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Changes in the Wash as affected by training walls and reclamation works†

by

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and

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Discussion

Sir Claude Inglis, introducing the Paper, said that everything in it was in agreement with, and followed directly from, the regime concept and its laws. An estuary was said to be in regime when the silt and sand carried into it by its rivers and from the sea during flood tides, was washed out again during ebb tides; so that no overall change took place. This tacitly assumed that the level of the sea relative to the land, and the materials exposed on the bed of the estuary, showed no progressive change—that, in fact, the whole of the material coming down the rivers was washed out to sea. This could not occur in an estuary with a loose boundary of silt and sand unless it had developed a regime shape—that was to say, a shape which tapered gradually from its seaward end—so that the loss of energy, due to friction as the tidal wave progressed upstream, was a minimum for the material in the estuary.

68. Where the sea level was rising relative to the land—as was the case at the mouths of the Thames[8] and the Wash—not merely did the depth increase because of the relative rise of water level, but the velocity/depth relation also increased; so, where the bed of the estuary was mobile, it scoured, increasing the depth still further.

69. In an estuary which differed widely in shape from the tapering regime outline—as in the Wash—little if any of the silt reached the sea, most of it depositing in the shoaler parts of the estuary near the mouths of the rivers and around the margin.

70. In the case of the Wash, however, the marginal accretion could not have been wholly, or even mainly, due to rivers, for two reasons; first, because the volume of accretion in the reclaimed areas shown in Fig. 2a, Plate 1, and Fig. 16, Plate 2, far exceeded the volume of silt carried by the rivers; and secondly, because the greatly accelerated and long-continued accretion which resulted from building training walls and reclamation embankments could only be explained by assuming that, as in the case of the Lune and the Mersey, only part of the silt carried in from the sea by the flood tides was washed out again by the ebb tides, the quantity of silt retained increasing as the rate of accretion increased. This silt from the sea then progressed upstream; because in an estuary which was not in regime the suspended silt tended to concentrate near the bed where the upstream flow during flood tides exceeded the downstream flow during the ebb tides. The rate of this upstream progression of silt was observed to exceed 1 mile/day in the Thames[6] and was much greater in the Mersey.

71. Fig. 28a showed the margin of the Wash and the M.L.W.S. contour in 1917–18, when the last complete Admiralty survey had been carried out. This contour could be considered as the approximate dividing line between the sandy bed and the silty foreshore; and when compared with the margin, it would be seen that there was a marked tendency for the Wash to develop a more natural outline than its present margin. This tendency was still more clearly seen in Fig. 28b, which showed the deep water contours at 30 ft and 60 ft below M.L.W.S.

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† Proc. Instn civ. Engrs, vol. 11, p. 435 (Dec. 1958).

[8] Reference 8 *et seq.* are given on p. 407.

FIG. 28a.—FORESHORE IN THE WASH 1917–18

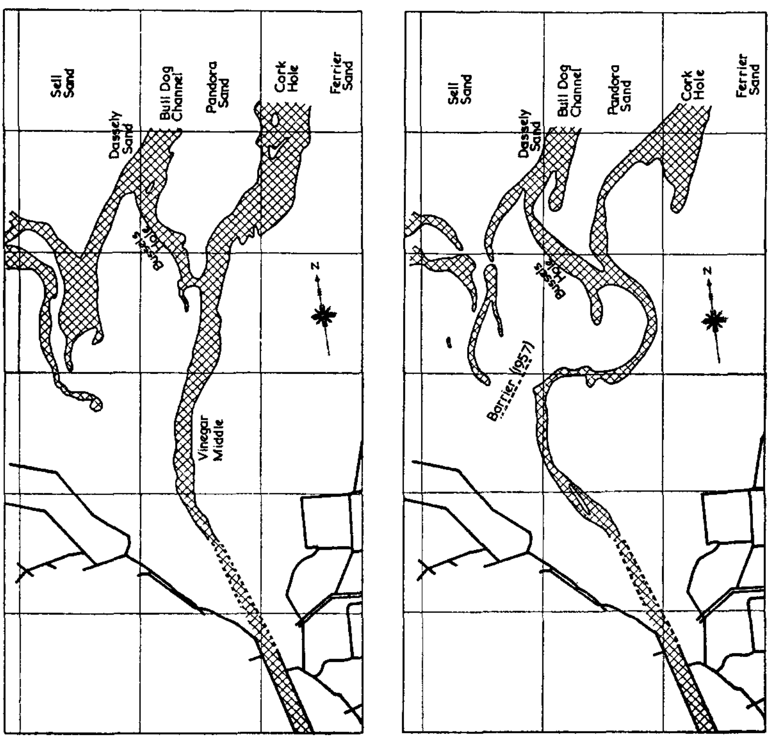
FIG. 28b.—30-FT AND 60-FT CONTOURS BELOW M.L.W.S., 1917–18

FIG. 28c.—SIR CLAUDE INGLIS'S ESTIMATE OF FINAL REGIME CONDITION

72. Fig. 28c showed Sir Claude's forecast of the approximate regime conditions which would eventually develop in the Wash if the present flow conditions were to persist for a very long time, and indicated the approximate curved alignments required in the main estuary and the river approaches to maintain the maximum energy of tidal flow as far upstream as possible, in the interests of both shipping and land drainage.

73. Unfortunately, as could be seen in Fig. 9c, the only river with a direct approach to Lynn Deeps was the Nene. The Witham flowed into Boston Deeps, the Welland through various channels into both Boston and Lynn Deeps, while the Great Ouse passed through several widely scattered channels before reaching various parts of Lynn Deeps.

74. The ever-changing conditions in the various channels during the period 1828 to 1957 were shown in Figs 9 and 27. These indicated that the rates of growth and decline of various channels differed widely, the more natural channels—by which he meant those approximating to final regime—being more stable and persisting longer than the less natural channels. Between 1828 and 1943 the main shipping channel to King's Lynn had been from the north-west. In 1943 the present shipping channel from the north through Cork Hole—shown in Fig. 29a—had been adopted. This had soon begun to erode its banks and meander, as shown on Fig. 29b. By 1956 it had been considered that the shipping channel showed signs of returning to the earlier north-west approach and it had been decided to construct a low level barrier wall across it, on the alignment shown in Fig. 29b. Since the completion of this wall the shipping



(a) 1943 (b) 1955

FIG. 29.—APPROACHES TO KING'S LYNN

channel had been moving towards the barrier wall at about 30 ft/month and was now within about 200 ft of it.

75. There was a wide divergence of opinion as to how the approach channel to King's Lynn would now develop. Clearly the Cork Hole approach had not been a success; and because of the extensive marginal accretion that had occurred during the past 150 years and was still occurring, it could not now provide a satisfactory shipping channel.

76. Sir Claude said in conclusion that, owing to the Wash diverging widely from regime shape, conditions were unstable, some channels waxing while others waned, the more natural channels being more stable and persisting longer. It was consequently not possible to stabilize a permanent approach channel to King's Lynn except at prohibitively high cost. On the other hand, limited training works—for instance, extending the present training walls some hundreds of feet—would, after a short period of local improvement, be followed by greatly increased instability and accretion, and, after some years, the present condition would be approximately reproduced at a corresponding distance to seaward; this would not be in the interests of either shipping or land drainage.

Mr Kestner, continuing the introduction, also emphasized the importance of balance in loose boundary changes in estuaries and described how this balance was maintained by quite different processes for sand and silt. Sand moved upstream and downstream close along the bed; silt was carried in suspension deposited at slack water, accumulated on the bed in layers, and was eroded by varying processes such as scar erosion which kept the accretion processes from continuing indefinitely.

78. Under natural conditions there was a constant movement, backwards and forwards, of the edge of the mud flats as accretion alternated with erosion, but neither obtained the upper hand. Even if the most important of the erosional forces—bank erosion—had been suppressed by stabilizing a low-water channel, and the saltings advanced as a result, the various subsidiary erosional mechanisms which he had described would eventually take over and prevent an unlimited advance of the mud flats into the low-water channel. There was, therefore, a definite limit to the silt banks.

79. The silting process affected only the sides and not the bed of the low-water channel. In the bed, current velocities were always too great during part of the tidal cycle to allow silt to accumulate. The bed of the low-water channel was therefore sand, which moved in ripples closely along the bed, upstream on the flood and down again during the ebb. That was true of each of the outfall channels Witham, Welland, Nene, and Ouse as they discharged into the Wash. Although they had to pass through a wide mud belt and their sides consisted of silt banks, and although the concentration of silt in suspension in the tidal water flowing up and down these channels was very high, their beds consisted of sand. However much the silting process might have reduced the width of such a channel, any changes in its depth (shoaling) could take place only if there was a shift in the relation between flood and ebb-current velocities and therefore a change in the balance of sand transport to and fro.

80. The first effect of training such estuaries would be an advance of the saltings within the trained portion of the estuary and a consequent loss of tidal volume. That was not so disastrous as it sounded, because this loss of cubature would not directly affect the depth of the low-water channel. The silt, as had been shown, could not live in the channel itself. The position in the trained channel was, therefore, that there would be a reduced volume of water flowing up and down through a proportionally reduced cross-section, so that velocities on both the flood and the ebb, and therefore sand transport up and down, would be virtually unchanged and depths would remain unchanged.

81. The danger-spot was the seaward end of the training walls. In the first place, if the training walls ended within the silt area they would not prevent channel meander downstream. Wherever they ended, however, the main difficulty was likely to be shoaling, caused by a net upstream movement of sand just seaward of the training walls;

because, although the volume of water and the cross-section of the channel would have been reduced proportionally in the trained stretch, this would not be so below the works. A greatly reduced volume of water would therefore be flowing to and fro through an initially unchanged cross-section, so that velocities on both the flood and the ebb would be substantially reduced. If flood and ebb velocities were identical this still would not matter, but in fact balance was normally maintained in the sandy loose boundary by a shorter period of rapid velocities on the flood balancing against a longer period of slower velocities on the ebb. If both velocities were proportionally reduced, this had a greater than proportionate effect on the sand-carrying capacity of the slower ebb currents, so that there was a net increase in the upstream movement of sand. To put it more simply, silt reduced tidal volume by reducing widths. Sand could compensate for this only by reducing depths, so that a balance was held between conditions upstream and downstream.

82. Those difficulties did not mean, however, that training walls were never to be recommended, but the important rules to remember were: (i) that they should if at all possible, be carried right through the silt area; and (ii) that they should in any case be carried out to water deep enough to allow for the inevitable sand shoaling seaward of the works.

83. Dealing with the supply of silt, in all the descriptions of the building-up of new saltings he had assumed that supplies of silt carried in suspension were more or less unlimited. In the Lune and Wyre estuaries, where supplies of silt were carried in from Morecambe Bay, that was certainly true for all practical purposes. There were sufficient supplies of silt out in the bay to fill these small estuaries completely, and what was interesting was not where did the silt come from, but that the estuaries were still there in spite of the supply of silt. In the various Wash outfalls the same was probably true, for these estuaries were small in relation to the enormous supplies already in the Wash.

84. When considering the foreshore of the Wash itself, however, and the possible effect of really large-scale reclamation works, the question of whether supplies of silt were merely circulating on the foreshore or were being renewed from the North Sea became more interesting. Since this was a subject on which it was difficult to obtain conclusive evidence, engineers might like to consider it further.

85. Mr Kestner's view was that although some material might be coming in from the North Sea, it could not be coming in at rates sufficient to allow for the large-scale accretion and land reclamation measured over the past hundred or so years. He thought it more likely that any supplies from the North Sea were adding to the total quantity of mud in the Wash at a very much slower rate and that the changes in the Wash over the past 300 years had been brought about mainly by a redistribution of material already present on the foreshore.

86. Evidence as to concentrations of silt in suspension had been that under calm neap-tide conditions the suspended load was everywhere negligible—at the seaward end of the Wash, in the centre, and along the foreshore. Under stormy and spring-tide conditions the concentrations which had been measured to the seaward and in the centre of the Wash were still very low, but under these conditions there was a very considerable suspended load towards the landward margin of the Wash. Erosion from the lower mud flats along the foreshore was the immediate source of these very large supplies. In the Paper the Authors had plotted typical core-sampling results from the lower mud belt, showing the rise and fall of the mud surface. A series of suspended load samples just seaward of the mud belt suggested that this very cohesive mud was mainly picked up at periods of maximum turbulence, shortly before half-ebb of spring tides, and was carried seawards on the falling tide, but did not have time to get as far as the centre of the Wash, much less right out of it, before the tide turned and carried it back to landward, and here it was redeposited at slack water of high tide right over the foreshore and up the estuaries.

87. A very large quantity of material from the lower mud flats was thus put into

circulation at every spring tide and there was a constant pattern of erosion and redeposition. As the Authors had shown, when engineering works interfered with part of this cycle very rapid progressive changes could occur. The foreshore mud flats thus supplied an enormous reserve of circulating material which made rapid changes possible. These large circulating supplies of silt, eroded from the lower foreshore, might mask smaller supplies from the seaward and landward which, over geological time, had built up this reservoir of mud, but the main immediate source of silt was erosion in the lower mud belt along the foreshore; and land reclamation was to some extent merely a process of consolidation.

Mr W. E. Doran (Chief Engineer, Great Ouse River Board) described the Paper as a logical continuation of the previous Paper[1] by the same Authors on "The long-term effects of training walls, reclamation, and dredging on estuaries". The work had been possible only because of the existence of the Hydraulics Research Station. In dealing with such a problem it was essential to cover the whole field of inquiry and this would never have been possible by an investigation made on behalf of some particular interest such as a river board or port authority.

89. The most striking fact which had emerged from the Authors' work was the period of time during which the effect of training walls could make itself felt. For example, the effects of the Witham training walls (§ 29) had not yet worked themselves out, and possibly the effects of walls constructed now would still be felt a hundred years hence. Without the evidence of the Authors' investigation, it was doubtful if those facts would be believed, and it should cause the prospective constructors of training works to think very hard.

90. From Fig. 17, there would seem to have been a sudden change in the rate of accretion at all four sites simultaneously in 1917/18. There was nothing in §§ 34–39 that would explain this, nor was there any reason for it in the form of engineering works. He thought that in fact the curves showed the position at the dates given on the bottom line, and since there had been no information available between the recent investigation and the Admiralty survey of 1917/18, those two points had been joined together. If that were so, the curves did not give a correct picture of the rate of accretion. It was probable that the accretion had begun at different dates on different sites, so that the curves would not have the slopes shown.

91. The training walls at the mouth of the Ouse had been raised and extended in 1935/37, and immediately there had been a very rapid accretion behind the walls, followed by an increase in the saltings. Had not the accretions at sites (d), (c), and (b) been caused by the construction of those walls? If so, the accretion had probably started at some time after 1937 and not in 1917, and the slopes shown in Fig. 17 would be much steeper.

92. It seemed to be clearly established that the construction of training walls would ultimately result in the deterioration of an estuary and, by causing a rise in the low-water level at the outfalls, must in the long term have an adverse effect on land drainage. The evacuation of floods from the River Ouse and the River Nene was dependent upon a critically flat surface gradient. Any alteration of this gradient could have serious effects.

93. Mr Kestner had said that the depth of the channel would remain unchanged after training. Could he say what would be the effect on the bed of the river itself and on the low-water level at some distance from the mouth of the training works? Would the bed of the river rise and the slope required for the evacuation of a given discharge be increased because of the deterioration in the hydraulic mean depth?

Mr H. W. Clark (Engineer, Nene River Board) said that recently, apart from survey work in the Wash, the Nene River Board had prepared a supervised reclamation works for the Crown Estates. He did not agree with the Authors' statement in § 7 that the reclamation of the saltings had added to the drainage problems, because 120 years ago John Rennie had cut a new outfall channel on the River Nene; he had obtained another

10–12 ft of fall and drained about 100,000 acres of land by gravity, at the same time reclaiming 7,500 acres of land. Nothing but good had resulted from that, and the new saltings had not aggravated the drainage problem.

95. The Wash was not in balance and never would be. In the thirteenth century a large part of the Ouse, the whole of the Nene, and a large part of the Welland had discharged through one central channel. The separation of that single channel into three—Nene, Welland, and Ouse—had caused trouble in the outfall ever since. There was not sufficient water in the Nene to maintain its own channel. Reference had been made to work done on the Ouse outfall and works had also been carried out on the Witham, the Welland, and the Nene for land drainage and reclamation purposes within the past 30 years; the Wash had never had an opportunity to get into balance.

96. Fig. 28c showed an outfall with the channels all coming together. It was almost identical with the outfall survey and plan prepared by the Nene River Board some years ago for the ultimate extension of the River Nene. The basis adopted by the Board had been that their river, and in fact all the rivers flowing into the Wash, were trying to get into the deep water in the centre of the Wash. (The oscillations of the Ouse throughout 300 years showed that this was so.) More than 10 years ago they had prepared a plan on this basis, with a channel exactly the same as that shown by Sir Claude Inglis in Fig. 28a.

97. In reference 1 the Authors had referred to the volume of silt in the Wash being gradually used up. The Nene River Board were certain that this silt came from the sea. They had had their tidal river sluices closed for a year, and the river-bed had made-up by 6 ft—and it was seaward silt. Before it was possible to carry out reclamation it was necessary to have about 3½–4 ft of silt covering the sands. That material was then formed into a bank, and the same process continued year after year. He did not know how many thousands of acres had been reclaimed from the Wash, but the silt which formed new land and banks had not been gained from the Nene.

98. The tests made by his Board confirmed the Authors' statement that the silt was carried on the spring tides; very little was carried on the neap tides. In § 40 of reference 1 the Authors had stated that there had been practically none of the progressive silting which had been expected in front of the newly completed embankment at King's Lynn. In fact, there was a great deal of silt off the new bank. It did not start a ½ mile out; it started from the bank and worked seawards. Observations made ½–1 mile out did not count for purposes of assessing the accretion. Mr Clark hoped that some comprehensive authority—presumably the Ministry—would "father" the whole of the Wash, so that instead of the rivers being considered separately, the Wash would be considered as a whole.

Mr Marshall Nixon (Chief Engineer, Trent River Board) pointed out that the Mersey, during the past 20 years, had suffered very considerably; within 6 years of building a barrage the River Eider had deteriorated rapidly; and the Lune had suffered within 5 years of building training works. Compared with these the Wash had remained comparatively stable for a surprisingly long time.

100. In the past 200 years about 75,000 acres of land—20% of the surface area had been reclaimed from the Wash. This reclamation did not appear to be having a disastrous effect; there was accretion of the saltings, but it was comparatively slow.

101. The Authors had said that because of the rise of the sea relative to the land the cubature of the Thames Estuary was increasing; and the Thames Estuary was improving. Why had not the Wash similarly improved? The answer, he thought, must be that there was a considerable supply of material coming from the sea, and that this was roughly in balance with the effect of the increased cubature due to the rise of sea level. The material necessary to retain the rate of progress of the saltings, calculated from §§ 24, 25, and 42 of the Paper, was about 21 million cu. ft/year. The rivers would perhaps not add more than 1 million cu. ft/year, so that there must be about 20 million cu. ft of material coming annually from the sea.

102. Research workers at Nottingham University had found[9] that Gibraltar Point

had been extending considerably over the past few years, while from a comparison of the marine surveys given in the Paper it would appear that the Knock Sand had been getting smaller. It was suggested that Gibraltar Point suffered a cyclic change of size which indicated that it must be fed with sand from the Lincolnshire coast and that it must at times lose sand. This, therefore, was the point of supply of sand. How had this sand got to the bottom of the "Well" as the Wash had formerly been called? Despite the evidence of balance in Figs 7 and 8 was there a general trend of movement from the sea towards the land?

103. If mainly sand originated from the sea and mainly silt from the rivers the deposits would be a mixture of sand and silt. Fig. 3 showed that this was in fact the case. How thoroughly was the sand and silt mixed?

104. In the River Wyre it had been discovered[10] that the silt and sand were stratified. Had any borings been taken in the progressive accretion on the foreshore of the Wash which would indicate whether there was simply a layer of silt on top of sand or the mixing was complete right down to the original bed? For a full understanding of what was going on it was necessary to know where the material was coming from. Did the Authors intend to use radioactive tracers to determine the movements of sand and silt in the Wash itself?

105. Since the works in the Wash had been carried out over such a long period, Mr Nixon doubted if they alone were now having so much effect. Before reclamation, there was presumably a considerable exchange of mobile material between the foreshore and the deeps. This exchange would be governed by the meandering of the river channels, floods, and storms. The meandering of the Ouse channel may still be having some effect.

106. In Fig. 17, curve (*a*) indicated accretion which was obviously due to the training walls of the River Nene, for it had occurred immediately behind the walls where silt might be expected to accumulate; but that should have happened behind the training walls of the Ouse, and curves (*d*) and (*a*) should be much the same. Could not the shapes of curves (*b*), (*c*), and (*d*) be explained by the movement of the Ouse channel beyond the end of the training walls? In 1850, before the curves in Fig. 17 started, the Ouse channel had been in a westerly position, nearer the shore; at the time that the curves started, the channel had been half-way between the westerly and easterly positions and this was associated with accretion; presumably it had moved right across and back to the west again by 1917 when the foreshore was receding. Between 1917 and 1952 the channel had moved to the east and it was during this period that there had been the raising of the foreshore along the whole frontage. With the channel in the west there was recession, and when it was in the east there was accretion. Would the Authors comment on this hypothesis? It would, of course, mean that the movement of the foreshore between the Ouse and the Nene had been independent of the training works.

Commander Robert Dalby, R.N.(Ret.) (Norfolk Estuary Company) contended that accretion took place away from sea walls that were built at right angles to the ebb and flow of the tides and not from training walls, which merely kept a channel in the desired direction and were built in the direction of the tidal flow; it did not matter whether such training walls were at mean tide level or high enough to confine the river. There were both types of wall in the rivers Nene and Great Ouse, where in both cases strip reclamation had had to proceed from the banks which had been built at right angles to the run of the tides. (Fig. 16, Plate 2.) It had taken 100 years to enclose up to the beginning of the half-tide walls.

108. Mr Doran had said that the accretion had been very rapid since the extension (Commander Dalby preferred the word "rebuilding") of the half-tide training walls of the Ouse in 1937. Mr Doran's statement was clearly correct in fact, but Commander Dalby believed that it could not be correct in principle because, as he had said, the half-tide training walls on the east side stood out from the sand and the tide ran along both sides, and he had only recently struck upon the explanation. Not only had the

Norfolk Estuary Company, in 1904, 1910, and 1911, completed embankments that would still be causing accretion away from the banks, but they had reclaimed a large area (about 600 acres) to the south in 1927 and 1928 and another (175 acres) to the north in 1931–32. The effect of these enclosures from 1937 onwards was rapid accretion which was still taking place away from the banks. Since the 1950 enclosures the saltings formed by them had again been increasing very fast and very obviously, in particular at the southern end, and again away from the sea banks and towards the training wall.

109. Commander Dalby referred to the Roman banks and suggested that research could discover when the areas behind these banks had been built. The dates of building of the churches must surely be known and he expected that the Muniment Rooms of the Portland and Bedford Estates, or church documents and local museums could provide further information. Such research might not be worth while but it certainly would be interesting.

110. Land reclamation had proceeded but slowly after 1870, because of the fall in land values. The same factor may account for the extensive reclamation which had been possible (about 6,000 acres) since 1947. He asked if this latter reclamation had nearly used up all the available matter liable to suspension, with the result that reclamation would be much slower over the next 50 years.

111. Bentinck's Bank, the sea wall running from the end of the West Cut of the River Great Ouse for about 2 miles, had been a continual source of trouble and expense to the Company. Fig. 16, Plate 2, showed that there had been no salt marsh in front of it in 1903. Commander Dalby believed that the reed *Esparta townshendii*, introduced in about 1890, was partly responsible for the grassing-up of the marsh in front of this bank and its consequent protection. All the old documents mentioned only samphire or marsh grass.

112. The Authors had claimed that the soil of the reclaimed area was of good quality. Would particle-size and chemical analysis help the inquiry? Commander Dalby believed that however fine were the particles of sand it would not make a first-class soil. If so, the soil clearly came from somewhere else.

113. Three related civil engineering problems were mentioned in § 5—drainage, reclamation, and navigation. Commander Dalby believed that the ideal drain was straight and deepened slowly towards its outfall and thought that the same conditions should apply to a shipping channel. He understood the formation of a bar at the entrance of the trained channel (§ 2) but believed that that would affect both navigation and drainage, since it both limited the draught of shipping and reduced the depth available for drainage.

114. In the Wash it appeared that saltings would form until reaching a state of regime, which had probably never been attained since enclosure was started in the sixteenth and seventeenth centuries. If it ever were to be reached, the drainage and shipping channels would be very difficult to keep open. He concluded therefore, that reclamation helped to keep the channels open by trapping material that would otherwise be likely to form a bar or to be deposited high up the river. However, all good things had to be paid for and there was no reason to suppose that ports can be kept open without expense, or that drainage would not have to be maintained. He felt that the extension of guide banks would eventually solve both difficulties and that they should finally join up into one outfall channel so as to reduce the expense of keeping two channels open. The guide banks could be extended a little at a time giving each extension time to consolidate and open a channel in front of it.

Mr G. A. Wilson (Chief Engineer, Port of London Authority) observed that there were two baffling problems on which hydraulic research was concentrated at present, the first being the movement of material around the coasts of the country and the second the behaviour of tidal estuaries and inlets. Progress was inevitably slow but the work reported on the Wash when coupled with the Wyre, Lune, and Thames represented a break-through on the second front.

116. The subjects were important because of the need to protect the coasts and increase the depth of water leading to ports. There were examples of serious silting, such as the Mersey, where, although the annual dredging was 15,000,000 cu. yd the reduction in volume of the estuary each year was said to be of the order of 5,000,000 cu. yd. On the other hand training and dredging could be successful, as in Bremen and Glasgow, where natural conditions were favourable, and as these conditions in nature became more closely understood, alterations might be introduced, as at Le Havre where efforts were being made to produce the ideal funnel-shaped estuary which Sir Claude had indicated.

117. The Authors' opening remarks on the silt balance in the Wash were an important addition to the record of the investigation.

Mr Archibald Thomson (Chief Engineer, Clyde Navigation), said that there was a very simple explanation of why the dredging of the Clyde had been very successful. All silt in the estuary came down from the river itself and nothing came in from the sea.

Mr R. J. Hindmarsh (Engineer, Humber Conservancy Board) said that the information given in § 4 supported his contention that the Wash was not an estuary, but a very large inlet of the sea. Its area was considerably greater than that of the Humber, but its catchment area, which was situated in a much drier part of the country, was only about one-half that of the Humber. Whereas the Humber estuary was kept in some sort of balance by its fresh-water flow, the Wash was not affected by the rivers that discharged into it, except where they crossed the shoal headwaters.

120. The Wash was so orientated as to form a natural trap for the littoral drift, which was from north to south. The Admiralty Pocket Tide Stream Atlas indicated that the Wash had a profound effect on the North Sea tides, and that over a period of about 3 hours of the flood tide the tidal streams converged into the Wash from north and south.

121. In the middle of June 1953, during the neap tides, he had observed marked discoloration by suspended silt in the vicinity of the Protector Overfalls Buoy. The weather had been calm, and the tide had been ebbing northwards out of the Wash.

122. It was stated in § 1 that if tidal conditions were unfavourable a ship of 18-ft draught might have to anchor for more than a week before it could enter the Wash. He would make the following comments:

(i) No successful shipowner should allow his ship to arrive under such conditions. He would either send a ship of suitable draught, wait for suitable tides, or load his ship down to a suitable draught only.

(ii) The 1938 edition of the "North Sea Pilot" stated that at spring tides vessels drawing 20 ft, and at neaps 14 ft, could enter Boston or King's Lynn. These governing depths were in the immediate approaches to the ports, which might well be capable of improvement.

(iii) No amendments to these draughts had been shown in the 1956 supplements to the "North Sea Pilot", so that a good measure of stability must have been maintained over the past 10 years.

(iv) The depths of the approaches should be improved only if the ports could handle larger ships, and if the value of the additional trade justified the cost.

123. In § 3 the Authors had referred to the "drying out" of the Lune. Surely they had not used this term in a literal sense? They had also stated in the same paragraph that the charge of silt entering the Wash from the sea was very much less than that entering the Lune. Did this imply that there was appreciably less movement of silt in the North Sea than on the west coast? Quoting from the "North Sea Pilot", the flood tide in the main stream of the Wash was a little faster, but the duration of the ebb was a little longer. A balance of movement of silt should therefore be maintained, although a slow accretion at the head of the inlet was possible.

124. Mr Hindmarsh was impressed by the almost uninterrupted build-up of the

inshore end of the Wash. Eventually, engineering works would be necessary to maintain the present depths. This situation might add to the agricultural wealth of the country, but it might also result in the channels becoming too costly to maintain at their present depths. Could the Authors say if there was an appreciable difference between the agricultural values of land which warped up quickly and of that which built up over a long period? Did the Authors think it possible that the changes they described were part of a long-term cycle under whose influence the sea might return to reclaim its own?

Mr F. H. Allen suggested that more attention might usefully be given to the four major rivers which entered the Wash, thinking of them as sources of silt. Frequent measurement of the suspended silt concentrations in several rivers over a period of 2 or 3 years presented considerable practical difficulties, but only thus could a reliable though approximate estimate of the total quantity reaching the Wash be made. However, he had made some rough computations which should serve at least to indicate the order of magnitude of the quantities involved. He had assumed that the combined mean annual flow of the Great Ouse, Nene, Welland, and Witham amounted to 2,000 cusecs; and that the average concentration of suspended solids in these rivers could be taken as 50 p.p.m. by weight. On this basis about 87,750 tons of suspended solids (dry weight) entered the Wash each year. If the foreshores or saltings could be assumed to have a moisture content of 50% (by weight) when they were ripe for reclamation, then the quantity of solids entering from the rivers was equivalent to the formative material of 175,500 tons of reclaimable land per annum. Assuming an in-situ density of 90 lb/cu. ft, this was equivalent to 4,370,000 cu. ft of potentially reclaimable land *each year*, or an area of about 33½ acres with a depth of 3 ft.

126. What were the Authors' views on the extent to which this river-borne material could be regarded as the source-material of the reclamations, now and in the past; and, in the light of these probable quantities, what proportion of the material in the reclaimed areas must be assumed to have entered the Wash through the seaward limit?

The Authors, in joint reply, confirmed Mr Doran's surmise (§ 90) that the curves on Fig. 17 had necessarily been based on the Admiralty Survey of 1917/18. Had more data been available, the curves would have been somewhat modified. The Authors considered, however, that the differences would not have been considerable and that the very rapid increase in the rate of advance of saltings after 1917/18 had not been merely the result of the small extension of the training walls in 1935, but mainly the effect—actually beginning to show in curve (d), nearest the Ouse, before 1917/18—of the successive works, first begun in 1852 with the Marsh Cut of the Ouse, finally reaching this area.

128. The effects of having walls in a silty estuary would be (i) a considerable loss of depth outside the low water channel in the trained portion of the estuary, (ii) a reduction in width of the low water channel itself, and (iii) shoaling, caused by the upstream movement of sand along the bed, seawards of the training walls.

129. The Authors agreed with Mr Clark that new saltings did not necessarily add to drainage problems, at least in cases where a new channel was cut. They only caused difficulty if saltings reduced the volume of an essential drainage outlet.

130. As to the statements made in reference 1 about the saltings in front of the newly completed embankment at Wingland, these had been amplified and modified in §§ 41–47, which described the alternation of accretion and scour on the lower foreshore and the progressive accretion higher up.

131. The Authors were very interested in Mr Clark's remarks about the existence of one central channel in the 13th century and his plans for the ultimate extension of the River Nene.

132. They agreed with Commander Dalby that walls built across the flanks of estuaries near river mouths at right angles to the run of the tides led to accretion; but his contention that training walls did not cause accretion ignored a great mass of

evidence to the contrary and was wholly unacceptable. The Commander had agreed that Mr Doran's statement that accretion had been very rapid since the rebuilding and extension of the training walls of the Ouse was clearly correct in fact; but he believed it could not be correct in principal because "the half-tide training walls on the east side stood out from the sand, and the tides ran along both sides". Similar conditions had developed in the Lune where there were no cross-walls or reclamation embankments to confuse the issue, yet the volume of the estuary had decreased by 47% as a result of building the training walls.

133. With regard to the effect of vegetation, Commander Dalby believed that siltation in front of Bentinck's Bank was partly due to the introduction of rice grass, but the Authors considered the effects must have been very small, because the variety then introduced did not propagate itself from seed. Even in the case of varieties propagated by seed their spread was restricted for two reasons, first, because the accretion led to the establishment of other maritime weeds and to the dying out of Spartina along the portion which had accreted; and secondly, because the accretion led to increased velocities to seaward, and so produced conditions unfavourable to further spread. There was good reason to believe therefore that the expansion of the saltings at that time had been mainly due to the powerful hydraulic effects of the construction of reclamation works and only to a small extent to the spread of Spartina.

134. The Authors agreed with Mr Hindmarsh that the Wash was a large inlet rather than an estuary, and, unlike the Humber, was little affected by the rivers discharging into it. He had expressed the opinion that the Wash was orientated so as to form a natural trap for the littoral drift, which was from north to south; this point had also been raised by Mr Nixon. The Authors recognized the importance of the question of littoral drift in the Wash, but in this Paper, which was mainly concerned with the landward changes, they had not dealt with it.

135. In reply to Mr Hindmarsh's statement in § 122, the ship of 18-ft draught had been observed during the course of the investigation to be held up for more than a week during neap tides. The pilot had not been prepared to take it in sooner, because difficulties caused by lack of depth were added to by the very sharp bends in the meandering channel.

136. As to the relative movements of silt on the West Coast and in the North Sea, there was a much heavier suspended load in the Severn, the Mersey, and the Morecambe Bay estuaries than there was in the Wash. That was associated with tidal range—the greater the range the greater the suspended load. There were, however, additional factors relating to the ease in dispersal of local supplies and these presumably affected estuaries like the Humber which had also a very high suspended load.

137. In reply to Mr F. H. Allen, although 50 parts per million was a low concentration, the actual concentration of silt in suspension carried by the Wash rivers was probably very much lower. In a letter to the Hydraulics Research Station, dated 14th August, 1957, Mr W. E. Doran, Chief Engineer to the Great Ouse River Board, had confirmed that although he had no measurements for this, the concentration of silt in suspension in the Great Ouse, even during flood times, was extremely small. In the case of the Bedford branch of the Ouse, the main flood flow was taken on the Hundred Foot Washes, which had an area of 5,000 acres and acted as a settling basin. These Washes had been in operation for 300 years and the amount of silt deposited on them was very small indeed. An estimate of 5 p.p.m. would probably be on the generous side and this, on the basis of Mr Allen's calculations, would allow only sufficient material for about 3 acres of reclaimable saltings a year.

Mr Kestner referred separately to the source of supply of silt for accretion. He felt that the picture of the transport of suspended silt in the Wash which seemed to have emerged from the discussion was of a constant tide-to-tide movement of material from the sea to the shore and back again to the sea. A consideration of the mechanisms of silt deposition and erosion described in the Paper would show that this was an over-simplified picture. The material which was deposited in any one tide in a thin layer over the foreshore was not, in the main, the same material which was eroded at a later stage of the same tide. Owing to the cohesive nature of this silty mud, once it was deposited on the foreshore or in the estuaries it would remain there until it was attacked by side erosion of a periodically fluctuating channel, or a runnel, or by scar erosion. The interval between deposition and erosion might vary from a few weeks on the lower foreshore to several years in the estuaries. This foreshore, therefore, could act as a store.

139. Owing too, to the cohesive nature of the mud flats, erosion only became effective at a fairly late stage of the falling tide. This meant that it was difficult for material eroded from the mud flats to escape from the Wash. The tide turned when the silt had been carried only a few miles to seaward and this material was washed back and re-deposited along the foreshore. This constant re-working of material masked the much smaller supplies coming in from the sea.

140. The effect of an engineering work on the foreshore was to suppress erosion in a limited local area in its vicinity. In such an area progressive accretion would continue until salt-marsh level was reached. This would reduce supplies of re-worked silt available for accretion elsewhere on the foreshore, but would not affect erosion in other stretches, so that there would be some balancing progressive erosion elsewhere on the foreshore.

141. Supplies of silt which were coming in directly from the sea could not be substantially increased as the result of the suppression of erosion in a limited stretch of the foreshore. Suspended load over the Wash as a whole was about one-tenth of that measured near the mud flats. At the most, therefore, about one-tenth of the material to build up new saltings rapidly as a result of an engineering work might be assumed to be material retained from the sea and the remainder was material re-worked from the foreshore. The engineering works could not affect the remote seaward source of supply, neither could they affect erosion over most of the foreshore, so that they could neither directly increase suspended load from the seaward nor could they cause the retention of any greater proportion of deposits from the sea except in a very local area.

142. In the absence of any man-made interference it was, of course, the small and steady seaward and landward supplies of new material which caused a gradual steady advance of the saltings and probably over a very long period of time, measured in thousands of years, built the Wash towards the ideal shape as Sir Claude had described. In the short period, however, it was the sudden re-distribution of local supplies of material constantly being re-worked on the foreshore and in the estuaries which produced rapid and dramatic changes.

Sir Claude Inglis also referred to this problem. He had been endeavouring for many months, without success, to persuade Mr Kestner to modify his ideas on the source of silt supplies for accretion along the margin of the Wash. He had regretfully to dissociate himself completely from Mr Kestner's views; but he felt he must do so, bearing in mind that clear thinking on this subject was of such great importance at the present time, when the best policy to adopt in controlling estuaries was being worked out.

144. Mr Kestner's ideas on this question could be epitomized by quoting from §§ 85 and 87. From § 85: "Mr Kestner's view was that although some material might be coming in from the North Sea, it would not be coming in at rates sufficient to allow for the large-scale accretion and land reclamation measured over the past hundred or so years. . . . and that the changes in the Wash over the past 300 years had been brought about mainly by a redistribution of material already present on the foreshore." From § 87: "These large circulating supplies of silt, eroded from the lower foreshore, might mask smaller supplies from seaward and landward which, over geological time, had built up this reservoir of mud . . .".

145. Mr Kestner had not produced any data to justify these views; he had, indeed, ignored the data produced in the Paper, part of which was illustrated in Figs 28a and 28b. That data showed alternating accretion and scour; but no progressive change of

the lower foreshore. There was also no considerable recession of the saltings anywhere along the margin to compensate for the enormous overall extension of the saltings, followed by reclamation, which had been rendered possible by the deposition of about 150,000 acre-ft or 6,500 million cu.-ft of silt since 1645.

146. With regard to Mr Kestner's "reservoir of mud built up over geological time". Where was it? During neap tides the quantity of silt in suspension was, Sir Claude agreed, exceedingly small; so the reservoir of mud was limited to the quantity scoured into suspension from the lower foreshore during spring tides—something less than 3 in. on the average—plus, possibly, some silt that may have deposited on the flats during neaps, though Mr Kestner had not produced any evidence to show that this occurred. Unless, however, there was progressive deepening on the foreshore and the flats—whereas the Ordnance Surveys show that accretion has been taking place above M.L.W.S.—"the redistribution of material already on the foreshore" could not provide a continuing large source of supply. There were, in fact, only two such sources, the rivers and the sea.

147. Accepting the assumptions made by Mr F. H. Allen in § 124; but altering his figure of 50 p.p.m. to 5 p.p.m. (see § 125) the silt carried into the Wash by its rivers would suffice to reclaim 3 acres/year, or less than 2% of the average area reclaimed annually, leaving more than 98% to be reclaimed by silt from the sea.

148. On the assumption that the silt concentration measured at Station A in the middle of the Wash was a fair value for the whole flow—though heavier concentration might be expected inshore where there is littoral drift—and basing the figures for average charges and discharges on data collected in other estuaries, an average charge of 10 p.p.m. on the average discharge of 3,000,000 cusecs was adopted, compared with 120 p.p.m. maximum at spring tides, when the discharge was also a near maximum of 12 million cusecs.

149. Based on these assumptions, the relation between river silt and sea silt entering the Wash in a year, would be 5 p.p.m. × 2,000 cusecs from the rivers compared with 10 p.p.m. × 3,000,000 cusecs from the sea or 3,000 times as much entering from the sea as from the rivers; so that less than 2% of the silt entering from the sea had to be retained to provide the silt required for accretion along the margin. What was surprising, therefore, was not the large quantity of silt retained, but that it was so small. That was important, because it suggested that the rate of accretion and reclamation could be considerably increased—if considered desirable—by constructing suitably designed and positioned structures.

150. Many of those who joined in the discussion provided evidence which in Sir Claude's opinion established, beyond doubt, that the North Sea was the main source of supply of fine silt for land reclamation. Mr Hindmarsh's contribution was notable in this respect, because he had emphasized that the Wash was so oriented as to form a natural trap for the littoral drift, which was from north to south, and that during a period of about 3 hours of the flood tide, the tidal streams converged into the Wash from north and south. He had also referred (§ 121) to having observed in mid-June 1954, in calm weather, during neap tides, marked discoloration by suspended silt as the tide ebbed from the Wash; that was to say, under conditions when silt in suspension would be minimum.

151. Mr Wilson had observed that there were two baffling problems on which hydraulic research was concentrated at present—namely the movement of material around the coast and the behaviour of estuaries and inlets. The work reported on the Wash, Wyre, Lune, and Thames represented a break-through on the second front. Sir Claude was of the opinion that the work on the Wash, when correctly interpreted, went far to link up what was happening on the coast with conditions in the estuaries. Although heavy erosion had been in progress along the east coast, very little material finer than 0·16 mm had remained on the coast, and it had generally been assumed that most of the silt was washed out to sea. There was little doubt, however, that much of the material eroded on the east coast found its way into the Wash. There was also no doubt that when the amount of accretion increased in the Wash, less silt was carried

seawards, the deficiency thus caused being made good, as explained in § 70, because in estuaries which were not in regime, silt concentrated near the bed, was carried further upstream by the flood tide than it was carried downstream by the ebb, so that the silt moved progressively upstream. There was no question, however, of increased accretion on the foreshore causing any increase of supplies of silt coming directly from the sea; actually there would be a small decrease, owing to the silt carried out during ebb tides decreasing; but the reduction would be small, owing to the large supplies of silt available from the North Sea.

References

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