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TIDES AND CURRENTS IN SAN FRANCISCO BAY

BY

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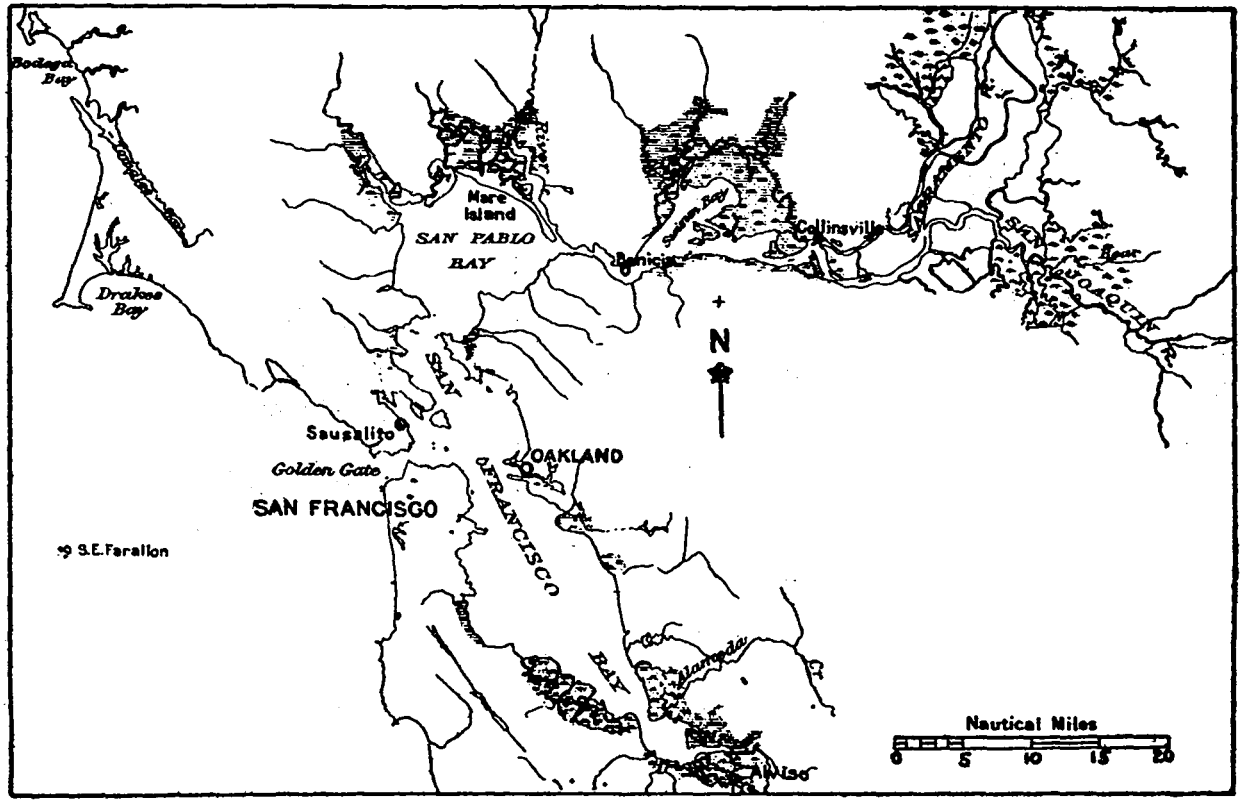

FRONTISPIECE.—San Francisco Bay and tributaries.

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TIDES AND CURRENTS IN SAN FRANCISCO BAY

INTRODUCTION

Tidal and current observations have been made at numerous stations throughout San Francisco Bay and tributaries at various times over a period of more than 70 years. The first record of tidal observations in this vicinity was obtained in 1852 when readings were made on a box gauge located on Rincon Point, San Francisco. The first current observations by the Coast and Geodetic Survey were not made until four years later, or in 1856, when records were obtained for several stations in San Pablo Bay. Since these dates numerous tidal observations of varying lengths have been made throughout the bay and tributaries and primary tide stations have been established and maintained in the vicinity of San Francisco. In connection with hydrographic surveys current observations have been made on several occasions in widely separated parts of San Francisco Bay, but in the fall of 1923 a systematic current survey was made of San Francisco Bay and tributaries.

Owing to the recognized importance of San Francisco Bay and the numerous requests from engineers and others for tidal and current data for this vicinity it was deemed advisable to compile and publish all of these data on file in the Coast and Geodetic Survey. Included in these data are the results derived from tidal observations made by the United States Navy Department and by city and county engineers, the tabulations for which are on file in this office. The data pertaining to currents, however, were derived from observations made entirely by this bureau.

The publication is not devoted to the discussion of any involved mathematical theory of tides and currents but is intended to present and discuss the results of observations in such a manner that it will be of interest and practical value to the mariner, the engineer, and the scientist.

This is the second of a series of special publications issued by the United States Coast and Geodetic Survey presenting the results of tidal and current observations made in the important waterways of the United States. The first, Tides and Currents in New York Harbor, was issued in 1925 as Special Publication No. 111. In that publication the first two sections are devoted to a consideration of the general features of tides and currents and for convenience of reference are reproduced in this volume as an appendix.

Attention is also directed to the Tide and Current Tables published annually by the Coast and Geodetic Survey. These tables contain tide and current predictions for many places, including stations in San Francisco Bay and vicinity.

Part I.—TIDES IN SAN FRANCISCO BAY

By L. P. Disney, *Assistant Mathematician, U. S. Coast and Geodetic Survey*

THE TIDE AT PRESIDIO, SAN FRANCISCO, CALIF.

1. THE PRESIDIO TIDE STATION

The tides at Presidio were observed by means of a United States Coast and Geodetic Survey automatic tide gauge located on what is known as the Presidio Wharf situated near the eastern end of the reservation in latitude 37° 48′ N. and longitude 122° 27′ W. All of the observations were reduced to a staff the zero of which was carefully connected by spirit levels with adjacent bench marks.

The accompanying photograph of the Presidio Tide Station shows the float box extending down from the right corner of the tide house, and the tide staff used for comparative readings attached to the side of the wharf just to the right of the tide house. This location of the gauge in the Golden Gate insures a characteristic record of the tide as it sweeps in through the Golden Gate into San Francisco Bay.

Observations were begun July 15, 1897, and continued uninterruptedly to date (1924) thus giving a well-determined series of 26 years of continuous tidal observations for the years 1898 to 1923, inclusive.

2. LUNITIDAL INTERVALS

The lunitidal interval or the time between the moon's transit and the succeeding high or low water gives a most useful time relation.

In Table 1, columns 5 and 6, are given the daily lunitidal intervals at Presidio for a typical summer month. Column 2 contains the moon's transits for the meridian of Greenwich. The times inclosed by parentheses refer to the lower transits of the moon, the unmarked ones being for the upper transits. Columns 3 and 4 give the times of high and low water, respectively, as tabulated from the tide gauge record. The lunitidal intervals are obtained by subtracting from the time of each high and low water the time of the next preceeding moon's transit except in the case where the time of high or low water is nearly the same as that of the moon's transit in which case the transit which proceeds the tide by about 12 hours is taken.

It should be noted that the intervals thus obtained are uncorrected, the true lunitidal interval being the difference between the mean local time of the tide and the mean local time of the moon's transit over the local meridian. But on account of the use of standard time instead of local time and the inconvenience of changing the moon's transits to the local meridian, these uncorrected lunitidal intervals are computed and then rectified by applying a correction to the mean, thus saving considerable work. For Presidio this correction is −0.45 hour.

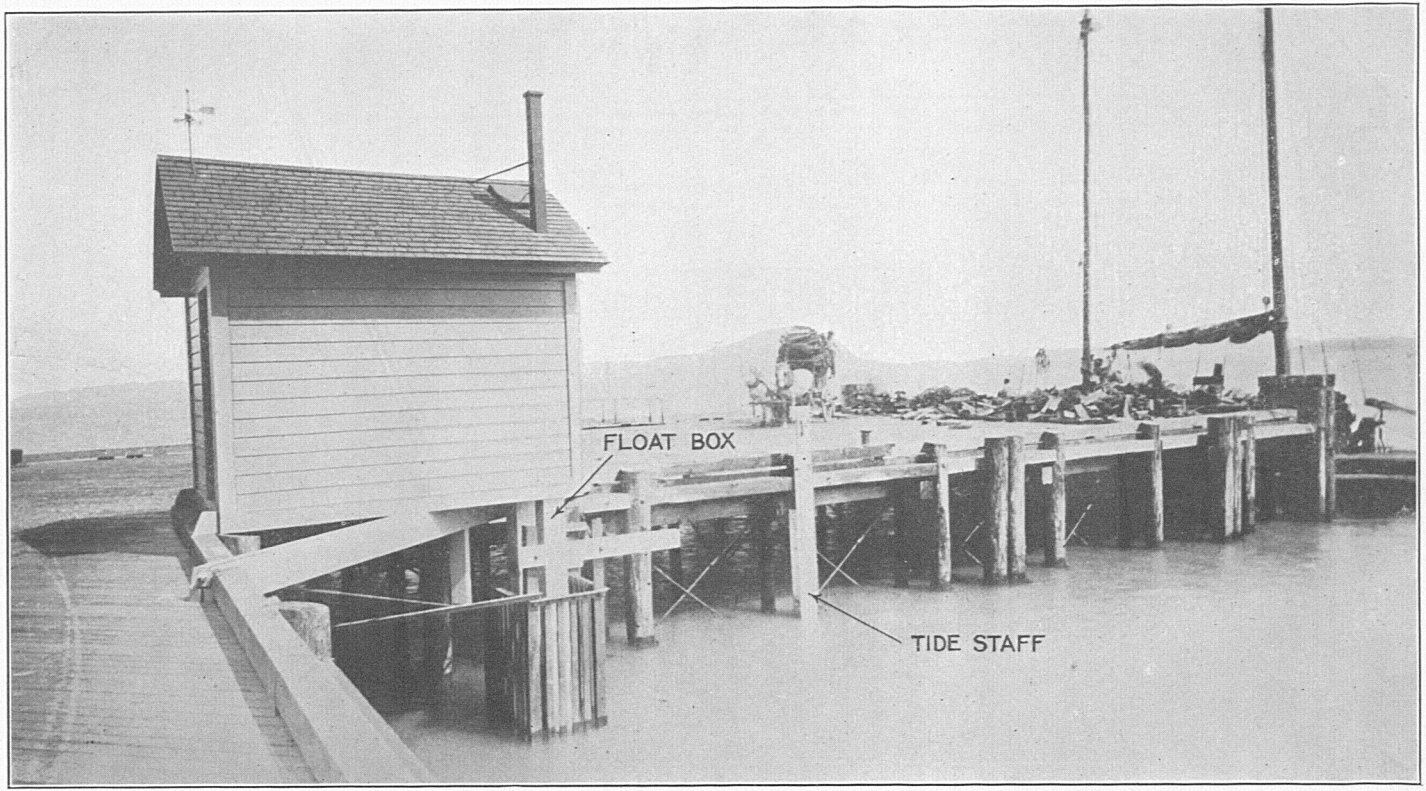

FIG. 1.—PRESIDIO TIDE STATION

TABLE 1.—*Daily lunitidal intervals and high and low waters, Presidio, San Francisco, Calif.*

Date	Moon's transits (Greenwich mean civil)	Time of—		Lunitidal interval		Height referred to standard sea level	
		High water	Low water	High water	Low water	High water	Low water
1920	*Hr. Dec.*	*Hr. Dec.*	*Hr. Dec.*	*Hr. Dec.*	*Hr. Dec.*	*Feet.*	*Feet.*
June 1	(11.8)	12.8	5.4	13.4	6.0	1.4	−3.5
	----------	23.0	17.2	(11.2)	(5.4)	2.8	−0.1
2	0.2	13.5	6.0	13.3	5.8	1.5	−3.4
	(12.6)	23.7	17.9	(11.1)	(5.3)	2.8	0.0
3	1.0	14.0	6.6	13.0	5.6	1.5	−3.8
	(13.4)	----------	18.4	----------	(5.0)	----------	+0.1
4	1.8	0.2	7.2	(10.8)	5.4	2.6	−3.2
	(14.2)	14.5	19.2	12.7	(5.0)	1.6	+0.1
5	2.6	0.7	7.6	(10.5)	5.0	2.3	−3.1
	(15.0)	15.2	20.0	12.6	(5.0)	1.5	+0.1
6	3.3	1.5	8.2	(10.5)	4.9	2.1	−3.0
	(15.7)	15.9	20.7	12.6	(5.0)	1.6	0.0
7	4.1	2.0	8.9	(10.3)	4.8	1.6	−2.7
	(16.5)	16.6	21.9	12.5	(5.4)	1.5	−0.4
8	4.8	3.1	9.2	(10.6)	4.4	1.1	−2.5
	(17.2)	17.2	22.9	12.4	(5.7)	1.7	−0.9
9	5.6	4.4	10.2	(11.2)	4.6	0.9	−2.2
	(18.0)	18.0	23.8	12.4	(5.8)	2.0	−1.3
10	6.4	5.7	11.2	(11.7)	4.8	0.6	−1.7
	(18.7)	18.5	----------	12.1	----------	2.4	----------
11	7.1	7.2	0.8	(12.5)	(6.1)	0.7	−1.7
	(19.6)	19.2	12.2	12.1	5.1	2.7	−1.5
12	8.0	8.4	1.8	(12.8)	(6.2)	0.9	−2.5
	(20.4)	20.0	13.3	12.0	5.3	3.1	−1.1
13	8.9	9.6	2.7	(13.2)	(6.3)	1.1	−3.1
	(21.4)	20.6	14.2	11.7	5.3	3.4	−0.8
14	9.9	10.6	3.6	(13.2)	(6.2)	1.4	−3.6
	(22.4)	21.3	15.0	11.4	5.1	3.8	−0.5
15	10.9	11.5	4.5	(13.1)	(6.1)	1.6	−4.1
	(23.4)	22.2	16.0	11.3	5.1	3.9	−0.5
16	11.9	12.3	5.3	(12.9)	(5.9)	1.7	−4.5
	----------	23.0	16.9	11.1	5.0	3.7	−0.5
17	(0.5)	13.2	6.1	(12.7)	(5.6)	1.7	−4.7
	13.0	23.9	17.8	10.9	4.8	3.5	−0.7
18	(1.5)	14.0	6.9	(12.5)	(5.4)	1.9	−4.7
	14.0	----------	18.7	----------	4.7	----------	−0.7
19	(2.5)	0.7	7.6	10.7	(5.1)	3.2	−4.4
	15.0	14.7	19.7	(12.2)	4.7	2.1	−0.8
20	(3.4)	1.7	8.4	10.7	(5.0)	2.8	−3.6
	15.9	15.5	20.9	(12.1)	5.0	2.4	−0.7
21	(4.3)	2.7	9.2	10.8	(4.9)	2.3	−3.1
	16.7	16.4	22.1	(12.1)	5.4	2.5	−1.1
22	(5.1)	3.8	10.0	11.1	(4.9)	1.7	−2.6
	17.5	17.2	23.4	(12.1)	5.9	2.7	−1.4
23	(5.9)	5.1	10.9	11.6	(5.0)	1.1	−2.0
	18.3	17.9	----------	(12.0)	----------	2.7	----------
24	(6.7)	6.6	0.5	12.3	6.2	0.9	−1.9
	19.0	18.7	11.9	(12.0)	(5.2)	2.9	−1.4
25	(7.4)	8.1	1.4	13.1	6.4	1.0	−2.3
	19.8	19.5	13.0	(12.1)	(5.6)	3.0	−0.8
26	(8.2)	9.2	2.5	13.4	6.7	1.4	−2.4
	20.6	20.2	13.9	(12.0)	(5.7)	3.3	−0.1
27	(9.0)	10.1	3.2	13.5	6.6	1.5	−2.6
	21.4	20.9	14.7	(11.9)	(5.7)	3.3	0.0
28	(9.8)	11.2	4.0	13.8	6.6	1.6	−2.9
	22.2	21.5	15.7	(11.7)	(5.9)	3.3	+0.3
29	(10.6)	11.7	4.6	13.5	6.4	1.7	−2.9
	23.0	22.2	16.2	(11.6)	(5.6)	3.3	+0.2
				56	56	56	56
Sums, 29 days: June 1–29	----------	----------	----------	674.6	305.6	119.3	−102.7
Means	----------	----------	----------	12.05	5.46	2.13	−1.83
Correction to intervals	----------	----------	----------	−0.45	−0.45	----------	----------
				11.60	5.01	3.96 Mn 0.15 MTL	

A glance at Table 1 shows that the lunitidal intervals differ considerably from day to day and even on the same day the intervals as obtained from the upper and lower transits may differ by as much as 2.2 hours. As determined from this single month of 29 days record the corrected high water interval is 11.60 hours and the low-water interval 5.01 hours.

Table 2 contains the monthly means for the corrected high and low water lunitidal intervals for the two years 1898 and 1923, the first and last years of the series. These means are from 29-day series beginning with the first day of each calendar month. When the month of February contains but 28 days the 1st day of March is added to complete the series.

TABLE 2.—*Lunitidal intervals, Presidio, San Francisco, Calif., monthly means, 1898 and 1923*

HIGH-WATER INTERVALS

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
	Hours	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*
1898	11.77	11.68	11.79	11.76	11.73	11.73	11.80	11.80	11.82	11.75	11.69	11.75	11.76
1923	11.61	11.51	11.52	11.50	11.58	11.59	11.59	11.57	11.54	11.49	11.54	11.55	11.55

LOW-WATER INTERVALS

1898	5.09	5.07	5.08	5.09	5.08	5.14	5.11	5.17	5.04	5.15	5.16	5.14	5.11
1923	4.90	4.89	4.93	4.84	4.91	5.01	5.04	5.05	4.98	4.93	4.99	4.97	4.95

Table 2 reveals the fact that there is a variation in the high and low water lunitidal intervals from month to month. For the high-water interval the greatest variation throughout the year 1898 amounts to 0.14 hour while for 1923 it is 0.11 hour.

During the year 1898 the greatest variation in the monthly means of the low-water lunitidal intervals is 0.13 hour while for 1923 the maximum is 0.21 hour or about 13 minutes.

In Table 3 are tabulated the yearly means of both the high and low water lunitidal intervals for the years 1898 to 1923, inclusive.

TABLE 3.—*Lunitidal intervals, Presidio, San Francisco, Calif., yearly means, 1898–1923*

High-water lunitidal intervals				Low-water lunitidal intervals			
Year	HWI	Year	HWI	Year	LWI	Year	LWI
	Hours		*Hours*		*Hours*		*Hours*
1898	11.76	1911	11.74	1898	5.11	1911	4.88
1899	11.70	1912	11.72	1899	5.08	1912	5.03
1900	11.72	1913	11.63	1900	5.02	1913	4.99
1901	11.71	1914	11.71	1901	4.99	1914	4.98
1902	11.78	1915	11.66	1902	5.08	1915	4.94
1903	11.75	1916	11.68	1903	5.09	1916	4.98
1904	11.77	1917	11.67	1904	5.08	1917	5.00
1905	11.73	1918	11.65	1905	5.02	1918	5.02
1906	11.71	1919	11.60	1906	4.93	1919	4.98
1907	11.77	1920	11.56	1907	4.96	1920	5.00
1908	11.71	1921	11.65	1908	5.04	1921	4.95
1909	11.74	1922	11.63	1909	4.94	1922	4.93
1910	11.70	1923	11.55	1910	4.95	1923	4.95
Mean	11.73	Mean	11.65	Mean	5.02	Mean	4.97

It has been shown that the lunitidal intervals vary from day to day and from month to month. Table 3 discloses the fact that there is also a variation from year to year.

From the high-water lunitidal intervals the greatest variation between two consecutive years is 0.09 hour or about 5 minutes, but the variation between any two years is considerably larger than this. For example, in 1902, HWI = 11.78 hours, while in 1923, HWI = 11.55 hours, a difference of 0.23 hour or 14 minutes.

All of the important motions of the moon are subject to inequalities which pass through a complete cycle in a period of approximately 19 years. It is therefore customary to consider as mean values the tidal constants derived from a 19-year series. The series at Presidio permits of two overlapping 19-year groups as follows: 1898–1916 and 1905–1923. For the first 19-year group high-water interval is derived as 11.72 hours, while for the second it is 11.67 hours. It is observed that the time for the second series is earlier than for the first.

The low-water lunitidal intervals also show a variation from year to year. The greatest variation between any two consecutive years is 0.15 hour or 9 minutes, while the greatest variation between any two years amounts to as much as 0.23 hour or about 14 minutes. If the 26-year series is divided into two overlapping 19-year groups the same as with the HWI, the mean for the first group 1898–1916 gives LWI = 5 hours, while for the second group 1905–1923, LWI is 4.97 hours. It is thus seen that the low-water lunitidal interval for the second 19-year series is earlier than for the first series the same as with the HWI.

A well-determined mean should be obtained from a 19-year series, consequently the variation between the two 19-year groups indicates that there may have been a change in the time of the tide at Presidio the tides occurring earlier in recent years than years ago. Due to this apparent change in the time of the tide at Presidio the intervals for the second 19-year series (1905–1923) will be accepted as giving results nearer the present-day values.

3. DURATION OF RISE AND FALL

The duration of rise is obtained by subtracting the low-water lunitidal interval from the high-water lunitidal interval. The average time between the upper and lower transits of the moon is 12.42 hours. Consequently to obtain the duration of fall it is only necessary to subtract the duration of rise in hours from 12.42.

Referring to Table 1 it is readily seen that both the duration of rise and duration of fall vary materially from day to day.

Table 4 contains the monthly means for two years 1898 and 1923 for both the duration of rise and duration of fall. These two years are the first and last years of the 26-year series.

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TABLE 4.—*Duration of rise and fall, Presidio, San Francisco, Calif., monthly means, 1898 and 1923*

DURATION OF RISE

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Means
	Hours	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*
1898	6.68	6.61	6.71	6.67	6.65	6.59	6.60	6.63	6.78	6.60	6.53	6.61	6.65
1923	6.71	6.62	6.59	6.66	6.67	6.58	6.55	6.52	6.56	6.56	6.55	6.58	6.60

DURATION OF FALL

1898	5.74	5.81	5.71	5.75	5.77	5.83	5.73	5.79	5.64	5.82	5.89	5.81	5.77
1923	5.71	5.80	5.83	5.76	5.75	5.84	5.87	5.90	5.86	5.86	5.87	5.84	5.82

Table 4 clearly shows that there is a variation from month to month in the duration of rise. For any two consecutive months the greatest variation is as much as 0.18 hour or approximately 11 minutes. Taking any two months within the year the variation is found to be as great as 0.25 hour or 15 minutes.

A similar variation is found for the duration of fall. The maximum variation for any two consecutive months is 0.18 hour or approximately 11 minutes, while the greatest variation between any two months within the year is 0.25 hour or 15 minutes, the same as the variation for the duration of rise.

In Table 5 are tabulated the yearly means of the duration of rise and duration of fall for 26 years, 1898 to 1923, inclusive.

TABLE 5.—*Duration of rise and fall, Presidio, San Francisco, Calif., yearly means, 1898–1923*

Duration of rise				Duration of fall			
Year	Duration	Year	Duration	Year	Duration	Year	Duration
	Hours		*Hours*		*Hours*		*Hours*
1898	6.65	1911	6.86	1898	5.77	1911	5.56
1899	6.62	1912	6.69	1899	5.80	1912	5.73
1900	6.70	1913	6.64	1900	5.72	1913	5.78
1901	6.72	1914	6.73	1901	5.70	1914	5.69
1902	6.70	1915	6.72	1902	5.72	1915	5.70
1903	6.66	1916	6.70	1903	5.76	1916	5.72
1904	6.69	1917	6.67	1904	5.73	1917	5.75
1905	6.71	1918	6.63	1905	5.71	1918	5.79
1906	6.78	1919	6.62	1906	5.64	1919	5.80
1907	6.81	1920	6.56	1907	5.61	1920	5.86
1908	6.67	1921	6.70	1908	5.75	1921	5.72
1909	6.80	1922	6.70	1909	5.62	1922	5.72
1910	6.75	1923	6.60	1910	5.67	1923	5.82
Mean	6.71	Mean	6.68	Mean	5.71	Mean	5.74

Inasmuch as the high and low water lunitidal intervals displayed a variation from year to year it is to be expected that the duration of rise and the duration of fall would also show a yearly variation. This is brought out by Table 5.

From this table it is seen that the duration of rise varies from year to year, the maximum variation between any two consecutive years being as much as 0.17 hour, and the variation between any two years amounting to as much as 0.30 hour or 18 minutes. The mean for the

26 years of continuous observations gives 6.70 hours for the duration of rise. If the series is divided into two overlapping 19-year groups, 1898–1916 and 1905–1923, respectively, the mean for the first group is 6.72 hours and for the second group 6.70 hours. The mean of the two 19-year groups gives 6.71 hours for the duration of rise. As the second 19-year series was adopted for HWI and LWI it should be adopted here also.

As the duration of fall is obtained by subtracting the duration of rise from a constant, 12.42 it is apparent that there is a similar yearly variation for the duration of fall. The mean for the 26 years of continuous observations gives 5.72 hours. Dividing the series into two 19-year groups as above the means are 5.70 hours and 5.72 hours, respectively. The mean of the two 19-year groups gives 5.71 hours for the duration of fall. The value of 5.72 hours for the second 19 years will be adopted for the reason stated above.

4. MEAN SEA LEVEL

The plane of mean sea level is of considerable importance as a tidal plane, being used as a datum plane for various scientific and engineering purposes. Mean sea level may be defined as the plane about which the tide oscillates or as the surface the sea would assume if undisturbed by the rise and fall of the tide. This plane may be determined by averaging, over a considerable length of time, the hourly heights of the sea with reference to a bench mark on shore.

Inasmuch as sea level is frequently used as a datum plane it will be of interest to note what variations take place between the different periods and the length of series necessary to give a well-determined sea level plane.

The variation in sea level at Presidio from day to day for a typical summer month is shown in Table 6. The values of sea level in this table were derived by averaging the 24 hourly heights of the tide for each day, and are referred to the fixed tide staff at Presidio.

TABLE 6.—*Daily sea level on staff, Presidio, San Francisco, Calif., June, 1920*

Day	Height	Day	Height	Day	Height
	Feet		*Feet*		*Feet*
1	8.42	11	8.54	21	8.61
2	8.48	12	8.55	22	8.65
3	8.53	13	8.55	23	8.61
4	8.52	14	8.56	24	8.63
5	8.49	15	8.50	25	8.74
6	8.45	16	8.34	26	8.96
7	8.35	17	8.19	27	8.91
8	8.31	18	8.18	28	8.89
9	8.42	19	8.32	29	8.85
10	8.49	20	8.54	30	8.75
Mean	8.45	Mean	8.43	Mean	8.76

It is readily seen from Table 6 that there is a material variation from day to day in sea level, and if the month is divided into groups of 10 days each, there still exists a variation between the means of these groups. The maximum variation between any 2 days within the month amounts to 0.78 foot, which conclusively proves that sea level determined from only 1 day of observations furnished a poorly

determined datum plane. Variation in sea level from day to day may be due to varying meteorological conditions or to the so-called long-period tides.

Sea level as determined from a period of a month will next be considered. In Table 7 are tabulated the heights of monthly sea levels on the tide staff for two years, 1898 and 1923, respectively. These heights are determined from the first 29 days of each month.

TABLE 7.—*Monthly sea level on staff, Presidio, San Francisco, Calif., 1898 and 1923*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Means
	Feet	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*
1898	8.24	8.30	8.11	8.09	8.20	8.34	8.37	8.54	8.48	8.31	8.29	8.28	8.30
1923	8.49	8.49	8.18	8.52	8.33	8.44	8.54	8.56	8.74	8.71	8.78	8.47	8.52

Can a well-determined sea level datum plane be obtained from a month of continuous observations? By referring to Table 7 it is seen that there is still an appreciable variation in sea level between any two months of observations. Sea level for March, 1923, is 8.18 feet, while for November of the same year it is 8.78 feet, a variation of 0.60 foot. It is thus seen that a well-determined sea level datum can not be obtained from a month of continuous observations.

Having found that the variation in sea level from day to day and month to month is of such size as to exclude the adoption of sea level datum from a day or month of observations, it is logical that the variations in sea level from year to year should next be studied. Table 8 contains the tabulated values of yearly sea level on the tide staff at Presidio for 26 years of continuous observation from 1898 to 1923, inclusive.

TABLE 8.—*Sea level on staff, Presidio, San Francisco, Calif., yearly means, 1898–1923*

Year	Height	Year	Height
	Feet		*Feet*
1898	8.30	1911	8.61
1899	8.44	1912	8.49
1900	8.50	1913	8.51
1901	8.46	1914	8.81
1902	8.57	1915	8.69
1903	8.53	1916	8.52
1904	8.63	1917	8.48
1905	8.65	1918	8.70
1906	8.58	1919	8.61
1907	8.66	1920	8.54
1908	8.43	1921	8.58
1909	8.53	1922	8.55
1910	8.42	1923	8.52
Mean	8.52	Mean	8.59

It might reasonably be expected that a year of continuous observations would furnish a fairly well-determined plane of sea level. But such is not the case as will be seen by referring to Table 8. If sea level were determined from the observations during the year 1913, it would be 8.51 feet on the staff at Presidio, whereas if 1914 were selected the plane would be 8.81 feet, giving a variation of 0.30 foot

between the two years. Thus it is seen that a well-determined sea level plane can not be obtained even from a year of continuous observations. For the sake of convenience the tabulations in Table 8 have been arranged into two groups of 13 years each. The mean of the first group, 1898–1910, gives 8.52 feet for sea level while the mean of the second group gives 8.59 feet. It will be observed that even with series of these lengths variations still exist but fortunately the variation is not as large as before, amounting to but 0.07 foot. If a mean of the entire 26 years is taken, the plane of mean sea level is 8.55 feet on the staff at Presidio. Dividing the 26 years of observations into two overlapping 19-year groups, mean sea level for the first group, 1898–1916, is 8.54 feet and for the second group, 1905–1923, is 8.57 feet on the staff at Presidio. The variation between these two groups is but 0.03 foot. Taking a mean of the two groups gives 8.555 feet, which may be taken as a well-determined value of mean sea level for Presidio.

During the 26 years of observations sea level was lowest in 1898 with a value of 8.30 feet, and highest in 1914 with a height of 8.81 feet. The value for 1914 is principally affected by the extreme height of 9.16 feet for December of that year. It is recorded that during that month the tides were unusually high and that the Key-route Ferry steamers between San Francisco and Oakland were obliged to shorten their flagpoles in order to avoid striking the sheds in their slips on the Oakland side.

Meteorological conditions vary from year to year and these variations are reflected by changes in sea level. Thus it is reasonable to conclude that the variation in the height of sea level shown in Table 8 is due primarily to varying meteorological conditions. It is not evident as yet whether the variations in sea level from year to year possess any periodicity, but it is found that the variations from month to month exhibit considerable peridoicity. At Presidio it is found that mean sea level is lowest in the spring with a minimum generally in April or May, and highest in the fall with the maximum generally in September or October.

It has been shown that there is a variation in mean sea level even when determined from a number of years of observations. Continual changing of the datum of mean sea level as additional observations become available is extremely bothersome to the engineer and for this reason the United States Coast and Geodetic Survey has adopted a standard sea-level datum at Presidio of 8.519 feet on the tide staff of 1897. This plane is based upon 16 years of continuous observations from 1898 to 1913.

5. THE PLANE OF HALF-TIDE LEVEL

Half-tide level, also called mean-tide level, may be defined as a plane lying exactly halfway between the planes of mean high water and mean low water. The planes of half-tide level and mean sea level would coincide if the rise of mean high water above sea level were exactly equal to the fall of mean low water below sea level. But for the 26-year period at Presidio the rise of high water is 0.11 foot greater than the fall of low water. Consequently it follows that the plane of half-tide level lies 0.055 foot above sea level, or to the nearest hundredth the plane of half-tide level may be taken as 0.06

foot above mean sea level. The planes of half-tide level and mean sea level are frequently used as if there were no difference between the two. For practical purposes this may be permissible but for the sake of clearness the two must be distinguished.

The yearly variations in half-tide level from 1898 to 1923, inclusive, are presented in Table 9.

TABLE 9.—*Half-tide level on staff, Presidio, San Francisco, Calif., yearly means, 1898–1923*

Year	Height	Year	Height
	Feet		*Feet*
1898	8.36	1911	8.67
1899	8.50	1912	8.57
1900	8.56	1913	8.58
1901	8.51	1914	8.90
1902	8.62	1915	8.76
1903	8.55	1916	8.58
1904	8.67	1917	8.53
1905	8.70	1918	8.74
1906	8.64	1919	8.65
1907	8.72	1920	8.57
1908	8.49	1921	8.62
1909	8.60	1922	8.58
1910	8.49	1923	8.55
Mean	8.57	Mean	8.64

6. THE PLANES OF HIGH WATER AND LOW WATER

It is quite generally known that the height of both high and low water varies considerably from day to day, high water being noticeably higher and low water lower during one period of the month than during another. These variations in the height of high and low water from day to day are due primarily to the varying positions of the moon relative to the earth and sun. When the moon is new and full, high water rises higher and low water falls lower than usual. The tides occurring during these phases of the moon are known as spring tides. When the moon is in its first and third quarters and the so-called neap tides occur, the rise of high water and the fall of low water is less than usual. In a like manner, high water rises higher and low water falls lower than the average at the times when the moon is in perigee. When the moon is in apogee the rise and fall is less than the average. Besides these variations from day to day, changes in the moon's declination also bring about a difference in the heights of the two high waters and two low waters of a day. It is seen that all of these variations are due to astronomic causes, but apart from them there is also a variation brought about by varying meteorological conditions. Thus it is seen that there may be various planes of high and low water, their respective designations being mean high water and mean low water, spring high water and spring low water, neap high water and neap low water, perigean high water and perigean low water, apogean high water and apogean low water, higher high water and lower low water, lower high water and higher low water, and some arbitrary storm high water or low water. With so many various planes in use it is apparent that the term "high-water plane" or "low-water plane" is ambiguous and confusing. To be precise the exact high or low water plane referred to should be definitely designated as "mean high water" or "higher high water," etc.

It is often desirable to know the average height of high and low water. These values are readily obtained by averaging the heights of the high and low waters, respectively, over a considerable period of time.

Due to the diurnal inequality at Presidio there is a wide variation in the heights of the two high and two low waters of each day. This is shown in Table I, columns 7 and 8, in which the heights of high and low waters are tabulated for each day of the month for June, 1920. The heights of both high and low waters in this table have been referred to standard sea level which reads 8.519 feet on the staff.

Table 10 contains the tabulated monthly means of both high and low waters for the years 1898 and 1923. These means are for groups of 29 days beginning with the 1st day of the month.

TABLE 10.—*Mean high water and mean low water, Presidio, San Francisco, Calif., monthly means, 1898 and 1923*

MEAN HIGH WATER ON STAFF

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
	Feet	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*
1898	10.30	10.35	10.12	10.09	10.22	10.39	10.41	10.58	10.51	10.36	10.38	10.34	10.34
1923	10.51	10.47	10.18	10.53	10.36	10.50	10.59	10.59	10.78	10.77	10.87	10.60	10.56

MEAN LOW WATER ON STAFF

1898	6.29	6.40	6.23	6.19	6.31	6.43	6.45	6.62	6.54	6.39	6.36	6.32	6.38
1923	6.54	6.55	6.20	6.55	6.37	6.48	6.56	6.56	6.76	6.71	6.77	6.44	6.54

Table 10 reveals the fact that there is considerable variation in the monthly means of both high and low waters. Inasmuch as high and low water oscillate about mean sea level it is evident that any variation in mean sea level will cause a variation in corresponding high and low water means. A comparison of Tables 7 and 10 will illustrate this point.

The yearly means of both high and low waters for 26 years, 1898 to 1923, inclusive, are tabulated in Table 11.

TABLE 11.—*Mean high water and mean low water, Presidio, San Francisco, Calif. yearly means, 1898–1923*

Mean high water on staff				Mean low water on staff			
Year	Height	Year	Height	Year	Height	Year	Height
	Feet		*Feet*		*Feet*		*Feet*
1898	10.34	1911	10.61	1898	6.38	1911	6.74
1899	10.45	1912	10.54	1899	6.55	1912	6.59
1900	10.54	1913	10.54	1900	6.57	1913	6.62
1901	10.48	1914	10.80	1901	6.54	1914	7.00
1902	10.60	1915	10.67	1902	6.63	1915	6.85
1903	10.54	1916	10.50	1903	6.57	1916	6.67
1904	10.64	1917	10.47	1904	6.70	1917	6.59
1905	10.71	1918	10.71	1905	6.68	1918	6.77
1906	10.63	1919	10.63	1906	6.65	1919	6.67
1907	10.68	1920	10.58	1907	6.77	1920	6.56
1908	10.50	1921	10.62	1908	6.47	1921	6.62
1909	10.55	1922	10.57	1909	6.65	1922	6.59
1910	10.45	1923	10.56	1910	6.53	1923	6.54
Mean	10.55	Mean	10.60	Mean	6.59	Mean	6.68

It is seen from Table 11 that there is also a variation in the yearly means of both high and low waters. By a comparison of Tables 8 and 11 it is evident that the fluctuations in mean sea level account for most of the variations in the high and low waters.

Dividing the 26-year series into two overlapping 19-year groups, 1898 to 1916 and 1905 to 1923, respectively, the means for the high water are 10.57 and 10.60 feet, respectively, on the staff at Presidio. A mean of the two 19-year groups gives 10.58 feet on the staff for mean high water.

For the low waters the mean of the first 19-year group gives 6.64 feet, while the second group gives 6.66 feet on the staff. The mean of the two 19-year groups gives the value of 6.65 feet as the height of mean low water on the staff at Presidio.

It is occasionally useful to know the relation of mean high and low water to sea level. For this purpose Table 12 is presented. This table contains the yearly mean high and low waters referred to standard sea level. As previously stated, standard sea level at Presidio is 8.519 feet on the staff.

TABLE 12.—*Mean high water and mean low water referred to standard sea level, Presidio, San Francisco, Calif., yearly means, 1898–1923*

Mean high water above standard sea level				Mean low water below standard sea level			
Year	Elevation	Year	Elevation	Year	Depression	Year	Depression
	Feet		*Feet*		*Feet*		*Feet*
1898	1.82	1911	2.00	1898	2.14	1911	1.78
1899	1.93	1912	2.02	1899	1.97	1912	1.93
1900	2.02	1913	2.02	1900	1.95	1913	1.90
1901	1.96	1914	2.28	1901	1.98	1914	1.52
1902	2.08	1915	2.15	1902	1.89	1915	1.67
1903	2.02	1916	1.98	1903	1.95	1916	1.85
1904	2.12	1917	1.95	1904	1.82	1917	1.93
1905	2.19	1918	2.19	1905	1.84	1918	1.75
1906	2.11	1919	2.11	1906	1.87	1919	1.85
1907	2.16	1920	2.06	1907	1.75	1920	1.96
1908	1.98	1921	2.10	1908	2.05	1921	1.90
1909	2.03	1922	2.05	1909	1.87	1922	1.93
1910	1.93	1923	2.04	1910	1.99	1923	1.98
Mean	2.03	Mean	2.08	Mean	1.93	Mean	1.84

The variations in Table 12 are the same as in Table 11 because a constant has been used in obtaining the data in Table 12 from Table 11. It should be borne in mind that Table 12 is referred to standard sea level and not to the yearly mean sea level. If it is desired to refer the mean high and low waters to mean sea level in order to eliminate the variation due to fluctuation in mean sea level from year to year, it is only necessary to subtract the values of Table 8 from corresponding values of Table 11.

If the high water values in Table 12 are divided into two 19-year groups—that is, 1898–1916 and 1905–1923, respectively—the means are 2.05 feet and 2.08 feet, respectively. A mean of the two groups gives 2.06 feet for the height of mean high water above standard sea level.

For the low waters the mean of the first 19-year group gives 1.88 feet, while the second 19-year group gives 1.86 feet. A mean of the

two 19-year groups gives 1.87 feet for the depression of mean low water below standard sea level.

A study of the monthly means of mean high and low waters and mean sea level discloses the fact that the annual variations in the planes of mean high water and mean low water closely resemble those exhibited by the plane of mean sea level. High water and low water are generally lowest in April and highest in September. This leads to the conclusion that the annual variation in the height of high water and low water is directly due to the variation in the plane of mean sea level.

The planes of spring high water and spring low water are determined by averaging over a considerable length of time all the high and low waters, respectively, that occur at the time of spring tides; that is, when the effects of the new and full moon are greatest in increasing the range of the tide. As before mentioned, spring tides occur a little after the times when the moon is new or full. This lag in the occurrence of spring tides with reference to new or full moon is known as the phase age of the tide and will be considered later in connection with the other "ages" of the tide.

It is customary in determining the heights of spring high and low waters to take the two consecutive high or low waters, respectively, which fall nearest the time obtained by adding the phase age of the tide to the times of new and full moon. Thus for any month there will be but four heights each entering, respectively, into the determination of the spring high water and spring low water for that month. Since these heights are affected by the moon's parallax, declination, and any accidental meteorological conditions, it follows that the monthly means may differ considerably. Thus it is apparent that the determination of these planes with any degree of precision from high and low water observations requires a series extending over a number of years. From a single year of observations (1898), which have been reduced for the phase tides spring high water on the Presidio staff reads 10.69 feet and spring low water 6.09 feet. The plane of standard sea level reads 8.52 feet on the staff, consequently the plane of spring high water as determined from the observations of 1898 is 2.17 feet above standard sea level and the plane of spring low water 2.43 feet below standard sea level.

From the fact that the planes of mean high and low waters exhibit the same annual variations as that of mean sea level it is reasonable to conclude that the planes of spring high and low water will do likewise.

The planes of spring high and low water may also be derived from the harmonic constants by means of the formulae developed by R. A. Harris.[1] This method requires considerably less time than the method of direct tabulation, but the results from the harmonic constants may differ a little from the results of the direct tabulation.

For Presidio there are at hand the computations of nonharmonic quantities from harmonic constants for a period of six years during the period 1904–1913. From these computations the plane of spring high water is 2.34 feet above standard sea level, while that of spring low water is 2.23 feet below standard sea level. Giving the deter-

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

minations from the series of six years a weight of six the plane of spring high water may be taken as 2.32 feet above standard sea level and the plane of spring low water 2.26 feet below standard sea level.

The planes of neap high and low waters are derived by substituting in the preceding paragraphs relating to spring high and low waters the moon's first and third quarter for the new and full moon. For the one year of direct tabulation, 1898, the plane of neap high water is 1.41 feet above standard sea level and the plane of neap low water 1.76 feet below standard sea level. From the harmonic constants for six years the plane of neap high water is 1.60 feet above while the plane of neap low water is 1.49 feet below standard sea level. Giving a weight of six to the values from the six-year series a mean of the two determinations gives 1.57 feet above standard sea level for the plane of neap high water and 1.53 feet below standard sea level for the plane of neap low water.

When the moon is at its least distance from the earth the high waters are higher and the low waters are lower than the average. Conversely, when the moon is at its greatest distance from the earth the high waters are lower and the low waters are higher than the average. These periodic variations in the moon's distance from the earth give rise to two other sets of tidal planes which are known, respectively, as the planes of perigean high and low waters and apogean high and low waters. There is usually a lag in these tides which varies for different localities. At Presidio, for example, perigean and apogean tides occur about two days after the corresponding positions of the moon. There are no direct tabulations of perigean and apogean tides available for Presidio but these planes have been determined from the harmonic constants for six years, 1904–1913. For the perigean tides these results give 2.39 feet for the height of perigean high water above standard sea level and 2.16 feet for the depression of perigean low water below standard sea level.

For the apogean tides the results are 1.69 feet for the height of apogean high water above standard sea level and 1.59 feet for the depression of apogean low water below standard sea level.

The moon moves in an orbit which makes an average angle of approximately 23½° with the plane of the Equator. Thus the moon's declination is constantly changing, varying from zero to a maximum north and south declination, the complete period being about 27 days. This periodic change in the moon's declination gives rise to four tidal high water and four tidal low water planes, namely, the planes of higher high water, lower high water, tropic higher high water, and tropic lower high water, and lower low water, higher low water, tropic lower low water, and tropic higher low water. These datum planes are called declinational planes since they depend on the moon's declination. The average height of the higher of the two high waters of each day over a considerable period of time determines the plane of higher high water, while the average height of the lower determines the plane of lower high water. Similarly with the low waters, the average height of the lower of the two low waters of each day over a considerable period of time determines the plane of lower low water, while the average height of the higher determines the plane of higher low water. The planes of tropic higher high and lower high water are determined, respectively, by averaging the heights of

the higher high and lower high waters that occur at the times of tropic tides; that is, the tides occurring fortnightly at the time of the moon's extreme north and south declinations. In a like manner, the planes of tropic lower low and higher low water are determined, respectively, by averaging the heights of the lower low and higher low waters that occur at the times of tropic tides.

As before mentioned, the diurnal inequality in the height of the tide at Presidio is considerable, consequently the declinational datum planes are of material importance. This is illustrated by columns 7 and 8 of Table 1, the difference between the two heights of the tide of a day being well marked.

The variations from month to month in higher high water and lower low water are given in Table 13 for two years, 1898 and 1923. These monthly means are for groups of 27 days, the first and last days of the 29 day group being omitted.

TABLE 13.—*Higher high water and lower low water, Presidio, San Francisco, Calif., monthly means, 1898 and 1923*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct..	Nov.	Dec.	Mean
	HIGHER HIGH WATER ON STAFF												
	Feet	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*
1898....	11.12	11.02	10.65	10.59	10.90	11.17	11.18	11.20	10.94	10.74	10.98	11.14	10.97
1923....	11.12	10.95	10.49	10.81	10.82	11.14	11.28	11.22	11.21	11.09	11.33	11.26	11.06
	LOWER LOW WATER ON STAFF												
1898....	4.96	5.31	5.13	4.98	4.92	5.01	5.12	5.56	5.65	5.29	5.06	4.94	5.16
1923....	5.49	5.74	5.47	5.76	5.40	5.40	5.43	5.59	5.99	5.83	5.66	5.12	5.57

An inspection of Table 13 shows that there is considerable variation in the height of higher high water and lower low water from month to month. It is thus seen that a declinational datum plane based upon only one month of observations gives but a rough approximation. This is of special interest on the Pacific coast, as the plane of lower low water is frequently used as a datum plane and is the datum plane to which the soundings on the United States Coast and Geodetic Survey Charts are referred.

With this in mind, it will be of interest to note what, if any, variations there are from year to year. This can be done by a study of Table 14, which contains the yearly heights of higher high water and lower low water for 26 years of continuous observations from 1898 to 1923, inclusive.

TABLE 14.—*Higher high water and lower low water, Presidio, San Francisco, Calif., yearly means, 1898–1923*

Higher high water on staff				Lower low water on staff			
Year	Height	Year	Height	Year	Height	Year	Height
	Feet		*Feet*		*Feet*		*Feet*
1898	10.97	1911	11.22	1898	5.16	1911	5.46
1899	11.08	1912	11.18	1899	8.41	1912	5.30
1900	11.14	1913	11.16	1900	5.52	1913	5.31
1901	11.04	1914	11.43	1901	5.52	1914	5.70
1902	11.16	1915	11.30	1902	5.61	1915	5.61
1903	11.08	1916	11.13	1903	5.60	1916	5.46
1904	11.17	1917	11.09	1904	5.74	1917	5.41
1905	11.22	1918	11.37	1905	5.68	1918	5.66
1906	11.18	1919	11.20	1906	5.58	1919	5.63
1907	11.21	1920	11.13	1907	5.69	1920	5.57
1908	11.06	1921	11.16	1908	5.30	1921	5.62
1909	11.11	1922	11.11	1909	5.44	1922	5.63
1910	11.07	1923	11.06	1910	5.26	1923	5.57
Mean	11.11	Mean	11.20	Mean	5.50	Mean	5.53

From Table 14 it is quite evident that there is a variation from year to year in the declinational tides. For the higher high water the greatest difference in the height between any two consecutive years is 0.28 foot while the variation between any two years within the series amounts to 0.46 foot.

As a matter of convenience in compiling Table 14 the 26-year series has been divided into two 13-year groups. It will be seen that the mean for the first of these groups gives HHW as 11.11 feet while from the second group HHW is 11.20 feet, giving a variation of 0.09 foot between two 13-year series. It has been shown that a series of 19 years gives a mean value. Dividing the 26-year series into two overlapping 19-year series, 1898–1916 and 1905–1923, respectively, the values of HHW are derived as 11.15 and 11.18 feet, respectively. A mean of the two 19-year series gives 11.16 feet as the height of HHW on staff.

Lower low water also shows a variation between the yearly means. For any two consecutive years the variation is as much as 0.41 foot while for any two years within the series the variation amounts to as much as 0.58 foot. The two 13-year groups give heights of 5.50 and 5.53 feet, respectively, with a variation of 0.03 foot. If the 26-year series is divided into two overlapping 19-year series as was done with the HHW, the heights of LLW on the staff for the two series are 5.49 and 5.52 feet, respectively. A mean of the two 19-year series gives 5.50 feet as the height of LLW on staff.

It has previously been mentioned that the plane of mean lower low water is the datum plane for the United States Coast and Geodetic Survey charts on the Pacific coast. Lower low water has been shown to vary from year to year, but it is very bothersome to have a datum plane changed from time to time as additional observations became available. For this reason the Coast and Geodetic Survey has adopted a standard lower low water plane of 5.55 feet on the staff of 1897 at Presidio. This plane is based upon 10 years of observations from 1897 to 1907. It will be observed that there is but 0.05 foot difference between the adopted standard lower low water plane and the plane determined from 26 years of observations.

Table 15 is here presented to show the relation of higher high water and lower low water to standard sea level.

TABLE 15.—*Higher high water and lower low water, referred to standard sea level, Presidio, San Francisco, Calif., yearly means, 1898–1923*

Higher high water above standard sea level				Lower low water below standard sea level			
Year	Elevation	Year	Elevation	Year	Depression	Year	Depression
	Feet		*Feet*		*Feet*		*Feet*
1898	2.45	1911	2.70	1898	3.36	1911	3.06
1899	2.56	1912	2.66	1899	3.11	1912	3.22
1900	2.62	1913	2.64	1900	3.00	1913	3.21
1901	2.52	1914	2.91	1901	3.00	1914	2.82
1902	2.64	1915	2.78	1902	2.91	1915	2.91
1903	2.56	1916	2.61	1903	2.92	1916	3.06
1904	2.65	1917	2.57	1904	2.78	1917	3.11
1905	2.70	1918	2.85	1905	2.84	1918	2.86
1906	2.66	1919	2.68	1906	2.94	1919	2.89
1907	2.69	1920	2.61	1907	2.83	1920	2.95
1908	2.54	1921	2.64	1908	3.22	1921	2.90
1909	2.59	1922	2.59	1909	3.08	1922	2.89
1910	2.55	1923	2.54	1910	3.26	1923	2.95
Mean	2.59	Mean	2.68	Mean	3.02	Mean	2.99

For the 26 years of observations higher high water was lowest in 1898, its height for that year being 2.45 feet above standard sea level, and highest in 1914 with a height of 2.91 feet above standard sea level. A mean of the two overlapping 19-year series gives 2.64 feet as the height of HHW above standard sea level.

Lower low water was lowest in 1898 with a height of 3.36 feet below standard sea level and highest in 1904 when its height was 2.78 feet below standard sea level. A mean of the two overlapping 19-year series gives 3.02 feet as the height of LLW below standard sea level.

From the two overlapping 19-year series of observations the plane of higher high water lies 0.58 foot above the plane of mean high water. The plane of lower high water lies as much below the plane of mean high water as the plane of higher high water is above; hence, the plane of lower high water at Presidio lies 1.48 feet above the plane of standard sea level.

The plane of lower low water for the same series lies 1.15 feet below mean low water, consequently the plane of higher low water will lie 1.15 feet above the plane of mean low water. Thus the plane of higher low water lies 0.72 foot below standard sea level.

There are no direct tabulations of the tropic planes available, but these planes have been determined from the harmonic constants for six years, period 1904–1913. From these results the plane of tropic higher high water is 2.70 feet and the plane of tropic lower high water 1.41 feet above standard sea level.

The plane of tropic lower low water is found to be 3.53 feet below standard sea level while the plane of tropic higher low water is derived as 0.08 foot above standard sea level.

Data pertaining to extreme tides are frequently desired by the engineer and contractor as a guide for various projects. In this connection it is often desirable to know not only the highest and lowest tides that have been observed but also the average of such tides

that are likely to be encountered. These tides suggest the adoption of two other planes of considerable importance, and since these abnormal tides usually occur as the result of storms they may be designated as storm high water and storm low water. It is evident that the effect of storms in raising or lowering the height of the water will be greater at times of spring or perigean than it will at times of neap or apogean tides, consequently it is seen that the plane of storm high or low water must be rather arbitrarily defined. As here used the plane of storm high water for any given year is determined as the average of the 12 highest waters of that year, 1 for each month. In a like manner the plane of storm low water for any given year is determined as the average of the 12 lowest waters of that year, 1 for each month. It might reasonably be assumed that these planes would exhibit very material variations from year to year as only 12 heights enter into the determination of the yearly values. An inspection of Table 16, however, shows that there are no great variations from year to year, in fact the variations are quite consistent with those occurring between the yearly means of other tidal planes.

TABLE 16.—*Yearly extremes, Presidio, San Francisco, Calif., 1898–1923*

STORM HIGH WATER ABOVE STANDARD SEA LEVEL

Year	Average	Highest		Year	Average	Highest	
	Feet	*Date*	*Feet*		*Feet*	*Date*	*Feet*
1898	3.30	July 1, 2, 3	3.9	1911	3.67	Jan. 14	4.4
1899	3.54	Jan. 10	4.7	1912	3.61	July 13	4.1
1900	3.57	Jan. 2	4.7	1913	3.58	Dec. 25	4.2
1901	3.56	Jan. 3	4.4	1914	3.92	Dec. 16, 17	4.9
1902	3.50	Dec. 15, 16	3.9	1915	3.86	Jan. 29	4.9
1903	3.38	Jan. 13	4.0	1916	3.69	Jan. 3, Dec. 24	4.7
1904	3.53	Dec. 7	4.2	1917	3.46	Feb. 25	4.4
1905	3.69	Nov. 26, 27	4.2	1918	3.79	Nov. 18	5.2
1906	3.54	Mar. 12	4.0	1919	3.76	Dec. 5	4.5
1907	3.78	Jan. 14	4.6	1920	3.60	Jan. 4	4.1
1908	3.60	Feb. 2	4.9	1921	3.58	Dec. 25	4.7
1909	3.54	Jan. 21	4.6	1922	3.47	Feb. 10	4.6
1910	3.58	Jan. 23	4.1	1923	3.44	Nov. 9	4.0
Mean	3.55	Feb. 2, 1908	4.9	Mean	3.65	Nov. 18, 1918	5.2

STORM LOW WATER BELOW STANDARD SEA LEVEL

Year	Average	Lowest		Year	Average	Lowest	
	Feet	*Date*	*Feet*		*Feet*	*Date*	*Feet*
1898	4.50	Jan. 20, 21	5.2	1911	4.34	June 26, 27	4.9
1899	4.23	Feb. 8	5.1	1912	4.56	Dec. 25	5.3
1900	4.05	May 28, 29, Dec. 5	4.5	1913	4.36	Jan. 22, 23	4.9
1901	4.23	May 19	4.9	1914	4.16	June 8, 9, Nov. 18	4.6
1902	4.10	June 7	4.6	1915	4.27	June 26	5.1
1903	4.04	June 25, 26	4.6	1916	4.50	May 20	4.9
1904	3.93	Jan. 4, 5	4.8	1917	4.25	Jan. 22	4.9
1905	3.95	Dec. 25, 26, 27	4.7	1918	4.03	May 11	4.6
1906	4.15	Nov. 18	5.0	1919	4.04	Nov. 9, Dec. 8	4.7
1907	3.96	June 26	4.5	1920	4.29	Jan. 5	4.8
1908	4.40	Jan. 5	5.0	1921	4.01	June 8, Dec. 15, 16	4.3
1909	4.33	Nov. 27	5.2	1922	4.03	Jan. 12, 13, May, 11, Nov. 19	4.4
1910	4.43	Dec. 16	5.1	1923	4.04	Dec. 9	5.3
Mean	4.18	Jan. 20, 21, 1898; Nov. 27, 1909	5.2	Mean	4.22	Dec. 25, 1912; Dec. 9, 1923	5.3

Table 16 contains the storm high and low waters for every year of the series. The second and sixth columns give the average height of the 12 monthly highest and lowest waters for each year, reckoned above standard sea level for the storm high water and below standard sea level for the storm low water. The date and height, referred to standard sea level, of the highest and lowest tide for each year of the series are given in columns three and four, and seven and eight. For convenience the series has been divided into two 13-year groups and at the foot of the table there are given in columns two and six the mean of the storm high or low water for each group, while in columns three and four, and seven and eight there are given the date and height of the highest or lowest tide in each 13-year group.

The mean for the first 13-year group gives a height of 3.55 feet for storm high water above standard sea level. For the second 13-year group the mean is determined to be 3.65 feet, the variation between the two 13-year groups being but one-tenth of a foot. A mean of the entire 26 years gives 3.60 feet as the height of the plane of storm high water above standard sea level. The highest tide during the 26 years of observation occurred November 18, 1918, the height being 5.2 feet above standard sea level.

For the storm low water the mean of the first 13-year group is 4.18 feet below standard sea level, while the mean for the second group gives 4.22 feet, a variation of but 0.04 foot. Taking a mean of the entire 26 years the plane of storm low water is determined to be 4.20 feet below standard sea level. The lowest tide observed during the series occurred on December 25, 1912, and December 9, 1923, the height on both dates being 5.3 feet below standard sea level.

It should be noted that these heights are referred to standard sea level, a fixed datum with a height of 8.519 feet on the staff at Presidio.

In order to show the heights of storm tides above or below the datum of soundings on the United States Coast and Geodetic Survey charts Table 17 is here presented. In this table the data is arranged the same as in Table 16 but the heights are referred to the datum plane of standard lower low water which is 5.55 feet above the zero of the tide staff at Presidio.

TABLE 17.—*Yearly extremes, Presidio, San Francisco, Calif., 1898–1923*

STORM HIGH WATER ABOVE STANDARD LOWER LOW WATER

Year	Average	Highest		Year	Average	Highest	
	Feet	*Date*	*Feet*		*Feet*	*Date*	*Feet*
1898	6.27	July 1, 2, 3	6.9	1911	6.64	Jan. 14	7.4
1899	6.51	Jan. 10	7.7	1912	6.58	July 13	7.1
1900	6.54	Jan. 2	7.7	1913	6.55	Dec. 25	7.2
1901	6.53	Jan. 3	7.4	1914	6.89	Dec. 16, 17	7.9
1902	6.47	Dec. 15, 16	6.9	1915	6.83	Jan. 29	7.9
1903	6.35	Jan. 13	7.0	1916	6.66	Jan. 3, Dec. 24	7.7
1904	6.50	Dec. 7	7.2	1917	6.43	Feb. 25	7.4
1905	6.66	Nov. 26, 27	7.2	1918	6.76	Nov. 18	8.2
1906	6.51	Mar. 12	7.0	1919	6.73	Dec. 5	7.5
1907	6.75	Jan. 14	7.6	1920	6.57	Jan. 4	7.1
1908	6.57	Feb. 2	7.9	1921	6.55	Dec. 25	7.7
1909	6.51	Jan. 21	7.6	1922	6.44	Feb. 10	7.6
1910	6.55	Jan. 23	7.1	1923	6.41	Nov. 9	7.0
Mean	6.52	Feb. 2, 1908	7.9	Mean	6.62	Nov. 18, 1918	8.2

STORM LOW WATER BELOW STANDARD LOWER LOW WATER

Year	Average	Lowest		Year	Average	Lowest	
	Feet	*Date*	*Feet*		*Feet*	*Date*	*Feet*
1898	1.53	Jan. 20, 21	2.2	1911	1.37	June 26, 27	1.9
1899	1.26	Feb. 8	2.1	1912	1.59	Dec. 25	2.3
1900	1.08	May 28, 29, Dec. 5	1.5	1913	1.39	Jan. 22, 23	1.9
1901	1.26	May 19	1.9	1914	1.19	June 8, 9, Nov. 18	1.6
1902	1.13	June 7	1.6	1915	1.30	June 26	2.1
1903	1.07	June 25, 26	1.6	1916	1.53	May 20	1.9
1904	0.96	Jan. 4, 5	1.8	1917	1.28	Jan. 22	1.9
1905	0.98	Dec. 25, 26, 27	1.7	1918	1.06	May 11	1.6
1906	1.18	Nov. 18	2.0	1919	1.07	Nov. 9, Dec. 8	1.7
1907	0.99	June 26	1.5	1920	1.32	Jan. 5	1.8
1908	1.43	Jan. 5	2.0	1921	1.04	June 8, Dec. 15, 16	1.3
1909	1.36	Nov. 27	2.2	1922	1.06	Jan. 12, 13 May 11, Nov. 19	1.4
1910	1.46	Dec. 16	2.1	1923	1.07	Dec. 9	2.3
Mean	1.21	Jan. 20, 21, 1898 Nov. 27, 1909	2.2	Mean	1.25	Dec. 25, 1912 Dec. 9, 1923	2.3

From Table 17 the mean of 13 years of observation 1898–1910, gives a value of 6.52 feet for the height of storm high water above standard lower low water, while for the second 13 years 1911–1923 the mean is determined to be 6.62 feet. For the entire series of 26 years the mean storm high water is determined to be 6.57 feet above standard lower low water. The highest tide during the 26 years of observations occurred November 18, 1918, its height being 8.2 feet above standard lower low water or in other words at the time of the highest tide at Presidio the water stood 8.2 feet above the plane of lower low water used as the datum on Coast and Geodetic Survey charts.

Storm low water for the 13 years 1898–1910 is determined to be 1.21 feet below standard lower low water while for the second 13 years of the series, 1911–1923, the mean is 1.25 feet. The mean of the entire 26 years of observations gives a value of 1.23 feet as the depression of storm low water below standard lower low water. The lowest tide at Presidio occurred on two different dates, namely, December 25, 1912, and December 9, 1923. On these dates the low water fell 2.3 feet below the datum plane of standard lower low water, or it might be said that on these dates at the times of lowest tide the water stood 2.3 feet below the plane of lower low water used as the datum on Coast and Geodetic Survey charts.

7. THE RANGE OF THE TIDE

The range of the tide is the difference in height between high water and low water. It varies from day to day due primarily to the positions of sun and moon relative to the earth. At the time of spring tide and perigean tide the range is increased while at the time of neap tide and apogean tide the range is decreased. The various ranges of the tide may thus be classified in a manner similar to that used for the datum planes, giving mean range, spring range, neap range, perigean range, apogean range, and several kinds of tropic ranges.

The variation in the range of the tide at Presidio from day to day for a typical summer month is shown in Table 1. The varia-

tion from year to year may be obtained by subtracting the yearly means of low water from the corresponding yearly mean of high water in Table 11, or by adding the yearly values of mean low water below standard sea level to the corresponding yearly values of mean high water above standard sea level in Table 12. These results are given in Table 18.

TABLE 18.—*Yearly mean range, Presidio, San Francisco, Calif., 1898–1923*

Year	Mean	Year	Mean
	Feet		*Feet*
1898	3.96	1911	3.87
1899	3.90	1912	3.95
1900	3.97	1913	3.92
1901	3.94	1914	3.80
1902	3.97	1915	3.82
1903	3.97	1916	3.83
1904	3.94	1917	3.88
1905	4.04	1918	3.95
1906	3.97	1919	3.97
1907	3.90	1920	4.03
1908	4.04	1921	4.00
1909	3.90	1922	3.98
1910	3.92	1923	4.02
Mean	3.96	Mean	3.92

The range of the tide exhibits from year to year a change which occupies a period of about 19 years and is due to the variation in the longitude of the moon's node. This brings about a change in the inclination of the lunar orbit to the plane of the earth's equator, which passes through a cycle varying from a minimum of 18.3° to a maximum of 28.6° and then back to a minimum of 18.3° again, the average period of this variation being 18.6 years. The tidal forces are less than the average at the time of maximum inclination, and hence the range of the tide is less than the average at such times. Similarly, the tidal forces are greater than the average when the lunar orbit has its minimum inclination, and at such times the range of the tide is greater than the average. Thus, it is seen that if a series of 19 years can be obtained this variation should be eliminated. The 26 years of observations at Presidio permit of two overlapping 19-year groups, 1898–1916 and 1905–1923. The mean range for the first 19-year group is 3.93 feet, while for the second it is 3.94 feet. A mean of the two overlapping 19-year periods gives a mean range of 3.93 feet.

The corrected mean range for each year may be obtained by multiplying the mean range as directly obtained from the tabulations by factors $F(Mn)$ [2] devised to take account of the variation in the longitude of the moon's node. These results are given in Table 19.

[2] Manual of Tides, Part III, by R. A. Harris (United States Coast and Geodetic Survey Report for 1894), p. 247.

TABLE 19.—*Yearly corrected mean range, Presidio, San Francisco, Calif., 1898–1923*

Year	Mean.	Year	Mean.
	Feet		*Feet*
1898	3.98	1911	3.92
1899	3.90	1912	4.01
1900	3.94	1913	3.99
1901	3.89	1914	3.86
1902	3.91	1915	3.87
1903	3.90	1916	3.86
1904	3.87	1917	3.89
1905	3.97	1918	3.94
1906	3.92	1919	3.94
1907	3.87	1920	3.97
1908	4.04	1921	3.93
1909	3.92	1922	3.90
1910	3.96	1923	3.95
Mean	3.93	Mean	3.93

A study of Tables 18 and 19 brings out some significant facts. As previously stated the variation in the longitude of the moon's node should cause a periodic variation in the uncorrected mean range, but Table 18 containing the uncorrected mean range shows no such periodic variation except for the last few years or from about 1914 to the end of the series. The corrected mean range should be a mean value and consequently should approximate closely the value of 3.93 feet as determined from two overlapping 19-year periods. An inspection of Table 19, however, shows that there is still considerable fluctuation between the yearly values of the corrected mean range and that the values do not show the approximation to the mean value expected. It will be of interest to ascertain just what results are obtained by correcting the mean range for the longitude of the moon's node. Throughout the entire series of 26 years it is found that for 7 different years the uncorrected mean range gives better results than the corrected, on 14 different years the corrected mean range gives better results than the uncorrected while on the remaining 5 years the corrected and uncorrected values are the same. Thus it is seen that during a period of 26 years at Presidio the corrected values of mean range give better results for 14 different years but fail to improve upon the uncorrected values for 12 different years.

The results derived above indicate that for certain localities correcting the mean range for the longitude of the moon's node does not always give a well-determined value. In fact, it has been shown that approximately only 50 per cent of the mean range values at Presidio are improved by applying the factor $F(Mn)$ to them and furthermore about 27 per cent of the time the corrected values give a poorer determination than the uncorrected. For tides in which the dirunal inequality is small the application of the factor $F(Mn)$ has been shown to give a satisfactory mean range. Consequently the failure of the correcting factor to give entirely satisfactory results at Presidio must be attributed in a large measure to the large diurnal inequality at that place.

The various ranges previously mentioned are readily determined by obtaining the difference in height between the corresponding high and low water datum planes. A number of these ranges have designations which are self-evident as, for example, the mean, spring, neap, perigean, and apogean ranges, but it will be well to define some of the

others. Thus, the great diurnal range is the distance between the mean higher high water and mean lower low water; the small diurnal range is the distance between mean lower high water and mean higher low water; the great tropic range is the distance between tropic higher high water and tropic lower low water; the small tropic range is the distance between tropic lower high water and tropic higher low water; the storm range is the distance between storm high water and storm low water; and the greatest range is the distance between the highest observed high water and the lowest observed low water. These various ranges are compiled in Table 20.

TABLE 20.—*Ranges of the tide, Presidio, San Francisco, Calif.*

Designation	Feet	Designation	Feet
Mean range	3.93	Small diurnal range	2.20
Spring range	4.58	Great tropic range	6.23
Neap range	3.10	Small tropic range	1.33
Perigean range	4.55	Storm range	7.80
Apogean range	3.28	Greatest range	10.5
Great diurnal range	5.66		

8. DIURNAL INEQUALITIES

It has been shown that there is a material variation between the heights of the two high waters, and the low waters of each day at Presidio, hence the diurnal inequalities are of considerable importance. The diurnal high water inequality is derived by subtracting mean high water from mean higher high water. Similarly, the diurnal low water inequality is obtained by subtracting mean lower low water from mean low water.

The variations in high and low water diurnal inequalities from year to year may be derived by taking the corresponding differences between the values of Table 11 and Table 14. These results for the years 1898 to 1923, inclusive, are given in Table 21.

TABLE 21.—*Diurnal inequalities, Presidio, San Francisco, Calif., yearly means, 1898–1923*

Diurnal high water inequality				Diurnal low water inequality			
Year	DHQ	Year	DHQ	Year	DLQ	Year	DLQ
	Feet		*Feet*		*Feet*		*Feet*
1898	0.63	1911	0.61	1898	1.22	1911	1.28
1899	0.62	1912	0.63	1899	1.14	1912	1.29
1900	0.60	1913	0.63	1900	1.05	1913	1.31
1901	0.56	1914	0.63	1901	1.03	1914	1.29
1902	0.56	1915	0.63	1902	1.02	1915	1.24
1903	0.54	1916	0.63	1903	0.97	1916	1.21
1904	0.52	1917	0.62	1904	0.96	1917	1.18
1905	0.51	1918	0.65	1905	0.99	1918	1.11
1906	0.55	1919	0.57	1906	1.08	1919	1.04
1907	0.53	1920	0.54	1907	1.08	1920	0.99
1908	0.55	1921	0.54	1908	1.17	1921	1.00
1909	0.56	1922	0.54	1909	1.21	1922	0.96
1910	0.62	1923	0.50	1910	1.27	1923	0.97
Mean	0.57	Mean	0.59	Mean	1.09	Mean	1.14

The diurnal inequalities exhibit from year to year variations due to the variation in the longitude of the moon's node similar to that discussed under mean range. It has been shown that this variation passes through a cycle in 18.6 years, consequently in a series of 19 years the variations complete a cycle and a well-determined mean value should be obtained. Two overlapping 19 year series can be obtained from the 26 years of observations at Presidio, namely, 1898–1916 and 1905–1923.

The high water diurnal inequality from the 19-year series 1898–1916 is 0.58 foot while for the second 19-year series 1905–1923 it is the same, 0.58 foot. A mean of the two 19-year series thus gives a value of 0.58 foot for the diurnal high water inequality.

For the low water diurnal inequality a mean of the first 19-year series, 1898–1916 gives 1.15 feet, while the second series 1905–1923 gives 1.14 feet. A mean of the two 19-year series gives a value of 1.15 feet for the diurnal low water inequality.

The corrected inequalities for each year may be obtained by multiplying the inequalities as directly obtained from the tabulations by "Factor 1.02 F_1." These factors which correct for the longitude of the moon's node have been computed by Harris.[3] By applying these factors to the values of table 21 the corrected inequalities are derived for the years 1898 to 1923 inclusive. The results are given in Table 22.

TABLE 22.—*Corrected diurnal inequalities, Presidio, San Francisco, Calif., yearly means, 1898–1923*

Corrected diurnal high water inequality				Corrected diurnal low water inequality			
Year	DHQ_c	Year	DHQ_c	Year	DLQ_c	Year	DLQ_c
	Feet		*Feet*		*Feet*		*Feet*
1898	0.61	1911	0.56	1898	1.17	1911	1.16
1899	0.62	1912	0.56	1899	1.14	1912	1.16
1900	0.63	1913	0.56	1900	1.11	1913	1.17
1901	0.62	1914	0.57	1901	1.15	1914	1.16
1902	0.65	1915	0.57	1902	1.19	1915	1.13
1903	0.65	1916	0.59	1903	1.16	1916	1.14
1904	0.62	1917	0.60	1904	1.15	1917	1.15
1905	0.60	1918	0.67	1905	1.16	1918	1.14
1906	0.61	1919	0.62	1906	1.21	1919	1.12
1907	0.57	1920	0.61	1907	1.16	1920	1.12
1908	0.56	1921	0.64	1908	1.19	1921	1.18
1909	0.54	1922	0.65	1909	1.17	1922	1.15
1910	0.58	1923	0.60	1910	1.19	1923	1.16
Mean	0.60	Mean	0.60	Mean	1.17	Mean	1.15

It is of interest to note that the "Factor 1.02 F_1" has not completely eliminated the yearly variations in the diurnal inequalities. Between two consecutive years there remains a variation as much as 0.07 foot for the DHQ_c while for any two years within the series a variation as large as 0.13 foot is found. For the DLQ_c there is found a variation of 0.06 foot between two consecutive years, while if any two years within the series is taken the variation may be as large as 0.10 foot. It should be observed however that the corrections have eliminated any periodic variation and consequently the remaining fluctuations must be due to meteorological conditions.

[3] R. A. Harris, Manual of Tides, Part III, United States Coast and Geodetic Survey Report for 1894) p. 260.

9. TIDAL HARMONIC CONSTANTS

Tidal harmonic constants from harmonic analysis [4] of the hourly ordinates of the tide at Presidio have been determined for six years, 1904, 1905, 1906, 1907, 1908, and 1913. Each year was based upon a series of 369 days beginning with the 1st of January. The results [5] for these six years of analysis are given in the table below. The amplitudes are expressed in feet, and the epochs are referred to the local meridian. Values inclosed in parentheses have been inferred.

TABLE 23.—*Harmonic constants, Presidio, San Francisco, Calif.*

Component	H		Component	H	κ
	Feet	*Degrees*		*Feet*	*Degrees*
J_1	(0.068)	(114)	S_1	0.020	147
K_1	1.208	106	S_2	0.404	335
K_2	0.120	320	S_4	0.002	246
L_2	0.055	353	S_6	0.002	112
M_1	0.039	104	T_2	0.064	194
M_2	1.773	330	λ_2	0.027	335
M_3	0.013	332	μ_2	0.029	224
M_4	0.077	25	ν_2	0.073	311
M_6	0.009	22	ρ_1	(0.029)	(82)
M_8	0.006	64			
N_2	0.376	304	MS	0.024	24
2N	0.041	276			
O_1	0.756	89			
OO	(0.038)	(123)			
P_1	0.377	104	Sa	0.110	94
Q_1	0.128	82	SSa	0.154	304
2Q	(0.020)	(72)			
R_2	(0.003)	(335)			

Series, 1904–1913; length, 6 years.

A number of tidal characteristics may be readily derived from the harmonic constants by means of the formulae given in Harris's Manual of Tides.

Thus the ages of the tide are determined from the following formulae:

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

The phase age of the tide is defined as the time that elapses between full or new moon and the spring tides, or the time that elapses between the moon's first and third quarters and the neap tides. Substituting the values of the harmonic constants from Table 23 in the above formula the phase age of the tide at Presidio is derived to be 4.9 hours.

The parallax age of the tide is defined as the time by which the perigean and apogean tides follow the corresponding positions of the moon. The above formula gives 47.8 hours for the parallax age of the tide at Presidio.

The diurnal age of the tide is defined as the time by which the tropic tides follow the moon's semimonthly maximum north or south decli-

[4] For a detailed discussion of harmonic analysis see Harmonic Analysis and Prediction of Tides by Pau Schureman, United States Coast and Geodetic Survey.
[5] Ibid., p. 334.

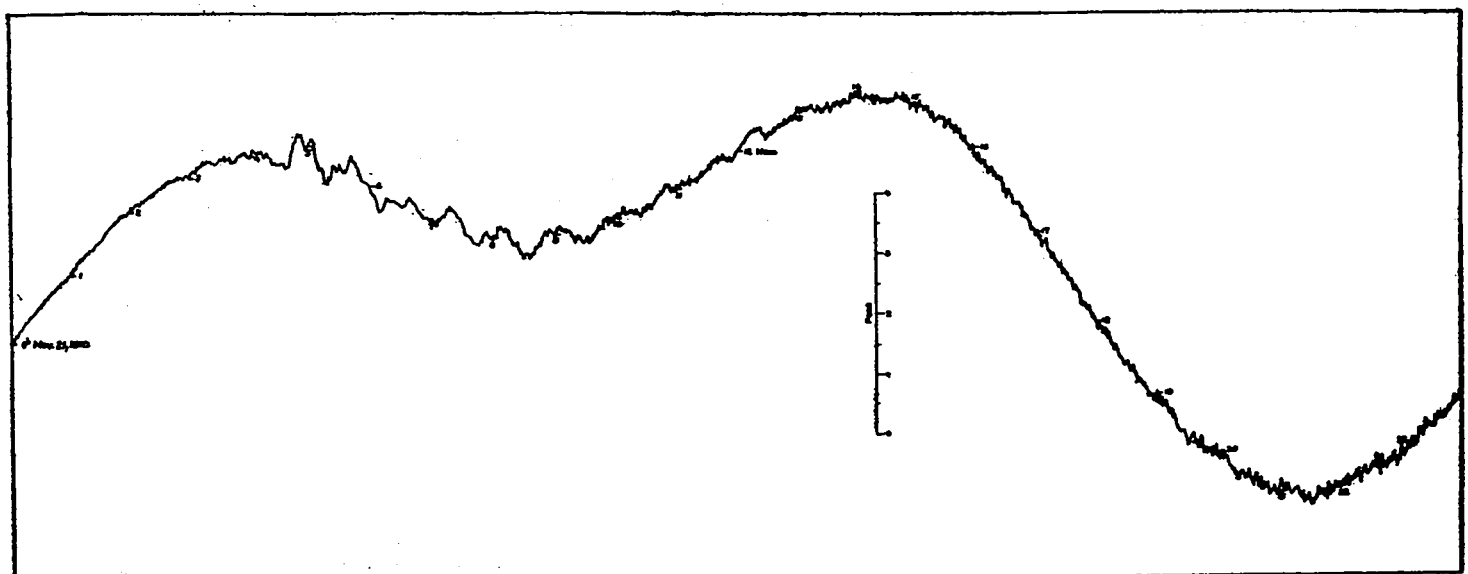


FIG. 2.—Marigram, Presidio, San Francisco, Calif., November 21, 1910

nation. The diurnal age of the tide at Presidio as derived from the above formula is determined to be 15.5 hours.

The type of the tide at Presidio may be inferred from the harmonic constants by the ratio of K_1+O_1 to M_2+S_2. Substituting the constants from Table 23 it is found that the ratio is 0.90. When the ratio is between 0.25 and 1.25 the tide is of the mixed type, consequently the tide at Presidio is deduced to be of the mixed type. This is also borne out by the fact that the diurnal inequality in the heights of high and low water is large.

The order of occurrence of the tides may also be determined from the harmonic constants. The formulae entering into this determination are rather involved and will not be reproduced here but can be found in Harris's Manual of Tides, Part II (Coast and Geodetic Survey Report for 1894), page 145. These formulae give the order of occurrence of the tide at Presidio to be as follows: Higher high water, lower low water, lower high water, higher low water.

10. METEOROLOGICAL AND SEISMOLOGICAL EFFECTS

Winds and sudden barometric changes may exert a marked influence upon the water surface. Where the tidal range is small these effects may be sufficient to completely mask the tide, while in other localities, where the tidal range is appreciable, the effects are sufficient to materially affect the water surface, causing sudden elevations and depressions and thereby probably reversing the direction of the current for short intervals. The effects of these nontidal forces are frequently quite evident from a marigram.

A very good illustration is found on the marigram from the Presidio tide gauge for November, 1910. Figure 2 is taken from a tracing of this tide roll and shows the hourly variations in the tide on November 21, 1910. In this figure the numbers from 0 to 23, increasing from left to right, represent the hours of the day beginning with midnight. The hours are thus numbered consecutively to 23 to eliminate all uncertainty as to whether morning or afternoon is meant. Referring to the figure it is noticed that there is a marked jog in the curve between 4 and 5 hours. During these hours the water surface was suddenly elevated approximately 0.6 foot in a period of about 10 minutes, and this occurred on a falling tide when the tidal forces were tending to lower the water surface. After a few minor oscillations, probably due to the continuation of the small oscillations existing before the abrupt elevation, the water surface rapidly dropped back approximately 0.8 foot in about 15 minutes and then almost immediately began to rise again. These sudden elevations and depressions of the water continued about every 25 minutes over a period of about 6 hours after which they gradually died out. Marked oscillations of this character probably materially affect the current. In some instances the effect may be sufficient to temporarily reverse the current in the Golden Gate.

Climatological records from the United States Weather Bureau clearly indicate that these disturbances were meteorological. Figure 3 is a copy of the barogram obtained at the San Francisco office on November 21, 1910. This curve shows the variations in the air pressure in inches of mercury from midnight to midnight on the day indicated. It is noted that there is a sudden drop in the air

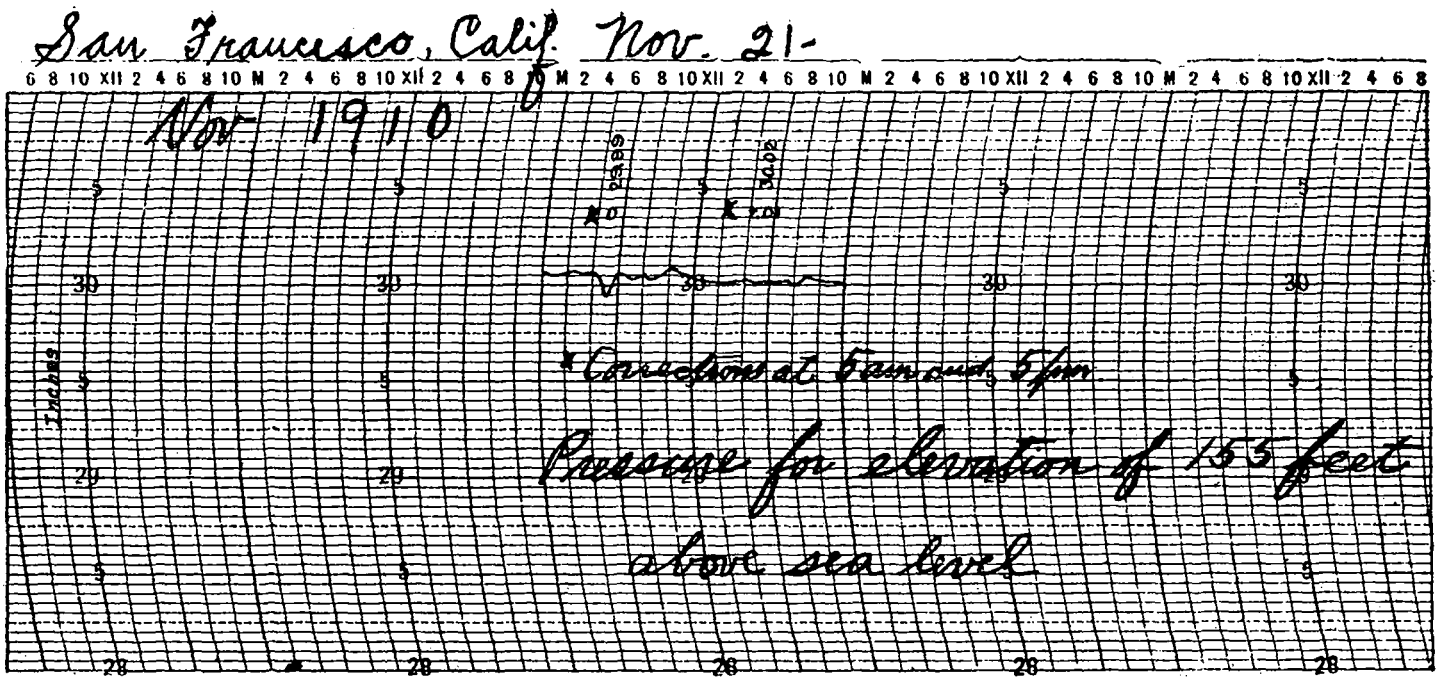


FIG. 3.—Barogram, San Francisco, Calif., November 21, 1910

pressure between 4 and 5 a. m., followed by a rapid rise to about 6 a. m., after which there are several much smaller variations. These fluctuations occur about the same time as those noted on the marigram, the sudden drop in pressure between 4 and 5 a. m. being reflected by a sharp rise in the water surface between the same hours. The extent of the pressure drop was about 0.14 inch which in itself was insufficient to cause a 0.6 foot change in water level. It is probable that the water surface was affected to a greater extent by the sudden wind from the south which accompanied the drop in the barometer. The variations of the wind at San Francisco on November 21, 1910, as obtained from the anemometer records of the United States Weather Bureau are tabulated below. These tabulations include the hourly wind velocity in miles with corresponding prevailing direction.

Hourly wind velocity and direction, San Francisco, Calif., November 21, 1910

Item	A. M., hour ending—											
	1	2	3	4	5	6	7	8	9	10	11	12
Hourly wind velocity (miles)	2	2	2	4	11	11	6	3	3	3	4	4
Prevailing hourly wind direction	NW	NW	NW	S	S	NW	NW	N	S	NW	NW	SE
	P. M., hour ending—											
	1	2	3	4	5	6	7	8	9	10	11	12
Hourly wind velocity (miles)	7	6	8	9	8	10	8	6	7	4	2	2
Prevailing hourly wind direction	NW	NW	W	W	W	W	W	W	W	NW	SW	S

Referring to the data above it is seen that until 3 a. m., on November 21, 1910, the wind was blowing from the northwest with a velocity of 2 miles. Between 3 and 4 a. m., it shifted to south, the velocity increasing to 4 miles. During the next hour, 4 to 5 a. m., the prevailing direction remained south and the velocity continued to increase, the average velocity for the hour being 11 miles. It will be noted that it was between 4 and 5 a. m., that the marigram indicated a sharp rise in the water surface and the barogram gave a sudden drop in air pressure. During the next hour the wind maintained a velocity of 11 miles but the wind shifted back to northwest. It was during this period, 5 to 6 a. m., that the water surface dropped rapidly and the air pressure underwent a corresponding rise. After 6 a. m., the wind lulled considerably with the prevailing direction shifting occasionally as shown in the above data. From the climatological records it appears evident that the sudden fluctuation in the water surface shown in Figure 2 must be attributed to the sudden drop in the air pressure and the accompanying sudden wind from the south on that date.

With regard to the effects of earthquakes upon sea level it is found that the water surface may be affected by a shock in the immediate

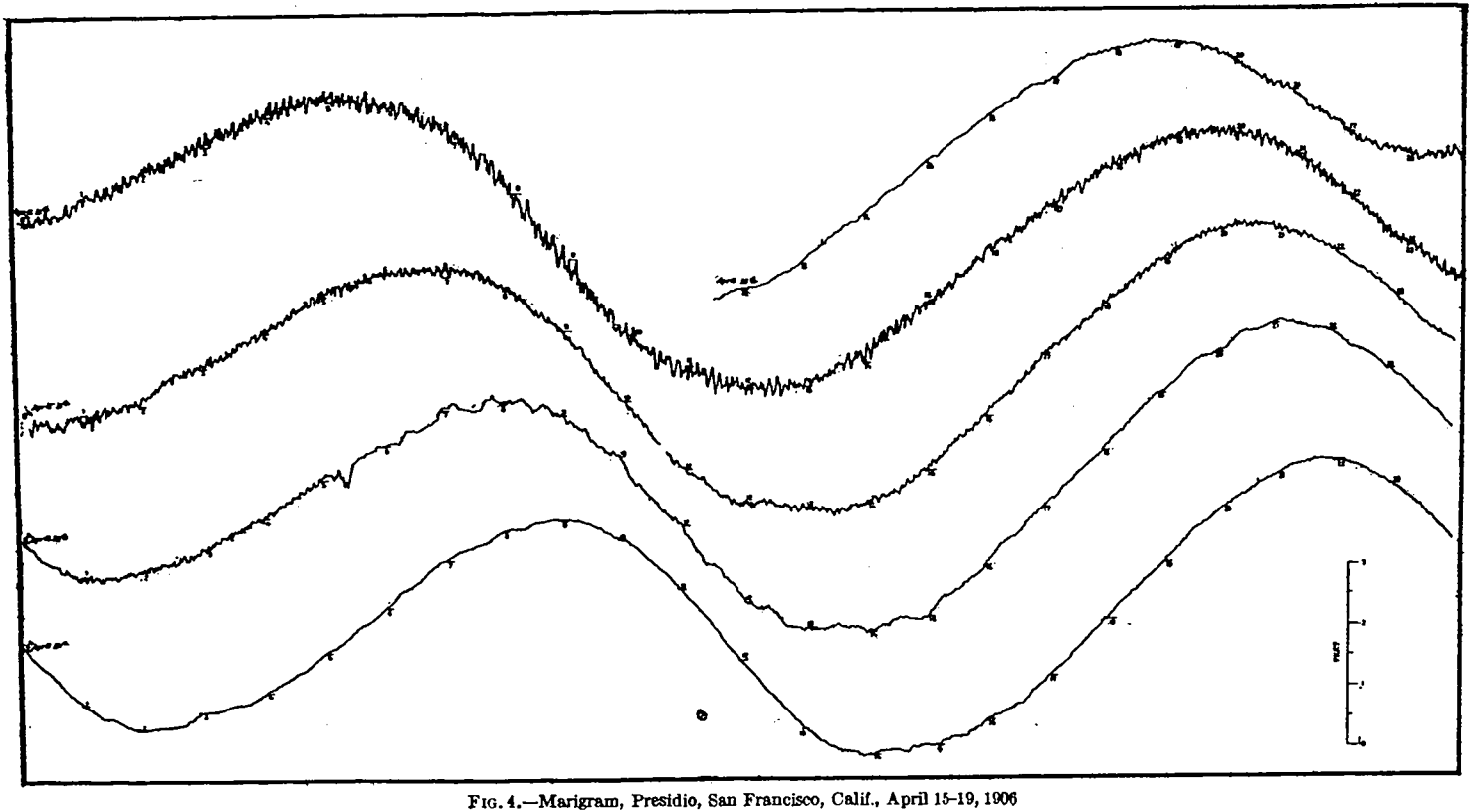


FIG. 4.—Marigram, Presidio, San Francisco, Calif., April 15–19, 1906

vicinity or by one which is thousands of miles away. The amplitude of the water oscillation is dependent to a large extent upon the intensity of the shock, the displacement of the sea bottom, and the magnitude of the vertical component of the earth movement.

Figure 4 shows the effect of the destructive California earthquake of April 18, 1906, upon the marigram at the Presidio tide station. In this figure the hours of the day are numbered consecutively from 0 to 23 to eliminate any ambiguity as to whether a. m. or p. m. is meant. Although the earthquake occurred on April 18 around 5 a. m., the tide curve is given for several days prior to and one day after that date to show the normal fluctuation recorded by the gauge.

From 12 noon to between 17 and 18 hours on April 15 the curve is smooth. A little before 18 hours on the 15th a slight disturbance was recorded which increased in magnitude until about noon April 16, after which it slowly diminished but continued to prevail until the time of the shock on April 18. These fluctuations were probably due to an imperfect oscillation across the Golden Gate set up by the wind. The effect of the shock is shown on the marigram shortly after 5 a. m. on April 18, the curve showing a depression of the water level in the Golden Gate slightly in excess of 4 inches. This depression of the water surface did not begin instantaneously with the earthquake, but followed after an interval of about 9 or 10 minutes. The minor vertical movement during the drop in the level of the water was probably due to the continuation of the oscillations existing before the shock.

The record shows that the lowering of the water lasted about 9 minutes, after which it immediately began to recover and rose to its normal level without minor oscillations in about 7 minutes. That the movement was not periodic is indicated by the fact that the depression was not followed by a complementary rise of the water surface.

It is to be noted that the amplitude of the wind oscillation which occurred several days prior to the earthquake is at times greater than the water disturbance caused by the earthquake. This is attributed to the fact that in the fault of April 18, 1906, the movement was chiefly horizontal. The vertical component of the displacement was quite small and consequently the resultant sea wave was practically insignificant.

The effect of an earthquake in a distant part of the Pacific Ocean upon the waters in the Golden Gate is shown by Figure 5. The tide curves in this figure were copied from the marigram obtained at the Presidio tide station and show the fluctuations produced by an earthquake off the coast of Chile on November 11, 1922.

From computations based on the records from numerous scattered seismographs it appears that this earthquake occurred on November 11, at 4.33 a. m. (Greenwich civil time), the origin being in the vicinity of Carrizal, Chile.

The marigram for Presidio shows that the first seismic sea wave arrived at that station about 10.20 a. m., one hundred and twentieth meridian west, or 6.20 p. m., Greenwich civil time. Thus the time of transmission of the sea wave was about 13 hours and 47 minutes. Figure 5 also shows that the oscillations at Presidio reached a maximum amplitude about 11 hours after the first disturbance with a

range of more than 1 foot. The principal oscillations had a period of from 30 to 40 minutes and persisted for several days with gradually diminishing amplitude, finally disappearing from the record on November 14.

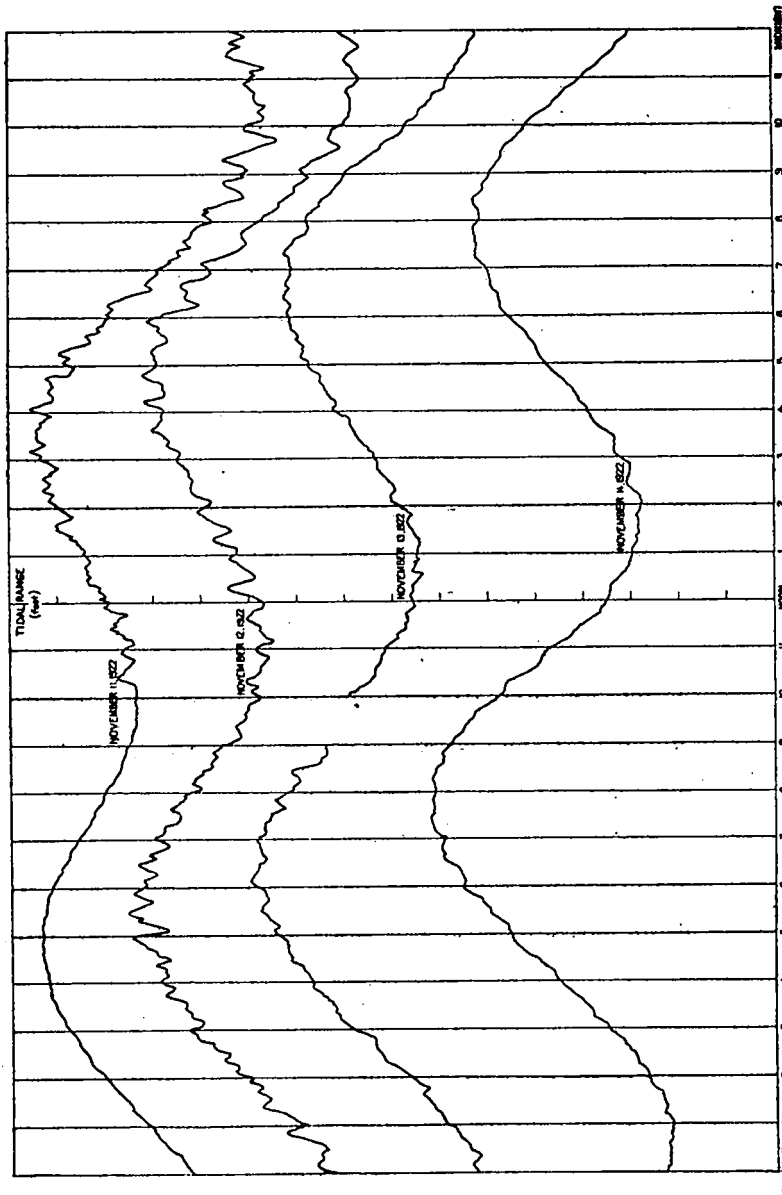


FIG. 5.—Marigram, Presidio, San Francisco, Calif., Nov. 11-14, 1922

As San Francisco is about 4,890 nautical miles from Carrizal it may appear unusual that the Chilean earthquake should affect the water in the Golden Gate to a greater extent than the disastrous California earthquake of April 18, 1906. This is readily explained however, by

the fact that the California shock consisted primarily of a horizontal displacement while the Chilean earthquake of November 11, 1922, was a submarine disturbance in which the vertical component of the displacement was considerable. When there is a vertical displacement, one portion of the sea bottom is dropped relative to an adjacent portion and the ensuing displacement of the prism of water over the region affected generates a periodic wave. The amplitude of this wave is dependent upon the amount of the vertical component. If this is considerable the amplitude of the resulting wave is apt to be large.

11. SUMMARY OF TIDAL DATA

For the sake of convenience the results derived and discussed in this section have been compiled in one table and the results are tabulated below. The more frequently used constants given in this table are based upon 26 years of observations while others are based upon shorter series and still others are derived from harmonic constants. Since each of the constants given in Table 24, however, has been discussed separately in this section, the basis for the determination of each value given in the table may be ascertained by referring to the proper paragraph.

TABLE 24.—*Tidal data, Presidio, San Francisco, Calif.*

TIME RELATIONS	Hours
High-water interval	11. 67
Low-water interval	4. 97
Duration of rise	6. 70
Duration of fall	5. 72
Phase age	4. 9
Parallax age	47. 8
Diurnal age	15. 5

Sequence of tides is HHW to LLW.

RANGES AND INEQUALITIES	Feet
Mean range	3. 93
Great diurnal range	5. 66
Small diurnal range	2. 20
Great tropic range	6. 23
Small tropic range	1. 33
Spring range	4. 58
Neap range	3. 10
Perigean range	4. 55
Apogean range	3. 28
Storm range	7. 80
Greatest range	10. 5
Diurnal high-water inequality	0. 58
Diurnal low-water inequality	1. 15
	Ratio
Spring range÷mean range	1. 16
Neap range÷mean range	0. 79
Perigean range÷mean range	1. 16
Apogean range÷mean range	0. 83
Great diurnal range÷mean range	1. 44
Great tropic range÷mean range	1. 59

HEIGHT RELATIONS

	Feet
Mean high water above standard sea level	2. 06
Mean higher high water above standard sea level	2. 64
Mean lower high water above standard sea level	1. 48
Tropic higher high water above standard sea level	2. 70
Tropic lower high water above standard sea level	1. 41
Spring high water above standard sea level	2. 32
Neap high water above standard sea level	1. 57
Perigean high water above standard sea level	2. 39
Apogean high water above standard sea level	1. 69
Storm high water above standard sea level	3. 60
Highest high water above standard sea level	5. 2
Storm high water above standard LLW	6. 57
Highest high water above standard LLW	8. 2
Half tide level above mean sea level	0. 06
Mean low water below standard sea level	1. 87
Mean lower low water below standard sea level	3. 02
Mean higher low water below standard sea level	0. 72
Tropic lower low water below standard sea level	3. 53
Tropic higher low water above standard sea level	0. 08
Spring low water below standard sea level	2. 26
Neap low water below standard sea level	1. 53
Perigean low water below standard sea level	2. 16
Apogean low water below standard sea level	1. 59
Storm low water below standard sea level	4. 20
Lowest low water below standard sea level	5. 3
Storm low water below standard LLW	1. 23
Lowest low water below standard LLW	2. 3
Standard sea level on staff of 1897 (16 years)	8. 519
Mean sea level on staff of 1897 (26 years)	8. 555
Standard lower low water on staff of 1897 (10 years)	5. 55
Mean lower low water on staff of 1897 (26 years)	5. 50

TIDAL DATA FOR SAN FRANCISCO BAY AND TRIBUTARIES

12. GENERAL REMARKS

In order to give the tidal characteristics in the different parts of San Francisco Bay and its tributaries and to show the location of the various tide stations, the bay as a whole has been arbitrarily divided into seven unequal segments. These segments are designated as follows: 1, Approaches to San Francisco Bay; 2, Golden Gate; 3, South San Francisco Bay; 4, North San Francisco Bay; 5, San Pablo Bay and tributaries; 6, Carquinez Strait; and 7, Suisun Bay and tributaries.

For each segment there is presented a figure which covers the area of that particular segment and shows the location of the tide stations in that area. These stations are indicated by means of circles with designative letters. The tidal data for each of these various sections of the bay are presented in the form of tables. These tables of tidal data give the station letter as shown on the figure for the corresponding section, the name or location of the station, the period during which the observations were made, the length of the observations, the high-water and low-water lunitidal intervals, the duration of rise, and the mean range of the tide.

Unless otherwise noted all intervals and ranges in these tables have been reduced to mean values by comparison with simultaneous observations at some standard station such as Fort Point, Sausalito, or Presidio. In some instances where there were no simultaneous observations for comparison the mean range was corrected for the

longitude of the moon's node. Wherever the mean range has been thus corrected it is indicated by the subscript *c* after the value of the mean range. In using the data from the tables, consideration should be given to the length of observations, for obviously values obtained from only a day or two of observations are rather poorly determined and should not be given the same weight as values derived from observations covering a period of several months or more. Due to the difficulty of keeping accurate time, the time relations for stations derived from early observations contain an element of uncertainty.

It should be noted that, in general, the direct difference between the lunitidal intervals at two stations does not give the difference in time of tide at the two stations. If the two stations have the same longitude the direct difference of the intervals gives the difference in time of tide, but when the stations have different longitudes it is necessary to apply a correction for this difference. In explaining this method of obtaining the time difference it is convenient to select one station as the reference station. Let the longitude in degrees of this reference station be called L_1 and the longitude of the secondary station L_{11} and consider west as positive and east as negative. The difference in time of tide at the two stations expressed in hours is then given by the following formula:

$$\text{Time difference} = (I_{11} - I_1) + 0.069\ (L_{11} - L_1)$$

in which I_1 and I_{11} are, respectively, the intervals in hours at the reference and secondary stations. If the final result is positive, the tide occurs later at the secondary station than at the reference station, while if the result is minus, the tide occurs earlier at the secondary station.

13. THE TIDE IN THE APPROACHES TO SAN FRANCISCO BAY

The approaches to San Francisco Bay for the purposes of this discussion may be considered as extending from southeast Farallon Island to the entrance to Golden Gate or to a line drawn from Point Bonita to Mile Rock. The location of the tide stations in this section are shown in Figure 6.

The tidal data for the stations shown on Figure 6 are presented in Table 25.

TABLE 25.—*Tidal data, approaches to San Francisco Bay*

Station	Location	Series	Length	Lunitidal intervals		Duration of rise	Mean range
				HWI	LWI		
				Hours	*Hours.*	*Hours*	*Feet*
A	Southeast Farallon Island	May–Oct., 1855	4½ months	10.80	4.33	6.47	3.46
B	Rodeo Cove	Mar.–Apr., 1895	2 days	11.28	4.70	6.58	3.73

The intervals and ranges for stations A and B were reduced to mean values by comparison with simultaneous observations at Fort Point and Sausalito, respectively.

Cotidal lines indicate that the tide sweeps in toward San Francisco Bay nearly parallel to the coast line and this is supported by the data

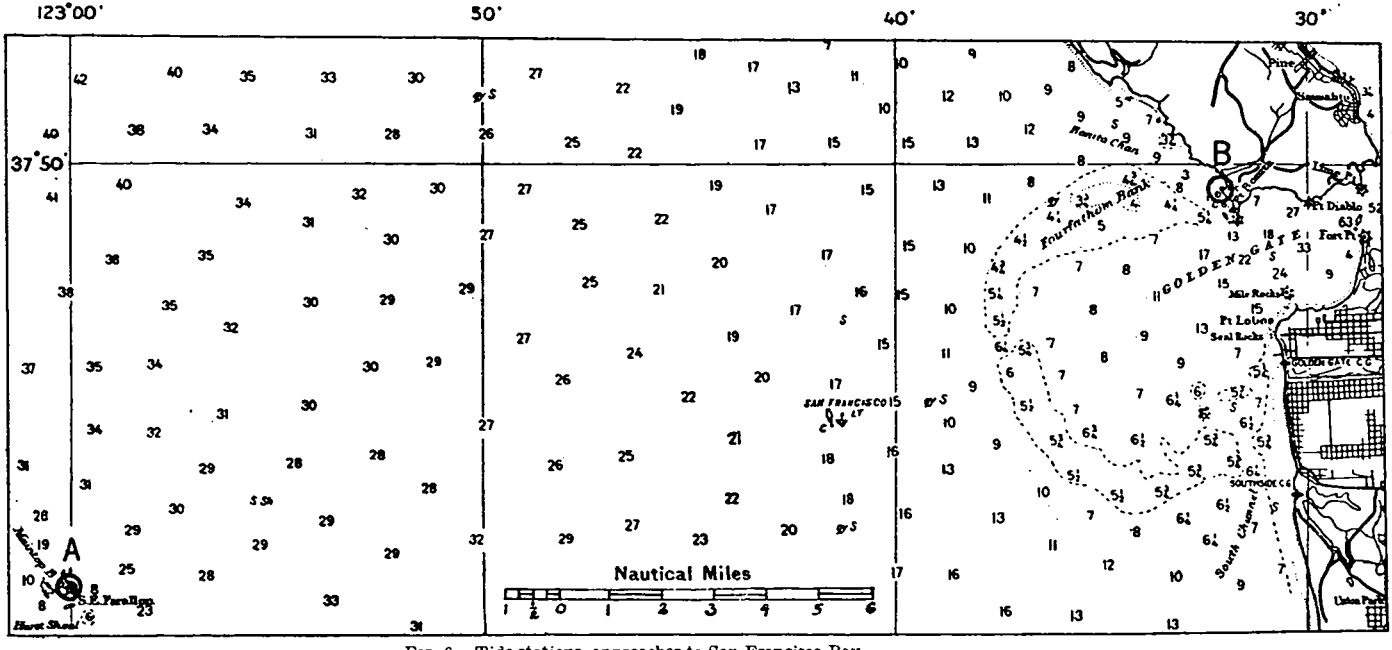


FIG. 6.—Tide stations, approaches to San Francisco Bay

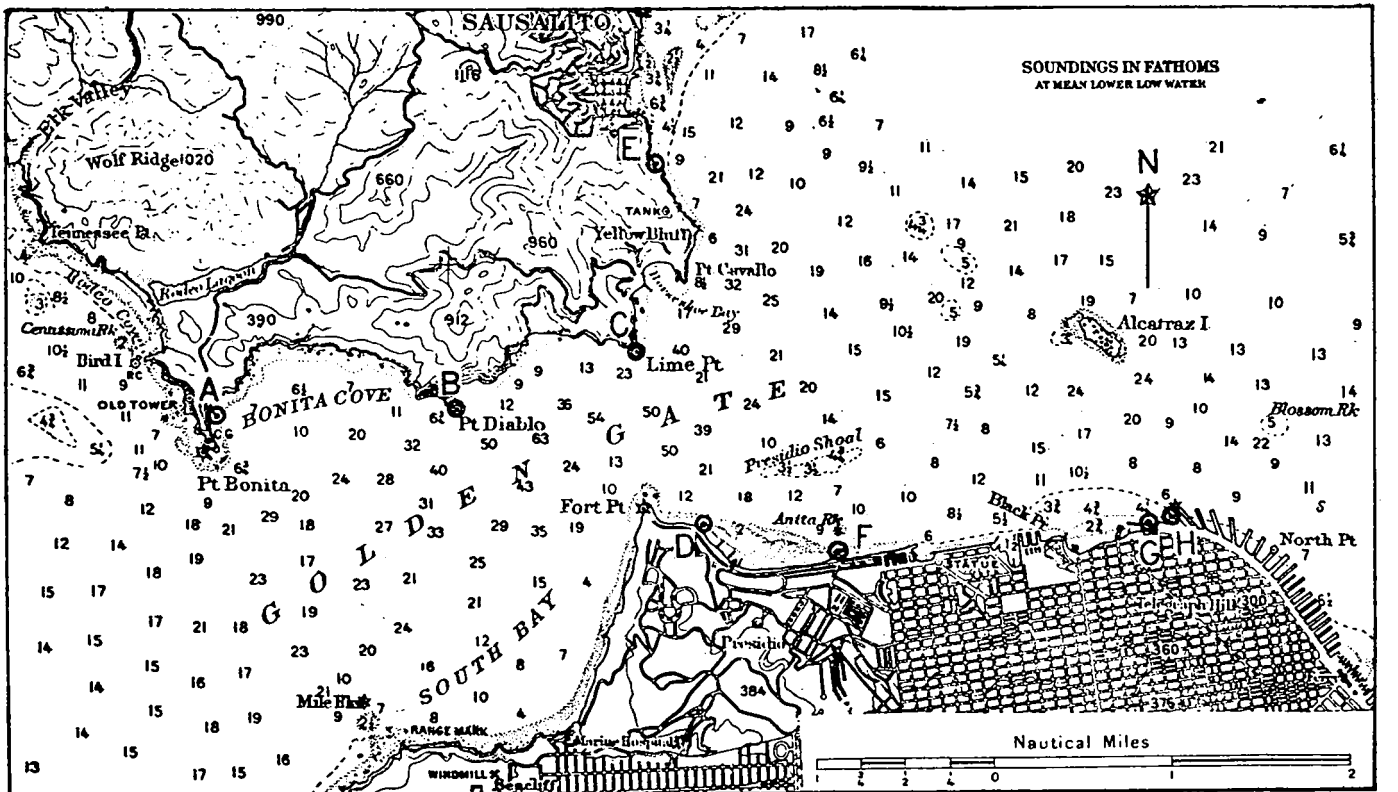


FIG. 7.—Tide stations, Golden Gate

from Table 25, the lunitidal intervals indicating that the tide occurs earlier at southeast Farallon Island than at Rodeo Cove.

Referring to Figure 6 it is seen that there is a shoal extending across the entrance to Golden Gate. Gradual shifting or changes in this shoal probably cause changes in the character of the tide in Golden Gate and San Francisco Bay.

The mean range at southeast Farallon Island, station A, as derived from observations made in 1855 is 3.46 feet, while at Rodeo Cove, station B, observations made in 1895 give a mean range of 3.73 feet. It should be noted, however, that the data for Rodeo Cove are based upon only two days of observations.

14. THE TIDE IN THE GOLDEN GATE

San Francisco Bay communicates with the Pacific Ocean through a strait, the Golden Gate, the northern shore of which is bold and rugged with cliffs rising abruptly from the water's edge to heights of over 600 feet.

As here defined Golden Gate comprises the area between lines drawn from Point Bonita to Mile Rock on the west and Sausalito Point to North Point on the east. At the western end the width between Point Bonita and Mile Rock is 1½ nautical miles and from this it contracts to less than seven-eighths nautical mile between Lime Point and Fort Point while its length as defined above is between 4 and 5 nautical miles. Considerable depth can be carried throughout the strait, the depths increasing from less than 23 fathoms at the western end to over 60 fathoms near Point Diablo and then decreasing toward the eastern end, the deeper water favoring the northern shore. As the gateway to San Francisco Bay and its tributaries, one of the large and important harbors on the Pacific coast of the United States, Golden Gate ranks as one of the leading waterways on the Pacific coast of America.

The locations of the tide stations in the Golden Gate at which observations have been made are shown in Figure 7 and the tidal data for these stations are given in Table 26.

TABLE 26.—*Tidal data, Golden Gate*

Station	Location	Series	Length	Lunitidal intervals		Duration of rise	Mean range
				HWI	LWI		
				Hours	*Hours*	*Hours*	*Feet*
A	Bonita Cove	January, 1917	2 days	11.53	4.78	6.75	4.32
B	Point Diablo	September-November, 1895.	7 days	11.58	4.97	6.61	3.68
C	Lime Point	December, 1916-January, 1917.	4 days	11.65	4.92	6.73	3.86
D	Fort Point	1860-1876	17 years	11.85	5.05	6.80	3.77
E	Sausalito	1878-1896	(1)	11.97	5.37	6.60	3.56
F	Presidio	June-November, 1853 [2]	4 months	12.05	5.20	6.85	3.45 c
	Do	1898-1923	20 years [3]	11.67	4.97	6.70	3.93
G	North Beach	December, 1853-July, 1854.[2]	7 months	12.15	5.52	6.63	3.75 c
	Do	February-November, 1871.	52 days	11.85	5.35	6.50	4.02
H	Powell Street Wharf	September, 1895	2 days	12.30	5.52	6.78	3.93

[1] Intervals based upon 7 years: 1880-1883, 1887, 1889, 1893; mean range based upon 19 years: 1878-1896.
[2] Not compared with a standard station.
[3] Intervals based upon last 19 years (1905-1923).

The list of tide stations included in Table 26 contains the three used as standard stations in the comparison of simultaneous observations with other tide stations throughout the bay and its tributaries. Of these three stations Presidio has already been discussed in a previous section and the remaining two, Fort Point and Sausalito, will be taken up separately under this section.

The observations at Fort Point, Sausalito, and the 1898–1923 series at Presidio each cover a period of a number of years and the tidal data for these stations are taken directly from the reduction of the observations. All the other stations in Table 26, with the exception of the June–November, 1853, series at Presidio, and the December, 1853–July, 1854 series at North Beach for which no simultaneous observations were obtained, were compared with simultaneous observations at one of the above standard stations.

Omitting station H the observations for which cover a very short period of time a number of years ago, the data from Table 26 indicate that the tide at the western end of the Golden Gate occurs about one-third of an hour earlier than at the eastern end. It will be noted that the tidal data show that the tide at Presidio occurs earlier than at Fort Point although from Figure 7 it is seen that Presidio is east of Fort Point. This relation has been brought about by the change in the character of tide at these places. It should be noted that the intervals for Fort Point are based upon an early series extending from 1860–1876 while the intervals for Presidio are based upon 19 years of observations from 1905–1923. A study of the yearly values at Fort Point shows that the intervals for the first part of the series are later than those for the latter part of the series. Furthermore, it has already been shown in section 2 that from two overlapping 19-year series at Presidio from 1898–1923 the intervals for the 19-year series from 1898–1916 are later than the intervals for the 19-year series from 1905–1923. Thus it is reasonable to conclude that the tide in the Golden Gate, particularily in the vicinity of Fort Point and Presidio, has undergone a change, the tides occurring earlier now than years ago. This fact is further borne out by the June–November, 1853, series at Presidio which gives considerably later intervals than the 1898–1923 series. Although this series is not compared with a standard station it is based upon four months of observations and should give approximate values. Thus the relation shown by Table 26 of the tides occurring earlier at Presidio than at Fort Point should be attributed to a difference in the time of observations at the two stations and not to a true tidal phenomenon. The duration of rise of the tide in the Golden Gate varies from 6.5 to 6.8 hours.

The mean range of the tide at stations F and G marked with the subscript *c* have been corrected for the longitude of the moon's node. Table 26 shows that the mean range of the tide in the Golden Gate varies from about 3.6 to 4.3 feet. The value of 4.3 feet at Bonita Cove, however, is based upon only a few days of observations during which there was a heavy swell and probably gives a range larger than the true mean range.

FORT POINT

Tidal observations were made at Fort Point by means of an automatic tide gauge from June 30, 1854, to November 27, 1877, but owing to the difficulties in operation of tide gauges in earlier years some of the results do not permit of detailed discussion.

The tidal data for Fort Point as obtained from these observations are given in Table 27. For the sake of convenience the high and low water lunitidal intervals, the duration of rise, and the mean range have been repeated. The diurnal high water inequality has been reduced to a mean value by correcting it by the factor 1.02 F_1. This is indicated by the subscript *c* after the value for the *DHQ*. A number of the tidal constants are based upon observations covering a period of 17 years or more, while others are based upon but 1 year of observations. The series and length of observations used in the determination of each of the tidal constants, however, are indicated in the table.

TABLE 27.—*Tidal data, Station D, Fort Point, San Francisco, Calif.*

	Time relations (hours)	Observations (years)
High water lunitidal interval	11.85	17 (1860–1876).
Low water lunitidal interval	5.05	Do.
Duration of rise	6.80	Do.
Duration of fall	5.62	Do.
	Ranges and inequalities (feet)	**Observations (years)**
Mean range	3.77	17 (1860–1876).
Spring range	4.5	1 (July 1863–June 1864).
Neap range	3.0	Do.
Great diurnal range	5.54	1 (Aug. 19, 1875–Aug. 22, 1876).
Diurnal high water inequality	0.57c	Do.
Diurnal low water inequality	1.19	20 (1855–1874).
	Height relations (feet)	**Observations**
Highest tide observed above mean sea level (Nov. 5, 1869)	4.9	17 (1860–1876).
Lowest tide observed below mean sea level (May 24, 1872)	5.4	Do.

It should be noted that the tidal data in Table 27 are based on observations made a number of years ago and consequently the values given do not necessarily represent the present-day characteristics. In fact, it has already been shown that the tide in the vicinity of Presidio occurs earlier now than it did a number of years ago. With regard to the mean range a study of the yearly values indicates that the range at Fort Point increased during the latter part of the series and it is probable that the mean range at Fort Point is approximately the same as at Presidio.

The highest tide observed at Fort Point during the period 1860–1876 occurred on November 5, 1869. On this date the high water was

2.9 feet above mean high water, or 4.9 feet above mean sea level. For the same period the lowest tide occurred on May 24, 1872, when the low water was 3.5 feet below mean low water, or 5.4 feet below mean sea level. The greatest range of the tide at Fort Point for this period is thus 10.3 feet.

SAUSALITO

In 1877 the tide station at Fort Point was transferred to Sausalito where observations were continued from February 19, 1877, to September 1, 1897, by means of an automatic tide gauge. As with Fort Point all of the observations have not been completely reduced; in most cases, however, sufficient reductions have been made to give the more important tidal constants.

In order to make available a long series of mean sea level the yearly values at Sausalito for a period of 19 years are presented in Table 28. This table gives the heights referred to the tide staff at Presidio as well as to the local tide staff. By combining this table with Table 8, given in section 4, the yearly values of mean sea level, referred to the staff at Presidio, are obtained for a period of 45 years.

TABLE 28.—*Mean sea level, Sausalito, Calif., annual means, 1878–1896*

Year	Referred to Sausalito staff	Referred to Presidio staff
	Feet	*Feet*
1878	8.60	8.76
1879	8.29	8.45
1880	8.38	8.54
1881	8.42	8.58
1882	8.31	8.47
1883	8.35	8.51
1884	8.64	8.80
1885	8.49	8.65
1886	8.36	8.52
1887	8.27	8.43
1888	8.33	8.49
1889	8.47	8.63
1890	8.52	8.68
1891	8.30	8.46
1892	8.22	8.38
1893	8.32	8.48
1894	8.26	8.42
1895	8.46	8.62
1896	8.44	8.60
Means	8.39	8.55

Mean sea level for the 19-year period from 1878 to 1896 referred to the tide staff at Sausalito is 8.39 feet. This same period referred to the tide staff at Presidio gives mean sea level as 8.55 feet, which is the same value as obtained from the 26-year period of observations at Presidio.

The detailed tidal data for Sausalito as determined from observations made during the period 1878–1896 are given in Table 29. The diurnal high-water and low-water inequalities have been reduced to mean values by correcting them by the factor 1.02 F_1, as indicated by the subscript *c* after the values. It should be noted that all the tidal constants are not based upon the same length of observations, for example, the mean range is based upon observations covering a

period of 19 years while the spring range is based upon only 1 year of observation.

TABLE 29.—*Tidal data, Station E, Sausalito, Calif.*

	Time relations (hours)	Observations (years)
High water lunitidal intervals	11.97	7 (1880–83, 1887, 1889, 1893).
Low water lunitidal intervals	5.37	Do.
Duration of rise	6.60	Do.
Duration of fall	5.82	Do.
	Ranges and inequalities (feet)	**Observations (years)**
Mean range	3.56	19 (1878–1896).
Spring range	4.23	1 (1889).
Neap range	2.91	Do.
Great diurnal range	5.26	Do.
Diurnal high-water inequality	0.58	6 (1877, 1885–1889).
Diurnal low-water inequality	1.17	1 (1889).
	Height relations (feet)	**Observations**
Highest tide observed above mean sea level (Jan. 16, 1878)	5.1	19 (1878–1896).
Lowest tide observed below mean sea level (June 15, 1893)	5.3	Do.

The highest tide observed at Sausalito during the period 1878–1896 occurred on January 16, 1878, when the high water rose 3.1 feet above mean high water, or 5.1 feet above mean sea level. The lowest tide observed during the same period occurred on June 15, 1893, when the low water fell 3.5 feet below mean low water, or 5.3 feet below mean sea level. The greatest range of the tide at Sausalito for this period is therefore 10.4 feet. This compares with 10.3 feet at Fort Point for the period 1860–1876 and 10.5 feet at Presidio for the period 1898–1923.

TIDAL HARMONIC CONSTANTS

Part of the observations at the three standard stations in the Golden Gate—Fort Point, Sausalito, and Presidio—have been subjected to harmonic analysis. The harmonic constants derived from these analyses of the hourly heights of the tide are shown in Table 30. The amplitudes are expressed in feet and the epochs are referred to the local meridian. Values inclosed in parentheses were not obtained directly from the analysis but were inferred from the other constants.

The combined length of the series, together with the first and last year of the observations from which the constants were derived, is shown for each station. In combining the results from several analyses at a station the direct means of the amplitudes and epochs were taken.

TABLE 30.—*Harmonic constants, Stations D, E, and F, Golden Gate*

Component	Station D, Fort Point		Station E, Sausalito		Station F, Presidio	
	H	κ	*H*	κ	*H*	κ
	Feet	*Degrees*	*Feet*	*Degrees*	*Feet*	*Degrees*
J_1					(0.068)	(114)
K_1	1.218	106	1.592	110	1.208	106
K_2	0.116	327	0.094	336	0.120	329
L_2	0.073	0	0.039	353	0.055	353
M_1	0.044	83	0.040	65	0.039	104
M_2	1.696	331	1.570	337	1.773	330
M_3					0.013	332
M_4	0.086	32	0.033	55	0.077	25
M_6	0.012	342	0.021	338	0.009	22
M_8					0.006	64
N_2	0.364	304	0.333	310	0.376	304
2N					0.041	276
O_1	0.766	88	0.717	94	0.756	89
OO					(0.038)	(123)
P_1	0.368	104	0.371	109	0.377	104
Q_1	0.124	83	0.124	82	0.128	82
2Q					(0.020)	(72)
R_2					(0.003)	(335)
S_1					0.020	147
S_2	0.382	335	0.354	348	0.404	335
S_4					0.002	246
S_6					0.002	112
T_2					0.004	194
λ_2					0.027	335
μ_2			0.049	218	0.029	224
ν_2			0.044	297	0.073	311
ρ_1					(0.020)	(82)
MS					0.024	24
Sa	0.398	156	0.150	244	0.110	94
SSa	0.184	221	0.043	233	0.154	304
Series	1863-1870		1889-1890		1904-1913	
Length	4 years.		1 year.		6 years.	

A number of the tidal characteristics may be obtained by substituting the constants from Table 30 in the formulas developed by R. A. Harris. Although these formulas do not in all cases give as well-determined values as a good series of high and low waters, they do give a number of characteristics that can not easily be obtained from a direct reduction of the high and low waters. The tidal data thus derived from the harmonic constants in Table 30 are presented in the following table:

TABLE 31.—*Tidal data from harmonic constants, Stations D, E, and F, Golden Gate*

	Station D, Fort Point	Station E, Sausalito	Station F, Presidio
	Feet	*Feet*	*Feet*
Mean range	3.74	3.56	3.87
Great diurnal range	5.56	5.78	5.64
Great tropic range	6.16	6.52	6.23
Spring range	4.48	4.12	4.57
Neap range	2.91	2.91	3.08
Perigean range	4.37	4.17	4.55
Apogean range	3.23	3.05	3.28
Diurnal high water inequality	0.51	0.66	0.45
Diurnal low water inequality	1.31	1.56	1.32
	Hours	*Hours*	*Hours*
Phase age	4.5	10.8	4.9
Parallax age	48.7	49.6	47.8
Diurnal age	16.2	14.6	15.5
Sequence of the tide	HHW-LLW	HHW-LLW	HHW-LLW.
Series	1863-1870	1889-1890	1904-1913
Length	4 years.	1 year.	6 years.

15. THE TIDE IN SOUTH SAN FRANCISCO BAY

South San Francisco Bay as here defined includes all of that part of San Francisco Bay south of a line drawn from North Point, San Francisco, to Shellmound on the east side of the bay. It thus includes the greater part of San Francisco water front as well as those of

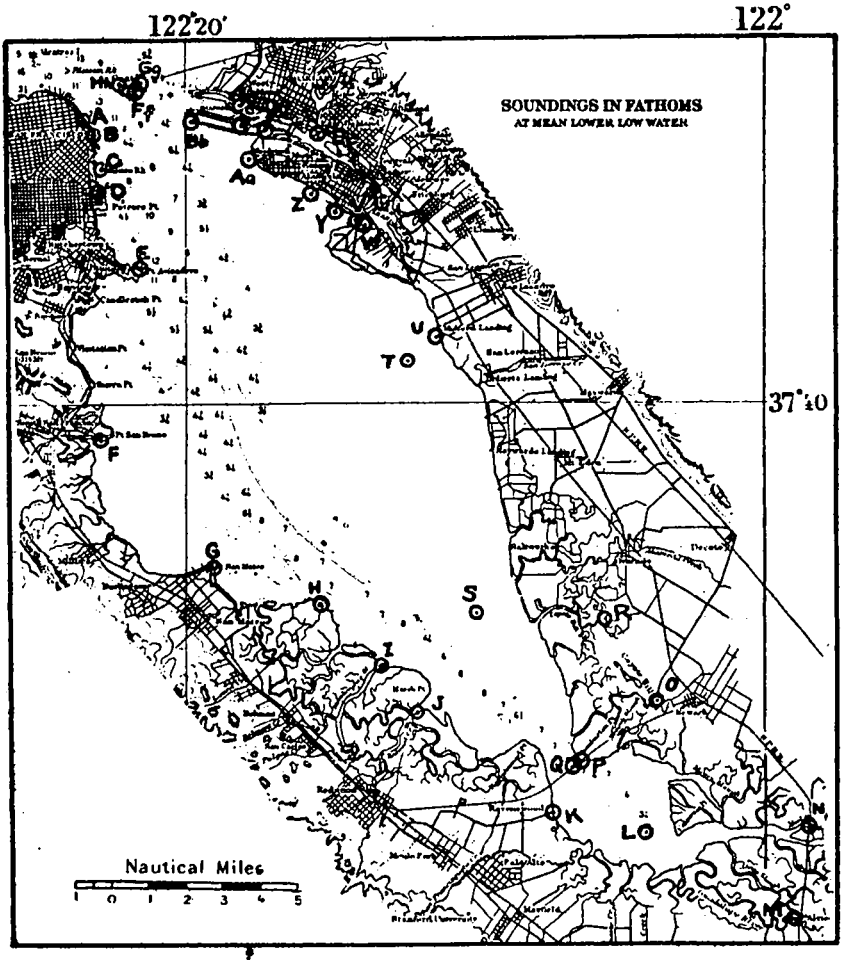


FIG. 8.—Tide stations, South San Francisco Bay

Oakland and Alameda. North of Point San Bruno the channel is wide and of good depth, while south of this point the shores are low with marshes and flats, intersected by numerous winding sloughs extending to the head of the bay.

In Table 32 are recorded the tidal data determined from observations made at the various stations shown in Figure 8.

TABLE 32.—*Tidal data, South San Francisco Bay*

Station	Location	Series	Length	Lunitidal intervals		Duration of rise	Mean range
				HWI	LWI		
	WEST SHORE			*Hours*	*Hours*	*Hours*	*Feet*
A	Mission Street	Sept.-Dec., 1889	2½ months	12.15	5.57	6.58	4.24
B	Rincon Point	Jan., 1852-Mar., 1853 [1]	4½ months	12.02	5.50	6.52	4.12
	do	Nov., 1864	4 days	12.02	5.50	6.52	4.62
C	Mission Rock	Feb.-Apr., 1872	1 month	12.05	5.70	6.35	4.30
D	Union Iron Works	Mar.-June, 1895	4 months	12.32	5.80	6.52	4.56
	do	Oct., 1919-June, 1920	8½ months	12.22	5.58	6.64	4.53
E	Point Avisadero	Feb., 1917-Feb., 1920	1 month	12.28	5.78	6.50	4.89
F	Point San Bruno	Apr.-Aug., 1897	do	12.22	6.13	6.09	5.90
	do	May, 1917-Nov., 1919	10 days	12.23	5.93	6.30	5.58
G	Point San Mateo	April, 1857	12 days	11.75	5.23	6.52	5.26
H	Guano Island	Mar.-Apr., 1857	13 days	12.03	5.55	6.48	5.46
I	Entrance Steinbergen Slough.	May-Sept., 1898	3½ months	0.10	6.72	5.80	6.06
J	Entrance Redwood Slough.	May, 1897-Jan., 1899	2¾ months	0.30	6.33	6.39	6.23
K	Ravenswood	Mar., 1857-June, 1858	4 months	12.37	6.02	6.35	6.41
	do	Nov., 1898	2 days	0.28	6.63	6.07	6.70
L	Off Calaveras Point	Sept.-Nov., 1898	2¼ months	0.25	6.60	6.07	6.92
M	Alviso	Oct., 1898	2 days	0.42	6.72	6.12	7.56
	EAST SHORE						
N	North Drawbridge, Mud Slough.	Oct., 1898	2 days	0.33	6.63	6.12	7.44
O	Jarvis landing, Newark Slough.	May, 1897	do	0.45	6.60	6.27	7.23
P	Dumbarton Point	Sept.-Nov., 1898	3 days	0.08	6.42	6.08	6.55
Q	Dumbarton Bridge	Oct.-Nov., 1923	1½ months	0.47	6.79	6.10	6.29
R	Coyote Hill Slough	May, 1897	4 days	0.66	6.86	6.22	6.11
S	Coyote Oyster House	May-June, 1897	7 days	0.01	6.50	5.93	5.94
T	Off Mulford landing	Nov. 1919-Jan., 1920	4 days	0.08	6.08	6.42	5.89
U	Mulford landing	Dec.-Jan., 1857-8	2 days	0.07	5.73	6.76	6.12
	SAN LEANDRO BAY						
V	Bay Farm Island Bridge.	Oct., 1921-Oct., 1922	13 months	12.37	5.83	6.54	4.83
W	East of Bay Farm Island Bridge.	Oct., 1896	5 days	0.20	5.97	6.65	4.88
X	Mercantile Box Co	Feb., 1920	3 days	0.08	5.70	6.80	4.77
	ALAMEDA						
Y	Municipal light plant	Feb., 1920	3 day	0.03	5.98	6.47	4.87
Z	Encinal Boat Club	Feb.-Aug., 1895	7 days	0.10	6.10	6.42	4.97
Aa	Peralta Wharf	Mar., 1857-Jan., 1858	1⅛ months	11.80	5.17	6.63	4.33
Bb	Narrow gauge pier	Feb.-Aug., 1895	7 days	12.27	5.87	6.40	4.21
	OAKLAND HARBOR						
Cc	Oakland Bar	May-June, 1860	4 days	11.90	5.73	6.17	4.33
Dd	East of light tower	May-June, 1912	1⅛ months				4.51
Ee	Sessions Basin	Aug.-Sept., 1896	9 days	12.33	5.60	6.73	4.80
	GOAT ISLAND						
Ff	East Side	Sept.-Oct., 1874	6 days	11.92	5.65	6.27	4.13
Gg	Naval Training Station	Apr., 1920-Feb., 1921	do	12.05	5.52	6.53	4.53
Hh	Northwest Point	May, 1895-Apr., 1897	11 days	11.93	5.23	6.70	4.06

[1] Not compared with a standard station.

All the stations in Table 32, with the exception of the January, 1852–March, 1853, series at Rincon Point for which no simultaneous observations were available, were reduced to mean values by comparison with simultaneous observations at either Fort Point, Sausalito, or Presidio, but it should be observed that a number of the series are based on only a few days of observations.

The mean range increases from the northern part of the bay toward the head of the bay varying from about 4 feet at stations A

and Hh to approximately 6 feet at stations T and U near the middle of the section and continuing to increase to over 7 feet at stations M and N in the sloughs at the head of the bay. This material increase in the range of the tide near the head of South San Francisco Bay may be ascribed in part to its configuration and hydrographic features. It will be observed from Figure 8 that the lower part of the bay shows a contraction in width with extensive flats and a narrowing channel. Thus the tidal wave as it advances up this narrowing funnellike form with shoaling bottom is practically cooped up, thereby piling up the water and giving a large range. With reference to the mean range on the two sides of the bay it is noted that in general the range is greater on the western shore than on the eastern shore. For example, station A has a range of 4.24 feet while station Bb has a range of 4.21 feet, station E, 4.89 feet, station Y, 4.87 feet, station I, 6.06 feet, and station S, 5.94 feet, respectively. This difference in the range of the tide on the two shores is due to the deflecting force of the earth's rotation.

Table 32 gives the lunitidal intervals at station A as 12.15 hours and 5.57 hours and at station L near the head of the bay as 0.25 or 12.67 hours and 6.60 hours, respectively. An average of the intervals gives a time difference between stations A and L of 0.78 hour. The distance between the two stations is approximately 24.5 nautical miles and the mean depth of South San Francisco Bay is 17.6 feet. The formula for a progressive wave is $r=\sqrt{gh}$. Using this formula it is found that the tide should traverse this waterway in 1.74 hours, which is considerably longer than the time derived from the observations. Thus the tide is not of the purely progressive wave type.

It will be interesting to see if this body of water permits of a stationary wave. For this type of wave the formula is $T=\frac{4L}{\sqrt{gh}}=$ approximately 12 hours. The total length L of the bay is about 26.5 nautical miles and the mean depth is 17.6 feet which gives a value of 7.5 hours for T. This indicates that the tide is not of the pure stationary type but is undoubtedly partly stationary and partly progressive. The fact that the tide in South San Francisco Bay is largely of the stationary type helps to explain the large increase in the mean range of the tide throughout the bay.

The stations in South San Francisco Bay for which the high and low water diurnal inequalities have been determined from observations covering a period of one month or more are given in the following table:

TABLE 33.—*Diurnal inequalities, South San Francisco Bay*

Station	Location	Series	Length	Diurnal high water inequality	Diurnal low water inequality
			Months	*Feet*	*Feet*
D	Union Iron Works	October, 1919–May, 1920	8	0.61	1.14
E	Point Avisadero	February, 1917–February, 1920.	1	0.59	1.19
I	Ent. Steinbergen Slough	May–September, 1898	3½	0.63	1.24
K	Ravenswood	March, 1857–June, 1858	4	[1] 0.45	[1] 1.24
L	Off Calaveras Point	October, 1898	1	0.60	1.23
Q	Dumbarton Bridge	October, 1923	1	0.57	1.24
V	Bay Farm Island Bridge	October, 1921–October, 1922	13	0.58	1.14

[1] Corrected by factor 1.02 F_1.

With the exception of station K for which no simultaneous observations were available all of the inequalities in Table 33 were reduced to mean values by comparison with simultaneous observations at Presidio. Station K was corrected by applying the empirical factor 1.02 F_1 to the values as obtained from the observations.

Omitting station K the observations for which were made many years ago, Table 33 shows that the diurnal high water inequality for the whole of South San Francisco Bay may be taken to the nearest tenth as 0.6 foot. Table 33 also indicates that the diurnal low water inequality varies from 1.1 to 1.2 feet, the inequality apparently increasing slightly near the head of the bay.

Knowing the diurnal inequalities the great diurnal range—that is, the range between higher high water and lower low water—is readily obtained by means of the formula $Gt = Mn + DHQ + DLQ$. From this formula it is seen that the great diurnal range may be derived by merely adding the mean range and the diurnal inequalities.

16. THE TIDE IN NORTH SAN FRANCISCO BAY

For the purpose of this discussion North San Francisco Bay includes that part of San Francisco Bay included between a line drawn from Point Blunt, Angel Island, to Carlton on the south and a line from Point San Pedro to Point San Pablo on the north.

Short series of tidal observations have been made at a number of stations in this section. The tidal data derived from these observations are given in the table below. The lunitidal intervals and ranges in this table have been reduced to mean values by comparison with simultaneous observations at a standard station.

TABLE 34.—*Tidal data, North San Francisco Bay*

Station	Location	Series	Length	Lunitidal intervals		Duration of rise	Mean range
				HWI	LWI		
	WEST SHORE						
	Angel Island:			*Hours*	*Hours*	*Hours*	*Feet*
A	Point Blunt	Feb., 1873–Dec., 1874	22 days	12.00	5.48	6.52	3.74
B	Quarry Point	May, 1895–Mar., 1896	9 days	12.12	5.57	6.55	3.80
C	Immigrant Cove	Sept.–Oct., 1905	21 days	12.00	5.58	6.42	3.71
D	Tiburon	May–July, 1895	2 days	12.07	5.72	6.35	3.59
E	California City	Oct., 1903–Jan., 1904	2⅓ months	12.27	5.72	6.55	3.70
F	El Campo	Oct., 1895–July, 1897	8 days	12.40	5.88	6.52	3.42
G	Point San Quentin	Jan., 1900–Apr., 1901	16 days	0.05	6.03	6.44	3.96
	Do	Dec., 1916–Feb., 1917	17 days	0.12	6.00	6.54	3.94
	EAST SHORE						
H	Point San Pablo	Dec., 1916	1 day	0.03	5.68	6.77	4.42
I	Point Richmond	Dec., 1916–Feb., 1917	2 months	12.25	5.65	6.60	4.14
J	Ellis Landing	Aug., 1905	3 days	12.25	5.75	6.50	4.12
K	Brooks Island	Oct., 1895–Aug., 1897	4 days	12.20	5.77	6.43	4.25
	Do	Apr., 1899–Mar., 1901	13 days	12.07	5.60	6.47	4.31
L	Southampton Shoal	Jan.–Feb., 1873	4 days	12.33	5.58	6.75	3.90
M	West Berkeley	May, 1895–Apr., 1897	14 days	12.08	5.67	6.41	4.12
	Do	Dec., 1916–Mar., 1921	6 days	12.08	5.70	6.38	4.15

From Table 34 it is seen that the data for the stations in North San Francisco Bay are for the most part based on observations covering short periods of time, varying from only 1 day to 2⅓ months, also

that several of the observations were made as long ago as 50 years. For these reasons care should be used in any study involving the time relations between the various stations.

With regard to the mean range it will be noted that in all cases the range is greater on the eastern shore than on the western shore.

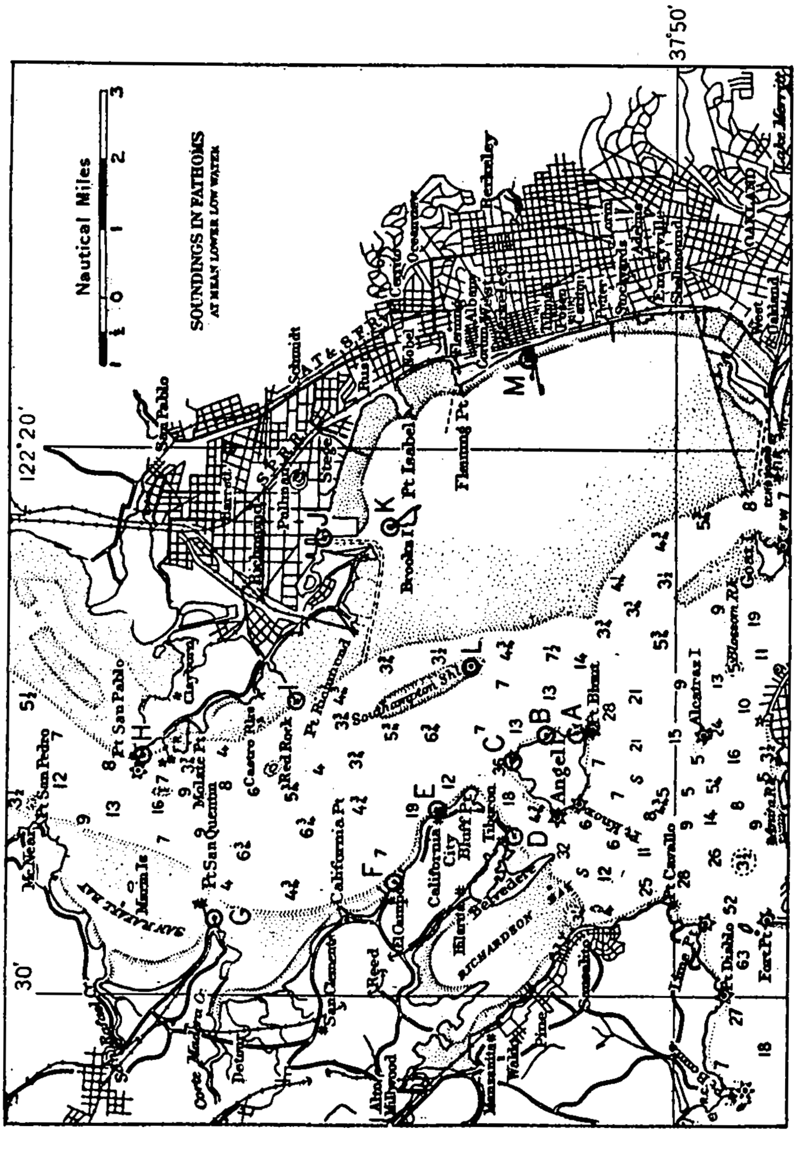


FIG. 9.—Tide stations, North San Francisco Bay.

This phenomenon is due to the deflecting force of the earth's rotation which causes the water to be deflected to the right. Thus with a rising tide the water is deflecting toward the eastern shore, giving a higher tide on that shore than on the western. When the tide falls the water is again deflected toward the right but now it is the western

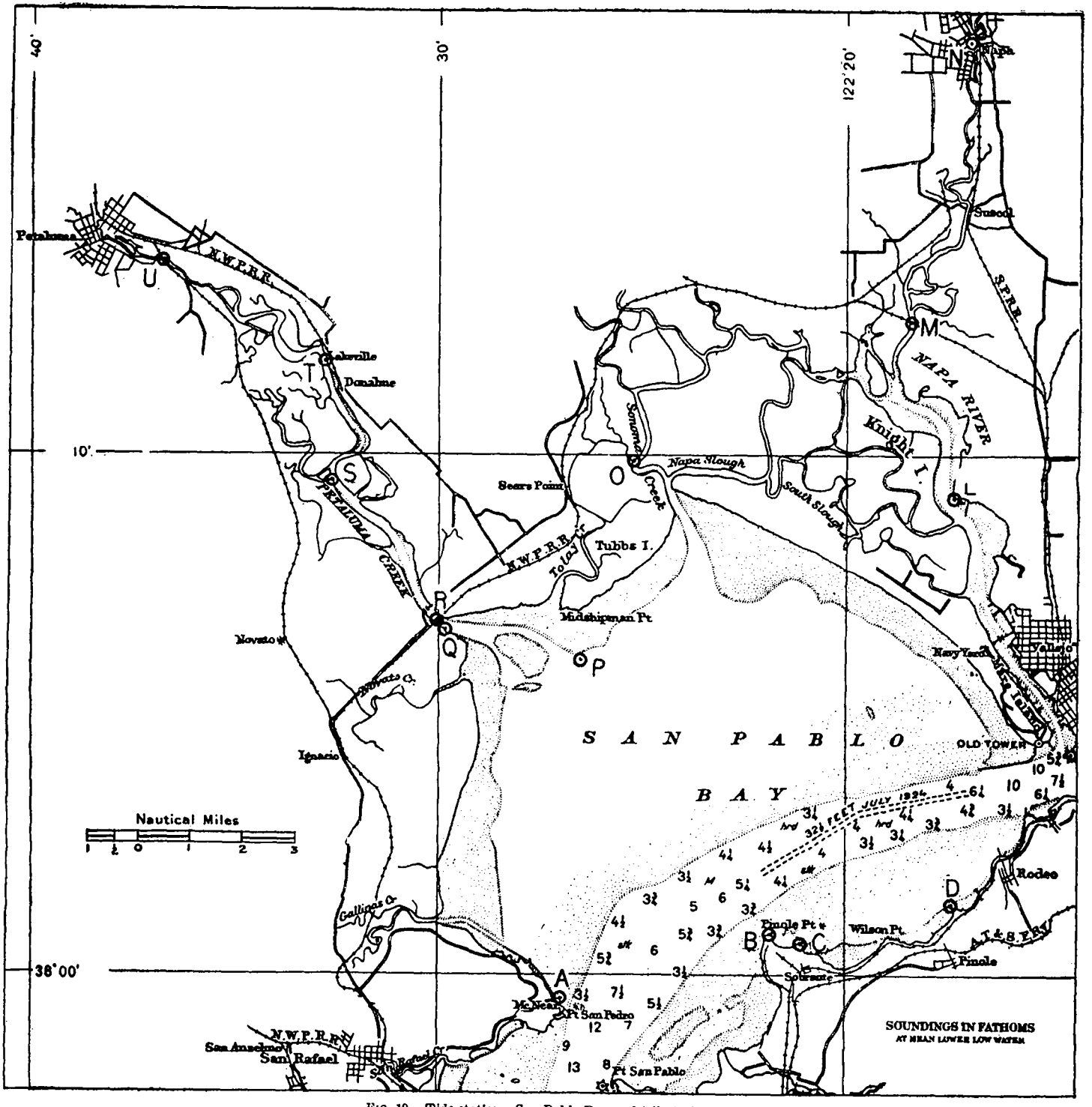


FIG. 10.—Tide stations, San Pablo Bay and tributaries.

shore that has the higher water elevation. This then gives to the eastern shore a higher water level on the rising tide and a lower water level on the falling tide and consequently a larger range of the tide than the eastern shore.

The diurnal inequalities have been obtained for the two following stations in North Francisco Bay where the observations extended over a period of a month or more:

Station	Location	Series	Length	DHQ	DLQ
			Months	*Feet*	*Feet*
E	California City	Nov.-Dec., 1903	2	0.54	1.06
I	Point Richmond	Dec., 1916-Feb., 1917	2	0.56	1.16

The inequalities for both stations were reduced to mean values by comparison with simultaneous observations at Presidio.

The great dirunal range may be obtained for these stations by adding the above inequalities to the corresponding mean ranges.

17. THE TIDE IN SAN PABLO BAY AND TRIBUTARIES

San Pablo Bay is a nearly circular basin of water about 10 nautical miles in length in a northeast and southwest direction, with a greatest width of about 9 nautical miles. The northern part consists of low marshes intersected by numerous sloughs with a large area of shoals and mud flats that bare at extreme low tides. Its southern end joins North San Francisco Bay at the narrows between Point San Pedro and Point San Pablo, while at its eastern end it communicates with Suisun Bay through Carquinez Strait. The tributaries of San Pablo Bay to be discussed in this section consist of Petaluma Creek, Sonoma Creek, and Napa River including Mare Island Strait. Owing to the importance of Mare Island Strait and the number of stations in the small area a separate figure showing the location of these stations is presented.

The tidal data for the stations in San Pablo Bay and its tributaries are given in Table 35. With the exception of the 1856 series at station B and the 1857–1858 series at station I, for which no simultaneous observations were available, the lunitidal intervals and mean range in this table have all been reduced to mean values by comparison with simultaneous observations at one of the standard stations.

FIG. 11.—Tide stations, Mare Island Strait

TABLE 35.—*Tidal data, San Pablo Bay and tributaries*

Station	Location	Series	Length	Lunitidal intervals		Duration of rise	Mean range
				HWI	LWI		
				Hours	*Hours*	*Hours*	*Feet*
A	McNear's Landing	Dec., 1897–Dec., 1899	2½ months	0.35	6.07	6.70	3.90
		Dec., 1916–Feb., 1917	2 months	0.45	6.22	6.65	4.08
		Dec., 1921–Jan., 1922	4 days	0.29	6.18	6.53	4.21
B	Pinole Point	Jan.–Feb., 1856 [1]	25 days	12.37	6.83	5.54	5.25
		Sept., 1896–Apr., 1899	5 days	0.62	6.38	6.66	4.51
C	East Pinole Point	Feb., 1879	2 days	0.52	6.72	6.22	4.46
D	Refugio Landing	Jan.–Mar., 1887	1½ months	0.75	6.87	6.30	4.73
		July, 1896–Mar., 1897	½ months	0.70	6.83	6.29	4.93
		Nov., 1921–May, 1922	5½ months	0.85	6.78	6.49	4.68
E	Mare Island Light	1905–1907	2 years	0.93	7.08	6.27	4.76
	MARE ISLAND STRAIT						
F	Magazine Wharf	Aug., 1878–Mar., 1879	7 months	0.98	7.15	6.25	4.50
		June–Oct., 1896	6 days	1.01	7.00	6.43	4.70
G	Hospital Wharf	May–July, 1876	1½ months	1.07	7.40	6.09	4.56
H	Independence Wharf	May, 1922	3 days	0.96	7.25	6.13	5.07
I	Dry dock	Oct., 1857–Mar., 1858 [1]	4½ months	1.20	7.33	6.29	4.29
J	Ferry slip	Jan.–Mar., 1901	3 months	0.88	7.32	5.98	4.86
K	North end sea wall	Nov., 1906–Mar., 1907	3¾ months	1.21	7.36	6.27	4.95
	NAPA RIVER						
L	Slaughter House Point	Aug.–Sept., 1860	2 days	1.28	7.45	6.25	5.32
M	Drawbridge	May, 1922	4 days	1.45	7.75	6.12	5.42
N	Napa (Third Street) bridge.	do	3 days	1.48	8.33	5.57	5.58
O	Sonoma Creek	Jan.–Apr., 1922	9 days	0.88	7.43	5.87	4.94
P	Off Midshipmen Point	Mar., 1899	3 days	0.62	6.70	6.34	4.64
	PETALUMA CREEK						
Q	Black Point	Nov., 1921–Mar., 1922	5 days	0.67	7.23	5.86	4.60
R	Railroad bridge	Mar.–May, 1899	1½ months	0.80	7.05	6.17	4.73
S	Entrance San Antonio Creek.	May, 1899	2 days	1.13	7.15	6.40	5.24
T	Lakeville Landing	July, 1860	9 days	1.25	7.40	6.27	5.30
		Mar., 1922	4 days	1.32	8.00	5.74	4.96
U	Upper drawbridge	do	3 days	1.45	8.03	5.84	5.82

[1] Not compared with a standard station.

The data in Table 35 for the stations in San Pablo Bay are based on observations varying from two years at station E to only two days at station C. Neglecting the 1856 series at station B the observations for which were made many years ago and which were not compared with a standard station, the high water lunitidal intervals in San Pablo Bay may be taken as varying from 0.4 to 0.9 hour which indicates that high water throughout San Pablo Bay varies only by about a half hour. Table 35 also indicates that the duration of rise in San Pablo Bay varies from 6.2 to 6.7 hours. With regard to the mean range of the tide a comparison of Tables 34 and 35 shows that the rise and fall of the tide is greater in San Pablo Bay than in the adjoining North San Francisco Bay, and furthermore the data in Table 35 indicate that the mean range increases toward the head of the bay giving larger ranges at stations P and E than at stations A and B.

Most of the stations in Petaluma Creek and Sonoma Creek are based upon short series of observations and consequently the results are subject to revision as longer series of observations become available. The results as given in Table 35 indicate that the duration of

rise is less in these creeks than in San Pablo Bay but the mean ranges increase up these streams.

The observations in Mare Island Strait and Napa River cover a considerable period of time, the observations for station I being made in 1857–58 while the results for stations M and N were derived from observations made in 1922. The high water lunitidal intervals for the stations in Mare Island Strait may be taken as about one hour. The stations up the Napa River give gradually increasing values up to Napa where the observations for station N give a HWI of about 1.5 hours. The observations indicate that the mean range increases up the Napa River varying from about 4.6 feet at station F in Mare Island Strait to approximately 5.6 feet at station N at Napa.

The diurnal high water and low water inequalities have been obtained from a number of the stations in San Pablo Bay and tributaries. The results for those stations where the observations were of sufficient length to give approximately accurate values are presented below:

Station	Location	Series	Length	DHQ	DLQ
				Feet	*Feet*
A	McNears Landing	Dec., 1916–Feb., 1917	2 months	0.54	1.14
D	Refugio Landing	Nov., 1921–Mar., 1922	5 months	0.56	1.08
E	Mare Island Light	1905, 1907	2 years	0.52	1.15
J	Ferry Slip	Jan.–Mar., 1901	3 months	0.50	1.21

All of the inequalities given above were reduced to mean values by comparison with simultaneous observations at Presidio. Having these inequalities the great diurnal range—that is, the rise and fall between higher high water and lower low water—may readily be obtained by adding the diurnal high and low water inequalities to the respective mean ranges. Using this formula the great diurnal range at Mare Island Light is derived to be 6.43 feet while at Ferry Slip, Mare Island Strait, it is 6.57 feet.

18. THE TIDE IN CARQUINEZ STRAIT

Carquinez Strait, running in a generally easterly direction from San Pablo Bay, is the connecting link between San Pablo and Suisun Bays. This strait is about 6 nautical miles in length and its width varies from a little less than ½ mile for the first 3½ miles to about 1½ miles at its widest part opposite Benicia. It is deep throughout with the exception of a small stretch of flats on the northern shore, and a smaller area in the bight on the southern shore near the eastern end.

Tide stations have been maintained during different periods at various localities throughout the strait. The results derived from the observations at these stations are presented in Table 36.

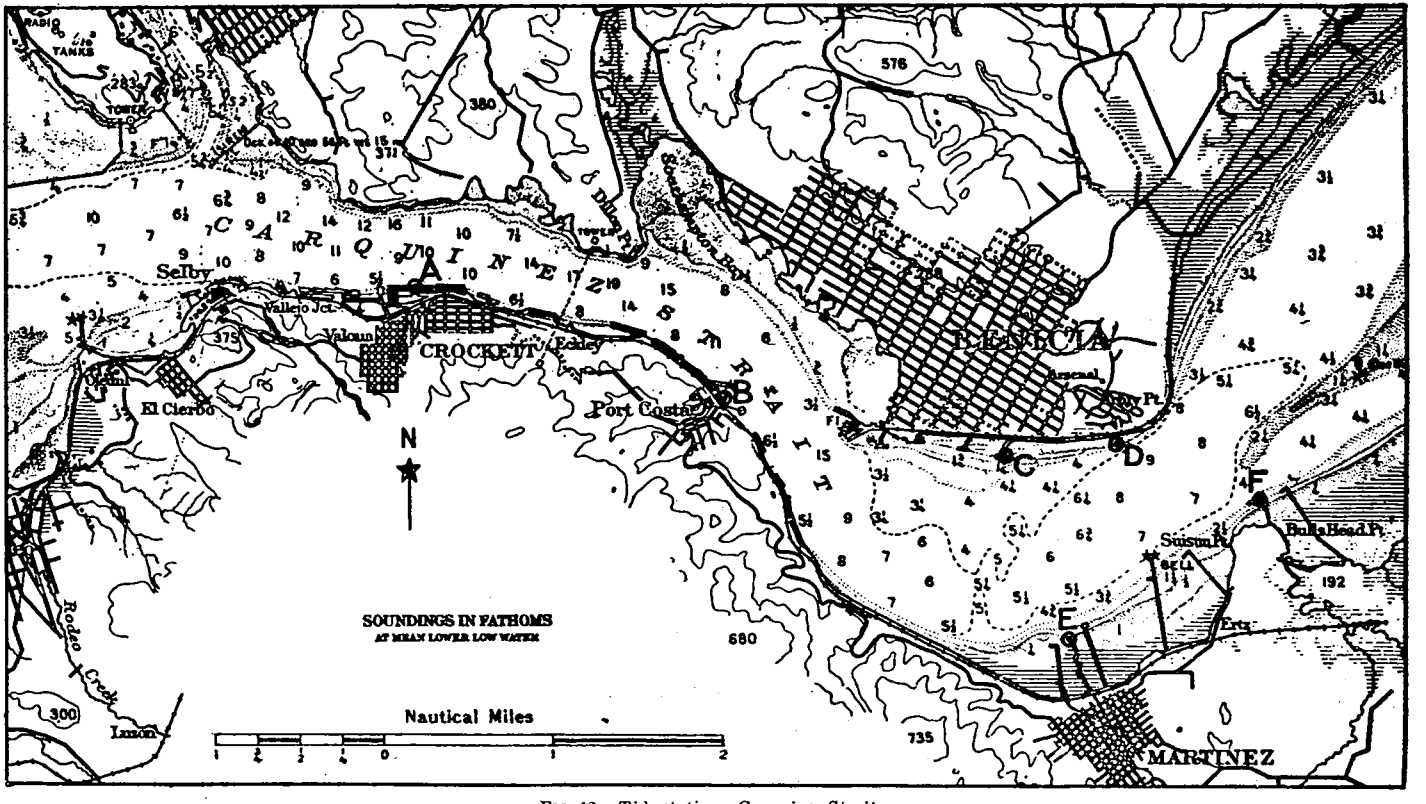


FIG. 12.—Tide stations, Carquinez Strait

TABLE 36.—*Tidal data, Carquinez Strait*

Station	Location	Series	Length	Lunitidal intervals		Duration of rise	Mean range
				HWI	LWI		
				Hours	*Hours*	*Hours*	*Feet*
A	Crockett	Oct., 1886	1 month	1.15	7.32	6.25	4.56
		Apr.-May, 1890	3 days	1.17	7.10	6.49	4.76
		Aug.-Oct., 1896	5 days	1.17	7.17	6.42	5.19
		Apr.-Sept., 1922	do	0.95	7.05	6.32	5.04
B	Port Costa	Aug., 1911	3 days	1.25	7.32	6.35	4.98
	BENICIA						
C	P. M. S. S. Co. Dock	Dec., 1856-Oct., 1858 [1]	5 months	1.70	7.72	6.40	4.62
		Feb., 1862-Mar., 1863	5 days	1.52	7.38	6.56	4.19
		Mar., 1866	10 days	1.23	7.18	6.47	4.93
		Aug., 1911	2 days	1.35	7.35	6.42	4.87
D	Army Point	Nov., 1865-Mar., 1866	1½ months	1.55	7.40	6.57	4.75
		Nov.-Dec., 1878	20 days	1.48	7.48	6.42	4.76
		Apr.-May, 1890	3 days	1.53	7.53	6.42	4.72
		Sept., 1915	1 day	1.35	7.40	6.37	5.31
E	Martinez	Feb.-Mar., 1909	4 days	1.30	7.42	6.30	5.30
F	Suisun Point	Aug.-Dec., 1922	5 months	1.57	7.58	6.41	4.66
		Sept.-Nov., 1923	1⅓ months	1.69	7.60	6.51	4.47

[1] Not compared with a standard station.

In Table 36, as in previous tables, the lunitidal intervals and ranges have been reduced wherever possible to mean values by comparison with simultaneous observations at one of the standard stations. The December, 1856–October, 1858, series at station C was not thus reduced since there were no simultaneous observations available at any of the standard stations.

Omitting the shoals inside of the 3-foot line in Southampton Bay and along the west shore of Benicia, together with the flats in the arm of the strait off Martinez, the average depth of Carquinez Strait at mean sea level is approximately 46.5 feet. The distance from station A to station F measured along the channel is about 6 nautical miles. Referring to Table 36 it is seen that observations were made at stations A and F in the same year, 1922. From the intervals for this year for these two stations the average time difference is derived to be 0.57 hour. According to the formula, $r=\sqrt{gh}$, a progressive wave should take but 0.26 hour to traverse this waterway. In this connection, however, it might be mentioned that the theory for the progressive wave is based upon the assumption that the waterway is straight whereas Carquinez Strait has several sweeping bends.

In some instances the mean ranges for the various series at the stations in Carquinez Strait show appreciable fluctuations. This is probably due in part to the meteorological conditions existing at the time of these observations.

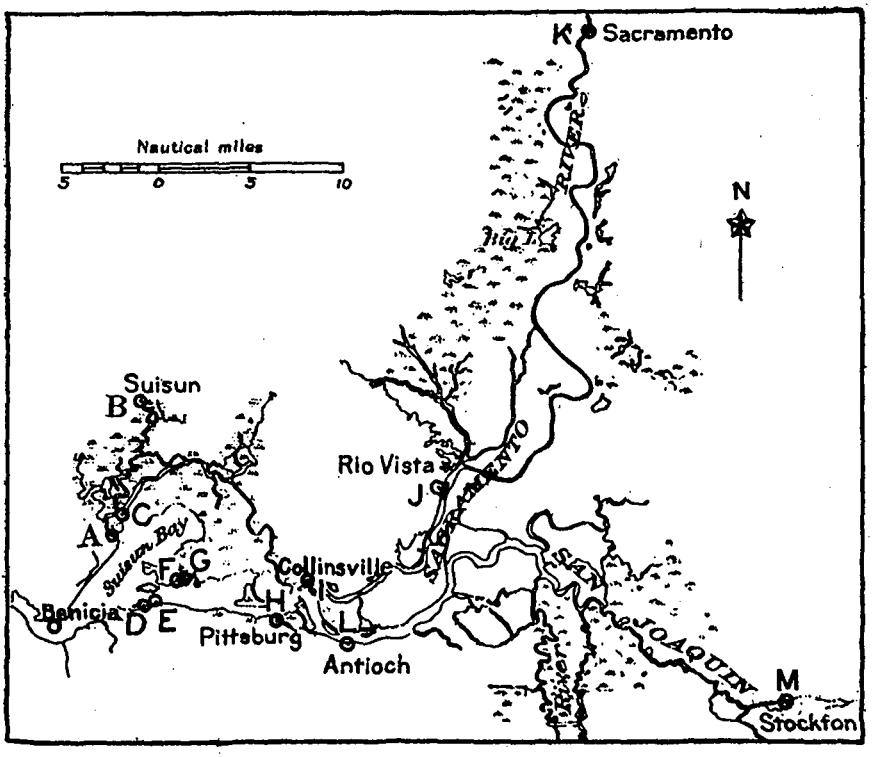
The diurnal inequalities for the stations where the observations extended over a period of a month or more are tabulated below. The results for stations A and F were reduced to mean values by comparison with simultaneous observations at Sausalito and Presidio, respectively, while those for stations C and D were corrected by the factor 1.02 F_1 as indicated by the subscript *c* after the values for the inequalities.

Station	Location	Series	Length	DHQ	DLQ
			Months	*Feet*	*Feet*
A	Crockett	Oct., 1886	1	0.63	1.09
C	P. M. S. S. Co. Dock	June-Oct., 1858	4	0.48	1.14
D	Army Point	Nov.-Dec., 1865	1	0.44	1.05
F	Siusun Point	Aug.-Dec., 1922	5	0.49	1.03
		Oct., 1923	1	0.53	1.02

The great diurnal ranges for the stations given above may be readily obtained by adding the diurnal high water inequalities and diurnal low water inequalities to the respective mean ranges from Table 36.

19. THE TIDE IN SUISUN BAY AND TRIBUTARIES

From Carquinez Strait the tide sweeps easterly into Suisun Bay, a broad, shallow body of water with marshy shores and numerous islands. In the eastern end of the bay these islands practically form a delta with the Sacramento and San Joaquin Rivers. The approaches to these two rivers are by narrow winding channels which have undergone changes due to improvements for increasing the depth, removing obstructions, and providing relief during seasons of freshets.



F 10. 13.—Tide Stations, Suisun Bay and tributaries

Tidal observations have been made at various localities in Suisun Bay and its tributaries over a considerable period of time. The results derived from these observations are given in Table 37. The lunitidal intervals and mean ranges in this table, with the exception of the November, 1857, series at station K for which no simultaneous observations were available, have been reduced to mean values by comparison with simultaneous observations at one of the standard stations previously mentioned.

TABLE 37.—*Tidal data, Suisun Bay and tributaries*

Station	Location	Series	Length	Lunitidal intervals		Duration of rise	Mean range
				HWI	LWI		
	SUISUN SLOUGH			*Hours*	*Hours*	*Hours*	*Feet*
A	Entrance	Dec., 1865–Aug., 1867	13 days	1.67	8.23	5.86	5.09
B	Suisun	Mar., 1913–Mar., 1915	2 years	2.43	8.42	6.43	5.02
	MONTEZUMA SLOUGH						
C	Entrance	Jan., 1923	3 days	1.95	8.30	6.17	5.16
	SUISUN BAY						
D	Seal Bluff	Oct.–Nov., 1886	1 month	1.95	8.33	6.14	4.70
E	Bay Point	Sept., 1915	2 days	1.88	8.10	6.20	5.20
		Oct., 1922	3 days	1.95	8.13	6.24	4.36
F	Ryer Island	Oct.–Nov., 1878	15 days	1.93	8.35	6.00	4.14
		May–July, 1890	1 month	1.72	8.52	5.62	4.65
G	Freeman Island	Feb., 1866	8 days	1.92	8.73	5.61	4.72
H	Pittsburg, New York Slough.	Mar.–Apr., 1867	4 days	2.63	9.18	5.87	4.58
		Dec., 1922–Mar., 1923	2½ months	2.75	9.27	5.90	3.83
I	Collinsville	Mar.–Apr., 1867	1 month	2.68	9.53	5.57	4.22
		Sept.–Nov., 1878	19 days	2.82	9.22	6.02	4.04
		May–June, 1890 [1]	15 days	2.43	9.42	5.43	3.20
		Mar., 1908–Apr., 1909	13 months	2.62	9.35	5.69	4.01
	SACRAMENTO RIVER						
J	Rio Vista	Feb.–Nov., 1908	7½ months	3.80	10.82	5.40	2.84
K	Sacramento	Nov., 1857 [2]	15 days	7.44	3.13	4.31	1.47
		Oct.–Dec., 1911	2 months	9.37	3.70	5.67	0.34
	SAN JOAQUIN RIVER						
L	Antioch	Apr.–May, 1867	7 days	2.87	9.90	5.39	3.83
		Dec., 1886	1 month	3.28	9.95	5.75	3.72
M	Stockton	Apr.–Oct., 1908	6 months	6.67	1.28	5.39	1.87

[1] Observations made during a freshet. [2] Not compared with a standard station.

Considerable quantities of fresh water are continually discharged into Suisun Bay by the Sacramento and San Joaquin Rivers. Besides materially affecting the temperature and salinity of the bay this fresh water has a considerable influence on the character of the tide in this locality. During the periods of freshets the tidal characteristics are often considerably masked and consequently observations made during such periods frequently give results differing materially from the mean values. These varying meteorological conditions afford an explanation of the variation in the tidal data given in Table 37. The fluctuations in the lunitidal intervals and ranges for the different series at the various stations given in this table indicate that observations based upon short series, or made during periods when meteorological conditions are abnormal, give poorly determined mean values. They are of value, however, in that they indicate the tidal conditions existing at the time of meteorological disturbances. During a

freshet the lunitidal intervals may be retarded or advanced depending upon the action of the freshet, but the mean range is always reduced. The May–June, 1890, series at station I is based on observations made during a freshet and shows the effect on the mean range. In this particular case the range is approximately 0.8 foot less than the mean value based on 13-month observations.

The data indicate that the rise and fall of the tide in Suisun Slough is greater than in the other tributaries, the 2-year series at Suisun, station B, giving a mean range of approximately 5 feet.

The results from Table 37 also show that the intervals gradually increase and the ranges decrease up the Sacramento and San Joaquin Rivers. Considering the more recent observations at stations along these rivers it is seen that for the Sacramento River the results indicate that the tide occurs about 6.75 hours later at Sacramento, station K, than at Collinsville, station I, which is approximately at the mouth of the river. It might be noted at this time that the low-water lunitidal intervals for Sacramento and Stockton are referred to a different transit than the other low-water intervals in this table. In order to refer them to the same transit used for the other stations 12.42 hours should be added. With regard to the mean range the 13-month series at Collinsville gives 4.01 feet, while the 2-month series at Sacramento gives but 0.34 foot. Observations are available in the San Joaquin River as far up as Stockton, station M. The results from the 6-month series, April–October, 1908, at this station give high-water lunitidal interval as 6.67 hours, low-water lunitidal interval as 1.28 hours, and the mean range as 1.87 feet as compared with HWI = 2.75 hours, LWI = 9.27 hours and mean range = 3.83 feet for the 2⅓ month series during December, 1922–March, 1923, at Pittsburg, station H, which is near the entrance to San Joaquin River.

The following table gives the diurnal inequalities for those stations in Suisun Bay and tributaries where the observations extended over a period of a month or more. The values marked with a subscript c were reduced to mean values by correcting the observed value by the emperical factor 1.02 F_1. The remaining inequalities were reduced to mean values by comparison with simultaneous observations at Presidio or Sausalito.

TABLE 38.—*Diurnal inequalities, Suisun Bay and tributaries*

Station	Location	Series	Length	Diurnal inequalities	
				High water	Low water
			Months	*Feet*	*Feet*
B	Suisun, Suisun Slough	March, 1913–March, 1915	24	0.44	0.96
D	Seal Bluff	October–November, 1886	1	0.41 c	1.01 c
F	Ryer Island	July, 1890	1	0.50 c	0.95 c
H	Pittsburg, New York Slough	January–February, 1923	2	0.48	0.75
I	Collinsville	April, 1867	1	0.43 c	0.68 c
		March, 1908–April, 1909	14	0.42	0.68
	SACRAMENTO RIVER				
J	Rio Vista	March–August, 1908	6	0.35	0.46
K	Sacramento	October–December, 1911	2	0.08 c	0.04 c
	SAN JOAQUIN RIVER				
L	Antioch	December, 1886	1	0.52	0.54
M	Stockton	April–October, 1908	6	0.24 c	0.23 c

From Table 38 it is seen, as is to be expected, that the diurnal inequalities are smaller in Suisun Bay and tributaries than in the other sections of San Francisco Bay and tributaries. The data indicate that for Suisun Bay proper the diurnal high-water inequality is about 0.4 to 0.5 foot and the diurnal low-water inequality approximately 1 foot, as compared with a *DHQ* of 0.6 foot and a *DLQ* of 1.2 feet in the vicinity of Presidio. In the tributaries the inequalities become much smaller, the data available indicating that at Stockton, station M, on the San Joaquin River both inequalities are only about 0.2 foot while up the Sacramento River at Sacramento, station K, the inequalities are negligible, being less than 0.1 foot.

Part II. CURRENTS IN SAN FRANCISCO BAY

By W. H. Overshiner, *Lieutenant (j. g.), U. S. Coast and Geodetic Survey*

GENERAL CONSIDERATIONS

1. EARLY OBSERVATIONS

Current observations have been made in San Francisco Bay at various times by parties of this survey. The earliest were made in 1856 by R. M. Cuyler and included observations of 1 day each at 5 stations in various parts of San Pablo Bay. The next observations on record are those at 2 stations southwest and southeast of Goat Island, respectively, occupied by A. F. Rogers in 1862. Following these are the observations of Edward Cordell made at 10 stations off the San Francisco water front between the years of 1865 and 1867. Continuous observations were made at each station for periods varying from 1 to 16 days. The next survey was made by Gershom Bradford between the years 1871 and 1875. This work consisted of observations made at 44 widely distributed stations located between Southampton Shoal and Point Avisadero. Continuous observations with a duration of 1 to 3 days were made at each station.

No further current observations were undertaken in San Francisco Bay until the fall of 1923, nearly half a century later. This survey was in charge of R. L. Schoppe and included 56 stations extending from the Golden Gate to Dumbarton Bridge on the south, and to Petaluma and Sonoma Creeks and Carquinez Strait on the north.

2. EARLY METHODS OF OBSERVING CURRENTS

In general, on the early surveys, the observations were made with float, log line, and sand glass, the log line being graduated in knots for a 28-second run and the float being a weighted pole reaching about 12 feet below the surface in order that the results might be applicable to vessels of average draft in those days. Occasionally the direction and velocity of subsurface currents were observed by means of two connected cylinders, the lower cylinder being set at the depth at which the observation was desired and the upper cylinder set so as to float on the surface, the two cylinders being connected by a wire.

The velocity and the direction of the surface cylinder obviously represented the velocity and direction of the resultant current, from which the velocity and direction of the current at the bottom could be computed.

3. PRESENT METHOD OF OBSERVING WITH POLE AND METER

The present method of observing currents as employed by the Coast and Geodetic Survey is as follows: The vessel from which the observations are to be made is anchored on the station with the shortest scope of chain possible and when practicable she is anchored

fore and aft so that her position will be the same on flood as on ebb. It is particularly advisable to anchor fore and aft when the station is located near a bend in a narrow channel or river since under these conditions a small change in position may mean a considerable difference in the velocity and direction of the current observed. Where the station is located in an open area, however, and the contour of the bottom is uniform, it is not so important that the vessel be anchored in this manner. The exact location of the vessel is determined by sextant angles taken between plotted signals on shore and a position is taken at least once on each ebb and each flood whenever possible. The position of the station is then plotted on a section of a large-scale chart which is pasted in the record book.

At each station observations are made with both the pole and the meter. The pole used is the standard 15-foot pole (except where shallow water makes a shorter one necessary), 2½ inches in diameter and loaded at one end with sufficient lead to allow it to float with 1 foot out of water. The log line is marked in knots for a 60-second run, the interval being determined by a stop watch. The direction of the pole is determined by use of a pelorus mounted on the taffrail of the vessel or other suitable place. The ship's heading at the time of the observation is noted on a standard compass, the deviation of which has been well determined; then after applying the deviation and variation to this reading and combining it with the pelorus reading, the true direction of the current as determined by the pole is obtained. The direction can also be determined by a sextant angle taken between the pole and some prominent and well-located object on shore, and it is advisable to determine the direction frequently in this manner as a check. Observations for both the direction and velocity of the current are made with the pole every hour during the series.

With the meter, which is of the Price or Gurley type, observations are made half hourly and at three depths, namely, 0.2, 0.5, and 0.8 of the depth at the station. Care should be taken, however, that observations near the surface are made below all noticeable wave action. In making the meter observations the one near the surface is made first followed by the mid-depth and near-the-bottom observations. Then the order is reversed and before the meter is drawn up the observation near the bottom is repeated, then the mid-depth observation and finally the one near the surface. In this way a duplicate set of observations is obtained for each half hour with but little outlay of time. In every case the time to the nearest minute at which the observations were begun is recorded in the record book.

As noted above the meter is of the Price or Gurley type with telephone attachment for counting the number of revolutions. The number of revolutions for a period of 60 seconds, as determined by a stop watch, is noted in the record. Then from a rating table which has been previously prepared the velocity of the current in knots is tabulated.

The meter is lowered from the vessel by means of a specially designed triple-strand insulated wire; two of the wires carry the electric current and the third and heavier wire carries the weight of the meter. From the meter the triple-strand wire leads over a registering sheave swinging outboard from the vessel and thence to a small sounding machine upon which is wound a supply of the wire

necessary for the depths to be encountered and also enough to allow for waste as the wire becomes unserviceable from wear. . A registering sheave serves to show the depths at which the meter is lowered, but once the depth at the station is determined the wire itself is marked by a small piece of tape for the 0.2, 0.5, and 0.8 depths and no further reference made to the registering sheave. The end of the wire which is attached to the sounding machine is led through a hole in the flange of the machine and fitted with a connection for "plugging in" with a small dry-cell battery and telephone receiver.

Considerable trouble was experienced with the contact point in the meter head due to corrosion and gradual deterioration from electrolysis when used in salt water. To obviate this difficulty the meter head was filled with heavy cylinder oil which prevented the entrance of salt water and in no way hindered the operation of the meter. The meter itself is rather light and to prevent its being carried downstream by the current it is allowed to slide on a one-fourth-inch steel cable at the lower end of which is attached a 250-pound concrete block, moulded to stream lines. The cable supporting the concrete block is led over a sheave and thence to a small hand winch for lowering and raising the block on arriving at and leaving the station. The block when in use is lowered to within a few feet of the bottom.

4. DIRECTION INDICATING DEVICES

Various methods have been used for determining the direction of the subsurface currents during the history of current surveys, possibly the earliest of these being the one previously described as employed by Bradford; that is, the use of a surface cylinder and a subsurface cylinder connected by a fine wire. The Canadian Tidal and Current Survey has used a modification of this method for determining both the velocity and the direction of subsurface currents. A description of the method may be found in W. Bell Dawson's Report of Canadian Tidal and Current Survey for the year 1896. The apparatus consists of two sheets of galvanized iron about 26 inches deep by 18 inches wide, slit so as to pass through each other at right angles, thus forming four wings of equal area. This apparatus is suspended in the water by a fine sounding wire and is used in connection with a sounding machine on which the depth to which the vanes are submerged can be read at any instant. The direction of the subsurface current is taken as the direction which the wire assumes at the surface with respect to its support. The inclination of the wire with the vertical is taken also by means of a clinometer and from a table previously prepared the velocity corresponding to the observed inclination is recorded.

Pillsbury in his Gulf Stream work used a meter of his own design, described in Appendix 10 of the Coast and Geodetic Survey Report for 1890. It was used for obtaining both the direction and velocity of the current at any depth. The subsurface direction was obtained by means of a device that locked a compass needle with respect to a direction vane and was brought into action by the force of the water when the meter was being raised. When the meter was raised to the surface the azimuth of the vane was read. The velocity of the cur-

rent was obtained from a device that automatically recorded the number of revolutions of a set of cups.

Another direction indicating current meter used was the Ritchie-Haskell meter, a joint invention of E. S. Ritchie and E. E. Haskell. A description of this apparatus is found in part 2 of the Coast and Geodetic Survey Report for 1891. It consisted essentially of a compass needle so supported in a chamber in the meter body as to be free to assume the magnetic meridian at all times. This chamber was kept filled with oil giving stability to the motion of the needle and preventing rusting. By means of an electric circuit, the angle to the nearest degree between the direction of the meter and the magnetic meridian was transmitted to a repeater or direction recorder on the deck of the vessel. The number of revolutions of a set of cups was also indicated electrically by means of which the velocity was determined. This meter proved to be a rather delicate apparatus to withstand the hard use it was necessarily put to in the field.

The Ekman meter is still another direction indicating apparatus. A description and illustration of this meter may be found in A Textbook of Oceanography by J. T. Jenkins. Quoting Jenkins:

> The direction of the current is ascertained by means of an apparatus attached to the revolving arm which leads off from the propeller. This apparatus consists of a rotating wheel divided into compartments, each of which contains a separate shot. Every 30 revolutions of the propeller liberates a shot which falls into a box containing a compass needle which is suitably grooved. Below the needle is a box divided into 36 compartments, each of which therefore corresponds to 10° of the compass. The shot rolls down the compass into one of these compartments. From the distribution of the shot in the various compartments the average direction of the current can be asertained.

The number of revolutions of the propeller is also automatically recorded from which the velocity of the current is determined.

At the present time there is being tested by this bureau another direction and velocity recording meter of foreign make, an invention of Prof. O. Pettersson, of Sweden. A description of it may be found in the Quarterly Journal of The Royal Meteorological Society (Vol. XLI, No. 173, January, 1915). By a system of mechanical, electrical, and photographic devices both the velocity and direction of the current are photographically recorded at any depth at which the meter may be set, for a period of two weeks without attention in the meantime.

It can readily be seen that the accurate determination of the direction of a subsurface current with a simple apparatus that will withstand the hard use it is necessarily put to in the field is quite a problem and one that is still not satisfactorily solved.

5. THE BIFILAR CURRENT DIRECTION INDICATOR

The apparatus for determining subsurface directions that has been used for the past few seasons on harbor work by this bureau, and the one that has so far proven the most successful is the bifilar suspension apparatus of triple vane form, commonly called the bifilar current direction indicator. It consists essentially of three pipes of different lengths built in arrow form, each one of which is suspended horizontally at a different depth by two fine wires. The wires from each pipe connect, respectively, to three upper vanes which journal on ball bearings around a single center axis. Just below each vane on

the axis and mounted with its 0–180° line parallel to the fore and aft line of the vessel is a pelorus on which the aximuth of the current may be read. Mounted on each vane also is a winding device fitted with a ratchet control so that the arrows may be raised or lowered as desired. The wire leading from the drum of the winding device is lead over pulleys of 1 foot circumference at the end of the arms of the vane and one of these pulleys operates a counter on each revolution so that the depth of the arrow may thus be determined. The upper vanes are of graduated sizes, corresponding to the different length of arrows thus allowing each set of vanes and arrows to rotate independently without fouling one another.

It was found in practice, however, when strong currents were encountered, that the weighted arrows had a tendency to be carried downstream and the upper arrows foul the supporting wires of those below. To eliminate this difficulty and to keep the apparatus vertical, a ½-inch hole was made in the midsection of each pipe so that the arrows could be run down a ¼-inch cable attached to the center shaft about which the upper vanes rotate, and to a 250-pound concrete block swung from the lower end of the cable. Since the cable had to be of various lengths, depending on the depth of water at the particular station, a length was used sufficient for the greatest depth to be encountered during the season. The cable was threaded through an eye on the end of the center shaft, doubled back on itself at the desired length, and a wire clamp placed just below the eye. The extra cable, if any, was then coiled up and tied out of the way on the shaft. This arrangement proved very effective in preventing the fouling of the wire, but in extreme depths and with very strong currents the entire apparatus still had a tendency to be carried downstream. In order to overcome this difficulty a line was made fast to the concrete block and carried as far forward on the deck of the observing vessel as possible; that is, considering that the bifilar was swung from the stern or an after davit and that the vessel was swinging to one anchor only. This line was then hauled taut until the apparatus assumed a vertical position. The line also proved useful in lowering and raising the concrete block. In some instances, however, it was found that this line would foul the forward end of the lower arrow, and it then became necessary to attach an additional weight at some point on the line in order to hold it low enough to clear the arrow. Observations for subsurface directions are made at the same depths and at the same time that meter observations for velocity are taken.

6. PRESENT SCHEME FOR CURRENT SURVEY OF A HARBOR

In making a current survey of a large harbor the present practice is to divide the area to be covered into suitable sections, depending somewhat on the shape and extent of the various bays, rivers, etc., of which the harbor is composed. In each section stations are suitably located, one of which is designated the "control station." The control station is kept in operation continuously during the time that the other stations in the section are being occupied. Two or more observing units are thus employed, and while one remains on the control station the others are occupying the various secondary stations in the section.

The secondary stations are occupied for either 13 or 25 consecutive hours, depending upon their location and importance. Stations located on a cross section of a channel are occupied simultaneously wherever possible. In moving from one section to another, 25 hours of simultaneous observations are made at the two control stations of contiguous sections, thus tying in the observations made in the different sections.

In the earlier surveys no such scheme as this was followed; usually but one observing unit was employed and the stations were occupied for various lengths of time and at various intervals as occasion permitted. As has been previously stated, Bradford's occupation of 44 stations extended between the years of 1871 and 1875.

CURRENT DATA FOR SAN FRANCISCO BAY AND TRIBUTARIES

7. PREPARATION OF TABLES GIVING CURRENT DATA

Due to dredging operations that have been carried on and to the various changes in the harbor that have been made from time to time, as well as to the manner in which the observations were made, slight differences in the results obtained in the earlier and later surveys may be expected. In Tables 42 to 51, inclusive, all the results of various surveys of San Francisco Bay have been tabulated as obtained. In these tables the following data are given: The number of each station corresponding to the number of the station as shown on the accompanying print of each section of the bay; the general locality of the station; the officer in charge of the survey; the year and month in which the survey was made; the time of slack water; the time, true azimuth, and velocity of the maximum flood and ebb; the duration of the flood and ebb; and the length of the series of observations at each station. The times of the current, as given, refer to the times that the corresponding predicted phenomena occur at San Francisco Entrance or the Golden Gate as tabulated for each day of the year in the Current Tables for the Pacific Coast issued annually in advance by this bureau. The tabulated maximum velocities are the observed strength of flood or ebb corrected for the mean range of the tide as explained in the Appendix, page 121.

In the Current Tables issued each year in advance by this bureau the current predictions for San Francisco Entrance as heretofore made contain only the predicted times of slack water for each day of the year with suitable indication as to whether the current is about to turn from east to west, or vice versa. Beginning with the year 1926, however, the predictions have been considerably elaborated. For each day there are tabulated the time of each slack before flood, the time and velocity of each maximum flood, the time of each slack before ebb, and the time and velocity of each maximum ebb. The tables prepared from the various surveys have therefore been made comparable with the present predictions.

Since there were no predictions, however, of the time of each maximum flood and ebb published for 1923, and no predictions at all published for the periods of the earlier surveys, it became necessary to make these predictions for the desired periods in order that the observed currents might be referred to the predictions at San Francisco Entrance as made to-day.

On the other hand, practically continuous tidal observations have been carried on at Fort Point or some other principal station in San Francisco Bay since 1854. The early current observations, therefore, were referred to the tide at the station in operation at that time and these results were in turn referred to the tides at Fort Point. In each case the time of slack before flood and the time of strength of flood were referred to the time of low water, and the time of slack before ebb and strength of ebb to the time of high water at Fort Point. Then, using the 1926 predictions, a relation was determined between the time of the tide at Fort Point and the time of the current at San Francisco Entrance. Using the first four months of the year, tabulations were made of the time of occurrence of each slack water with respect to the corresponding low or high water. The mean valves obtained for each month are shown in Table 39.

TABLE 39.—*Relation between time of slack water at San Francisco Entrance and time of the tide at Fort Point*

Month	Time of slack before flood after low water	Time of slack before ebb after high water
	Hours	*Hours*
January	2.04	1.74
February	2.04	1.78
March	2.04	1.75
April	2.06	1.74
Mean	2.05	1.75

It was deemed unnecessary to employ a longer period than four months for determining the relations between the times of slack water at San Francisco Entrance and the times of tide at Fort Point, since a close agreement was found to exist between these monthly means. Using these relations, the observed currents were referred to the time of slack water at San Francisco Entrance; that is, the time of slack before flood and the time of maximum flood at each station were referred to the time of slack before flood at San Francisco Entrance, and similarly the time of slack before ebb and maximum ebb were referred to the time of slack before ebb.

There yet remained the times of maximum flood and ebb at each station to be referred to the corresponding maxima at San Francisco Entrance. In order to accomplish this, Tables 40 and 41 were prepared from the first four months of the 1926 predicted currents. Table 40 shows the relation between the duration of flood and the corresponding time of the occurrence of maximum flood after slack water. It was prepared as follows: The duration of each flood was computed to tenths of hours by taking the difference between the time of slack before flood and the time of slack before ebb; then the corresponding time of the occurrence of each strength of flood after slack water was computed and tabulated under the appropriate duration of flood. A mean of the results thus obtained was plotted on cross-section paper using the duration of flood, in hours, as abscissa and the mean values for the maximum flood after slack water, in hours, as ordinates. A smooth curve was then drawn through these points and the corresponding ordinates scaled off the curve for each tenth of hour of abscissa, giving the values that were used.

TABLE 40.—*Relation between duration of flood and time that strength of flood occurs after slack water at San Francisco Entrance*

DURATION OF FLOOD (HOURS)																					
4.9	5.0	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	6.0	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	7.0
CORRESPONDING TIME OF STRENGTH OF FLOOD AFTER SLACK WATER (HOURS)																					
2.2	2.3	-------	2.4	2.6	2.6	2.7	2.5	2.8	2.7	2.6	3.0	2.9	2.8	3.1	3.1	3.0	3.1	3.0	3.0	3.1	3.1
-------	2.3	-------	2.5	2.7	2.6	2.6	2.7	2.9	2.8	2.9	2.9	3.0	3.0	3.0	2.9	3.2	3.1	3.0	3.1	3.1	-------
-------	-------	-------	2.5	2.5	2.6	2.7	2.7	2.9	2.8	2.8	2.9	2.7	3.1	3.1	3.0	3.2	3.0	3.0	3.1	-------	-------
-------	-------	-------	2.6	-------	2.5	-------	2.7	2.9	2.8	3.0	2.8	2.9	2.9	3.2	3.2	3.2	3.0	3.1	3.1	-------	-------
-------	-------	-------	-------	-------	2.5	-------	2.7	2.9	2.8	2.9	2.9	2.9	2.9	2.8	3.0	3.1	3.0	3.1	3.3	-------	-------
-------	-------	-------	-------	-------	2.7	-------	2.7	2.8	2.9	2.8	2.7	2.8	3.0	2.9	2.9	2.9	3.0	3.0	3.1	-------	-------
-------	-------	-------	-------	-------	2.7	-------	2.8	2.8	2.7	2.8	3.1	2.8	2.9	3.1	2.9	3.0	3.0	3.0	-------	-------	-------
-------	-------	-------	-------	-------	2.5	-------	2.8	2.7	2.8	2.8	2.9	2.8	3.0	3.0	3.0	3.2	3.0	3.1	-------	-------	-------
-------	-------	-------	-------	-------	2.8	-------	2.7	2.8	3.0	2.8	2.8	2.9	2.9	3.0	3.0	3.3	3.0	3.2	-------	-------	-------
-------	-------	-------	-------	-------	2.7	-------	2.7	2.8	2.8	2.8	2.9	3.0	3.0	3.0	3.1	3.2	3.0	3.1	-------	-------	-------
-------	-------	-------	-------	-------	2.6	-------	2.7	2.7	2.8	2.8	2.9	3.1	3.2	3.0	3.2	3.0	3.1	-------	-------	-------	-------
-------	-------	-------	-------	-------	2.6	-------	2.8	2.8	2.8	2.8	2.9	3.1	2.9	3.0	3.0	3.3	3.0	-------	-------	-------	-------
-------	-------	-------	-------	-------	2.8	-------	2.7	2.7	2.8	-------	2.8	2.8	3.0	3.2	3.0	3.1	3.2	-------	-------	-------	-------
-------	-------	-------	-------	-------	-------	-------	2.7	2.8	2.6	-------	2.9	2.9	2.9	-------	3.1	3.0	3.3	-------	-------	-------	-------
-------	-------	-------	-------	-------	-------	-------	2.8	2.8	2.9	-------	-------	3.0	-------	-------	3.2	3.0	3.1	-------	-------	-------	-------
-------	-------	-------	-------	-------	-------	-------	2.9	2.8	2.9	-------	-------	2.9	-------	-------	3.0	-------	3.1	-------	-------	-------	-------
-------	-------	-------	-------	-------	-------	-------	3.0	3.0	3.0	-------	-------	3.0	-------	-------	3.0	-------	3.3	-------	-------	-------	-------
-------	-------	-------	-------	-------	-------	-------	-------	3.0	2.8	-------	-------	3.1	-------	-------	3.0	-------	-------	-------	-------	-------	-------
-------	-------	-------	-------	-------	-------	-------	-------	2.7	2.8	-------	-------	2.9	-------	-------	3.2	-------	-------	-------	-------	-------	-------
-------	-------	-------	-------	-------	-------	-------	-------	2.8	2.8	-------	-------	-------	-------	-------	3.0	-------	-------	-------	-------	-------	-------
-------	-------	-------	-------	-------	-------	-------	-------	2.9	2.8	-------	-------	-------	-------	-------	3.0	-------	-------	-------	-------	-------	-------
-------	-------	-------	-------	-------	-------	-------	-------	2.8	-------	-------	-------	-------	-------	-------	3.0	-------	-------	-------	-------	-------	-------
-------	-------	-------	-------	-------	-------	-------	-------	2.8	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
MEANS																					
2.20	2.30	-------	2.50	2.60	2.63	2.67	2.74	2.82	2.81	2.82	2.89	2.92	2.96	3.03	3.04	3.11	3.08	3.06	3.12	3.10	3.10
VALUES OBTAINED FROM A SMOOTH CURVE DERIVED FROM ABOVE MEANS																					
2.20	2.30	2.39	2.48	2.56	2.62	2.68	2.74	2.78	2.82	2.86	2.90	2.94	2.97	3.00	3.04	3.06	3.08	3.10	3.12	3.13	3.14

TABLE 41.—*Relation between duration of ebb and time that strength of ebb occurs after slack water at San Francisco Entrance*

DURATION OF EBB (HOURS)																										
5.0	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	6.0	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	7.0	7.1	7.2	7.3	7.4	7.5	7.6
CORRESPONDING TIME OF STRENGTH OF EBB AFTER SLACK WATER (HOURS)																										
2.2	2.1	2.1	2.1	2.2	2.9	2.2	2.4	2.5	2.4	2.7	2.7	2.5	3.0	3.0	2.9	2.7	3.0	3.2	2.9	3.3	3.1	3.4	3.4	3.5	3.5	3.6
------	2.1	2.2	2.3	2.2	2.3	2.4	2.5	2.6	2.5	2.6	2.8	2.9	2.8	2.8	2.9	3.0	3.1	3.2	3.2	3.2	3.3	3.2	3.4	3.4	3.4	------
------	2.2	2.2	2.3	2.4	2.3	2.7	2.4	2.4	3.5	2.6	2.7	2.8	3.0	2.8	2.9	2.9	2.9	3.0	3.2	3.3	3.1	3.4	3.4	3.4	3.3	------
------	2.2	2.1	2.4	2.8	2.1	2.4	2.6	3.2	3.4	2.6	2.7	2.7	2.8	2.8	2.9	3.1	3.0	3.4	3.1	3.1	3.2	3.3	3.4	3.4	3.5	------
------	2.3	2.1	------	2.6	2.4	2.6	2.4	2.4	2.6	2.8	2.7	2.7	2.8	2.8	------	3.0	3.0	3.1	3.2	3.2	3.2	3.3	3.5	3.6	3.8	------
------	------	2.1	------	2.4	------	2.4	2.5	2.5	2.5	2.6	3.6	2.8	2.8	2.9	------	3.0	3.0	3.2	3.3	3.4	3.3	3.2	3.4	3.4	3.4	------
------	------	2.2	------	2.3	------	3.1	2.6	2.8	2.6	2.6	------	3.6	2.8	2.9	------	3.2	3.0	3.2	3.1	3.2	3.6	3.3	3.5	3.3	3.3	------
------	------	2.4	------	2.2	------	3.2	2.3	2.6	------	2.7	------	3.5	3.1	2.8	------	2.9	------	------	------	3.2	------	3.5	3.4	3.4	------	------
------	------	2.1	------	2.4	------	3.0	2.5	2.3	------	3.1	------	2.7	------	3.0	------	3.2	------	------	------	3.5	------	3.3	3.4	3.4	------	------
------	------	2.4	------	2.1	------	2.6	------	2.2	------	2.8	------	------	------	2.9	------	3.0	------	------	------	3.5	------	3.2	3.3	------	------	------
------	------	2.1	------	2.5	------	2.4	------	2.4	------	2.6	------	------	------	2.8	------	3.0	------	------	------	3.2	------	3.6	3.4	------	------	------
------	------	------	------	------	------	2.3	------	3.5	------	2.6	------	------	------	------	------	2.9	------	------	------	3.2	------	3.7	3.4	------	------	------
------	------	------	------	------	------	2.2	------	2.4	------	------	------	------	------	------	------	------	------	------	------	3.4	------	3.2	3.2	------	------	------
------	------	------	------	------	------	------	------	2.2	------	------	------	------	------	------	------	------	------	------	------	------	------	3.4	3.6	------	------	------
------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	3.5	------	------	------
------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	3.2	------	------	------
MEANS																										
2.20	2.18	2.18	2.28	2.37	2.40	2.58	2.47	2.57	2.79	2.69	2.87	2.91	2.89	2.86	2.90	2.99	3.00	3.19	3.14	3.28	3.26	3.36	3.40	3.42	3.46	3.60
VALUES OBTAINED FROM A SMOOTH CURVE DERIVED FROM ABOVE MEANS																										
2.16	2.20	2.26	2.31	2.37	2.43	2.48	2.54	2.60	2.66	2.72	2.78	2.83	2.89	2.94	2.99	3.05	3.10	3.16	3.21	3.26	3.32	3.37	3.42	3.47	3.53	3.58

The method employed in the preparation of Table 40 was followed in preparing Table 41. The times of slack water at San Francisco Entrance were then computed, covering the periods during which current observations were obtained at the early stations. From these computations the duration of both the flood and ebb at the Entrance was obtained for the periods in question. Using Tables 40 and 41 the times of occurrence of the maxima phenomena at each station, after the similar occurrence at the entrance, were determined. For the 1923 stations these relations could be determined with much less difficulty as the published predictions of the slack waters at San Francisco Entrance were available.

DISCUSSION OF RESULTS

For the purpose of discussing the results obtained from the various current surveys made from time to time in San Francisco Bay and tributaries, the entire body of water included therein was divided into five sections designated as follows: (1) San Francisco Entrance; (2) South San Francisco Bay; (3) North San Francisco Bay; (4) San Pablo Bay; (5) Carquinez and Mare Island Straits.

Section 1 includes the Golden Gate and the area between a line drawn from Bluff Point to Berkeley on the north and from Potrero Point to Alameda on the south.

Section 2 includes all the bay between the southern limit of section 1 and Dumbarton Bridge.

Section 3 includes all the area north of section 1 to a line drawn from Point San Pedro to Point San Pablo.

Section 4 includes all of San Pablo Bay and its tributaries with the exception of Carquinez and Mare Island Straits; that is, it includes all the area above the limit of section 3 to a line drawn from the western end of Mare Island jetty to the town of Rodeo.

Section 5 includes that portion of Carquinez Strait lying between the eastern limit of section 4 and the town of Crockett and also that portion of Mare Island Strait lying below South Vallejo.

For each station two tables have been prepared giving the current data obtained at the various stations in the section. For the first table the results of all surface observations are tabulated for each station in the section. In this tabulation the times of occurrence and duration of the various phases of the current are given to the nearest tenths of hours, the velocities to the nearest tenths of knots, and the directions to the nearest 5°. In the second table of the section are tabulated the results obtained at the stations occupied in 1923 giving the observations obtained at various depths with both the pole and the meter. Here the various times are given to hundredths of hours, the velocities to hundredths of knots, and the direction to whole degrees as obtained. The results are given to hundredths only to permit of the comparison of the results at the various depths. Unfortunately, during the survey, the bifilar current direction indicator was only in the stage of development and direction observations at various depths were not obtainable in every instance. This fact accounts for the omission of directions in the azimuth columns of the tables.

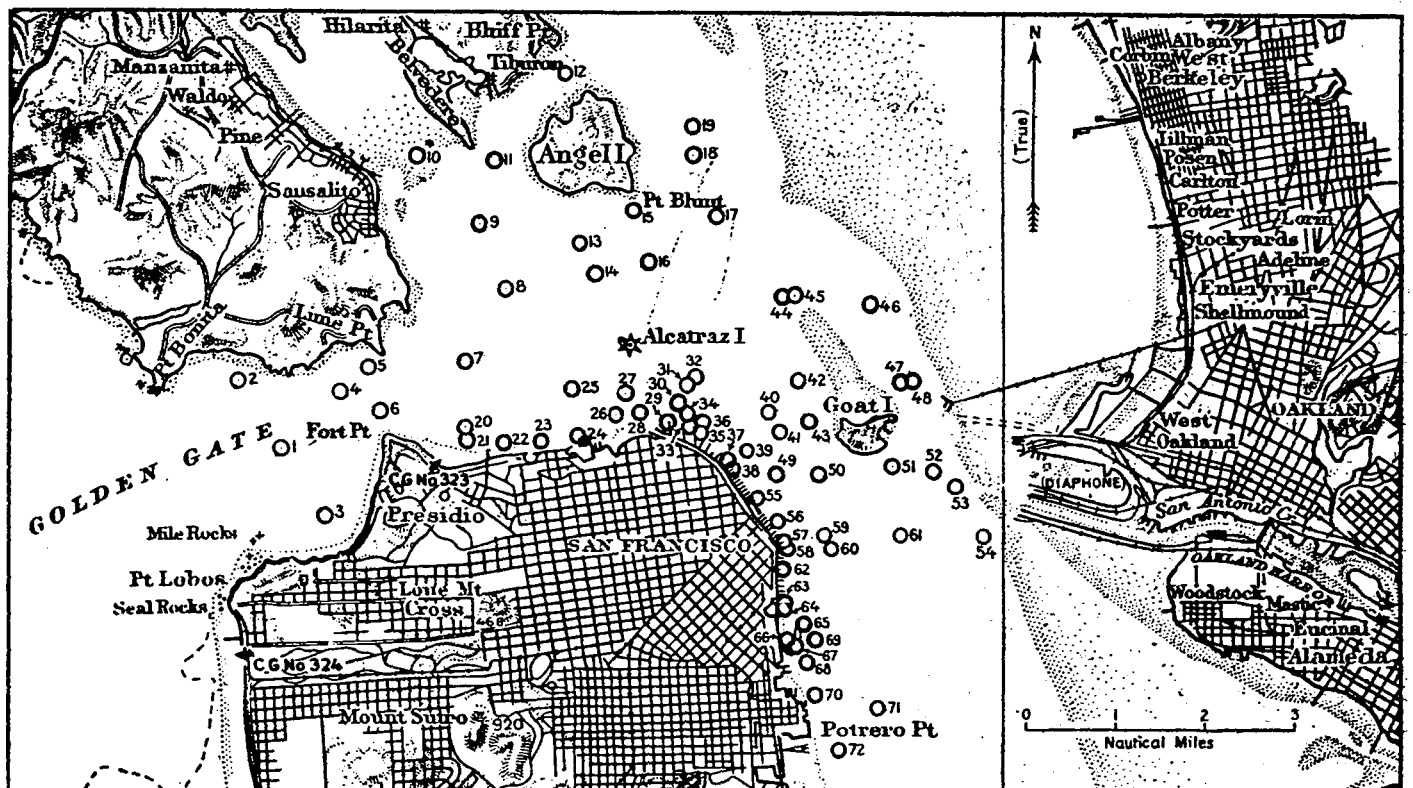


FIG. 14.—Current stations, San Francisco Entrance

8. THE CURRENT IN SAN FRANCISCO ENTRANCE AND SOUTH SAN FRANCISCO BAY

For the entrance section, Figure 14 shows the location of 72 stations at which current observations have been made at various times. The data obtained from all pole observations at these stations have been tabulated in Table 42. Twenty-eight of the 72 stations were occupied during the survey of 1923 and for these stations observations at different depths are available. The results derived from these observations are tabulated in Table 43.

Figure 15 shows the location of 7 current stations in South San Francisco Bay, 5 of which were occupied in 1923. The data for these stations are presented in Tables 44 and 45. In these tables a minus (−) sign indicates that the time of current at the given station is earlier than the corresponding predicted phenomenon at San Francisco Entrance. When no sign is given the plus (+) sign is understood and indicates that the time is later.

It was considered advisable to discuss these two sections as one since the currents occurring therein are very similar, being brought about by like causes.

It might be well here to define flood and ebb current. As the terms are commonly used, the flood current is the one which sets inland or upstream and the ebb current the one which sets seaward or downstream. In a narrow channel or river there can be no doubt as to these directions; however, in a large area interspersed with islands and with several different channels leading to and from it there may be some ambiguity arising from these definitions based on directions. The flood current is therefore defined as the one which attains its strength on a rising tide and the ebb current as the one which attains its strength on a falling tide.

Referring to Tables 42 and 44 it may readily be seen that all phases of the current occur consistently earlier throughout sections 1 and 2 than do the corresponding phases of the current as predicted for the Golden Gate. Also, there seems to be no marked progression in the times; that is, the current appears to occur simultaneously throughout the two sections and it would thus appear that it is caused by a stationary wave rather than a progressive one. It has been previously pointed out in the discussion of the tides of South San Francisco Bay that the tidal movement found there approaches the stationary wave and the same type of wave is probably found in section 1.

The fact that the current occurs earlier in sections 1 and 2 than it does at the entrance may be explained somewhat by referring to Figures 19 to 30. On these prints of the entire bay arrows have been drawn showing approximately the direction in which the surface current is moving for each hour throughout a complete current cycle at the entrance. The times are referred to high water slack and low water slack. The high water slack is the slack which occurs after high water and low water slack is the slack which occurs after low water. That the flood current occurs earlier in parts of sections 1 and 2 than it does at the entrance may be explained by the fact that the last of the ebb current coming down from the northern reaches of the bay flows south through the eastern part of section 1 and into section 2, being felt as the first of the flood current in these sections. This movement is shown in Figures 20 and 21.

Considering the ebb current, first referring to section 2 and to Figures 26 and 27, it is seen that the current after the first of the ebb in this section flows north through the eastern portion of section 1 and into section 3, appearing in this part of section 1 and in section 3 as

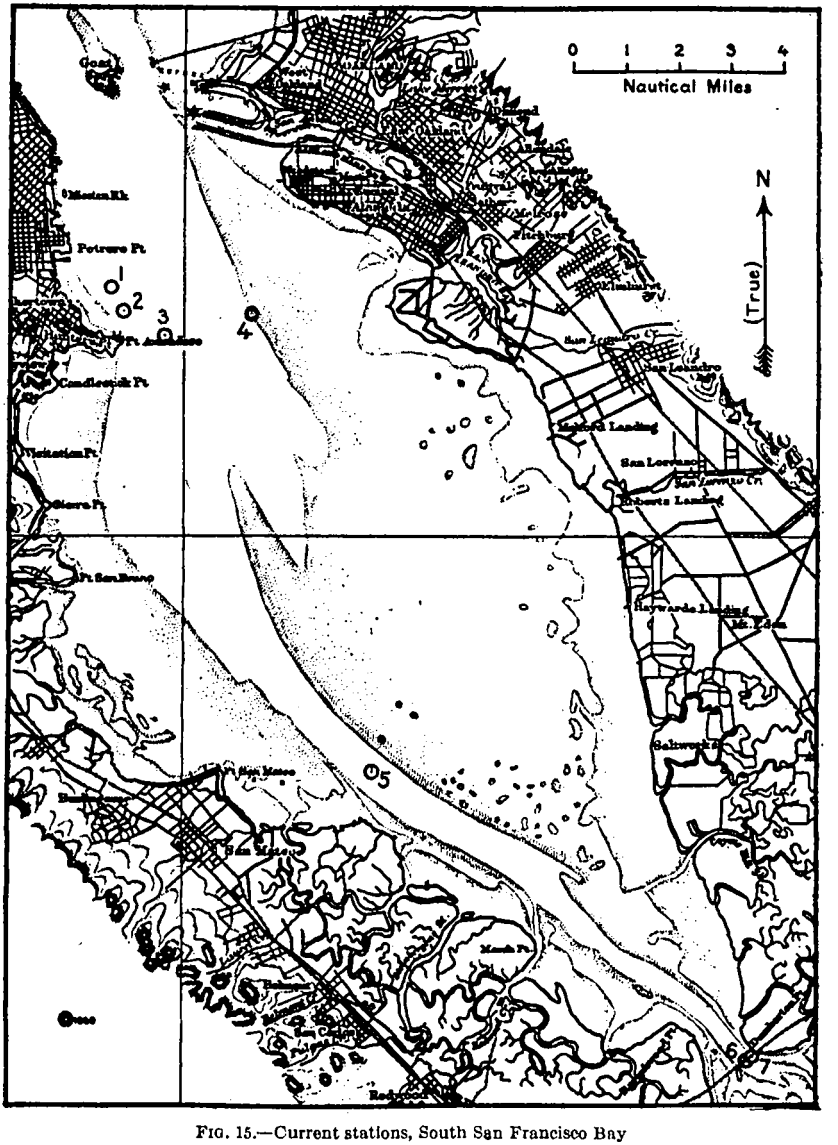


FIG. 15.—Current stations, South San Francisco Bay

the last of the flood current. That the ebb current also occurs earlier in section 1 than at the entrance is a much more difficult matter to account for since the current movement, especially at the time of the beginning of the ebb in this section, seems to be very involved and a complete explanation of its action is not apparent.

TABLE 42.—*Current data for San Francisco Entrance*

[Referred to times of predicted currents at San Francisco Entrance]

Station No.	Location	Party of—	Date	Slack	Maximum flood			Flood duration	Slack	Maximum ebb			Ebb duration	Length of series
					Time	Azimuth (true)	Velocity			Time	Azimuth (true)	Velocity		
				Hours	*Hours*	*Degrees*	*Knots*	*Hours*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Days*
1	Golden Gate	R. L. Shoppe	Oct., 1923	0.2	0.0	55	2.8	6.1	−0.2	−0.3	225	3.0	6.3	7
2	Bonita Cove	do	do	−3.0	−4.7	25	1.0	4.0	−5.5	−6.6	250	0.9	8.4	½
3	South Bay	do	do	−3.6	−5.1	70	1.3	6.1	−4.0	−4.0	245	1.1	6.3	½
4	Golden Gate	do	do	−0.3	0.1	70	2.6	6.3	−0.5	−0.6	260	3.4	6.1	1¼
5	Southwest of Lime Point	do	do	−0.7	−0.4	70	2.8	6.7	−0.5	−1.0	230	1.2	5.7	1¼
6	North of Fort Point	do	do	−0.4	−0.8	25	2.6	6.3	−0.6	−1.2	260	3.5	6.1	1¼
7	Off Presidio	Edward Cordell	Dec., 1866	−0.2	−0.3	70	3.0	6.3	−0.4	0.1	250	2.6	6.1	1¼
8	Northeast of Lime Point	do	do	−0.5	−0.5	35	2.5	5.9	−1.1	0.0	215	2.9	6.5	1
9	Southwest of Angel Island	R. L. Schoppe	Oct., 1923	0.1	0.0	10	1.8	6.4	0.0	−0.1	240	1.6	6.0	1
10	Richardson Bay	do	do	−1.0	−0.9	330	0.3	6.1	−1.3	−1.2	130	0.4	6.3	1
11	Entrance Racoon Straits	do	do	−0.3	0.0	15	1.3	6.0	−0.8	−0.8	225	2.0	6.4	1
12	Racoon Straits	G. Bradford	Nov., 1871	−0.3	1.0	70	3.3	6.0	−0.8	−0.5	230	3.4	6.4	2
13	South of Angel Island	do	do	−1.7	−1.4	120	1.2	7.0	−1.2	−2.2	300	1.2	5.4	1
14	Between Alcatraz and Angel Island	R. L. Schoppe	Oct., 1923	0.4	−0.9	75	0.8	5.2	−0.9	0.0	285	2.0	7.2	1
15	Off Point Blunt	G. Bradford	Nov., 1871	−0.2	−0.1	100	1.6	5.9	−0.8	−1.1	220	2.1	6.5	2
16	South of Point Blunt	do	do	0.3	−0.1	75	1.2	5.0	−1.2	−0.6	300	1.3	7.4	2
17	East of Point Blunt	do	Feb., 1875	−1.7	−1.9	135	2.2	8.0	−0.2	−0.5	300	1.8	4.4	1
18	East of Angel Island	R. L. Schoppe	Oct., 1923	1.6	1.1	350	1.1	5.4	0.5	1.1	195	1.2	7.0	1½
19	Northeast of Angel Island	G. Bradford	Jan., 1875	1.6	1.2	350	2.2	5.5	0.6	1.8	175	2.4	6.9	2
20	Off Presidio	R. L. Schoppe	Oct., 1923	−0.4	−1.7	130	0.8	5.0	−1.9	−1.4	275	1.8	7.4	¾
21	do	G. Bradford	Jan., 1875	−0.5	−2.2	100	1.2	4.3	−2.7	−1.5	275	2.1	8.1	2
22	do	do	do	−0.5	−1.6	85	1.2	5.2	−1.8	−1.4	280	1.9	7.2	2
23	do	do	Dec., 1874	−0.6	−1.4	95	1.3	5.5	−1.6	−1.3	270	1.6	6.9	2
24	Off Black Point	do	Nov., 1874	−0.6	−1.3	85	1.3	5.5	−1.6	−1.5	260	1.3	6.9	2
25	North of Black Point	Edward Cordell	Dec., 1866	−0.3	−0.2	100	2.8	5.6	−1.2	−0.9	280	2.3	6.8	1½
26	Northeast of Black Point	G. Bradford	Nov., 1874	−0.7	−0.9	90	1.8	6.0	−1.2	−1.4	270	1.7	6.4	2
27	South of Alcatraz Island	R. L. Schoppe	Oct., 1923	−0.8	−0.8	105	1.5	6.3	−1.1	−1.5	275	1.8	6.1	1
28	do	G. Bradford	Oct., 1874	−1.0	−0.8	100	1.8	6.2	−1.3	−1.8	285	2.0	6.2	2
29	End of Pier 41, San Francisco	R. L. Schoppe	Nov., 1923	−2.1	−0.9	70	1.3	7.5	−1.0	−0.8	250	0.4	4.9	½
30	Southeast of Alcatraz Island	Edward Cordell	Dec., 1866	−0.4	−0.1	110	2.5	6.1	−0.8	−0.9	290	3.0	6.3	3
31	do	do	Jan., 1867	−0.4	−1.3	130	2.0	4.8	−2.1	−0.7	310	3.0	7.6	16
32	do	G. Bradford	Nov., 1871	−1.0	−1.5	110	1.6	6.0	−1.5	−1.3	305	1.8	6.4	1
33	Off North Point	do	Mar. 1873	−0.1	−0.7	120	1.4	3.8	−2.8	−1.5	310	2.1	8.6	2
34	do	Edward Cordell	Mar., 1866	−0.3	−0.6	130	1.5	4.7	−2.1	−0.8	310	2.3	7.7	4
35	do	G. Bradford	Nov., 1871	−1.3	−2.3	120	1.4	6.0	−1.8	−1.0	300	1.6	6.4	2½
36	do	R. L. Schoppe	Nov., 1923	−1.0	−0.9	130	2.8	5.9	−1.6	−1.7	305	2.8	6.5	½
37	do	G. Bradford	Oct., 1874	−1.0	−1.7	140	2.3	5.1	−2.4	−1.4	315	2.4	7.3	2
38	End of Pier 17, San Francisco	R. L. Schoppe	Nov., 1923	−1.2	−1.7	85	0.6	5.4	−2.3	−1.9	290	0.9	7.0	½
39	Off North Point	do	Oct., 1923	−0.5	−1.0	145	1.9	6.0	−1.0	−0.6	320	2.0	6.4	1½
40	West of Goat Island	G. Bradford	July-Aug., 1874	0.0	−0.4	135	1.4	5.4	−1.1	−0.5	330	1.8	7.0	2
41	do	R. L. Schoppe	Oct., 1923	−0.3	−0.4	150	1.9	6.3	−0.5	−0.6	320	2.1	6.1	2½
42	Northwest of Goat Island	G. Bradford	July, 1874	−0.1	−0.6	135	2.0	5.7	−0.9	−0.9	350	2.1	6.7	2
43	West of Goat Island	R. L. Schoppe	Oct., 1923	−0.4	−0.6	165	1.5	5.8	−1.0	−0.7	325	2.1	6.6	16
44	Northwest of Goat Island Shoal	G. Bradford	Nov., 1871	−1.7	−1.0	130	1.6	7.1	−1.1	−1.6	300	1.2	5.3	1
45	do	R. L. Schoppe	Nov., 1923	−2.2	−1.5	130	1.3	6.9	−1.8	−1.8	285	1.2	5.5	½
46	North of Goat Island	G. Bradford	July, 1874	−0.9	−0.5	125	1.6	6.1	−1.3	−0.5	335	1.7	6.3	2¼
47	Northeast of Goat Island	do	Mar., 1872	−0.7	−1.1	145	2.1	5.8	−1.4	−1.0	355	1.9	6.6	1
48	do	R. L. Schoppe	Oct., 1923	−1.1	−0.1	160	1.0	6.9	−0.6	−1.2	340	1.1	5.5	1
49	Southwest of Goat Island	Edward Cordell	Mar., 1866	−0.2	−1.5	165	2.0	4.8	−1.9	−0.9	345	2.5	7.6	4½
50	do	G. Bradford	Mar., 1872	−0.4	−1.1	145	2.8	6.0	−0.9	−0.6	340	2.8	6.4	1
51	South of Goat Island	do	do	−0.7	−1.0	185	1.6	5.9	−1.3	−0.8	340	2.0	6.5	1
52	Southeast of Goat Island	A. F. Rodgers	Oct., 1862	−1.3	−0.4	150	2.0	6.9	−0.9	−1.1	330	2.1	5.5	1¾
53	do	G. Bradford	Mar., 1872	−1.5	−0.1	160	1.4	6.7	−1.3	−1.6	340	1.3	5.7	1
54	do	R. L. Schoppe	Oct., 1923	−1.8	−0.9	170	1.8	7.0	−1.2	−1.8	320	1.6	5.4	1
55	Off Ferry Building, San Francisco	G. Bradford	Oct., 1874	−0.9	−1.5	105	1.5	4.7	−2.7	−1.9	330	1.4	7.7	2
56	Southeast of Ferry Building, San Francisco.	do	Apr., 1872	−0.3	−1.1	160	1.8	5.6	−1.2	−0.2	350	2.4	6.8	1
57	End of Pier 24, San Francisco	R. L. Schoppe	Oct.-Nov., 1923	−1.6	−1.2	170	0.8	6.1	−2.0	−2.0	345	0.9	6.3	1
58	Off Rincon Point	Edward Cordell	Nov., 1865	−0.6	−1.6	180	1.6	4.9	−2.2	−1.2	0	2.1	7.5	3¼
59	East of Rincon Point	A. F. Rodgers	Oct., 1862	−0.2	−0.4	125	2.1	5.6	−1.1	−0.8	5	2.1	6.8	1
	do	R. L. Schoppe	Oct., 1923	−0.6	−0.3	180	2.3	6.4	−0.6	−0.5	340	2.6	6.0	1
60	do	Edward Cordell	Apr., 1866	−0.5	−1.3	160	2.7	5.6	−1.4	−0.3	340	2.4	6.8	5½
61	South of Goat Island	R. L. Schoppe	Oct., 1923	−1.0	−0.9	165	2.2	6.2	−1.2	−1.0	320	2.0	6.2	1
62	South of Rincon Point	G. Bradford	Sept., 1874	−0.8	−0.9	175	1.9	5.5	−1.8	−1.3	0	2.2	6.9	2
63	End of Pier 46, San Francisco	R. L. Schoppe	Oct., 1923	−1.0	−2.1	180	1.0	4.4	−3.0	−1.0	20	1.4	8.0	1
64	North of Mission Rock	G. Bradford	Aug., 1874	−1.0	−1.3	170	1.4	5.1	−2.4	−0.9	10	1.6	7.3	3
65	East of Mission Rock	do	do	−0.7	−0.7	155	2.4	5.5	−1.7	−0.8	0	2.2	6.9	2
66	Southwest of Mission Rock	do	Sept., 1874	−1.2	−1.7	150	1.9	5.3	−2.4	−1.2	350	1.8	7.1	2
67	South of Mission Rock	Edward Cordell	Nov., 1866	−0.8	−1.5	180	1.5	5.0	−2.3	−1.3	0	1.4	7.4	2
68	do	G. Bradford	Aug., 1874	−0.8	−1.1	155	1.4	5.4	−1.9	−1.1	355	1.8	7.0	3
69	Southeast of Mission Rock	R. L. Schoppe	Oct., 1923	−0.8	−0.8	180	2.0	5.3	−2.0	−1.9	5	2.0	7.1	1
70	Northeast of Potrero Point	do	do	−1.1	−0.6	175	1.6	6.0	−1.6	−1.3	0	1.4	6.4	1
71	East of Potrero Point	G. Bradford	Aug., 1874	−1.0	−1.4	155	1.8	5.6	−1.9	−1.3	350	2.1	6.8	2
72	Southeast of Potrero Point	do	Sept., 1874	−1.1	−1.3	155	2.1	6.3	−1.3	−1.2	335	2.2	6.1	2

TABLE 43.—*San Francisco Entrance, current data for various depths*

[Referred to times of predicted currents at San Francisco Entrance]

Station No.	Location	Party of—	Date	Observed with	Depth	Slack	Maximum flood			Flood duration	Slack	Maximum ebb			Ebb duration	Length of series
							Time	Azimuth (true)	Velocity			Time	Azimuth (true)	Velocity		
			1923		*Feet*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Days*
1	Golden Gate	R. L. Schoppe	Oct. 19–26	Pole	7	0.22	−0.02	54	2.78	6.13	−0.15	−0.30	223	3.03	6.29	7
				Meter	36	0.23	−0.51		2.39	6.20	−0.07	−0.43		3.02	6.22	7
				do	90	−0.10	−0.49		2.18	6.60	0.00	−0.25		3.02	5.82	7
				do	144	−0.62	−0.16		1.84	7.36	0.25	−0.45		3.00	5.06	7
2	Bonita Cove	do	Oct. 23–24	Pole	7	−3.00	−4.71	25	1.00	4.00	−5.50	−6.55	250	0.86	8.42	½
				Meter	14	−4.20	−4.71		0.84	5.60	−5.10	−5.95		0.87	6.82	½
				do	34	−3.90	−4.56		0.90	5.10	−5.30	−6.35		1.10	7.32	½
				do	54	−4.10	−4.76		0.95	5.40	−5.20	−6.15		1.00	7.02	½
3	South Bay	do	Oct. 25–26	Pole	7	−3.60	−5.14	70	1.33	6.10	−4.00	−4.00	247	1.08	6.32	½
				Meter	11	−2.80	−5.14		1.23	5.10	−4.20	−3.50		0.88	7.32	½
				do	29	−2.80	−5.04		1.27	5.10	−4.20	−3.70		0.97	7.32	½
				do	46	−2.90	−4.89		1.08	5.20	−4.20	−3.50		0.88	7.22	½
4	Golden Gate	do	Oct. 24–25	Pole	7	−0.30	0.09	69	2.62	6.30	−0.50	−0.63	261	3.39	6.12	1¼
				Meter	72	−0.15	−0.46		2.32	6.19	−0.47	−0.86		3.07	6.23	1¼
				do	180	−0.45	−0.61		2.15	6.55	−0.40	−0.73		3.12	5.87	1¼
				do	288	−0.90	−0.51		1.93	7.10	−0.30	−0.73		3.16	5.32	1¼
5	Southwest of Lime Point.	do	do	Pole	7	−0.70	−0.36	71	2.75	6.67	−0.53	−1.00	228	1.15	5.75	1¼
				Meter	26	−0.80	0.09		2.66	6.67	−0.63	−0.76		1.13	5.75	1¼
				do	66	−0.85	0.09		2.51	6.75	−0.60	−0.63		1.18	5.67	1¼
				do	106	−0.75	−0.11		2.54	6.55	−0.70	−0.53		1.09	5.87	1¼
6	North of Fort Point	do	do	Pole	7	−0.40	−0.76	24	2.63	6.34	−0.57	−1.18	260	3.51	6.08	1¼
				Meter	14	−0.30	−0.81		2.75	6.15	−0.65	−0.95		3.56	6.27	1¼
				do	35	−0.40	−0.56		2.54	6.30	−0.60	−0.87		3.36	6.12	1¼
				do	56	−1.05	−0.46		2.25	6.99	−0.57	−0.68		3.02	5.43	1¼
9	Southwest of Angel Island.	do	Oct. 19–20	Pole	7	0.07	−0.03	10	1.81	6.43	0.00	−0.08	238	1.59	5.99	1
				Meter	9	0.00	0.02		1.91	6.60	0.10	−0.08		1.46	5.82	1
				do	22	−0.10	−0.03		1.72	6.70	0.10	−0.13	228	1.30	5.72	1
				do	35	−0.40	−0.03	355	1.48	7.10	0.20	−0.23	216	1.15	5.32	1
10	Richardson Bay	do	Oct. 20–22	Pole	1	−0.95	−0.92	328	0.28	6.15	−1.30	−1.20	130	0.36	6.27	1
				Meter	3	−0.83	−1.07		0.45	6.27	−1.07	−0.30	122	0.44	6.15	1½
				do	6	−0.93	−1.07		0.39	6.33	−1.10	−0.30	122	0.37	6.09	1½
				do	10	−0.90	−1.07		0.30	6.37	−1.03	−0.30	122	0.36	6.05	1½
11	Racoon Straits	do	Oct. 19–20	Pole	7	−0.27	0.00	14	1.27	6.02	−0.75	−0.78	226	1.97	6.40	1
				Meter	15	−0.43	−0.16		1.40	6.38	−0.55	−0.48		1.74	6.04	1
				do	37	−0.60	−0.46		1.41	6.55	−0.55	−0.73	251	1.43	5.87	1
				do	59	−0.87	−0.76		1.41	6.81	−0.55	−1.08		1.23	5.61	1
14	Between Alcatraz and Angel Islands.	do	Oct. 22–23	Pole	7	0.35	−0.87	76	0.84	5.25	−0.90	−0.05	284	2.02	7.17	1
				Meter	24	−0.05	−0.82		1.16	5.90	−0.65	0.20		1.69	6.52	1
				do	60	−0.05	−0.87	85	1.24	5.85	−0.70	−0.05	293	1.64	6.57	1
				do	96	−0.05	−0.97		1.25	5.90	−0.65	−0.05		1.55	6.52	1
18	East of Angel Island	do	Oct. 20–22	Pole	7	1.62	1.09	348	1.13	5.38	0.50	1.14	196	1.25	7.04	1½
				Meter	21	1.58	1.26		1.42	5.65	0.73	0.77		1.12	6.77	1½
				do	53	1.12	0.96	330	1.45	6.02	0.63	0.64		1.07	6.40	1½
				do	85	1.20	1.09	340	1.28	5.90	0.60	0.47		1.01	6.52	1½
20	Off Presidio	do	Oct. 23–24	Pole	7	−0.45	−1.66	132	0.76	5.05	−1.90	−1.44	274	1.81	7.37	¾
				Meter	12	−0.65	−1.96		0.89	5.35	−1.80	−1.74		1.94	7.07	¾
				do	30	−0.95	−2.06		0.95	5.75	−1.70	−1.54		1.70	6.67	¾
				do	48	−1.00	−2.16		0.92	6.00	−1.50	−1.44		1.42	6.42	¾
27	South of Alcatraz Island.	do	Oct. 22–23	Pole	7	−0.85	−0.82	104	1.51	6.29	−1.07	−1.50	275	1.81	6.13	1
				Meter	16	−0.55	−0.67		1.37	6.09	−0.97	−1.15		1.84	6.33	1
				do	39	−0.55	−0.52		1.51	6.05	−1.00	−0.75		1.45	6.37	1
				do	63	−0.75	−0.82		1.22	6.22	−1.03	−0.80		1.19	6.20	1
29	End of Pier 41, San Francisco.	do	Nov. 2	Pole	7	−2.10	−0.87	71	1.32	7.55	−1.05	−0.84	252	0.42	4.87	½
				Meter	8	−2.20	−1.07		1.55	7.65	−1.05	−1.04		0.50	4.77	½
				do	20	−2.20	−0.67		1.60	7.65	−1.05	−0.94		0.50	4.77	½
				do	32	−2.30	−0.37		1.59	7.75	−1.05	−1.34		0.39	4.67	½
36	Off North Point	do	Nov. 1–2	Pole	7	−1.00	−0.90	131	2.82	5.90	−1.60	−1.67	306	2.82	6.52	½
				Meter	13	−1.00	−1.00		2.57	6.10	−1.40	−2.07		2.67	6.32	½
				do	33	−1.00	−0.70		2.32	6.10	−1.40	−1.67		2.42	6.32	½
				do	52	−1.00	−0.80		1.81	5.90	−1.60	−1.67		1.91	6.52	½
38	End of Pier 17, San Francisco.	do	Nov. 2	Pole	7	−1.20	−1.67	84	0.57	5.40	−2.30	−1.94	289	0.87	7.02	½
				Meter	8	−0.70	−1.07		0.56	5.30	−1.90	−1.44		0.71	7.12	½
				do	20	−0.70	−1.17		0.60	5.30	−1.90	−1.44		0.70	7.12	½
				do	31	−0.80	−1.27		0.61	5.50	−1.80	−1.44		0.76	6.92	½
39	East of North Point	do	Oct. 6–9	Pole	7	−0.50	−0.97	144	1.88	5.97	−1.03	−0.58	318	1.95	6.45	1½
				Meter	15	−0.35	−1.07		1.93	5.95	−0.90	−0.63		1.98	6.47	1½
				do	38	−0.45	−0.77		1.76	6.19	−0.77	−0.63		1.76	6.23	1½
				do	61	−0.55	−0.67		1.56	6.32	−0.73	−0.73		1.53	6.10	1½
41	West of Goat Island	do	Oct. 6–10	Pole	7	−0.30	−0.40	150	1.86	6.30	−0.50	−0.55	319	2.09	6.12	2½
				Meter	20	−0.08	−0.67		1.56	6.25	−0.33	−0.62		2.13	6.17	2½
				do	50	−0.12	−0.62		1.55	6.28	−0.33	−0.56		1.87	6.14	2½
				do	80	−0.38	−0.50		1.43	6.57	−0.32	−0.52		1.53	5.85	2½
43	Do	do	Oct. 1–6	Pole	7	−0.35	−0.63	164	1.51	5.84	−1.01	−0.71	323	2.08	6.58	16
			Oct. 8–10	Meter	29	−0.18	−0.64		1.52	5.78	−0.90	−0.61		1.90	6.64	16
			Oct. 25–31	do	72	−0.22	−0.66	167	1.59	5.98	−0.73	−0.38	347	1.78	6.44	16
			Nov. 1–2	do	115	−0.33	−0.28	168	1.56	6.20	−0.63	−0.36	331	1.61	6.22	16
45	Northwest of Goat Island.	do	do	Pole	7	−2.20	−1.50	130	1.28	6.92	−1.78	−1.77	285	1.17	5.50	½
				Meter	4	−2.20	−1.00		1.44	6.92	−1.78	−1.67		1.24	5.50	½
				do	11	−2.20	−0.80		1.15	6.92	−1.78	−1.87		1.10	5.50	½
				do	18	−2.20	−0.50		0.84	6.92	−1.78	−1.97		0.89	5.50	½
48	Northeast of Goat Island.	do	Oct. 6–9	Pole	7	−1.07	−0.12	162	1.04	6.91	−0.65	−1.18	342	1.14	5.51	1
				Meter	8	−0.80	−0.37	178	1.04	6.70	−0.60	−1.28	347	1.14	5.72	1
				do	20	−0.90	−0.47		1.03	6.80	−0.60	−1.23	338	1.00	5.62	1
				do	31	−1.00	−0.62	168	0.97	6.95	−0.55	−1.18	338	0.80	5.47	1
54	Southeast of Goat Island.	do	Oct. 29–30	Pole	7	−1.75	−0.88	171	1.75	7.05	−1.20	−1.84	322	1.58	5.37	1
				Meter	6	−1.55	−0.78		1.70	7.00	−1.05	−1.80		1.46	5.42	1
				do	15	−1.55	−0.83		1.42	6.85	−1.20	−1.74		1.24	5.57	1
				do	24	−1.55	−1.33		1.16	6.40	−1.65	−1.64		0.96	6.02	1

TABLE 43.—*San Francisco Entrance, current data for various depths*—Continued

Station No.	Location	Party of—	Date	Observed with	Depth	Slack	Maximum flood			Flood duration	Slack	Maximum ebb			Ebb duration	Length of series
							Time	Azimuth (true)	Velocity			Time	Azimuth (true)	Velocity		
			1923		*Feet*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Days*
57	End of Pier 24, San Francisco.	R. L. Schoppe	Oct. 31-Nov. 1	Pole	7	−1.65	−1.16	172	0.84	6.10	−2.05	−2.00	344	0.94	6.32	1
				Meter	13	−1.65	−0.89		0.86	6.35	−1.80	−1.30		0.61	6.07	1
				do	33	−1.75	−0.93		0.95	6.50	−1.75	−1.30		0.77	5.92	1
				do	53	−1.85	−1.19		1.08	6.75	−1.60	−1.30		0.71	5.67	1
59	East of Rincon Point	do	do	Pole	7	−0.55	−0.27	180	2.32	6.40	−0.65	−0.50	341	2.62	6.02	1
				Meter	16	−0.25	−0.12		2.16	6.35	−0.40	−0.30		2.36	6.07	1
				do	39	−0.20	−0.22		1.90	6.40	−0.30	−0.25		2.10	6.02	1
				do	62	−0.15	−0.52		1.46	6.25	−0.40	−0.40		1.59	6.17	1
61	South of Goat Island	do	Oct. 30-31	Pole	7	−1.00	−0.92	166	2.15	6.25	−1.25	−1.00	322	2.05	6.17	1
				Meter	11	−0.80	−0.52		2.10	6.05	−1.25	−1.14		2.24	6.37	1
				do	28	−0.70	−0.72		1.83	6.00	−1.20	−0.90		1.73	6.42	1
				do	46	−0.85	−0.77		1.38	6.40	−0.95	−0.70		1.14	6.02	1
63	End of Pier 46, San Francisco.	do	Oct. 29-30	Pole	7	−0.95	−2.06	181	0.99	4.45	−3.00	−1.04	22	1.39	7.97	1
				Meter	10	−1.00	−2.36		0.71	4.80	−2.70	−1.34		1.03	7.62	1
				do	26	−1.45	−2.31	197	0.77	5.40	−2.55	−1.14	38	1.07	7.02	1
				do	42	−1.45	−2.06	197	0.70	5.45	−2.50	−1.29	38	0.95	6.97	1
69	Southeast of Mission Rock.	do	Oct. 30-31	Pole	7	−0.80	−0.77	180	2.02	5.30	−2.00	−1.89	4	1.97	7.12	1
				Meter	9	−1.00	−0.62		1.80	6.20	−1.30	−1.54		1.84	6.22	1
				do	23	−0.95	−0.92	140	1.53	6.15	−1.30	−1.44	329	1.60	6.27	1
				do	36	−1.00	−1.12	131	1.16	6.10	−1.40	−1.34	335	1.24	6.32	1
70	North of Potrero Point	do	Oct. 29-30	Pole	7	−1.10	−0.60	174	1.58	5.95	−1.65	−1.34	2	1.38	6.47	1
				Meter	9	−1.15	−1.05		1.56	6.20	−1.45	−1.09		1.58	6.22	1
				do	21	−1.05	−1.15		1.45	6.10	−1.45	−1.19		1.43	6.32	1
				do	34	−1.00	−1.25		1.13	5.85	−1.65	−1.29		1.18	6.57	1

TABLE 44.—*Current data for South San Francisco Bay*

[Referred to times of predicted currents at San Francisco Entrance]

Station No.	Location	Party of—	Date	Slack	Maximum flood			Flood duration	Slack	Maximum ebb			Ebb duration	Length of series
					Time	Azimuth (true)	Velocity			Time	Azimuth (true)	Velocity		
				Hours	*Hours*	*Degrees*	*Knots*	*Hours*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Days*
1	North of Port Avisadero	G. Bradford	December, 1874	−0.7	−0.6	160	1.6	6.2	−1.0	−1.1	320	1.4	6.2	2
2	do	do	do	−1.2	−0.5	160	1.9	6.5	−1.2	−1.1	330	1.6	5.9	2
3	East of Port Avisadero	R. L. Schoppe	October, 1923	−0.6	−0.3	160	1.8	6.1	−1.0	−0.4	345	1.7	6.3	1
4	do	do	do	−1.2	−1.6	150	1.1	6.5	−1.2	−1.2	315	1.2	5.9	1
5	East of Port San Mateo	do	do	−0.4	−0.3	120	1.5	6.4	−0.5	−0.4	280	1.0	6.0	1
6	Dumbarton bridge	do	do	−0.8	−0.2	140	1.8	7.0	−0.2	−0.6	320	1.2	5.4	1
7	do	do	do	−0.4	−0.6	140	1.6	6.0	−0.9	−0.5	310	1.7	6.4	1

TABLE 45.—*South San Francisco Bay, current data for various depths*

[Referred to times of predicted currents at San Francisco Entrance]

Station No.	Location	Party of—	Date	Observed with—	Depth	Slack	Maximum flood			Flood duration	Slack	Maximum ebb			Ebb duration	Length of series
							Time	Azimuth (true)	Velocity			Time	Azimuth (true)	Velocity		
			1923		*Feet*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Days*
3	East of Port Avisadero	R. L. Schoppe	Oct. 3–4	Pole	7	−0.60	−0.29	160	1.80	6.10	−1.00	−0.38	344	1.70	6.32	1
				Meter	12	−0.60	−0.39		1.77	6.50	−0.60	−0.58		1.67	5.92	1
				do	29	−0.70	−0.59		1.55	6.60	−0.60	−0.58		1.48	5.82	1
				do	46	−0.75	−0.49		1.38	6.65	−0.60	−0.73		1.30	5.77	1
4	do	do	do	Pole	7	−1.20	−1.59	148	1.14	6.50	−1.20	−1.19	317	1.22	5.92	1
				Meter	5	−1.05	−1.49		1.31	6.55	−1.00	−1.39		1.44	5.87	1
				do	12	−1.15	−1.24		1.20	6.65	−1.00	−1.39		1.25	5.77	1
				do	19	−1.45	−1.29		1.06	6.95	−1.00	−1.39		1.11	5.47	1
5	East of Port San Mateo.	do	Oct. 2–3	Pole	7	−0.45	−0.31	122	1.47	6.45	−0.50	−0.44	282	0.97	5.97	1
				Meter	10	0.15	0.04		1.64	6.65	0.30	0.36		1.41	5.77	1
				do	25	0.10	0.29		1.46	7.02	0.62	0.26		1.26	5.40	1
				do	40	−0.30	0.04		1.18	7.05	0.25	−0.04		1.03	5.37	1
6	Dumbarton bridge	do	Oct. 1–2	Pole	7	−0.75	−0.16	141	1.75	7.00	−0.25	−0.58	320	1.25	5.42	1
				Meter	10	−0.35	−0.31		1.75	6.70	−0.15	−0.63		1.37	5.72	1
				do	26	−0.35	0.04		1.46	6.35	−0.50	−0.73		1.26	6.07	1
				do	42	−0.40	−0.21		1.21	6.25	−0.65	−0.53		1.16	6.17	1
7	do	do	do	Pole	7	−0.35	−0.56	139	1.60	5.95	−0.90	−0.53	310	1.72	6.47	1
				Meter	10	−0.30	−0.61		1.77	5.90	−0.90	−0.23		1.70	6.52	1
				do	25	−0.25	−0.56		1.59	5.75	−1.00	−0.43		1.69	6.67	1
				do	40	−0.25	−0.61		1.22	5.75	−1.00	−0.63		1.45	6.67	1

9. THE CURRENT IN NORTH SAN FRANCISCO BAY

For this section there are at hand observations at 19 current stations the locations of which are shown on Figure 16. Ten of these stations were occupied during the survey made in 1923. The data have been tabulated in Tables 46 and 47. In these tables a minus (−) sign indicates that the time of current at the given station is earlier than the corresponding predicted phenomenon at San

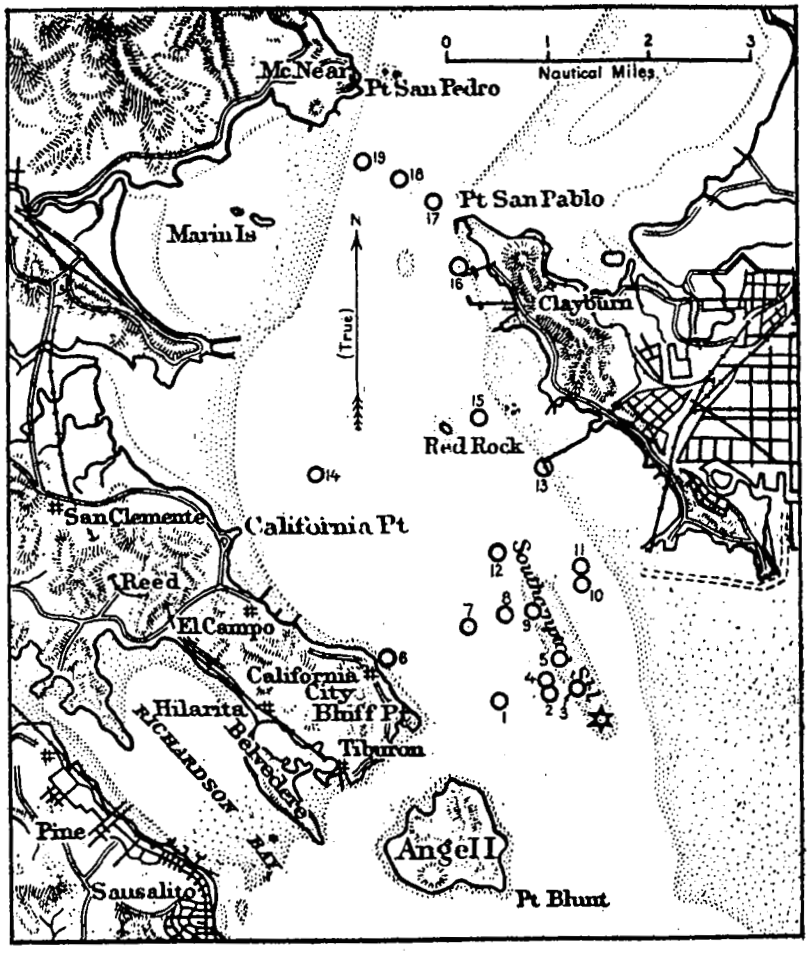


FIG. 16.—Current stations, North San Francisco Bay.

Francisco Entrance. When no sign is given the plus (+) sign is understood and indicates that the time is later.

In this section, as well as the following ones, it may be noted that the time of the current gradually becomes later as one progresses up the bay. Although this fact is not so noticeable in section 3 it is nevertheless making its appearance and indicates that the wave action is gradually changing from that of a predominant stationary type to that of a progressive type.

TABLE 46.—*Current data for North San Francisco Bay*

[Referred to times of predicted currents at San Francisco Entrance]

Station No.	Location	Party of—	Date	Slack	Maximum flood			Flood duration	Slack	Maximum ebb			Ebb duration	Length of series
					Time	Azimuth (true)	Velocity			Time	Azimuth (true)	Velocity		
			1923	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Days*
1	East of Bluff Point	G. Bradford	November, 1871	0.7	0.7	350	0.9	6.4	0.6	1.0	165	1.2	6.0	2
2	West of Southampton Shoal	do	April, 1873	1.1	0.7	355	1.4	5.5	0.1	1.2	185	1.7	6.9	2
3	Southampton Shoal	do	February, 1873	−0.6	0.3	15	1.1	7.2	0.1	−0.3	190	1.1	5.2	2
4	West of Southampton Shoal	do	do	1.4	1.5	340	0.8	5.3	0.2	0.5	170	1.1	7.1	2
5	Southampton Shoal	do	do	−1.2	−0.3	20	1.0	7.3	−0.4	−0.4	190	1.2	5.1	2
6	Off California City	R. L. Schoppe	October, 1923	0.5	−0.3	330	0.2	4.9	−1.1	0.5	145	1.9	7.5	½
7	West of Southampton Shoal	do	do	0.4	0.2	335	1.6	6.7	0.6	0.1	180	1.5	5.7	6
8	do	G. Bradford	May, 1873	1.1	0.6	5	1.5	5.5	0.1	0.0	165	1.9	6.9	2
9	Southampton Shoal	do	February, 1873	−0.1	−0.2	15	1.3	6.4	−0.2	−0.4	200	1.4	6.0	1
10	Off Point Richmond	do	do	1.2	0.9	330	2.0	5.9	0.6	0.4	150	2.0	6.6	1¾
11	do	R. L. Schoppe	October, 1923	0.4	0.4	335	0.9	6.2	0.1	0.2	160	1.5	6.2	1
12	Northwest of Southampton Shoal	G. Bradford	February, 1873	0.2	0.4	355	2.5	6.1	−0.2	0.2	165	2.5	6.3	1¾
13	End of Standard Oil dock, Richmond	R. L. Schoppe	November, 1923	−0.4	0.1	325	0.6	6.6	−0.3	−0.7	180	0.4	5.8	¾
14	Northeast of California Point	do	October, 1923	1.1	0.6	5	0.9	5.8	0.4	1.2	190	1.7	6.6	1
15	East of Red Rock	do	do	0.2	0.2	320	1.3	6.7	0.4	0.4	175	1.4	5.7	1
16	End of dock, Point Orient	do	November, 1923	0.3	−0.3	315	0.7	5.2	−1.0	0.1	190	1.5	7.2	¾
17	Northwest of Point San Pablo	do	October, 1923	0.9	0.5	40	1.5	5.5	−0.1	0.2	220	2.0	6.9	1
18	Southeast of Point San Pablo	do	do	1.2	0.8	30	2.1	5.6	0.3	0.8	205	3.0	6.8	4½
19	South of Point San Pablo	do	do	0.6	0.6	35	1.6	6.2	0.4	−0.2	200	1.9	6.2	1

TABLE 47.—*North San Francisco Bay, current data for various depths*

[Referred to times of predicted currents at San Francisco Entrance]

Station No.	Location	Party of—	Date	Observed with—	Depth	Slack	Maximum flood			Flood duration	Slack	Maximum ebb			Ebb duration	Length of series
							Time	Azimuth (true)	Velocity			Time	Azimuth (true)	Velocity		
			1923		*Feet*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Days*
6	Off California City	R. L. Schoppe	Oct. 11	Pole	7	0.50	−0.30	329	0.20	4.90	−1.10	0.54	147	1.90	7.52	½
				Meter	20	0.60	−0.80		0.07	4.60	−1.30	0.44		1.92	7.82	½
				do	51	0.50	−1.00		0.32	4.90	−1.10	0.54		1.67	7.52	½
				do	81	0.10	−0.90		0.59	5.40	−1.00	0.54		1.29	7.02	½
7	West of Southampton Shoal.	do	Oct. 9–13	Pole	7	0.37	0.20	334	1.56	6.72	0.58	0.14	179	1.46	5.70	6
			Nov. 3–4	Meter	10	0.37	0.13	334	1.55	6.82	0.68	0.04		1.38	5.60	6
				do	24	0.20	0.00	347	1.47	7.02	0.72	−0.11	170	1.11	5.40	6
				do	38	0.00	0.00	352	1.32	7.14	0.63	−0.06	163	0.90	5.28	6
11	Off Point Richmond	do	Oct. 10–11	Pole	7	0.40	0.39	336	0.87	6.20	0.10	0.19	162	1.47	6.22	1
				Meter	6	0.35	0.44		0.89	6.55	0.40	0.09		1.39	5.87	1
				do	15	0.25	0.44		0.88	6.65	0.40	−0.21		1.18	5.77	1
				do	24	0.20	0.54		0.81	6.70	0.40	−0.51		0.86	5.72	1
13	End of Standard Oil Dock, Richmond.	do	Nov. 3–4	Pole	7	−0.40	0.08	325	0.58	6.60	−0.30	−0.66	180	0.43	5.82	¾
				Meter	7	−0.20	−0.32		1.10	6.80	0.10	−1.26		0.35	5.62	¾
				do	18	−0.20	−0.32		1.15	7.00	0.30	−1.16		0.50	5.42	¾
				do	29	−0.40	−0.32		1.00	7.20	0.30	−0.91		0.57	5.22	¾
14	Northeast of California Point.	do	Oct. 11–12	Pole	7	1.10	0.55	3	0.94	5.80	0.40	1.20	190	1.72	6.62	1
				Meter	8	1.10	0.40		1.03	5.85	0.45	0.75		1.58	6.57	1
				do	18	0.50	0.50	346	1.11	6.30	0.30	0.75	188	1.28	6.12	1
				do	29	0.15	0.20	346	0.92	6.55	0.20	0.80	186	1.00	5.87	1
15	East of Red Rock	do	do	Pole	7	0.15	0.24	318	1.28	6.75	0.40	0.35	175	1.38	5.67	1
				Meter	11	0.15	0.09		1.29	6.80	0.45	0.05		1.45	5.62	1
				do	27	0.05	−0.06		1.29	6.90	0.45	−0.05		1.12	5.52	1
				do	43	−0.35	−0.36		1.25	7.35	0.50	0.00		0.78	5.07	1
16	End of Oil Dock, Point Orient.	do	Nov. 3	Pole	7	0.30	−0.32	315	0.72	5.20	−1.00	0.09	190	1.47	7.22	¾
				Meter	6	−0.20	−1.02		0.62	5.30	−1.40	−0.41		1.62	7.12	¾
				do	15	−0.21	−1.12		0.50	5.30	−1.40	−0.41		1.55	7.12	¾
				do	24	−0.20	−1.22		0.45	5.30	−1.40	−0.41		1.15	7.12	¾
17	Northwest of Point San Pablo.	do	Oct. 12–13	Pole	7	0.90	0.54	41	1.46	5.50	−0.10	0.20	220	1.99	6.92	1
				Meter	16	0.50	0.59		1.54	5.60	−0.40	0.10		1.98	6.82	1
				do	39	0.60	0.34		1.19	5.45	−0.45	0.40		1.89	6.97	1
				do	62	0.40	0.00		1.14	5.85	−0.25	0.35		1.59	6.57	1
18	Southeast of Point San Pedro.	do	do	Pole	7	1.17	0.84	30	2.06	5.62	0.28	0.78	203	3.00	6.80	4½
			Oct. 16–19	Meter	17	0.98	0.75	36	2.11	6.20	0.68	0.66	228	2.68	6.22	4½
				do	42	0.68	0.52	37	2.06	6.71	0.90	0.83	234	2.37	5.71	4½
				do	67	0.28	0.72	15	1.74	7.08	0.87	0.78	215	1.86	5.34	4½
19	South of Point San Pedro.	do	Oct. 12–13	Pole	7	0.60	0.64	37	1.62	6.25	0.35	−0.20	202	1.89	6.17	1
				Meter	11	0.55	0.24	41	1.67	6.50	0.55	0.15	196	1.61	5.92	1
				do	28	0.45	1.00	29	1.62	6.80	0.75	0.15	187	1.32	5.62	1
				do	45	0.05	1.00	33	1.66	7.15	0.70	0.00	197	1.02	5.27	1

In the tables giving current data for various depths it will be seen that the flood current generally starts earlier at the lower depths, the time gradually becoming later as the surface is approached. It may also be noted that the ebb current begins at approximately the same time for all depths or, if anything, slightly later at the lower depths. These differences are caused by the fresh water, since it is of lesser density and hence remains near the surface; and, as it is constantly coming down from the upper sections of the bay, it has a tendency to delay the flood current and cause the ebb current to occur slightly earlier near the surface. These time differences are not so noticeable in South San Francisco Bay, indicating that there is relatively very little fresh water coming from this section. This is to be expected, since most of the fresh water flowing into the bay comes down from the northern reaches.

This time difference is clearly brought out at station 18, section 3, located in the center of the channel between Point San Pedro and Point San Pablo. All of the fresh water flowing down from the north must pass between these two points. Upon referring to Table 47, station 18, it may be seen that the flood current begins nine-tenths of an hour later and that the ebb current begins six-tenths of an hour earlier at the 7-foot depth than it does at the 67-foot depth. The fact that there is a large volume of fresh water passing this point is also clearly brought out by comparing the flood and ebb velocities at this station. At the 7-foot depth it is noted that the maximum ebb velocity is nearly 100 per cent greater than that of the flood, and it is also noticeable that this difference gradually decreases with the depth until at the 67-foot depth the ebb velocity is only about 7 per cent greater.

In general, the effect of this nontidal water is to decrease the flood velocity by the same amount that it increases the ebb velocity. A nontidal or permanent current of approximately one-half a knot may therefore be said to exist near the surface at this station.

The duration of the ebb near the surface is also seen to be greater than the duration of the flood at station 18.

In practically all instances where the current station is located inshore, at the end of a dock or in shoal water, it will be noticed that all phases of the current occur earlier than they do at closely related stations located in channels or in deeper water. This is obviously due to friction. For instance, consider the ebb current at stations 1 and 5. Station 1 is located in about the center of the channel between Bluff Point and Southampton Shoal in 8 fathoms of water, while station 5 is located on Southampton Shoal in about 2 fathoms of water. As the ebb begins to slacken the retarding effect is stronger at station 5 due to the greater friction caused at that point by the shoal water, thus making the time of slack water occur earlier and causing the current to flood at station 5 while it is still ebbing at station 1.

For the stations in this section located in deep water the directions of the maximum currents seem to set fair with the channel in that particular locality. For the stations, however, located on Southampton Shoal—namely, Nos. 3, 5, and 9—the currents run not parallel with the shoal or directly across it but rather diagonally over it, caused probably by the two deep-water channels on either side of the shoal.

10. THE CURRENT IN SAN PABLO BAY

In this section nine current stations have been occupied from time to time, five of them during 1923. The location of these stations is shown in Figure 17. The data resulting from the various observations have been tabulated in Tables 48 and 49. In these tables a minus (−) sign indicates that the time of current at the given station is earlier than the corresponding predicted phenomenon at San Francisco Entrance. When no sign is given the plus (+) sign is understood and indicates that the time is later.

It is noted in this section, as well as in section 3, that the time of the current is gradually becoming later, showing more strongly the progressive wave effect. The stations located in the main ship channel indicate generally the effect of the fresh-water run-off in both the time and velocity of the current. Stations 7, 8, and 9, however, show practically none of this effect in the time of occurrence of the current and very little of it in the difference of the ebb and flood velocities, indicating that only a small amount of fresh water was discharged from Petaluma or Sonoma Creeks at the time of the year in which these observations were made. Observations made at other seasons of the year, on the other hand, may show a considerable discharge of fresh water from these streams.

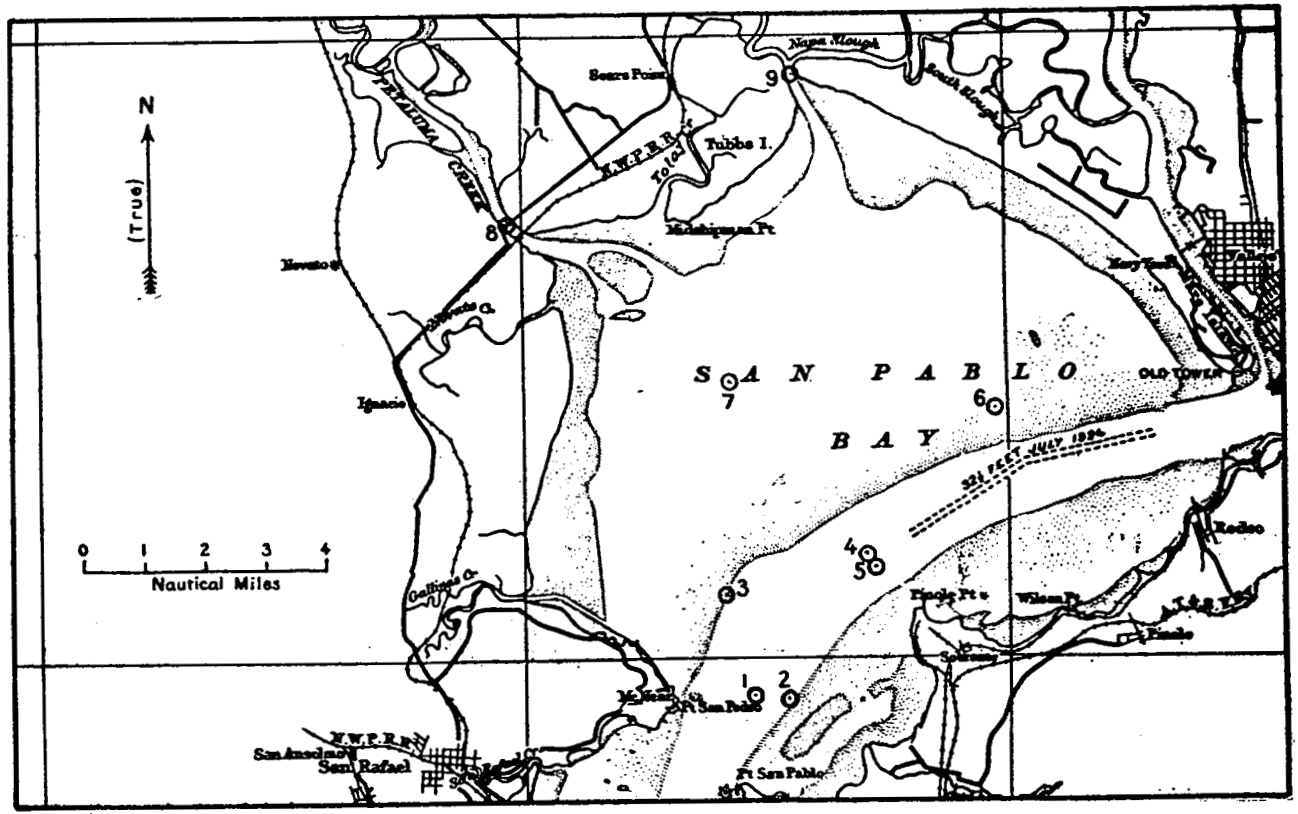


FIG. 17.—Current stations, San Pablo Bay

TABLE 48.—*Current data for San Pablo Bay*

[Referred to times of predicted currents at San Francisco Entrance]

Station No.	Location	Party of—	Date	Slack	Maximum flood			Flood duration	Slack	Maximum ebb			Ebb duration	Length of series
					Time	Azimuth (true)	Velocity			Time	Azimuth (true)	Velocity		
			1923	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Days*
1	East of Point San Pedro	R. M. Cuyler	Mar., 1856	0.0	0.3	40	1.5	6.5	0.0	0.2	225	2.7	5.9	1
2	Northeast of Point San Pablo	R. L. Schoppe	Oct., 1923	0.4	1.1	50	1.6	6.8	0.8	0.0	230	1.9	5.6	¾
3	North of Point San Pedro	R. M. Cuyler	Feb., 1856	0.0	1.4	20	1.4	6.9	0.4	0.2	205	2.4	5.5	1
4	Northwest of Pinole Point	R. L. Schoppe	Oct., 1923	1.4	1.4	65	1.6	6.2	1.1	1.5	245	2.1	6.2	1
5	Do	R. M. Cuyler	Sept., 1856	0.7	0.4	45	1.7	6.0	0.2	0.8	260	1.9	6.4	1
6	Southwest of Mare Island	do	Mar., 1856	0.7	0.4	75	1.1	5.6	−0.2	0.1	255	1.6	6.8	¾
7	Off Petaluma Creek	R. L. Schoppe	Oct., 1923	−0.6	−0.4	350	0.8	7.3	0.2	0.0	145	0.8	5.1	1
8	Petaluma Creek	do	do	1.2	1.3	335	1.0	5.8	0.6	−0.1	150	1.2	6.6	1
9	Sonoma Creek	do	do	0.8	1.7	335	1.2	6.4	0.7	−0.5	180	1.5	6.0	¾

TABLE 49.—*San Pablo Bay, current data for various depths*

[Referred to times of predicted currents at San Francisco Entrance]

Station No.	Location	Party of—	Date	Observed with—	Depth	Slack	Maximum flood			Flood duration	Slack	Maximum ebb			Ebb duration	Length of series
							Time	Azimuth (true)	Velocity			Time	Azimuth (true)	Velocity		
			1923		*Feet*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Days*
2	Northeast of Point San Pablo.	R. L. Schoppe	Oct. 18–19	Pole	7	0.45	1.10	48	1.56	6.85	0.80	−0.03	230	1.88	5.57	¾
				Meter	5	0.20	1.15		1.48	7.20	0.90	0.17		1.78	5.22	¾
				Do	12	0.30	0.70		1.33	6.70	0.50	0.07		1.63	5.72	¾
				Do	19	0.25	1.55		1.57	6.65	0.40	0.17		1.29	5.77	¾
4	Northwest of Pinole Point.	do	Oct. 17–18	Pole	7	1.40	0.37	64	1.64	6.20	1.10	1.48	246	2.12	6.22	1
				Meter	8	1.30	1.12		1.54	6.40	1.20	1.23		2.04	6.02	1
				Do	19	1.20	1.07		1.31	6.45	1.15	0.78		1.72	5.97	1
				Do	31	1.05	1.02		1.07	6.60	1.15	0.73		1.37	5.82	1
7	Entrance to Petaluma Creek Channel.	do	Oct. 16–17	Pole [1]												
				Meter	2	−0.55	0.33	350	0.74	7.30	0.25	0.18	145	0.55	5.12	1
				Do	5	−0.55	−0.37		0.79	7.30	0.25	−0.02		0.84	5.12	1
				Do	8	−0.55	−0.17		0.68	7.30	0.25	−0.62		0.72	5.12	1
8	Petaluma Creek	do	do	Pole	7	1.25	1.28	336	1.03	5.80	0.55	−0.12	150	1.15	6.62	1
				Meter	5	1.30	1.28		1.08	6.05	0.85	−0.52		1.41	6.37	1
				do	13	1.10	1.18	336	1.00	6.25	0.85	−0.62	148	1.25	6.17	1
				do	21	1.25	1.03	334	0.74	6.10	0.85	−1.02	133	0.99	6.32	1
9	Sonoma Creek	do	Oct. 17–18	Pole [1]												
				Meter	3	0.80	0.38	334	1.35	6.40	0.70	−0.22	169	1.58	6.02	¾
				do	7	0.80	0.68	333	1.25	6.40	0.70	−0.52	178	1.53	6.02	¾
				do	11	0.80	0.53	336	1.07	6.40	0.70	−0.62	188	1.27	6.02	¾

[1] No observations.

11. THE CURRENT IN CARQUINEZ AND MARE ISLAND STRAITS

This section contains nine current stations, of which all but one were occupied during the survey made in 1923. The resulting data have been tabulated in Tables 50 and 51. In these tables, as in the preceeding, a minus (−) sign indicates that the time of current at the given station is earlier than the corresponding predicted phenomenon at San Francisco Entrance. When no sign is given the plus (+) sign is understood and indicates that the time is later. It is to be noted, on referring to Table 50, that all phases of the current for stations located in Mare Island Strait occur considerably earlier than they do for the stations located in Carquinez Strait, which are either above or below the entrance to Mare Island Strait. As the current is flooding for approximately two hours in Mare Island Strait before it starts to flood at any station in Carquinez Strait, it is seen that the two last hours of the ebb current in Carquinez Strait must be divided, part of it flowing up Mare Island Strait, where it appears as flood current, and the remainder flowing on out to San Pablo Bay. A great deal of this ebb current is fresh water, as may be seen by referring to the data in Table 51, stations 1, 3, 4, and 5. For the first two hours of the flood current in Mare Island Strait we then have a current composed mostly of fresh water and it may be expected therefore, that there would not be a considerable difference in the time of the beginning of flood current at various depths for stations located in this strait. That this is the case may be seen by referring to Table 51, stations 6–9.

In a similar manner, consider the ebb current. The current is ebbing in Mare Island Strait for approximately one and one-half hours before it begins to ebb in Carquinez Strait. For this length of time, therefore, we have the ebb current from Mare Island Strait flowing into and up Carquinez Strait as flood current.

Figure 18 shows the location of the current stations in this section.

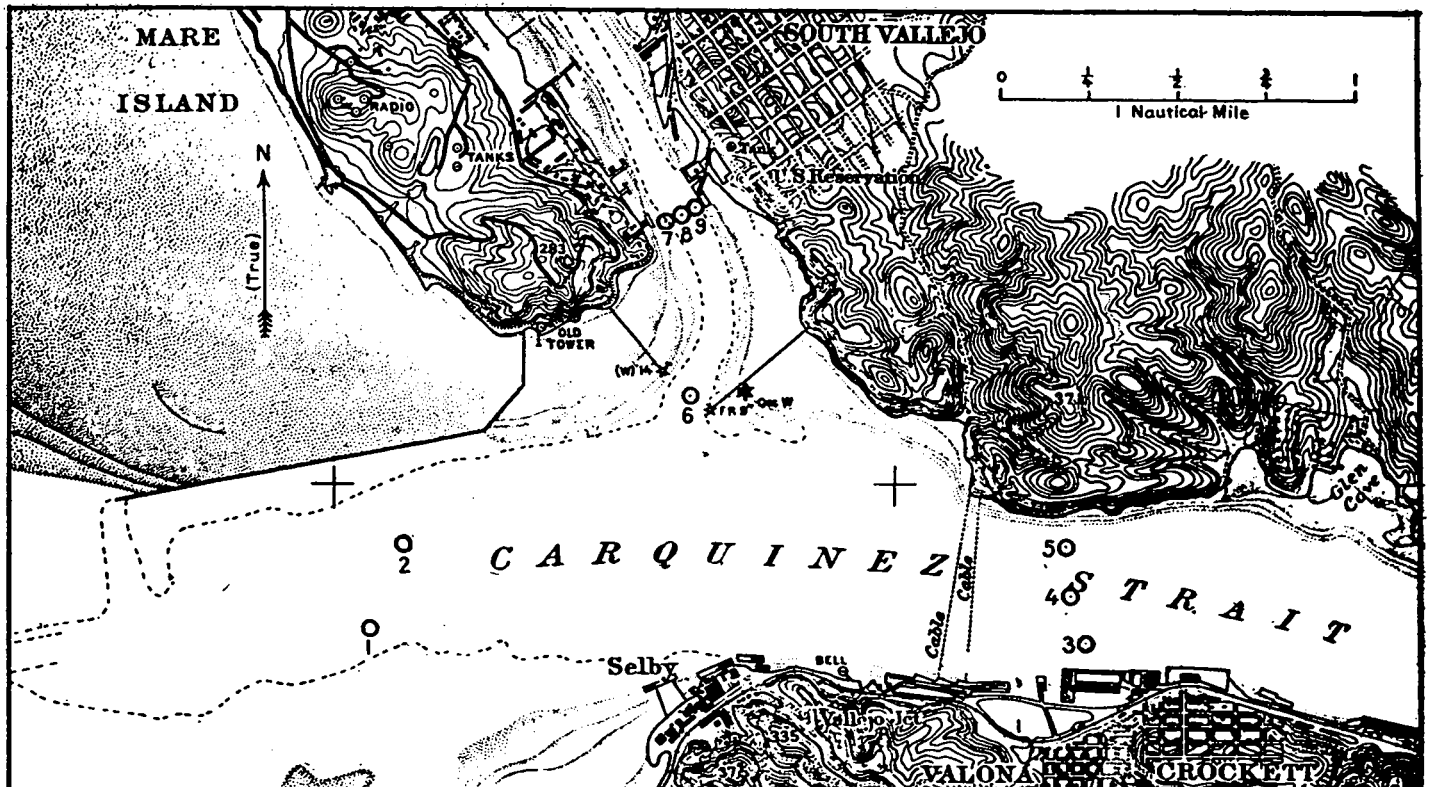


FIG. 18.—Current stations, Carquinez and Mare Island Straits

TABLE 50.—*Current data for Carquinez and Mare Island Straits*

[Referred to times of predicted currents at San Francisco Entrance]

Station No.	Location	Party of—	Date	Slack	Maximum flood			Flood duration	Slack	Maximum ebb			Ebb duration	Length of series
					Time	Azimuth (true)	Velocity			Time	Azimuth (true)	Velocity		
			1923	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Days*
1	South of Mare Island	R. L. Schoppe	Oct., 1923	2.1	1.8	90	2.1	6.0	1.6	1.9	255	2.5	6.4	4
2	do	R. M. Cuyler	Sept., 1856	1.9	0.8	75	1.7	6.2	1.6	2.6	255	2.2	6.2	1
3	Carquinez Strait	R. L. Schoppe	Nov., 1923	2.0	2.1	105	2.0	6.0	1.6	1.8	260	2.9	6.4	1
4	do	do	do	2.5	1.8	110	2.2	5.8	1.8	1.7	270	3.1	6.6	1
5	do	do	do	2.4	2.1	105	1.9	5.8	1.6	1.5	270	2.9	6.6	1
6	Entrance to Mare Island Strait	do	do	0.2	0.8	40	1.3	6.8	0.5	0.4	210	1.8	5.6	1
7	Mare Island Strait	do	do	0.3	0.4	325	1.0	5.8	−0.4	−0.2	180	2.2	6.6	½
8	do	do	do	0.6	0.7	325	1.5	6.2	0.2	0.0	165	2.0	6.2	1
9	do	do	do	0.2	0.9	310	1.8	6.6	0.3	0.2	170	2.0	5.8	½

TABLE 51.—*Carquinez and Mare Island Straits, current data for various depths*

[Referred to times of predicted currents at San Francisco Entrance]

Station No.	Location	Party of—	Date	Observed with—	Depth	Slack	Maximum flood			Flood duration	Slack	Maximum ebb			Ebb duration	Length of series
							Time	Azimuth (true)	Velocity			Time	Azimuth (true)	Velocity		
			1923		*Feet*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Hours*	*Hours*	*Degrees*	*Knots*	*Hours*	*Days*
1	South of Mare Island	R. L. Schoppe	Oct. 18-19	Pole	7	2.13	1.78	89	2.07	6.01	1.65	1.91	254	2.53	6.41	4
			Nov. 5-8	Meter	10	2.10	1.78	83	2.01	6.19	1.78	2.13	255	2.29	6.23	4
			do		24	2.72	1.68	96	2.03	6.67	1.88	2.05	254	1.65	5.75	4
			do		38	1.18	2.02	68	1.62	7.13	1.82	1.68	228	1.31	5.29	4
3	Carquinez Strait	do	Nov. 5-6	Pole	7	2.05	2.06	105	2.01	6.00	1.55	1.77	262	2.91	6.42	1
				Meter	10	2.10	2.21		1.93	5.95	1.55	2.17		2.48	6.47	1
				do	25	1.90	1.96		1.98	6.35	1.75	2.02		1.98	6.07	1
				do	40	1.45	1.71		1.70	6.80	1.75	2.12		1.37	5.62	1
4	do	do	do	Pole	7	2.50	1.76	108	2.19	5.75	1.75	1.72	270	3.09	6.67	1
				Meter	18	2.20	1.96		2.26	6.20	1.90	1.97		2.61	6.22	1
				do	44	1.70	1.86		2.37	6.80	2.00	1.82		1.97	5.62	1
				do	70	1.50	1.81		2.50	7.00	2.00	1.67		1.55	5.42	1
5	do	do	do	Pole	7	2.35	2.13	105	1.87	5.75	1.60	1.47	270	2.87	6.67	1
				Meter	18	2.15	1.66		2.10	6.05	1.70	1.52		2.43	6.37	1
				do	45	2.00	1.66		2.03	6.40	1.90	1.62		2.36	6.02	1
				do	72	1.35	0.91		1.90	7.05	1.90	1.62		2.10	5.37	1
6	Entrance to Mare Island Strait.	do	Nov. 7-8	Pole	7	0.15	0.80	40	1.32	6.85	0.50	0.36	210	1.77	5.57	1
				Meter	8	0.25	0.90		1.38	6.80	0.55	0.31		1.63	5.62	1
				do	21	0.10	1.03		1.30	7.30	0.90	0.46		1.35	5.12	1
				do	34	−0.05	0.77		1.29	7.55	1.00	0.16		1.17	4.87	1
7	Mare Island Strait	do	Nov. 6-7	Pole	7	0.30	0.44	324	0.95	5.80	−0.40	−0.25	178	2.15	6.62	½
				Meter	6	0.60	−0.16		0.96	6.20	0.30	−0.35		1.96	6.22	½
				do	16	0.60	0.04		0.98	6.40	0.50	−0.25		1.73	6.02	½
				do	25	0.70	1.44		1.00	6.50	0.70	−0.35		1.45	5.92	½
8	do	do	do	Pole	7	0.55	0.66	324	1.49	6.20	0.25	0.03	166	2.01	6.22	1
				Meter	9	0.70	0.56		1.44	6.15	0.35	−0.07		2.00	6.27	1
				do	23	0.60	0.56		1.52	6.70	0.80	−0.02		1.62	5.72	1
				do	37	0.30	1.06		1.31	7.10	0.90	−0.17		1.29	5.32	1
9	do	do	Nov. 7	Pole	7	0.20	0.88	312	1.79	6.60	0.30	0.25	172	1.97	5.82	½
				Meter	8	0.50	0.98		1.62	6.50	0.50	0.20		1.87	5.92	½
				do	20	0.70	1.08		1.54	6.60	0.80	−0.05		1.59	5.82	½
				do	32	0.40	1.28		1.65	7.20	1.10	0.25		0.81	5.22	½

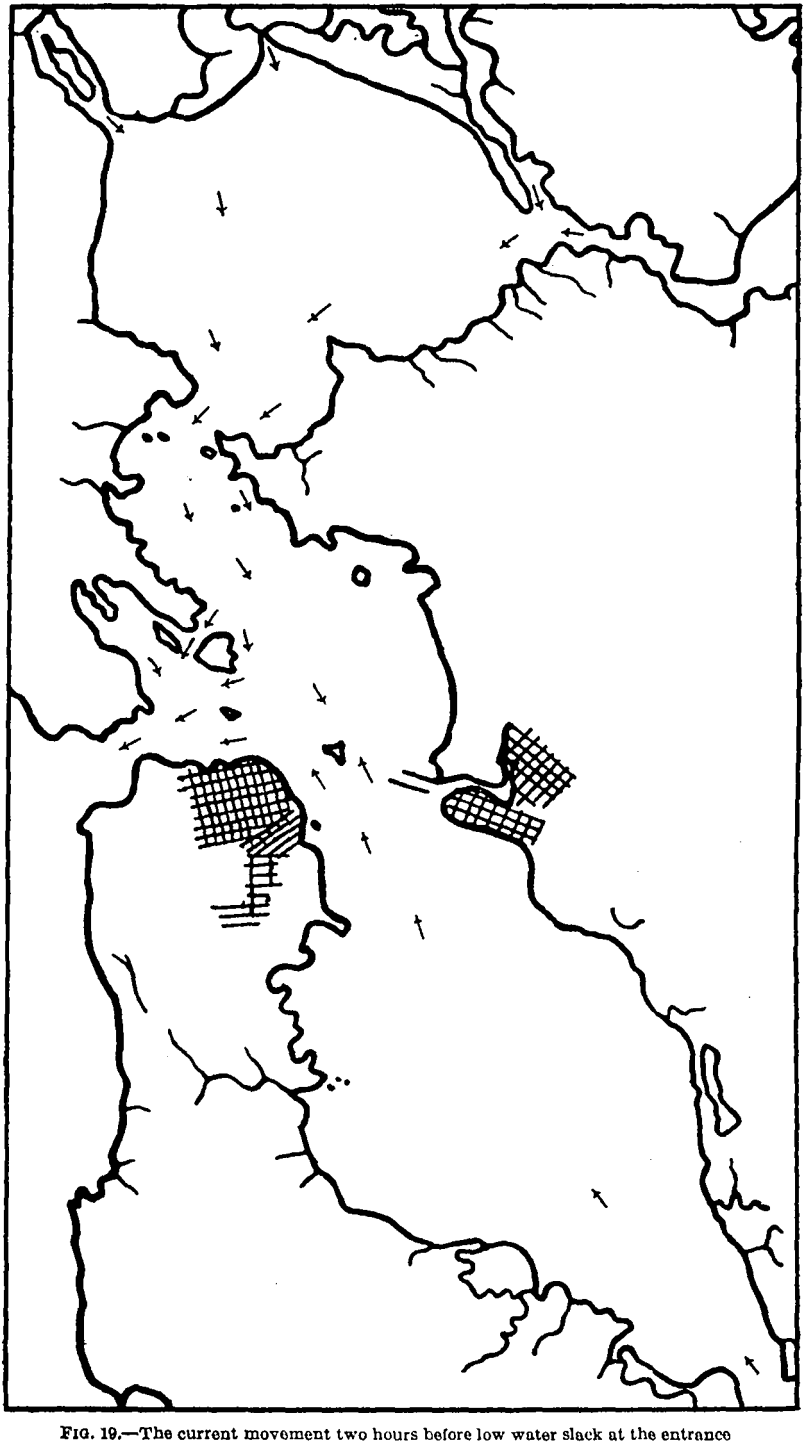


FIG. 19.—The current movement two hours before low water slack at the entrance

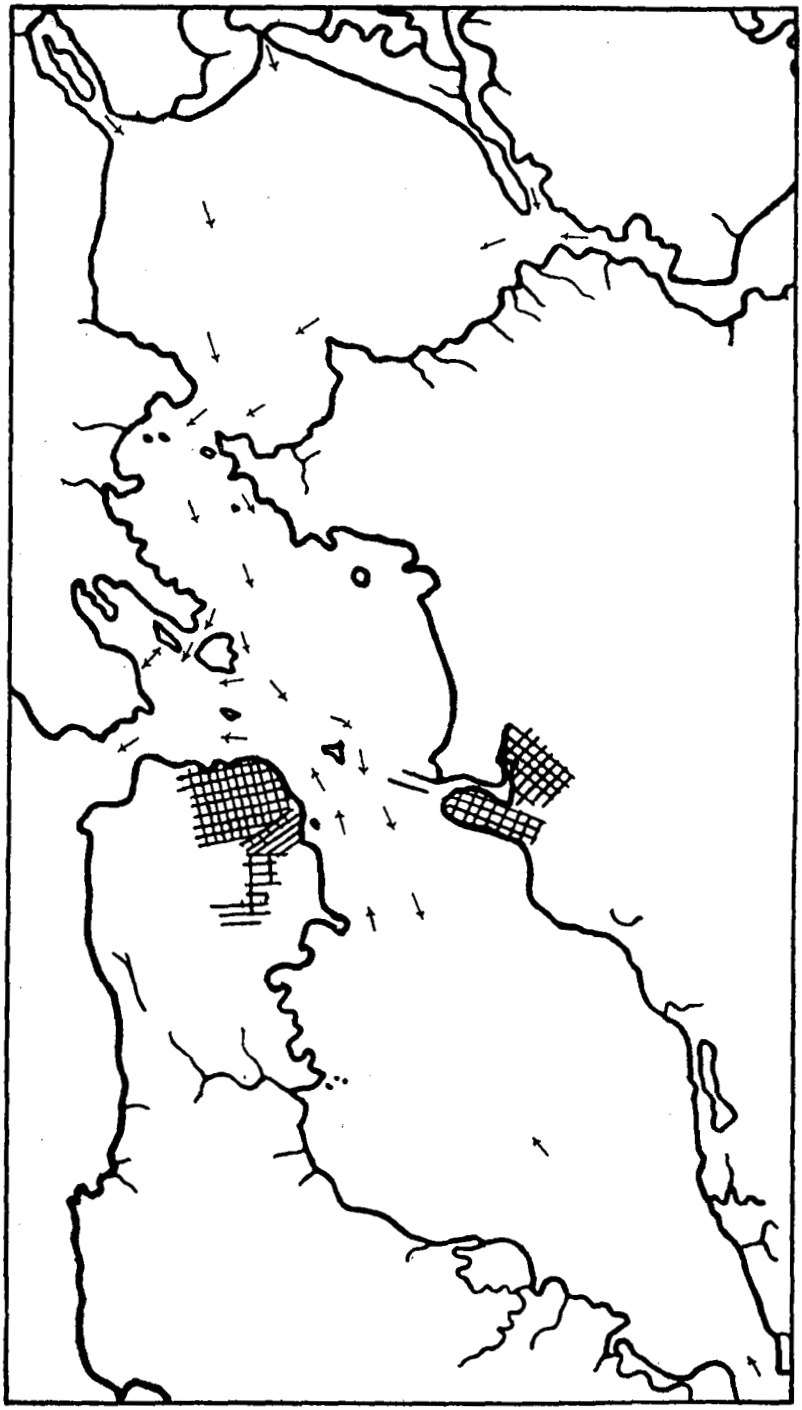


FIG. 20.—The current movement one hour before low water slack at the entrance

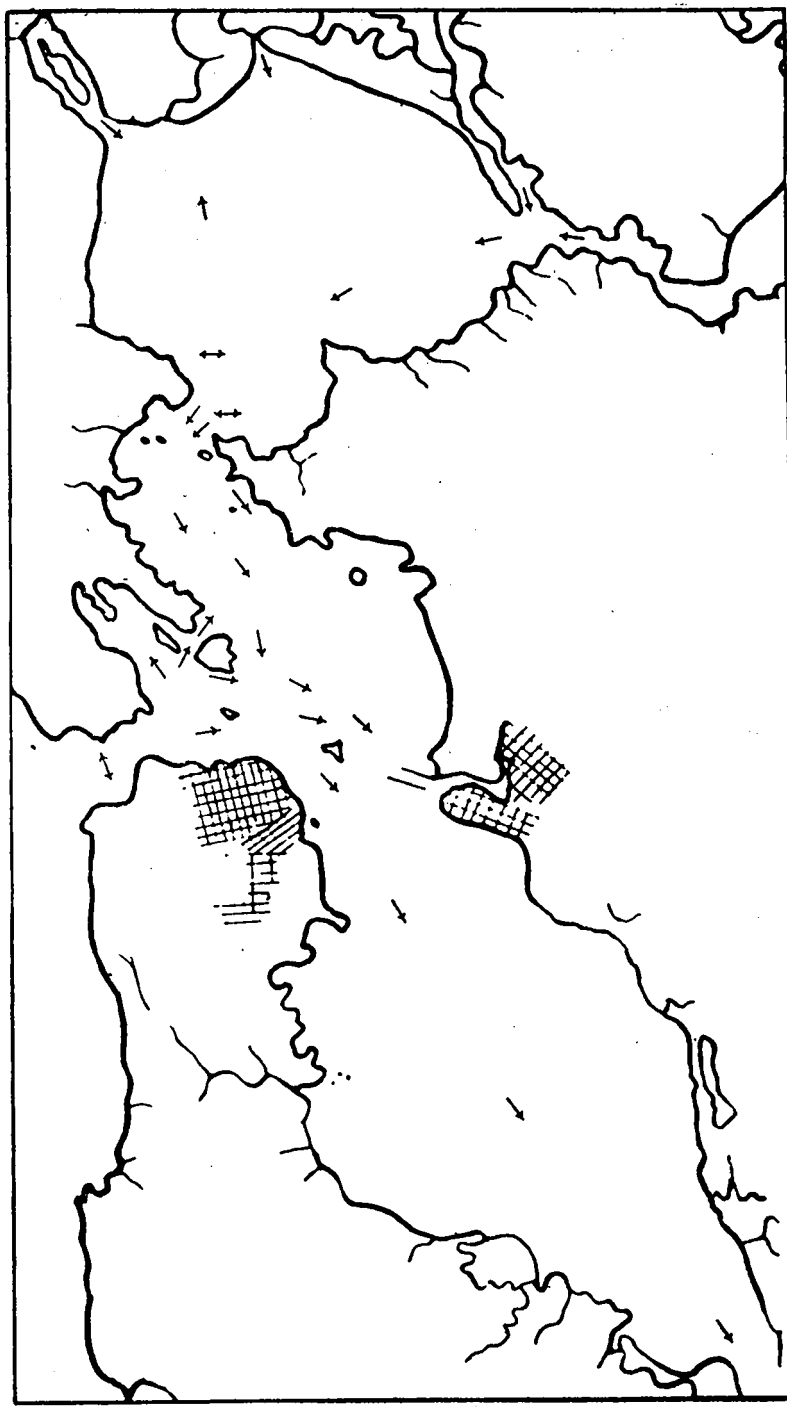


FIG. 21.—The current movement at the time of low water slack at the entrance

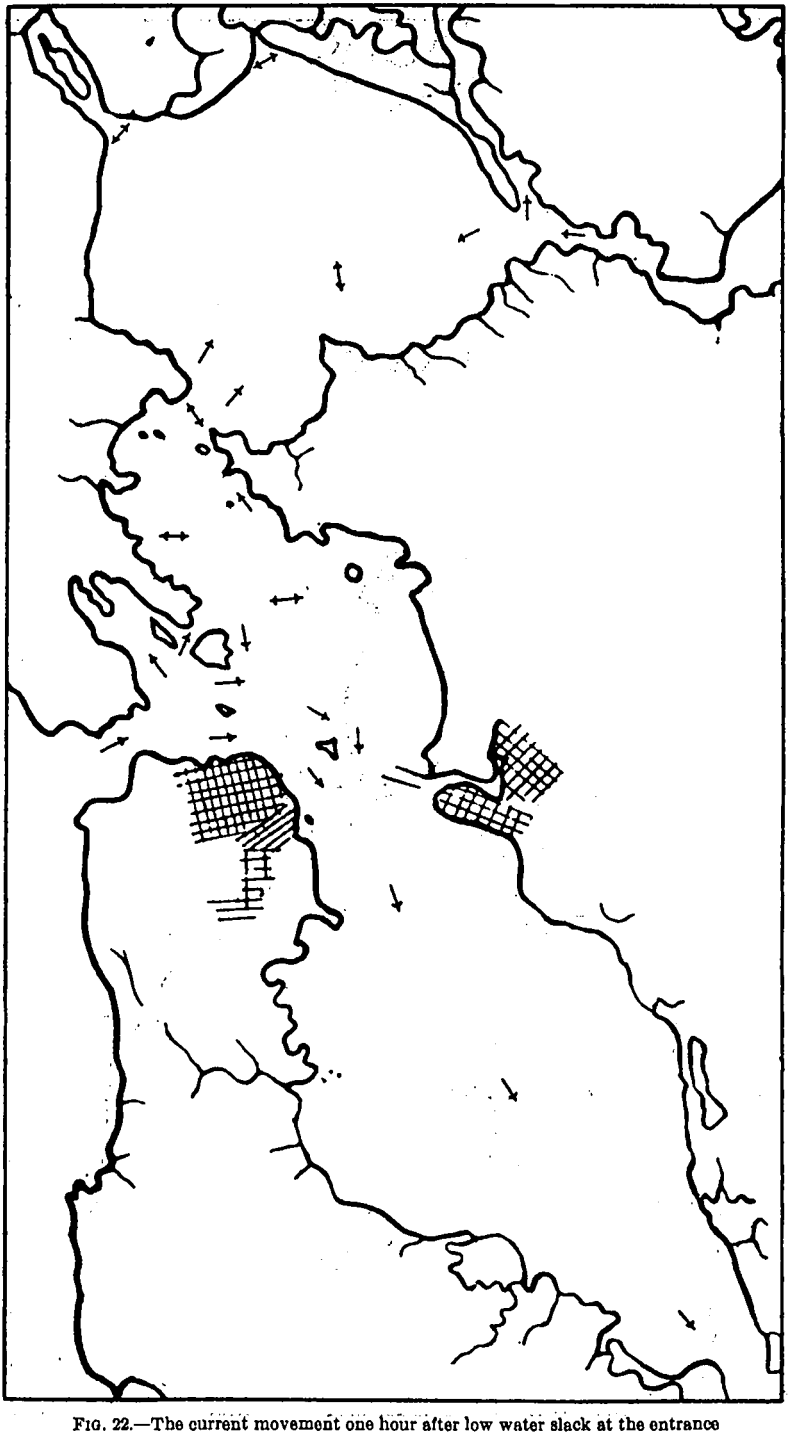


FIG. 22.—The current movement one hour after low water slack at the entrance

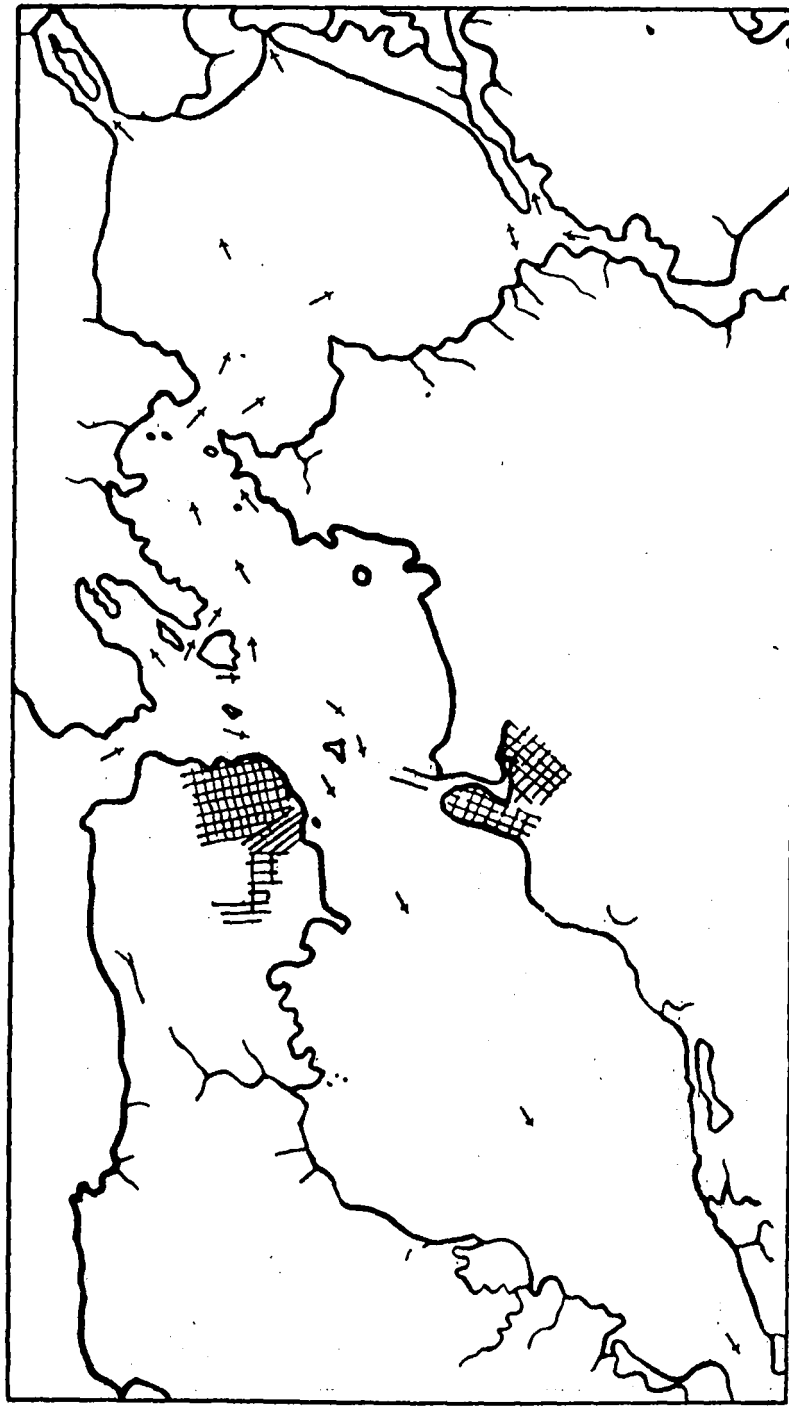


FIG. 23.—The current movement two hours after low water slack at the entrance

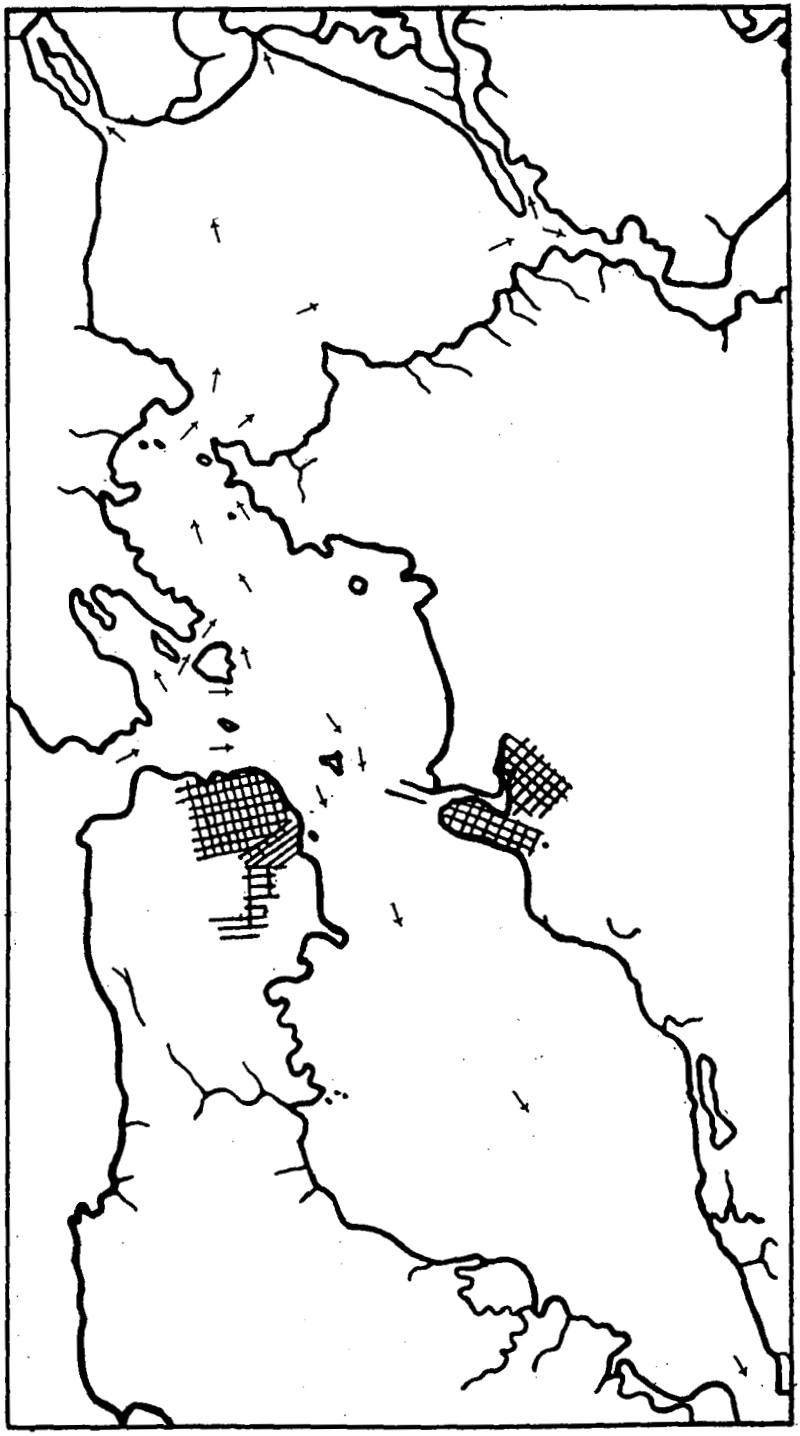


FIG. 24.—The current movement three hours after low water slack at the entrance

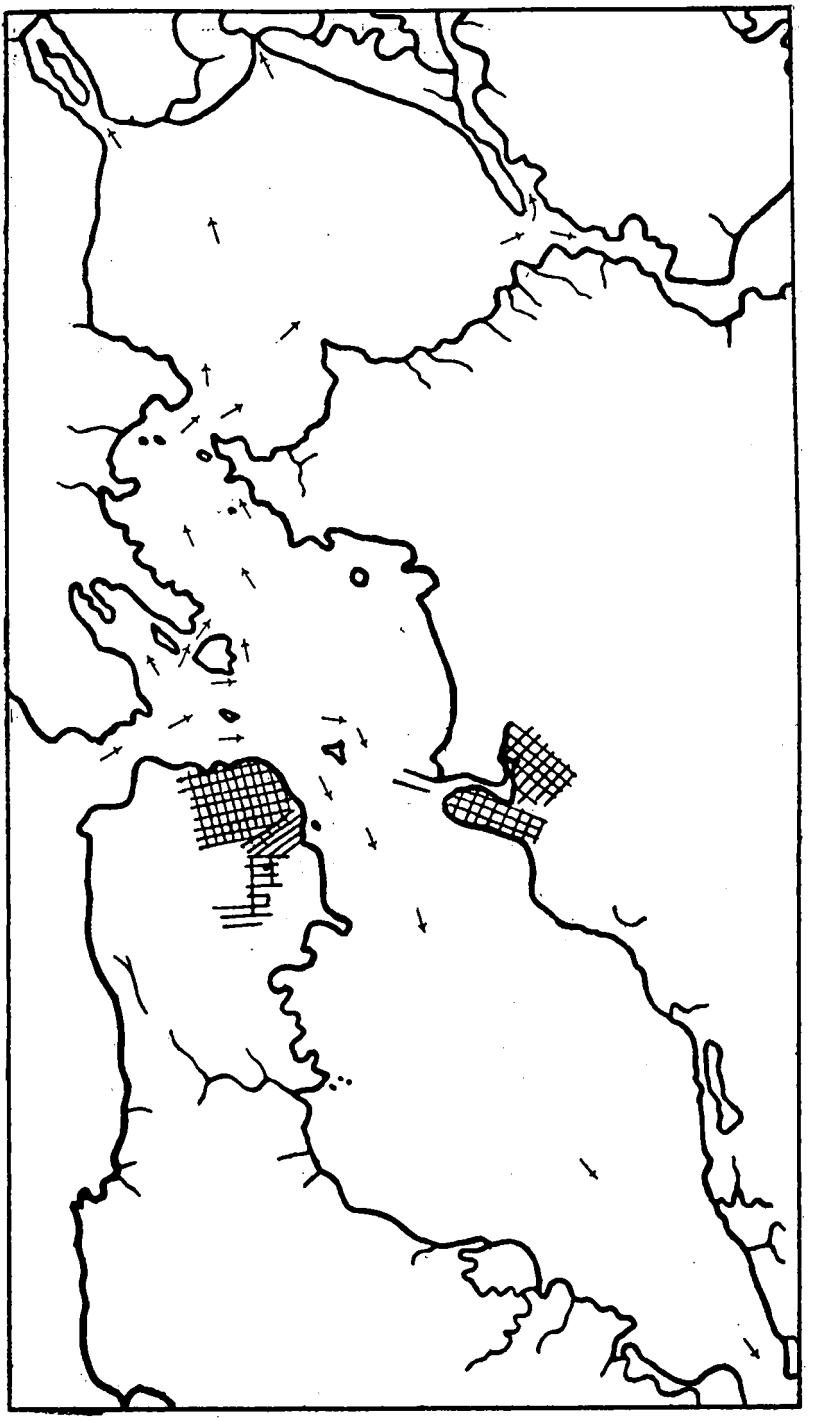


FIG. 25.—The current movement two hours before high water slack at the entrance

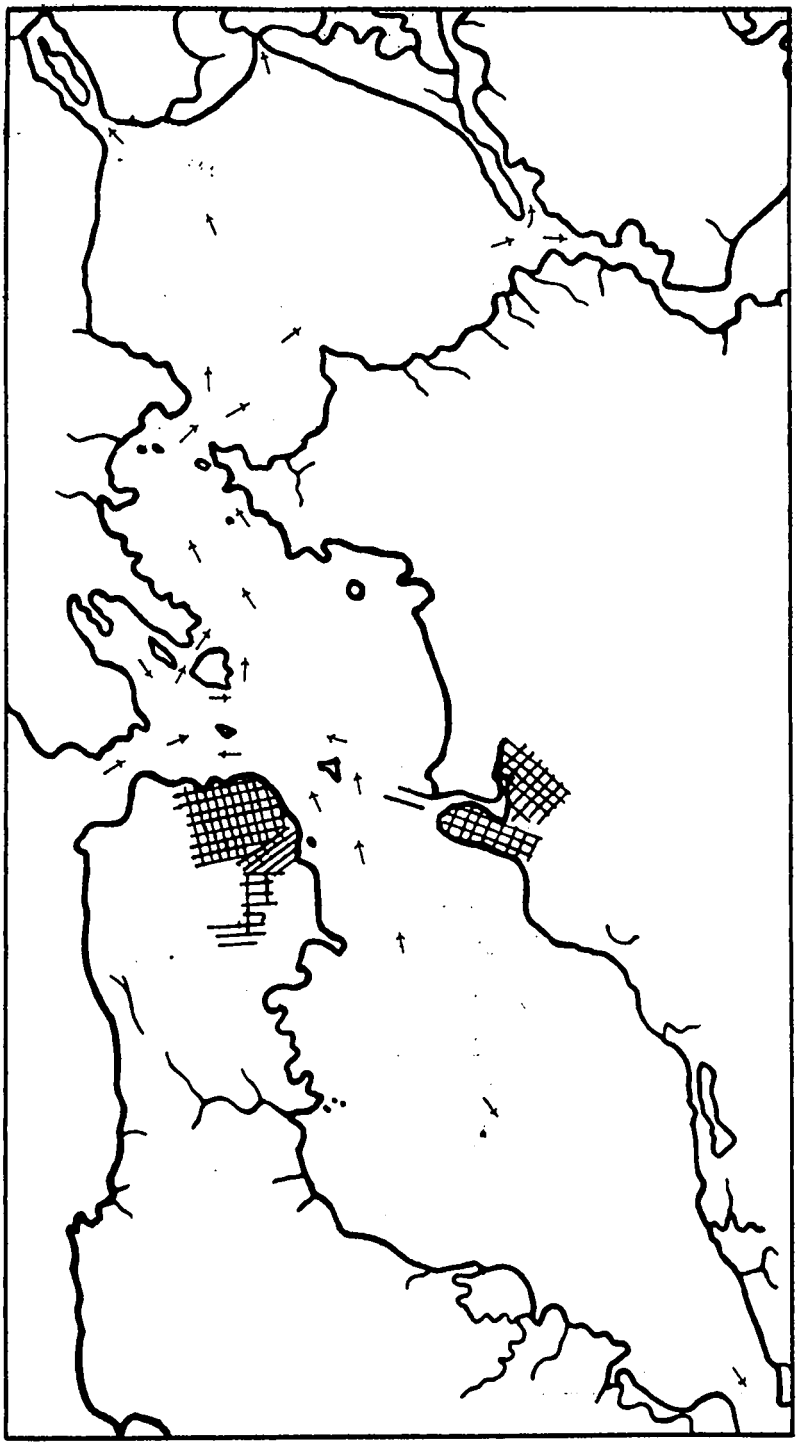


FIG. 26.—The current movement one hour before high water slack at the entrance

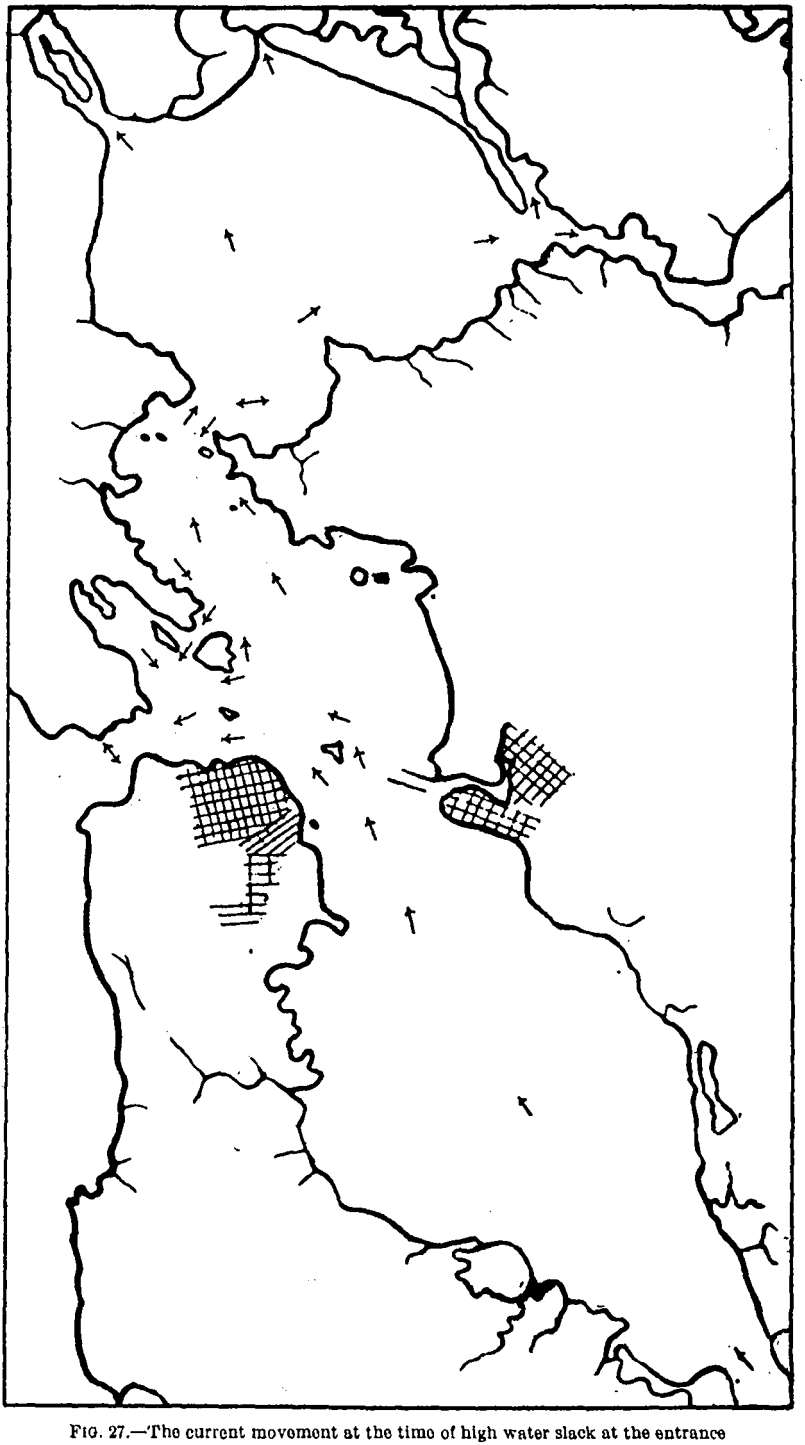


FIG. 27.—The current movement at the time of high water slack at the entrance

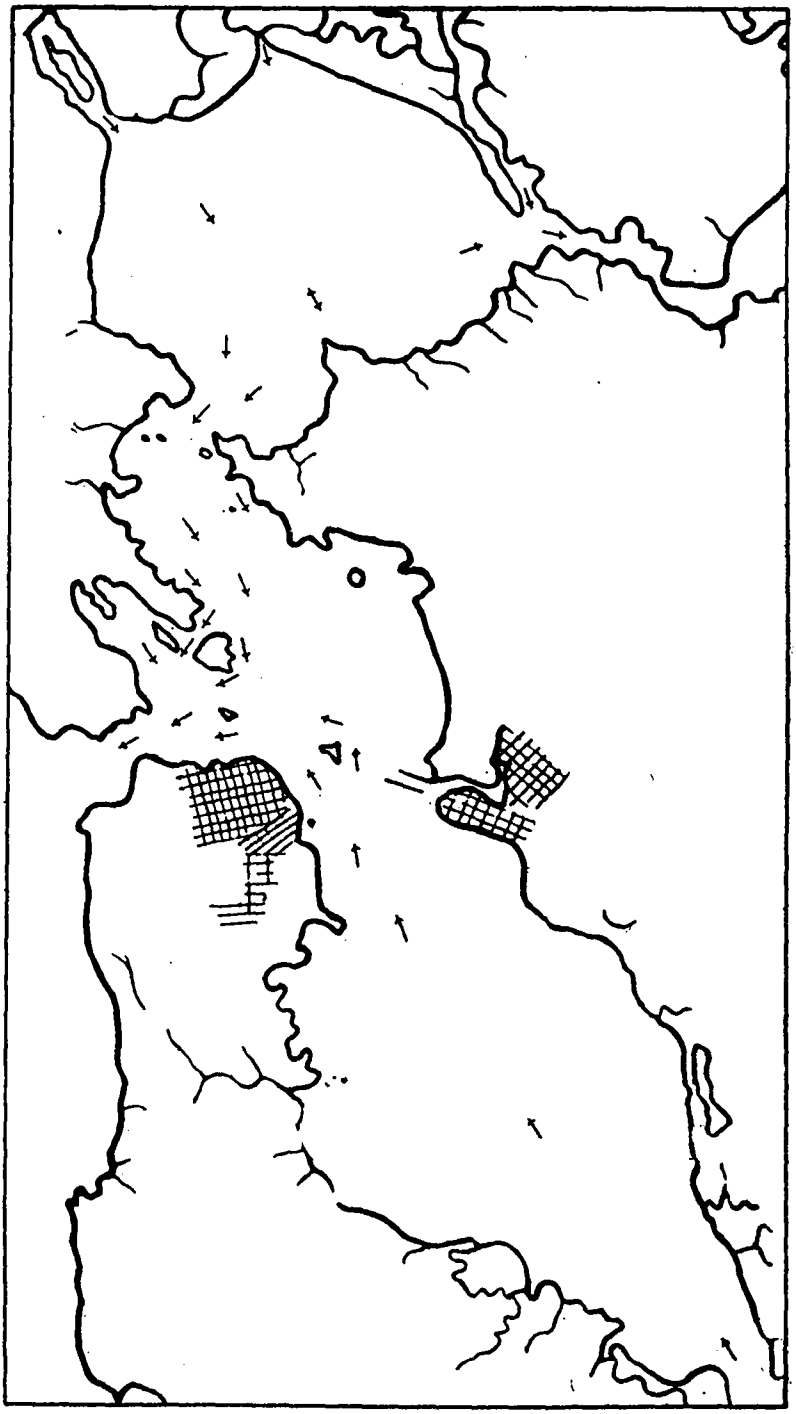


FIG. 28.—The current movement one hour after high water slack at the entrance

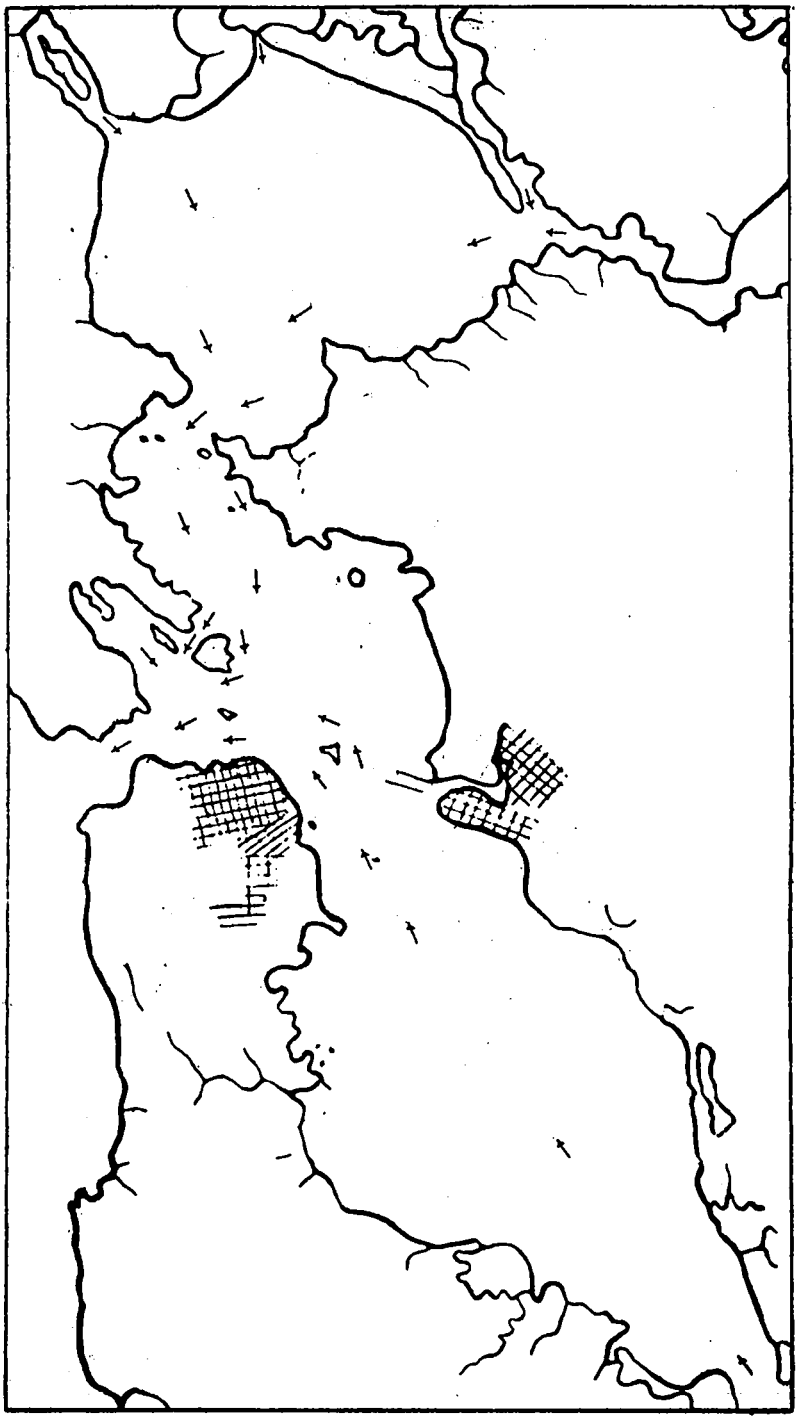


FIG. 29.—The current movement two hours after high water slack at the entrance

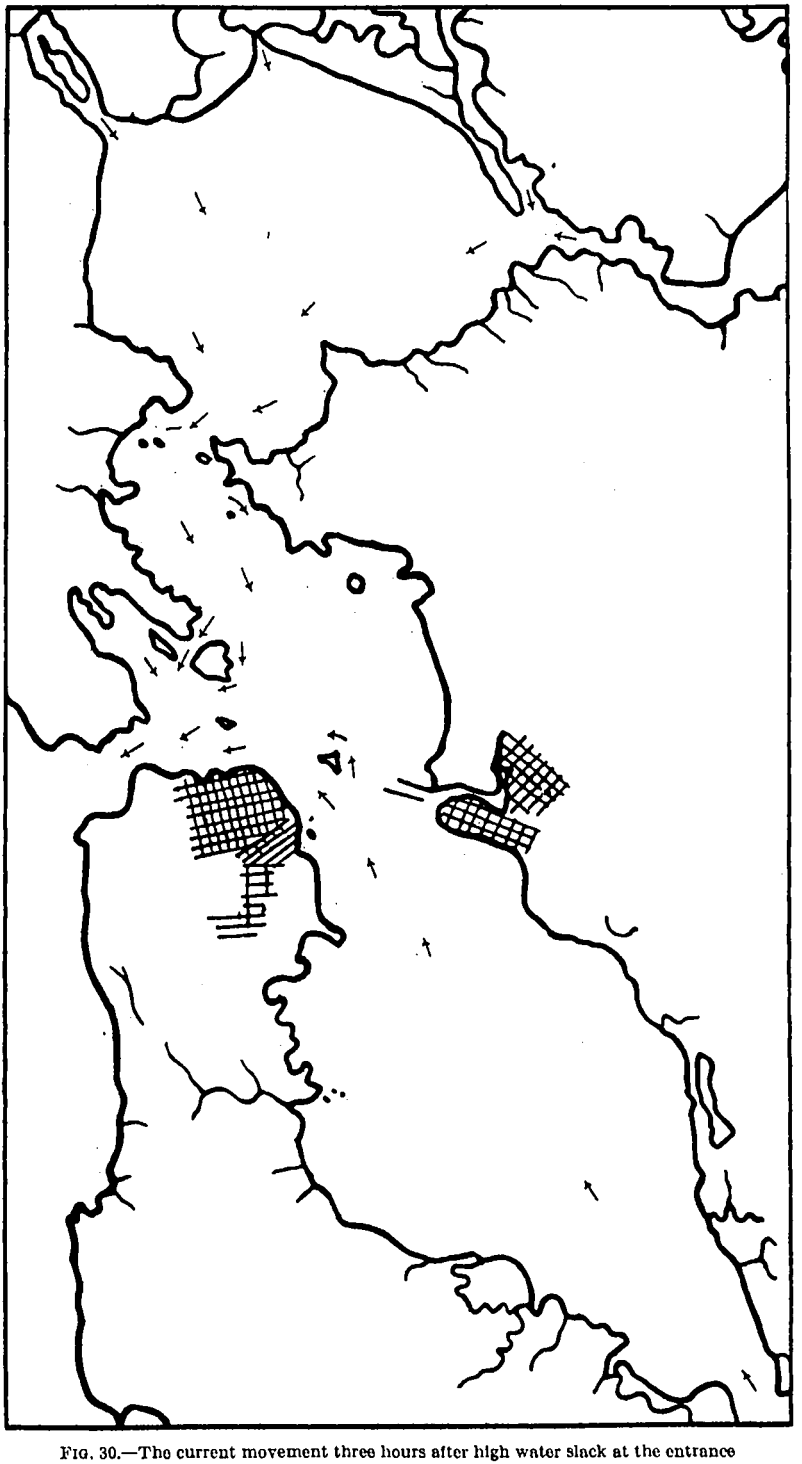


FIG. 30.—The current movement three hours after high water slack at the entrance

12. THE CURRENT AT SAN FRANCISCO LIGHT VESSEL

San Francisco Light Vessel is stationed about 9 miles southwest of the entrance to San Francisco Bay in 17 fathoms of water. Its position with reference to the coast may be seen in Figure 31.

Current observations made hourly by the personnel of the light vessel consist of three series with the standard current pole and log line. The first series of approximately 1 year and 5 months duration began January 23, 1915, and ended June 30, 1916. No further observations were made from the vessel until September 1, 1918, when a series was begun which lasted for 2 years and 11 months, or until July 31, 1921. Observations were again resumed on September 21, 1923, just prior to the beginning of the recent current survey of San Francisco Bay and were carried on throughout the time that the survey was in progress and until November 19, 1923.

Offshore, away from the influences of the coast, the tidal current is quite different from that found in a tidal bay or river. Here, instead of flowing in one direction for about 6 hours and then in a direction approximately 180° opposite for another 6 hours, the current is always flowing and continually changing its direction. Therefore in the period of a tidal cycle, or about 12½ hours, it will have set in all directions of the compass. This type of current is known as a rotary current.

In the rotary current there are no slack waters; there are, however, periods of minimum current which correspond to the slack waters found in the bays and rivers, and there are also periods of maximum current which correspond to the strength of current as found inshore. These maximum and minimum currents are related to each other in the same way as are the slacks and strengths of current; that is, one follows the other at intervals of approximately three hours.

To determine the velocity and direction of such currents it has been the practice to tabulate them with respect to the times of high and low water at some suitable port, and, because of the large diurnal inequality of currents on the Pacific coast, it is necessary to distinguish between the higher high and lower high waters of a day and also between the lower low and higher low waters.

The results derived from such a tabulation give the current at the point in question as observed; that is, with wind effect and other nontidal currents included. By a process of resolution and reduction, however, these nontidal currents may be eliminated and the true tidal current tabulated with respect to the high and low waters of the port of reference. Such a table (Table 52) has been prepared for the current found at San Francisco Light Vessel. It was prepared from the observations taken during the years 1915, 1916, 1919, and 1920, and represents average conditions as found throughout the year.

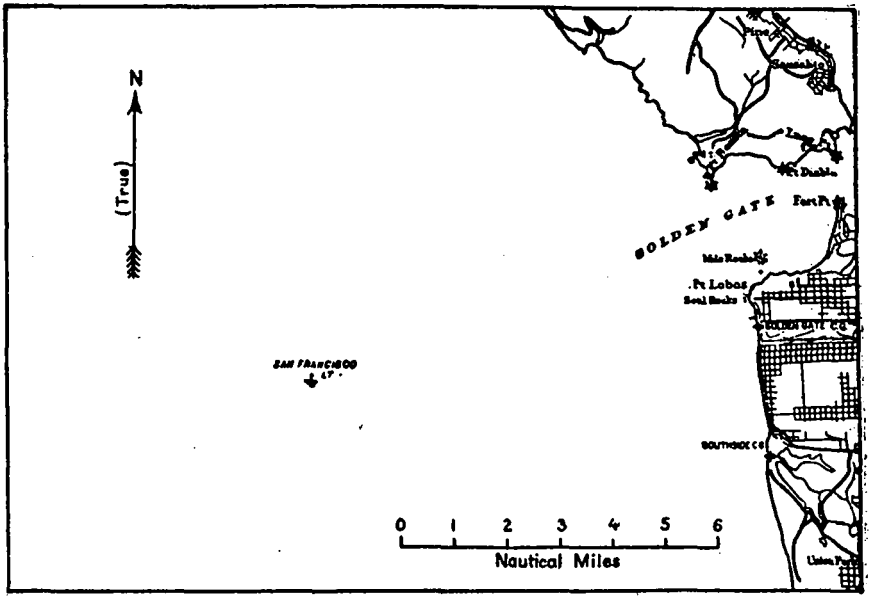


FIG. 31.—Current station, San Francisco Light Vessel

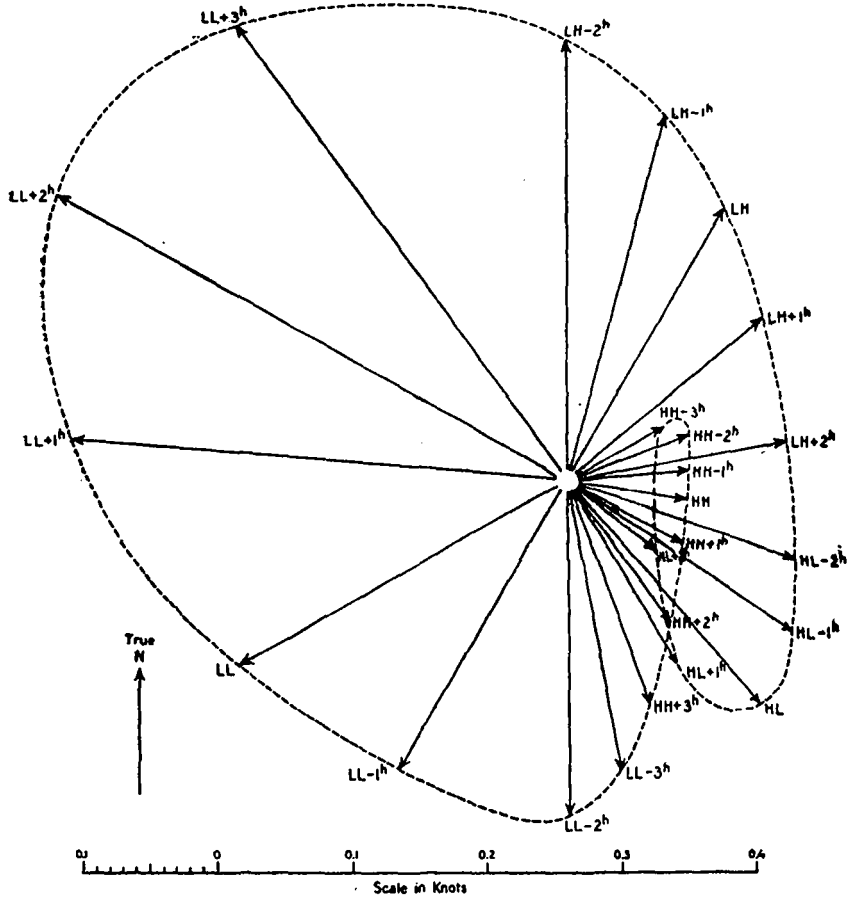
TABLE 52.—*Relation between tidal current at San Francisco Light Vessel and tide at Fort Point*

Time referred to tide at Fort Point	Current at San Francisco Light Vessel		Time referred to tide at Fort Point	Current at San Francisco Light Vessel	
	Velocity	Direction (true)		Velocity	Direction (true)
	Knots	*Degrees*		*Knots*	*Degrees*
3 hours before higher high water	0.1	60	3 hours before lower low water	0.2	170
2 hours before higher high water	0.1	70	2 hours before lower low water	0.3	180
1 hour before higher high water	0.1	85	1 hour before lower low water	0.3	210
Higher high water	0.1	100	Lower low water	0.3	240
1 hour after higher high water	0.1	120	1 hour after lower low water	0.3	275
2 hours after higher high water	0.1	145	2 hours after lower low water	0.4	300
3 hours after higher high water	0.2	160	3 hours after lower low water	0.4	325
2 hours before lower high water	0.3	0	2 hours before higher low water	0.2	110
1 hour before lower high water	0.3	15	1 hour before higher low water	0.2	125
Lower high water	0.2	30	Higher low water	0.2	140
1 hour after lower high water	0.2	50	1 hour after higher low water	0.2	150
2 hours after lower high water	0.2	80	2 hours after higher low water	0.1	130

Figure 32 shows diagrammatically the tidal current at the light vessel for various phases of the tide at Fort Point and shows that the current is rotary, turning clockwise.

In order to refer the currents at the light vessel to the currents at San Francisco Entrance (to make them comparable with the results in San Francisco Bay), it was necessary to determine the relation between each phase of the tide at Fort Point and each phase of the current at the entrance. The previous table showing the relation between the tide and current at these places merely gave the time of occurrence of the slack waters after the corresponding low or high

waters of a day. However, diurnal inequality exists in the currents as well as in the tides, although the effect is generally not as large as in the tides. Table 53 shows the relation between the tide and current taking into account the effect of diurnal inequality. It shows not only the time of occurrence of slack water with respect to the



Referred to predicated time of tide at San Francisco (Fort Point), Cal.

FIG. 32.—Tidal current curve, San Francisco Light Vessel.

tide but also the time of occurrence of the maximum current with respect to the tide. It was prepared from the first four months of the predictions for 1926 using the tides at Fort Point and the currents at San Francisco Entrance A plus (+) sign indicates that the phase of the current is later than the corresponding phase of the tide and a minus (−) sign that it is earlier.

TABLE 53.—*Relation between each phase of the current at San Francisco Entrance and corresponding phase of the tide at Fort Point*

Month	Time of slack before—				Time of strength of—			
	Lesser flood	Greater flood	Lesser ebb	Greater ebb	Lesser flood	Greater flood	Lesser ebb	Greater ebb
	Hours	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*
Jan.	HL+2.21	LL+1.86	LH+1.58	HH+1.88	HH−1.00	LH−2.00	HL−0.98	LL−2.00
Feb.	HL+2.20	LL+1.88	LH+1.66	HH+1.90	HH−1.10	LH−1.81	HL−0.94	LL−1.93
Mar.	HL+2.16	LL+1.91	LH+1.66	HH+1.84	HH−1.08	LH−1.71	HL−1.01	LL−1.79
Apr.	HL+2.19	LL+1.94	LH+1.64	HH+1.85	HH−0.99	LH−1.88	HL−1.00	LL−1.78
Mean	HL+2.19	LL+1.90	LH+1.64	HH+1.87	HH−1.04	LH−1.85	HL−0.98	LL−1.88

From the above table it may be noted that the strength of a lesser flood current occurs with a higher high water and the strength of a greater flood current with a lower high water. Considering an ebb current the relation is different, however; the strength of a lesser ebb current occurs with a higher low water and the strength of a greater ebb current with a lower low water.

From the relations brought out in this table the tidal current at the light vessel may then be referred to the current at San Francisco Entrance. Table 54 shows the current at the light vessel so referred.

TABLE 54.—*Relation between tidal current at San Francisco Light Vessel and current at San Francisco Entrance*

Time referred to current at San Francisco Entrance	Current at San Francisco Light Vessel		Time referred to current at San Francisco Entrance	Current at San Francisco Light Vessel	
	Velocity	Direction (true)		Velocity	Direction (true)
	Knots	*Degrees*		*Knots*	*Degrees*
Slack before greater flood	0.4	300	2 hours before lesser flood	0.1	50
1 hour before greater flood	0.4	340	1 hour before lesser flood	0.1	70
Greater flood	0.3	0	Lesser flood	0.1	85
1 hour after greater flood	0.3	15	1 hour after lesser flood	0.1	100
2 hours after greater flood	0.2	30	2 hours after lesser flood	0.1	120
3 hours after greater flood	0.2	50	Slack before greater ebb	0.1	145
Slack before lesser ebb	0.2	70	2 hours before greater ebb	0.2	160
1 hour before lesser ebb	0.2	110	1 hour before greater ebb	0.2	170
Lesser ebb	0.2	125	Greater ebb	0.3	185
1 hour after lesser ebb	0.2	140	1 hour after greater ebb	0.3	215
2 hours after lesser ebb	0.2	150	2 hours after greater ebb	0.3	240
Slack before lesser flood	0.1	115	3 hours after greater ebb	0.4	270

The current due to tidal effect alone is very small. When the fresh water discharge from San Francisco Bay is considerable, the combined tidal and nontidal current generally attains a velocity of 1½ knots in a northwesterly direction. The greatest observed velocity at the light vessel is 2.9 knots. This abnormal velocity was due to a combination of tidal current, fresh water run-off from the bay, and a strong wind. The observations at the light vessel indicate a permanent current due to fresh water discharge, averaging about 0.1 knot and setting in a northwesterly direction. This permanent current is especially noticeable during the winter months. Table 55

shows this average monthly set computed from observations made between 1915 and 1920.

TABLE 55.—*Monthly set of current at San Francisco Light Vessel*

Month	Velocity	Direction (true)
	Knots	*Degrees*
January	0.29	312
February	0.30	300
March	0.16	292
April	0.08	248
May	0.10	288
June	0.06	297
July	0.11	329
August	0.06	347
September	0.02	44
October	0.03	18
November	0.09	329
December	0.20	308
Mean	0.12	319

APPENDIX

GENERAL CHARACTERISTICS OF TIDES AND CURRENTS

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

I. TIDES, GENERAL CHARACTERISTICS

DEFINITIONS

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

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

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

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

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

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

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

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

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

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

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

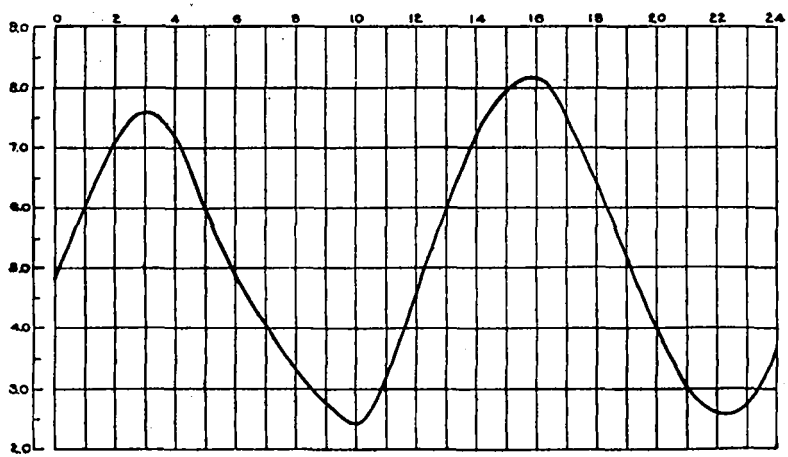


FIG. A.—Tide curve for Fort Hamilton, N. Y., July 4, 1922

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

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

THE TIDE-PRODUCING FORCES

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

The mathematical development of these forces shows that the tide-producing force of a heavenly body varies directly as its mass and inversely as the cube of its distance from the earth. The sun has a mass about 26,000,000 times as great

as that of the moon; but it is 389 times as far away from the earth. Its tide-producing force is therefore to that of the moon as 26,000,000 is to $(389)^3$, or somewhat less than one-half.

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

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

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

VARIATIONS IN RANGE

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

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

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

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

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

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

The moon does not move in the plane of the Equator, but in an orbit making an angle with that plane of approximately 23½°. During the month, therefore, the moon's declination is constantly changing, and this change in the position of the moon produces a variation in the consecutive ranges of the tide. When the moon is on or close to the Equator—that is, when its declination is small—consecutive ranges do not differ much, morning and afternoon tides being very much alike. As the declination increases the difference in consecutive ranges increases, morning and afternoon tides beginning to show decided differences, and at the times of the moon's maximum semimonthly declination these differ-

ences are very nearly at a maximum. But, like the response to changes in the moon's phase and parallax, there is a lag in the response to the change in declination, this lag being known as the "age of diurnal inequality" or "diurnal age." Like the phase and parallax ages, the diurnal age varies from place to place, being generally about one day, but in some places it may have a negative value.

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

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

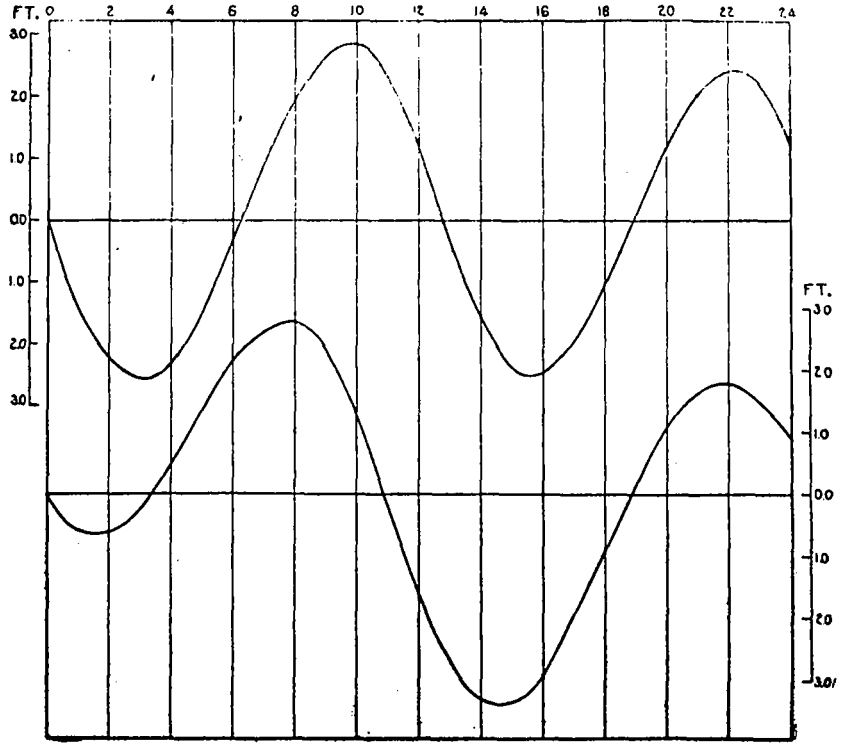


FIG. B.—Tide curves, San Francisco, Calif., October 18 and 24, 1922

regions it is the variation from equatorial to tropic tides that is the predominant variation.

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

DIURNAL INEQUALITY

The difference between morning and afternoon tides due to the declination of the moon is known as diurnal inequality, and where the diurnal inequality is considerable the rise and fall of the tide is affected to a very marked degree both in time and in height. Figure B represents graphically the differences in the

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

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

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

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

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

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

TYPES OF TIDE

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

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

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

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

It is to be noted that when the tide at any given place is assigned to any particular type, it refers to the characteristics of the predominating tide at that place. At the time of the moon's maximum semimonthly declination the semidiurnal type exhibits more or less diurnal inequality and thus approaches the mixed type; and when the moon is on or near the Equator the diurnal inequality

of the mixed type is at a minimum, the tide at such times resembling the semidiurnal type. It is the characteristics of the predominating tide that determine the type of tide at any given place. With the aid of harmonic constants the type of tide may be defined by definite ratios of the semidiurnal to the diurnal constituents.

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

HARMONIC CONSTANTS

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

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

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

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

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

It is obvious that the principal lunar tidal component will be one which gives two high and two low waters in a tidal day of 24 hours and 50 minutes, or more exactly in 24.84 hours. Its speed per solar hour, therefore, is $\frac{2\times 360^\circ}{24.84}=28^\circ.98$. This component has been given the symbol M_2. Likewise, the principal solar tidal component is one that gives two high and two low waters in a solar day of 24 hours. Its angular speed per hour is therefore $\frac{2\times 360^\circ}{24}=30^\circ.00$. The symbol for this principal solar component is S_2.

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

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

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

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

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

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

TIDAL DATUM PLANES

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

The principal tidal plane is that of mean sea level, which may be defined as the plane about which the tide oscillates, or as the surface the sea would assume when undisturbed by the rise and fall of the tide. At any given place this plane may be determined by deriving the mean height of the tide. This is perhaps best

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

done by adding the hourly heights of the tide over a period of a year or more and deriving the mean hourly height. It is to be noted that in such a determination the mean sea level is not freed from the effects of prevailing wind, atmospheric pressure, and other meteorological conditions.

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

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

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

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

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

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

MEAN VALUES

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

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

As will be seen in the detailed discussion of the tides at Fort Hamilton, the values determined from two different 29-day or 27-day periods may differ very considerably. This is due to the fact that these periods are not exact synodic periods for the different variations, and to the further fact that variations having

periods greater than a month are not taken into account. Furthermore, meteorological conditions, which change from month to month, leave their impress on the tides. For accurate results the direct determination of the tidal datum planes and other tidal quantities should be based on a series of observations that cover a period of a year or preferably three years. Values derived from shorter series must be corrected to a mean value.

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

II. TIDAL CURRENTS, GENERAL CHARACTERISTICS

DEFINITIONS

Tidal currents are the horizontal movements of the water that accompany the rising and falling of the tide. The horizontal movement of the tidal current and

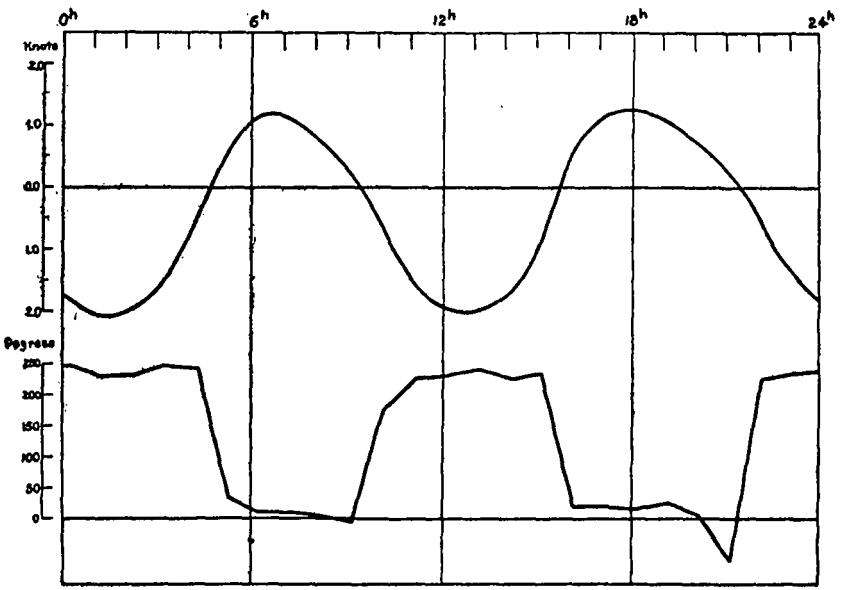


FIG. C.—Velocity and direction curves for the current, Hudson River, July 22, 1922

the vertical movement of the tide are intimately related parts of the same phenomenon brought about by the tide-producing forces of sun and moon. Tidal currents, like the tides, are therefore periodic.

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

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

RECTILINEAR TIDAL CURRENTS

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

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

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

ROTARY TIDAL CURRENTS

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

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

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

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

VARIATIONS IN STRENGTH OF CURRENT

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

when the moon has considerable variation, the currents, like the tides, are characterized by diurnal inequality.

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

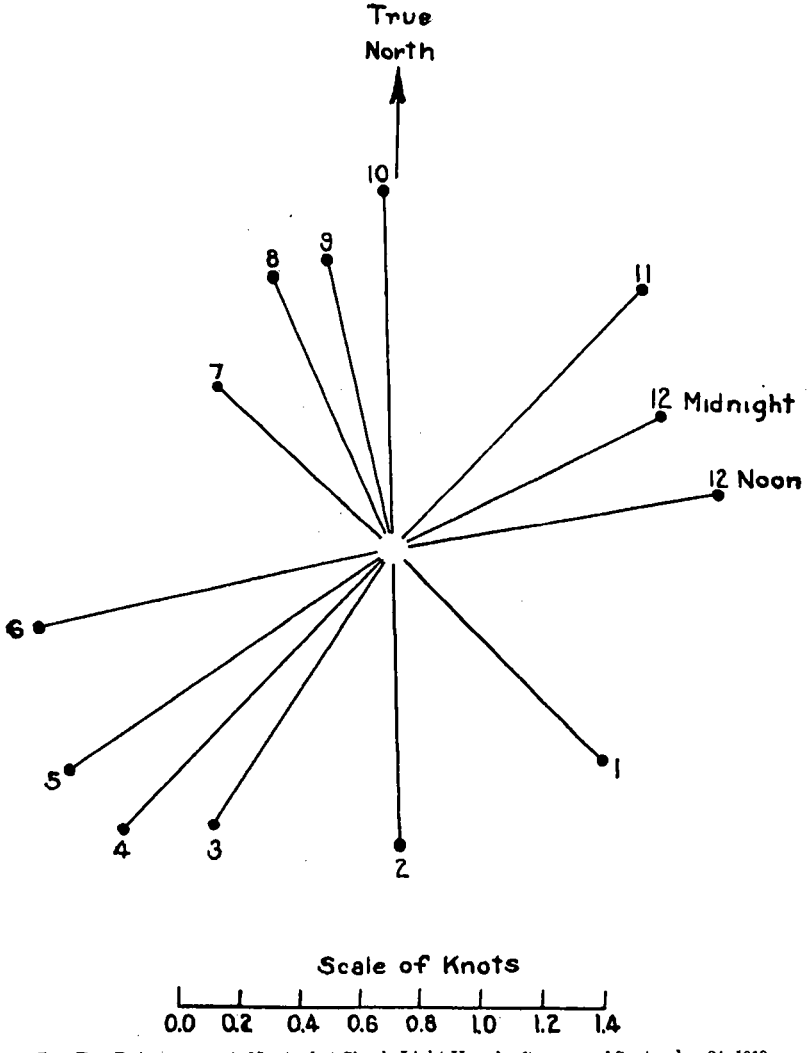


FIG. D.—Rotary current, Nantucket Shoals Light Vessel, afternoon of September 24, 1919

alike, the diurnal variation in the tide at any place being generally greater than the diurnal variation in the current.

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

RELATION OF TIME OF CURRENT TO TIME OF TIDE

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

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

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

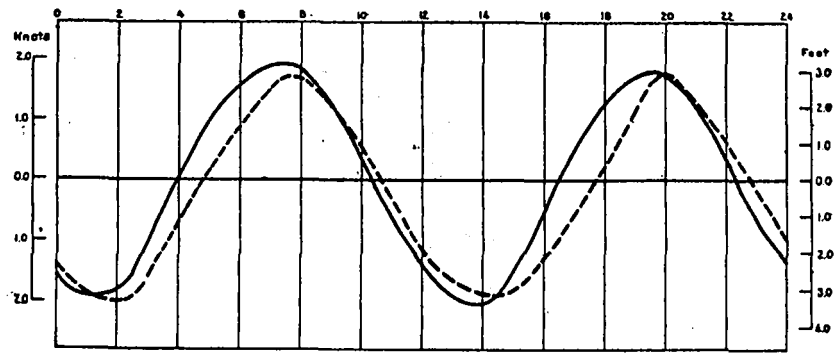


FIG. E.--Tide and current curves, New York Harbor, October 9, 1919

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

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

Apart from the disturbing effect of nontidal agencies, the time relations between tide and current are subject to variation in regions where the tide exhibits considerable diurnal inequality; as for example, on the Pacific coast of the United

States. This variation is due to the fact, previously mentioned, that the diurnal inequality in the current at any given place is, in general, only about half as great as that in the tide. This brings about differences in the corresponding features of tide and current as between morning and afternoon. However, in such cases it is frequently possible to refer the current at a given place to the tide at some other place with comparable diurnal inequality.

EFFECT OF NONTIDAL CURRENT

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

When unaffected by nontidal currents, the periods of flood and ebb are, in general, equal as represented in the diagram, and slack water occurs regularly three hours and six minutes after the times of flood and ebb strengths. But if we assume a steady nontidal current introduced which has, in the direction of the tidal current, a velocity component represented by the line *CD*, it is evident that the strength of ebb will be increased by an amount equal to *CD*, while the

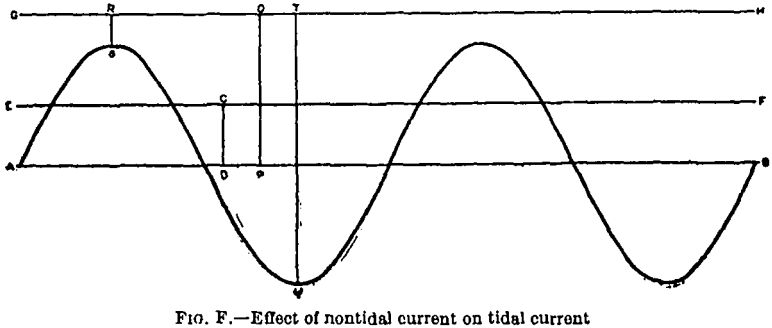


FIG. F.—Effect of nontidal current on tidal current

flood strength will be decreased by the same amount. The current conditions may now be completely represented by drawing, as a new axis, the line *EF* parallel to *AB* and distant from it the length of *CD*.

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

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

VELOCITY OF TIDAL CURRENTS AND PROGRESSION OF THE TIDE

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

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

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

DISTANCE TRAVELED BY A PARTICLE IN A TIDAL CYCLE

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

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

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

DURATION OF SLACK

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

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

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

for the duration of slack the following values: For a current with a strength of 1 knot, slack water is 24 minutes; for currents of 2 knots strength, 12 minutes; 3 knots, 8 minutes; 4 knots, 6 minutes; 5 knots, 5 minutes; 6 knots, 4 minutes; 8 knots, 3 minutes; 10 knots, 2⅓ minutes.

HARMONIC CONSTANTS

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

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

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

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

MEAN VALUES

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

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

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

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