river has freer or more restricted entry, resulting in an increase or decrease of range, and therefore in a change of datums.

In the interest of navigation artificial changes in the hydrographic features of tidal rivers are frequently made. With the increased draft and size of modern vessels, changes in depth or other changes are frequently found necessary; and such improvements if of sufficient magnitude, result in changing the range of the tide, and consequently bring about changes in datums.

Normally the cross-sectional area of a river increases seaward, due to the seaward slope of the river bed and to the increasing width of channel. As a consequence the mean sea level, or more accurately the mean river level, becomes higher in going upstream. For example, precise leveling by the Coast and Geodetic Survey has brought out the fact that mean river level at Philadelphia, about 100 miles up the Delaware, is about three-quarters of a foot higher than mean sea level on the coast, notwithstanding the fact that the range of tide at Philadelphia is somewhat larger than at the mouth of the river.

Widening or deepening the channel of a river, especially near the entrance, results in giving freer ingress and egress to the waters. As a consequence both a lowering of the mean river level and an increase in the range of the tide takes place. If as a result of such improvements, the mean river level at a given point is lowered D feet, and the range increased A feet, the datum of mean low water becomes lowered $D + \frac{1}{2}A$ feet.

The slope of mean river level up a tidal stream is relatively slight, and hence D, the change in mean river level at any point consequent upon river improvement, is small. The increase in range, however, may be considerable. Thus at Glasgow, on the Clyde, the range was increased 8 feet by river improvements.

In this connection it should be noted that the magnitude of the change consequent on change in tidal régime is different for the different datums. Thus for the datum of mean low water, in the example cited above, the change is $\frac{1}{2}A + D$ feet. But for the datum of mean high water the change is $\frac{1}{2}A - D$ feet, while for mean river level (which corresponds to mean sea level) the change is only D feet.

NECESSITY FOR BENCH MARKS

In the tide observations made at any place, the heights are referred to a graduated tide staff maintained in a fixed position. To insure replacement at the same elevation, should the tide staff be disturbed during the period of observations, its elevation with respect to one or more bench marks on shore is carefully determined. The maintenance of a fixed elevation of tide staff is thus the primary purpose of bench marks in connection with tide observations.

In connection with datum planes, however, bench marks serve other important purposes. In the first place they preserve for future use the various datum planes derived from the tide observations. These datum planes are determined as so many feet below the different bench marks, making the recovery of the datum plane a simple matter, so long as the bench marks are maintained.

The existence of good bench marks also permits the detection of changes taking place in datum planes. For such changes become immediately evident by differences in the elevations of the same datum with respect to bench marks, when derived from tide observations made at different times. Indeed, it is only through the medium of bench marks that changes in datums can be measured accurately.

It is the practice of the Coast and Geodetic Survey to establish and maintain at each tide station one standard bench mark for each

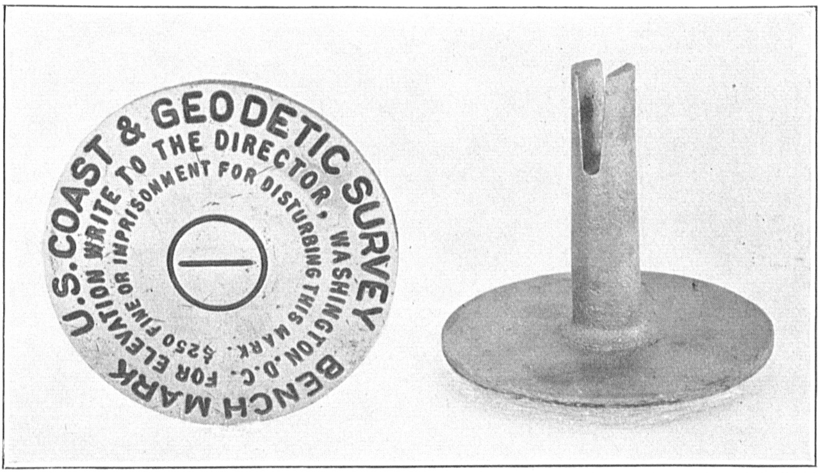

FIGURE 20.—STANDARD TIDAL BENCH MARK, U. S. COAST AND GEODETIC SURVEY

year of tide observations up to 10 years, with a minimum of five bench marks for a series one year in length and a minimum of three for a short series. These bench marks are distributed to insure against loss by a common cause.

The qualities that distinguish a good bench mark are freedom from likelihood of change in elevation, and ease of finding and identification. Disk bench marks fulfill these requirements well. The standard tidal bench mark of the Coast and Geodetic Survey consists of a brass disk about 3 inches in diameter, with a shank about 2½ inches long for insertion into a building or other substantial support, and carries the inscription shown on Figure 20.

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PUBLICATION NOTICES

The Coast and Geodetic Survey maintains a mailing list of persons interested in its airway maps, nautical charts, and miscellaneous publications. On the issuance of new or revised editions, descriptive circulars are promptly mailed to those interested in the subject matter.

Should you desire to receive such notices please check any of the lists mentioned below, grouped by subject matter, using the form prepared for your convenience.

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The DIRECTOR, U. S. COAST AND GEODETIC SURVEY,
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Dear SIR: I desire that my name be placed on the mailing lists indicated by check below to receive notification of the issuance of publications referring to the subjects indicated:

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