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“The Relative Value of Tidal and Upland Waters in maintaining Rivers, Estuaries, and Harbours.”

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The two natural agencies which tend to keep clear the channels of tidal rivers and estuaries are: the tidal flow, *i.e.*, the run of the tide, passing up and down such channels twice in about every twenty-four hours; and the low-water flow, *i.e.*, the current, mainly of fresh water, passing through such channels at the end of each ebb tide and up to the beginning of the next flood. The object of this Paper is to investigate the relative value of these two agencies, in preserving the full depth and section of such channels.

The determination of this relative value is a matter of very great moment in many practical questions of marine engineering, and much discussion has taken place upon it. The reports for 1845, 1846, and 1847 of the Commissioners on Tidal Harbours in particular contain many opinions, and a considerable amount of information, bearing on the subject, but they cannot be said to furnish a solution of the problem.

One preliminary remark must be made, *viz.*, that no universal rule can be laid down, and that each case must be judged on its own merits. This remark is so much an accepted dictum in matters of engineering, especially marine engineering, that it may appear superfluous. But in this particular instance a universal rule has been laid down, and supported by engineers of eminence, that no encroachment on tidal waters should ever

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be permitted; in other words, that nothing should ever be done to diminish the amount of tidal water flowing up and down a channel. The object of this rule is to prevent the silting up of the channel, and its ground can only be the assumption that the main, if not the only, cause which prevents this silting up is the tidal flow. In the Author's opinion, this assumption cannot be maintained, and grounds quite as solid might even be found for exactly the opposite rule, viz., that tidal water should be wholly excluded from a channel, wherever possible. As already stated, the Author declines to lay down any universal rule; but his study of the subject has led him to accept as a principle, that the main and essential agent, which keeps clear the channels of tidal rivers, is not in general the tidal but the low-water flow.

This principle may be supported by the following line of argument:—

(I.) The silt, which tends to choke up tidal channels, is almost wholly due to the tidal water, and not to the fresh water.

(II.) The tidal water brings up more silt on the flow than it takes down on the ebb; *i.e.*, on the whole it tends to choke the channel, not to scour it.

(III.) The low-water flow, if left to itself, scours away the deposit, and keeps the channel open.

(IV.) Therefore, where the two act together, the scour must be due mainly, if not entirely, to the low-water flow, and not to the tidal flow.

(I.) The silt, which tends to choke up tidal channels, is almost wholly due to the tidal water, and not to the fresh water.—In some quarters the idea still seems to prevail, that the mud of tidal rivers is all brought down by those rivers themselves. But if this were true, then rivers, above the tidal area, would carry as much silt as below; and since they are there much smaller, the amount of silt per cubic foot, or the muddiness of the water, would be greater. The contrary is notoriously the case. Let any one compare the current of the Severn at Worcester with the immense mass of turbid water which occupies the Bristol Channel; or even the Thames at Richmond, with the Thames at Erith.¹ A good example on this head is furnished by the river Parret, at Bridgwater. This river is formed by several streams, which spring from the sandstone and limestone hills of Somerset, and unite in a great level plain many miles above Bridgwater. Any small amount of silt which they might wash down in their earlier course would be

¹ For a full discussion of the question, as regards the Mersey, see "Report on the Improvement of the rivers Mersey and Irwell," by H. R. Palmer. London, 1840. [Inst. C.E. Tracts 8vo, vol. lxxi.]

deposited in this plain long before it could reach Bridgwater. But above and below that town the banks are regularly cut into level benches, for the sake of collecting the silt, which is eventually made into what is known as "Bath Brick." The silt is deposited on these benches with great rapidity, requiring to be excavated every two or three months, and many thousands of tons are thus abstracted from the river annually; an amount which would be utterly beyond the capacity of the river itself to supply in that limited area.

To complete the proof, it is only necessary to answer the question, Where does this silt come from? In the case last described, this is an easy matter. At Stert Point, close to where the Parret debouches into the Severn, the river can be seen washing and undermining, for a considerable distance, a vertical bank of sandy clay, exactly resembling the silt which it deposits higher up. In other cases, such as the Severn, the silt is due to the constant motion of the waves beating upon the wide muddy flats which lie between high and low water. The mud on these flats, originally derived from the eating away of alluvial lands near the estuary, combined with a small portion of mud brought down by the river from inland, has been rising and settling alternately under the variations of weather, probably for centuries.

The effect of waves, even of small ripples, in stirring up mud, has been well illustrated in a Paper by Mr. Charles Richardson, M. Inst. C.E., read before the British Association at Bristol in 1875. Speaking of the Avon between Bristol and Avonmouth, he says:—"At the ferry from Pill to Lamplighters, the Lamplighters shore is entirely alluvial, and it will be found that during a quiet season the mud on that shore will rise to a level of 5 or 6 feet, on both sides, above the level of the ferry path. If after this a continuance of strong westerly winds sets in, the ripple on the water will gradually wash away the accumulated mud again, until it becomes almost level with the ferry path. This fact proves that the tidal waters do of themselves have a tendency to deposit mud, but that the ripple, caused by the wind, washes it away again in exposed situations near the mouth of the river."

(II.) The tidal water brings up more silt on the flow than it takes down on the ebb; *i.e.*, on the whole it tends to choke the channel, not to scour it.—That tidal waters do bring up the silt from the large estuaries, where it is raised by wave action, into river channels, is made clear by Section (I). That this silt is rapidly deposited at the bottom, during the period of slack

water at the top of the tide, is an unquestioned fact, and follows from the laws of the mechanical suspension of solids in water. That a certain quantity of the silt so deposited is removed again during the run of the ebb, and carried out to sea, may also be granted. The question is whether the whole, or only part, of the silt is so removed. If the latter, then a certain quantity is left behind after each tide, and unless some other agency supervenes, the channel will gradually but surely silt up. Now that only part and not the whole of the silt is so removed may be proved, in the Author's opinion, as follows:—

(1) To ascertain the effect of any cause, the best course is to examine cases where that cause alone is operative. This, in the matter of tidal scour, can fortunately be done. The banks of any tidal and muddy river, between high and low water, are fully exposed to the action of the tidal scour, and to that alone. It is well known that these banks are generally covered, from top to bottom, with a thick deposit of silt. This deposit has certainly been brought up by the flood tides, and as certainly has not been swept away by the ebb. Here, therefore, is a proof that tidal waters cannot sweep away as much mud as they deposit.

(2) It might be argued that this only applies to the upper portions of these banks, which, from the rapid fall of the tide, are not so long exposed to its influence. But, apart from other considerations to be subsequently mentioned, not only does the deposit retain about the same thickness from the top to the bottom of the slope, but in muddy waters the rise and fall of a single tide is sufficient to leave a distinct film of silt over the whole surface of that slope. For instance, during tidal work at or near low water in the Avon near Bristol, the planks, wheelbarrows, &c., had always to be washed before commencing operations at each ebb tide.

(3) It may be asked how it happens, if this deposit is always going on, that the channel is not finally choked up. The answer is, that the deposit does accumulate, until the angle at which it lies becomes greater than the angle of stability of this soft and wet material; a portion then slides down into mid-channel, to be carried away by the low-water flow, and the accumulation commences afresh. This is well described in Mr. Richardson's Paper already alluded to, as follows:—

“Now if the river channel be carefully observed at low water of a spring tide, flakes of mud may be observed to slip down into the low-water stream here and there as the tide recedes; the hollows these mud-slips leave are characteristic, and are plainly observable all along the river at low water. These patches of mud slip into the low-water channel as they lose the support of the tidal water,

and are then carried out into the Severn by the stream of fresh water. This process is constantly going on, and is evidently the way in which the channel is kept at its regular width, notwithstanding the increasing deposit of mud by the tidal waters at every tide."

(4) It is known (*see* Bouniceau, "*Étude sur la navigation des rivières à marées*"), that the amount of deposit is always less in winter than in summer. Since the tidal flow is the same in winter and in summer, this can only be due to the deposit being swept away by the winter freshes; and it therefore shows that the deposit diminishes as the scouring power of the low-water flow increases.

(5) Hitherto the question has perhaps been complicated by the low water and the tidal flow being both present in the same river channels. But it is easy to find examples where the former is entirely absent. In all such, so far as the Author is aware, the result is the same, viz., that complete silting up does actually occur, unless artificially prevented. Every half-tide basin is a case in point, and it is well known that in muddy waters these have always to be kept to the proper depth by artificial means. Two special cases of a more general character may be given as further illustrations.

The first refers to the mode in which the Avon debouches into the deep water of the Severn at King Road. In former years the fresh water was discharged through two channels, embracing between them Dumball Island, and named respectively the Swash and the North Channel. The latter was the larger, and was chiefly used by the shipping. When the Bristol Port and Pier railway was made from Bristol to Avonmouth, two timber jetties, with landing-places and pontoons, were constructed in the North Channel, to enable goods and passengers to be landed for conveyance by the railway. About twenty years ago, however, the tugs and other steamers plying between Bristol and places down the Bristol Channel found that they saved time, as well as distance, by taking the Southern or Swash Channel, whenever the tide was sufficiently high to admit of it. The passage of these steamers, often almost scraping the bottom, gradually deepened the Swash Channel, until the whole of the low-water flow was diverted down it.¹ From that moment the North Channel, though still exposed to the run of the ebb tide

¹ For the great scour produced by the wash of steamers, see "Report of Tidal Harbour Commissioners," 1846, p. 25

down the Avon and the Severn, began to silt up; and so rapidly has this process gone on that no vessels can now use this entrance; the landing-places and jetties have been completely abandoned; and Dumball Island bids fair, in a few years, to be connected with the mainland by an expanse of mud only overflowed at high tides.

The second case is that of the Chesel Pill, near New Passage on the Severn. A "pill" in this district means a tidal creek, into which are discharged, through a sluice, the waters of an inland watercourse or "rhine." A plan of the Chesel Pill is given in Fig. 1, Plate 1. The sluice originally stood at Redwick, about a mile inland, and the channel below this was tidal. Some years ago it was resolved, for the benefit of the level, to dam the stream nearer to its mouth. For this purpose a new sluice D was built within the horse-shoe bend A C B, and a straight cut was made from A to B. The original course was then dammed at B, and the new cut opened, causing the water to pass through the new sluice D. The results have been as follow: (1) Above the sluice D the high banks, which were formerly covered by the tidal waters only, have been overgrown with grass, the fresh-water channel remaining the same; (2) Below the sluice D the whole channel remains as deep as ever, in spite of its having lost the scour of all the tidal water which formerly ran up to the old sluice; (3) The horse-shoe A C B has completely silted up, although it has had the daily scour of the tide running up to B.¹

These two cases have been dwelt upon as peculiarly instructive; but ordinary experience and observation in such matters are enough to teach that a creek, or any other space, left exposed simply to the flux and reflux of the tide, will in time silt up to something like high-water level; and this can only be because tidal waters tend on the whole to choke and not to scour.

(III.)—That the low-water flow, if left to itself, scours away the deposit and keeps the channel open, is evident from the remarks already made as to the Chesel Pill, which form a salient instance of the truth of this statement. Further, ordinary rivers, in parts above tidal influences, keep, with slight oscillations, a constant regimen, and require no artificial means to maintain their channels. The only exceptions are where rivers, previously charged with silt, descend into wide and level plains, such as those of Lombardy. But these cases rarely occur in tidal waters, where the fall practically coincides with the slope of the land towards the sea, and is seldom very small. As confirmatory of

¹ The Author is indebted to Mr. C. Richardson for these particulars.

this it may be mentioned that even in tidal waters the bottom is kept clean by the low-water flow. This has been proved in the Avon, where, in the course of the improvements, it was desired to deepen the channel for some distance below the Clifton Suspension Bridge. Although the tidal banks are here covered with mud to the depth of some feet, and the water is always thickly charged with sediment, the spoil, brought up by the dredger, proved to be entirely composed of gravel and stones, so clean that it only needed the breaking up of the larger pebbles, and the addition of lime or cement, to form excellent concrete. An exactly similar layer of clean gravel, mixed with bones, trees, &c., is found over the whole of the alluvial lands of the Avon, covered by about 25 feet of tidal silt. This must be the old bottom of the river, silted over as the stream gradually worked its way from one side of the valley to the other. What can be the cause of this phenomenon, unless the silt, which is certainly deposited after each tide (and most thickly in the deepest water), is regularly swept away by the low-water flow, in the period before the next tide begins?

The Author has now, he believes, succeeded in establishing the three propositions stated at the outset, as constituting the premises of his argument. If so, there appears to be no means of avoiding the conclusion, (IV.) that where the tidal and the low-water flow act together, the scour of the channel must be mainly due to the latter, and not to the former. A few subsidiary arguments may be added. The scour of a low-water flow is in its nature self-regulating. The velocity, and therefore the scouring power, of the water, depend on the slope of the bottom. If the bottom be anywhere too deeply cut into, this slope, from thence downward, will be lessened; the velocity will thereby fall, and the bottom will silt up again. But the scour of tidal flow would seem to be of an opposite character. It is due to the flowing down of a mass of water, following the fall in the level of the ocean outside; and in proportion to the size of this mass, so apparently would be its scouring effect. Hence a tidal channel, in which the amount scoured out once becomes larger than the amount deposited, should go on enlarging indefinitely. It is needless to say that such a case is unknown. On the contrary, there is good reason for the belief that, in alluvial soils, the section of a channel always bears a fixed relation to the amount of fresh water coming down. This is illustrated by the accompanying cross sections of the Avon, Plate 1, Fig. 2,

Sections 1—5, taken at different points between Bristol and King Road. It will be seen that the low-water stream occupies a similar position at the bottom of each section (becoming somewhat larger in the lower sections), and that the mud-banks slope up from this at a regular angle, which is less at the sections near the mouth, because the mud there is softer and wetter. In this view the Author is supported by Mr. Richardson, who has been a close observer for many years of such phenomena in the Bristol Channel, and who says: "If any one will look carefully at the different streams in the neighbourhood, he will see little streams with little estuaries, medium streams with middle-sized estuaries, and big streams with large estuaries; the channel formed being always in proportion to the amount of fresh water. This cannot be accounted for by any other supposition than that the volume of the fresh water determines the size of the estuary, and that the tidal waters have nothing at all to do with it."¹

But whatever may be the worth of the above argument as to the slight value of tidal, compared with low-water scour, it is desirable to check it, if possible, by direct experiments. Now obviously the scouring action of any current is due solely to the layers of water in immediate proximity to the sides and bottom; and the main body, flowing above, has no direct effect. This has been frequently ignored, and perhaps not unnaturally. If an observer stands on the brink of such a river as the Avon, and sees the ebb-tide rushing past, at a speed of several feet per second, he is easily led to the idea that an immense work of scouring must inevitably be going on. But a moment's reflection will show that it is only the velocity at the surface which he sees; and that unless he knows the ratio of this surface velocity to that at the bottom, he really knows nothing as to the intensity of the scour.

It is thus a matter of great importance to determine the ratio between the surface and the bottom velocity in tidal currents; and this point the Author set himself to investigate. The data which he was able to discover were at first extremely meagre. While a multitude of experiments are recorded on the surface and middle velocities of rivers, yet, owing perhaps to the difficulties of

¹ It is obvious that another factor enters directly into the determination of the size of an estuary, viz., the size of the valley of which the estuary forms part; but as the size of the valley will as a rule govern the size of the stream which flows down it, the effects of the two factors are generally the same. Of course this does not hold when the valley has been excavated by ice or otherwise in solid rock, like the glens of Scotland or of Norway.—W. R. B.

measurement, the bottom velocities have been generally omitted, or at least have not been recorded with exactness.

Mr. W. Bald¹ states that the bottom velocity of the tidal flow in the Clyde is about $\frac{2}{3}$ that at the surface, but unfortunately the depths are not mentioned. Rankine gives the ratio as $\frac{2}{3}$ for ordinary, or $\frac{1}{2}$ for very slow currents.²

The best observations the Author was at first able to meet with were those of Graeve in the Oder and the Warthe, published in the "Civil Ingenieur."³ But these experiments were only in depths varying from about 2 to 3 metres (6 feet 7 inches to 9 feet 10 inches), while even in small rivers like the Avon the tidal current has a depth of more than 30 feet. The Author, however, prepared the following Table I. (page 10), showing, for gradually increasing depths, the surface velocity (or the maximum velocity where this was not exactly at the surface), the bottom velocity, and the ratio of the two, deduced from Graeve's experiments. The figures added for the depths of 1·4 metre, 1·8 metre, and 1·9 metre, are from Schlichting's observations on the Memel.⁴

These results present considerable anomalies, especially in the figures for the depth of 2·8 metres. Taking, however, a mean of the observations from 1·9 metre to 2·1 metres, and also of the observations from 2·9 metres to 3·1 metres, it appears roughly that the ratio of the bottom to the surface velocity has diminished, between the depths of 2 metres and 3 metres (6 feet 7 inches and 9 feet 10 inches), from 0·61 to 0·55, or by about 10 per cent. It is clear that if anything like this rate of diminution goes on as the depth increases, the velocity at such depths as 20 to 30 feet must always be a mere fraction of that at the surface. This conclusion is confirmed by two experiments at such depths, given in Révy's "Hydraulics of Great Rivers." These, reduced to French measures for comparison, are as under :—

Depth.	Surface Velocity.	Bottom Velocity.	Ratio of Bottom to Surface Velocity.
Metres.	Metre per second.	Metre per second.	
6·9 (22 feet 8 inches)	0·593	0·256	0·43
7·4 (24 feet 4 inches)	0·549	0·178	0·32

¹ *Vide* Minutes of Proceedings Inst. C.E., vol. v., p. 234.

² *Vide* Manual of Civil Engineering, p. 674.

³ *Vide* vol. xxv., p. 184.

⁴ *Vide* Zeitschrift für Bauwesen, vol. xxvii., p. 87.

TABLE I.—GRAEVE'S AND SCHLICHTING'S OBSERVATIONS.

Reference Number of Experiment.	Depth.	Surface or Maximum Velocity.	Bottom Velocity.	Ratio of Bottom to Surface Velocity.	Mean.
	Metres.	Metre per sec.	Metre per sec.		
S. I.	1.4	0.636	0.4926	0.77	..
S. V.	1.8	0.551	0.3296	0.60	..
S. II.	1.9	0.714	0.4752	0.69	} 0.61
20	2.0	0.79	0.50	0.64	
23	2.0	0.82	0.48	0.59	
22	2.0	0.75	0.43	0.56	
24	2.0	0.78	0.50	0.64	
29	2.0	0.83	0.46	0.55	
33	2.1	0.786	0.46	0.585	
49	2.1	0.78	0.47	0.60	
21	2.1	0.79	0.52	0.66	
53	2.1	0.78	0.45	0.58	
28	2.1	0.84	0.53	0.63	} ..
15	2.2	0.83	0.45	0.54	
17	2.2	0.78	0.49	0.63	
14	2.3	0.82	0.50	0.61	
32	2.4	0.805	0.48	0.596	
48	2.4	0.81	0.48	0.59	
52	2.4	0.82	0.47	0.57	
9	2.5	0.82	0.52	0.64	
11	2.5	0.82	0.56	0.68	
10	2.6	0.81	0.44	0.54	
7	2.7	0.82	0.52	0.64	..
6	2.8	0.87	0.55	0.63	..
31	2.8	0.855	0.55	0.64	..
39	2.8	1.12	0.55	0.49	..
47	2.8	0.86	0.55	0.64	..
40	2.8	1.19	0.55	0.45	..
51	2.8	0.86	0.55	0.64	..
42	2.9	1.13	0.55	0.49	} 0.55
1	2.9	0.88	0.55	0.57	
41	2.9	1.08	0.57	0.53	
44	2.9	1.19	0.67	0.56	
46	3.0	1.10	0.60	0.545	
36	3.0	1.18	0.70	0.59	
50	3.0	1.10	0.60	0.55	
43	3.0	1.16	0.60	0.52	
54	3.0	1.10	0.60	0.54	
45	3.0	1.07	0.65	0.61	
35	3.1	1.14	0.62	0.54	} ..
37	3.1	1.13	0.60	0.53	
2	3.1	0.89	0.50	0.56	
38	3.1	1.18	0.70	0.59	
35	3.1	1.14	0.57	0.50	

It is to be observed, moreover, that such observations cannot be taken exactly at the bottom (Mr. Révy's were 1 foot from it), and that the diminution in velocity close to the bottom is very rapid, as is shown by Graeve's curves of velocities, at different sections, four of which are reproduced in Figs. 3 and 4, Plate 1.

The Author's attention was subsequently directed, by Mr. Robert Gordon, M. Inst. C.E., to the Report of the Chief Engineer of the U.S. Army for 1878, which contains a valuable record of experiments made by General Ellis in the Connecticut river, at a part where the width varied from 1,400 to 1,000 feet, and the depth exceeded 20 feet. The velocities at the surface, and at various depths from thence to the bottom, were measured, partly by floats but chiefly by meter. With the meter, observations could be got as near to the bottom as 0·4 foot in some cases; with the floats they could not be nearly so close, and with these the results as to bottom velocities are so irregular that the Author decided to reject them. The meter observations also presented several anomalous results, some in one direction, some in another, and these also have been rejected. The remainder are grouped, in Table II., (page 12) into two classes, according as the surface velocity was above or below 2 feet per second; a division practically suggested by General Ellis, and justified by the result.

From this Table it appears that for low velocities the results are too irregular to allow any rule to be formulated, but that the ratio of bottom to surface velocity is always small, varying on the average from 0·40 to 0·20, and in some cases falling as low as 0·03. In the higher velocities the results are far more regular; the average ratio for the observations at 7 feet and 8 feet is 0·61, and for those at 20 feet and 21 feet it is 0·44, showing a diminution between those depths of 28 per cent. The latter ratio, 0·44, agrees closely with one of Mr. Révy's, given above, and the results as a whole certainly go to confirm the conclusion already formed.

Another series of experiments, to which the Author was also directed by Mr. Gordon, are contained in the Report to the King of Holland on Dutch Public Works, for the year 1873. These experiments were carried out at several places in the various channels of the Rhine and the Meuse. These channels, though not deep are about 500 yards wide, and the results appear to indicate an intermediate position between first-class rivers, such as the Mississippi and the Irrawaddy, on the one hand, and ordinary rivers on the other. There is a considerable difference, generally ranging from 40 to 50 per cent., between the records of the surface and bottom velocities; but the ratio is irregular, and it does not decrease with increase of depth to the same extent shown by the experiments given in Tables I. and II. The detail of some of these experiments is given in Table III. (page 13).

TABLE II.—OBSERVATIONS on the CONNECTICUT RIVER.

Velocity above 2 feet per Second.						Velocity below 2 feet per Second.					
Depth.	Number of Experiment.	Surface velocity.	Bottom velocity.	Ratio.	Mean Ratio.	Depth.	Number of Experiment.	Surface velocity.	Bottom velocity.	Ratio.	Mean Ratio.
Feet.						Feet.					
7	34	3.88	2.22	0.57	0.65	7	..	..	..	..	..
	35	3.39	2.29	0.67							
	33	3.99	2.81	0.70							
	28	3.96	2.18	0.55							
	32	3.75	2.86	0.76							
8	26	3.68	1.83	0.50	0.54	8	48 70	1.03 1.38	0.50 0.41	0.49 0.40	0.44
	27	4.07	2.09	0.51							
	26	3.10	1.91	0.62							
9	..	..	..	..	..	9	81 83	1.48 1.33	0.30 0.28	0.20 0.21	0.20
10	29 11	4.05 2.54	2.00 1.48	0.49 0.58	0.53	10	23	1.61	0.53	0.33	0.33
11	..	..	..	..	..	11	..	..	..	..	..
12	10	2.65	1.34	0.51	0.51	12	54 80	1.06 1.70	0.46 0.16	0.43 0.27	0.35
13	..	..	..	..	..	13	39 47	1.27 1.54	0.04 0.61	0.03 0.40	0.21
14	79	2.10	1.34	0.59	0.59	14	14 22	1.29 1.83	0.25 0.72	0.19 0.39	0.29
15	21	2.14	1.09	0.51	0.51	15	59	1.23	0.64	0.52	0.52
16	2 30 20 78	3.12 4.30 2.17 2.18	1.43 1.89 1.14 1.09	0.46 0.44 0.52 0.50	0.48	16	46 53	1.66 1.30	0.56 0.29	0.34 0.22	0.28
17	8	3.36	1.58	0.47	0.47	17	18	1.57	0.73	0.47	0.47
18	77	2.49	0.97	0.39	0.39	18	17	1.60	0.46	0.29	0.29
19	..	..	..	..	..	19	15 19 73 75	1.49 1.62 1.37 1.91	0.36 0.64 0.43 1.24	0.24 0.39 0.31 0.64	0.39
20	44	2.54	1.07	0.42	0.42	20	..	..	..	..	..
21	42 3 41	3.03 2.31 2.80	1.43 0.96 1.30	0.47 0.42 0.46	0.45	21	..	..	..	..	..

TABLE III.—EXPERIMENTS ON LOWER RHINE.

Width of river 460 metres, distance from bank to nearest section 70 metres.

Date of Experiment.	Number of Section.	Depth.	Surface or Maximum Velocity.	Bottom Velocity.	Ratio of Bottom to Surface Velocity.	Mean.
		Metres.	Metre.	Metre.		
July 11	V.	2.6	1.095	0.70	0.64	0.63
„ 6	V.	2.85	1.085	0.65	0.61	
July 22	IV.	3.4	1.395	0.825	0.59	
June 10	IV.	4.0	1.27	0.85	0.67	
July 15	V.	4.7	1.34	0.93	0.69	..
„ 6	IV.	4.9	1.265	0.65	0.51	..
July 6	II.	5.4	1.71	1.20	0.70	..
July 22	III.	6.5	1.515	0.875	0.58	0.575
„ 6	III.	6.6	1.535	0.85	0.55	
June 30	III.	6.6	1.475	0.77	0.52	
July 15	III.	7.0	1.62	1.025	0.63	
„ 15	III.	7.2	1.725	0.95	0.55	
„ 12	II.	7.5	1.775	1.10	0.62	

The above observations were all made in ordinary fresh-water rivers, and, in the Author's opinion, would not fully represent the circumstances of the ebb in a tidal channel a short distance from the sea. An ordinary river, in a condition of steady flow, may be taken for theoretical purposes as being of unlimited length, and a horizontal line, B C (Fig. 1), drawn through the

FIG. 1.

bottom of any section A B, will cut the surface at some point, C, determined by the average fall of the river. The triangle of water A B C may be considered as acted on by the full force due to the pressure on A B, and will move with a velocity such that the work done by this pressure is just sufficient to overcome the various resistances to the flow. At every point between B and C the conditions will be the same, and the water will be moving with the same steady motion. But the case of a tidal channel is different. There the water at some intermediate point,

D, falls into an estuary or ocean, whose waters are either at rest, or at any rate are moving in a direction different from that of the current in the channel. The waters of the channel, below the level D E, can only make their way into this estuary by displacing the waters already there; and to do this must require some expenditure of energy, especially as the estuary waters will in general have the higher specific gravity of the two. The result must be a back pressure on the water at B, additional to the resistance of friction, &c., and in consequence a retardation of its velocity. This retardation or loss of energy will apparently be greater as the depth increases; and therefore near the bottom, where the speed is in all cases low, it would seem probable that, in tidal channels of this character, the velocity may be reduced to a very small amount, or may even disappear.

Influenced by these considerations, the Author became anxious to obtain some actual observations on the velocity at the bottom of such channels during an ebb tide. Some time elapsed before such an opportunity presented itself; but at length, in March 1880, Mr. Thomas Howard, M. Inst. C.E., Docks Engineer to the Corporation of Bristol, kindly placed men and materials at the Author's disposal, and the necessary experiments were undertaken and carried out with much zeal and ability by Mr. H. S. Hele Shaw, Assoc. M. Inst. C.E., Whitworth and Miller scholar, and assistant to the Professor of Engineering, University College, Bristol. The observations were taken at a point, shown in Fig. 5 (Plate 1), on the "New Cut," at Bristol, between the Bathurst and Cumberland basins. This cut is nearly straight and is well levelled at the bottom, being excavated in the New Red Sandstone rock; it is therefore eminently suited for such observations, as it is free from errors due to bends in the river, or to inequalities in the bottom. The observations were made by means of a current meter, kindly lent by Mr. Baldwin Latham, M. Inst. C.E. The observed velocities at the surface were checked by floats, and in almost all cases the meter gave the higher value, so that its error, if any, was one of excess. The bottom velocities were taken by means of a strong rod, let down perpendicularly from the boat to the bottom, and having a piece of sheet iron, 8 inches square, on the end, to prevent its sinking in the mud.¹ The meter was passed down this rod as far as it would go, and was then

¹ This was found practically to be needless, as the bottom was clean rock; a fact which confirms the previous assertion, as to the power of low-water flow to keep the bottom clear.

allowed to run for a fixed time (five or three minutes). It was then stopped, pulled up to the surface, and the reading taken. The middle velocities were determined in the same manner. The results are contained in Table IV., and although, like all current

TABLE IV.—EXPERIMENTS ON VELOCITIES OF the EBB TIDE in the RIVER AVON, MARCH 31, 1880.

Ebb commenced about 10 25 A.M. Depth at high-water about 23 feet 6 inches.

Series and Number.	Total Depth at Time of Experiment.	Position of Meter.	Time of commencing Experiment.	Duration of Experiment.	Distance run by Meter.	Velocity by Meter.	Surface Velocity by Surface Floats.	Level of Surface at Avonmouth below Surface.
			h. m.					
A 1 2 3	22 11	At surface	10 55	5	627	2·09	1·9	1 5
		11 feet below	11 10	5	312	1·04	2·6	
		1 foot from bottom	11 3	5	55	0·18	2·6	
B 1 2 3	21 5	At surface	11 17	5	902	3·01	3·0	2 1
		9½ feet below	11 32	5	309	1·03	..	
		1 foot from bottom	11 24	5	38	0·13	..	
C 1 2 3	18 4	At surface	11 40	5	932	3·11	3·1	1 1
		8 feet below	11 55	5	905	3·02	..	
		1 foot from bottom	11 47	5	39	0·13	..	
D 1 2 3	15 2	At surface	12 2	5	905	3·02	..	1 2
		7 feet below	12 19	5	901	3·00	3·3	
		1 foot from bottom	12 12	5	26	0·09	3·0	
E 1 2 3	12 9	At surface	12 25	3	699	3·89	3·3	1 10
		6 feet below	12 35	3	564	3·09	3·3	
		2 feet from bottom	12 38	3	244	1·36	3·3	
F 1 2 3 4	10 10	At surface	12 40	3	524 ¹	2·92	3·3	1 11
		5 feet below	12 56	3	614	3·41	3·3	
		2 feet from bottom	12 45	3	300	1·67	3·3	
		9 ins. from bottom	12 51	3	19	0·11	No observation	
G 1 2 3 4 5	9 0	At surface	1 0	3	689	3·83	Do.	3 3
		7 feet from bottom	1 5	3	528	2·94	Do.	
		5 " "	1 10	3	524	2·91	Do.	
		3 " "	1 16	3	514	2·86	Do.	
		1 foot "	1 21	3	417	2·32	Do.	

observations, they present some anomalies, they will be found very instructive. The small difference, varying from 1 foot 1 inch to 2 feet 1 inch, between the surface level at Avonmouth (where the Avon debouches into the Bristol Channel, 7¼ miles

¹ Probably there is an error in this reading.

lower down) and that at the place of observation, brings out strongly the difference already pointed out between this case and that of an ordinary river. It is only in the last series, G, that the ordinary conditions may be said to appear. Unfortunately, no levels were taken on the tide gauges after 1 P.M.; but from the rapid increase in the difference between the Bristol and Avonmouth levels from 12 40 to 1 P.M., it may be conjectured that at 1 20 P.M. this difference would have amounted to at least 4 feet, while at the same time the depth at the place of observation had diminished to 7 feet. The conditions thus approximated to those of an ordinary river; and it will be seen that here, and here alone, the bottom velocity becomes considerable, and its ratio to the surface velocity approaches the ratios given by Graeve for similar depths.

The bottom velocities shown in Table IV. are very small, and not in themselves sufficient to move even the finest silt. That in E3 was 2 feet from the bottom; and it will be seen from F3 and F4 that the velocity at 2 feet may be considerable when that at 1 foot is practically zero. These velocities, however, are given only because they were actually recorded on the meter, and not as being absolutely correct. Preliminary experiments had shown that it was not possible satisfactorily to put the meter into gear while it was at the bottom, and therefore during these experiments it was put into gear before being lowered into the water. The effect, of course, was that the meter was running during the time it took to descend through the current, and that the distance thus run must properly be subtracted from the distance indicated at the end of the experiment.¹ If this subtraction were made, there could be little doubt but that the bottom velocity, already very small, would turn out to be absolutely nothing. This was confirmed by those who were conducting the experiments noticing that the small plate, which has been mentioned as attached to the bottom of the rod, whenever it was lifted to the top of the water, was found to have a deposit of fine silt on its upper surface. This seems to prove that, at the very moment when an ebb tide is running down at a speed of 3 to 4 feet per second, not only may there be no scour whatever going on at the bottom, but an actual deposit of silt may be taking place. It is obvious that the theoretical views already stated have met with the fullest confirmation.

In order, however, that this point might be put beyond all

¹ It will be noticed that in the later experiments, where the depth was less, the distance thus run was also less.

doubt, the Author arranged with Mr. Shaw to make a fresh set of experiments with improved apparatus, and these were successfully carried out on the 21st of September, 1880. In this case, following an ingenious suggestion of Mr. Shaw, the rod on which the meter was mounted (Fig. 2) was made with a feather on it, which fitted into a recess in the socket of the meter. By this means the meter, which was specially constructed for the purpose by Mr. Shaw, could be turned into any direction with regard to the current by simply turning the rod. When being lowered through the water, the meter was thus held in such a position that the screw had no

FIG. 2.

Current Meter. General View and Plan. $\frac{1}{4}$ full size.

tendency to revolve at all, a position which was found to be nearly, but not quite, at right angles to the direction of the current. When it reached the required depth (which was marked upon the rod) the meter was shifted, by turning the rod, into the position parallel to the current, in which it was maintained by the vane; and it then began immediately to revolve. Its scale of measurement was carefully ascertained by preliminary trials, in comparison with floats—a ship's log, which was first used for the

8 40 A.M. The first observation was taken at 9 40 A.M.; the ebb had then been running for about one hour, and had lowered the surface level by about 3 feet 9 inches, or to a depth of 22 feet 8 inches. The first observation showed that the conclusion drawn from the former set of experiments, viz., that there was absolute stillness at the bottom, was correct, for while the velocity at the surface was 3·57 feet per second, that at the bottom was zero. The observations were repeated, with the same result, till about 11 A.M., when the ebb had been running about two and a half hours, and the depth had fallen to about 11 feet, or 15 feet below high-water level. The bottom layers of water then appeared to start into activity, and to assume a velocity which from that period continued to bear a tolerably uniform ratio of about 0·7 to the surface velocity. The experiments were ended at 12.37 P.M., when the whole of the ebb was over, four hours after it had commenced, and one hour and a half after the bottom velocity had become apparent. The depth was then 5 feet 6 inches, and the velocity, 1 foot from the bottom, about two-thirds that at the surface, a result which agrees very fairly with the conditions for an ordinary river, as determined by Graeve's and Ellis's observations.

The foregoing experiments, combined with others, appear to justify the laying down of the following rules as to the relation between bottom and surface velocities in various cases.

A. In the largest rivers the bottom velocity may for the present purpose be taken as the same as the surface velocity, varying within small limits only. This seems to be fully established by the observations of Humphreys and Abbot on the Mississippi, and more recently by the numerous and careful observations of Mr. Robert Gordon on the Irrawaddy, some of the MS. records of which he has most kindly placed at the Author's disposal. In such cases the whole mass of water appears to move almost like a solid body, independently of the resistances of the sides and bottom. It is possible that the same may hold of great tidal estuaries, such as that of the Mersey, but on this the Author offers no opinion, as he is unable to find any observations of bottom velocities made under such circumstances.

B. In rivers of ordinary size, such as the Connecticut and the Memel, the bottom velocity bears to the surface velocity a ratio which diminishes as the depth increases, but with too much irregularity to allow of a formula being constructed. Roughly, the ratio may be said to be about three-fourths at a depth of 5 feet, one-half at 15 feet, and probably one-third at 25 feet.

C. In ordinary tidal channels, such as the Avon below Bristol, the

course of events during an ebb seems to be as follows. At first the slope of the surface is exceedingly small (in the Avon it was about $1\frac{1}{2}$ foot in $7\frac{1}{4}$ miles), and, while the velocity at the surface is considerable, it diminishes rapidly from thence downwards, and at some distance from the bottom becomes *nil*. This continues for about two-thirds of the ebb, the surface velocity increasing up to a certain point, and then becoming nearly constant. During all this time not only is no scour going on at the bottom, but, if the water be muddy, an actual deposition of silt is taking place. At this time, after about two-thirds of the ebb, the water has fallen about three-quarters of its total height, the slope of the surface has considerably increased, and the conditions approximate to those of an ordinary river. The bottom layers of the water then spring suddenly into motion, and the ratio of bottom to surface velocity is from thenceforward approximately as in the last paragraph, the surface velocity diminishing steadily as the tidal waters disappear, until it assumes the normal rate of the low-water flow. During this period a scour of the bottom is of course going on; but as the velocity is not much higher than in the subsequent period of low-water flow, the rate of scour will not be much greater; and the actual scour will be insufficient to compensate for the amount of deposit from the tidal waters which has taken place, not only during the period of high water, but also during the first two-thirds of the ebb. It must follow, therefore, that the scouring effect of the ebb tide is little or nothing, and the observed incapacity of tidal flows to sweep away the silt they have deposited is amply and satisfactorily explained.

The general investigation as to the relative value of tidal and low-water scour on river channels may now be considered as concluded. It was begun by adducing numerous facts to establish the proposition, that the effect of tidal flow was to cause channels to silt up, while the effect of low-water flow was to keep them open. It was then pointed out that the former circumstance could only be explained by the hypothesis that the current at the bottom of such tidal channels (the only current which has any scouring effect) was very slow, even when the surface current might be rapid. Observations were quoted to show that in ordinary rivers this diminution of velocity does exist to a large extent, and that it increases rapidly with increased depth. Theoretical reasons were then given for believing that in tidal channels this reduction of velocity would again be much larger than in fresh-water rivers, otherwise similar. Lastly, it was shown that this view was amply borne out by direct experiments, which have demonstrated

that, in some cases at least, the bottom velocity is not only reduced, but destroyed, and that silt may be settling on the bottom when the speed of the surface current is at its highest.

To complete the subject, however, it must be observed that there are certain circumstances in which the passage of tidal waters through a channel may have some effect in keeping it open. These are, briefly, any circumstances in which the tidal waters are so far kept back on the ebb, that a portion of them remain to increase the velocity of the low-water flow. Thus a large tidal basin may be supposed to be connected with the sea by a very narrow sluice. Then the flow through the sluice would not be able either to fill or to empty the basin with sufficient rapidity to keep pace with the variation of level outside; hence, on the ebb, it would be low water outside for some time before the current would cease to run through the sluice; and the waters thus impounded would go practically to increase the volume of the low-water flow, and no doubt to add to its scouring effect. This is probably a very rare case. A common one is that of a harbour having a narrow entrance, but expanding inside into a wide extent of mud flats. A large quantity of water soaks into these flats during flood tide, when they are covered with the sea; and when the tide has ebbed this water oozes out again, not immediately, but gradually, and, winding through innumerable depressions and channels, finds its way to the main entrance. It thus forms, as it were, a spurious low-water flow, which, if the inland waters entering the harbour are small, may have a decided effect in preserving the depth of this main entrance. In the Author's belief, it is in a great measure from the observation of such cases, which are common in some localities but rare in others, that the strong predilection in favour of tidal scour has taken its rise.

It remains to inquire how far these views agree with the facts and opinions adduced by various authorities on the question, and also to consider briefly their practical effect on some of the problems of marine engineering.

It has been already mentioned that the chief discussion of the subject, as far as English literature goes, is to be found in the reports of the Tidal Harbour Commissioners for 1845, 1846, and 1847. From these reports may be quoted the evidence of Mr. James Walker, Captain Washington, Sir John Rennie, Mr. D. Stevenson, Mr. Scott Russell, and others, as strongly insisting on the value of tidal scour, and deprecating any interference with tidal areas under any circumstances. But the value of these opinions is somewhat lessened on account of the very meagre substratum

of facts on which they appear to be based. Thus special reference is made to Southwold (Report, 1845, pp. 9, 169, 174), as a case where great injury was done to a harbour by embanking lands inside, and so diminishing the amount of the tidal flow. But from Mr. Walker's evidence the true nature of the injury appears to be this. The action of the tides on the East coast, as is well known, is to keep a bank of shingle continually travelling parallel to the shore, at a certain depth below high water. So long as the harbour in question was kept open to its full extent, the stream issuing from thence on the ebb was sufficient to sweep away the encroaching shingle as fast as it advanced, and so to preserve a clear entrance. After the embanking this was no longer the case; the shingle (aided, according to Mr. Ellis, by a strong easterly gale) pushed forward in spite of the current, formed a bar across the tideway of the basin, and thus made it comparatively inaccessible. This statement indicates a most peculiar case, which must be treated on its own merits, but must not for a moment be allowed to have any weight on the general question of the relative value of tidal and low-water flow.¹ Again, in the case of Rye, Sir John Rennie states (Report, 1845, p. 193), that the harbour was greatly deepened by the blowing up of a sluice, which enabled the tide to run further up the country. But it appears that the failure of the sluice was due to a heavy land fresh; and it seems pertinent to ask, whether the deepening of the harbour might not possibly be due to the land fresh also. In its general history Rye appears almost a typical case of a harbour gradually silting up from the deposit of tidal mud, the fresh-water flow being insufficient to keep it open. Beyond the evidence, such as it is, of these two cases, the Author has been able to find little but simple expressions of opinion, and general axioms, of a more or less doubtful character.

Nor is the weight of opinion entirely on one side. Mr. William Cubitt (Report 1845, p. 126), while disposed to attach considerable value to tidal scour, is most emphatic in pointing out that there are no principles of universal application to harbour engineering, and that there may be many cases where to embank lands would not be injurious, and to open them to the sea would not be beneficial. Mr. John Murray and Mr. W. C. Mylne, in their reports recommending the "dockizing" of the River Wear (Report, 1846, pp. 605-610),

¹ It appears that there was always shoal water outside the harbour entrance, and that the shingle bar formed across the top of this shoal. If so this would bring the advancing shingle within the range of the surface-current of the ebb, and enable that current to have its proper scouring effect.—W. R. B.

speak of the excellent results achieved in France by sluicing from back-water reservoirs, or, in other words, by forming an artificial low-water flow. This is confirmed by Sir John Macneill in his report on Hartlepool Harbour (Report, 1846, p. 360), where he points out that the channel was kept open by sluicing, while it had silted up when left to the operation of the tide. To this testimony may be added that of perhaps the earliest of English marine engineers. Smeaton's report on Wells harbour (Report 1846, p. 452), is an admirable account of what may be considered almost a typical case of the effects of scour. This harbour receives practically no inland waters, but has a narrow entrance, and a considerable extent of marshy flats inside, through which the tide used formerly to find its way by small creeks and channels. Smeaton's report shows that the harbour has always been in a state of slow decay from the deposit of silt; but that the entrance was kept partially clear by the tidal water, which, oozing among these creeks and channels, gradually found its way back to the ocean; that, to improve this scour, a sluice, or rather a dam with one narrow opening, was erected to form a back-water reservoir; that this, for the whole time it lasted, proved efficient in keeping the harbour open; that, when it fell into decay, the authorities, instead of repairing it, chose to expend their money on a lawsuit with certain parties who had embanked a portion of the marsh lands; and that the natural consequence of this policy was the destruction of the harbour. In commenting upon these circumstances, he makes the following remarks, which in the main coincide with the Author's views, and are well worth careful consideration:—

“The reason why the waters passing the sluice have a greater effect in scouring than those which return to sea without passing the sluice, is, because by the contracted opening of the passage of the sluice, the waters that lie in the creeks behind it are detained from ebbing so quickly as they otherwise would have done; that is, their numerous mouths when always open, reduced the level of the water contained therein, to nearly the same level as that of the water in the main channel of the harbour, being stopped by dams made across and united by cross passages into one, and the mouth of this being contracted by the work called the sluice, a body of water is held back in these creeks, as reservoirs, which not being able to escape so fast as the tide ebbs in the main channel, it follows, that a body of water by these means is vended upon, and after the half ebb, which discharging itself into the harbour's creek, forms a scour when the depth is so much lessened

as to operate with power in grinding the bottom, which otherwise would have been so languid as not to have stirred a grain of sand or mud, in which case its effect would be little or nothing. This artificial scour thus procured, in some degree imitates the effect of a fresh-water river, which in these situations is very greatly beneficial, not from any virtue there is in fresh water preferable to salt in these cases (if anything rather less on account of its less specific weight), but from its having a fall from the land, and proceeding therefrom continually it not only strengthens the ebb, but running to sea at low water when the fall being greatest, and the sandy bottom exposed to its action, it continues to work at a time when it can operate to the best advantage; and when the ordinary current of a river is assisted by extraordinary land floods and freshes from downfalls of rain and snow, and this operating at low water, when, as just remarked, the fall is the greatest, in such cases it is capable of producing extraordinary effects, and of keeping a harbour continually open with a channel of a given magnitude, though loaded with sands in any possible degree: for a fresh-water river has this peculiar advantage, that at the same time that it strengthens the scouring power of the ebb, it operates most forcibly at low water, when there is the least to obstruct its operation; it opposes the tide of flood from the sea, and thereby prevents its bringing so much sand and silt into the harbour as otherwise it would.

"The defect therefore of this sluice of Wells is, that though it retains the waters so as to be behind the general ebb, and thereby strengthens the latter part of it considerably; yet being at low water all spent, when the greatest good might otherwise be obtained, it loses that good effect which would be had from a fresh-water river, or from a proper sluice; that is, one that will retain the water wholly till a proper time of tide, and then being let go in one collected body, is capable in a short space of time of producing marvellous effects."¹

Lastly, the Author may venture to cite, in support of his views, the following passage from the important work of Bouniceau ("*Etude sur la navigation des rivières à marées*," 1845, p. 68). After speaking of the way in which estuaries become charged with silt, especially after storms, he continues: "Deposits are thus formed throughout almost the whole tidal course of the river; the ebb carries back only a part of these deposits, and the next tide, passing over the remainder, takes up a part, and deposits

¹ *Vide* Reports of the late John Smeaton, F.R.S., vol. iii., p. 33.

it higher up the river; so that the finest silt is borne to a great distance from the mouth. Each tide thus augments the quantity of the deposits thus formed, until a fresh in the river scours away the whole of this alluvium, bears it to the sea, and deposits it outside the mouth. It follows that, when the river is low, the depositing power of the flood tide exceeds the scouring power of the ebb, aided by the fresh water, and by the natural slope of the channel; during freshes, on the contrary, the latter power exceeds the former. It will be seen, therefore, that the ebb would not alone be able to keep open the entrance of a river, did not considerable freshes occur from time to time to increase its effect. On our coasts the ebb only serves partially to maintain the channel, until the winter comes and re-establishes it, scouring the bed, and enabling it to form in the next summer a vast reservoir for scouring purposes. If the fresh waters, and mainly the freshes, did not thus lend their aid to the ebb, if, from any cause, their flow was interrupted, rivers whose estuaries are charged with mud would be soon silted up by the action of the sea, and before long would be turned into cultivable land. A striking example of this effect has been given by the Somme. A lateral canal had been constructed beside this river from Abbeville to St. Valery. As this was large enough to convey the whole of the waters, it was decided to dam the channel near Abbeville, and thus direct the fresh waters from their accustomed channel. The silting up of the bed of the Somme was the almost immediate consequence of this alteration."¹

Finally there has to be considered briefly the practical application of the principles brought out in the course of this inquiry. These principles may be stated as follows. The scouring power of any current depends wholly on its velocity at the bottom. This bottom velocity, except in rivers of the largest size, is much less than that at the surface, and in a ratio which decreases rapidly as the depth increases. In the case of a deep tidal channel not far from the mouth, it appears to be absolutely *nil* for at least the greater part of the ebb. Such channels, if muddy, are never kept open by the operation of tidal scour alone. Hence in general, excluding the largest rivers and estuaries, the maintenance of the channel is mainly, if not entirely, owing to the low-water flow.

¹ A similar case is the silting up of the bend in the Ouse, after the opening of the Eau Brink Cut. (Palmer "Report on the Improvement of the rivers Mersey and Irwell, etc.," p. 21.)

This flow is of course chiefly due to the fresh waters of the rivers; but the rivers are swollen, slightly perhaps in all cases, and considerably in some, by the salt waters which continue to ooze out from the muddy banks or flats when not covered by the tide. This addition to the fresh waters will of course make the depth at any point, and therefore the slope and the velocity, greater than it would be if the fresh water acted alone. This greater velocity will no doubt give a certain advantage in scouring power. But the extent of this advantage cannot be estimated off-hand. Theoretically, however, it may be roughly gauged as follows. Take the section whose bottom is exactly at the same level as the surface of the water outside the mouth—a level which will obviously be the same whatever the discharge of the river may be. Then the depth at this section will be proportional to the slope. Let this depth be H , and the mean velocity V . Then, by the ordinary principles of hydraulics, $V^2 = CH$, where C is a constant. Suppose that it be ascertained by measurements that half of this depth H is due to salt water; and now consider the effect of diminishing the area covered by the tide, to such an extent that half of the salt water, which at present goes to swell the low-water flow, is subtracted. Believers in tidal scour would no doubt assert that the scour, in other words the bottom velocity, would be reduced by one-half also. To see how far this would be the case, let h be the new depth, v the new velocity. Then, since the discharge is only $\frac{3}{4}$ of what it was before,

$$v h = 0.75 V H.$$

$$\text{But } h = \frac{v^2}{C}, \text{ and } H = \frac{V^2}{C}; \text{ hence } v^3 = 0.75 V^3, v = 0.91 V;$$

in other words, the mean velocity will be diminished, not by 50 per cent., but by 9 per cent. only. The bottom velocity will be diminished, if at all, by a much smaller percentage, since it has been shown that the ratio of bottom to surface velocity increases rapidly as the depth decreases.

The above, which is merely an illustration, will suffice to indicate the course which it seems desirable to adopt in advising on the question, whether a given diminution should be allowed to be made in the tidal area of any particular river. The low-water discharge at some point below the proposed embankment should be carefully measured, and the total discharge of the inland or fresh waters should be measured at their entrances into the tidal area. The difference between the two will show the extent to which the low-water flow is increased by tidal waters.

The effect of the proposed operations may then be judged of, by ascertaining how far they will reduce, not the cubic content of water passing up and down on each tide, but the area of mud, which is submerged by the tide, and thence contributes to the low-water flow. It should be noticed, however, whether this mud lies nearly horizontal, as inside a harbour, or inclined at a considerable angle, as on the banks of a river; since in the former case it will clearly retain the water longer, and therefore be a more effectual feeder, than in the latter.

This process is neither difficult nor costly; and the Author submits that it would at least give a more satisfactory result than the course, at present common, of condemning embankments altogether. It would seem that embankments are only to be feared where the fresh-water flow is exceedingly small, or its current exceedingly sluggish. Many rivers have been embanked, especially in early times, with favourable rather than unfavourable results. That the results should be favourable may at first sight seem impossible, but the Author's experiments suggest a ready explanation. It will be remembered that the bottom velocity of the Avon remained at zero until the surface had sunk by about three-quarters of its total fall. This sinking is of course due to the passing away of the waters sent up by the flood tide. Now if the Avon were embanked, say by building quay walls on each side from low-water mark, the content of these tidal waters would be reduced, but the slope of the surface and the velocity of the ebb would remain as before. Hence the level would fall more rapidly, and the point at which the water at the bottom began to move would be at an earlier period of the ebb. The result of this would be to diminish the time during which sediment was being deposited, and lengthen the time during which it was being scoured away; and therefore it would be favourable, not unfavourable, to the maintenance of the channel.

Among recent instances of such embanking may be mentioned those at Aberdeen, at Lynn, and on the Forth; and among early cases of the kind it is impossible to forget that the three largest rivers of England, the Thames, the Severn, and the Trent, were all embanked in the course of the middle ages, with results the reverse of disastrous. Had the modern school of engineering existed in those times, it is at least probable that all those embankments would have been condemned and forbidden; and in consequence England would have failed to acquire many hundreds of square miles of her most fertile lands.

There is another operation which may be applied to tidal

ivers, besides that of embanking their shores, *i.e.* the process of "dockizing," or excluding the tide altogether by a dam at or near the mouth, so as to turn the river, above this point, into a floating harbour or canal. Any individual case of this kind will have many peculiar circumstances, which must be carefully considered before a decision is arrived at; and no attempt will be made here to discuss the general question. But if there is any truth in the foregoing investigation it at least shows the groundlessness of an objection frequently made to such proposals, namely the fear of some unknown injury to the river thus treated, or to the estuary into which it flows. It appears that wherever silting takes place in a channel it is due to the tidal waters laying down a greater amount of deposit than they can sweep away; and that from this fact all tidal rivers, at least of ordinary size, would gradually silt up, if it were not for the corrective influence of the fresh-water flow. Thus, looked at from the point of view of maintaining the channel, the entrance of tidal water into an ordinary river can be nothing but an evil; whilst any deposit that may result in the estuary outside can be easily removed by judicious scouring at low water, to the effect of which the Author can bear witness from his own experience. It would seem, therefore, that this mode of turning dangerous rivers into canals deserves fuller consideration than of late years it has received. It is well known that Smeaton recommended the "dockizing" of the Clyde; and it has since been remarked, how happy the Corporation of Glasgow may esteem themselves in that they rejected his advice. The Author ventures to think otherwise; and the labour of preparing this Paper will have been sufficiently recompensed if it helps to vindicate the wisdom of the first, and perhaps the greatest, of English marine engineers.

The Paper is accompanied by several diagrams, from which Plate 1 and the woodcuts have been prepared.

Fig. 1.

GRAEVE'S VELOCITY CURVES.

SECTION OF THE RIVER AVON, NETHAM TO AVONMOUTH.