TIDAL PHENOMENA IN EAST RIVER, NEW YORK HARBOR.

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During the past year a comprehensive tide and current survey of the waterways of New York Harbor has been carried out jointly by the U.S. Coast and Geodetic Survey and the Corps of Engineers, U.S. Army. In this work, the Unemployment Relief Organization of New York City made available to these two services a number of men for the purpose of observing tides. This made it possible to observe the tides at a large number of places, and has resulted in bringing out the local features of the tide and the change in time and range of tide from place to place.

East River has a length of fourteen nautical miles and unites Upper Bay on the west with Long Island Sound on the east. In the recent survey, tides were observed at some 80 places along both banks of the fourteen mile stretch, and the peculiarities of the tidal movement in this so-called river have been determined with precision. The results are not only of interest for this important waterway, but throw light on the general problem of the tides in a waterway connecting two independently tided bodies of water.

THE TIDE IN EAST RIVER.

In Upper Bay, where the East River empties, the lunitidal intervals are 8.20 hours for the high water and 2.15 hours for the low water. Where the East River empties into Long Island Sound these intervals are respectively 11.30 hours and 5.60 hours. This means that the tides at the two ends of East River differ by about three hours.

It would therefore be reasonable to assume that the tide in the East River would change in time at an approximately uniform rate throughout its fourteen mile length. But the observations prove that this is not the case. Beginning at the Upper Bay end, the tide in the East River becomes later at the rate of about 1/4 hour per mile for a distance of about 6 miles; in the next two miles it becomes later at the rate of about 2/3 hour per mile; and for the last 6 miles there is very little change in time.

This behavior of the tide in the East River in regard to time is in marked contrast to the tide in a true tidal river. Like the East River, the Hudson River, too, empties into Upper Bay. Taking the first 14 miles in the latter river, it is found that the tide becomes later in going upstream by 1.2 hours or at the rate of a little less than one-tenth of an hour per mile. Moreover, this change in time takes place at an approximately uniform rate. The contrast in the time of tide in the two rivers is the more striking because of the fact that the average depth in this 14 mile stretch of the Hudson is practically the same as in the East River.

Turning now to a consideration of the range of the tide, observations show that the range at the two ends of the East River is not the same. In the Upper Bay the mean range of the tide is 4.4 feet, while at the western end of Long Island Sound it is 7.2 feet. For the 14 mile stretch, therefore, there is a change in the range of the tide in the East River of 2.8 feet. And like the change in time, the change in range is not at a uniform rate. For the first three miles there is actually a decrease, the range three miles from the Upper Bay entrance being 4.2 feet. For the next 3 miles the range increases gradually, at the rate of about 0.2 foot per mile, after which follows a more rapid increase, at the rate of 0.75 foot per mile for a distance of 2 miles. For the next four miles the range increases at an approximately uniform rate of 0.2 foot per mile; and for the last two miles there is practically no change in range.

In regard to change in range, too, East River is in marked contrast to true tidal rivers. Taking Hudson River again, it is found that for the first 14 miles of its course from Upper Bay the range of tide decreases at a more or less uniform rate of approximately 0.05 foot per mile. The difference in the tide as regards range and time in the East and Hudson Rivers is shown graphically in Fig. 1.

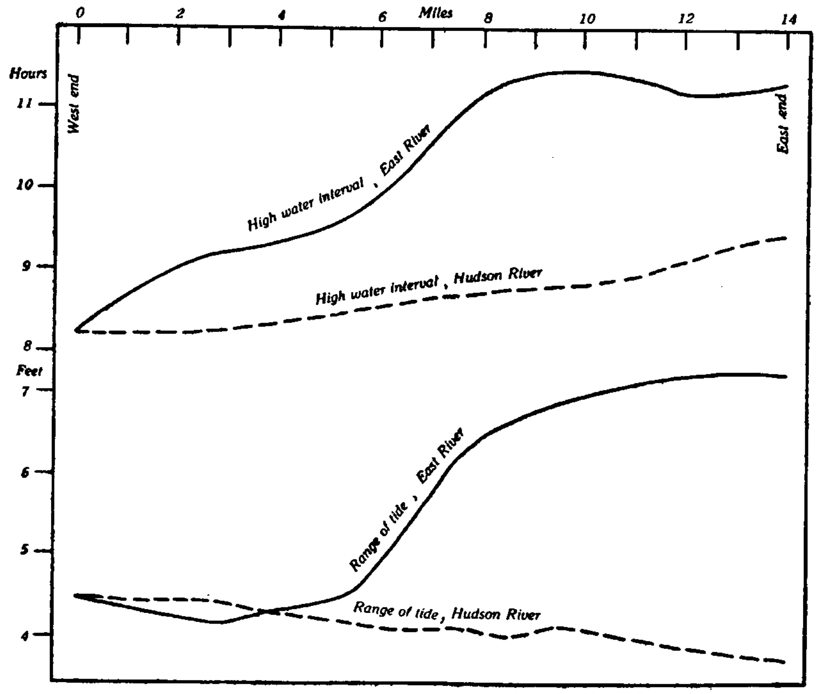

FIG. 1
Time and range of tide ı East River and Hudson River.

In view of the varying changes in range through East River, it follows that the high water and low water datum planes change from point to point throughout the stretch of this river by relatively large amounts. From precise leveling it has been determined that mean sea level at the two ends of this river is practically the same. So that mean sea level throughout the river may be represented by a straight line. If now the mean high and mean low water at various points in the river are plotted with reference to mean sea level, the lines of mean high and mean low water appear as shown in Fig. 2.

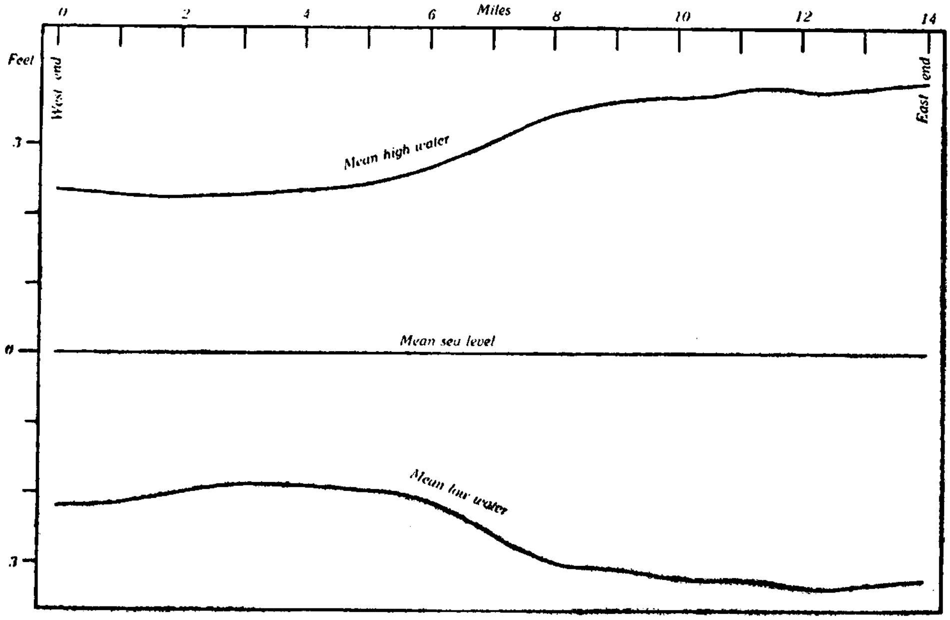

FIG. 2
High Water and Low Water lines ɪ East River.

The change in the high water and low water lines, as Fig. 2 shows, is not uniform. From Upper Bay both lines slope toward mean sea level for about three miles, after which they slope away from mean sea level. In this regard, too, the East River differs from Hudson River. In the latter river the high water and low water lines for the first fourteen mile stretch slope toward mean sea level uniformly, corresponding to the decrease in range for that stretch of the river. Disregarding minor fluctuations in Fig. 2, it may be said that in the East River the high water and low water lines are convex toward the line of mean sea level.

THE CURRENT IN EAST RIVER.

In so far as the volocity of the current in the East River is concerned, no unusual features are brought out by the observations. At strength, the velocity of the current for the river as a whole averages about two knots. But as is to be expected, the velocity differs in different stretches of the river, in accordance with the changes in width and depth of channel, the velocity being greatest in the most constricted stretches. In Hell Gate, where the channel is very considerably constricted, the velocity of the current at strength is very nearly five knots. In regard to velocity of current, therefore, the East River shows no features markedly different from those in true tidal rivers. In the Hudson, for example, the velocity of the current at strength in the first fourteen mile stretch, is very nearly two knots.

As regards the time of the current in East River the observations show that the current is an hour earlier at the eastern end than at the western end. This is in marked contrast to the behavior of the tide which becomes three hours later in the same stretch. In the Hudson River on the other hand, the current in the first fourteen mile stretch, like the tide, becomes about an hour later.

In the time relations of current to tide, therefore, the Hudson and East River exhibit striking differences. Since both tide and current in the fourteen mile stretch of the Hudson under discussion become later by about an hour, the time relations of current to tide remain approximately the same throughout this stretch. The strengths of the current come about the times of high and low water and the slacks come about the times the tide is at sea level. In the East River, however, the time of current in relation to time of tide changes throughout its length. At the Upper Bay end of the river the current attains its strength about 4 ½ hours after the times of high and low water, while at the Long Island Sound end the strength of the current comes about half an hour after high or low water. There is thus a change of four hours in these time relations in the fourteen mile stretch.

THE TIDAL MOVEMENT IN EAST RIVER.

The foregoing discussion makes it clear that in the East River the tidal movement (embracing by that term both tide and current) is radically different than that in the Hudson River. In the latter, the phenomena are those usually found in a tidal river, and find ready explanation in terms of a tide wave moving as a progressive wave in a restricted channel. How is the tidal movement in the East River to be explained ?

Obviously the peculiar features in the tides and currents in the East River arise from the fact that the tide enters from both ends of the fourteen mile stretch — from Upper Bay on the west, and from Long Island Sound on the east — these tides being independent tides. In other words, while in the ordinary tidal river the tide progresses from the mouth up stream, in the East River two different tides set in from the opposite ends.

It should therefore be possible to explain the tidal movement in the East River on the basis of two tide waves entering into the channel from opposite ends, the tidal features at any particular point arising from the resultant interaction of these tide waves at that point. Such a study, however, would clearly be a rather involved matter and necessitate considerable mathematical calculation. Can we not arrive at an understanding of the tidal movement in the East River from general considerations ?

Since East River is a channel which unites two relatively large bodies of water having independent tides, suppose we regard the movement of the water in this channel as primarily hydraulic in character. In other words, let us regard the movement of the water in the East River as due to the instantaneous difference in head of water in the two bodies of water which it connects. This means that we are considering East River merely as a channel through which the water at any moment flows from the body having the higher level to the one having the lower level. What features would the tidal movement in such a channel present ?

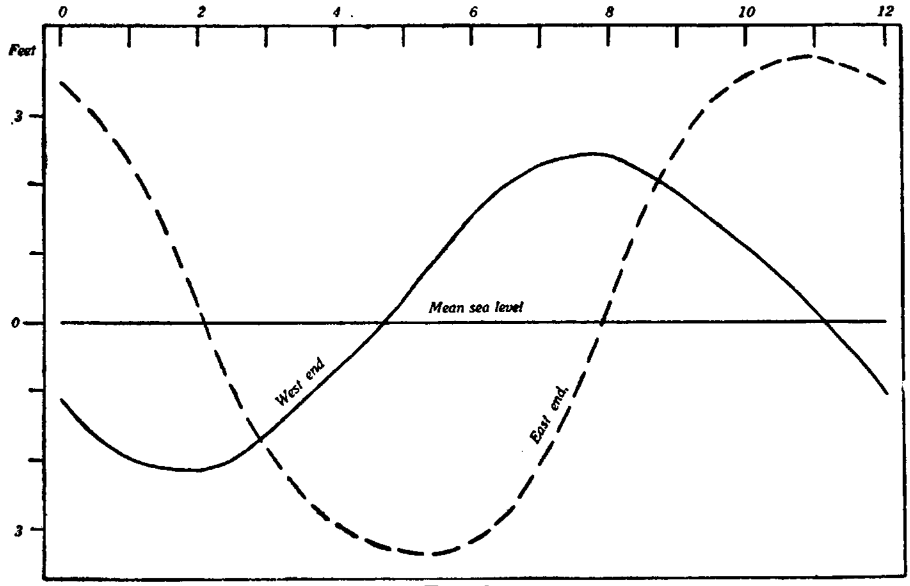

FIG. 3
Mean tide curves : East and West ends of East River.

In Fig. 3 are shown the average tidal curves for the east and west entrances of the East River, the full line curve representing the tide in Upper Bay and the dashed curve the tide in Long Island Sound. The curves are shown for a tidal cycle of twelve lunar hours, zero hours being the time of the moon's local meridian passage. From this diagram the instantaneous difference in head of water between the two ends of the East River can be readily determined for any time in the tidal cycle. To visualize the movement of the water in the East River under the action of the constantly changing differences in head we may construct a slope-line diagram as in Fig. 4.

On the vertical line to the left, the heights of the tide in Upper Bay are plotted for each lunar hour of the tidal cycle, while on the vertical line to the right the hourly heights of the tide in Long Island Sound are plotted. In both cases the heights are measured from mean sea level as derived from the corresponding curves in Fig. 3. The figures along the vertical lines denote the hours to which the indicated heights apply, hours and heights being placed to the left of each vertical line for the rising tide and to the right for the falling tide. The scales of heights and distance are given on the marginal lines of the figure.

If the movement of the water in the East River be regarded as due to the difference in the height of the water at the two ends, then the surface of the water in this river at any given time may be represented by the straight line joining the instantaneous heights at the two ends. These lines, which may be called slope lines, have been drawn in Figure 4 for each hour of the tidal cycle. The slope lines have been drawn as full lines when the slope is from Long Island Sound to Upper Bay and as dashed lines when the slope is from Upper Bay to Long Island Sound.

On the assumption that the movement of the water in the East River is primarily hydraulic in character, the height of high water at any point in the channel should be given by the highest slope line at that point, while the height of low water should be given by the lowest slope line. It follows too, that the range of the tide at any point will be given by the vertical distance between the highest and lowest slope lines at that point. Finally, since the

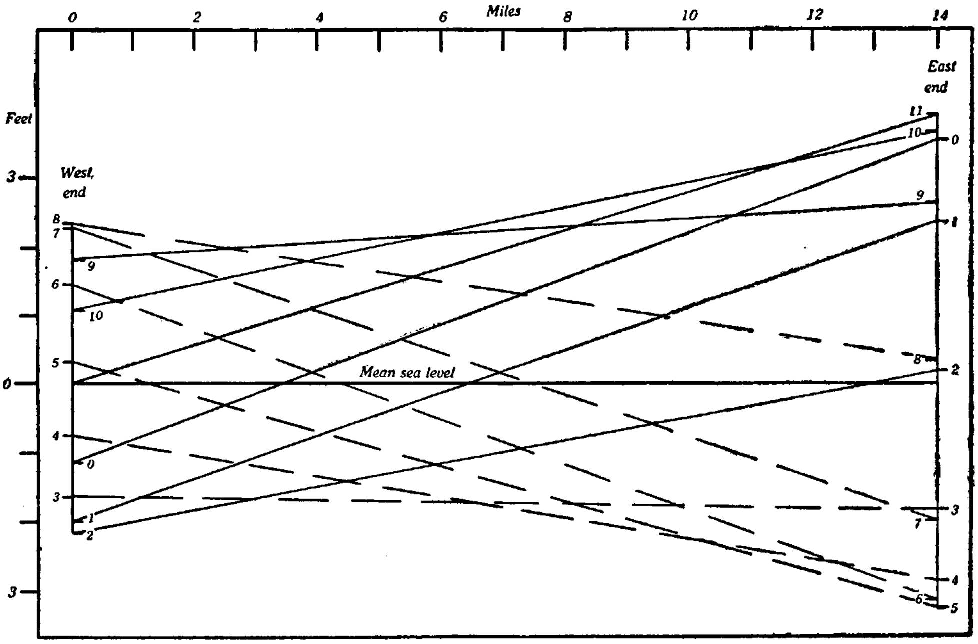

Fig. 4
Slope-line diagram : East River.

slope lines are time lines, the times of high and low water at any point will be given respectively by the highest and lowest slope lines at the point.

The validity of the assumption that the movement of the water in a channel like the East River is primarily hydraulic in character may therefore be tested by the closeness with which the features of the tides and currents found in the East River are approximated by Fig. 4. Taking first the range of the tide, Figure 4 shows that the range decreases somewhat for the first three miles from the western end, the range at that point, from the diagram, being 3 3/4 feet. The observations, as Figure 2 shows, give for this point a range of 4.2 feet.

Taking now the time of tide, the slope lines indicate a much more rapid rate of change at the Upper Bay end than at the Long Island Sound end, which fact the observations brought out. The very rapid change in time which the observations show to occur near the middle of the river is not clearly brought out by the slope line, but this is indicated. But if the slope lines are drawn at more frequent intervals than for each hour, this fact is brought out clearly.

Finally, the diagram of Figure 4 brings out the fact that the lines of mean high and mean low water along the river are curved lines convex to the line of mean sea level. In fact for this feature the diagrams of Figures 2 and 4 resemble each other as closely as can be expected under the circumstances. For it is not to be overlooked that the slope lines of Figure 4 are drawn as if the channel of the East River ran straight for the fourteen mile stretch with unvarying width and depth. This is actually not the case, and the changes in direction, width and depth introduce features which are not taken account of in the slope-line diagram. Notwithstanding this it appears that the assumption that in the East River the movement of the water is primarily hydraulic is a valid assumption, so far as the larger features of rise and fall are concerned.

Turning now to the currents that should result on the assumption of hydraulic conditions, it is clear that the strength of the current must come at the times of the greatest differences in head between the two bodies of water which East River connects. From Figure 4 it is seen that the 0-hour and 6-hour slope lines have the greatest slopes. Hence the strengths of the current in the opposite directions should occur about these times This means that with regard to the times of local tide, the strength of the current at western end should come about 4 hours after high and low water, while at Throgs Neck (Long Island Sound end of East River) the strength should come about 1 hour after high and low water. And these time relations of tide to current, it will be recalled, approximate to the relations actually found to subsist from the observations.

It is clear therefore that the principal features of the peculiar tidal phenomena in the East River find ready explanation on the assumption that the movement of the water in this channel is primarily hydraulic in character. To be sure, in detail some of the features which are brought out by the tide and current observations differ somewhat from the idealized conditions based on hydraulic considerations. In part, however, this difference is to be ascribed to the fact that the channel of the East River varies considerably in width, which must bring about modification of the simple conditions represented in Figure 4. In part too, it is to be taken for granted that wave movement from both ends of the river brings about some modification.

APPLICABILITY OF HYDRAULIC CONSIDERATIONS.

The advantage of deriving the tidal fatures in a channel which connects two independently tided bodies of water from hydraulic considerations becomes apparent in connection with the problem of an artificial canal. In this case the characteristics of the tides and currents in the canal can be easily derived from a slope-line diagram based on the tides in the bodies of water which the canal is to connect. Moreover, the velocities of the current that will obtain in the canal can be computed from the slope-line diagram. For the strength of the current will occur at the times of greatest slope, and the velocities corresponding to these greatest slopes can be computed from the usual formulae for hydraulic flow.

In this connection, however, it is to be noted that hydraulic considerations are applicable only to canals of relatively short length. If the canal is sufficiently long for the movement of the water to partake of the nature of wave movement, hydraulic considerations no longer apply. As to whether a given canal which is to connect two independently tided bodies of water is long enough to permit wave movement depends not on its absolute length, but on the ratio of the maximum horizontal displacement of a particle of water during the tidal cycle to the length of the canal. If this ratio is less than 0.25 the canal will be sufficiently long for wave movement; if greater than 0.25, hydraulic considerations apply. (1)

The maximum displacement of a particle during a tidal cycle is the greatest distance which a particle is carried upstream or downstream during a flood or ebb period. Taking the flood or ebb period as 6.21 hours, and the average velocity during the cycle as 0.64 that of the strength, the maximum displacement will be $6.21 \times 0.64\, S = 3.97\, S$, where S is the velocity at strength. In round numbers, therefore, the maximum displacement may be taken as 4 times the strength of the current. It follows therefore that hydraulic considerations apply in the case of canals whose length is less than 16 times the velocity of the current at strength.

DESIGNATION OF FLOOD AND EBB CURRENTS.

A question that arises in connection with the tidal movement in a canal connecting two independently tided bodies of water, such as the East River, is that of the designation of the flood and ebb currents. As ordinarily understood, the flood current is the one that sets inland or upstream, and the ebb current the one that sets seaward or downstream. This usage leads to no confusion in the case of bays and rivers, since there is generally no question as to which direction is upstream and which downstream. But in the case of a canal which connect two bodies of water each of which has an independent passageway to the sea the terms upstream and downstream no longer have precise meanings.

To take a concrete example, which is the flood current in the East River, the one that sets from Upper Bay into Long Island Sound or the reverse? The mariner entering East River from Upper Bay may, not inconsistently, claim he is going inland or upstream and hence the current setting into the East River from Upper Bay — the easterly setting current — would by him be called the flood current. But a fellow mariner entering East River from Long Island Sound can with as much show of consistency claim to be going upstream and thus call the westerly setting current flood. Which of these two directions is to be chosen as the flood direction?

The problem is solved by making use of the time relations of current to tide. In tidal movement, whether of the progressive or stationary wave varieties, the flood current is that which attains its strength about the time of high water or on a rising tide. Similarly the ebb current is the one that attains its strength about the time of low water or on the falling tide. In the East River, as the slope-line diagram of Figure 4 shows, the current which

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(1) See R. A. Harris *Manual of Tides* Part IV-A, p. 600.

attains its strength on the rising tide is that setting from Upper Bay toward Long Island Sound or the easterly current. This is therefore the flood current. The current which attains its strength on the falling tide is seen to be that setting from Long Island Sound into Upper Bay — the westerly current — and this is therefore the ebb current.

The slope-line diagram thus furnishes also the criteria for determining the proper designations of the flood and ebb currents in a short canal that connects two independently tided bodies of water.