TIDES AND CURRENTS

INTERSTATE SANITATION COMMISSION — NEW YORK HARBOR

STUDY OF

TIDES AND CURRENTS

IN THE WATERWAYS OF THE
INTERSTATE SANITATION DISTRICT

FEDERAL WORKS AGENCY

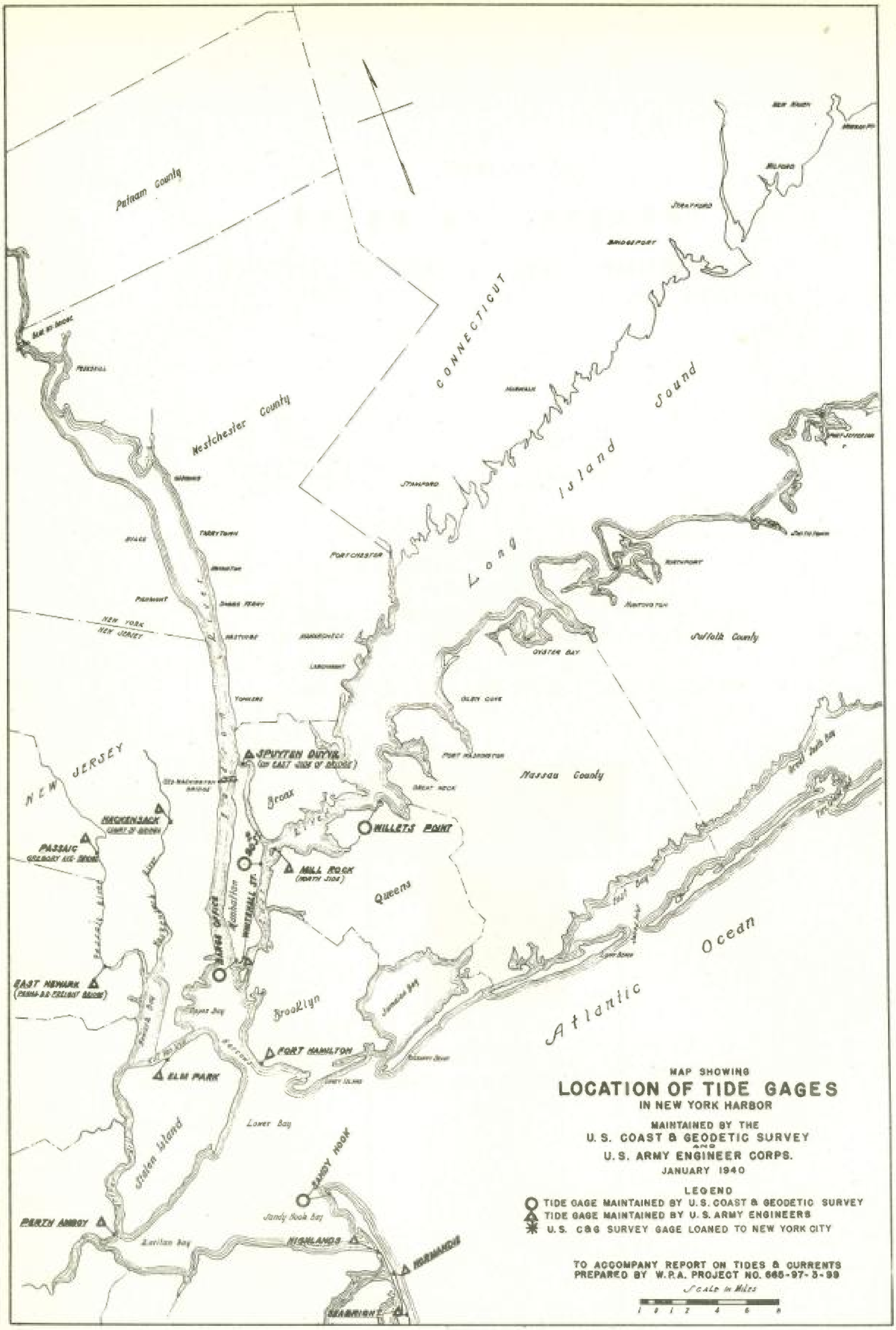
WORK PROJECTS ADMINISTRATION
FOR THE CITY OF NEW YORK

REPORT OF OFFICIAL PROJECT NO. 665-97-3-99

SPONSORED BY

INTERSTATE SANITATION COMMISSION
60 HUDSON STREET NEW YORK, N. Y.

MARCH 1940



MAP SHOWING

LOCATION OF TIDE GAGES

IN NEW YORK HARBOR

MAINTAINED BY THE
U. S. COAST & GEODETIC SURVEY
AND
U. S. ARMY ENGINEER CORPS.
JANUARY 1940

LEGEND

- ○ TIDE GAGE MAINTAINED BY U. S. COAST & GEODETIC SURVEY
- △ TIDE GAGE MAINTAINED BY U. S. ARMY ENGINEERS
- ✱ U. S. C&G SURVEY GAGE LOANED TO NEW YORK CITY

TO ACCOMPANY REPORT ON TIDES & CURRENTS
PREPARED BY W. P. A. PROJECT NO. 665-97-3-99

Scale in Miles

1 0 1 2 4 6 8

INTERSTATE SANITATION COMMISSION

COMMISSIONERS

NEW YORK	NEW JERSEY
Joseph P. Day	William C. Cope
Dr. E. S. Godfrey, Jr.	J. Lester Eisner
William F. Hoffman	Joseph N. Fowler
J. Noel Macy	J. Spencer Smith
Jeremiah D. Maquire	George C. Warren

* * * * * *

Seth G. Hess,	Chief Engineer, Executive Secretary
J Raymond Tiffany,	General Counsel
Thomas K. Smith,	Associate Counsel

WORK PROJECTS ADMINISTRATION

Brehon Somervell,	Administrator
David Standley,	Manager Manhattan District Office
Walter P. Warendorff,	Chief, Survey Section
Maurice Lubin,	Project Manager
Chester G. Wigley,	Engineer in Charge

SUPERVISING STAFF OF PROJECT

665 - 97 - 3 - 99

Chester G. Wigley, C. E.	Engineer in Charge
George H. Clark	Assistant Engineer in Charge
William F. Probst	Clerical Supervisor
Antonio Giglio	Drafting Supervisor

FOREWORD

THE STUDY OF TIDES & CURRENTS OF THE WATERWAYS OF THE INTERSTATE SANITATION DISTRICT

The abatement of pollution in New York Harbor and the adjacent waters is the principal objective of the Interstate Sanitation Commission. This pollution emanates from one of the greatest concentrations of population the world has ever known. The problem is complicated by the many uses made of the waters of the District, and by the complex tides and currents that may carry pollution from one area to another.

Notable studies have been made of these tidal phenomena in New York Bay and the adjacent water, In order that these studies may be more readily available, they have been consolidated and are presented herewith. They are important in this Commission's studies of the effects of pollution.

The United States Government, through the Work Projects Administration, makes it possible to bring this information to many other agencies to whom the natural movements of the waters within this District may be of valued interest.

The names of the principal officials under whose administration and direction this work was carried out are set forth elsewhere. Without their effort this work could not have been accomplished. Mr. Charles D. Sugrue, an engineering employee of the Project has labored energetically and conscientiously to make this work available. The Project was fortunate in having at its disposal the abilities and Sanitation experience that were brought to it by the Engineer in charge.

In the reproduction of the plates for this report, the assistance of The Board Of Education of The City Of New York is gratefully acknowledged.

This report on Tides and Currents is one of several parts of the Work Projects Administration Project under this Sponsorship and administration. The other reports are issued separately.

Seth G. Hess
SETH G. HESS
CHIEF ENGINEER - EXECUTIVE SECRETARY
INTERSTATE SANITATION COMMISSION

CONTENTS

PAGE

GENERAL DISCUSSION

GENERAL TIDAL PHENOMENA

TIDES IN THE NEW YORK AREA

TIDAL AND NON-TIDAL CURRENTS

CURRENTS IN NEW YORK AREA

ILLUSTRATIONS

T A B L E S

STUDY OF

TIDES AND CURRENTS

IN THE WATERWAYS OF THE
INTERSTATE SANITATION DISTRICT

GENERAL DISCUSSION

REASON FOR MAKING STUDY

Pollution

Into the waters of New York Harbor and surrounding waters flows the discharge from sewers serving 9,900,000 people. Industrial plants of almost every description sully the waters and tributaries with oil, dyes, and chemical wastes. Vessels of all types, from ocean liners to ferry boats, traverse the harbor and add their waste to the waters. In addition to these wastes, the rivers entering the harbor carry the domestic and industrial wastes from an area of 15,000 square miles. Some of these wastes are treated or purified before being discharged into the rivers, but at the present time this is only a small percentage of the total.

Effect of tidal flow

If the water of the harbor were stagnant or remained unchanged for any length of time, it is quite obvious that the results would be calamitous. Nature, however, has provided the tides which give the harbor a change of water twice daily, and fair sanitary conditions have been maintained except in some local areas. Of course, the change of water is not a complete one. If the flood and ebb of the tide were equal, almost all of the polluted waters receding on the ebb would return on the flood. The conditions in New York Harbor are also affected to a very considerable extent by the fresh water from the Hudson, which, in its attempt to get to the sea, decreases the period of flood and increases the period of ebb, so that gradually the water in the harbor moves out to sea.

The tides and currents in New York Harbor are, for this reason controlling factors in determining the character and cost of sewage treatment works that must be provided to maintain satisfactory sanitary conditions. In some instances, the flow of a large volume of tidal water, together with the fact that the currents would not transport polluting material to recreational areas, would permit the construction of less costly works than where conditions are of an opposite character, such as where tidal volume of flow is comparatively small and the currents would affect areas used for recreational or other purposes by the resident population.

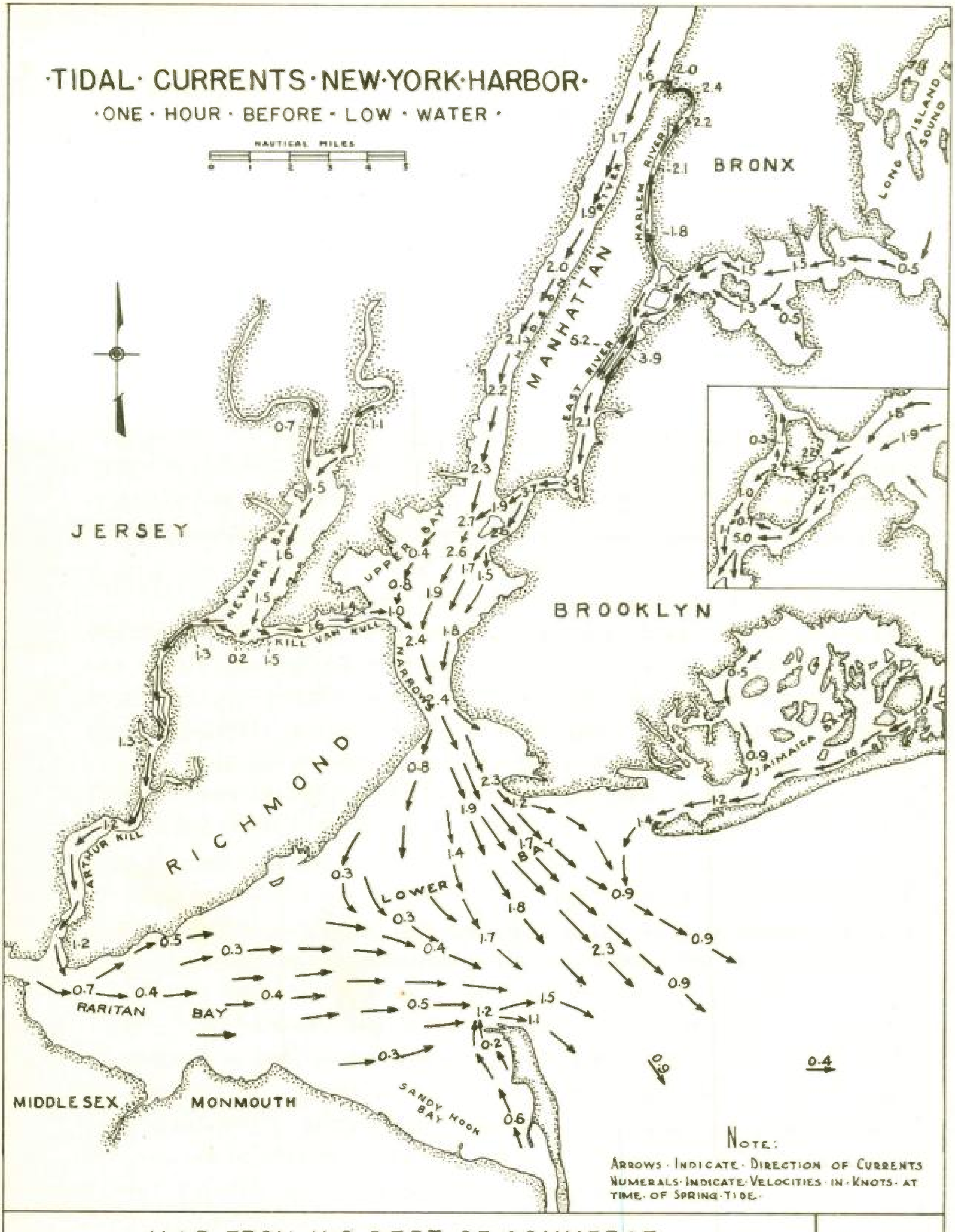
Effect of Tides

The information necessary for a complete understanding of the various tidal and current effects in New York Harbor are scattered through a long period of years. In order to make the major part of this information available for ready reference, this report has been written. • A brief description of the tidal and current phenomena in the New York Harbor area will be given in this report. The directions and velocities of the tidal and non-tidal currents will be explained and their effects examined.

SCOPE OF WORK

The area under consideration (See Map No. 1) comprises five large bays, Upper, Lower, Jamaica, Newark, and Raritan Bays; five straits, the Narrows, Kill van Kull, Arthur Kill, East River, and Harlem River; one large tidal river, the Hudson River, Long Island Sound, and the Atlantic Ocean. The tides enter at two points miles apart; the one through the Lower Bay and the other through Long Island Sound.

Area Included



·TIDAL· CURRENTS·NEW·YORK·HARBOR·

·ONE · HOUR · BEFORE · LOW · WATER ·

NOTE:

ARROWS · INDICATE · DIRECTION OF CURRENTS
NUMERALS · INDICATE · VELOCITIES · IN · KNOTS · AT TIME · OF SPRING · TIDE ·

MAP FROM U.S. DEPT. OF COMMERCE
COAST AND GEODETIC SURVEY
TO ACCOMPANY REPORT MADE BY
W.P.A. WATER · POLLUTION · PROJECT NO. 665-97-3-99-SU

MAP
No. 1
OCT. 23, 1939

PLAN OF OPERATION

In order to get information on past surveys of this complex area, a staff of men were kept at work at the New York Public Library from April 20, 1939, to August 31, 1939. Abstracts were made from eighty publications, including reports of the United States Coast and Geodetic Survey, the United States Army Engineering Corps, and various municipal agencies. A list of the publications consulted will be found in the Bibliography at the end of this report.

Work Methods

The abstracted material has been indexed and gathered into 4 loose-leaf volumes arranged chronologically. Thus, a total of approximately eleven hundred typewritten pages of selected tidal information has been made available in permanent form for future reference.

After the information had been collected the work of selection and interpretation began. Early reports of surveys contained much that had to be discarded in the light of later observations. The erection of a bridge or even the extension of a pier at an already narrow point on a river may cause a very noticeable variation in both the direction and velocity of the current.

During this work of compilation contact was maintained with the New York office of the United States Coast and Geodetic Survey. That office was courteously made available for checking our own records and for further research.

GENERAL TIDAL PHENOMENA

ATTRACTION OF HEAVENLY BODIES

Popular View

The fall and rise of the tide and the currents which accompany them are familiar phenomena. Popular opinion ascribes their cause to the moon's attraction, and with this opinion science is in agreement. Many factors, however, must be considered before an accurate prediction can be made of the action of the tide, and it is here purposed to give a general description of these tide producing forces.

Law of Mutual Attraction

The existence of a mutually attractive force between heavenly bodies has been recognized since the time that Sir Isaac Newton made know his theory of universal gravitation. We also know that the attractive force which any celestial body will have upon the earth will be great if the mass of the attracting body is great, and that it will decrease as its distance from the earth becomes greater. We can now state the law of attraction, i.e., that the attractive force (F) of a heavenly body varies directly with the mass (M) of the body and inversely as the square of its distance (D). This is generally expressed as $F = \frac{M}{D^2}$

With this in mind, we can readily see that the attractive force of the moon, because of the comparative nearness of that body, must be great, and likewise that of the sun because of its immense mass. The effects of the other heavenly bodies, because of their relatively small masses or great distances, are comparatively small and need not be considered in connection with our study. Thus, it is with the moon and the sun only that we are concerned.

TIDE PRODUCING FORCES

Tide Producing Force

The intensity with which the moon (or sun) attracts a particle of water on the earth is greater if that particle is on the side toward the moon (or sun) and less if it is on the side away from the moon (or sun). For the attraction upon the solid earth as a whole, the effective distance (D) is obviously to be measured from the center of the earth, since that is the center of mass of the solid body. The differences in these attractions give rise to the tidal 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. It is to be noted that the tide producing force varies as the cube of the distance while in Newton's general Law of Mutual Attraction, the attractive force varies as the square of the distance. The sun has a mass 27,000,000 times as great as that of the moon, but it is 389 times as far away from the earth. The sun's tide producing force is, therefore, to that of the moon's as 27,000,000 is to 58,800,000 (the cube of 389), or approximately one-half.

Figure 1

Graphic Illustration of Forces

Fig. I illustrates graphically the tide-producing forces. The relative magnitudes of the forces are given by the numbers on the arrows. The vertical components of the tide producing forces coincide in direction with the gravitational force of the earth itself, and thus act as a very slight modification of weight. The effective tide producing forces, however, are the horizontal components of the forces shown. Thus, we see that the tidal forces tend to move the water towards the moon on the side of the earth facing the moon and, seemingly, away from the moon on the opposite side of the earth. This is readily understood when we realize that it is the difference between the moon's attraction on particles on the surface and at the center of the earth, which causes the tide producing forces. In other words, if we consider the two points

P and P' upon the same parallel of latitude, but 180 degrees apart in longitude, the force of attraction at P is greater than at the earth's center by the same amount that the force at P' is less. The particle at P is drawn toward the moon by a force greater than the force on a particle at the earth's center, the resultant being a force on the particle away from the earth's center. But the force on a particle at the earth's center is greater than that at P', the resultant being a force on the particle at the earth's center away from P', or what is to the same effect an apparent force on P' away from the earth's center. At the points V and I the horizontal components of the moon's disturbing force must vanish, the force itself being vertical. The horizontal components are likewise zero at D and D', being points on a great circle of longitude midway between V and I, for all points along this circle are very nearly as far from the moon as is the earth's center.

The resultant effect of the tidal forces is to cause a tendency to recede from the earth's center in those particles on the side facing the moon (or sun), and a like tendency on the opposite side of the earth. The waters on the surface of the earth are free to yield to this tendency with the result that ordinarily there are four tidal waves being raised on the waters, two caused by the moon and two caused by the sun.

Force Of Moon And Sun

However, since the tide producing force of the moon is approximately twice that of the sun, the effect of the sun's attraction on the tides is most noticeable as it works in the same (or opposite) direction to the moon, and is noticed the least when in a direction perpendicular to that of the moon's attraction. Thus the range of the tide increases in magnitude as the moon approaches her conjuction (or opposition) with the sun at new or full moon, and diminishes as the moon reaches the quadrature, or first and third quarters; or, in other words, the range of tide varies with moon's phase.

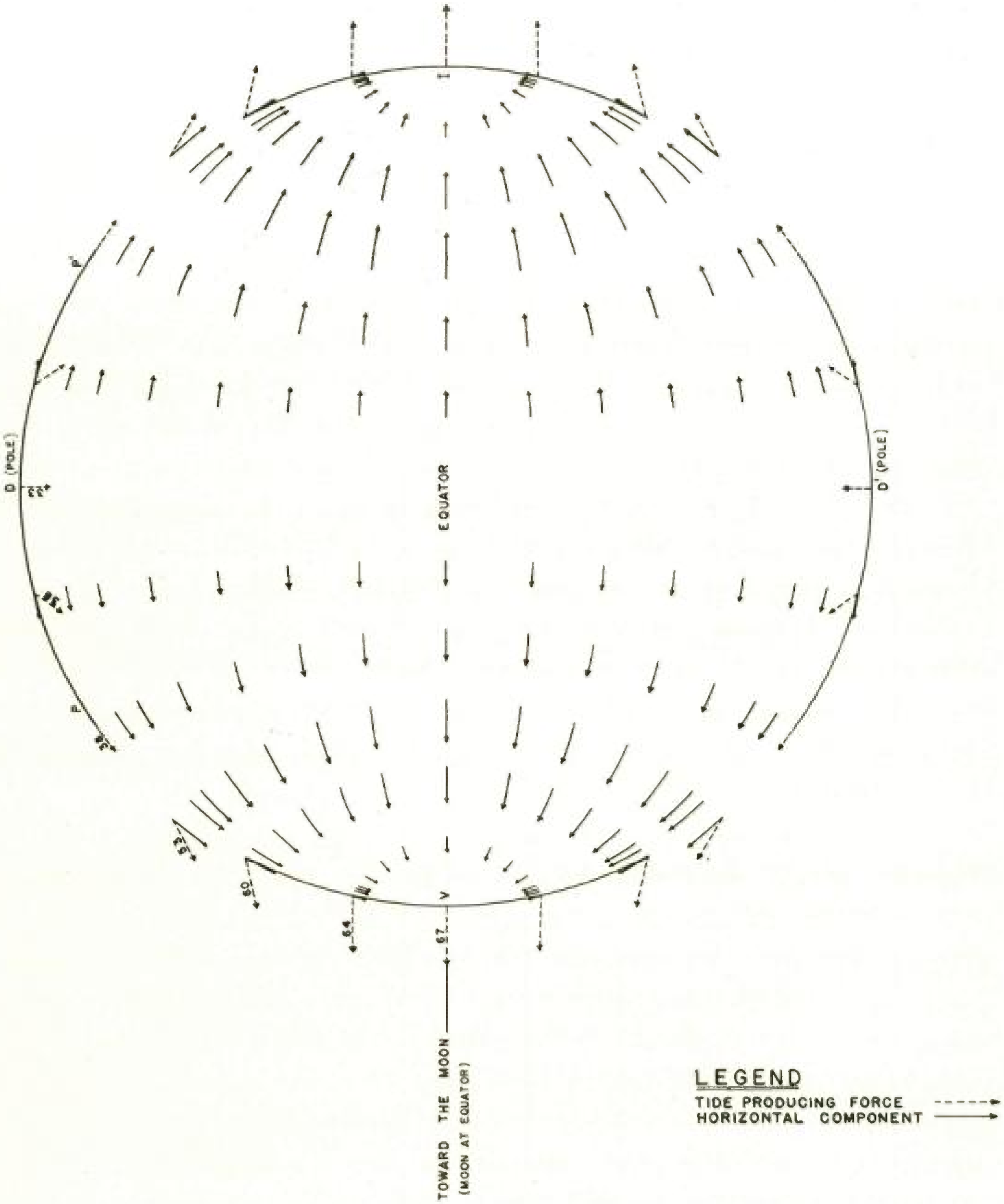


CHART OF TIDAL FORCES

From Manual Of Tides By R.A. Harris (U.S. Coast & Geodetic Survey) and Encyclopedia Britannica

To Accompany Report Made By —

W.P.A. – WATER POLLUTION PROJECT No. 665-97-3-99- SU. 1.

Figure

No. 1

Date Oct. 31, 1939

VARIATIONS IN TIDES

Causes of Tidal Variations

In its rise and fall the tide clearly reveals the presence of three variations, each related to a particular movement of the moon. The most noticeable variation, that related to the moon's phase, we have just discussed. It was shown that at the time of new or full moon, the tide will rise higher and fall lower than usual, so that the tidal range at such times is greater than the average,. The tides at such times are called "spring tides" and the range is known as the "spring range." When the moon is in its first or third quarters the tide does not rise as high or fall as low as usual, hence the range at such time is less than average. The tide at such times is called the "neap tide" and the corresponding range is called the "neap range."

It is to be noted that at most places there is a lag of a day or two between the time of a full or new moon and the corresponding spring tide. This lag is known as "phase age" and is generally ascribed to the effects of earth and water friction. At Fort Hamilton, as an example, the phase age is about 27 hours, which means that the spring tide occurs that many hours later than the full moon.

The second variation in the rise and fall of the tide is related to the moon's varying distance from the earth. In its movement around the earth the moon describes an ellipse. The earth is at one of the foci of the ellipse, with the result that at one point in its orbit the moon is nearest the earth, or in perigee, and at the opposite point of the orbit it is farthest away, or in apogee. When the moon is nearest the earth the tide rises higher and falls lower than usual, the tides being known as "perigean tides." When the moon is farthest from the earth the range is small and the tides are known as "apogean tides." Here again, the perigean or apogean tides lag behind the time of the moon's passage through its perigee or apogee. At Fort Hamilton this lag, known as the "parallax age" of the tide, is about 31 hours.

The third periodic variation in the rise and fall of the tide is that associated with the moon's changing declination, due to the fact that the plane of the moon's orbit is inclined to the plane of the equator. This variation of the moon's declination causes inequality in the two high tides of one day, but is of minor importance on the Atlantic Coast, having very little effect there. When the moon is on or close to the equator, and the difference in morning and afternoon tides is small, the tides are known as equatorial tides. At the time of the moon's maximum semi-monthly declination, when the difference in tides, due to this factor, is a maximum, the tides are called "tropic tides."

Period Of Variations

There are other periodic variations in the rise and fall of the tides, but the three discussed above are the most important. Each of these variations has a different period, the month of the moon's phases being 29½ days of the moon's distance 27½ days, and of the moon's declination 27-1/3 days. It follows, therefore, that very considerable variation in the rise and fall of the tide occurs during a year due to the changing relationships of these three lunar movements.

TYPES OF TIDES

Professor Henry Mitchell, in a paper prepared for the Navigation Bureau of the United States Navy, says:

The Tide Wave

> "To form a clear notion of the tide, it must be conceived to be a long wave or undulation, propagated to our shores from mid-ocean without necessarily causing visible agitation of the water particles. Its range is the vertical distance between the low and high water levels; its length the distance measured on the surface of the sea from one low water to the next. The tide wave, considered as an undulation, is always moving in a single direction, but is subject to changes of figure from point to point in its journey, by which its range and its length are altered. The rate with which the tide wave moves depends upon the depth of water; it is measured by comparing the times of high water observed at different determined points along its path." (24)

The observed tide is not a simple wave. It is a compound of several elementary undulations. There is thus great variety in tides, and therefore in undertaking to investigate the tides of a port it is important to ascertain as early as possible the form of the tide. For convenience, all tides are grouped in three classes, namely, semi-daily, daily and mixed.

Type of Tides

The semi-daily type is one in which two high and two low waters occur in a single day with little variation between the heights of the A.M. and P.M. tides. In the daily type of tide there is but one high and one low tide per day, while in the mixed type there are two lows and two highs in a day, the A.M. and P.M. highs (or lows), which are of marked inequality.

New York Tides

The tide at the Battery in New York Harbor is representative of the semi-daily type of tide; in fact, this type predominates all along the Atlantic Coast. Although New York tides are designated as semi-daily, they are not free from the daily inequalities caused by the moon's declination. Thus, when the moon is at its semi-monthly maximum declination, the tides exhibit more diurnal inequality and then approach the mixed type. It is in this varying relation of the magnitudes of the daily and semi-daily tide producing forces through a half-month period that we find the explanation of the different heights of the two high (or low) tides of a single day. This subject will be given more attention in the discussion of the tides at Fort Hamilton.

TIME OF TIDE

As we have seen, high water at any given place is caused by the passage of the moon across the meridian of the locality, or when it is at the opposite point of its orbit, 180 degrees distant, the tides being greater or less depending on the relative positions of the sun and moon. But since the moon in its movement around the earth crosses a given meridian on the average fifty minutes later each day, the tide is, likewise, later. The tidal day, therefore, like the lunar day, has an average length of 24 hours and 50 minutes.

Tidal Time Lag

High water, however, does not occur at the moment of the moon's passage across the meridian. There is a time lag known as the "high water lunitidal interval," which we shall see amounts to about eight hours at Fort Hamilton. There is also, of course, a lag in the time of low water after the moon's meridian passage, known as the "low water lunitidal interval," which, at Fort Hamilton, amounts to about 1.6 hours. (See Table I).

TIDAL DATUM PLANES

The tidal planes of reference form the basis of all rational datum planes for elevations used in engineering or scientific work. Each plane is the imaginary horizontal surface containing all points at the specified level.

Tidal Planes

The principal tidal plane is that of <u>mean sea level</u>, which may be defined as the surface the sea would assume if undisturbed by the rise and fall of the tide. The height of mean sea level is best derived by adding the hourly heights of the tide over a period of a year or more and computing the mean hourly height.

The planes of <u>mean high water</u> and <u>mean low water</u> are determined as the average of all the high waters and low waters over a period of a year or more.

The plane of <u>half-tide level</u> or <u>mean tide level</u> lies half-way between the planes of mean low water and mean high water. On the open coast the plane of mean tide level does not ordinarily differ from the plane of mean sea level by more than a tenth of a foot, but in some localities there is a considerable difference.

The tidal planes here described are the principal ones and the ones most generally used. The other planes, sometimes used, are not necessary for understanding the subject matter of this report.

Before proceeding to the examination of the tidal phenomena in New York Harbor, we should call to mind that there will probably be a difference between the observed behavior of the tides and what it should be theoretically, as it is only in protected waters during periods of calm weather that the tide curve is free from irregularities.

Effect of Wind

The principal disturbing agency is the wind. It is a well-known fact that onshore winds tend to raise the level of the water along the coast, while offshore winds tend to lower it. The extent to which the waters are raised or lowered depends not only on the direction and velocity of the wind, but also on local hydrographic features, places situated on shallow waters being generally most affected.

TIDES IN THE NEW YORK-AREA

THE RECORD OF TIDES AT FORT HAMILTON

Tidal Observations

The record of the tides at Fort Hamilton constitutes the longest continuous series of observations in New York Harbor. Observations were begun in 1893 by the U. S. Coast and Geodetic Survey, using a standard Coast and Geodetic Survey tide gauge. In 1921 the work was taken over by the U. S. Engineer Office of the War Department, which now maintains the tide station.

THE LUNITIDAL INTERVAL

Due to the changes in the relative positions of the sun and moon, the lunitidal interval at Fort Hamilton varies from day to day. Changes in wind and weather also affect the length of the lunitidal interval, but ordinarily it varies less than an hour from the mean. (See Table I).

High and Low water Intervals

If we take the 19 year period, 1912 to 1930, as giving the best determination, we derive 7.64 hours for the high water interval (H.W.I.) and 1.63 hours for the Low Water Interval (L.W.I). It is pertinent to note here that the Low Water Interval given is the time elapsed after that transit of the moon, which causes the succeeding high water.

DURATION OF RISE AND FALL

Since the lunar day is approximately 24.84 hours, it is obvious that at places such as Fort Hamilton, where there are two tidal cycles daily, the duration of each cycle will be 12.42 hours. (See Table 2).

TABLE I

ANNUAL VARIATION

IN LUNITIDAL INTERVALS -- FORT HAMILTON

1893 - 1911		
MONTH	HWI	LWI
Jan.	7.72	1.64
Feb.	7.75	1.66
Mar.	7.68	1.59
Apr.	7.63	1.56
May	7.64	1.60
June	7.67	1.66
July	7.72	1.69
Aug.	7.71	1.70
Sept.	7.72	1.70
Oct.	7.76	1.69
Nov.	7.77	1.71
Dec.	7.72	1.67
Mean	7.71	1.66
1912 - 1930		
Jan.	7.69	1.62
Feb.	7.65	1.61
Mar.	7.59	1.55
Apr.	7.53	1.52
May	7.60	1.58
June	7.59	1.62
July	7.65	1.64
Aug.	7.65	1.67
Sept.	7.69	1.69
Oct.	7.67	1.67
Nov.	7.70	1.68
Dec.	7.71	1.67
Mean	7.64	1.63

TABLE 2

DURATION OF RISE - FORT HAMILTON

(Annual Means - 1893 to 1932)

YEAR	HOURS
1893	6.06
1894	6.04
1895	6.07
1896	6.07
1897	6.09
1898	6.08
1899	6.07
1900	6.04
1901	6.06
1902	6.02
Sum	60.60
Mean	6.06
1903	6.03
1904	6.04
1905	6.03
1906	6.04
1907	6.01
1908	6.06
1909	6.07
1910	6.02
1911	6.04
1912	6.03
Sum	60.37
Mean	6.04

YEAR	HOURS
1913	6.06
1914	6.05
1915	6.02
1916	5.98
1917	6.00
1918	5.99
1919	6.01
1920	6.04
1921	6.05
1922	6.04
Sum	60.24
Mean	6.02
1923	6.02
1924	6.01
1925	5.99
1926	5.97
1927	6.03
1928	5.94
1929	6.04
1930	6.06
1931	6.09
1932	6.06
Sum	60.21
Mean	6.02

Flood and Ebb. Periods

Taking the mean of the 19 year period from 1912-1930 inclusive as probably giving the best determination, the average duration of rise at Fort Hamilton is found to be 6.01 hours, and the average duration of fall, 6.41 hours. As noted with regard to the lunitidal interval, the variation from the average is not great, being generally less than one hour. The greatest duration of rise occurs in the winter and the least in the summer. Of course, the corresponding duration of fall will increase or decrease in such degree as to produce a total duration of tidal cycle of 12.42 hours.

PLANES OF HIGH WATER

The height to which high water rises varies from day to day, as was indicated in our discussion of the moon's variations and meteorological changes. The plane of mean high water at Fort Hamilton is derived from the average height of all the high waters recorded. (See Table 3).

Mean High Water

Taking the result from the 19 year series, 1912 to 1930 as best representing present day condition, mean high water at Fort Hamilton is 2.33 feet above mean sea level.

The phase age, or lag in occurrence of spring tide after a full or new moon, is about 27 hours at Fort Hamilton, but this may vary considerably, since it is affected by the moon's parallax and declination.

Perigean And Apagean High water

The average spring tide at Fort Hamilton is found after observation to be about 19 per cent higher than mean high water, or 2.77 feet (2.33 ft. +19 per cent). The average neap tide at Fort Hamilton is 20 per cent less than mean high water of 1.86 ft. (2.33 ft. - 20 per cent).

The changes in height of tide due to the varying distance of the moon from the earth are as follows:

TABLE 3

HIGH WATER ABOVE SEA LEVEL - FORT HAMILTON

(Annual Means Corrected For Longitude Of Moon's Node)

YEAR	FEET
1893	2.26
1894	2.26
1895	2.26
1896	2.30
1897	2.29
1898	2.28
1899	2.28
1900	2.29
1901	2.26
1902	2.29
Sum	22.77
Mean	2.28
1903	2.30
1904	2.32
1905	2.31
1906	2.29
1907	2.32
1908	2.32
1909	2.33
1910	2.34
1911	2.32
1912	2.33
Sum	23.18
Mean	2.32

YEAR	FEET
1913	2.32
1914	2.30
1915	2.31
1916	2.32
1917	2.32
1918	2.34
1919	2.30
1920	2.33
1921	2.32
1922	2.34
Sum	23.20
Mean	2.32
1923	2.32
1924	2.36
1925	2.34
1926	2.34
1927	2.32
1928	2.34
1929	2.35
1930	2.33
1931	2.33
1932	2.32
Sum	23.35
Mean	2.34

The plane of perigean high water is 2.88 feet above mean sea level or 24 per cent higher than mean high water (M.H.W.).

The plane of apogean high water is 1.87 feet above mean sea level or 19 per cent less than mean high water.

At the time of tropic tides, which occurs at the time of the moon's maximum semi-monthly declination, when the difference in daily tides is a maximum, the resulting high waters at Fort Hamilton are as follows:

The plane of *tropic higher high water* is 2.70 feet above mean sea level, or 16 per cent greater than mean high water.

The plane of *tropic lower high water* is 1.71 feet above mean sea level, or 26 per cent less than mean high water.

Extreme High Water

In addition to the high waters caused by periodic variations of the heavenly bodies, we have the high water planes caused by meteorological changes, known as the plane of extreme or storm high water and the plane of highest high water. While not strictly tidal datum planes, these planes are of considerable practical value. *Extreme high water* for any year is the average of the highest high waters of *each month*. At Fort Hamilton it is 4.13 feet above mean sea level. The plane of *highest high water* is the average over a period of years of the highest high waters of each of the *years*. For the period of 1912-1930 the height of this latter plane is 5.13 feet above mean sea level, or 120 per cent greater than the plane of mean high water.

PLANES OF LOW WATER

For each of the high water datum planes discussed, there is a corresponding low water datum plane. Most important, of course, is the plane of mean low water. The average height of this plane over the period 1912 to 1930 is 2.42 feet below mean sea level. (See Table 4).

For heights of other low water planes see Table 6.

RANGE OF TIDE

Range of Tide

The mean range of the tide at Fort Hamilton for the period 1912-1930 is 4.75 feet. (See Table 5). In recent years the range has shown an increase of about 0.11 feet, the rise increasing 0.06 feet and the fall increasing 0.05 feet. This augmentation in range must be ascribed to the deepening of the channel, leading from the sea into the Narrows. Other ranges representing the distances between corresponding datum planes already discussed, are shown in Table 6.

EFFECT OF WIND AND WEATHER

When the relative position of the moon and sun is most favorable for the occurrence of a high high water, that is, at the time of a tropic higher high water that occurs when the moon is full or new and also in perigee, the increase of high water over mean high water should be about as follows:

Increase caused by tropic high water -- 16%
Increase caused by spring high water -- 19%
Increase caused by perigean highwater-- 24%
Total-- 59%

Fort Hamilton Tides

Thus, high water, under these propitious circumstances, should be 59% greater than mean high water, or 3.70 feet above mean sea level (2.33 ft. + 59%). Similarly, low water under most favorable circumstances should be 49% lower than mean low water, or 3.60 feet below mean sea level (2.42 feet + 49%). But our records at Fort Hamilton show high waters considerably higher and low waters considerably lower than the theoretical extremes. In fact, the plane of extreme high water is 4.13 feet above and the plane of

TABLE 4

LOW WATER BELOW SEA LEVEL - FORT HAMILTON

(Annual Means Corrected For Longitude Of Moon's Node)

YEAR	FEET
1893	2.35
1894	2.35
1895	2.36
1896	2.38
1897	2.37
1898	2.36
1899	2.34
1900	2.34
1901	2.36
1902	2.38
Sum	23.59
Mean	2.36
1903	2.39
1904	2.38
1905	2.37
1906	2.37
1907	2.40
1908	2.41
1909	2.38
1910	2.41
1911	2.43
1912	2.43
Sum	23.97
Mean	2.40

YEAR	FEET
1913	2.40
1914	2.41
1915	2.42
1916	2.44
1917	2.43
1918	2.41
1919	2.41
1920	2.44
1921	2.40
1922	2.42
Sum	24.18
Mean	2.42
1923	2.40
1924	2.45
1925	2.43
1926	2.41
1927	2.41
1928	2.43
1929	2.44
1930	2.40
1931	2.41
1932	2.41
Sum	24.19
Mean	2.42

TABLE 5

RANGE OF TIDE - FORT HAMILTON

(Annual Means Corrected For Longitude Of Moon's Node)

YEAR	FEET
1893	4.61
1894	4.61
1895	4.62
1896	4.66
1897	4.66
1898	4.64
1899	4.62
1900	4.64
1901	4.63
1902	4.67
Sum	46.36
Mean	4.64
1903	4.69
1904	4.70
1905	4.68
1906	4.66
1907	4.72
1908	4.72
1909	4.70
1910	4.75
1911	4.75
1912	4.76
Sum	47.13
Mean	4.71

YEAR	FEET
1913	4.71
1914	4.71
1915	4.74
1916	4.76
1917	4.75
1918	4.75
1919	4.72
1920	4.76
1921	4.72
1922	4.76
Sum	47.38
Mean	4.74
1923	4.72
1924	4.81
1925	4.78
1926	4.75
1927	4.73
1928	4.76
1929	4.78
1930	4.73
1931	4.73
1932	4.72
Sum	47.51
Mean	4.75

TABLE 6

SUMMARY OF TIDAL DATA - FORT HAMILTON - NEW YORK, N. Y.

THE RELATIONS

HIGH-WATER INTERVAL	HOURS - 7.64
LOW WATER INTERVAL	HOURS - 1.63
DURATION OF RISE	HOURS - 6.01
DURATION OF FALL	HOURS - 6.41
PHASE AGE	HOURS -26.50
PARALLEX AGE	HOURS -30.00
DIURNAL AGE	HOURS - 4.60

SEQUENCE OF TIDES IS HHW TO LLW.

RANGES

MEAN RANGE	FEET - 4.75
GREAT DIURNAL RANGE	FEET - 5.29
SMALL DIURNAL RANGE	FEET - 4.17
GREAT TROPIC RANGE	FEET - 5.34
SMALL TROPIC RANGE	FEET - 3.73
SPRING RANGE	FEET - 5.65
NEAP RANGE	FEET - 3.76
PERIGEAN RANGE	FEET - 5.77
APOGEAN RANGE	FEET - 3.85
EXTREME RANGE	FEET - 8.06
GREATEST RANGE	FEET - 12.80

HEIGHT RELATIONS

MEAN HIGH WATER ABOVE MEAN SEA LEVEL	FEET - 2.33
MEAN HIGHER HIGH WATER ABOVE MEAN SEA LEVEL	FEET - 2.65
MEAN LOWER HIGH WATER ABOVE MEAN SEA LEVEL	FEET - 1.98
TROPIC HIGHER HIGH WATER ABOVE MEAN SEA LEVEL	FEET - 2.70
TROPIC LOWER HIGH WATER ABOVE MEAN SEA LEVEL	FEET - 1.71
SPRING HIGH WATER ABOVE MEAN SEA LEVEL	FEET - 2.77
NEAP HIGH WATER ABOVE MEAN SEA LEVEL	FEET - 1.86
PERIGEAN HIGH WATER ABOVE MEAN SEA LEVEL	FEET - 2.88
APOGEAN HIGH WATER ABOVE MEAN SEA LEVEL	FEET - 1.87
EXTREME HIGH WATER ABOVE MEAN SEA LEVEL	FEET - 4.13
HIGHEST HIGH WATER ABOVE MEAN SEA LEVEL	FEET - 6.41
MEAN LOW WATER BELOW MEAN SEA LEVEL	FEET - 2.42
MEAN LOWER LOW WATER BELOW MEAN SEA LEVEL	FEET - 2.64
MEAN HIGHER LOW WATER BELOW MEAN SEA LEVEL	FEET - 2.18
TROPIC LOWER LOW WATER BELOW MEAN SEA LEVEL	FEET - 2.64
TROPIC HIGHER LOW WATER BELOW MEAN SEA LEVEL	FEET - 2.02
SPRING LOW WATER BELOW MEAN SEA LEVEL	FEET - 2.88
NEAP LOW WATER BELOW MEAN SEA LEVEL	FEET - 1.90
PERIGEAN LOW WATER BELOW MEAN SEA LEVEL	FEET - 2.89
APOGEAN LOW WATER BELOW MEAN SEA LEVEL	FEET - 1.98
EXTREME LOW WATER BELOW MEAN SEA LEVEL	FEET - 3.93
LOWEST LOW WATER BELOW MEAN SEA LEVEL	FEET - 6.50
HALF-TIDE LEVEL BELOW MEAN SEA LEVEL	FEET - 0.04

extreme low water is 3.93 feet below mean sea level, and considerably greater tides have been recorded. The discrepancy is due to changes in wind and weather. By noting the weather that has prevailed on the days when the highest and lowest tides occurred, we find that highest high waters generally come with strong north easterly winds. Furthermore, higher high waters come almost invariably with a falling barometer. Observation shows that extreme tides are due not to change in range of tide, but to an unusual rise or fall of sea level. Thus, it would appear that storms affect the sea level in general and not the specific range of the tide.

SUMMARY

A summary of tidal data at Fort Hamilton will be found in Table 6.

THE TIDES IN LOWER NEW YORK BAY

Tides have been observed, also, in Lower Bay at a number of places, and for various periods of time, generally for periods much shorter than the series of observation at Fort Hamilton for the purpose of this discussion, Sandy Hook Bay are included as a part of the Lower Bay.

Sandy Hook Tide

As compared with the tide at Fort Hamilton, the tide at Sandy Hook is a tenth of a foot less in range and about 3 minutes earlier. In this connection, it is to be noted that, in general, the direct difference between the lunitidal intervals at two stations does not give the difference in time of tide at the two stations, except when the two stations have the same longitude. A correction of 0.069 of an hour per degree of difference in longitude must be applied. In the western hemisphere this correction is added to the time of tide of the station of greater longitude. Tides in Lower New York Bay rise higher and fall lower on the northern shore, being greater by more than 0.10 ft. This is probably due to the rotation of the earth, which in the northern hemisphere deflects moving bodies to the right of the direction of movement. On the rising tide the water moving into Lower Bay is deflected to the right, or northern shore. On the falling tide the ebbing waters are again deflected to the right, but now it is the southern shore that is to the right of the moving water. The tide, therefore, rises higher and falls lower on the northern shore, giving a greater range here than on the southern shore. (78)

Raridan Bay

From table 7 it is seen that time of tide throughout the Lower Bay does not change to any considerable extent. Toward the western end of the bay the duration of rise is seen to decrease due to the influence of the non-tidal waters flowing from the Raritan River. Toward the western end, also, the range of tide increases, and this, probably is due to the rapidly converging shore lines, though possibly to the tides meeting the river water flowing into the Bay.

TABLE 7

TIDAL DATA - LOWER BAY

Locality	Lunitidal Intervals		Duration of rise in Hours	Mean Range in Feet
	HWI in Hours	LWI in Hours		
Sandy Hook, N. J.	7.59	1.48	6.11	4.68
Sandy Hook, N. J.	7.61	1.57	6.04	4.56
Romer Shoal Light, N. Y.	7.48	1.37	6.11	4.53
Port Monmouth, N. J.	7.53	1.78	5.75	4.65
Conaskonk Point, N. J.	7.57	1.63	5.94	5.02
Keyport, N. J.	7.52	1.55	5.97	4.98
South Amboy, N. J.	7.75	1.83	5.92	5.07
Perth Amboy, N. J.	7.95	1.89	6.06	5.28
Red Bank, N. Y.	7.40	1.43	5.97	5.22
Great Kills, N. Y.	7.50	1.53	5.97	5.07
New Dorp Beach, N. Y.	7.55	1.62	5.93	4.82
16th Ave. Bklyn, N. Y.	7.61	1.53	6.08	4.71
Gravesend Bay, N. Y.	7.52	1.60	5.92	4.64
Gravesend Bay, N. Y.	7.67	1.48	6.19	4.53
Norton Point, N. Y.	7.45	1.23	6.22	4.87
Coney Island, N. Y.	7.65	1.33	6.32	4.92
Coney Island, N. Y.	7.50	1.15	6.35	4.82

THE TIDES IN THE NARROWS AND UPPER NEW YORK BAY

Table 8 lists the results of tidal observations in the Narrows and Upper New York Bay. The actual difference in time of tide between Fort Hamilton and the Battery is seen to be 0.47 hours. Now, the distance along the channel between Fort Hamilton and the Battery is six nautical miles and the average depth of the channel is twenty-six feet. Using the formula $r = \sqrt{gh}$ for the rate of advance of a progressive wave, and substituting the depth, 26 feet

Tide At The Battery

for "h", we determine "r" to be 17.1 knots per hour. This formula is based on Airy's theory that the true velocity of the tidal wave is the same as that which a free body would acquire by falling from rest under the action of gravity through a space equal to half the depth of the water. At this theoretical rate the tide wave should move from Fort Hamilton to the Battery in 0.35 hours. This approximates the 0.47 hour obtained from observation, and we may, therefore, conclude that through the Narrows and Upper Bay the tidal movement is of the progressive wave type.

Throughout the area the duration of rise is approximately six hours, giving the fall a duration of about 6.4 hours. Within the Narrows the range decreases about a tenth of a foot from south to north as a result of the gradually diverging shore lines, and a further decrease of about a tenth of a foot prevails in Upper Bay.

TABLE 8

TIDAL DATA - THE NARROWS AND UPPER BAY

LOCALITY	LUNITIDAL INTERVALS		DURATION OF RISE IN HOURS	MEAN RANGE IN FEET
	HWI IN HOURS	LWI IN HOURS		
Fort Hamilton, N. Y.	7.64	1.63	6.01	4.75
92nd St., Bklyn, N.Y.	7.76	1.65	6.11	4.62
83rd St., Bklyn, N.Y.	7.82	1.75	6.07	4.64
72nd St., Bklyn, N.Y.	7.85	1.78	6.07	4.62
68th St., Bklyn, N.Y.	7.86	1.83	6.03	4.63
Bay Ridge, N.Y.	7.91	1.90	6.01	4.53
51st St., Bklyn, N.Y.	7.90	1.88	6.02	4.63
Gowanus Canal, Bklyn, N.Y.	7.95	1.93	6.02	4.65
Erie Basin (South side) Bklyn, N.Y.	7.99	1.83	6.16	4.66
Van Dyke St., Bklyn, N.Y.	8.04	1.97	6.07	4.67
Atlantic Basin, Bklyn,N.Y.	8.07	2.02	6.05	4.60
Hamilton Ave., Bklyn, N.Y.	8.07	2.13	5.94	4.40
Governors Island, N.Y.	8.10	2.06	6.04	4.49
Governors Island, N.Y.	8.10	2.25	5.85	4.45
Governors Island, N.Y.	8.21	2.13	6.08	4.45
The Battery, N.Y.	8.11	2.11	6.00	4.52
Fort Wadsworth, S. I.	7.73	1.65	6.08	4.56
Fort Wadsworth, S. I.	7.77	1.67	6.10	4.46
Fort Wadsworth, S. I.	7.77	1.69	6.08	4.48
Rosebank, S. I.	7.81	1.58	6.23	4.39
Clifton, S. I.	7.81	1.72	6.09	4.48
Stapleton, S. I.	7.76	1.75	6.01	4.48
Stapleton, S. I.	7.88	1.76	6.12	4.47
St. George, S. I.	8.07	2.07	6.00	4.34
St. George, S. I.	7.90	1.85	6.05	4.48
St. George, S. I.	7.93	1.87	6.06	4.52
Bayonne, N. J.	7.95	2.03	5.92	4.52
Claremont, N. J.	8.05	1.94	6.11	4.41
Jersey City, N. J.	8.02	2.13	5.89	4.45

Summaries of the tidal characteristics at Governors Island and at the Battery are contained in Table 9. For purposes of comparison, tidal characteristics at Fort Hamilton are also included.

TABLE 9

TIDAL DATA - THE NARROWS AND UPPER BAY

		FORT HAMILTON	GOVERNORS ISLAND	THE BATTERY
Mean range	Feet	4.75	4.50	4.45
Great diurnal range	"	5.29	4.83	4.79
Small diurnal range	"	4.17	4.17	4.11
Great tropic range	"	5.34	4.92	4.86
Small tropic range	"	3.73	3.66	3.58
Spring range	"	5.65	5.39	5.32
Neap range	"	3.76	3.53	3.50
Perigean range	"	5.77	5.40	5.38
Apogean range	"	3.85	3.88	3.68
Phase age	Hours	26.5	25.6	25.2
Parallax age	"	30.9	37.8	36.7
Diurnal age	"	4.6	1.8	0.0

It is of interest to note that, with the exception of the apogean range at Governors Island, the various tidal ranges decrease from Fort Hamilton to the Battery.

ARTHUR KILL

Tide in Arthur Kill

The length of Arthur Kill measured along the channel is about 11½ nautical miles, and while the channel has depth of 30 feet at mean low water, the average depth over the entire waterway is about 18½ feet measured from mean sea level. From Table 10 it is seen that the tide becomes later along Arthur Kill from Lower Bay to Newark Bay, the difference being about 0.7 hour. Theoretically, a progressive wave would traverse the distance in 0.8 hour, which approximates the observed 0.7 hour, indicating that the tide through Arthur Kill is of the progressive wave type.

The range of tide is greater by about 0.3 foot at the southern entrance than at the northern. The duration of rise is approximately the same throughout Arthur Kill, being about 5.9 hours as against a duration of fall of about 6.5 hours.

TABLE 10

TIDAL DATA - ARTHUR KILL

LOCALITY	LUNITADAL INTERVALS		DURATION OF RISE IN HOURS	MEAN RANGE FEET
	HWI IN HOURS	LWI IN HOURS		
Perth Amboy, N.J.	7.95	1.89	6.06	5.28
Perth Amboy, N.J.	7.72	1.82	5.90	5.15
Perth Amboy, N.J.	7.95	1.96	5.99	5.07
Tottenville, S.I., N.Y.	7.93	1.70	6.23	4.98
Rossville, N.Y.	8.02	2.02	6.00	5.12
Cartaret, N.J.	8.38	2.37	6.01	5.18
Cartaret, N.J.	8.30	2.36	5.94	5.16
Near Pralls Creek, N.Y.	8.52	2.42	6.10	5.25
Elizabeth, N.J.	8.22	2.45	5.77	5.00
Elizabeth, N.J.	8.47	2.33	6.14	4.99
Elizabeth, N.J.	8.62	2.62	6.00	4.75

KILL VAN KULL

The tidal data derived from observations in Kill Van Kull are shown in Table 11. The tide at the eastern end is seen to be about twenty minutes earlier than at the western end. The duration of rise throughout the waterway is approximately 6.1 hours, giving for the duration of fall a period of 6.3 hours.

TABLE 11

TIDAL DATA - KILL VAN KULL

LOCALITY	LUNITIDAL INTERVALS		DURATION OF RISE IN HOURS	MEAN RANGE FEET
	HWI IN HOURS	LWI IN HOURS		
Constable Point, N.J.	7.97	1.90	5.98	4.47
Constable Point, N.J.	8.12	1.95	6.17	4.50
Bergen Point, N.J.	8.28	2.32	5.96	4.64
Bergen Point, N.J.	8.35	2.13	6.22	4.64
New Brighton, N.Y.	8.03	1.87	6.16	4.48
West New Brighton, N.Y.	8.20	2.13	6.07	4.48
Port Richmond, N.Y.	8.38	1.87	6.51	4.48
Port Richmond, N.Y.	8.36	2.52	5.84	4.49

NEWARK BAY

Data derived from observations in Newark Bay are shown in Table 12. From the east, Newark Bay receives the tide from Kill Van Kull, while from the west it receives the tide from Arthur Kill, and throughout the Bay the range of tide approximates that of the tides coming from Arthur Kill and from Kill Van Kull.

With regard to time in the lower part of the Bay, the duration of rise is between 5-3/4 and 6 hours, while in the upper part in the entrance to the Passaic and Hackensack Rivers, it is 5-1/2 hours or less.

TABLE 12

TIDAL DATA - NEWARK BAY

LOCALITY	LUNITIDAL INTERVALS		DURATION OF RISE IN HOURS	MEAN RANGE FEET
	HWI IN HOURS	LWI IN HOURS		
Mariners Harbor, N.Y.	8.45	2.46	5.99	4.76
Shooters Island, N.Y.	8.32	2.43	5.89	4.59
Bergen Point Light, N.J.	8.70	2.57	6.13	4.41
Off Bayonne, N.J.	8.40	1.83	6.57	4.42
Port Newark, N.J.	8.58	2.84	5.74	4.73
Off Newark, N.J.	8.54	2.71	5.83	4.93
Greenville, N.J.	8.70	3.00	5.70	4.58
Hackensack River, N.J.	8.48	3.25	5.23	4.58
Passaic River, N.J.	8.85	3.33	5.52	4.73

THE TIDE IN THE HUDSON RIVER

The tide in the Hudson is of the progressive wave type, advancing approximately at a rate equal to the square root of gh. Table 13 contains most of the data as observed by the United States Coast and Geodetic Survey.

TABLE 13

TIDAL DATA - HUDSON RIVER

LOCALITY	LUNITIDAL INTERVALS		DURATION OF RISE IN HOURS	MEAN RANGE IN FEET
	HWI IN HOURS	LWI IN HOURS		
The Battery - Pier A	8.11	2.11	6.00	4.52
Chambers Street	8.14	2.15	5.99	4.41
Christopher Street	8.19	2.20	5.99	4.40
20th Street	7.80	2.18	5.62	4.31
22nd Street	8.28	2.25	6.03	4.40
28th Street	7.92	2.10	5.82	4.55
41st Street	8.28	2.30	5.98	4.16
42nd Street	8.34	2.35	5.99	4.28
43rd Street	8.23	2.17	6.06	4.31
70th Street	8.47	2.45	6.02	4.19
96th Street	8.27	2.48	5.79	4.11
98th Street	8.58	2.57	6.01	4.05
129th Street	8.71	2.63	6.08	4.13
155th Street	8.43	2.62	5.81	4.28
156th Street	8.80	2.77	6.03	3.97
157th Street	8.94	2.90	6.04	3.77
George Washington Bridge	8.79	2.74	6.05	4.15
Tubby Hook	8.94	2.84	6.10	3.92
Spuyten Duyvil	9.22	3.06	6.16	3.78
Riverdale	9.40	3.09	6.31	3.71
Yonkers	9.45	3.37	6.08	3.65
Alpine	9.44	3.33	6.11	3.59
Irvington	9.66	3.68	5.98	3.38
Tarrytown	10.10	4.10	6.00	3.25
Nyack	10.08	4.22	5.86	2.82
Ossining	10.39	4.65	5.74	3.07
Haverstraw	10.52	4.96	5.56	2.89
Peekskill	10.65	5.18	5.47	2.85
Iona Island	10.52	5.22	5.30	2.79
West Point	10.54	5.57	4.97	2.60

(continued on next page)

TABLE 13 (cont'd)

Newburgh	12.14	6.35	5.79	2.64
Beacon	11.77	6.07	5.70	2.59
Poughkeepsie	0.03	7.51	4.94	2.95
Hyde Park	0.62	7.27	5.77	3.11
Barrytown	1.07	7.73	5.76	4.09
Catskill	1.85	8.51	5.76	4.08
Van Wies Point	4.75	12.38	4.79	1.98
Albany	5.02	12.19	5.25	3.57
Troy	6.13	1.33	4.80	1.42

Seasonal Changes

The computed tides in the Hudson differ considerably from the observed tides due to seasonal changes in the quantity of drainage water and the effect of storms. Previous to the tropical storm of September 21, 1938, the highest tides recorded at the Battery, near the mouth of the river, were 6.0 feet above mean sea level on February 20th, 1927, and 6.2 feet above mean sea level on November 10th, 1932. The astronomical conditions on February 20th, 1927, were such as would be expected to cause a tide below the average. This exceptionally high water resulted from a very severe storm which had been raging over the North and Middle Atlantic States for two days. Meteorological records for February, 1920, show that for the three days preceding the 20th of February a northeast wind prevailed. The wind on February 20th was northeast by east, averaging about twenty-one miles per hour. For the four days from February 17th to February 20th inclusive, the wind was of moderate velocity, averaging 15.8 miles per hour. However, the controlling factor appears to have been the persistency of the northeast wind over the preceding three day period, causing a gradual piling up of the water in the Bay and resulting in the abnormally high tide of February 20th. Similar weather conditions accompanied the unusually high tide of November 10th, 1932. For the three days preceding November 10th, the prevailing wind was from the northeast and varied between northeast and northwest on the 10th. As with the previous exceptionally high water, the velocity of the wind was moderate, averaging 13.2 miles per hour from November 7th to 10th inclusive. Again, the persistency of the northeast wind appears to have been the controlling factor.

Hudson At Mouth

The highest high tide recorded at the Battery was 6.4 feet above mean sea level on September 21st, 1938. The date is that of the tropical storm which caused considerable damage to the North Atlantic seaboard. The extreme high tide of that day is unusual, not only for its height, but for the fact that it occurred about two hours before the predicted time of high water when, theoretically, the purely tidal waters were about half way between mean sea level and the plane of high water. At the Battery, as well as at other tide gauges in the New York area, there were two high waters instead of the scheduled one. The second high tide at the Battery occurred about four hours after scheduled high tide, and rose to about the height of mean high water. The wind on the 21st of September reached a maximum velocity of seventy miles per hour from the northwest. The average wind velocity for the day was 29.2 miles per hour, the prevailing direction being north. The atmospheric pressure on September 21st dropped to 28.72 inches, which was the lowest September reading since 1882.

Tide At Albany

Extreme high waters at Albany are given in Table 14, which includes heights that have been reported as being 14 feet or more above the datum of the tabulations, which is 2 feet below the Sandy Hook sea level datum.

Albany High Water

The two highest waters recorded at Albany occurred on February 9th, 1857, and March 28, 1913. Each of these reached a height of approximately 23-1/2 feet above the datum of tabulations, or 21-1/2 feet above the Sandy Hook sea level datum. The high water of 1857 resulted from an ice gorge above Van Weis Point. That of 1913 was due to a freshet that followed unusually heavy rains during the latter part of March and the rapid melting of snow in the Adirondacks caused by the mildness of the weather. The height reached by the water below the dam at Troy was 29-1/2 feet above the sea level datum, or 8 feet higher than at Albany, making a slope of a little more than 1 foot per mile.

Extreme low waters at Albany are given in Table 15, which includes the lowest recorded tide for each year from 1920 to 1932.

Albany Low Water

It is interesting to note that for each of the last three years the extreme low water at Albany occurred on the same date as the lowest tide for the same year at the Battery, and during the two preceding years the extreme low water at Albany occurred when the tides were exceptionally low at the Battery, although not the lowest for the year. This indicates that at low water stages the tides at Albany reflect somewhat the tidal conditions at the mouth of the river. Similar conditions, however, cannot be expected at the high water stages which result largely from excessive drainage into the river.

Hudson River Tide Relations

Figures 6, 7 and 8, which appear in a later section of this report (CURRENT IN HUDSON RIVER), represent graphically the tide and current conditions in the Hudson from the Battery to Troy. The varying time relationships of the tides to the currents in the Hudson River are there discussed in detail.

TABLE 14

EXTREME HIGH WATER - ALBANY, N.Y.

(Datum is 2 ft. below Sandy Hook sea level)

DATE	HEIGHT IN FEET	DATE	HEIGHT IN FEET	DATE	HEIGHT IN FEET
1839 - Jan. 27	20.2	1901 - Dec. 12	16.0	1922 - Apr. 12-13	18.0
1846 - Mar. 15	20.7	1902 - Mar. 2	21.0	1923 - Apr. 7	15.0
1857 - Feb. 9	23.7	1903 - Mar. 2	18.8	1924 - Apr. 8	15.7
1869 - Jan. 11	20.5	1903 - Mar. 24	17.5	1925 - Feb. 12-13	14.2
1869 - Apr. 22	21.5	1903 - Oct. --	18.5	1926 - Apr. 26	14.1
1869 - Oct. 5	21.0	1910 - Jan. 23	15.8	1927 - Nov. 5	18.0
1876 - Feb. 6	16.5	1913 - Mar. 28	23.4	1927 - Dec. 9	14.2
1886 - Feb. 14	20.4	1914 - Mar. 29	16.8	1928 - Apr. 9	11.9
1887 - Apr. 12	17.5	1914 - Apr. 2	14.0	1929 - Mar. 16	14.7
1893 - Mar. 26	20.9	1914 - Apr. 9	15.8	1929 - Apr. 22	14.1
1893 - May 5	18.6	1914 - Apr. 21	17.5	1930 - Jan. 15	9.3
1895 - Apr. 10	18.4	1916 - Apr. 2	17.0	1930 - Mar. 9	9.3
1896 - Mar. 1	20.2	1920 - Mar. 17-18	14.5	1931 - July 22	8.6
1900 - Feb. 14	22.4	1920 - Mar. 27	15.1	1932 - Nov. 19	10.9
1901 - Apr. 22	16.5	1921 - Mar. 10	12.1		

TABLE 15

EXTREME LOW WATER - ALBANY, N.Y.

(Datum is 2 ft. below Sandy Hook sea level)

DATE	HEIGHT IN FEET	DATE	HEIGHT IN FEET	DATE	HEIGHT IN FEET
1920 - Aug. 23	0.8	1923 - Aug. 22	0.8	1928 - Dec. 30	0.3
1920 - Sept. 19	0.8	1924 - Nov. 17	1.8	1929 - Dec. 1	1.2
1921 - June 14	0.9	1925 - Oct. 11	0.2	1930 - Nov. 7	1.7
1921 - Oct. 23	0.9	1926 - Aug. 15	0.9	1931 - Dec. 8	2.2
1922 - Dec. 7	0.8	1927 - July 4	0.8	1932 - Mar. 8	1.7

TIDES IN THE EAST RIVER AND THE HARLEM RIVER

The East River and the Harlem River taken together comprise a system of straits which interconnect the Upper Bay, Long Island Sound and the Hudson River. The tidal phenomena in East and Harlem Rivers is therefore dependent upon tidal conditions in the bodies of water which they connect. In order to simplify as much as possible the complex system of waterways which they constitute, the East and Harlem Rivers will first be considered separately.

THE EAST RIVER

Affected By Two Tidal Sources

The East River connects Upper Bay on the west with Long Island Sound on the east. In the Upper Bay the tide has a range of 4-1/2 feet, while in the western end of Long Island Sound the range of tide is 7 feet. In like manner, the lunitidal interval varies from 8 hours (H.W.I.) in the Upper Bay to 5 hours in the Sound. It is evident then that East River derives its tide from two bodies of water, the tides in which differ by 3 hours in time and by nearly 3 feet in range.

Since East River is relatively narrow below (or west of) Hell Gate and wider and shallower above Hell Gate, it is convenient to divide the river into two sections, Lower East River and Upper East River.

LOWER EAST RIVER

Lower Bay To Hell Gate

Tables 16 and 17 contain the tidal data derived from observations in Lower East River. At the western end the durations of rise and fall are very nearly equal. Going upstream the rise becomes somewhat the longer, but at the entrance to Hell Gate the durations of rise and fall are again about equal. The range of tide changes from 4.4 feet at the westerly mouth to 4.9 feet at Hell Gate, but the rate of change is not constant; in fact, the range actually decreases for the first 2-1/2 miles. Therefore, with regard to range, as well as time, the tidal movement in the lower East River is not of the progressive wave type, but rather of the hydraulic type due to the instantaneous difference in head of water in Lower Bay and Long Island Sound.

TABLE 16

TIDAL DATA - LOWER EAST RIVER

WEST SHORE

(Battery to Hell Gate)

LOCALITY	LUNITIDAL INTERVALS		DURATION OF RISE IN HOURS	MEAN RANGE IN FEET
	HWI IN HOURS	LWI IN HOURS		
Barge Office Pier (Battery)	8.24	2.19	6.05	4.45
Whitehall St. (Battery)	8.29	2.19	6.10	4.41
Cuylers Lane	8.34	2.14	6.20	4.42
Fulton Street	8.46	2.26	6.20	4.41
Catherine Slip	8.56	2.34	6.22	4.34
Jefferson Street	8.72	2.34	6.38	4.33
Jackson Street	8.99	2.43	6.56	4.32
Corlears Hook	9.33	2.78	6.55	4.01
Rivington Street	9.09	2.70	6.39	4.22
East 5th Street	9.19	2.83	6.36	4.18
East 17th Street	9.35	3.06	6.29	4.22
East 18th Street	9.28	2.97	6.31	4.18
Bellevue Hospital	9.40	3.20	6.20	4.42
East 29th Street	9.37	3.12	6.25	4.23
East 40th Street	9.38	3.15	6.23	4.29
East 41st Street	9.77	3.33	6.44	4.11
Belmont Island	9.58	3.12	6.46	4.26
East 49th Street	9.46	3.18	6.28	4.36
Blackwells Is. (S.W. corner)	9.62	3.24	6.38	4.33
Blackwells Is. (No.of Queensboro Bridge)	9.63	3.32	6.31	4.42
East 61st Street	9.63	3.34	6.29	4.37
Blackwells Is. (opp. 71st St.)	9.77	3.43	6.34	4.50
Blackwells Is. (opp. 79th St.)	9.77	3.59	6.18	4.82
Blackwells Is. (opp. 84th St.)	9.90	3.80	6.10	4.88
East 80th Street	9.84	3.58	6.26	4.79
East 84th Street	10.10	3.87	6.23	4.90
East 86th Street	9.90	3.79	6.11	4.85
East 90th Street	10.05	3.85	6.20	4.90

TABLE 17

TIDAL DATA - LOWER EAST RIVER

EAST SHORE

(Hell Gate to Battery)

LOCALITY	LUNITIDAL INTERVALS HWI IN HOURS	LUNITIDAL INTERVALS LWI IN HOURS	DURATION OF RISE IN HOURS	MEAN RANGE IN FEET
Studio St. (Astoria)	10.01	3.82	6.19	4.98
Astoria	9.17	3.40	5.77	3.94
Halletz Cove	9.95	3.80	6.15	4.91
Gibbs Point	9.92	3.76	6.16	4.76
Blackwells Is. (Opp. Gibbs Pt.)	9.70	3.56	6.14	4.86
Webster Ave. (Long Is. City)	9.88	3.43	6.45	4.53
Freeman Ave. (Long Is. City)	9.64	3.34	6.30	4.48
Blackwells Is. (Opp. Harsell St.)	9.64	3.26	6.38	4.45
14th St. (Long Is. City)	9.55	3.18	6.37	4.38
3rd St. (Long Is. City)	9.39	3.06	6.33	4.29
Borden Ave. (Long Is. City)	9.72	3.31	6.41	4.14
Newtown Creek (Long Is. City)	9.86	3.15	6.71	4.07
Vernon Ave. (Long Is. City)	9.42	3.03	6.39	4.14
Dupont St., Brooklyn	9.39	3.01	6.38	4.25
Quay St., Brooklyn	9.26	3.01	6.25	4.11
N. 3rd St., Brooklyn	9.33	2.92	6.41	4.09
N. 2nd St., Brooklyn	9.20	2.88	6.32	4.18
S. 2nd St., Brooklyn	9.41	2.69	6.73	4.09
S. 6th St., Brooklyn	9.02	3.29	5.73	4.02
S. 10th St., Brooklyn	8.86	2.73	6.13	4.25
Fleeman St., Brooklyn	8.81	2.63	6.18	4.19
Navy Yard Basin, Brooklyn	8.95	2.80	6.15	4.16
Hudson Ave., Brooklyn	8.88	2.58	6.30	4.28
Adams St., Brooklyn	8.74	2.31	6.43	4.39
Fulton St., Brooklyn	8.55	2.17	6.38	4.42
Clark St., Brooklyn	8.25	2.12	6.13	4.48
State St., Brooklyn	8.16	2.12	6.04	4.52

UPPER EAST RIVER

Hell Gate To Long Island Sound

Table 18 and 19 contain data from observations in the Upper East River. The durations of rise and fall of tide are seen to be approximately equal at the lower end of Hell Gate, but within Hell Gate and the remainder of Upper East River the duration of fall exceeds the rise by about one hour. Continuing the trend of lower East River the range of the tide increases from Hell Gate to the entrance to Long Island Sound, changing rapidly through Hell Gate, but decreasing in rate of change in the end near Long Island Sound.

The observations considered above clearly indicate that the tide through the East River is decidedly different from that in the Hudson, a true tidal river. Thd East River may best be regarded as a channel through which the water flows from the body having temporarily the higher level to the one having the lower level. The height of the water in the river is therefore due to the relative elevations of the water at the ends.

TABLE 18

TIDAL DATA - UPPER EAST RIVER

NORTH SHORE

(Hell Gate to Long Island Sound)

LOCALITY	LUNITIDAL INTERVALS		DURATION OF RISE IN HOURS	MEAN RANGE IN FEET
	HWI IN HOURS	LWI IN HOURS		
Mill Rock	10.05	3.78	6.27	4.93
E. 94th St.	10.02	3.76	6.26	5.10
E. 100th St.	10.15	3.82	6.33	4.99
Wards I. (Near S.W.End)	10.17	4.00	6.17	5.06
Wards I. (Opp. E. 103rd St.)	9.83	3.82	6.01	5.14
Wards I. (Opp. E. 108th St.)	9.77	3.75	6.02	5.07
Wards I. (Opp. E. 109th St.)	9.70	3.73	5.97	4.89
Wards I. (Little Hell Gate)	9.79	3.51	6.28	4.74
Bronx Kill (Near East End)	11.49	5.82	5.67	6.32
Bronx Kill (East End)	11.81	5.61	6.20	6.80
Port Morris (E. 132nd St.)	11.26	5.46	5.80	6.37
Port Morris (E. 133rd St.)	11.59	5.86	5.73	6.32
Port Morris (E. 141st St.)	11.71	5.60	6.11	6.84
North Brother I. (west side)	11.30	5.66	5.64	6.47
North Brother I. (south side)	11.32	5.62	5.70	6.62
Port Morris	11.38	5.55	5.83	6.55
Rikers Island (north end)	11.32	5.50	5.82	6.61
Rikers Island (northeast cor.)	11.49	5.78	5.71	6.75
Hunt Point	11.50	5.85	5.65	6.91
Clason Point	11.34	5.59	5.75	7.01
Old Ferry Point	11.91	5.78	6.13	7.41
N.E. of Old Ferry Point	11.08	5.68	5.40	7.19
N.W. of Fort Schuyler	11.12	5.60	5.52	7.10
Fort Schuyler	11.27	5.58	5.69	7.18

TABLE 19

TIDAL DATA - UPPER EAST RIVER

SOUTH SHORE

(Long Island Sound to Hell Gate)

LOCALITY	LUNITIDAL INTERVALS		DURATION OF RISE IN HOURS	MEAN RANGE IN FEET
	HWI IN HOURS	LWI IN HOURS		
Willets Point	11.29	5.53	5.76	7.10
Whitestone	11.16	5.49	5.67	7.12
Nalba (Powell Cove)	11.17	5.50	5.67	7.01
Tallman I. (north end)	11.44	5.61	5.83	6.76
College Point Dry Dock	11.35	5.63	5.72	6.97
College Point	11.64	5.90	5.74	6.67
Flushing	11.43	5.66	5.77	6.82
East Elmhurst	11.48	5.70	5.78	6.67
Sanford Point	11.17	5.72	5.45	6.72
North Beach	11.51	5.92	5.59	6.57
Lawrence Point	11.40	5.75	5.65	6.55
Winthrop Ave.	11.11	5.43	5.68	6.13
Wolcott Ave.	11.05	5.33	5.72	6.27
Ditmars Ave.	9.40	5.84	5.56	5.56
Wards I. (opp. Wolcott Ave.)	10.51	5.56	4.95	6.35
Wards I. (Hell Gate Bridge)	10.71	5.35	5.36	5.96
Wards I. (Opp. Potter Ave.)	10.46	5.68	4.78	5.54
Wards I. (Negro Point)	10.25	4.95	5.30	5.46
Pott Cove (Hoyt Ave.)	10.63	4.67	5.96	5.25
Pot Cove	10.51	4.56	5.95	5.35
Hallets Point	11.27	5.58	5.69	5.64

GENERAL CHARACTER OF TIDES IN EAST RIVER

In figure 2 the simultameous heights of the water at the two ends of East River are represented for each lunar hour of the tidal cycle, hours being reckoned from the moon's transit at the Battery. The figures along the outside end vertical lines denote the height at the indicated hours. The hours are placed to the left of the inner vertical line for the rising tide and to the right for the falling tide. The slope lines which join simultaneous heights are drawn full when the slope is from Long Island Sound to Upper Bay and dashed when the slope is in the reverse direction. These slope lines thus permit the time and range of the tide throughout the river to be determined, since the time and height of the high water at any place will be represented by the highest point in the slope lines passing that place, while the low tide will be indicated by the lowest point. Fig. 2 indicates a greater volume of water flowing westward through the East River than in the reverse direction because the former prevails during higher stages of the local tide than the latter.

Tidal slope

Figure 2

EFFECT OF WIND ETC. ON TIDES

Obviously, this method can give only a first approximation, since changes in direction, depth or width of channel are not considered, but notwithstanding this, the principal tidal phenomena may be easily derived from the sketch as shown. However, no such method can be devised to take into account the effects of variable weather conditions which we must consider. From the information available, it appears that moderate easterly winds, particularly northeasterly, tend to raise the level of the waters of the East River as much as two feet, while westerly winds have the opposite effect to a somewhat less degree.

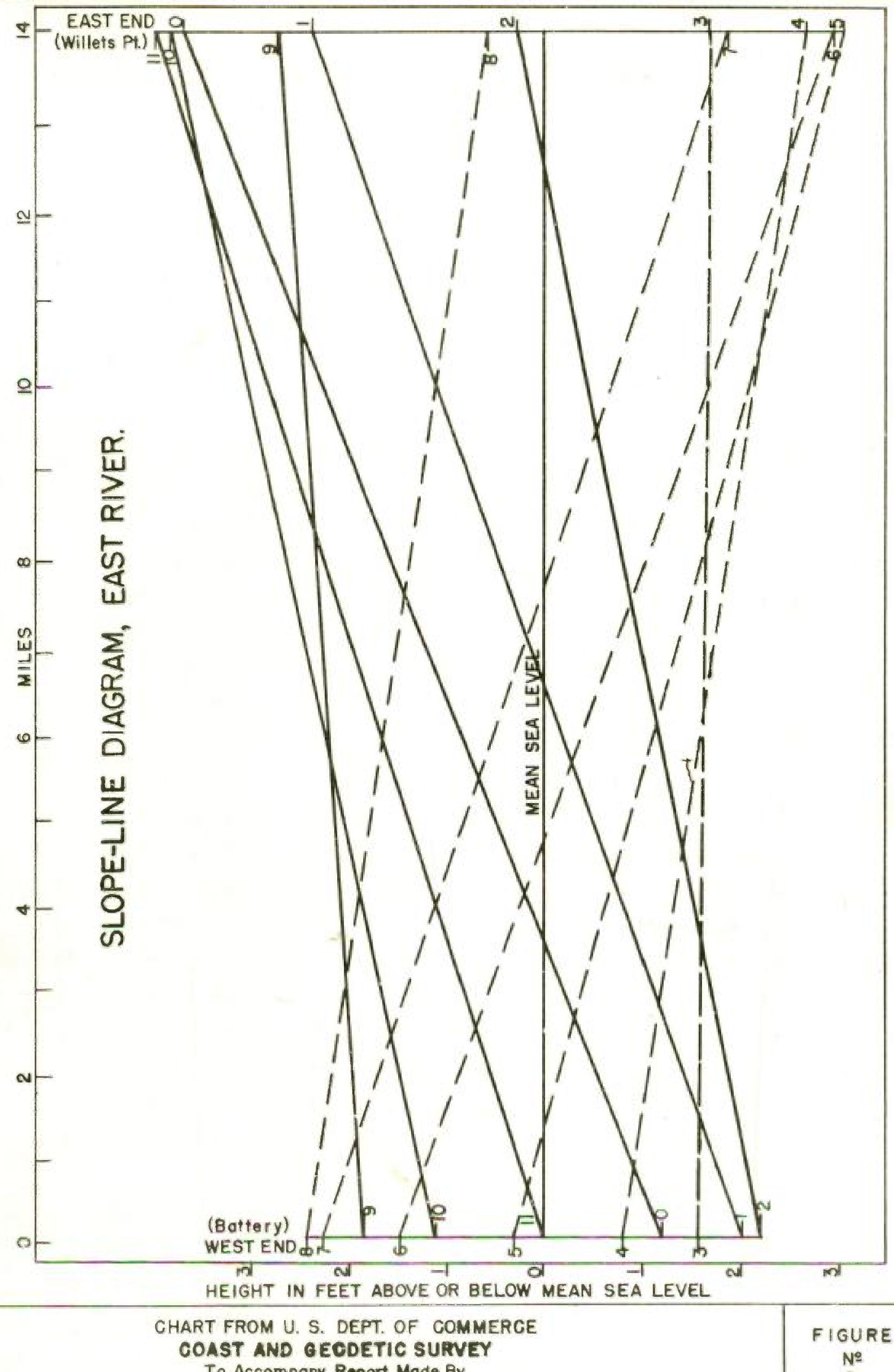

SLOPE-LINE DIAGRAM, EAST RIVER.

CHART FROM U. S. DEPT. OF COMMERCE
COAST AND GEODETIC SURVEY
To Accompany Report Made By
W.P.A WATER POLLUTION PROJECT ·· Nº 665-97-3-99 SU·1

FIGURE
Nº
2
OCT. 24, 1939

Climatic Effects

On certain days during which the wind is from the southwest, the water surface may, however, be higher than usual due to the fact that on the preceding day the wind was from the northeast and had piled up the water in the Sound. The level will be gradually lowered by the southwest wind, but it will remain above normal for a day or so, depending upon the velocity and duration of the wind and other factors.

A low barometric pressure centered at the western entrance of the Sound will result in a piling up of water in the East River similar to that caused by a northeast wind. A well developed high pressure area similarly situated will depress the sea level.

It is obvious that changes in wind velocity, wind direction, and barometric pressure can produce extremely complex variations in the behavior of the East River tides.

HARLEM RIVER

Table 20 contains the results of tidal observations in the Harlem River. The data shows that tide is earlier at the Hudson River end than at the East River end, the difference being almost an hour between Spuyten Duyvil and Willis Avenue Bridge. Though the durations of rise and fall vary throughout the Harlem, they are, as a whole, approximately equal.

TABLE 20

TIDAL DATA - HARLEM RIVER

LOCALITY	LUNITIDAL INTERVALS		DURATION OF RISE IN HOURS	MEAN RANGE IN FEET
	HWI IN HOURS	LWI IN HOURS		
Spuyten Duyvil, N.Y.	9.22	3.06	6.16	3.78
Opposite Johnson Iron Works	9.29	3.17	6.12	3.81
Off Seaman Ave.	9.66	3.56	6.10	3.68
West 215th Street	9.56	3.42	6.14	3.97
West 207th Street	9.68	3.44	6.24	4.05
Sherman Creek	9.66	3.48	6.18	4.13
South of Sherman Creek	9.91	3.91	6.00	4.21
High Bridge	10.46	3.86	6.60	5.84
North of Putnam Railroad Bridge	9.72	3.55	6.17	4.48
North of Central Bridge	10.21	3.96	6.25	4.96
South of Central Bridge	10.21	4.11	6.10	4.90
Park Avenue Bridge	9.88	3.69	6.19	4.71
North of Willis Ave. Bridge	9.94	3.71	6.23	4.90
South of Willis Ave. Bridge	10.21	3.96	6.25	5.27
East 125th Street	10.01	3.77	6.24	4.91
East 120th Street	10.10	3.86	6.24	4.97
East 112th Street	10.13	3.81	6.32	4.97
East 110th Street	10.25	3.73	6.52	4.98
East 108th Street	10.14	3.81	6.33	5.08
Wards Island	10.20	3.99	6.21	5.06
Randalls Island, Southwest Pier	9.83	3.65	6.18	5.15
Randall's Island, opp. 122nd St.	10.19	3.63	6.56	5.24
Third Avenue Bridge	10.13	4.06	6.07	4.81
Madison Avenue Bridge	10.11	4.11	6.00	5.09
North of Madison Avenue Bridge	9.86	3.52	6.34	4.74
145th Street Bridge	9.78	3.63	6.13	4.62
South of Central Bridge	9.79	3.63	6.16	4.60
North of Central Bridge	10.11	4.01	6.10	4.86
South of High Bridge	10.01	4.01	6.00	4.59
North of High Bridge	8.96	3.91	6.05	4.49
Washington Bridge	9.73	3.57	6.16	4.29
North of Washington Bridge	9.77	3.52	6.25	4.21
Opposite Sherman Creek	10.87	5.80	5.07	4.13
West 207th St. Bridge	9.81	3.81	6.00	3.90
Broadway Bridge	9.52	3.32	6.20	3.89

TIDES IN LONG ISLAND SOUND

Long Island Sound has a length of approximately 95 nautical miles. In breadth it varies from a few miles to a maximum of approximately 20 nautical miles off New Haven, Conn.

Western Long Island Sound

Western Long Island Sound is that portion of Long Island Sound extending from Willets Point at the junction of the Sound with the East River to Old Field Point, Long Island. Tides have been observed at many locations in western Long Island Sound, but in general these observations have been for short periods of time. Tides at Willets Point have, however, been observed over a considerable period and the summary of the tides there is contained in Table 21.

TABLE 21

SUMMARY OF TIDAL DATA - WILLETS POINT

TIME RELATIONS

	HOURS
High Water Interval	11.30
Low Water Interval	5.71
Duration of rise	5.59
Duration of fall	6.83
Phase Age	23.4
Parallax Age	44.8
Diurnal Age	331.9

Sequence of tides is HHW to LLW

WILLETS POINT - RANGES

	FEET
Mean range	7.18
Great diurnal range	7.70
Small diurnal range	6.66
Great Tropic range	8.22
Small Tropic range	6.65
Spring range	8.55
Neap range	5.68
Perigean range	8.23
Apogean range	6.38
Mean Tropic range	7.44

TABLE 22

SUMMARY OF TIDAL DATA - NEW LONDON, CONN.

TIME RELATIONS

	HOURS
High Water Interval	9.50
Low Water Interval	3.70
Duration of rise	5.80
Duration of fall	6.62
Phase Age	12.0
Parallax Age	46.7
Diurnal Age	333.6

RANGES

	FEET
Mean Range	2.53
Great Diurnal Range	2.99
Small Diurnal Range	2.07
Great Tropic Range	2.82
Mean Tropic Range	2.28
Small Tropic Range	1.74
Spring Range	2.94
Neap Range	1.99
Perigean Range	2.97
Apogean Range	2.08

SUMMARY OF TIDAL DATA - NEW LONDON, CONN.

COMPARISON OF RANGES

		RATIOS
Great Diurnal Range	- mean range	1.182
Small Diurnal Range	- mean range	0.818
Great Tropic Range	- mean range	1.115
Mean Tropic Range	- mean range	0.901
Small Tropic Range	- mean range	0.688
Spring Tropic Range	- mean range	1.162
Neap Tropic Range	- mean range	0.787
Perigean Tropic Range	- mean range	1.174
Apogean Tropic Range	- mean range	0.822

TABLE 21 (cont'd)

TIME RELATIONS

	RATIOS
Great diurnal range - mean range	1.072
Small diurnal range - mean range	0.928
Great Tropic range - mean range	1.145
Mean Tropic range - mean range	1.036
Small Tropic range - mean range	0.926
Spring range - mean range	1.191
Neap range - mean range	0.791
Perigean range - mean range	1.146
Apogean range - mean range	0.889

HEIGHT RELATIONS

	FEET
Mean High water above mean sea level	3.59
Mean Higher high water above mean level	3.91
Mean Lower high water above mean level	3.27
Tropic Higher high water above mean level	4.20
Tropic Lower high water above mean level	3.23
Spring High water above mean sea level	4.27
Neap High water above mean sea level	2.84
Mean Low water below mean sea level	3.59
Mean Lower low water below mean sea level	3.79
Mean Higher low water below mean sea level	3.39
Tropic Lower low water below mean sea level	4.02
Tropic Higher low water below mean sea level	3.42
Spring Low low water below mean sea level	4.28
Neap low water below mean sea level	2.84
Half-tide level below mean sea level	0.00

Eastern Long Island Sound

Eastern Long Island Sound extends from Old Field Point to Fishers' Island Sound and the Race. Tides have been observed in eastern Long Island Sound since 1838, and the average values of the observations at New London, Conn., are given in Table 22.

TABLE 22 (cont'd)

HEIGHT RELATIONS

	FEET
Mean High water above mean sea level	1.22
Mean Higher high water above sea level	1.49
Mean Lower high water above sea level	0.95
Tropic Higher high water above mean sea level	1.53
Tropic Lower high water above mean sea level	0.74
Spring High water above mean sea level	1.43
Neap High water above mean sea level	0.96
Mean Low water below mean sea level	1.32
Mean Lower low water below mean sea level	1.51
Mean Higher low water below mean sea level	1.13
Tropic Lower low water below mean sea level	1.29
Tropic Higher low water below mean sea level	1.01
Spring Low water below mean sea level	1.51
Neap Low water below mean sea level	1.08
Half-tide Level water below mean sea level	0.05

It is seen that there is a difference in the time of tide as well as in the range of tide at the extremities of Long Island Sound.

Long Island Sound Tides

If only the time of tide changed while the range remained rather constant throughout the waterway, a progressive type of wave might be expected. On the other hand, if the time of tide differed but little, while the range increased considerably, a stationary type of wave might be expected. Since both time and range differ considerably from one extremity to the other, it is obvious that a combination of the stationary and progressive types of tide wave prevails in Long Island Sound.

TIDAL AND NON-TIDAL CURRENTS

GENERAL CHARACTERISTICS

Tidal currents are the horizontal movements of the water that accompany the rise and fall of the tide, and, like the tide, are caused by the same phenomena. They are periodic as distinguished from non-tidal currents, which are of no known periodicity.

Two Currents

Tidal and non-tidal currents occur together in the open sea and in inshore tidal waters, the actual current experienced at any point being the resultant of the two classes of currents. In some places tidal currents predominate and in others non-tidal. Tidal currents generally attain considerable velocity in narrow entrance to bays, in constricted parts of rivers, and in passages from one body of water to another. Along the coast and farther offshore tidal currents are generally of moderate velocity, and in the open sea, calculation based on the theory of wave motion, gives a tidal current of less than 1/10th of a knot.

REVERSING TIDAL CURRENTS

Strength Of Flood Ebb

At the entrance to a bay, or, in general, when a restricted width occurs, the tidal current is of the reversing or rectilinear type, that is, the flood current runs about half a tidal cycle in one direction and the ebb current runs about the same length of time in the reverse direction. The change from flood to ebb and from ebb to flood gives rise to periods of slack water during which the current velocity is zero. The maximum velocity of the flood current is called the strength of flood, while the maximum of the ebb current is called the strength of ebb.

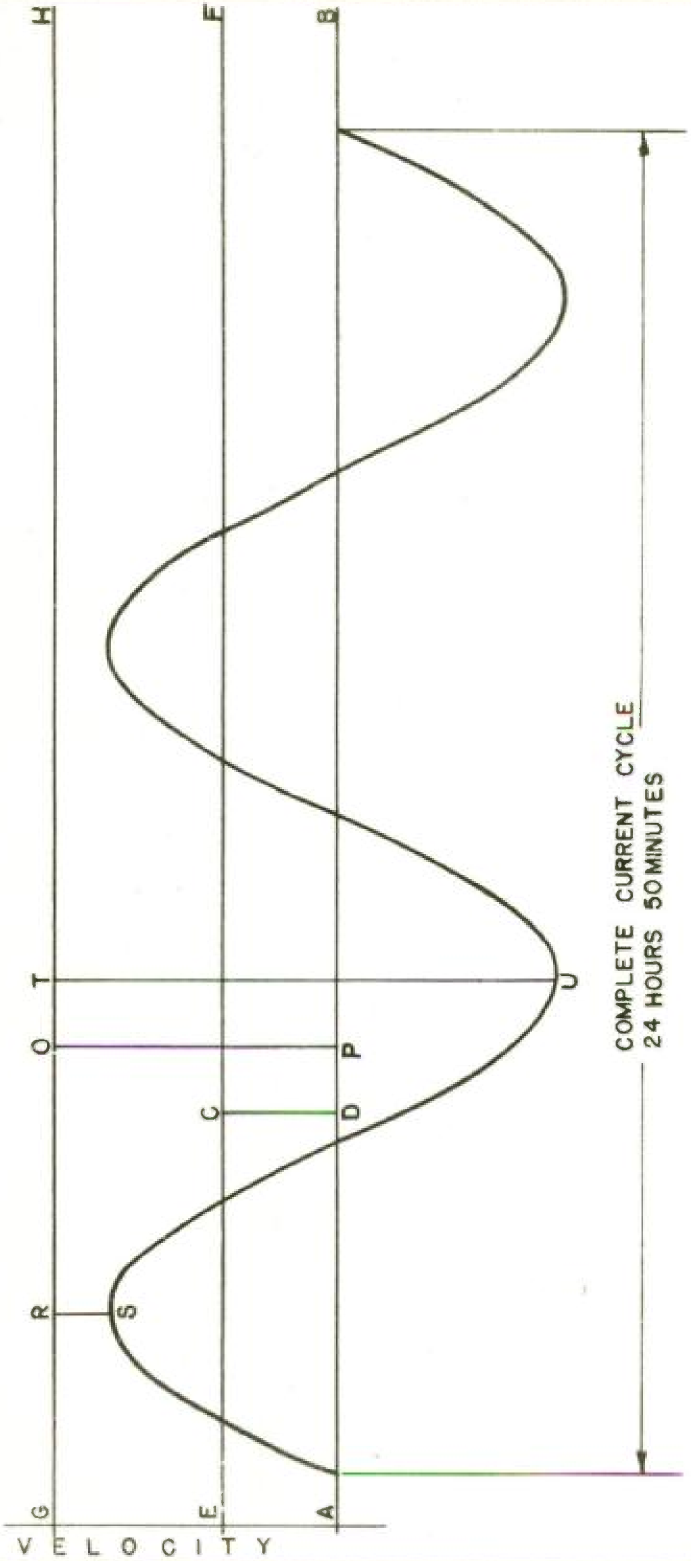
Channel Currents

Tidal currents extend from the surface of the water to the bottom. In general, the velocity of the tidal current decreases from the surface to the bottom, the velocity near the bottom being about two-thirds that at the surface (although wind and fresh water flow may cause a considerable variation in this velocity distribution). Again, in a rectangular channel of uniform cross-section, the velocity is greatest in the centre of the channel and decreases uniformly at both sides. Combining both the vertical and horizontal variations, it may be said that the average velocity of the current in a section of a regular channel is about three-quarters that of the central surface velocity.

Where the current is undisturbed by wind or fresh water flow, the flood and ebb velocities, and the duration of flood and ebb are approximately equal. In this case, too, the characteristics of the current from the surface to the bottom are much the same; that is, the strengths of the flood and ebb current occur at about the same time from top to bottom. If, however, non-tidal currents are present the characteristics of the tidal flow are modified considerably.

Figure 3

In figure 3 a theoretical tidal current is represented by the curve, referred to the line AB as the line of zero velocity. The strengths or maximum velocities of the flood and ebb are equal, as are also the durations of flood and ebb. In this case, slack water occurs regularly 3 hours and six minutes (one quarter of the current cycle of 12 hours and 25 minutes) after the times of flood and ebb strengths. If now a non-tidal current is introduced which sets in the ebb direction with a velocity represented by the line CD, the strength of ebb will obviously be increased by an amount equal to CD and the flood strength will be decreased by the same amount.



EFFECT OF NONTIDAL CURRENT ON REVERSING TIDAL CURRENT

CHART FROM U. S. DEPT. OF COMMERCE
COAST AND GEODETIC SURVEY
To Accompany Report Made By
W. P. A. WATER POLLUTION PROJECT · · Nº 665-97-3-99 SU.I

FIGURE No. 3
Nov. 21, 1939

The current conditions may now be represented by drawing, as the new line of zero velocities, the line EF parallel to AB and distant from it the length CD.

Effect of Non-tidal Current

Figure 3 now shows that non-tidal current not only increases the ebb strength while decreasing the flood strength, but also changes the time of slack water. Slack before flood now comes later, while slack before ebb comes earlier. Hence the duration of ebb increased while the duration of flood decreased.

If the velocity of the non-tidal current exceeds that of the tidal current at time of strength, the tidal current in the in the opposite direction will be completely masked and the resultant current will set at all times in the direction of the non-tidal current. Thus, if in figure 3 we let the line OP represent the velocity of the non-tidal current in the direction of ebb flow, the new axis for measuring the velocity of the current at any time will be the line GH 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

As regards the effect of the non-tidal current on the direction of the tidal current, it is only necessary to state that the resultant current will set in a direction which at any time is the resultant of the tidal and non-tidal currents at that time.

THE DIRECT EFFECT OF THE WIND

In his Manual of Tides the late R. A. Harris of the United States Coast and Geodetic Survey writes:

"If a wind blows for a considerable length of time in one direction over an inclosed body of water, the surface particles are carried or drifted from their original position through the impingement of the air upon them. The particles drag with them those situated immediately below the surface, and in time this dragging influence will be felt down to considerable depths.

Wind Currents

"The effect of these horizontal forces on the waters of a closed body is to increase the height of water level on the lee shore and to diminish it upon the opposite shore, although not generally by the same amount. In shallow bodies or along the shelving shore of the ocean, the amount of this elevation may be considerable. In deep bodies with abrupt shores the piling up is very small, although there may be a good surface drift maintained by the wind. The reason for this is that the horizontal forces due to the wind do not act alike upon the particles at all depths as do the tidal forces; for they are considerable at the surface and insignificant near the bottom. Consequently, the pressure due to the increased depth on the lee shore quickly gives rise to an acceleration in the reverse direction, which exceeds at even moderate depths the acceleration imparted to the liquid elements by the moving elements situated near the surface. Hence the retrograde movement of the water not only near the bottom, but for a considerable distance upward. Because of its much greater transverse section, the returning stream is, as a rule, scarcely perceptible, although the velocity of the surface stream may be considerable.

"this may be regarded as the circulation in vertical planes due directly to the wind striking the surface of the water.

"...... Ferrel makes constant use of the principle that a moving particle is deflected to the right in the northern hemisphere and to the left in the

Current Deflection

> southern hemisphere. Nansen suspected from observation and Ekman confirmed by computation that forced or sustained currents take, if circumstances permit, a direction to the right of the sustaining force in the northern hemisphere. Moreover, as **wind** action is from the surface downward (each layer moving the one underneath it) the direction of the lower layers will, likewise, be to the right of the one imparting the motion."(54).

Other tidal mathematicians have reached the conclusion that in the northern hemisphere the surface currents take a direction 45° to the direction of the wind and that this angle increases with the depth. However, Harris writes:

> "On account of the actual distribution of land and water, it is difficult to say to what extent Ekman's theory of force currents accounts for the existing ocean currents. The fact that there is a tendency for the water to flow to the right or left of the direction towards which the wind blows will doubtless be brought out for many regions."(54).

Amount of Deflection

Perhaps the best information on the subject is the following statement contained in Special Publication #174-1932 issued by the United States Coast and Geodetic Survey "......A 10 mile per hour wind produces a non-tidal current of about 0.2 knot, which sets about 20 degrees to the right of the direction in which the wind is blowing, while a 30 mile per hour wind produces a non-tidal current of about 0.3 knot."(74).

DISTANCE TRAVELED DURING A TIDAL CYCLE

If the velocity of the current during a tidal cycle were constant, the distance traveled by the water particles or by any object floating in the water would be found by multiplying the velocity by the time. However, the velocity of the current is not constant, but changes continually throughout the tidal cycle. The distance traveled by the water particles is therefore the average velocity during any interval multiplied by the time.

Average Velocity

The average velocity of the current during any given interval may be determined in a number of ways. From observations at frequent intervals, say every ten or fifteen minutes, the average velocity is easily derived. Or we may by means of a planimeter determine the area of the surface bounded by the current curve and the zero line of velocities, and derive the average velocity by dividing this area by the length of the zero line included within the current curve.

Computing Average Tidal Current

Much the simplest method consists, however, in making use of the well known ratio of the mean ordinate of the cosine curve to the maximum ordinate, which is 2 divided by pi or 0.637. Since the velocity of a tidal current is almost invariably specified by its velocity at time of strength, the average current by this method is given immediately by multiplying the strength of the current by 0.637.

Applying the above rule in the case of a current having a velocity of 2 knots at time of strength, a floating object will be carried during a flood or ebb period of 6.2 hours, a distance of $0.637 \times 2 \times 6.2 = 7.9$ nautical miles, or 48,000 feet. It may be of interest to note here that for the Hudson River and Upper Bay, the distance actually traversed by a float was found to agree closely with the distance calculated as above.

VARIATIONS IN STRENGTH OF CURRENT

Tidal currents exhibit changes in strength that correspond to the periodic changes in range of tides. Strong currents come with spring and perigean tides, while relatively weak currents, accompany neap and apogean tides.

There are three types of reversing tidal currents, semi-daily and mixed, corresponding to the different types of tides. These are:

Types of Currents

a- Semi-daily current, 2 Ebb strengths and 2 flood strengths per day, as in the Narrows.
b- Daily current, 1 ebb and 1 flood, in 24 hours.
c- Mixed current, 2 ebbs and 2 floods, but of considerable inequality between A. M. and P.M. cycles.

DURATION OF SLACK WATER

A glance at any current curve will show that the time of slack water is but a moment during which the current has no movement.

Definition

The instant that the current curve cuts the zero line of velocities is the time of slack water. However, slack water is popularly thought of as a period of time extending over a number of minutes, during which the current is at a standstill, neither flooding nor ebbing. Now if we consider the period of slack water to be the interval of time during which the velocity of the current is so small that for practical purposes it may be disregarded, we make the term connote the meaning attached to it in ordinary usage. Current velocities less than one-tenth of a knot may for all practical purposes be disregarded; and furthermore, such velocities are difficult to measure. It is, therefore, usual to give the term "slack water" a definite meaning in ordinary usage by defining it to be the period during which the velocity of the current is less than one-tenth of a knot.

Setting one-tenth of a knot as the limit of slack water permits us to compute the duration of slack for any current. All that need be done is to measure on the current curve for any given place the interval during which the velocity of the current is less than one-tenth of a knot.

Duration

Regarding the current curve as approximately a cosine curve, we may compute the duration of slack water based on the equation of the cosine curve. Based on this method, values for the duration of slack water have been computed. With currents which at strength have a velocity of one knot, the duration of slack water is 24 minutes; with currents of 2 knots strength, 12 minutes; 3 knots, 8 minutes; 4 knots, 6 minutes; and 5 knots, 5 minutes.

ROTARY TIDAL CURRENTS

Offshore Tidal Currents

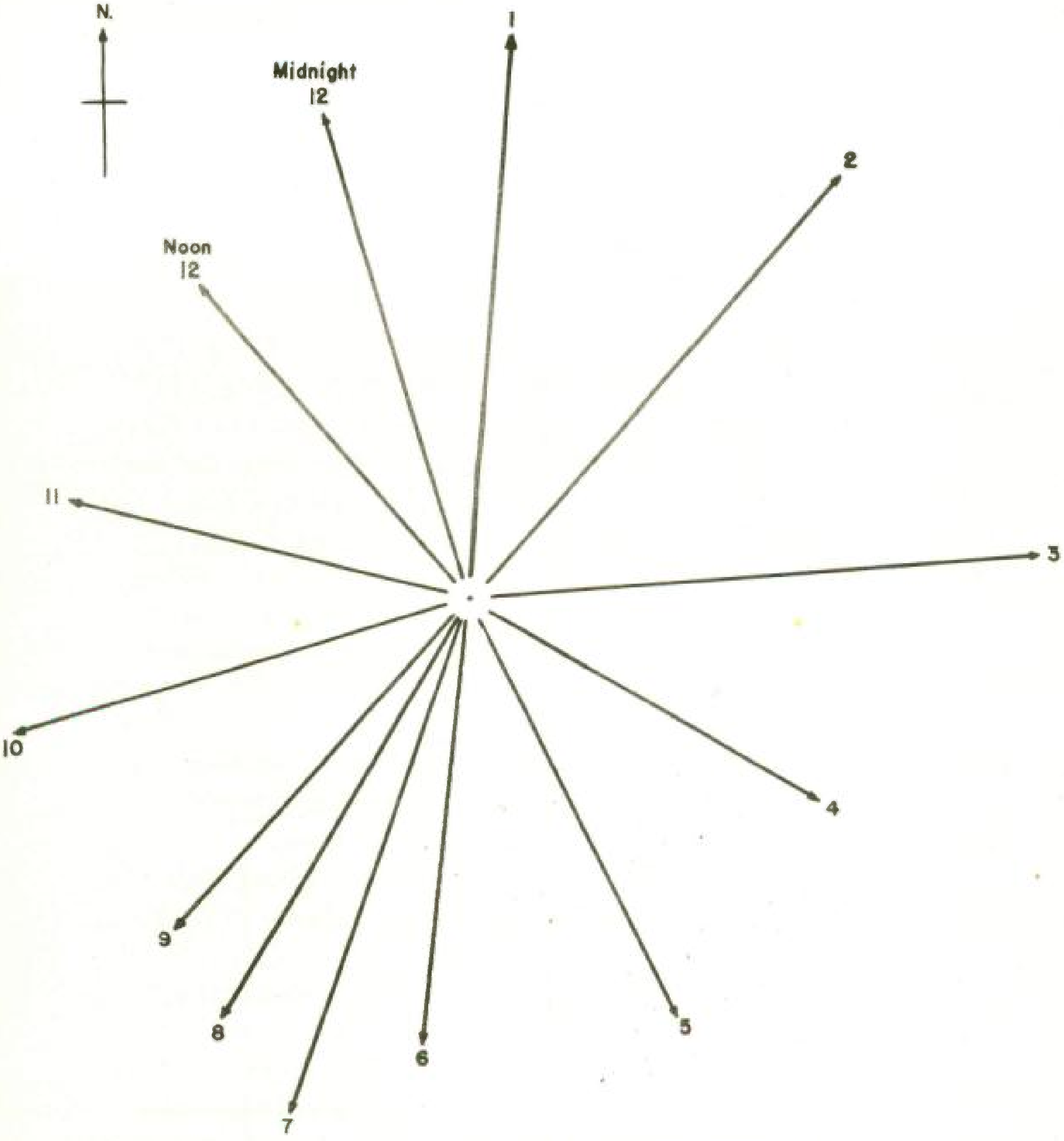
Figure 4

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 and out in the open sea change direction continually. Such currents are, therefore, called rotary currents. An example of this type of current is shown in Figure 4 which represents the velocity and direction of the current at the beginning of each hour between midnight and noon.

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. In a period of a little more than 12 hours it is seen that the current has shifted in direction completely around the compass.

Rotary Period

It will be noted that the tips of the arrows representing the velocities and directions of the current define a somewhat irregular ellipse. If a number of observations are average, 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 hours and 25 minutes. In other words, the current day for the rotary current, like the tidal day, is 24 hours and fifty minutes in length.



TYPE OF ROTARY CURRENT

CHART FROM U. S. DEPT. OF COMMERCE
COAST AND GEODETIC SURVEY
TO ACCOMPANY REPORT MADE BY
W. P. A. WATER POLLUTION PROJECT Nº 665-97-3-99 SU. I

FIGURE
No. 4
Dec. 7, 1939

No slack Current

Although a rotary current generally varies in strength from hour to hour this variation from greatest current to least current and back again to greatest 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 the maximum current. It is generally found that a minimum velocity follows a maximum by an interval of about three hours, showing the same relation to each other as the slack and strength of the rectilinear current.

Figure 5

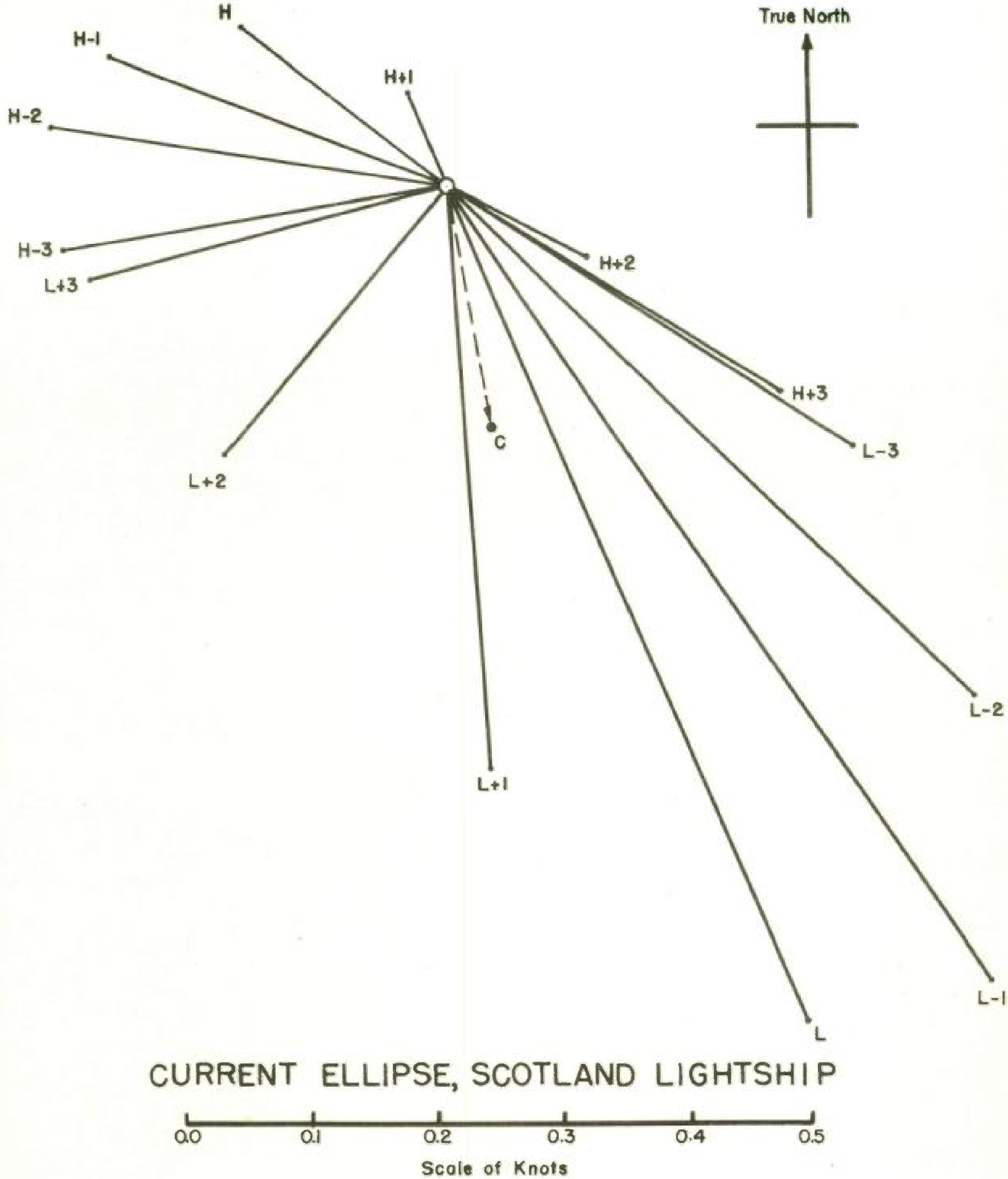
Since the current day corresponds to the tidal day, it is convenient in determining the average hourly velocity and direction of the rotary current, to make use of the times of high and low water at some nearby place for purpose of refrence. In figure 5 the average hourly velocity and direction of the tidal current at Scotland Lightship off Sandy Hook, N. J. is shown with reference to the times of high and low water at Sandy Hook. The data for this current ellipse was derived from observations made during the period, March - July, 1921. The point C gives the location of the average hourly value of the current; hence the line joining the origin with C gives the velocity and direction of the non-tidal current during the period of observations. (Figure 5 is further discussed under CURRENTS IN APPROACHES TO LOWER BAY).

Rotary tidal currents are subject to the periodic variations found in tides and reversing currents. In general, the percentage of increase or decrease in the velocity of the current in response to changes in phase and parallax is the same as the like increase or decrease of the local range of the tide.

VELOCITY OF CURRENT AND PROGRESSION OF TIDE

Tide and Current Relation

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 cannot from that alone infer the velocity of the current or vice versa. The rate of advance of the tide in any given body of water depends on the type of tidal movement, progressive wave, stationary wave or hydraulic. 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.



CURRENT ELLIPSE, SCOTLAND LIGHTSHIP

CHART FROM U. S. DEPT. OF COMMERCE COAST AND GEODETIC SURVEY TO ACCOMPANY REPORT MADE BY W. P. A. WATER POLLUTION PROJECT No. 665-97-3-99SU.I	FIGURE No. 5 Dec. 7, 1939

CURRENTS IN NEW YORK HARBOR

CURRENTS IN APPROACHES TO LOWER BAY

Along the whole stretch from Sandy Hook to Rockaway Point, the ebb current has a greater velocity than the flood current, the ebb averaging 1.4 knots and the flood 1.0 knot. The duration of ebb, likewise, is greater than that of flood, the ebb averaging 6.5 hours, while the flood averages 5.9 hours. At Scotland and Ambrose Lightships the current is of a rotary character, so that instead of a slack current there is a minimum current. At Scotland Lightship the tidal current at the minimum has a velocity of 0.15 knot, while at maximum the velocity is 0.50 knot and sets N. 55° W on the flood and S. 46° E. on the ebb. At Ambrose Lightship the velocity of the minimum tidal current is 0.03 knot and of the maximum 0.23 knot, the flood setting N. 82° W. and the ebb S. 86° E. These figures are for the purely tidal current and have been computed by substracting the non-tidal current from the observed current. The observed current at Scotland Lightship has, at strength of flood, a velocity of 0.34 knots and sets N. 88 W.; and at strength of ebb a velocity of 0.74 knots setting S. 31 E. The observed current at Ambrose Lightship has, at strength of flood, a velocity of 0.15 knots setting N. 51 W., and at strength of ebb a velocity of 0.34 knots setting S. 89 E.

At
Scotland
& Ambrose
Lightships

At both lightships the means of the hourly currents, over a considerable period of time, were taken for a complete tidal cycle and averaged. The average thus obtained is the non-tidal current, since the purely tidal currents will be neutralized in a complete tidal cycle. At Scotland Lightship this non-tidal current is 0.18 knots and sets S. 5 E. At Ambrose Lightship this non-tidal current is 0.10 knots and sets N. 74 E.

The velocity and direction of the hourly currents at Scotland Lightship have been represented in Figure 5. H and L refer to the times of High and Low waters at Sandy Hook.

CURRENTS IN LOWER BAY AND THE NARROWS

Some Causes Of Variations

In the entrance to Lower Bay the velocity of the current at strength averages between 1½ and 2 knots, but within the Bay itself the current is much weaker, being less than a knot at strength. In general, the ebb velocity is somewhat greater than the flood, this being brought about by the fresh water draining into the Bay. Variations are caused by hydrographic features, as, for instance, where the western tip of Coney Island prevents the main stream of the flood current from embracing in its sweep the waters immediately to the north of the island. On the ebb, however, these waters lie in the direct path of the main stream, and hence show the current velocity belonging to that main stream. Another variation from the expected is found in the behavior of the main current from the Narrows at flood tide. On the ebb the vertical distribution varies in accordance with the laws of ordinary hydraulic motion, the velocity decreasing with increasing depth, but on the flood the velocity shows an increase from the surface downward for a considerable depth. This is evidently due to the non-tidal or fresh water discharge through the Narrows. The fresh water being lighter, tends to remain on the surface and to move seaward, thus reducing the velocity of the incoming tidal current near the surface. Thus, off Gravesend Bay at flood strength the surface current has a velocity of 0.47 knot, while the current 22 feet below the surface has a velocity of 0.74 knot. Similarly, off Sandy Hook at strength of flood the surface velocity is 1.40 knots, while 44 feet below the surface the velocity is 1.60 knots.

The tidal movement through the Narrows is of the progressive wave type. In general, the strength of flood in the Narrows averages 1.4 knots and the strength of ebb 1.8 knots, the difference arising from the very considerable amount of fresh water that drains through the Narrows.

Velocities

Table 23 contains the record of the observation of the surface current at various stations in the Narrows. The velocities have been reduced to mean values. The average duration of the ebb is 7 hours and of the flood 5.4 hours. In different parts of the channel, however, the durations differ noticeably from the average. (See Table 23 on Page 64)

Velocity Variations

In Table 24 (page 65 et seq.) are found the subsurface current observations at the Narrows. Generally the observations were made at three depths - two-tenths, five-tenths, and eight-tenths of the depth at the station. The velocities of the current are seen to differ considerably at the various depths. In general, the strength of ebb decreases with the depth at the rate of about 0.01 knot per foot, but the strength of flood varies in a more complicated manner. In the deeper parts of the mid-channel the velocity of flood increases from the surface to near the bottom at about the rate of 0.01 knot per foot, while near the shore the increase is at a somewhat lesser rate. As a result, the difference between the ebb and flood velocities becomes less as the depth increases and at some points in mid-channel the flood current at the eight-tenths depth has a greater velocity than on the ebb.

TABLE 23

SURFACE CURRENT DATA - THE NARROWS

(Referred to times of HW and LW at Sandy Hook, N.J.)

LOCATION	FLOOD STRENGTH					EBB STRENGTH				
	SLACK HOURS After LW	TIME HOURS Before HW	DIRECTION (True) 0	VELOCITY Knots	FLOOD DURATION Hours	SLACK HOURS After HW	TIME HOURS Before LW	DIRECTION (True) 0	VELOCITY Knots	EBB DURATION Hours
Off Bklyn.	3.2	0.2	N. 10 W.	1.5	5.0	2.1	0.8	S. 45 E.	1.9	7.4
Off Bklyn.	1.7	0.9	N. 10 E.	1.5	6.2	1.8	1.3	S. 20 W.	1.8	6.2
Off Bklyn.	2.4	0.9	N. 20 E.	1.4	6.1	2.4	1.4	S. 10 W.	1.6	6.3
Off Bklyn.	2.0	0.2	N. 15 E.	1.5	6.1	2.0	1.5	S. 25 W.	1.5	6.3
Mid-Channel	3.3	0.7	N. 20 W.	1.1	4.8	2.0	-0.1	S. 20 E.	1.9	7.6
Mid-Channel	3.0	1.0	N. 25 W.	1.3	4.8	1.7	0.9	S. 20 E.	1.8	7.6
Mid-Channel	2.4	0.7	N. 5 W.	1.1	5.9	2.2	1.0	S. 5 E.	1.4	6.5
Mid-Channel	2.7	0.2	N. 5 W.	1.9	5.9	2.5	1.2	S. 10 W.	2.0	6.5
Mid-Channel	1.9	0.4	N.	1.5	6.6	2.4	0.7	S.	1.8	5.8
Mid-Channel	2.5	0.1	N. 5 E.	1.6	5.8	2.2	0.4	S. 15 E.	2.4	6.6
Off Staten I.	3.6	0.5	N. 25 W.	1.5	4.6	2.1	-0.3	S. 15 E.	2.3	7.8
Off Staten I.	2.3	0.7	N. 5 W.	0.9	5.3	1.5	0.9	S. 15 W.	1.5	7.1
Off Staten I.	2.5	0.4	N. 5 E.	1.3	5.3	1.7	1.1	S.	1.6	7.1
Off Staten I.	2.0	0.1	N. 15 E.	0.9	5.6	1.5	1.2	S. 10 W.	1.3	6.8
Off Staten I.	1.7	-0.2	N. 5 W.	1.2	6.4	2.0	1.5	S. 35 E.	1.6	6.0

TABLE 24

CURRENT DATA- VARIOUS DEPTHS- THE NARROWS

(Referred to times of HW and LW at Sandy Hook, N.J.)

		FLOOD STRENGTH					EBB STRENGTH				
LOCATION	DEPTH Feet	SLACK HOURS After LW	TIME HOURS Before HW	DIRECTION (True) o	VELOCITY Knots	FLOOD DURATION Hours	SLACK HOURS After HW	TIME HOURS Before LW	DIRECTION (True) o	VELOCITY Knots	EBB DURATION Hours
Off Bklyn	7	0.61	0.72	N. 17 W.	1.20	7.62	2.10	2.59	S.14 W.	0.90	4.80
Off Bklyn	5	0.51	0.92	---	1.10	7.82	2.20	2.79	---	0.90	4.60
Off Bklyn	12	0.51	0.72	---	1.00	7.82	2.20	2.79	---	0.90	4.60
Off Bklyn	20	0.51	0.12	---	1.10	7.82	2.20	2.79	---	0.70	4.60
Off Bklyn	7	3.21	0.21	N. 11 W.	1.49	4.96	2.04	0.81	S.45 E.	1.89	7.46
Off Bklyn	14	3.49	0.23	N. 26 W.	1.41	4.85	2.21	0.53	S.40 E.	1.65	7.57
Off Bklyn	36	3.45	0.59	N. 21 W.	1.24	4.89	2.21	0.56	S.55 E.	0.94	7.53
Off Bklyn	58	3.27	0.43	N. 40 W.	0.88	5.11	2.25	0.59	S.53 E.	0.78	7.31
Off Bklyn	7	2.70	0.31	---	1.40	5.33	1.90	2.56	---	1.61	7.09
Off Bklyn	18	2.33	0.15	---	1.41	5.84	2.04	2.73	---	1.40	6.58
Off Bklyn	29	1.97	0.33	---	1.69	6.09	1.93	2.79	---	1.37	6.33
Off Bklyn	7	1.71	0.92	N. 9 E.	1.50	6.22	1.80	1.42	S.22 W.	1.80	6.20
Off Bklyn	8	1.51	0.92	---	1.50	6.42	1.80	1.32	---	1.80	6.00
Off Bklyn	20	1.51	0.92	---	1.40	6.42	1.80	1.22	---	1.60	6.00
Off Bklyn	32	1.41	1.02	---	1.00	6.52	1.80	1.12	---	1.20	5.90
Off Bklyn	7	2.44	0.86	N. 20 E.	1.39	6.13	2.44	1.46	S.10 W.	1.64	6.29
Off Bklyn	8	2.19	0.71	N. 22 E.	1.26	6.53	2.59	1.16	S.18 W.	1.41	5.89
Off Bklyn	21	2.04	0.76	N. 30 E.	1.41	6.33	2.24	0.61	S.22 W.	1.31	6.09
Off Bklyn	33	1.69	1.31	N. 30 E.	1.34	6.53	2.09	0.96	S.20 W.	1.19	5.89
Off Bklyn	7	1.97	0.24	N. 15 E.	1.51	6.13	1.97	1.54	S.26 W.	1.51	6.29
Off Bklyn	9	2.34	0.63	---	1.49	6.01	2.22	0.97	---	1.65	6.41
Off Bklyn	22	2.27	0.69	---	1.56	5.87	2.01	0.97	---	1.40	6.55
Off Bklyn	35	2.24	1.29	---	1.32	5.83	1.94	0.95	---	1.26	6.59

TABLE 24 (cont'd)

		FLOOD STRENGTH					EBB STRENGTH				
LOCATION	DEPTH Feet	SLACK HOURS After LW	TIME HOURS Before HW	DIRECTION (True) 0	VELOCITY Knots	FLOOD DURATION Hours	SLACK HOURS After HW	TIME HOURS Before LW	DIRECTION (True) 0	VELOCITY Knots	EBB DURATION Hours
Mid-Channel	7	3.27	0.73	N. 20 W.	1.09	4.89	2.03	-0.09	S.19 E.	1.86	7.53
Mid-Channel	17	2.84	1.03	N. 17 W.	1.25	5.31	2.02	-0.17	S.18 E.	1.81	7.11
Mid-Channel	44	2.01	1.50	N. 27 W.	1.53	6.44	2.32	0.17	S.23 E.	1.81	5.98
Mid-Channel	70	1.08	0.39	N. 30 W.	1.75	7.11	2.06	1.38	S.23 E.	1.27	5.31
Mid-Channel	7	2.97	1.03	N. 25 W.	1.32	4.83	1.67	0.91	S.20 E.	1.82	7.59
Mid-Channel	18	2.57	1.19	-----	1.18	5.51	1.95	1.11	------	1.57	6.91
Mid-Channel	42	2.27	1.13	-----	1.38	6.09	2.23	0.85	------	1.43	6.33
Mid-Channel	60	1.84	1.11	-----	1.60	6.38	2.09	0.93	------	1.53	6.04
Mid-Channel	16	2.77	0.44	-----	1.39	5.44	2.08	1.35	------	1.45	6.98
Mid-Channel	39	2.03	0.49	-----	1.45	6.54	2.44	0.75	-----	1.07	5.88
Mid-Channel	62	1.69	0.81	-----	1.71	6.76	2.32	0.82	-----	1.08	5.66
Mid-Channel	17	2.75	0.69	-----	1.66	5.47	2.09	0.90	-----	2.03	6.95
Mid-Channel	42	1.79	0.57	-----	2.03	6.85	2.51	0.57	-----	1.76	5.57
Mid-Channel	67	1.27	0.83	-----	1.98	7.20	2.34	0.81	-----	1.59	5.22
Mid-Channel	7	2.72	0.74	N. 22 W.	1.46	5.32	1.91	0.98	S. 13 E.	1.54	7.10
Mid-Channel	18	2.72	0.78	N. 29 W.	1.37	5.80	2.39	0.71	S. 19 E.	1.49	6.62
Mid-Channel	45	1.82	1.11	N. 24 W.	1.67	6.75	2.44	0.64	S. 47 E.	1.51	5.67
Mid-Channel	72	1.36	1.28	N. 26 W.	1.66	7.21	2.44	0.41	S. 42 E.	1.42	5.21
Mid-Channel	16	2.77	0.76	-----	1.30	5.48	2.12	0.49	------	1.83	6.94
Mid-Channel	40	2.42	0.93	-----	1.36	5.99	2.26	0.28	------	1.57	6.43
Mid-Channel	63	1.93	0.62	-----	2.13	6.60	2.40	0.33	-----	2.27	5.82
Mid-Channel	7	2.73	0.21	N. 6 W.	1.85	5.87	2.47	1.25	S. 10 W	1.97	6.55
Mid-Channel	8	2.53	0.21	-----	1.83	5.81	2.21	1.39	-----	1.91	6.61
Mid-Channel	21	2.19	0.97	-----	1.64	6.15	2.21	1.29	-----	1.56	6.27

TABLE 24 (cont'd)

LOCATION	DEPTH	FLOOD STRENGTH					EBB STRENGTH				
	DEPTH Feet	SLACK HOURS After LW	TIME HOURS Before LW	DIRECTION (True) 0	VELOCITY Knots	FLOOD DURATION Hours	SLACK HOURS After HW	TIME HOURS Before LW	DIRECTION (True) 0	VELOCITY Knots	EBB DURATION Hours
Mid-Channel	36	2.25	1.07		0.98	6.05	2.17	1.03		1.00	6.37
Mid-Channel	7	1.91	0.42	N. 2 E.	1.50	6.62	2.40	0.69	S. 1 W.	1.80	5.80
Mid-Channel	9	2.01	0.52	---	1.60	6.42	2.30	0.59	---	1.90	6.00
Mid-Channel	21	2.01	0.42	---	1.50	6.42	2.30	0.49	---	1.70	6.00
Mid-Channel	33	2.01	0.82	---	1.40	6.32	2.20	0.69	---	1.70	6.10
Mid-Channel	7	2.47	0.06	N. 6 E.	1.59	5.90	2.24	0.46	S. 17 E.	2.35	6.52
Mid-Channel	12	2.79	0.41	---	1.55	5.38	2.04	0.46	---	1.97	7.04
Mid-Channel	30	2.37	1.63	---	1.61	5.95	2.19	0.34	---	2.00	6.47
Mid-Channel	48	2.07	2.43	---	1.30	6.12	2.06	0.24	---	1.64	6.30
Off Staten I.	7	3.55	0.51	N. 23 W.	1.52	4.67	2.09	-0.29	S. 17 E.	2.26	7.75
Off Staten I.	17	3.25	0.97	---	1.63	5.21	2.33	-0.39	---	2.41	7.21
Off Staten I.	42	2.03	1.19	---	1.47	5.77	1.67	0.97	---	1.89	6.65
Off Staten I.	67	1.51	2.71	---	0.92	6.13	1.51	1.59	---	1.55	6.29
Off Staten I.	15	2.71	1.11	---	1.25	5.55	2.13	0.39	---	1.73	6.87
Off Staten I.	38	2.21	1.34	---	1.36	5.89	1.97	0.61	---	1.85	6.53
Off Staten I.	60	1.86	1.12	---	1.21	5.92	1.65	0.81	---	1.76	6.50
Off Staten I.	7	2.29	0.71	N. 7 W.	0.94	5.33	1.49	0.91	S. 13 W.	1.54	7.09
Off Staten I.	10	2.39	0.31	N. 12 W.	1.18	5.43	1.69	1.01	S. 13 W.	1.63	6.99
Off Staten I.	24	2.19	1.11	N. 25 W.	1.39	5.93	1.99	1.41	S. 2 E.	1.09	6.49
Off Staten I.	38	1.19	0.51	N. 20 W.	0.62	6.93	1.99	1.61	S. 24 E.	0.62	5.49
Off Staten I.	7	2.51	0.42	N. 6 E.	1.30	5.32	1.70	1.09	S. 1 W.	1.60	7.10
Off Staten I.	10	2.51	0.42	---	1.30	5.32	1.70	0.79	---	1.60	7.10
Off Staten I.	25	2.41	1.62	---	1.60	5.92	2.20	0.79	---	1.40	6.50
Off Staten I.	40	2.01	2.12	---	1.30	6.22	2.10	0.79	---	1.00	6.20

TABLE 24 (Cont'd)

		FLOOD STRENGTH					EBB STRENGTH				
LOCALITY	DEPTH Feet	SLACK HOURS After LW	TIME HOURS Before HW	DIRECTION (True) 0	VELOCITY Knots	FLOOD DURATION Hours	SLACK HOURS After HW	TIME HOURS Before LW	DIRECTION (True) 0	VELOCITY Knots	EBB DURATION Hours
Off Staten I.	7	1.99	0.11	N. 15 E.	0.94	5.63	1.49	1.21	S. 8 W.	1.34	6.79
Off Staten I.	8	1.69	-0.09	N. 15 E.	1.08	6.03	1.59	1.41	S. 11 W.	1.73	6.39
Off Staten I.	21	1.69	0.41	N. 2 E.	1.53	6.23	1.79	1.21	S. 8 W.	1.28	6.19
Off Staten I.	34	1.69	0.61	N. 5 E.	1.34	6.23	1.79	1.01	S.	0.79	6.19
Off Staten I.	7	1.66	-0.22	N. 4 W.	1.19	6.46	1.99	1.54	S. 37 E.	1.59	5.97
Off Staten I.	10	1.52	0.01	N. 17 W.	1.55	6.85	2.24	1.94	S. 23 E.	1.48	5.54
Off Staten I.	24	1.99	1.14	N. 48 W.	1.77	6.58	2.44	0.68	S. 10 E.	1.34	5.80
Off Staten I.	38	1.82	1.48	N. 23 W.	0.98	6.52	2.31	0.48	S. 4 E.	1.01	5.86

CURRENTS IN THE UPPER BAY

Velocities

In the Upper Bay within the main channel leading to the Hudson the duration of the ebb, as in the Narrows, is considerably greater than the duration of the flood, averaging 7.0 hours for the ebb and 5.4 hours for the flood. But along the east and west shores of the Bay the flood and ebb have very nearly equal durations. Along the main channel of Upper Bay the ebb has also the greater velocity, averaging about 2-1/2 knots at strength of ebb as against a little less than 1-1/2 knots at flood strength. Along the Brooklyn shore the corresponding values are 1-1/2 knots and 1-1/4 knots. In general, therefore, the ebb strength is very nearly a knot greater than the flood along the main channel, but only 1/4 knot greater along the Brooklyn shore.

The variations of the current velocity at the different depths in Upper Bay are much like those found in the Narrows.

THE CURRENTS IN THE KILLS AND NEWARK BAY - ARTHUR KILL

Velocity And Duration

In the channel of Arthur Kill the velocity of the current at strength is approximately one knot. At the southern entrance, and for the greater part of the Kill, the flood and ebb strength have approximately equal velocities, but at the northern end the flood current has somewhat the greater velocity. At the surface the duration of flood in Arthur Kill is about half an hour less than that of ebb, averaging 5.9 hours for the flood and 6.5 hours for the ebb. (See Table 25). At various depths observations show that for Arthur Kill, as a whole, the duration of ebb is greater than that of flood from the surface to near the bottom. As regards velocity, observation indicates a decrease in both flood and ebb strengths with increasing depth.

TABLE 25

SURFACE CURRENT DATA - ARTHUR KILL

(Referred to times of HW and LW at Sandy Hook)

		FLOOD STRENGTH					EBB STRENGTH			
LOCATION	SLACK HOURS After LW	TIME HOURS Before HW	DIRECTION (True) o	VELOCITY Knots	FLOOD DURATION Hours	SLACK HOURS After HW	TIME HOURS Before LW	DIRECTION (True) o	VELOCITY Knots	EBB DURATION Hours
Off Perth Amboy, N.J.	1.4	1.9	N. 10 E.	0.9	6.0	1.3	2.4	S. 10 W.	0.9	6.4
Off Tottenville, N.Y.	1.9	1.5	N. 25 E.	1.4	5.5	1.3	1.8	S. 60 W.	1.4	6.9
Off Tufts Point, N.J.	1.9	1.4	S. 70 E.	1.2	5.9	1.7	1.9	S. 85 W.	1.2	6.5
Off Linoleumville, N.Y.	2.2	1.4	N. 15 E.	1.0	5.9	2.0	1.7	S. 15 E.	1.0	6.5
Off Tremley Point, N.J.	2.1	1.2	N. 25 E.	1.1	6.3	2.3	1.5	S. 25 W.	1.4	6.1
Off Elizabeth, N.J.	2.9	0.9	E.	1.4	5.8	2.6	1.0	S. 75 W.	1.2	6.6

KILL VAN KULL

The tidal movement through Kill Van Kull is not of the progressive wave type, but is conditioned by the fact that the KILL is a short strait connecting two much larger tidal bodies of water. Throughout Kill Van Kull the ebb has a greater duration than the flood, being 7.0 hours for the ebb, and 5.4 hours for the flood, except near the bottom, where the duration of flood is somewhat greater than that of ebb. The velocity of the ebb is, likewise, greater than that of the flood, averaging 1.8 knots for the ebb and 1.7 knots for the flood. (See Table 26).

Velocity of Currents

In regard to the relative velocities of flood and ebb at the different depths, KILL VAN KULL differs from ARTHUR KILL, for in the latter waterway the flood current has the greater velocity at all depths. In KILL VAN KULL, on the other hand, the ebb has the greater velocity to mid-depth, but below that the flood has the greater velocity.

NEWARK BAY

The flood current in Newark Bay comes both from KILL VAN KULL and from ARTHUR KILL. The cross-sectional area of KILL VAN KULL is, roughly, twice that of Arthur Kill, and the strength of flood in the former is about 70% greater. It follows, therefore, that KILL VAN KULL provides the greater part of the tidal waters flowing into Newark Bay. On the ebb, likewise, the velocity in KILL VAN KULL is greater than that in ARTHUR KILL, so that KILL VAN KULL is also the principal outlet for the ebb of Newark Bay.

Duration & Velocity

Throughout Newark Bay the duration of flood for the current near the surface is somewhat less than that of ebb, being 6.0 hours. In the main channel of the Bay the current at strength has a velocity of about 1-1/4 knots with but little difference between the ebb and flood velocities. (See Table 27).

TABLE 26

SURFACE CURRENT DATA - KILL VAN KULL

(Referred to time of HW and LW at Sandy Hook, N.J.)

		FLOOD STRENGTH					EBB STRENGTH			
LOCATION	SLACK HOURS After LW	TIME HOURS Before HW	DIRECTION (True) o	VELOCITY Knots	FLOOD DURATION Hours	SLACK HOURS After HW	TIME HOURS Before LW	DIRECTION (True) o	VELOCITY Knots	EBB DURATION Hours
Off New Brighton, N.Y.	1.3	2.4	S. 30 W.	1.7	5.7	0.9	2.8	N. 40 E.	1.8	6.7
Off Bergen Point, N. Y.	1.3	2.4	S. 60 W.	2.0	6.0	1.2	2.8	N. 75 E.	1.9	6.4
Off Port Richmond, N.Y.	1.3	2.0	S. 80 W.	2.3	5.7	0.9	2.6	N. 85 E.	1.9	6.7
Off Bergen Point Light,N.J.	1.6	1.4	N. 50 W.	1.2	5.5	1.0	1.2	S. 15 E.	1.7	6.9

TABLE 27

SURFACE CURRENT DATA - NEWARK BAY

(Referred to times of HW and LW at Sandy Hook, N.J.)

	FLOOD STRENGTH					EBB STRENGTH				
LOCATION	SLACK HOURS After LW	TIME HOURS Before HW	DIRECTION (True) °	VELOCITY Knots	FLOOD DURATION Hours	SLACK HOURS After LW	TIME HOURS Before HW	DIRECTION (True) °	VELOCITY Knots	EBB DURATION Hours
Off Bergen Pt. Light, N.J.	1.6	1.4	N. 50 W.	1.2	5.5	1.0	1.2	S. 15 E.	1.7	6.9
Off Mariners Harbor, N.Y.	-1.0	3.4	N. 80 W.	0.7	7.8	0.7	3.8	N. 85 E.	0.5	4.6
Off Elizabeth, N.J.	2.4	0.7	N. 60 E.	1.0	6.2	2.5	0.6	S. 75 W.	0.5	6.2
Off Bergen Pt., N.J.	1.8	1.8	N. 40 E.	1.2	5.9	1.6	1.2	S. 30 W.	1.2	6.5
Off Bayonne, N.J.	2.1	2.1	N. 45 E.	0.8	6.1	2.1	-0.6	S. 45 W.	1.4	6.3
Off Port Newark, N.J.	1.7	1.7	N. 5 E.	1.5	6.0	1.6	1.3	S.	1.4	6.4
Passaic River	2.4	0.5	N.	0.3	5.7	2.0	2.7	S. 10 E.	0.7	6.7
Hackensack River	2.5	0.5	N.	0.7	6.2	2.6	0.2	S.	0.8	6.2

With increasing depth the duration of flood increases while the duration of ebb decreases. However, the velocities of both ebb and flood strengths decrease with increasing depth.

CURRENT IN HUDSON RIVER

Table 28 gives the data from surface observations of the current in the Hudson River. For stations near the mouth of the Hudson the time relations are, on an average, as follows:

Mouth of Hudson

Slack before the flood comes about 2 hours before high water; strength of flood 0.3 hour after high water; slack before ebb 3 hours before low water; and strength of ebb 0.3 hour after low water. These times are referred to Sandy Hook high and low water and the tides at the mouth of the Hudson are about half an hour later than at Sandy Hook. Therefore, with respect to tides at the entrance to the Hudson, the current there is slack almost exactly half-way between high and low water; it is at strength of flood at about the time of high water; and is at strength of ebb at about the time of low water.

Velocities

On the fourteen mile stretch from the Battery to Mount St. Vincent, the tide in the Hudson becomes later by a little over one hour. The current phases, likewise, become later by a little more than an hour, so that throughout this portion of the Hudson the time relations of current to tide are practically constant, being the relations found in progressive wave motion. Along the axis of the channel the flood strength at the entrance to the Hudson averages about 1-1/4 knots. Further upstream as the channel narrows toward Castle Point, the velocity increase to a little over 1-1/2 knots, and off Fort Washington Point it has its greatest velocity, namely, 2-1/4 knots. For the whole stretch, the flood strength averages 1-1/2 knots. The ebb has a greater velocity than the flood, the average of the ebb being 2-1/4 knots as against 1-1/2 knots for the flood. This difference in the flood and ebb velocities is unquestionably due to the fresh water flow. This is reflected also in the great duration of the ebb flow. For the stations along the axis of the channel the flood duration averages 5.4 and the ebb duration 7.0 hours.

Effect of Channel

The axis of the channel lies near the eastern or Manhattan shore rather than in midstream, and, as a result, the greatest velocities are found to the east of mid-stream. Thus, in the Hudson off Morris Street, Manhattan, the strength of the tidal current, that is, the strength of the observed current freed from the effect of non-tidal water, or half the strength of the sum of the flood and ebb strengths, is 1.7 knots for the midstream station, 1.8 knots for the station near the New York shore, and 1.2 knots for the station near the New Jersey shore.

The velocity of the non-tidal current at any point in the river is approximately half the difference between the ebb and flood strengths. This non-tidal current in the Hudson depends on the amount of fresh water coming down the river, hence it will vary.

River Flow

The non-tidal current near the western shore is found to be greater than in midstream or near the eastern shore. Thus, off Morris St. ,the non-tidal current is 0.55 knot near the west shore, 0.5 knot in midstream, and 0.4 knot near the east shore. This greater velocity of the non-tidal current along the west shore of the Hudson indicates a greater flow of upland fresh water along that shore. This is due partly to the deflecting force of the earth's rotation and partly to the tendency of the heavier cold water to follow the deeper channel. As a check on the velocity observations, it is found that the duration of ebb along the west shore is greater than at midstream.

Surface & Subsurface Currents

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

Along the axis of the channel the flood and ebb velocities are, in general, approximately equal at mid-depth. As a general rule, too, the flood has the greater velocity at mid-depth near the New York shore, while near the New Jersey shore the ebb has the greater velocity at mid-depth. But since the channel runs nearer the New York shore, mid-depth is greater along the New York shore. For the same depth on both shores the ebb has the greater velocity along the Jersey shore, indicating that the greater part of the fresh water that comes from the Hudson flows along the New Jersey shore.

Figure 6 Battery To Troy

Figure 6 illustrates the tide and current relation for the entire length of the Hudson from the Battery to Troy. What has been pointed out with respect to time relations at the mouth of the river is evident in Figure 6. The slack of the current at the Battery comes midway between high and low water, and the strengths of current are at the times of high and low water. As we go up the Hudson the time relations of current and tide gradually change. That the time relations must change becomes obvious after a little consideration. Consider the head of the tidewater. Here, of course, the incoming tide must cause a rise of the water and when the tide ceases to flood at high water, the current is at slack before ebb. Therefore, in proceeding up the Hudson, the time that the slack before ebb is later than the time of high water must be made up so that high water and slack before ebb occur at the same time at

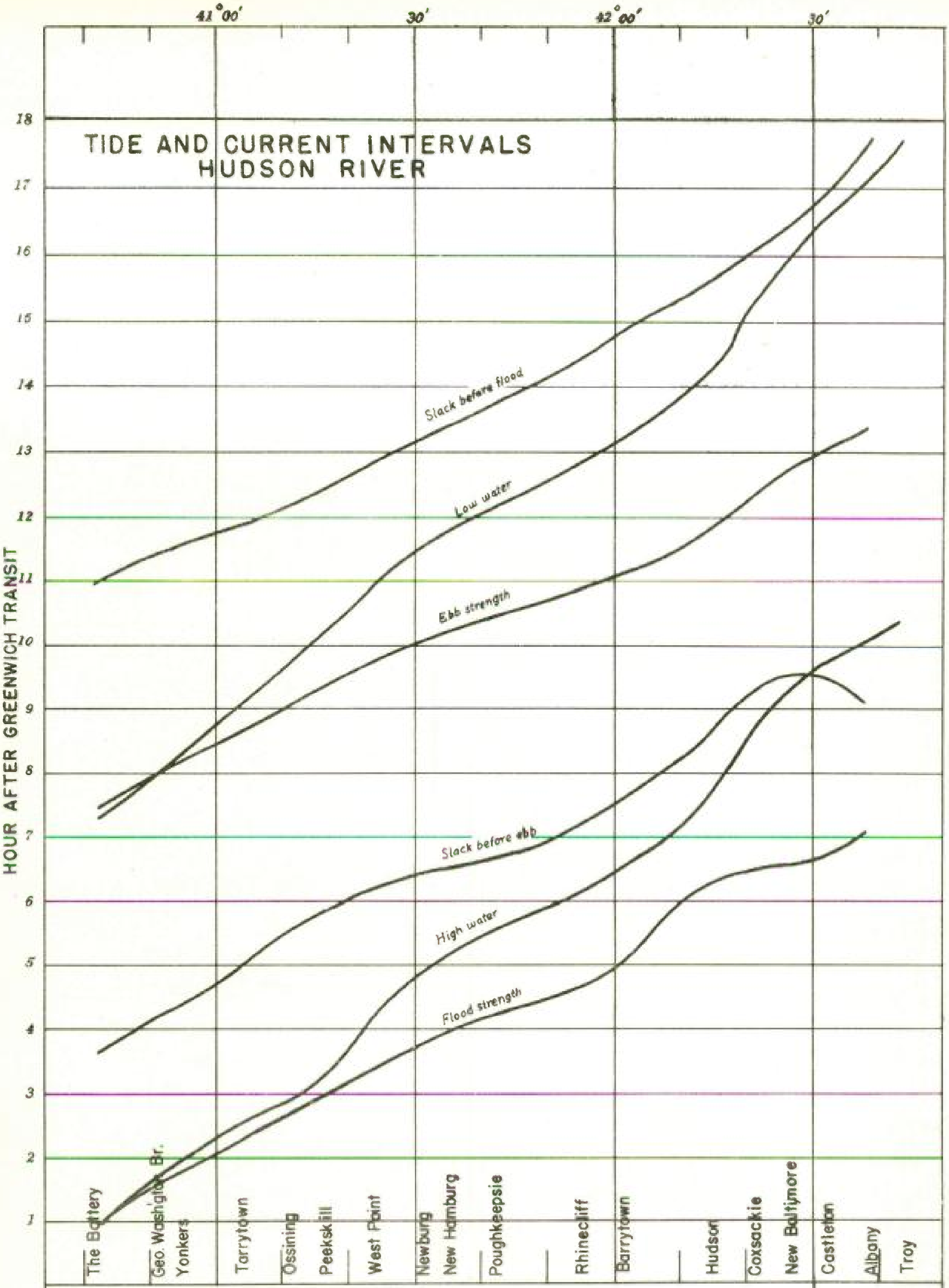


CHART FROM U. S. DEPT. OF COMMERCE
COAST AND GEODETIC SURVEY
To Accompany Report Made by

W.P.A. WATER POLLUTION PROJECT · · Nº 665-97-3-99 SU-I

FIGURE
Nº
6
OCT. 20, 1939

the head of the tidal river. The same considerations apply to the times of low water and slack before flood.

In like manner, the time that the slack before flood is later than low water at the mouth of the river must be made up so that both occur at the same time at the head of the river.

These changes in time intervals appear graphically in Figure 6. The data on which the figure is based is contained in Table 28.

Figures 7 and 8 illustrate the average tide and current conditions in the axis of the main channel of the Hudson at the times of high and low water at the Battery. The scale at the top of each figure represents latitude. The vertical scale on the side indicates height as referred to the Sandy Hook sea level datum. The vertical arrows indicate by their direction whether the tide is rising or falling, while the horizontal arrows show by their direction whether the current is flooding or ebbing. The numerals at each arrow show the velocity of the current in knots.

Figures 7 and 8

It should be remembered that velocities are for current at mid-channel. In approaching the shore diminished velocities are to be expected. Moreover, the time of the turning of the current from the flood to ebb or from ebb to flood may be from a half hr. to an hour earlier near the shore than is the case in mid-channel. The tides and currents as shown are representative of average condition during the summer months and are subject to large seasonal variations due primarily to fluctuations in the fresh water discharge.

CURRENT IN THE HARLEM RIVER

Since the Harlem River is in reality a strait, Upstream and Downstream have no precise meanings in the Harlem, and the designation of flood and ebb currents must be made with reference to the time relations between local current and tide. The tide in the Harlem

TABLE 28

ADJUSTED CURRENT DATA - HUDSON RIVER

(Referred to the Tides at the Battery)

LOCALITY (midchannel off place named)	LATITUDE NORTH °	LATITUDE NORTH '	SLACK Before flood HOURS After LW	FLOOD STRENGTH HOURS After HW	SLACK Before ebb HOURS After HW	EBB STRENGTH HOURS After LW	VELOCITY FLOOD STRENGTH Knots	VELOCITY EBB STRENGTH Knots
The Battery, N.Y.	40	42	3.70	0.07	2.77	0.13	1.5	2.3
Jersey City, (Penn. R.R. Ferry)	40	43	3.72	0.10	2.80	0.20	1.5	2.3
Jersey City, (DL & W. R.R. Ferry)	40	44	3.77	0.18	2.85	0.26	1.6	2.3
Castle Point, Hoboken	40	45	3.80	0.23	2.89	0.29	1.6	2.3
New York, 23rd Street	40	45	3.82	0.26	2.91	0.31	1.6	2.3
New York, 42nd Street	40	46	3.86	0.32	3.00	0.36	1.7	2.3
Days Point, Weehawken	40	46	3.88	0.34	3.02	0.38	1.7	2.3
New York(Union Stock yards)	40	47	3.90	0.37	3.04	0.40	1.7	2.3
New York, 96th Street	40	48	3.96	0.45	3.12	0.48	1.7	2.3
Grants Tomb(123rd St.)	40	49	4.00	0.52	3.18	0.53	1.6	2.3
New York, 130th Street	40	49	4.01	0.54	3.19	0.55	1.6	2.3
George Washington Br.	40	51	4.10	0.64	3.27	0.65	1.6	2.2
Tubby Hook	40	52	4.15	0.71	3.32	0.71	1.6	2.1
Spuyten Duyvil	40	53	4.20	0.77	3.38	0.76	1.6	2.1
Riverdale	40	54	4.25	0.84	3.43	0.82	1.6	2.0
Yonkers	40	56	4.34	0.95	3.54	0.92	1.5	1.9
Dobbs Ferry	41	01	4.51	1.20	3.82	1.19	1.3	1.7
Irvington	41	2	4.55	1.26	3.88	1.24	1.2	1.7
Tarrytown	41	5	4.64	1.41	4.10	1.40	1.1	1.5

TABLE 28 (Cont'd)

						VELOCITY	
LOCALITY (midchannel off place named)	LATITUDE NORTH ° '	SLACK Before flood HOURS After LW	FLOOD STRENGTH HOURS After HW	SLACK Before ebb HOURS After HW	EBB STRENGTH HOURS After LW	FLOOD STRENGTH Knots	EBB STRENGTH Knots
Nyack	41 5	4.66	1.44	4.13	1.42	1.1	1.5
Ossining	41 10	4.85	1.68	4.51	1.69	0.9	1.3
Haverstraw	41 12	4.94	1.78	4.65	1.80	0.8	1.3
Verplanck	41 15	5.08	1.94	4.86	1.96	0.8	1.2
Peekskill	41 17	5.18	2.05	4.97	2.06	0.8	1.2
Iona Island	41 18	5.24	2.11	5.02	2.12	0.8	1.1
Bear Mt. Bridge	41 19	5.29	2.16	5.07	2.17	0.8	1.1
West Point	41 24	5.55	2.43	5.27	2.43	0.9	1.1
Cold Spring	41 25	5.60	2.48	5.31	2.48	0.9	1.1
Storm King	41 25	5.65	2.54	5.35	2.53	0.9	1.1
Newburgh	41 30	5.85	2.75	5.47	2.72	0.9	1.1
New Hamburg	41 35	6.10	2.98	5.61	2.91	1.0	1.1
Poughkeepsie	41 42	6.45	3.26	5.78	3.19	1.1	1.2
Hyde Park	41 47	6.72	3.44	5.92	3.37	1.2	1.3
Rhinecliff	41 55	7.14	3.76	6.30	3.66	1.3	1.5
Tivoli	42 4	7.68	4.25	6.85	3.94	1.5	1.8
Catskill	42 13	8.28	5.26	7.58	4.46	1.6	2.0
Coxsackie	42 21	8.77	5.60	8.35	5.10	1.6	1.8
New Baltimore	42 27	9.22	5.71	8.64	5.52	1.3	1.5
Castleton	42 32	9.61	5.82	8.62	5.86	0.9	1.2
Van Wies Point	42 35	9.97	5.97	8.47	5.98	0.6	1.0
Albany	42 39	10.51	6.17	8.20	6.15	0.3	0.8
Troy	42 44	--	---	---	---	---	0.7

Direction Of Flood & Ebb

is about two hours later than at Sandy Hook. The strength of the southerly flowing current in the Harlem comes about an hour before Sandy Hook high water, and hence about three hours before local high water. It follows, therefore, that the southerly flowing current attains its strength on a rising tide, and is, therefore, the flood current. The northerly flowing current, from similar considerations, attains its strength on a falling tide and is therefore the ebb current.

The slack waters in the Harlem come at about the time of local high and low water, while the strengths come midway between high and low waters. Therefore, the times and velocities of the current are subject to variations additional to those found in tidal rivers, for any relative changes of the heights of water in the Hudson and East Rivers will introduce variations in the current in the Harlem. (See Table 29).

Strength of Currents

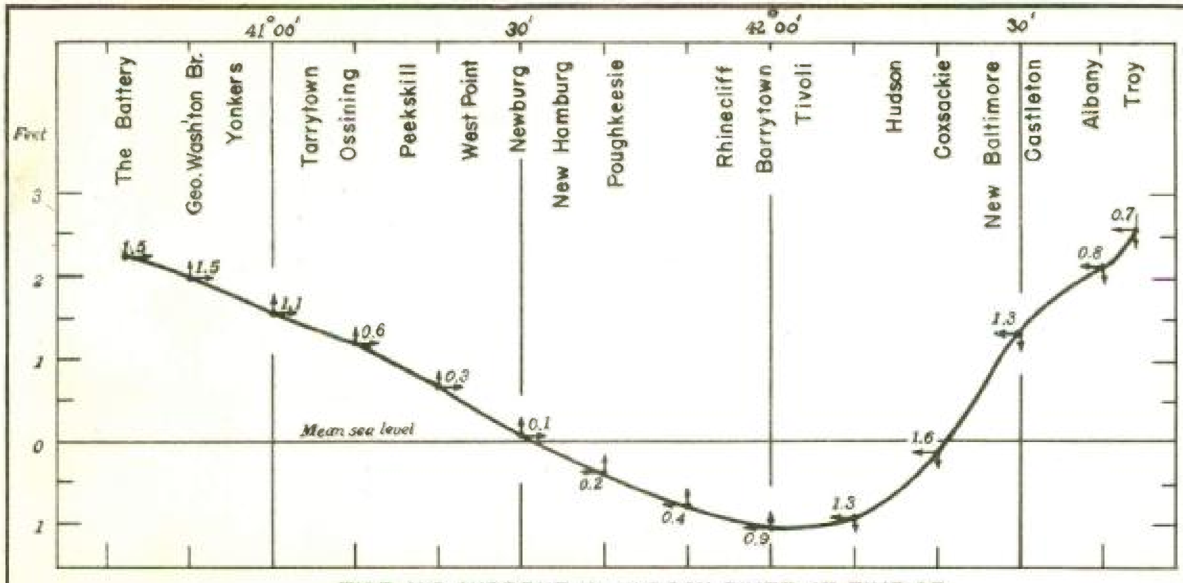
In general, the strength of ebb has the greater velocity, averaging about 1-3/4 knots against 1-1/2 knots for the flood strength. In constricted passages between bridge piers the current attains its greatest velocity; under High Bridge, for example, the current has an average velocity at strength of 3 knots.

Near the surface the ebb strength in the Harlem has the greater velocity, and since both flood and ebb strengths decrease at about the same rates with increasing depth, this preponderance of ebb over flood is characteristic of the Harlem at all depths.

THE CURRENTS IN EAST RIVER

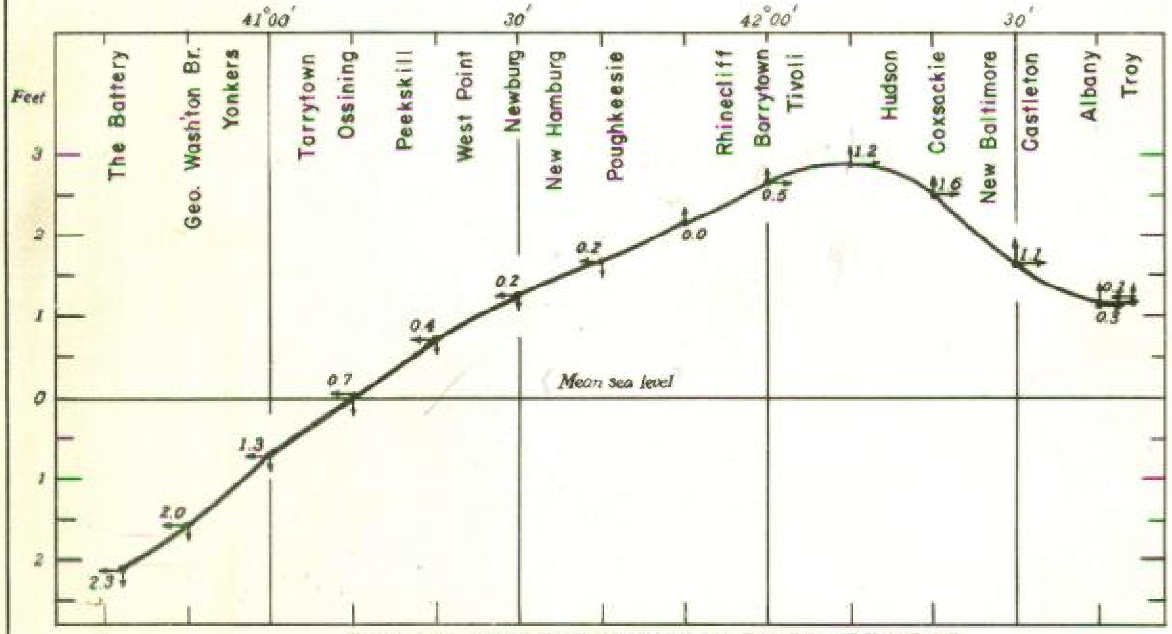
Lower East River: Governors Island to Hell Gate.

This section is a relatively narrow and deep waterway, while the section above Hell Gate is wider and shallower.



TIDE AND CURRENT IN HUDSON RIVER AT TIME OF
HIGH WATER AT THE BATTERY

Figure № 7



TIDE AND CURRENT IN HUDSON RIVER AT TIME OF
LOW WATER AT THE BATTERY

Figure № 8

CHART FROM U. S. DEPT. OF COMMERCE
COAST AND GEODETIC SURVEY
To Accompany Report Made By
W.P.A. WATER POLLUTION PROJECT · · № 665-97-3-99 SU·I

FIGURES
No.
7 & 8
OCT. 20, 1939

TABLE 29

SURFACE CURRENT DATA - HARLEM RIVER

(Referred to times of HW and LW at Sandy Hook, N.J.)

LOCATION	FLOOD STRENGTH					EBB STRENGTH				
	SLACK HOURS After LW	TIME HOURS Before HW	DIRECTION (True) °	VELOCITY Knots	FLOOD DURATION Hours	SLACK HOURS After HW	TIME HOURS Before LW	DIRECTION (True) °	VELOCITY Knots	EBB DURA TIO Hour
Off Spuyten Duyvil	2.1	0.5	S. 65 E.	1.5	6.1	2.1	1.0	N. 80 W.	2.2	6.3
Broadway Bridge	2.1	0.5	S. 65 E.	2.1	5.8	1.8	1.4	N. 60 W.	2.4	6.6
W. 207th St. Bridge	2.0	0.8	S. 35 W.	2.0	6.3	2.2	0.9	N. 35 W.	2.0	6.1
High Bridge	2.0	0.9	S. 10 W.	3.0	5.8	1.7	1.5	N. 15 E.	2.8	6.6
South of High Bridge	1.7	0.8	S. 35 W.	1.2	6.4	2.0	1.1	------	1.3	6.0
Central Bridge	2.1	1.1	S.	1.7	5.8	1.8	1.2	N.	1.4	6.6
Madison Avenue Bridge	2.0	1.0	S.	1.7	6.0	1.9	1.3	N.	1.6	6.4
Above Willis Ave. Br.	1.5	1.1	S. 35 E.	0.9	6.6	2.0	1.7	N. 40 W.	1.0	5.8
Off 117th Street	2.2	0.2	S. 35 W.	0.5	5.9	2.0	1.0	N. 50 E.	2.2	6.5
Off 116th Street	1.2	0.6	S. 15 W.	1.3	7.6	2.7	1.5	N. 35 E.	0.2	4.8
Off South Pier, Randalls Island	---	0.9	S. 15 W.	1.2	---	---	1.0	S. 55 E.	-0.1	---
Off Randalls & Wards Islands	2.0	0.4	S. 80 E.	3.1	5.9	1.8	1.3	N. 60 W.	2.9	6.5
Off Jefferson Park	2.1	0.3	N. 55 E.	0.5	6.3	2.3	1.8	S. 50 W.	0.6	6.1
Off 110th Street	1.7	1.5	N. 40 E.	0.9	5.7	1.3	0.8	S. 5 W.	1.0	6.7

Flood & Ebb

On entering East River from Upper Bay it is natural to regard the current setting from Upper Bay into East River as the flood current, but East River may also be entered from Long Island Sound, from which body it is just as natural to regard the westerly setting current as the flood current. Therefore, recourse must again be had to time relations in order to specify the flood and ebb currents. From these it is seen that in this portion of the East River the strength of current from Upper Bay occurs on a rising tide, and is, therefore, a flood current, while the ebb current is the one that sets from Long Island Sound toward Upper Bay. (See Table 30).

From the Battery to Hell Gate the time of tide becomes later by 1-3/4 hours, and, therefore, the time relations between tide and current change from point to point. But the flood duration remains approximately constant throughout, averaging 6.1 hours against 6.3 hours for the ebb.

The swiftest current in lower East River is found in the constricted passages at Blackwells or Welfare Island and in Hell Gate, where the mean velocity of the current is 4 knots or more.

Throughout lower East River the surface ebb current has the greater velocity and the greater duration, which would indicate a fresh waterflow toward Upper Bay. But an examination of the sub-surface velocity and duration does not bear this out. Unusual conditions cause a difference between the behavior of points in the same cross-section of the river, and points which are within the full sweep of the ebb current are located to one side of the main flood current.

UPPER EAST RIVER: HELL GATE TO WILLETS POINT

The easterly current here is the flood current and the westerly current the ebb current. The duration of flood increases from west to east, averaging about six hours at Hell Gate and about seven hours at Willets Point. For the Upper East River, as a

TABLE 30

SURFACE CURRENT DATA - LOWER EAST RIVER

(Referred to times of HW and LW at Sandy Hook, N.J.)

LOCATION	FLOOD STRENGTH					EBB STRENGTH				
	SLACK HOURS After LW	TIME HOURS Before HW	DIRECTION (True) °	VELOCITY Knots	FLOOD DURATION Hours	SLACK HOURS After HW	TIME HOURS Before LW	DIRECTION (True) °	VELOCITY Knots	EBB DURATION Hours
Off State St., Bklyn.	2.0	0.7	N. 60 E.	1.3	6.5	2.4	1.7	S. 25 W.	1.8	5.9
Off Joralemon St. Bklyn.	1.7	0.7	N. 60 E.	2.5	7.0	2.6	0.9	S. 50 W.	2.6	5.4
Off Montague St., Bklyn.	1.6	1.8	N. 70 E.	1.2	7.0	2.5	1.0	S. 25 W.	1.7	5.4
Off Coenties Slip, N.Y.	2.3	0.4	N. 55 E.	2.1	6.1	2.3	0.9	S. 50 W.	2.5	6.3
Off Wall Street, N.Y.	1.6	0.8	N. 50 E.	1.6	6.5	2.0	1.3	S. 30 W.	1.5	5.9
Off Fletcher St., N.Y.	2.2	0.8	N. 45 E.	2.3	6.1	2.2	0.8	S. 40 W.	3.2	6.3
Below Fulton St. Bklyn.	1.0	0.0	N. 40 E.	1.8	7.5	2.4	1.4	S. 55 W.	0.3	4.9
Off Dover Street, N.Y.	2.1	1.6	N. 45 E.	2.0	6.4	2.4	1.1	S. 40 W.	1.5	6.0
Mid-Channel, Bklyn Br.	2.1	0.2	N. 50 E.	3.2	6.7	2.7	0.4	S. 65 W.	3.8	5.7
Wallabout Bay	1.9	1.0	N. 75 E.	0.8	6.2	2.0	---	----	---	6.2
Off Jackson St., N.Y.	2.4	0.8	S. 85 E.	5.3	5.7	2.0	0.9	S. 80 W.	4.2	6.7
Wallabout Bay	2.4	0.4	N. 50 E.	1.9	5.9	2.2	1.1	S. 75 W.	2.3	6.5
Off Corlear St., N.Y.	2.4	0.7	N. 55 E.	3.9	6.0	2.3	1.0	S. 60 W.	3.3	6.4
Off Corlears Hook, N.Y.	2.3	0.8	N. 65 E.	4.5	6.1	2.3	1.1	S. 45 W.	3.9	6.3
Wallabout Bay	1.9	0.1	N. 35 E.	2.9	6.8	2.6	1.4	S. 40 W.	2.9	5.6
Off S. 9th St., Bklyn.	1.9	0.3	N. 25 E.	1.6	6.2	1.9	---	----	---	6.2
Off N. 2nd St., Bklyn.	3.4	-0.4	N. 15 W.	0.1	5.6	2.9	1.5	S. 45 W.	0.6	6.8
Off N. 4th St., Bklyn.	2.5	0.4	N. 35 E.	4.8	5.7	2.1	0.6	S. 40 W.	3.9	6.7
Off N. 6th St., Bklyn.	2.4	0.0	N. 25 E.	2.1	6.4	2.7	0.7	S. 20 W.	3.2	6.0
Off 17th Street, N.Y.	2.3	0.0	N. 25 E.	2.5	6.2	2.4	1.0	S. 5 W.	1.3	6.2
Off 18th St., N. Y.	2.0	0.7	N. 10 W.	1.4	6.0	1.9	1.1	S. 10 E.	2.2	6.4
Off 19th St., N. Y.	2.0	0.6	N. 5 W.	1.5	6.1	2.0	1.3	S.	2.0	6.3
Off 20th St., N. Y.	1.9	0.6	N.	1.9	6.1	1.9	1.6	S. 10 W.	1.8	6.3
Off 20th St., N. Y.	2.3	1.0	---	2.5	6.3	2.5	1.4	S. 20 E.	1.8	6.1

TABLE 30 (Cont'd)

LOCATION	FLOOD STRENGTH					EBB STRENGTH				
	SLACK HOURS	TIME HOURS	DIRECTION (True)	VELOCITY	FLOOD DURATION	SLACK HOURS	TIME HOURS	DIRECTION (True)	VELOCITY	EBB DURATION
	After LW	Before HW	o	Knots	Hours	After HW	Before LW	o	Knots	Hours
Off 21st Street, N. Y.	2.1	---	----	---	6.0	2.0	0.9	---	2.5	6.4
Off 23rd Street, N. Y.	2.3	0.8	----	2.0	6.1	2.3	1.4	---	2.3	6.3
Off Huron St., Bklyn.	2.4	0.8	N. 15 W.	2.1	6.2	2.5	1.1	S. 10 E.	2.3	6.2
Off Greene St., Bklyn.	2.1	0.9	N.	2.1	6.2	2.2	1.2	S. 15 E.	1.8	6.2
Off 25th Street, N. Y.	2.3	1.4	N.	1.4	5.7	1.9	1.6	S.	1.7	6.7
Off 26th Street, N. Y.	2.5	0.5	N. 5 W.	2.3	6.6	3.0	1.7	S. 15 W.	1.6	5.8
Newtown Creek Entrance	2.7	-0.1	N. 60 E.	0.3	5.6	2.2	1.2	S. 50 W.	0.3	6.8
Off 34th Street, N.Y.	2.5	0.9	N. 25 E.	1.3	5.8	2.2	0.6	S. 35 W.	2.1	6.6
Off 39th Street, N.Y.	2.1	1.1	N. 15 E.	2.3	5.4	1.4	0.2	S. 35 W.	1.5	7.0
Off 43rd Street, N.Y.	2.8	0.7	N. 20 E.	2.5	6.0	2.7	0.6	S. 25 W.	4.1	6.4
Off 52nd Street, N.Y.	2.2	0.6	N. 25 E.	2.7	6.1	2.2	1.4	S. 3[illegible] W.	3.2	6.3
East Channel, Blackwells Island	1.8	0.4	N. 30 E.	2.6	6.6	2.3	1.2	S. 30 W.	1.9	5.8
West Channel, Blackwells Island	2.3	1.0	N. 35 E.	3.8	5.9	2.1	1.0	S. 45 W.	4.7	6.5
East Channel, Blackwells Island	2.0	0.7	N. 25 E.	3.5	6.3	2.2	1.4	S. 30 W.	3.3	6.1
West Channel, Blackwells Island	2.1	1.1	----	4.8	6.3	2.3	1.4	---	5.0	6.1
East Channel, Blackwells Island	2.0	0.7	N. 10 W.	3.4	5.9	2.5	1.6	S. 15 E.	1.5	6.5
Hell Gate	2.2	1.2	N. 20 E.	4.2	6.2	2.3	1.8	S. 60 W.	3.0	6.2
Off 92nd Street, N.Y.	1.5	2.0	N. 25 W.	1.2	6.1	1.5	1.2	S. 20 E.	2.6	6.3

TABLE 31

SURFACE CURRENT DATA - UPPER EAST RIVER

(Referred to times of HW and LW at Sandy Hook, N.J.)

LOCATION	FLOOD STRENGTH					EBB STRENGTH				
	SLACK HOURS After LW	TIME HOURS Before HW	DIRECTION (True) o	VELOCITY Knots	FLOOD DURATION Hours	SLACK HOURS After HW	TIME HOURS Before LW	DIRECTION (True) o	VELOCITY Knots	EBB DURATION Hours
Between Randalls and Wards Island	1.8	0.9	E.	2.3	6.0	1.7	2.0	S. 85 W.	2.3	6.4
Between Randalls and Wards Island	2.0	0.4	S. 80 E.	3.1	5.9	1.8	1.3	N. 60 W.	2.9	6.5
Off Jefferson Park	2.1	0.3	N. 55 E.	0.5	6.3	2.3	1.8	S. 50 W.	0.6	6.1
Off 110th Street	1.7	1.5	N. 40 E.	0.9	5.7	1.3	0.8	S. 5 W.	1.0	6.7
Off 108th Street	2.5	-0.4	N. 45 E.	0.7	6.4	2.8	1.2	S. 20 W.	0.8	6.0
Off 105th Street	2.6	-0.6	N. 35 E.	0.6	5.9	2.4	1.6	S. 40 W.	0.8	6.5
Between Mill Rock & Wards Island	1.8	0.9	S. 75 E.	2.6	6.2	1.9	1.8	N. 70 W.	0.5	6.2
Hell Gate	2.4	0.4	N. 70 E.	4.5	6.0	2.3	1.0	S. 85 W.	4.3	6.4
East of Wards Island	2.5	0.8	N. 45 E.	3.2	6.3	2.7	1.3	S. 35 W.	2.3	6.1
Between Sunken Meadow and Randalls Island	2.1	1.3	N. 50 E.	1.2	5.7	1.7	1.3	S. 45 W.	2.0	6.7
Off Lawrence Point	2.6	0.5	N. 45 E.	3.8	6.1	2.6	1.3	S. 45 W.	2.5	6.3
Bronx Kill Entrance	2.1	1.4	S. 80 E.	0.6	6.0	2.0	2.4	N. 75 W.	0.8	6.4
Bronx Kill, East End	1.3	1.0	S. 65 E.	1.1	6.9	2.1	2.0	N. 50 W.	1.1	5.5
Bronx Kill	1.7	0.5	S. 35 E.	1.6	6.4	2.0	1.6	N. 50 W.	1.9	6.0
West of North Brother Island	2.5	0.7	N. 40 E.	22.1	6.3	2.7	1.0	S. 35 W.	1.7	6.1
South of North Bro. Island	1.7	0.9	N. 65 E.	2.8	6.9	2.5	1.1	S. 75 W.	1.7	5.5
Southwest of Rikers Island	2.5	0.7	S. 45 E.	1.1	5.8	2.2	0.9	N. 40 W.	1.3	6.6

TABLE 31 (Cont'd)

LOCATION	FLOOD STRENGTH					EBB STRENGTH				
	SLACK HOURS	TIME HOURS	DIRECTION (True)	VELOCITY	FLOOD DURATION	SLACK HOURS	TIME HOURS	DIRECTION (True)	VELOCITY	EBB DURATION
	After LW	Before HW	°	Knots	Hours	After HW	Before LW	°	Knots	Hours
Northeast of No. Bro. Island	2.5	0.7	E.	2.0	6.4	2.8	1.0	S. 75 W.	0.6	6.0
North of Rikers Island	2.7	0.2	S. 30 E.	1.0	6.5	3.1	1.5	N. 50 W.	0.6	5.9
Off Barretto Point	1.7	0.8	S. 70 E.	1.9	6.8	2.4	1.4	N. 80 W.	0.9	5.6
Off Hunts Point	2.4	1.0	S. 75 E.	1.9	6.3	2.6	1.3	N. 80 W.	1.3	6.1
Bronx River	3.7	-0.4	N. 55 W.	0.4	4.7	2.3	-0.4	S. 50 E.	0.3	7.7
Off Hunts Point	2.2	0.6	E.	1.3	6.2	2.3	1.1	N. 60 W.	1.1	6.2
E. of Rikers Island	2.8	1.4	N. 50 E.	0.5	6.3	3.0	1.5	N. 45 W.	1.0	6.1
Off Sanford Point	2.1	1.1	S. 85 E.	1.2	6.0	2.0	1.0	S. 80 W.	1.3	6.4
Flushing Creek Entrance	4.3	-1.2	N. 70 E.	0.4	6.6	4.8	-0.9	S. 85 W.	0.5	5.8
Off College Point	4.9	-1.7	S. 45 E.	0.6	5.4	4.2	-1.0	N. 25 W.	0.5	7.0
Off Clason Point	1.9	1.4	N. 80 E.	1.6	6.6	2.4	1.3	S. 70 W.	1.4	5.8
Off Old Ferry Point	0.9	1.3	N. 75 E.	2.0	7.3	2.1	1.8	S. 45 W.	1.4	5.1
Off Whitestone Point	1.0	1.6	S. 65 E.	1.4	6.9	1.8	1.6	N. 50 W.	1.1	5.5
Between Throggs Neck and Whitestone	1.8	1.5	S. 65 E.	1.5	6.6	2.3	2.0	N. 75 W.	1.5	5.8
Between Throggs Neck and Willets Point	0.0	2.8	N. 55 E.	0.9	5.9	-0.2	1.8	S. 85 W.	0.6	6.5

whole, therefore, the flood has the greater duration and velocity, which reverses the conditions found in Lower East River, where ebb was the greater. (See Table 31).

Relation To Harlem River

Upper East River being wider than Lower East River, the velocity of the current is much less in the upper section, but the change of width does not account for the reversal of relative magnitudes of the flood and ebb durations and strengths. If we examine the behavior of the current in the Harlem River, we find that the current in the Harlem is very nearly simultaneous with the current in the Upper East River. On the flood the Harlem is carrying water from the Hudson into East River, at which time the current is setting from lower East River into Upper East River. The Upper East River, therefore, should and does show evidence of fresh water flow from the Hudson and other streams tributary to Upper East River. This evidence is found in the greater duration and velocity of the flood strength.

Other characteristic effects of fresh water flow in the Upper East River may be observed. The slack before ebb comes earlier from the surface downward. Furthermore, the velocity of the flood strength decreases very slowly from the surface downward, and may even increase, while the strength of ebb decreases at a relatively rapid rate.

In Upper East River, therefore, the effects of fresh water flow are clearly evident in the current, while in lower East River we have seen that the current was free from such effects.

CURRENT AT WILLETS POINT

It is of interest in our current study to observe the behavior of the current at Willets Point, situated at the junction of the East River with Long Island Sound. For this localized study the easterly current in the vicinity of Willets Point is regarded as the flood current, and the westerly current as the ebb.

Tide Relation to Currents

It has been pointed out in our discussion of the current in the Upper East River that throughout the duration of the flood current the easterly flowing waters are augmented by the fresh water runoff from the Hudson via the Harlem River. This flow from the Hudson begins somewhat more than an hour after the time of low water at the Battery and continues slightly more than six hours. Just before the commencement of the flow from the Hudson (at about one hour after low water at the Battery) the current at Willets Point has already changed to flood, although it is still ebbing in the section of the river west and south of College Point. The velocity of this eastward current at Willets Point increases rapidly, reaching its strength (about 1.3 knots) shortly after the time of low water at Willets Point (about three hours after the time of low water at the Battery). The influence of the rising tide in the Sound then begins to decrease the velocity of the eastward current, and at the time of high water at the Battery (three hours after low water at Willets Point) the current is but 0.8 knot, and an hour later it is at slack. Slack waters in the Hudson and the Lower East River occur shortly thereafter, and the reverse or ebb current commences. The westwardly flowing current at Willets Point increases in velocity very gradually, and at the time of high water Willets Point (three hours after high water at the Battery) it is only 0.6 knot. It remains at about this velocity for an hour and then slowly diminishes, becoming slack again at about three hours after high water there (about the time of low water at the Battery).

In the foregoing description it is seen that the velocity of the flood current at Willets Point is greater than the ebb. This would indicate a greater flow of water past Willets Point on the flood current than on the ebb. But this velocity difference is more than balanced by the fact that the westwardly or ebb current prevails before, during and after the time of high water at Willets Point when the cross-sectional area of the channel is greatest; while the easterly or flood current prevails at low water when the cross-sectional area is least.

CURRENTS IN LONG ISLAND SOUND

The Coast and Geodetic Survey has observed tidal currents in Long Island Sound from time to time since 1846. The progression of the current through the middle of Long Island Sound may be summarized as follows:

West Of Bridgeport

Over the stretch of eastern Long Island Sound from the Race to Old Field Point, a distance of forty-eight nautical miles, the current is almost simultaneous owing to the wide expanse and good depths of the waterway. In western Long Island Sound over the stretch from Old Field Point to Execution Rocks, a distance of thirty nautical miles, the difference in the time of current is about one hour. In this stretch of the waterway the time of current is retarded considerably by the funnel shape of the waterway, which narrows rapidly from about 12 nautical miles off Bridgeport, Conn., to about 2-1/2 nautical miles off Execution Rocks. The extremely slow progression of the current southward of Execution Rocks is due to considerable tidal interference in this vicinity. Observations show that the current occurs much earlier in the bays and harbors along the shores of Long Island Sound than it does in mid-sound. In some cases the currents in these tributaries occur even earlier than it does at the Race at the entrance to Long Island Sound. The strength of flood current in these bays and harbors occur about three hours earlier than local high water, or approximately at the time of local mean tide level. At virtually no locality in Long Island Sound does the strength of current occur simultaneously with either high or low water. The fact that the strength of flood current throughout a large area in Long Island Sound from Orient Point, Long Island, to Eaton Point, Long Island, occurs from about 1-1/2 to 2-1/2 hours earlier than local high water, or approximately near the time of mean tide level, is due to the character of the tide wave in Long Island Sound, which is predominantly of the stationary type.

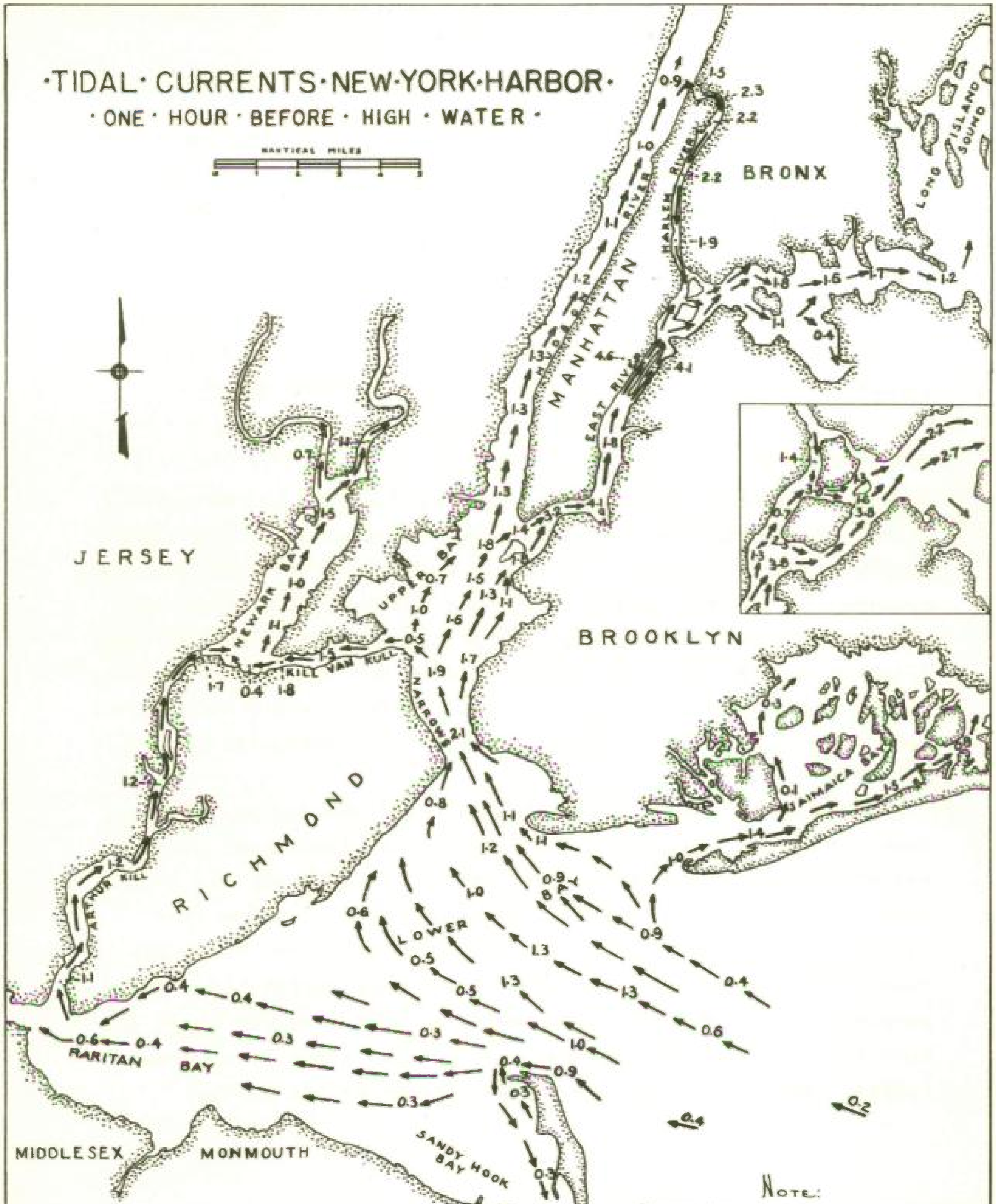
CURRENT CHARTS

Map 2, which follows, and Map I, which appears at the beginning of this report, represent the direction and velocity of the tidal current in New York Harbor at the times of maximum flood and ebb velocities. The velocities which are expressed in knots are for the current at the time of spring tide, and are stronger than the velocities ordinarily encountered. However, strong winds and freshets bring about non-tidal currents which may modify considerably the velocities and directions shown.

ACKNOWLEDGMENTS

The compilation of this report required frequent use of publications of the various Government agencies concerned with tidal observations. Since no tidal field work was done by the Project, practically all the data on tides and currents were taken from the latest available publications on the subject. Special Publication No. III, Revised (1935) Edition and Special Publication No. 180 (1934), describing tides and currents in New York Harbor and in the Hudson River, respectively, were particularly useful.

The Division of Tides, United States Coast and Geodetic Survey, Washington, D.C., supplied the Project with additional data on the tides at Willets Point, Long Island. The Operations Division of the United States Army Engineers Office in New York supplied the data for tidal observations later than those already published, as well as other invaluable assistance. The personnel of the New York office of the United States Coast and Geodetic Survey, whose cooperation has been previously acknowledged, assisted and advised on all phases of the survey.



MAP FROM U.S. DEPT. OF COMMERCE
COAST AND GEODETIC SURVEY

TO ACCOMPANY REPORT MADE BY

W.P.A. WATER · POLLUTION · PROJECT No. 665-97-3-99-SUI

MAP
No. 2
OCT. 23, 1939

RELATION OF TIDES AND CURRENTS TO SEWAGE DISPOSAL

The degree to which sewage is treated depends to some extent upon the character of the waterway into which the treated sewage may be discharged. In a situation such as the vicinity of New York, the methods used are often determined by the amount of water which daily passes the point of discharge. It is in this connection that tide and current phenomena are of importance to the Sanitary Engineer.

The importance of the waterways from the standpoint of sewage treatment may be briefly stated: as:

A. The amount of water available for diluting the sewage or effluent.
B. The direction and distance to which harmful ingredients in the sewage may be transported by currents.
C. The oxidation of organic matter and in salt water the precipitation and settling out of some of the obnoxious portions of the sewage.

Interstate Sanitation Comm.

The Interstate Sanitation Commission is required by law to divide the waters in this district into two classes; first those areas which are used for recreational purposes or for the growing of shellfish; and second, those areas which are used primarily for commercial or industrial purposes. The sanitary requirements in the first area are naturally much higher than is necessary in the second class areas.

It is obvious that in fixing the limits of such areas there will always be, at the dividing line between the two classes of waters, an indeterminate zone in which tidal currents will transport polluting material from one class of waterway into the other. In order to measure the probable effect of the dissemination of untreated or partly treated sewage, it is necessary to know the amount of water that is available for the dilution of the sewage, and also the probable direction and distance to which injurious elements of the sewage will be transported. It is also important to know what portions of the natural waterways are so situated that there is little or no current in them, as in these localities any sewage waste discharged tends to settle to the bottom causing offensive conditions. In such cases as those last mentioned, although the tide rises and falls, there is not sufficient flow from landward sources to transport the offensive material into the main channels so that it is carried away. New York Harbor as a whole is fortunate by virtue of the fact that the Hudson, Passaic, Hackensack and Raritan Rivers, as well as numerous smaller streams supply a continuous flow of water which causes the harbor waters to flow eventually into the Atlantic Ocean.

Relation to Currents

The determination of the quantity of water passing in and out of New York Harbor past any given point, is, theoretically, a simple matter for it is obviously equal to the product of four factors, namely, the width of the channel at that point, the average depth, the average volocity of the current, and the duration of flow. In tidal waters with reverse flows the difference between ebb and flood is ascertained to obtain the net amount of of dilution water available.

Quantity of Dilution

The precise determination of the average velocity in a tidaly section by field observations is very difficult. It is therefore not surprising that the values arrived at by different investigators, vary to some extent. From observations made in 1885, Henry Mitchell of the Coast & Geodetic Survey estimated

Average Quantities

that the volume of water passing through the Narrows was 12,703,616,481 cubic feet on the flood and 13,819,895,144 cubic feet on the ebb or a net seaward discharge of about 1,116,200,000 cubic feet each half day. Based on observations made by the Metropolitan Sewerage Commission of New York between 1907-09, Parsons estimated the flood and ebb volumes through the Narrows were 10,778,800,000 and 12,041,200,000 cubic feet respectively or a net seaward discharge of 1,262,400,000 cubic feet per tidal cycle. From later studies it appears that the above estimates are substantially correct and that in round numbers we may safely take the average volume passing the Narrows on the flood as 11,000,000,000 cubic feet and on the ebb 12,250,000,000 cubic feet. During each tidal cycle of 12.5 hours there is therefore on the average a net seaward movement of 1¼ billion cubic feet through the Narrows, that is, a movement at the rate of 2½ billion cubic feet per lunar day. This excess of the ebb volume over the flood is obviously to be ascribed, if not wholly, at least in very large part, to the run-off from the territory that drains into New York Harbor. Estimates of the amount of this fresh non-tidal water based on gaugings of the Mohawk and Hudson Rivers above Troy and on rainfall data for the territory below Troy give 25,000 or 26,000 cubic feet as the average discharge per second past the Narrows, or in round numbers a discharge of about 2¼ billion cubic feet per day.

Hudson R. & Kill Van Kull

From the Upper Bay the tide darries 5¾ billion cubic feet into the Hudson during the flood, while during the ebb the Hudson discharges into the Bay 6¾ billion cubic feet, the fresh water run-off being a little in excess of one billion cubic feet during a tidal cycle of 12½ hours or 2 billion cubic feet per day. Through Kill Van Kull the flood comes from New York Harbor into Newark Bay in the amount of 1½ billion cubic feet and the ebb returns into the Harbor very nearly 100 million cubic feet more, so that in a day Newark Bay pays tribute of almost 200 million cubic feet of water to New York Harbor.

Harlem River

For the Harlem River, Parson calculated a net ebb or northerly discharge into the Hudson River of 17½ million cubic feet for a full tidal cycle or about 35 million cubic feet per day. For the central portion of the Harlem his figures give a movement of about 162½ million cubic feet for the flood and 180 million cubic feet for the ebb. A considerably larger figure for the ebb excess in the Harlem is derived by Robinson from later observations. He gives 44 million cubic feet per tidal cycle as the excess of ebb over flood or nearly 90 million cubic feet per day. These figures have in all probability been considerably altered by straightening and improving the Harlem River section near the Hudson River in recent years.

East River

The question of the net resultant discharge of East River has been the subject of considerable discussion. Attention was first directed to the matter by Henry Mitchell who derived, from a short series of observations, a volume of 4,455 million cubic feet for the ebb and 4,007 million cubic feet for the flood, a net resultant discharge from Long Island Sound into New York Harbor of nearly 900,000,000 cubic feet per day. This excess of ebb over flood he attributed to the fact that in East River the depth of the water is greater when the current is flowing from Long Island Sound to Upper Bay than when the current is in reverse direction. This fact is indicated in figure 2 which shows that the slopelines from east to west toward the Narrows are as a whole higher than the slope lines in the opposite direction toward the Sound.

Effect on N. Y. Harbor

To this net resultant discharge from Long Island Sound into Upper Bay a very considerable importance has been attached. To quote Mitchell, the circulation of the sea by the way of East River, although relatively small in quantity, is the element which determines the superiority of New York Harbor over nearly all the sand barred inlets of the world. It is this circulation which keeps the port open in winter and sweeps the sand from its threshold. In connection with the disposal of sewage, it was thought that this resultant flow played an important part in flushing out New York Harbor; recently it has been suggested that the discharge from Long Island Sound be increased by the erection of tidal gates to shut off the return eastward flow through East River. It is probable, however, that the flow of the Hudson River, especially during spring flows, is a more vital factor.

Preponderance Of flow

A preponderance of about 400 million cubic feet in the ebb, or about 10% of the tidal flow in the Upper East River, was generally accepted until 1908, when, at the instance of the Metropolitan Sewerage Commission of New York, the the Coast & Geodetic Survey investigated the matter anew; the question being turned over to the late R.A. Harris of the Division of Tides. From a mathematical discussion of the flow of water in open channels, in connection with the current observations that had up to that time been made in the East River, he arrived at the conclusion that the volume of water flowing westerly was probably not more than 2% greater than the volume flowing easterly, This estimate would therefore make the net resultant discharge not over 100 million cubic feet per tidal cycle. Parsons follows Harris and gives 80 million cubic feet as the net discharge per tidal cycle.

However, from current observations made by the Corps of Engineers of the U.S. Army in 1910 and 1911 in the vicinity of Hell Gate, Robinson derives figures closely approximating Mitchell's.

Distance Traveled

From the large quantity of water circulating in the various channels of New York Harbor an exaggerated notion of the flushing action of the waters in the Harbor is frequently entertained. It is to be borne in mind that for the greater portion of the Harbor the water that is returned on the flood is not clean sea water but harbor water which has been carried to a lower portion of the

Harbor on the preceding ebb tide. In the section dealing with the distance traveled by a particle of water during a tidal cycle, it was shown that with a current which at strength has a velocity of 2 knots, a particle will be carried a distance of about 48,000 feet or 8 geographic miles during the period of a single flood or ebb.

If therefore, the flood and ebb velocities were equal a particle would merely move a given distance downstream on the ebb and return the same distance upstream on the flood. It is the excess of the ebb over flood that finally carries a particle from the upper reaches of the Harbor out past the Narrows and into the sea.

Ebb
Excess
Flow

In the circulation of the waters in the Harbor it is therefore the excess of the ebb volume over the flood that is the important feature. Two causes contribute to this ebb excess. The first and principal cause is the fresh water run-off from nearly 15,000 square miles of territory that drains into the Atlantic through New York Harbor and the second is the excess of the flow coming from Long Island Sound which circulates through the Harlem, Hudson and East Rivers and thence through the Narrows out to sea.

APPENDIX I

OF

TIDES & CURRENTS

The material contained in this appendix pertains to the general subject of beach formation, wind effects, and fluctuations in ocean levels.

DEPOSITION, BEACH FORMATION, ETC.

(FROM "MANUAL OF TIDES" BY R.A. HARRIS)

DESTRUCTIVE EFFECTS DUE TO WIND WAVES

Storm Currents

The destructive effects of the waves during severe storms upon an exposed coast line are frequently so great as to cause much alarm in the locality affected and to justify the expanditure of large sums of money in preventing them. The power of waves to tear down land is made far more effective where a littoral current, tidal or otherwise, is sufficiently strong to carry away much of the matter thus brought into the reach of the sea. Where no such current exists the tendency to form a protecting shoal along the exposed coast is greatly increase.

Through the encroachment of the sea upon the land, particularly noticenble after heavy storms, the nearby waters become discolored by the soluble ingredients of the soil while the heavier matter remains on the bottom, comparatively near to the scene of the erosion. In this manner, beds of sand and shingle are formed.

Effect of Rivers

Immense quantities of alluvial matter are brought to the shallow waters of the sea through the agency of rivers. Besides forming shoals and bars off the mouths of these streams this material through the action of the waves and currents is scattered and transported to nearby localities favorable to the formation of shoals, islands and shore extensions. It is, however, difficult to say how much of the material comprising the shallow bed of the ocean adjacent to the shore is transported from river mouths and how much is due to the degradation of the of the coast line. Maps of soundings constitute almost the only guide in this matter. It will be noticed that the alluvium in the littoral waters which is continually forming shoals and lowlands is especially abundent in the vicinity of river mouths.

Relation To Velocity.

The effect of currents becomes conspicuous only when their velocity at the bottom is in excess of 0.3 knot. Shoals thus formed, or at least modified, often appears as ridges whose direction coincides with the lines of flow of the maximum current. Any sunken object may serve as the nucleus of a detached shoal. The sand driven along the even bottom will be arrested if it come in contact with an object constituting an irregularity in the bottom. Both flood and ebb currents may bring up sand and from both direction. Such shoals occur in Lower New York Bay.

As time goes on shoals of this kind may rise to the surface and become low flat island. But even before they reach the surface, the ordinary action of the wind waves may be to drive the sand higher and higher upon the shoals and so to facilitate their growth just as heavy matter is continually being washed ashore.

LITTORAL DRIFT DEPOSITION AND BEACH FORMATION

Wind Waves

In driving material along the foreshore, the influence of the flood stream is much greater than that of the ebb, and so, as a rule, determines the prevailing direction of the drift; for the material available for transportation results from the disintegration of rocks and soil, which process goes on above high water mark, and is by the action of the destroying waves brought more within reach of the flood stream then within that of the ebb. Littoral drift is frequently due chiefly to the repeated impacts of wind waves. In fact, stones more than an inch or two in diamater, could seldom be moved by tidal currents alone. Moreover, there is abundant evidence of such drift in tideless lakes and seas. Wind waves deposit sand and stones upon the shore because the material driven along the bottom beneath the crest of the waves continues to advance as long as the water immediately surrounding it moves shoreward. In this way, sand and stones are driven high upon a shelving beach, the kinetic energy possessed by the moving material and surrounding water being consumed or converted into potential energy in the process. The receding wave cannot move all of the stony material thus brought in because energy must be consumed in moving and imparting velocity to it; the returning current is too feeble at and near the highest point reached by the wave to produce the necessary impact.

Effect of Groins

Whether matter is held in suspension or driven along the bottom, deposition will take place whenever the velocity of the water becomes sufficiently reduced . Therefore, if any current follows the shoreline and if groins or piers be extended outward, comparatively still water will be found between the groins; and in the course of time solid matter will be deposited there. In this way, the lines of high and low water may be carried seaward.

If a straight sandy coast turns suddenly away from the sea, a sharp point or narrow arm may spring from the angle and take the original direction of the coast, although its extreme tip, forming a hook, may be continually directed inland, receiving its direction from the flood tide or incoming waves.

Hook Capes

The streams along the coast following the general direction of a growing arm cannot turn aside immediately upon arriving at its extremity. There, comparatively slow streams and even eddies form the growth of the arm. A hook results when the end of the arm is so rounded off that the flood stream can follow it well and so drive matter inward before losing too much of its velocity. The effect of the ebb is to turn the hook in the opposite direction or outward. Hence, when the rise and fall of tide is great , the effect of the flood (where the tide is progressive) upon the foreshore will exceed that of the ebb and there will result a hook turning inward.But where the rise and fall of the tide is not great (or where the tide is stationary) a slender arm may be extended through shallow water and form a nearly straight beach, although the advancing end will often be turned slightly inward, e.g. Rockaway Beach and Coney Island. When a hook of considerable extent if formed at the end of the arm, the effect will be that of a receding shoreline and under some suitable circumstances another and much smaller arm will be formed following the direction of the outer shore of the main arm. This will grow and finally another slender arm may form an extension of the outer shoreline and so on. The result will be an arm whose outer shore is nearly straight while the inner shore is indented with bays. Sandy Hook is an example of this mode of growth. The deep water east of this peninsula indicates that the tidal streams in conjunction with the winds are responsible for its origin and growth. But Mitchell says (p.108 Coast & Geodetic Survey Report 1873):

Sandy Hook

"The material forming Sandy Hook is swept up from Long Branch Coast by the diagonal wash of the sea. This was placed beyond dispute by my observations of 1857. Materials of the same specific weight as the sand were placed in the sea at many different points down the outside shore, and at different distances off shore. Those within the action of the waves breaking near the shore were swept along to the northward, and finally collected at the point of the Hook. Those placed far off shore never came to land, so that I concluded that the tidal currents took very little part in the transaction."

Large Waves

In these cases of shore extension, it is almost certain that the wind waves play an important part, both by facilitating littoral drift and by building slender strips or beaches in shallow waters, as will be presently described. That the extremities of beaches hook or turn inland does not prove that their extensions are due to the flood tide; for similar forms occur around the Great Lakes and the Black Sea. Moreover, large waves, which chiefly cause the drifting of material, can only arise when the "fetch" is considerable, which implies an onshore wind.

Depth Effect

Generally speaking, beaches are formed by the action of the waves in shallow water upon the dotritus there occurring. The result is a slender strip of sandy beach remarkable for its straightness, particularly upon its outer side. The axis of such a beach generally follows what probably was a contour line before the existence of the beach. For the ocean, thus contour line probably lay 4 or 5 fathoms bellow oridnary low water; for the Gulf of Mexico 3 or 4 fathoms and for shallow bays 2 or 3 fathoms. Why a shoal should originate in waters of these depths is a question difficult to answer with certainty; but the following is probably a partial explanation.

Sand Bars

Owing to the shelving character of the sea bottom along the coast, an onshore wind will cause the surface (troughs and crests of waves being averaged) to assume a slope. This will cause the water at the bottom to flow seaward. This seaward current becomes feebler as the water becomes deeper. At some depth it will fail to drive sand before it, deposition will take place and a bar be formed along a certain contour line. As the bar grows in height, the current may be somewhat stronger than before immediately over the bar, but the bar itself would serve to intercept the detritus while being driven seaward. Finally when the shoal approaches the surface of the water, the waves become more like waves of translation and throw up sand and other material as if breaking upon the original shore line. Such waves produce an evening and compacting effect, thus explaining why the outer side of a beach is more regular then the inner. If separate islands are formed currents will aid the wind in joining them together through process of beach extension.

SPITS OR SUBMERGED CAPES

A sandy cape or point upon an alluvial shore is generally supplemented by a shoal or spit extending outward to a consider-

Two Types

able distance from the land; the littoral tidal currents have their velocities suddenly diminished in passing the cape because they are there largely deflected and turned into deeper water. By virtue of both flood and ebb, the spit generally takes a direction nearly normal to the coast line at the cape, thus differing from a beach extension. But these classes of points are not always distinct, because a shore extension originates at an angle in the coast line. As time goes on, more sand is deposited upon the point and shoals, and in this manner the point continues to grow until other agencies or altered conditions cause the growth to cease.

Long Island

Shoals of this character extend outward from Cape Hatteras, etc. , the character of the coast favoring the formation of detritus necessary in the building of shoals. Examples of smaller shoals off capes and even off gentle curves in the shore line which may deflect the streams outward may be found along the northern shore of Long Island. Examples of slender capes, formed like beaches chiefly by wave action, occur around the Peconic Bays and Gardiner's Bay, Long Island.

If a spit occurs at the junction of two tidal rivers, it may be regarded as the only portion of a bar off the mouth of the smaller river which the larger river will permit to remain owing to to its own considerable currents.

Nearly all matter deposited along rocky coasts is to be found in bays where the velocity of currents is diminshed.

WHY DEPOSITION TAKES PLACE NEAR INNER SHORE OF A BEND

Centrifugal Force

If we take, by way of experiment, a circular vessel partially filled with water, we can, by moving a paddle around and round, soon set up a circular motion or vortex. If finely divided material like cornmeal or fine sand be scattered upon the moving liquid, it will before long be found to be collecting at the center of the bottom. An inspection of the paths of these particles will show that they are driven along the bottom spirally toward the center. The explanation of this is that because of the friction of the bottom on the liquid, the motion is there somewhat reduced in amount. If there were no resistance in the vessel, the surface would be in equilibrium with the force of gravity and the centrifugal force. Since resistance exists, particularly at the bottom, the centrifugal force is there less than at the surface. The surface adjacent to the vessel is lowered because of the decreased motion of the underlying strata. Hence it is no longer in equilibrium, but its particles tend outward. Since the surface along the vessel is elevated too much to to correspond with the centrifugal force due to the smaller velocity near the bottom, an inward pressure gradient must exist at the bottom. Hence the inward velocity. The outer shore of a bend in a river corresponds to the edge of the vessel of water and the inner shore corresponds to an imaginary boundary of the central area.

THE DIRECT EFFECT OF THE WIND

If a wind blows for a considerable length of time in one direction over an inclosed body of water, the surface particles are carried or drifted from their original position through the impingement of the air upon them. These particles drag with them those situated immediately below the surface, and in time this dragging influence will be felt down to considerable depths.

Wind Forces

The effect of these horizontal forces on the waters of a closed body is to increase the height of water level on the lee shore and to diminish it upon the opposite shore, although not generally by the same amount. In shallow bodies or along the shelving shore of the ocean, the amount of this elevation may be considerable. In deep bodies with abrupt shores, the piling up is very small although there may be a good surface drift maintained by the wind. The reason for this is that the horizontal forces due to the wind do not act alike upon the particles at all depths as do the tidal forcesas they are considerable at the surface and insignificant near the bottom. Consequently the pressure due to the increased depth on the lee shore quickly gives rise to an acceleration, in the reverse direction which exceeds, at even moderate depths, the acceleration imparted to the liquid elements by the moving elements situated nearer the surface. Hence the retrograde movement of the water not only near the bottom but for a considerable distance upward. Because of its much greater transverse section, the returning stream is as a rule scarcely perceptible, although the velocity of the surface stream may be considerable. Of course this counter-movement also exists in the shallow bodies just referred to because, the winds' action cannot be alike at all depths (like tidal forces) and so the body cannot be in equilibrium under their action. Consequently there must be a drifting before the wind and a return current along the bottom.

This may be regarded as the circulation in vertical planes due directly to the wind striking the surface of the water. What may be regarded as the horizontal circulation will be briefly considered in describing the ocean currents.

All the above remarks suppose the wind to be constant for some time or at least prevailing, in the case of an ocean. If the wind is of comparatively short duration it may give rise to seiche oscillations.

Circulation in horizontal orbits constitute a very general and obvious effect of the direct action of the winds upon the surface.

The influence of the earth's rotation upon ocean currents is mentioned by Mac Louvin in his prize essay upon the tides. The equations of motion for a liquid upon a rotating sphere lie at the foundation of Laplace's dynamical theory of tides.

Deflection Of Currents

Ferrel makes constant use of the principle, following at once from Laplace's equations that a moving particle is deflected to the right in the northern hemisphere and to the left in the southern. Before the work of Bjerknes, the ocean currents were treated as free currents, i. e. , as if they would move onward by their own inertia after the forces ceased to act. Nansen suspected from observation and

Ekman confirmed by computation, that forced or sustained currents take, if circumstances permit, a direction to the right of the sustaining force in the northern hemisphere. Moreover, as wind action is from the surface downward (each layer moving the one underneath) the direction of the lower layers will likewise be to the right of the one imparting the motion.

Motions
In large
Bodias
Of water

Supposing all motions in an indefinitely larger body of water acted upon by the winds to be steady and horizontal, then the equations of motion become very simple. The external forces for a given water element are the components of the earth's deflecting force, and the only other forces acting are the components of the resistance due to viscosity. Integrating these equations and determining the arbitrary constants to suit the assumed problem, it follows that in the northern hemisphere the surface currents take a direction 45° to the right of the direction of the wind and that this angle increases with the depth. Ekman also considers currents caused by pressure gradient and the earth's rotation alone, and the wind currents influenced by the continents, currents which arise from a difference of density, and the action of both wind and density variation.

On account of the actual distribution of land and water it is difficult to say at this time to what extent Ekman's theory of forced currents accounts for the existing ocean currents. The fact that there is a tendency for the water to flow to the right or left of the direction toward which the wind blows will doubtless be brought out for many regions.

DIRECT ACTION OF WIND IN CAUSING THE ANNUAL HEIGHT INEQUALITY

In shallow arms of the ocean the direct action of the wind in altering the height of the surface is very apparent. Along the eastern coast of U.S. the prevailing wind is northwesterly during the winter season and southwesterly, south or southeasterly during the summer season. As a consequence, the height of the sea is considerably lowered in the winter season and, at least in many localities, increased during the summer season. This explains the annual inequality at

Governors Island, although upper-river stages are factors of some importance at this station.

The winter winds along the Atlantic Coast of the U.S. are the strongest of the year; consequently the water is most diminished in height during that season.

Seasonal Effects

The foregoing statements indicate that as a rule the water at most tidal stations stands highest in the summer or autumn and lowest in the winter or spring. This suggests that the annual fluctuation may be due to the alternate heating and cooling of the ocean waters, causing alternate expansion and contraction of the volumes. It will be noted that as sea breezes at the earth's surface occur by day and land breezes by night so the wind blows from the ocean in summer and from the land in winter. Without further assumptions we thus have an agency for producing the annual fluctuation whose potency in many instances cannot be doubted.

High pressure areas are formed on the lands in winter and in the oceans in summer. Hence, the annual inequality cannot be due directly to this cause. Moreover, the annual barometric fluctuations are too small to account for the annual inequality in sea level at most places. It seldom has a range of more than 0.3 of an inch, and this could give only about 0.3 of a foot for the range of the annual inequality.

Since winds along the surface of the earth are in a general way setting from high pressure areas toward low pressure areas, it follows that indirectly these annual fluctuations in the barometer do in this sense greatly influence and even occasion the annual inequality in sea level. But, as already intimated, the direct effect is often at variance with the indirect and far more important effect, viz, that due to resulting rains.

EFFECTS OF FLUCTUATION IN TEMPERATURE OF SEA WATER

In an ocean or portion of an ocean lying upon one side of the equator, the heat directly radiated from the sun will be absorbed most rapidly at the time of the summer solstice, The maximum rate of deriving heat from the earth's atomosphere and from inflowing streams must generally occur somewhat later. From the same sources least heat is being absorbed by the ocean soon after the winter solstice. From these considerations one may perhaps infer that the assumed body of water, all depths being considered, would contain the greatest amount of heat not earlier than the autumnal equinoxes, and the least not earlier than the vernal. For portions of the ocean lying in low latitudes, these times will be accelerated, and the range of the annual tempetature fluctuations will be less.

While it is undoubtedly true that the surface of the water in high latitudes stands on a slightly higher level than in low latitudes, and is higher in the early autumn than in the early spring, it can be easily seen that this annual fluctuation cannot be considerable, i.e., it can scarcely be a measurable quantity.

Example

Suppose the surface of the water at a point in high latitude to be 0.1 foot above the surface at a point 8000 miles away in the opposite hemisphere. The instantaneous slope will be 2 one billionths. And so, the accelerating force per unit mass will be 2g divided by one billion. But this, acting through say three months, will give rise to a velocity of 0.52 foot per second at the surface. The velocity will diminish in going downward and the flow near the bottom will generally be opposite in direction to that at the surface. If the assumed distance were less than 8000 miles, this velocity would be increased in proportion. As no such alternation of surface flow from one hemisphere to the other has been observed, it is practically certain that the results due to annual temperature changes in the water cannot cause an annual inequality in sea level with a range as great as 0.1 of a foot, and so this portion of it may be neglected.

In an inclosed body of water, the annual temperature changes may easily produce an annual height inequality, but this would be concealed by the much greater changes due to the varying amounts of evaporation and of tributary waters.

BIBLIOGRAPHY

TIDES AND CURRENTS

1. 1845 A.D. Bache, Progress of Work (1845) Middle Section, U.S. Coast & Geodetic Survey, Annual Report 1845, 29th Congress, 1st Session, Pages 17-19, Nov.29,1845.

2. 1848 David D. Porter, Dangers in Hell Gate, U.S. Coast & Geodetic Annual Report 1848, Appendix 12, 30th Congress, 2nd Session, Ex-Document 13, Pages 97-100, Oct. 30, 1848.

3. 1848 C.H. Davis, Examination of Hell Gate, U.S. Coast & Geodetic Annual Report 1848, Appendix 11, 30th Congress, 2nd Session, Document 13, Oages 93-96, Feb. 15, 1848.

4. 1850 H.L. Whiting, Progress of Sandy Hook, U.S. Coast & Geodetic Survey, Appendix #9, March 25, 1850. 31st Congress, 2nd Session, Document 12, Pages 81-82.

5. 1850 Professor A.G. Pendleton, Encroachment of the Sea & land on the south side of Long Island, U.S. Coast & Geodetic Survey, Annual Report 1850, Appendix 8, 31st Congress, 2nd Session, Document 13, Pages 80-81, Aug. 2, 1850.

6. 1853 Charles A. Schott, Tidal Currents of L.I. Sound approaches, U.S. Coast & Geodetic Survey, Annual Report 1853, Appendix 50, Pages 168-179, April 28, 1853 (Re-Written April 1854)

7. 1856 A.D. Bache, Abstract of Contents of Report, U.S. Coast & Geodetic Survey, Annual Report 1856, 34th congress, 3rd Session, Ex-Document 12, Pages 6-7, Dec. 1, 1856.

8. 1856 G. Wurdemann, Tidal observations Made at Stations Between New York City and Albany on Hudson River, U.S. Coast & Geodetic Survey, Annual Report 1856, Appendix 40, 34th Congress, 3rd Session, Ex-Document 12, Pages 266-267, Nov. 1, 1856.

9. 1856 A.D. Bache. Observations to Determine the Cause of the Increase of Sandy Hook, U.S. Coast & Geodetic Survey, Annual Report 1856, Appendix 38, 34th Congress, 3rd Session, Ex-Document 12, Pages 263-264.

10. 1856 H. Mitchell, Investigation of Tides and Tidal Currents of N.Y. Harbor, its Dependencies and at Sandy Hook, U.S. Coast & Geodetic Survey, Annual Report 1856, Appendix 39, 34th Congress, 3rd Session, Ex-Document 12, Pages 264-266, Nov. 22, 1856.

11. 1857 A. Boschke, New York Harbor, U.S. Coast & Geodetic Survey, Annual Report, 1857, Appendix 37, 35th congress, Ex-Document 33, Pages 370-373, Feb. 1857.

12. 1857 A. Boschke, Preservation of New York Harbor, U.S. Coast & Geodetic Survey, Annual Report 1857, Appendix 37, 35th Congress, Ex-Document 33, Pages 358-370, Feb. 1857.

13. 1857 H. Mitchell, Observations on Tides & Currents in the East River at Hell Gate, U.S. Coast & Geodetic Survey, Annual Report 1857, Appendix 35, 35th Congress, Ex-Document 33, Pages 350-353, Nov. 1, 1857.

14. 1858 A.D. Bache, Tidal Currents of New York Bay near Sandy Hook, American Journal of Science & Arts, Vol. 26, Series 2, 1858, Pages 334-340.

15. 1858 H. Mitchell, Currents in East River at Hell Gate & Throggs Neck, Subcurrents of N.Y. Bay & Harbor; Hudson River Banks Levelings, U.S. Coast & Geodetic Survey, Annual Report 1858, Appendix 28, 35th Congress, Ex-Document 14, Pages 204-207, Oct. 20, 1858.

16. 1858 A.C. Mitchell, Tidal Currents in N. Y. Harbor & Bay and Approaches, U.S. Coast & Geodetic Survey, Annual Report 185, 35th Congress, Ex-Document 14, Pages 36-38, 58-59, Oct. 28, 1858.

17. 1858 A.D. Bache, Tidal Currents of N.Y. Harbor near Sandy Hook, U.S. Coast & Geodetic Survey, Annual Report 1858, Appendix 27, 35th Congress, Ex-Document 14, Pages 197-203.

18. 1859 Henry Mitchell, Physical Surveys of N.Y. Harbor & L.I. Coast, U.S. Coast & Geodetic Survey, Annual Report 1859, Appendix 26, Pages 311-317, Sept. 30, 1859.

19. 1859 Supt. of Coast Survey, Tides and Currents in N.Y. Harbor and its approaches, U.S. Coast & Geodetic Survey, Annual Report 1859, Pages 50-51.

20. 1863 Currents of New York Harbor, U.S. Coast Survey, Annual Report 1863, 38th Congress, Document 11, Page 30.

21. 1866 H. Mitchell, Tidal Interferences at Hell Gate with Directions for Reducing the Sounding, U.S. Coast & Geodetic Survey, Annual Peport 1866, Appendix 6, 39th Congress, Ex-Document 87, Pages 44-46 November 7, 1866.

22. 1867 Samuel Mc Elroy, Survey of Hudson River to ft. Edward, U.S. Rivers, Harbors and Docks, Vol. #8 January 1867, Pages 21-22, (Vdna, P.V.8.)

23. 1867 Henry Mitchell, Chief. Tides & Currents of Hell Gate, U.S. Coast & Geodetic Survey, Annual Report 1867, Appendix 13, 40th Congress, 2nd Session, Ex-Document 275, Pages 158-169.

24. 1868 Henry Mitchell, Tides & Tidal Phenomena, U.S. Navy Dept. (Navigation Bureau) Navy Scientific Paper #2, Pages 1-56.

25. 1869 L.F. Pourtales, Characteristics of the Atlantic Sea Bottom off the Coast of the U.S. U.S. Coast & Geodetic Survey, Annual Report 1869, Appendix 11, 41st Congress, Ex-Document 206, Pages 220-225.

26. 1872 J.B. Weir, The Middle Ground Shoal, New York Harbor, U.S. Coast & Geodetic Survey, Annual Report 1872, Appendix 16, Pages 257-261.

27. 1873 Henry Mitchell, Changes in Submerged Contours off Sandy Hook, U.S. Coast & Geodetic Survey, Appendix 10, Pages 108-110.

28. 1873 Henry Mitchell, The Harbor of New York; its Condition in May 1873, U.S. Coast & Geodetic Survey, Annual Report, 1871, Appendix 8, 42nd Congress, Ex-Document 121, Pages 109-133, May 1873.

29. 1874 J.E. Hilgard, Tides & Tidal Action in New York Harbor, Smithsonian Institute Annual Report, Year 1874, Pages 226-226 (Class Mark E.A.)

30. 1876 H. Mitchell, Phsical Survey of N.Y. Harbor, U.S. Coast & Geodetic Survey, Appendix 10, 44th Congress, Ex-Document 37, Pages 147-185.

31. 1878 Lt. Col. John Newton, Examination at Junction of Newtown Creek and East River, N.Y. U.S., Engineers Bureau, Vol. 1, Pages 428-429 March 26, 1878.

32. 1876 Henry Mitchell, Current Movements of East River near Navy Yard, U.S, Coast & Geodetic Survey, Appendix #11, 1876, 44th Congress, Ex-Document 37, Pages 186-189.

33. 1878 J.W. Donn, Tides - N.Y. Harbor, U.S. Coast & Geodetic Survey, Annual Report 1878, Pages 17-20.

34. 1880 Henry Knapp, C.E., Create a Channel Thru Sandy Hook Bar, U.S. Rivers, Harbors and Docks, Volume 8, Series 5, Pages 1-4.

35. 1883 William Herrell, Harmonic Analysis of Tides at Sandy Hook, U.S. Coast & Geodetic Survey, Appendix 9, pages 247-251, July 31, 1883.

36. 1884 A. Lindenkohl, Geology of the sea Bottom in the approaches to N.Y. Bay, U.S. Coast & Geodetic Survey, Appendix 13, Pages 435-39.

37. 1885 Lt. Col. C.L. Gillespie, Improvement of New York Harbor (1885-1891), Article by Joseph Edwards, Pages 56-57.

38. 1885 William Ferrel, Harmonic Analysis of Tides at Governor's Island (N.Y. Harbor) U.S. Coast & Geodetic Survey, Annual Report 1885, Appendix 13, Pages 489-93.

39. 1886 Henry Mitchell, Circulation of Sea Thru N.Y. Harbor, U.S. Coast & Geodetic Survey, Annual Report 1886, Appendix 13, Pages 409-433.

40. 1886 Scientific American, The Harbor of New York, N.Y. Chamber of Commerce, Vol. 1, Pages 1-17, July 10, 1886.

41. 1886 A. Foster Higgins, The Harbor of New York, N.Y. Times (N.Y. Chamber of Commerce) Vol. 1, Pages 1-17, August 11, 1886.

42. 1887 1888 Henry Mitchell, Physical Survey of N.Y. Harbor, U.S. Coast & Geodetic Survey, Annual Report 1887, Appendix 15, Pages 301-311, March 24, 1888.

43. 1888 Henry S. Marendin, Tidal Levels & Flow of Currents in N.Y. Bay and Harbor, U.S. Coast & Geodetic Survey, Appendix 9, Pages 405-408.

44. 1889 Alex S. Christie, High & Low Water at Sandy Hook, U.S. Coast & Geodetic Survey, Annual Report 1890, Appendix 15, Pages 705-714.

45. 1889 B. A. Colonna. Currents of N. Y. Bay & Harbor, U. S. Coast & Geodetic Survey, Bulletin 8, No. 1-25, Pages 41-43.

46. 1889 C. A. Schott. Average Sea Level at Sandy Hook, U. S. Coast & Geodetic Survey, Annual Report 1887, January 2, 1889, Pages 296-300.

47. 1890 E. Haskel, Observations in Physical Hydrography on L. I. Sound, U. S. Coast & Geodetic Survey, Annual Report 1890, Section 2, Pages 29-33, December 9, 1890.

48. 1891 Joseph Edwards, Improvement of N. Y. Harbor Channels, American Society of Civil Engineers, Vol. 25, 513, Pages 523-614, December 1891.

49. 1893 Joseph Edwards, Improvement of Swash Channel of N. Y. Harbor, U. S. Engineers Bureau, Pages 54-57.

50. 1894 G. L. Gillespie. Improvement of Hudson River, N. Y. Harbor and Rivers and Harbors in their vicinity, N. Y. and N. J., U. S. Rivers, Harbors and Docks - September 29th, 1894, Annual Report 1894, Vol. 1, Pages 3,5,6,8.

51. 1896 David L. Bradly. Reminiscences of New York Harbor, Same, Pages 1-61, June 1896.

52. 1897 Rollin A. Harris, Introduction & Historical Treatment of the Subject, U. S. Coast & Geodetic Survey, Appendix 8, 1897, Manual of Tides, Pages 321-385.

53. 1905 N. Y. Bay Pollution Commission, New York Bay Pollution, Report to State Legislature, May 1, 1905, Senate #39 (Entire).

54. 1906 1907 Rollin Harris. Currents, Shallow Water Tides, Meteorological and Miscellaneous Matters, U. S. Coast & Geodetic Survey, Annual Report 1906-07, Appendix #6.

55. 1908 Metropolitan Sewage Commission, Relation to the Stage of Tide, Metropolitan Sewage Commission (N. Y. City) Pages 33, 51-54, 10-71.

56. 1909 Rollin Arthur Harris. The Tides, Their Causes and Representations, U. S. Coast & Geodetic Survey (Popular Science Monthly) June 1909.

57. 1913 Metropolitan Sewage Commission. Tidal Currents in N. Y. Harbor, Same; Preliminary Report #8, October 1913.

58. 1913 Colonel Wm. Black. Tidal Movements in East River, N.Y., Professional Memoirs, Vol. 5, 1913, U. S. Engineers Bureau, Pages 250-273.

59. 1913 H. de B. Parsons, C. E., Tidal Phenomena in New York Harbor, American Society of Civil Engineers; Paper 1278, Pages 1979-2106 Inc., May 17, 1913.

60. 1913 Harbor Channels and Freight Terminals. American Society of Civil Engineers, Paper 1274, Transactions #76, Pages - 1666, 1669.

61. 1914 Correspondence between Commission and U. S. Coast & Geodetic Survey, Tidal Information, N. Y. Metropolitan Sewage Comm, Preliminary Report #17, Pages 10-70.

62. 1921 Chief Engineers, U. S. Army, East River, N. Y., House Committee Rivers & Harbors, 67th Congress, 2nd Session, Document 3, Pages 9, 10, 18, December 20, 1921.

63. 1922 Cole & Alpert, Tidal Bench Marks in N. Y. State, U. S. Coast & Geodetic Survey, Special Publication 83, Serial 193, Pages 3-175.

64. 1923 H. A. Marmer. Flood & Ebb Tide in N. Y. Harbor, Geographical Review, Vol. 13.

65. 1923 Maj. General W. M. Black. Tidal Action on Coasts and in Estuaries, Military Engineers; Vol. 15, No. 82, Pages 309-318, July-August 1923.

66. 1923 G. T. Rude, Currents & Tides of N. Y. Harbor, Military Engineers; Vol. 15, No. 83, Pages 438-441; September - October 1923.

67. 1924 John M. Buckley. Measurements of Tides at New York, Military Engineers; Vol. 16, No. 90, November 1924, Pages 511-515.

68. 1925 H. A. Marmer. Tides & Currents of N. Y. Harbor, U. S. Coast & Geodetic Survey, Special Publication 111-113, Serial 285.

69. 1926 Chief Engineer (Board of Estimate), Inveetigation of Tidal Currents Report, Annual Report 1926, Pages 58-67.

70. 1926 Arthur S. Tuttle, Chief Engineer, Investigation of Tidal Currents in N. Y. Harbor, Based on Bottle Floats. Committee Report, October 21, 1926, Pages 1-9.

71. 1926 1927 L. H. Ziskind. Instructions for Tidal Current Surveys, U. S. Coast & Geodetic Survey, Special Report 124, Series 346, Pages 1-45.

72. 1927 Chief Engineer, Investigation of Tidal Currents, Annual Report 1927, Pages 59-61, Committee on Main Drainage.

73. 1928 G. F. Rude, Instructions for Tide Observations, U.S. Coast & Geodetic Survey; Special Publication 139, Pages 1-78.

74. 1932 Le Lacheur & Sammons, Long Island & Block Island Sounds, U. S. Coast & Geodetic Survey, Special Publication 174, Series 8, Pages 11-131.

75. 1934 Paul Schureman, Tide Observations in Hudson River, U. S. Coast & Geodetic Survey; Special Publication 180; Pages 179-185.

76. 1934 Tides & Currents in Hudson River, Coast & Geodetic Survey; Special Publication 180.

77. 1935 Chief Engineer (U. S. Army), Buttermilk Channel, N.Y. Harbor Committee on Rivers & Harbors (Letter), Pages 1-28, 74th Congress, 1st Session.

78. 1935 H. A. Marmer, Tides & Currents in New York Harbor, Coast & Geodetic Survey, Special Publication #111 (Revised 1935 Edition).

79. 1935 R. Stephins, Chairman, Pollution of Bronx Waterways "Bronx Boro", Vol. 13, Nov. 8, Pages 6-8, December 1935.

80. 1938 Joseph B. Tiffany, Jr., Simulation of Tidal Phenomena, Civil Engineering, Vol. 8, #8, Pages 537-539, August 1938.

81. 1938 Paul Thompson, Current Alignment in East River, Shore & Beach, Vol. 5-6, Series 1937-38, Pages 110-113, July 1938.

82. 1938 City of New York, Department of Parks. Report on Tropical Storm of September 21, 1938.

83. 1939 Tide Tables Atlantic Ocean, U. S. Department of Commerce, Coast & Geodetic Survey, Serial #604.