

The sea approaches to the Port of Liverpool

M. AGAR & D. M. McDOWELL

Mr Agar

The Paper brings up to date the very comprehensive paper by Cashin¹ in 1949.

32. Much of the cost of maintaining the approaches depends on the effectiveness of the chosen dumping site, i.e. effectiveness in terms of the proportion of material that is not returned to the system. It is now established that if the site is moved a few miles further westward much that at present finds its way back into the Mersey will no longer do so.

33. It is easy to find such sites, but to find one which is economical in terms of ton miles hauled is more difficult.

34. The Board, now The Mersey Docks and Harbour Company, has recently announced the closure of the south part of the Liverpool dock system. The possibilities of filling in these docks from dredgings are being examined.

35. There has been no expenditure on training banks since 1965. Formerly these were maintained, but where limited settlement has occurred it is now thought cheaper to allow the material to spill over, and dredge rather than carry out the expensive remedial work necessary.

36. Parts of the *Seaville* wreck have now been removed, enabling the channel to be widened to about 450 m at its narrowest point.

37. The recent increase in depth to 8.5 m below Liverpool Bay Datum enables 200 000-t tankers, part-laden, to enter the Mersey, and the Port can cater for all the in-docks trade that offers, including bulk cargo ships of up to 75 000 t.

Mr D. Perfrement, British Transport Docks Board

I should like to refer to Fig. 3 which shows the annual quantities of dredging from the Mersey. The variation year by year of the total quantities dredged is shown by the full black line and the dotted black line is an envelope of rounded-off figures.

39. When one is looking at physical phenomena it is interesting to try to ascertain what particular patterns can be derived from them. Ignoring the peaks and troughs due to special dredging, there is a cyclical variation of quantities which appears at a roughly 12½ year frequency with peaks starting in 1897. One can also see a possible 50 year cycle.

40. There has long been the contention of the Mersey that the physical states of the two ebb channels at Eastham and Garston are complementary, i.e. when the condition of one is good, the other is not so good.

41. The variation of dredging in, for example, the Garston Channel has been reviewed and this has tended to follow a roughly cyclical pattern similar to, but not in time phase with, the Mersey dredging shown in Fig. 3, but with the same average period of each cycle of about 12 years.

42. Consideration could also be given to possible natural phenomena which influence the tidal or other physical factors, and since sun-spot activity is generally a cyclical activity of some 17 years, curves relating to this have been plotted. The Mersey dredging appears to be in an inverse ratio to the sun-spot activity prior to World War II and directly in line with it after the war.

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43. The wartime period was when the dredging of the Mersey was kept to an absolute minimum, and the river condition was as near to its natural state at that time as was possible.

44. One wonders whether the normal progression of the cyclical change in the Lower Mersey may have been interrupted by that lack of dredging during the War. Once full-scale dredging restarted, the normal phase and frequency of dredging continued. I should be very interested to hear what the Authors consider of such a phenomena and what effect this would have on the whole of the Mersey, particularly on the dredging aspect.

Mr J. B. Pot, Intercontinental Dredging Co. Ltd

In § 4 the Authors say that in intensive dredging of the bar the techniques used were the best available at the time. I am surprised to read this because although the *Leviathan* itself was a remarkable craft the 'spot dredging' (digging of isolated holes) to which its operation was restricted was inefficient and not economic.

46. Why was trailer-suction dredging not undertaken instead? Since approximately 1870 the USA Corps of Engineers had been carrying out the deepening of various Atlantic coast harbour approaches by means of a series of about 30 trailing suction dredgers with every success. In Scotland and Germany the Fruehling type trailer has been developed and used in Africa and the Far East.

47. With reference to Fig. 5 could the Authors please give the following clarifications:

(a) is depreciation included in the cost figures?

(b) is the dredging expenditure of the Manchester Ship Canal Company included in the total cost figures?

48. With reference to future developments, the need to provide discharge facilities for ever larger tankers will rapidly increase. Lloyds List for 18 October, 1971, states:

'Between 1975 and 1980 the new building demand for VLCC (very large crude carriers) will be between 79.6 and 82.6 million tons dead weight, an annual output of 16 million tons.'

and in the same publication on the same date Prof. F. S. McFadzean, Chairman of Shell International, says:

'The world demand for oil this decade will be as great as the total consumption in the 100 years to 1970 and will double in the following decade'

and:

'By 1975 it is probable Japanese yards will have the capacity to build at least seventy 250 000 tonners a year, or one every five days!'

Mr A. H. Becket, Sir Bruce White Wolfe Barry & Partners

I wonder whether the Authors' reasoning on the cause of siltation may not be open to question, for it seems that they believe that a large tidal compartment is an advantage rather than a disadvantage from the point of view of maintenance dredging. From the diagrams it is plain that the tidal compartment of the Port of Liverpool is considerable. This remarkable attitude of mind is made clear from § 14 in which it is stated '... while reclamation along the shores of the inner Mersey would reduce tidal capacity to the detriment of stable depths in the Narrows.'

50. Surely it is understood that the large tidal compartment is responsible for the high velocities which are experienced on flood and ebb tides which, because of their strength, carry large quantities of material to and fro. There are unlimited quantities of material in the estuary capable of being brought into suspension by these velocities, and, due to the large tidal range, tidal energy is such that nature finds no difficulty in reducing the work of the largest dredgers.

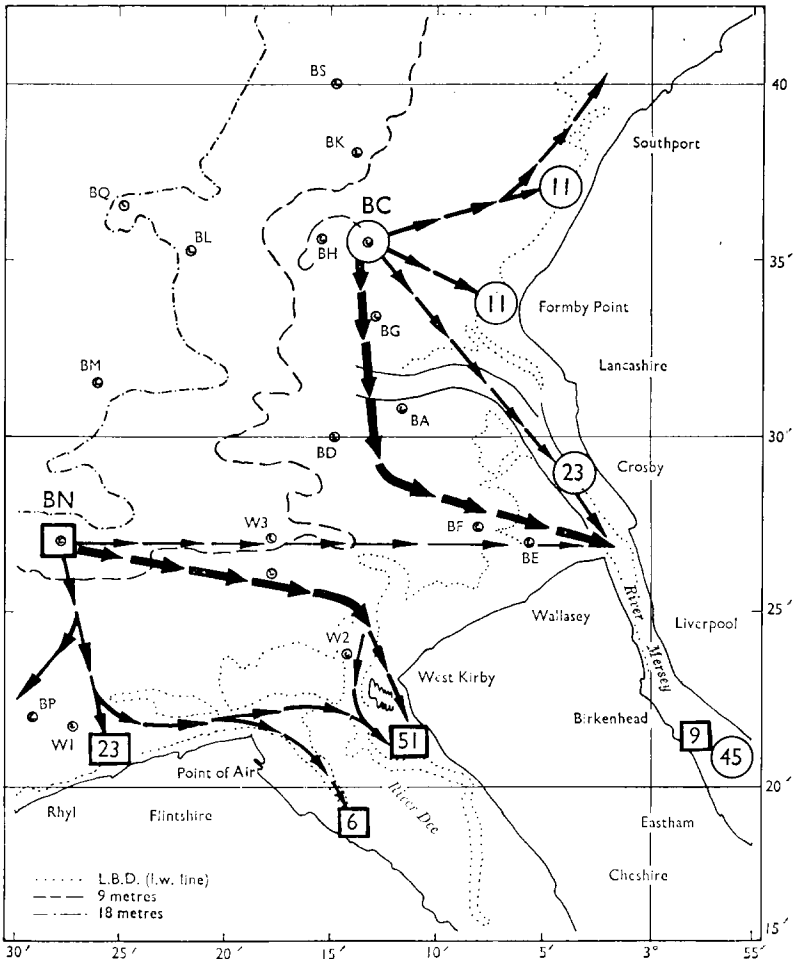


Fig. 9

51. If by man-made or natural causes the large tidal compartment landward of the Narrows were to be filled in, these velocities would be reduced, with the result that much less material would be carried to and fro by tidal action. The forces would be reduced and the existing plant would be able to sustain a deeper and wider channel through the estuary. The fear that the Narrows would be silted up is, I am sure, quite unfounded but even if it were there would be little disadvantage in some loss of depth as the Narrows is 30 ft deeper than the approaches through the estuary.

52. Many years ago Sir John Wolfe Barry recommended to the Mersey Docks and Harbour Board a reduction of the tidal compartment coupled with the introduction of training banks to produce a better access channel through the estuary. His recommendations were rejected in favour of intensifying the battle against nature. The *Leviathan*, in her time the largest suction dredger in the world, was purchased

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and put to work in the approaches. However, she was unable to cope, as the Paper records, and in due course training banks were built.

53. I wonder how much longer the battle against siltation must be waged before the other half of Sir John Wolfe Barry's proposal is brought into effect, namely, the reduction of the tidal compartment. It seems from the records given in the Paper that this may even happen without man's assistance, and if so, might it not represent one of the most inexpensive of today's port improvements?

Mr A. R. Halliwell, Liverpool University, Civil Engineering Dept

The movement of water and sediment in the Mersey Estuary and Liverpool Bay has been of particular interest to the Department of Civil Engineering at Liverpool University for a number of years. The studies carried out by the University on behalf of the Board, referred to in § 7, have required a considerable number of field measurements to be made and I would like to use some of the results of the research work to enlarge three points in the Paper.

55. The first point concerns § 9 which refers to 60% of the material being removed from the present dumping site by wave action and tidal flow, most of which is returned to the circulation system in Liverpool Bay and eventually re-dredged. I should like to amplify this by referring to a particular investigation carried out by the Liverpool University on behalf of the Mersey Docks and Harbour Board. The figure of 60% has been based on a number of pieces of work including many field observations of currents, suspended solids, etc, taken in the estuary and bay. One very important investigation which has been used is a sea-bed drifter study, and although the results must be carefully interpreted in the light of the other investigations, they nevertheless illustrate the situation very simply and well.

56. The sea bed drifter study was started in September 1969 on behalf of the Mersey Docks and Harbour Board and the Dee Estuary Scheme Technical Working Party.⁹ A total of more than 5000 drifters was released at various stations in the Bay over a period of some twelve months. Fig. 9 shows the considerable number of stations at which drifters were released. Drifters have been released at most of the stations at approximately monthly intervals in such a way that any spring/neap tide variations and weather or seasonal effects may be noticed. The number of drifters

Table 2. Number of drifters returned from different areas (as a percentage of the total returned by mid-September 1970 from those dropped between September 1969 and April 1970)

Area from which drifters were returned	Position at which drifters were dropped		
	BC	BH	BG
River Dee (East side), %	0.6	1.3	—
North Wirral shore, %	2.7	3.3	2.4
River Mersey (upstream of Rock Light), %	45.9	44.1	51.2
Crosby Foreshore (Seaforth to River Alt), %	22.3	22.4	25.6
Formby Foreshore (River Alt to Freshfield), %	12.0	11.8	14.4
Southport Foreshore (Freshfield to Southport), %	12.0	10.5	3.2
North of Southport, %	4.5	5.9	3.2
Other areas, %	—	0.7	—
Total number returned	292	152	125
Total number dropped	400	200	160
Percentage returned	73	76	78

returned from all the stations is about 75% of the total released, and there can be no doubt that there is a strong landward movement throughout the whole of the Bay. Fig. 9 shows a station BC at the position of the present dumping site Z, and two other stations, BH and BG, which are close to the deposit site. Table 2 shows the percentage of drifters returned from different areas for those drifters released at the three stations BC, BH and BG, and it is clear that the results from each station are very similar, showing that there is a consistent pattern of behaviour over quite a wide area. Although some drifters have travelled north of Formby, most have been picked up within the River Mersey or along the Crosby foreshore, and it is clear that the great majority remain trapped within the Mersey circulation system.

57. Mention is made in § 11 of the reduction in the quantity of material dredged that occurred when trailing suction hopper dredgers were introduced, and some comments are made concerning the differences between sand and silt dredgings. It is important to stress differences between the behaviour of the sand and silt and in particular, differences in the associated circulation patterns. Sand moves into the estuary with the predominantly landward flow of water near the bed.⁴ It may settle in the approach channels, at or near dock entrances, and if it reaches the upper estuary it remains there unless removed by dredging. Silt moves into the estuary in a similar manner to the sand, except that its flood and ebb excursions are much greater. However, when it reaches the upper estuary it can continue to have large excursionary movements. Most of the mud and silt in movement in the Narrows area centres upon the upper estuary in the area between Garston and Eastham. This silt is brought into suspension by the ebb currents and is spread out along the Narrows. It settles on the bed near the end of the ebb tide but the flood velocities are so great that the material is soon brought back with the flood tide. Some of this tongue of silt oscillating back and forth in the Narrows settles in areas where the velocities are not sufficiently strong to re-suspend it, e.g. dock entrances, while some is carried into the docks with water impounded by pumping or locking and levelling operations. Other things being equal, any reduction in the amount of silt dredged is therefore dependent upon a reduction in the total amount of silt in suspension along the estuary.

58. Lastly, § 14 considers the question of alternative dumping sites. The sea bed drifter study has shown that during most of the year there is a 'boundary' between the near-bed waters entering the Dee estuary and those entering the Mersey estuary.⁹ Station BC is in the Mersey system whereas BN for example is in the Dee system. These two stations are compared in Fig. 9, which shows the percentage of drifters returned from the various areas along the coastline for the two stations. It is clear that BN feeds the Dee estuary whereas BC feeds the Mersey system. Therefore sites do exist in the bay for spoil dumping from which material will not in general return directly to the Mersey; however, the overall economics of any new scheme need to be considered before any changes can be made.

Mr W. H. Jackson, British Transport Docks Board

I find this Paper interesting for two reasons. First, the Docks Board have a port in the Mersey, namely Garston, and we have our dredging problems here. Secondly, I read it to see what general lessons could be applied to other estuaries.

60. Referring to Table 1, the ratio of the silt sized fraction to the sand fraction stays fairly constant and, through the period when data are available, there is slightly more silt than sand in the deposit material. Considering the large amount of dredging and deterioration of the estuary, where is this material coming from? The Docks Board is carrying out an intensive field study in the Humber Estuary and the source of such material is of great importance in order to predict whether any improvement would result if the dredged material were taken completely clear of the estuary. There is no point in going to the expense of doing so if there is a large supply of similar material ready to replace any that has been removed. In the case of the Humber it is still a controversial point whether such removal of material would be advantageous or

not. The opposite extreme to removing the material is to agitate it and let the bed currents carry the material away.

61. With the changeover to suction dredging I would assume that quite a lot of material is removed by disturbance as well as by hopper and from the information in this Paper there is no indication that this has led to any increase in the rate of maintenance dredging required. I think the contrary appears to be the case.

Mr J. D. Mettam, Bertlin and Partners

I was horrified to see that over nearly 60 years on average 10% of the revenue of the port has been spent on maintaining channels and dredging. Possibly the revenue has been lower than it should have been. I think there is some evidence of that recently, but even if that has been corrected, it still seems a very high price to pay for access to the port. Mr Agar has said that these are only the operating costs, and there are interest and depreciation costs to be added.

63. Could the Authors to complete the picture give us the total dredging costs for some of these years. It is not easy to guess because some dredging is being done by contract, but there must be some for which capital charges ought to be added. Complete figures would add to the value of the Paper.

64. The Authors also expressed a doubt as to whether any further deepening of the port for very much larger ships should be considered or would be economic. I think one can share any reservations they may have on that. There must surely be better places to accommodate 200 000 ton ships than the Mersey; perhaps single point moorings out at sea.

65. I gather that no special charge is made for those deep ships for which the dredging is really done. If charges were adjusted so that the relatively few ships which really required this very expensive dredging paid for it, would they come to the port at all? Perhaps economic forces should be allowed to operate, in which case the Port of Liverpool might perhaps not handle ships of as large a size as it is now trying to handle. I wonder whether the Mersey Docks and Harbour Board has examined this approach.

66. Reclamation is mentioned and dismissed as being not economic at this stage. I wonder whether enough thought has been given to this. I am very dubious of Mr Becket's suggestion that reclamation should be up in the estuary. I should have thought that there are places, particularly along the east side of Crosby channel, where reclamation, if it could be permitted, would be beneficial in the training of the channel. Could the sand from dredging not be used to build banks which could have bituminous protection, rather than rock banks?

Mr T. D. Ruxton, Binnie & Partners

My organization is concerned with the Dee Estuary, and Mr Halliwell undertook a drifter study in Liverpool Bay on our behalf as well as on behalf of the Mersey Docks and Harbour Board.

68. One of the things that this drifter study showed was that drifters dropped immediately before a westerly storm moved eastwards towards the Mersey estuary rather than further south-eastwards towards the Wirral. They also reached the shore very much more quickly than those dropped under normal conditions. This could mean that the suggestion made for a more westerly choice of dumping ground will only be effective so long as there are no severe storms with a strong westerly influence in Liverpool Bay.

Dr S. K. Bhattacharya, Calcutta Port Commissioners

The Authors have provided useful information on developing the sea approaches to the Port of Liverpool and the financial implications of deepening the channel to provide access to 200 000 dwt vessels. Comments will be restricted to a comparison

of the cost of dredging in the Calcutta Port Commissioners and the economics of dredging.

70. The Commissioners for the Port of Calcutta have undertaken intensive estuarine dredging to develop the approach channel to the subsidiary dock system at Haldia, located 103 km downstream of Calcutta on the River Hooghly.

71. The selection of the alignment of the 106 km long channel is based on extensive hydraulic measurements and studies on tidal flow and sediment balance. I am happy to recollect that these studies were started, in a planned manner, in about 1962-1964 when Professor McDowell, as the Chief Hydraulic Engineer, set up the Hydraulic Study Department at Calcutta and laid the foundation for scientific study of the Hooghly and the estuary.

72. The route to Haldia from the deep waters of the Bay of Bengal traverses a shallow bar where the depth at low water is about 21 ft. It is proposed to deepen it to 28 ft below datum to provide passage with tides for bulk carriers of 70 000-80 000 dwt, in the first instance. The dredging programme in some of the places is being carried out simultaneously with the execution of engineering works, mainly designed to hold the banks. The dredging work is being carried out by a trailing suction dredger, 5000 ton hopper capacity. The annual output depends on the distance of the dumping ground from the dredged site. The average distance of dumping for the dredger *Mohana* is about 25 km. The dredging cost, including depreciation and debt charges, comes to about 2 p/t. The fuel cost is a significant parameter of the total cost and relative comparison between the cost in the UK and India cannot be meaningful unless suitable adjustments are made. The higher wage in the UK is compensated to a great extent by the higher manning scale for dredgers prevalent in Calcutta.

73. Fig. 8 shows that since the introduction of trailing suction dredgers from 1961, the cost of dredging the approaches has fallen in terms of the Port's revenue during the following years. A figure indicating progressive improvement of depth with dredging cumulated would be helpful. It is, however, seen that the channel improved from 7.3 m to 8.5 m during this period. Fig. 7 further shows that except for a rise in the dredging quantum during 1966 due to capital dredging, monthly dredging has more or less remained stationary at less than 1.5 million ton. It seems from this that maintenance dredging did not show any significant rise after the capital dredging in 1966, In this context, the Authors' conclusion in § 28, viz., 'depths greater than the ruling depths at present would involve increased maintenance costs', is not clear.

74. The Authors have indicated in a general way that further deepening should not be undertaken without the certainty of additional revenue. It is assumed that 'additional revenue' means 'port revenue'. It is in this context that I wish to point out that there has been wide acceptance in recent years that the cost of channel improvement cannot be related wholly to the port revenue. The port is a parameter in the transportation system of the commodity and the port revenue is one of the cost components which can be adjusted with other cost components within the ceiling of the total cost. Use of large vessels lowers transportation cost. The ability of the traffic to bear the cost of the channel improvement may be set as a cost function, defined by:

$$\sum_{i=0}^{t=N} C_i = \sum_{i=0}^{t=M} \frac{I_i}{(1+r)^i} + \sum_{i=1}^{t=N} \frac{A_i}{(1+r)^i} + \sum_{i=1}^{t=T} \frac{S_i}{(1+r)^i} + \sum_{i=1}^{t=N} \frac{P_i}{(1+r)^i} \dots \quad (1)$$

where C : total cost discounted at $r\%$

I : cost of capital dredging

A : annual operating and maintenance costs of equipment

S : investment on shipping

P : port revenue or charges for the trade.

Subscript i indicates i th year. The summation of different components over specified time periods are shown by N , M and T .

75. The cost needs to be balanced with the total benefits. This can be set up by considering an effectiveness measurement function (EMF) for the benefits as follows:

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Let C_{1t} = cargo of a specific commodity carried in million tons/ship per year corresponding to a channel depth D_{1t} in t th year.

C_{2t} = cargo of the same commodity as above, carried in million ton/ship per year corresponding to a channel depth D_{2t} in the t th year, i.e., the same year as D_{1t} .

Condition

$$\begin{aligned} C_{2t} &> C_{1t} \\ D_{2t} &> D_{1t} \end{aligned} \quad \dots \dots \dots (2)$$

F = unit freight rate of the commodity corresponding to D_{1t} with the return trip in ballast.

M = cargo in million ton/year.

Saving in the number of vessels due to D_{2t}

$$= M \left(\frac{1}{C_{1t}} - \frac{1}{C_{2t}} \right) \quad \dots \dots \dots (3)$$

Excess carrying capacity due to D_{2t}

$$\begin{aligned} &= C_{1t} M \left(\frac{1}{C_{1t}} - \frac{1}{C_{2t}} \right) \\ &= \frac{M(C_{2t} - C_{1t})}{C_{2t}} \quad \dots \dots \dots (4) \end{aligned}$$

Therefore

$$B_t = \frac{FM(C_{2t} - C_{1t})}{C_{2t}} \quad \dots \dots \dots (5)$$

where B_t = benefits in t th year.

76. Cumulating over a period of N years, at a discount rate of $r\%$, the EMF function is obtained as

$$\sum_1^N B_t = FM \sum_1^N \frac{C_{2t} - C_{1t}}{C_{2t}(1+r)^t} \quad \dots \dots \dots (6)$$

Evaluation of the functions in equations (1) and (6) will indicate whether the harbour deepening is economically viable.

Mr W. A. Price, Hydraulics Research Station

In the field of estuary hydraulics much can be learned from studying what has happened in the past. The Mersey and Liverpool Bay are particularly good areas for historical analysis because they have been the areas where major civil engineering works have dramatically altered the system and the changes have been well documented.

78. The Mersey demonstrates the importance of scientific method (a point stressed by the Authors); it started on a large scale in 1927 with the Bailey report¹⁰ which investigated the effects of the discharge of crude sewage into the River Mersey and concluded that the capacity of the estuary was being reduced as a result of the deposition of organic impurities. Next came the investigation by the Water Pollution Research Laboratory. They re-examined the problem and reached an opposite conclusion. The scientific content of both documents was very high and the Water Pollution Research Laboratory Paper No. 7¹¹ is an excellent account of their work. Then in 1956 the Mersey Docks and Harbour Board initiated the investigation that the Hydraulics Research Station carried out⁴ and were again far-sighted enough to continue with their efforts towards a greater understanding of the estuary and Bay—evidence of this is the excellent work done by Halliwell and O'Connor.⁶ None of these investigations could have gone so far without the excellent hydrographic surveys and other related data collected by the Mersey Docks and Harbour Board, the Manchester Ship Canal Company and the Upper Mersey Navigation Commission.

79. The Mersey is one of the best documented estuaries in the world. It is a good example of the importance of this type of work. More attention must be paid in Britain to better documentation, the vital need to collect basic field data (observations of waves, tidal currents, material in suspension, on the bed, etc.), and to scientific method. The troubles that the Mersey Docks and Harbour Board has gone through in 1970 and 1971 are well known. Large economies will be looked for. I hope that these will not affect the scale of scientific effort invested in this area. If they do, then in the long term the developments that might take place in the future will surely suffer. Hydrological research will suffer because of the information coming from the Mersey is needed to understand other estuary systems.

80. Turning to the question of dredging, much again, can be learned from the Mersey. Like many other estuaries it has suffered from overdredging in the past; the trouble with dredging is that the coarser material removed by the dredger is replaced by finer material and this can have serious consequences. I believe this is one of the reasons the capacity of the Upper Estuary has deteriorated in the last 70 years. The question is discussed in some detail in Price and Kendrick²² where shear force and current velocity are considered as possible explanations.

81. Dredging is a subject that could do with more scientific effort but I would suggest the following rules for dredging at present:

- (a) remove the minimum quantity of material commensurate with the depths required;
- (b) on capital dredging projects spread the dredging over as long a time as possible;
- (c) pay particular attention to the type of dredger used: when dredging channels 'hoover' the material up from the bed and deepen the channel slowly.

In other words, treat the system as gently as possible.

Mr Agar and Professor McDowell

Three speakers raised questions that can be answered only by reference to the behaviour of estuarial systems in general. Flowing water has considerable inertia, and its direction on leaving a curved channel is determined by the alignment of the outer boundary. In tortuous channels, currents due to flood and ebb tide are often guided into different paths. If the currents are strong enough to erode the banks at some points, it follows that the points of attack will usually differ during flood and ebb. The development of meandering channels thus depends on the relative strengths of flood and ebb, and on the arrangement of channels at a particular time. In the upper reaches of a tidal river, fresh water flow has a considerable effect in reinforcing the ebb and moving sediment seawards. In the middle tidal reaches, the flood currents are strong but of relatively short duration while the ebb tidal currents are weaker but of longer duration. Tidal action alone can cause landward movement of sediment, which is modified by two important effects. One is fresh water flow. The sheer volume of fresh water during freshets can overwhelm the tidal effect and produce net seaward movement, though moderate and weak freshets more commonly reinforce landward movement of sediment, especially of flocculated silt, by density currents. Silt often moves into the middle tidal reaches of an estuary from both land and sea. **Mr Halliwell** referred to this effect in the Mersey.

83. The other effect that modifies landward movement of sediment by tides is caused by rise and fall of water level. At low tide, seaward currents still run strongly in the deeper ebb channels. The rising tide gradually stems the ebb, and by the time the current has reversed the water level will have risen appreciably. This weakens the capacity of the stream to transport sediment. Conversely, during the longer duration of the ebb, the level falls progressively and the current becomes concentrated in the ebb channels. The power to transport sediment is enhanced. If the depth of channel at low tide is much less than at high tide, this effect will be very important.

DISCUSSION

In Liverpool Bay, the main navigation channel has a depth at spring tides of about 8.5 m below low water and 18 m below high water. The powerful ebb current, directed by the Narrows, has a vital role in keeping the channel clear.

84. **Mr Beckett** has described dredgers in the Mersey as scarcely able to cope with the rush of sand brought in by tidal currents, but in reality the amount of dredging needed to maintain the channels is comparatively small. Before 1960, a combination of ineffective dredging by stationary dredgers, spoil disposal at a site from which material could return rapidly to the estuary and consequently heavy over-dredging, all contributed to the deterioration of the inner Mersey. After the introduction of trailer dredging in 1960, deterioration in cubic capacity of the inner Mersey has ceased, and the quantity of sand being dredged annually has been halved.

85. Reclamation of the inner Mersey with the objective of reducing tidal currents would weaken the ebb. This has been done in other estuaries with disastrous results. Rapid deterioration of the main channel has changed tidal propagation which, in turn, has accelerated deterioration further, e.g. a branch of the River Hooghly provided an anchorage for small ships about 30 years ago, but following reduction of its tidal capacity, has now become a mere creek. The Dee estuary provides a good example of the ultimate fate of the Mersey if this policy were to be adopted.

86. **Mr Beckett** also suggested in § 51 that the Mersey Docks and Harbour Co. could afford to lose some of the depths in the Narrows because the depths there are 30 ft greater than those on the Bar. But the tidal rise during spring tides can be over 30 ft so that a ship just able to cross the Bar at high tide is just able to remain afloat in the Narrows at low tide.

87. **Mr Perfrement** referred to cyclical changes in the channels of the inner Mersey and suggested in § 42 that it might be worth considering the effect on such changes as sun-spot activity. An estuary with an active bed can respond quite quickly to changes in tidal strength and fresh water flow. The response at a given time will depend on the state of its channels, e.g. the low-water channel that carries most of the fresh water switched from the Eastham channel to the Garston channel in 1964 and has recently switched back again. The change of channels was inevitable, but the reason it took place in 1971 appears to be that fresh water flow was lower than usual for several weeks, with the result that the flood tide in the Eastham channel was able to break through and capture the ebb.

88. There are several factors that could have a cyclical effect. The most important of these is the tides, which vary periodically in a pattern repeating with comparatively small changes every 19 years. Another factor is river flow. If there is any effect due to sun-spot activity it could influence river flow, but careful study of other river systems has so far proved inconclusive. A third factor is the rate of response of the system. This depends on its physical size and on the nature of bed and banks.

89. If either of the external influences (tides and river flow) produces cyclical change, there will be an exact correlation between cause and effect. This does not appear to be the case with the Mersey, as the variation in dredging has been affected much more by mechanical influences than by natural changes. These mechanical influences include availability of machinery, technique of dredging, objectives as determined by requirements of shipping and interruptions during the First and Second World Wars.

90. **Mr Jackson** asked about the sources of silt in the Mersey and suggested that, if there were large amounts of silt available that could be brought into suspension, there would be no point in removing silt from the system during dredging operations. In the Mersey, most of the silt brought into the system by rivers is intercepted by the Manchester Ship Canal, from which it is dredged and placed on land. The main source of fresh silt is the Irish Sea. There are large quantities of silt along the margins of the estuary and on certain mid-river banks. However, silt contains enough clay-sized particles to affect its behaviour. If left undisturbed, it consolidates to form a cohesive mass that is not easily eroded by flowing water. If disturbed by

dredging, the flocculated material is broken up and then easily transported by flow. Once it is in this state, it can remain in a loose, easily transported form that enters docks and flows by gravity into deep pools. Only when left for several days is it able to consolidate enough to resist erosion by the tidal streams. A stream has a certain capacity to transport sand. If more sand is added to the stream, the amount in movement tends to remain constant for given flow conditions, and any excess is deposited on the bed. However silt is easily transported in large quantities, the quantity being transported depending more on the availability of solids in suspension than on the flow conditions.

91. Intensive dredging causes silt that would otherwise remain consolidated on the bed to be brought into suspension. Dredgers remove sand, but a large part of the silt that enters their hoppers is returned to the river, either directly over the overflow weirs or by tidal action at the spoil disposal ground. Mr Halliwell has shown that such silt returns to the Mersey from many points of Liverpool Bay. This is one of the major reasons for the excellent advice of Mr Price to treat a tidal system as gently as possible.

92. In an estuary that contains large reserves of mud outside the main flow channels, it is worth sampling the mud to determine the amount that is consolidated and not readily brought into suspension. Unconsolidated mud causes the real problems and it is often worth removing it and using dredging techniques that do not bring more into suspension, even when they appear to be inefficient in terms of cost per unit weight of silt dredged.

93. Mr Ruxton pointed out that seabed drifters dropped before a westerly storm moved eastwards. We do not agree that this necessarily invalidates the choice of a more westerly dumping ground in Liverpool Bay if it is exposed to a strong westerly influence. Spoil deposited before a westerly storm will certainly move predominantly back to the Mersey, but at other times it will either consolidate on the bed or move south-east. During the first year of seabed drifter studies only one set of drifters out of twelve returned predominantly to the Mersey from one possible disposal site.

94. Mr Pot criticized the Authors' statement that the dredging techniques used on the Bar from 1894 onwards were the best available at the time. The Authors accept that trailer dredging was available and that it is now known to be a much better technique. Trailer dredging had been used on mud in the Mississippi using a dustpan suction head and the Fruehling head had also been developed. The Fruehling head is effective in mud but in sand it behaves little better than the plain pipe of a stationary dredger, and it is believed that the Californian head is preferred as there is less tendency to choke.

95. The modern trailer suction dredger, fitted with swell compensator, came into use in the late 1950s. Earlier attempts to use this type of vessel in the Mersey were not satisfactory.

96. Mr Mettam referred to the high cost of maintaining the approaches to Liverpool in the past, which is really what the Paper was all about. It has been shown that this cost has been reduced considerably over the last few years. Closing the South Docks system this year will result in a further reduction of $1\frac{1}{2}$ million tons of dredging a year, much of which will be silt and mud.

97. Table 3 gives the total cost of maintenance dredging (inclusive of all capital charges) and as a percentage of Board's revenue over the last five years. The dredging expenditure of the Manchester Ship Canal Company is not included.

98. Mr Pot's further remarks on the probable increase of tanker tonnage are noted with interest.

99. Many possible sites for disposal of spoil by reclamation have been considered, including the margins of the Narrows, along the Crosby foreshore and on Burbo Bank off New Brighton. In each case the cost of the retaining bank was out of all proportion to the volume of reclamation that would be enclosed. The reason is that the tidal rise is up to 10 m and the foreshore is exposed to severe wave action in

Table 3

Year	Total cost of maintenance dredging including capital charges	Percentage of Board's revenue
	£	
1966	1 575 000	10.5
1967*	1 798 000	11.3
1968	1 570 000	9.9
1969	1 339 000	7.1
1970	1 311 000	6.3

* after channel deepening.

many places. The most important materials to remove from the system are silt and mud which amount to over half the total dredgings. Reclamations using these materials would have little commercial value for many years and would be regarded as a liability by riparian users.

100. Professor McDowell was pleased to see the contribution from **Dr Bhattacharya** with his comments about the Hydraulic Study Department of the Port of Calcutta. Dr Bhattacharya also developed a cost function to relate the total cost of transportation to channel improvements. This expression would be useful when considering transport of a particular commodity to a particular destination when there is no alternative route available, but when that destination can be reached with almost equal ease through a number of different ports, the port with the lowest charges will have the greatest advantage. The cost of maintaining the approaches to the Mersey has been high, but is falling. When it has been lowered further it will be possible to reconsider channel deepening. Whereas deepening to -8.5 m was achieved by removing a series of isolated shoals, deepening to, say, -10 m would require dredging over a considerable length of channel. It is this that makes the Authors believe that maintenance dredging would be increased by further deepening.

101. The Authors hope that their replies have answered adequately the many points that were raised.

Errata

Fig. 5. For year '1970' read '1969'.

Fig. 8. For year '1970' read '1968'.

References

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