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SIR J. W. BAZALGETTE, C.B., President,
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"On the Passage of Upland-Water through a Tidal Estuary."

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IN this Paper a description is given of a method, put forward by the Author, to ascertain the rate of progress of the sewage discharged at Crossness and at Barking in its journey out to sea. The results of the calculations, hereafter explained, were laid before the Royal Commission, on "Metropolitan Sewage Discharge" who have since reported that they "throw quite a new light upon the distribution of the sewage." The Author believes it is a new way of dealing with an important question, and that it may, therefore, be of interest to the Institution of Civil Engineers.

It is now well known that this problem cannot be dealt with satisfactorily by means of float-experiments; and the Author submits that its only true solution lies in the accurate measurement and localization of the sea-water and fresh-water contained in the river, considered together with the records of the upland-flow contributing to the latter.

If it were not for the incoming of sea-water the time occupied by the sewage-polluted Thames water at Barking in travelling to any lower point (say Gravesend) would be exactly the same as the time required by the Thames, with its tributaries and sewage, to fill the channel between Barking and that point.

But the effect of the salt-water is to occupy part of the channel, and by diminishing the space available for fresh-water, to reduce the time required for the fresh-water to fill that space and pass through it.

By a complete set of salt tests made at regular distances in the length of the river, and at fixed tidal periods, it is a simple matter to ascertain with great nicety to what extent any section of the river is occupied by sea-water, and consequently what space is left for sewage-polluted river-water. The time occupied by the journey of the upland-water will be the time required to fill the latter space.

When the problem had to be dealt with, about the end of the year 1882, it was found that the available information, which was not so ample as the Author could have wished, consisted of analyses of samples of water from ten points in the river between Teddington and Southend, taken at high- as well as at low-water, at each point on three different days, namely, the 14th and 22nd of September, and on the 30th of November.

Each result may be held to represent the average composition, at the moment referred to, of the water at the cross-section in which it was taken, as it was obtained from an average of numerous samples at different depths and at various distances from either shore. These samples were taken upon the crest and trough of the tidal wave, and therefore not simultaneously as they should have been for this purpose.

The best, however, had to be made of the materials at hand, and this the Author thought would be done with the least risk of error by dealing with the water in the river at the moments of high- and low-water at Southend, for at these two moments the volume is at its maximum and minimum respectively, and all adjustment is avoided at the lower end, where, the cross-section being greatest, error would be most important.

As high-water and low-water occur earlier at Southend than at each of the other points higher up the river, it was necessary, before using the results of the analyses of the upper samples, to reduce the saltness of those taken at high-water in proportion to the intervals between high-water at Southend and the times when the respective samples were taken, and to perform the opposite adjustment with respect to the low-water samples.

The extent of this modification, which would of course be avoided in future cases, is shown upon the annexed Table. The first two columns of figures represent the numbers of grains of chlorine in 100,000 grains of water found by analysis in samples taken at high-water and at low-water at each place, and the third and fourth columns represent the parts per 100,000 of chlorine in the water at these places at the time of high-water and of low-water at Southend, these being arrived at by assuming the saltness to increase and decrease uniformly throughout the rise and fall of the tide.

CHLORINE in 100,000 PARTS.

—	At High-Water.	At Low-Water.	At Southend.	
			High-Water.	Low-Water.
	September 14th, 1882.			
Teddington	1·7	1·7	1·7	1·7
Chiswick	4·7	1·9	4·0	2·6
St. Paul's Pier	210·7	4·1	161·0	72·0
Deptford	438·0	49·0	354·0	162·0
North Woolwich	671·0	180·0	581·0	303·0
Barking	745·0	319·0	673·0	420·0
Crossness	918·0	470·0	847·0	570·0
Erith	1,031·0	530·0	964·0	628·0
Gravesend	1,502·0	1,058·0	1,485·0	1,093·0
Southend	1,931·0	1,765·0	1,931·0	1,765·0
	September 22nd, 1882.			
Teddington	1·7	1·7	1·70	1·70
Chiswick	1·9	1·85	1·89	1·88
St. Paul's Pier	89·0	2·4	66·0	25·0
Deptford	311·0	28·8	253·0	89·0
North Woolwich	581·0	162·0	519·0	233·0
Barking	638·0	280·0	592·0	334·0
Crossness	754·0	440·0	719·0	481·0
Erith	886·0	555·0	860·0	588·0
Gravesend	1,352·0	1,062·0	1,344·0	1,079·0
Southend	1,891·0	1,816·0	1,891·0	1,816·0
	November 30th, 1882.			
Teddington	1·7	1·7	1·7	1·7
Chiswick	1·7	1·7	1·7	1·7
St. Paul's Pier	2·8	1·9	2·5	2·0
Deptford	20·0	1·8	16·0	7·0
North Woolwich	118·0	3·1	98·0	29·0
Barking	152·0	5·0	128·8	35·0
Crossness	276·0	18·7	241·0	65·0
Erith	314·0	83·7	291·0	116·0
Gravesend	No sample taken.			
Southend	1,785·0	1,522·5	1,785·0	1,522·5

In Figs. 1, 3 and 5, Plate 8, the half-capacity of the river at high-water is shown by the space between the centre line and the outside upper trumpet-mouthed line, and the half-capacity of the river at low-water by the space between the centre line and the lower trumpet-mouthed hard line. In the same manner the spaces between the centre line and the black lines above and below it, show the amount of fresh water in the river at high- and low-water respectively. The vertical ordinates to these lines represent, not the half-width of river, but half the cross-sectional area, measured on the cross-sectional scale. The mean cross-sectional area is shown by dotted lines. The white space along the centre of the Figs. represents the average quantity of fresh-water in the river during the tide referred to in each case.

These quantities have been arrived at by assuming the sea-water to contain 1,961 grains of chlorine in 100,000 parts, upland-water 1·7 grain of chlorine in 100,000 parts; and that 26,000,000 cubic feet a day of London sewage enter the river with 10 grains of chlorine in 100,000 parts. The daily quantity of upland-water having been ascertained during, and for some weeks previous to, the carrying out of the observations, it is easy to ascertain, first the amount of chlorine in the sewage-polluted upland-water, and from that the proportion in which this sewage-polluted upland-water must have been mixed with sea-water to produce the degree of saltness found in any sample of water taken from the river.

It was ascertained that in September the sewage-polluted upland-water contained about 2·75 grains of chlorine in 100,000 parts, and in November about 1·9 grain. In September, therefore, the proportion in which any cross-section of the river would be occupied by sewage-polluted upland-water $= \frac{1961 - c}{1961 - 2 \cdot 75}$, where c = the number of grains of chlorine in 100,000 parts found in the water of that part of the river. In November the process would be varied by substituting for 2·75 in the denominator of this fraction the 1·9 above mentioned. This was done, and by dividing the cross-sectional areas in the proportion so ascertained, the results shown upon the diagrams were arrived at. Contrary to what might have been expected, the fresh-water columns below London at high-water and low-water differ but little in volume, which makes the mean of the two extremely near the average column during the whole tide. It will be noticed that between Erith and Southend the form of the river is shown by a much larger number of cross-sections than that of the points at which samples were taken in the same length. The division of the intermediate cross-sections into sea- and polluted upland-water has been done by means of interpolating diagrams, Figs. 2, 4, and 6. On November 30th, this has been done for all the cross-sections between Erith and Southend, owing to no sample of water being taken at Gravesend on that day.

Of course the effect of this division of the river into upland-water and sea-water is only to show the relative proportions of each at various points in the river's length. The fact that the upland-water is mixed with the sea-water, instead of being collected at the centre of the channel, as shown on the diagrams, makes no difference so far as calculations as to progress of the upland-water through the estuary are concerned; for the progress is inversely proportional to the cross-sectional area of the space occupied by the upland-water, whether this water pass away to the sea as a concentrated column, or as myriads of infinitely small streaks equal in the aggregate to such a column. Having established the volume of the fresh-water column, the period occupied by the foremost water in it, in travelling from Barking to Southend, is arrived at by the following process, namely, by first ascertaining how many days' upland-water, counting back from the day to which the diagram refers, there is in the river between Teddington and Barking, and then by counting back from the earliest day that has contributed to the water above Barking, the number of days that must have contributed upland-water sufficient to form that part of the column between Barking and Southend.

The average daily flows of upland-water and of sewage contributing to the fresh-water columns shown on the diagrams were as follow:—

	Cubic feet.
14th September	172,364,082
22nd "	176,528,509
30th November	848,803,496

Thus, on the 14th of September, 1882, the mean column of upland-water between Teddington and Barking was nearly equal to that entering that part of the river during the thirteen previous days (Fig. 7); and the column between Barking and Southend contained nearly as much as passed over Teddington weir during the thirty-two days preceding those thirteen, namely, 1st August to 1st September inclusive, together with such increment as the Teddington water of these thirty-two days acquired up to the 14th of September. The Barking sewage of the 14th of September must have mixed with the water that passed over Teddington weir on the 1st of September, and that of the 14th of August with the Teddington water of the 1st of August. So, as will be seen on the diagram, Fig. 7, the sewage discharged at Barking on the 14th of August was off Southend on the 14th of September.

Fig. 7 shows how the water of to-day is pushed along the river by that of to-morrow; but by thus dividing the column into daily flows by means of vertical lines, each day's flow is made to occupy a portion of the river only a mile or two long. It is obvious, however, that this is incorrect, for while a day's fresh-water is entering any tidal portion of the river, the water occupying any given cross-section must have travelled something like 10 miles down the river and back again; so that each day's supply of fresh-water must occupy a part of the river some 10 miles in length; and although the arrangement of vertical lines serves to show how fast the water is made by displacement to pass out of the river, an oblique arrangement, as indicated in Fig. 8, would show more correctly how one day's fresh-water overlaps longitudinally those of previous days.

On the 14th of September, Figs. 1 and 2, the spring-tides were at their highest. On the 22nd of September, Figs. 3 and 4, the neaps were at their lowest; so that the mean between corresponding figures in the diagrams of these two days may be taken as average figures for the whole moon.

On the 22nd of September the quantity of fresh-water between Barking and Teddington was rather more than what had entered that part of the river during the previous thirteen days; and the column between Barking and Southend contained rather more than passed over Teddington weir during the thirty-three days preceding those thirteen, namely, from the 8th of August to the 9th of September inclusive, together with the increment acquired by the Teddington water of those thirty-three days up to the 22nd of September. The London sewage in the river between Barking and Southend was that which had been discharged between the 21st of August and the 22nd of September inclusive. The diagram of the 22nd of September is therefore a record of the sewage that left Barking on the 21st of August, being off Southend thirty-three days later. From thirty-two to thirty-three days may be taken as the average time required for sewage discharged at Barking in August, with such a season as that of the year 1882, to reach Southend.

Figs. 5 and 6 show the condition of the river, the tides being half-way between springs and neaps, on the 30th of November, after a period of considerable flood. There was then a quantity of upland-water between Barking and Teddington equal to the three previous days' flow of the Upper Thames and the tributaries joining it above Barking; and between Barking and Southend there was nearly as much upland-water as came over Teddington weir during the twelve preceding days, from the 16th to the 27th of November inclusive, together with the increment acquired by the Teddington water of those twelve days up to the 30th of November; and the Barking sewage in that part of the river must have been what was discharged between the 19th and 30th of November. Fig. 5, therefore, records the fact that sewage discharged at Barking on the 19th of November was by a heavy flood of upland-water carried down to Southend in twelve days.

Although, as appears from the diagrams, a heavy flood of upland-water reduces the saltness of all the water in the estuary, it may here be mentioned that, within certain limits, the quantity of sea-water coming up the river actually increases with the quantity of fresh-water coming down. This will be seen on comparing the quantity of sea-water found on the 30th of November to have been brought up by twelve days' upland-flow with the quantity found in September due to thirty-two and a half days' upland flow. In November the total sea-water between Barking and Southend would be 15,739,986,102 cubic feet, which divided by 12 gives a daily inflow from the sea of 1,311,665,508 cubic feet; whereas in September the mean volume of sea-water between Barking and Southend is 20,623,815,567 cubic feet, which divided by $32\frac{1}{2}$ gives a daily inflow from the sea of 634,578,940 cubic feet. Thus, in November, when the upland-flow was nearly five times as great as that of September, the daily inflow of fresh sea-water was more than twice as great. This is very interesting, because it has hitherto been supposed that the exchange of river- and sea-water is not a very large factor in tidal action.

Although the large volume of sea-water entering a river acts in a very important degree in removing dissolved impurities towards the ocean, and in a minor degree in carrying the same impurities up the river, the Author is satisfied that it has no mechanical effect upon material suspended in the water, for the action of the salt-water is simply one of circulation, which does not affect the mean outward current of the river.

Analyses show that the quantity of sea-water reaching Chiswick was never more than about one hundred and fiftieth part of that reaching Barking, and it is known that the water at Barking never contained more than about one-eighth part of its volume of sewage.

It follows then that not more than one twelve-hundredth part of the river at Chiswick could consist of water which had passed out of the Barking or Crossness outfalls.

It has been shown that the sea-water, which plays such an important part in driving the upland-water out to sea, has no such effect upon floating or suspended matter. It may, therefore, be worth while to mention one fact bearing upon the behaviour of the suspended matter in the river, namely, that in certain parts of the river the flood-tide is at springs considerably faster than the ebb. For instance, at Barking, when the Author had an opportunity of making a comparison, it was found that although the volume of water passing on the ebb was only 5½ per cent. more than had passed up with the preceding flood, the time occupied by the downward flow was nearly 30 per cent. longer. This greater velocity might, of course, remove substances upwards from the bottom of the channel which the previous ebb had failed to move downwards.

This fact no doubt accounts in some measure for the anomalous results obtained from float experiments, because floats travelling on the flood-tide at a higher velocity than on the ebb are less affected by the many outside and lateral influences which must operate upon them in any river.

The general effect of the foregoing calculations is to show that owing to the greater specific gravity of sea-water and its tendency to diffusion, the exchange of river-water and sea-water takes place much more quickly than is commonly supposed, so that the upland-water passes even more rapidly through the estuary at Southend than at Barking, where the cross-sectional area is not one-twelfth the size.

The Paper is accompanied by several diagrams, from which Plate 8 has been prepared.

[DISCUSSION.

PASSAGE OF UPLAND WATER THROUGH A TIDAL ESTUARY.

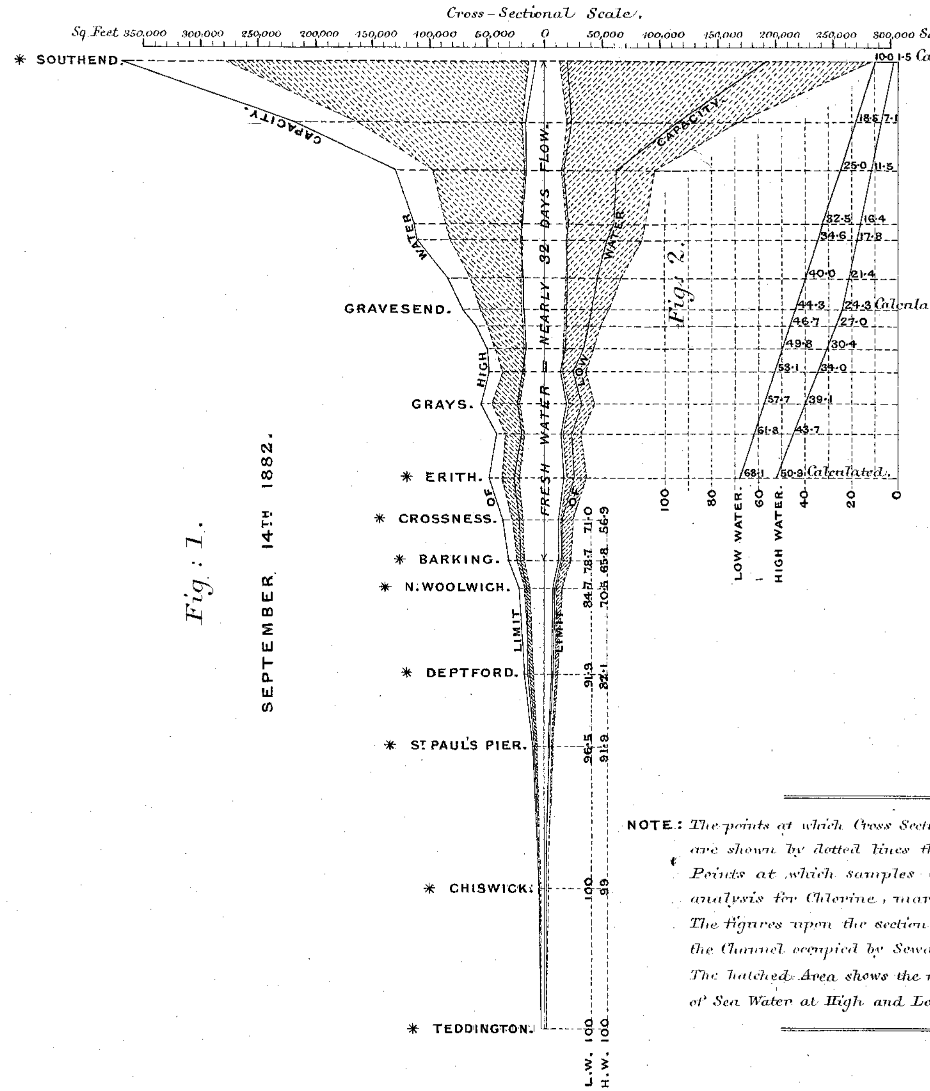

Fig: 1. SEPTEMBER 14TH 1882.

Fig: 2.

NOTE: *The points at which Cross Sections of the River were taken are shown by dotted lines through the Diagrams.— Points at which samples of Water were taken for analysis for Chlorine, marked thus:* ✱.— *The figures upon the section lines give the percentage of the Channel occupied by Sewage Polluted Upland Water.— The hatched Area shows the mean between the volumes of Sea Water at High and Low Water respectively.—*

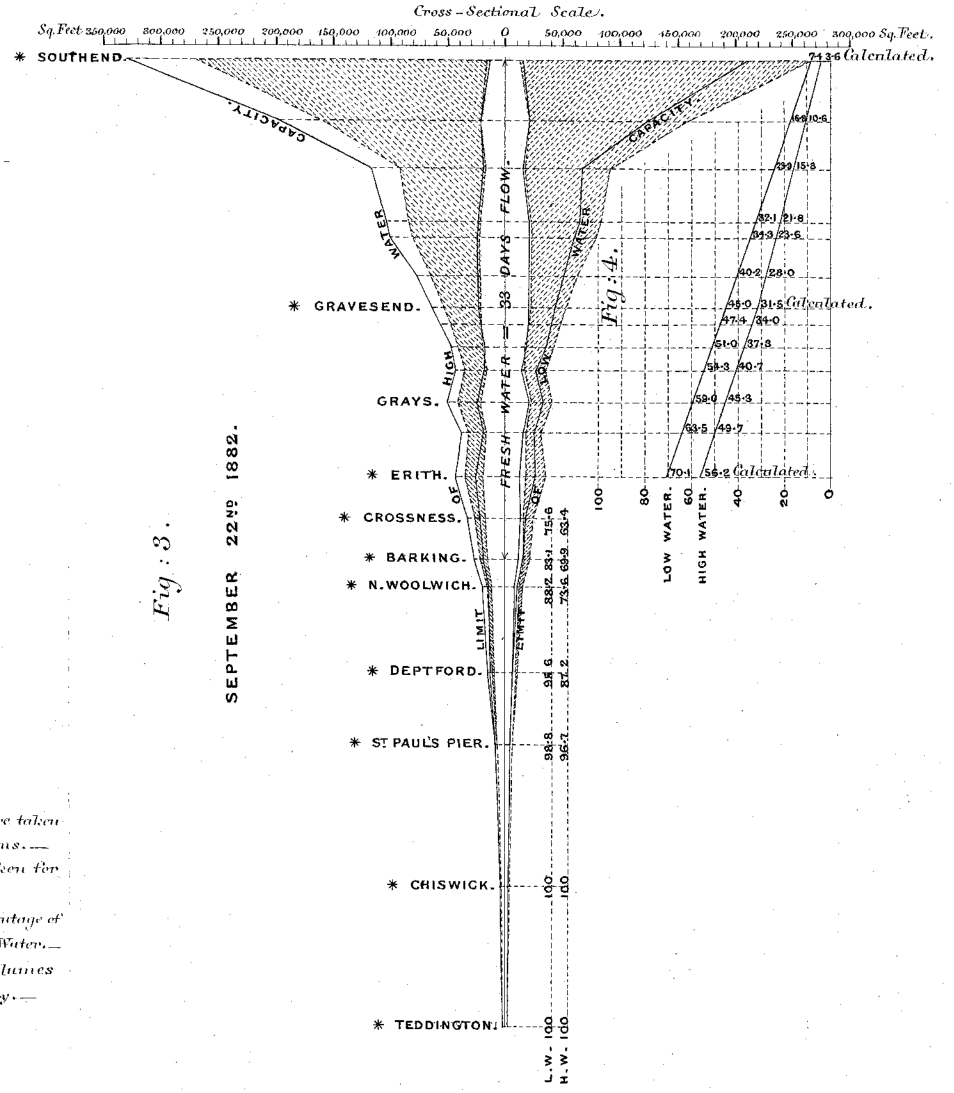

Fig: 3. SEPTEMBER 22ND 1882.

Fig: 4.

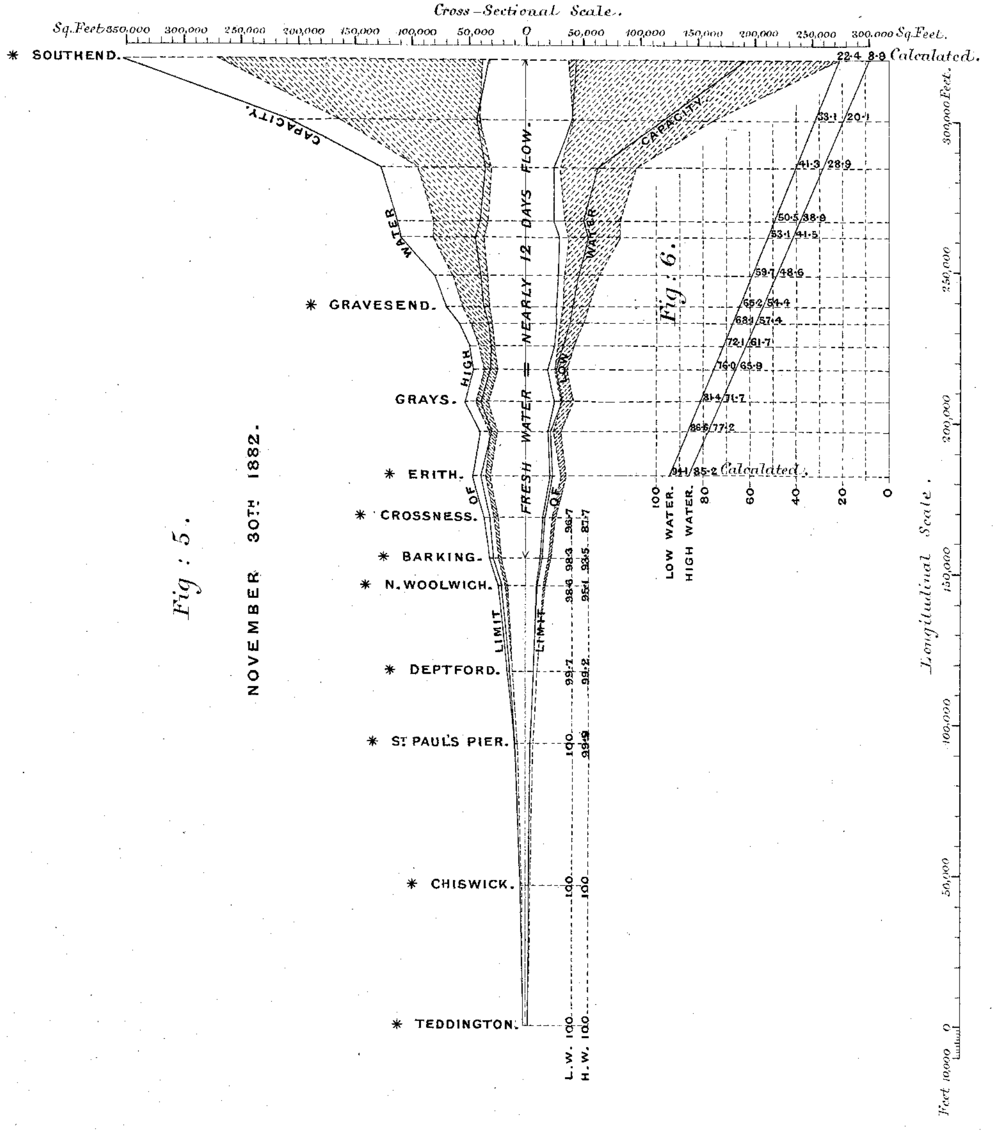

Fig: 5. NOVEMBER 30TH 1882.

Fig: 6.

Fig: 7.

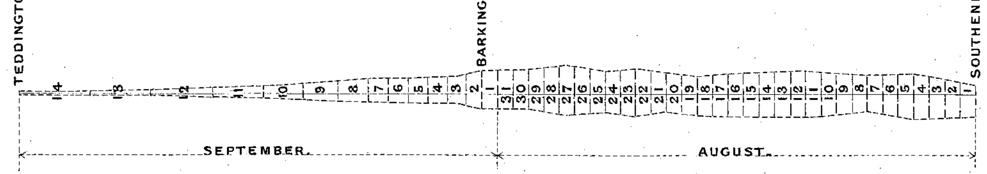

Fig: 8.