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INVESTIGATION OF SILTATION IN THE ESTUARY OF THE RIVER RIBBLE

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PREFACE

This report describes work carried out on behalf of the Port of Preston Authority. It deals with the possibility of improving the shipping channel in the Ribble estuary to Preston Dock and the probable effects on channel depths of the Fylde Water Board's scheme to abstract water from the Upper Ribble and thus reduce fresh water flow.

This main report concerns the collection and analysis of field data, comparisons of surveys and dredging figures, various calculations and recommendations. It should be read in conjunction with supplementary Report No. EX 280 describing a radioactive tracer experiment carried out as part of the field programme.

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IN THE ESTUARY OF THE RIVER RIBBLE

I. INTRODUCTION

1. The Port of Preston is situated about fifteen miles upstream of the general low water line of the Ribble estuary. Although not one of our largest ports it is very modern and handles considerable imports of wood-pulp, timber, oils, china clay and various general cargos from all over the world, including a regular banana and citrus fruit trade from the West Indies. In particular its trade with Ireland is growing increasingly important and now amounts to about 750 000 tons of cross channel cargo per year handled in about 40 sailings per week. Exports, apart from general cargo, include coal and coke. Navigation is tidal and although at low water depths are quite small, the high tidal range of from 21 ft at neaps to 27 ft at springs makes the port accessible to quite large ships of a maximum draught of 21 ft.

2. The Hydraulics Research Station was consulted by the Port of Preston Authority in 1963. The Authority finds it necessary to carry out continuous maintenance dredging in certain stretches of the shipping channel which is trained from the port right to the seaward end of the estuary. More than two million cubic yards were dredged during the year 1963-64 in this way. The primary object of the investigation is to devise an improved dredging scheme. H.R.S. was asked to advise on the most effective position for dredging, the most suitable time of year and the best position for dumping dredged material. If possible they were asked to estimate how much dredging was necessary, how long continued and how often repeated for a given increase in channel depths.

3. The Fylde Water Board was also interested in the investigation. They have a scheme to abstract fresh water from the Upper Ribble to help relieve the serious shortage in the north-west in general and Manchester in particular. The Ribble and its tributaries drain an area of just under 500 square miles above Preston and 217 square miles below it. Included in the area above Preston is the catchment area of the river Hodder which has a very high annual rainfall intensity (58.6 ins per annum). The rest of the catchment, too, has rainfall well above average. The rainfall is not distributed evenly over the year, however, but there are periods of very heavy rainfall in the winter, when during

freshets fresh water discharge can rise as high as 5000 M.G.D., and periods of drought in the summer, when it falls as low as 50 M.G.D. During these periods of drought and consequent low fresh water flow the bed of the shipping channel, immediately downstream of the dock entrance at Preston, tends to shoal, and it scours deeper again during the freshets. The scheme for abstracting fresh water supplies from the Ribble involves the construction of a river regulating reservoir on the Upper Ribble at Rathmell near Hellifield. This would both reduce the fresh water flow and make it more uniform throughout the year. H.R.S. was also asked by the Port of Preston Authority to advise on what effect this reduced but more uniform fresh water flow would be likely to have on the shipping channel.

4. Fig 1 is a map of the trumpet-shaped estuary of the river Ribble. At its seaward end, between St. Anne's and Southport it is more than ten miles wide, but at the Naze, ten miles further landward, it has narrowed to less than a mile between the high water mark at the Naze on the north side and Hesketh reclamation embankment on the south, and to as little as 800 ft between the salt marsh edges on either side of the low water channel there. Preston Dock is a further five miles upstream and at its entrance the estuary is even narrower, the distance between reclamation embankments on either side of the channel being 700 ft. The river is tidal for another 4½ miles upstream of the Dock Entrance.

5. The low water channel from Preston Dock to the seaward limit of the estuary is about fifteen miles long and fairly straight. This is because it has been trained in stages from 1840 onwards, until today its position is permanently fixed by fifteen miles of low rubble walls along its south side and fourteen miles along its north. In Fig 1 the North Wall appears to end at the thirteenth mile. This is because Salters Spit has covered it up with sand for the last mile. At the fifth mile (i.e. five miles seaward of the Dock Entrance) there is a gap in the South Wall to admit the river Douglas (see Fig 1) and there is also a gap in the North Wall between the ninth and tenth miles, opposite Lytham. The distance across the channel from wall to wall is 300 ft at the first mile, increasing slowly to 1300 ft at the thirteenth mile.

6. Fig 2 shows the longitudinal section of the channel from one mile upstream of the Dock Entrance to sixteen miles seaward of it, as it was on 22nd April 1964 at the end of a period of low fresh water flow. The bed was 6 ft above Ribble Datum (Ribble Datum is at L.W.O.S.T. which is 12.50 feet below O.D. (Newlyn)) at the 1st mile and 4½ ft at the 4th. From there it sloped down fairly steadily to 4 ft below Ribble Datum at the 10th mile and then much more rapidly to a maximum depth of 21½ ft below Ribble Datum just seaward of the 12th mile. From there the bed shoaled rapidly, reaching a minimum depth of 4 ft above Ribble Datum halfway between the 13th and 14th mile. Finally the bed slowly increased its depth once more sloping below Ribble Datum at the 15th mile.

7. Before the low water channel was trained the estuary was considerably wider than at present - the 25 ft contour on Fig 1 gives some idea of the original boundaries of the Ribble estuary. Four channels entered this pre-training estuary from the seaward. They were from north to south: the North, Gut, Penfold and South channels. The main flow from the Ribble joined up with one or several of them to form the main channel to Preston. Charts and maps surveyed at fairly regular intervals from 1736 onwards show that this main low water channel was continually changing its position and that there was no place in the estuary, whether seaward or landward of the Naze, over which the channel had not wandered at one time or another. The Ribble estuary was apparently very similar to the neighbouring Lune and Wyre estuaries to the north and the Inner Mersey to the south, the low water channel cutting its way through a silty area where mud flats were continuously being built up by deposition of silt from suspension and cut down again and re-worked by the meanderings of the channel.

8. Underlying the whole estuary was a hard floor, consisting of gravel, clay and rock (the Keuper red marls). In places this inerodible material outcropped on the bed of the estuary, for example in the low water channel between Preston and the Naze, and it still does so on the foreshore at Lytham. In other places the overlying layer of sand and silt is very thick, for example near Southport Pier-head, where a line of bore holes reached depths of up to 48 ft below low water without reaching the hard floor.

9. As this shallow, unstable channel was highly unsatisfactory for shipping Messrs. Robert Stevenson & Son, who also trained the neighbouring Lune, were called in and reported in 1837. They recommended the stabilisation of the main channel by the building of low training walls, starting at the upstream end of the estuary. As the inerodible hards in the channel were preventing it from developing its full depths, they proposed that once the channel had been made to flow permanently along one course, the hards should be dredged away.

10. Stevenson recognised that some engineers held that training walls caused silting in estuaries, but he hoped to avoid this by keeping the walls as low as possible, just high enough to guide the last of the ebb and the first of the flood. In this way engineering works were begun in 1840 and extended from time to time during the next one hundred years, until by 1937 the Ribble had, relative to its size, the most extensive system of training works of any estuary in this country. Two outstanding features of the works were first the great length to which the walls were pushed seaward, rather than allowed to end in the middle of the estuary, and secondly the way in which training was combined with dredging. Where hards obstructed the flow in the stable channel they were removed and quite often it was possible to use the inerodible material so dredged for the construction of the low rubble walls.

11. However, Stevenson was mistaken in his estimate of the effects of training walls on silting. Although the walls were kept as low as possible they did lead,

as they did in the Lune estuary, to silting on a large scale (Ref 1). The Ribble is an estuary where a high tidal range and wave action combine to provide the turbulent conditions that tend to scour the finer particles of the bed material into suspension and lead to a high concentration of suspended load. The effect of training walls is not to induce this material to settle. It settles constantly, at slack water and in sheltered stretches, whether there are training walls or not, the fine material being carried furthest upstream and settling only under very calm conditions, and the slightly coarser particles travelling less far. In such areas the freely meandering low water channel has an important function as an erosional mechanism. As the silts settle and build up to mud flats the channel periodically cuts them back and reworks the material. When the channel is held stable, the mud flats tend to go on rising in height until salt marsh level is reached. Velocities in the low water channel itself are usually too high to allow settlement of the silt, so that this process tends to reduce the width of the estuary rather than the depths in the channel.

12. An examination of Fig 1 shows how these changes have worked themselves out in the Ribble estuary. In the narrow stretch of the estuary, upstream of the Naze, the saltings advanced almost up to the low water channel and were reclaimed. In effect the channel here is held in position not only by the low rubble walls, but also by the reclamation embankments and by the very cohesive mud flats which slope steeply down from the salt marsh edge to the toe of the training wall. Seaward of the Naze, too, behind the south training wall, the saltings advanced and were reclaimed, the dates of the embankments giving some idea of the great speed with which these areas accreted and became grassed over since 1840.

13. From the sixth mile seawards, however, the saltings fall back on either side and the trained channel makes its way through sand and silt banks which, in places, are now considerably higher in level than the low rubble walls on either side of the channel. In this wide stretch of the estuary, seawards of the Naze, more than 50 square miles fall dry during low water. This shallow area is covered with highly mobile sand and silt, some of which is much coarser than the material on the upstream mud flats, and during westerly gales it is pounded by wave action.

14. At the seaward end of the estuary flow has been trained into the central Gut channel. Of the other three old, alternative channels, the Penfold channel remains as a blind channel, but only vestiges of the former North and South channels can still be detected. In short accretion of sand on a very large scale, though not so obvious to the eye as the accretion of silt further landward, has also taken place in the seaward stretch of the estuary.

II. FIELD WORK

15. In order to investigate the question about dredging and the effect of fresh water abstraction it was agreed that the Port of Preston Authority and the Hydraulics Research Station should collaborate in conducting field work in the Ribble estuary. The Port of Preston Authority was to continue to carry out all the regular survey work and to collect dredging and daily fresh water flow records. The Hydraulics Research Station was to make hydraulic measurements, collect samples from various stations and carry out a radioactive tracer experiment. This field work was begun in July 1963 and completed in January 1965.

16. When this programme was agreed between the Port of Preston Authority and the Hydraulics Research Station it was recognised that it might not be sufficient to answer all the questions asked and that further surveys and perhaps other studies might be needed to complete the investigation. The desirability of such further work will be discussed later in this report.

Field observations by the Hydraulics Research Station

17. A comparison of the regular half yearly surveys of the eight miles below the dock entrance between September 1935 and January 1947 which had been carried out by the Port of Preston Authority had shown a regular pattern of accretion and erosion. During high winter fresh water flow there had been an increase in depths of 3 to 4 ft for about 3 miles from the dock entrance and a decrease in depths of about the same amount between the 5th and 8th mile. During low fresh water flow in the summer these changes were reversed and there was accretion in the first three miles and erosion from the 5th to the 8th mile. This suggested a merely local shift to and fro of material according to variations in fresh water flow. The Hydraulics Research Station's field observations were aimed at measuring these known changes more precisely and also at finding out to what extent they were accompanied by other changes lower down the estuary. In particular it was hoped to find out if the fresh water flow made a sufficient difference in flow conditions further downstream to produce an upstream movement of material into the estuary from the seaward during low fresh water flow.

18. Four observation stations were set up along the low-water channel at points, 1, 7, 11 and 17 miles seaward of the entrance to the docks and are shown in Fig 1. Station A at the one mile and Station B at the seven mile light beacon were both within the known erosion - accretion zones. Station C, at the eleven mile light beacon and Station D, about 17 miles below the dock entrance, near the deposit buoy outside the estuary, at the position where dredged material was being dumped, were both in stretches about which little information was available. Tidal heights and currents were measured at each

of these stations during two $12\frac{1}{2}$ hour mean-spring tide-cycles. The first coincided with high fresh water discharge (in November 1963 for Stations A, B and C, and in April 1964 for Station D) and the second with a low fresh water discharge (in June 1964 for all four stations). Over the same periods salinity and suspended solids were sampled near the surface, at half depth, and close to the bed. Solids were also sampled from the bed itself.

19. Station C was chosen as the site of the radioactive tracer experiment made during a period of low fresh water flow. The object of the experiment was to measure the extent to which seaward supplies of material move landward under these conditions. Very briefly particles of radioactive glass (half-life 84 days) were deposited on the bed at Station C during a period of low fresh water flow in September 1964, and their dispersal was tracked over a period of six weeks, with the aid of a scintillation counter. The experiment and its result is fully described in Report No. EX.280. Additional radio-active and fluorescent tracer experiments were considered at the planning stage of the field work, but it was decided to cancel or postpone them until the result of the injection at Station C, together with the results of all the other field work had been reviewed.

Survey of longitudinal section (profile) of channel at regular intervals

20. The Port of Preston Authority surveyed a bed profile of the whole length of the channel from one mile upstream of Preston Dock Entrance to Wallend Buoy, just over fifteen miles downstream of that entrance, at intervals of fourteen days approximately.

21. The first survey of this series was carried out on 1st July 1963 and the last on 18th January 1965. Between these two dates the channel was surveyed on 42 separate occasions, but owing to adverse weather conditions - mainly rough seas at the seaward end of the channel - it was not possible to survey the whole length of the channel each time and some of the profiles end at the 8th, 10th, 13th or 14th mile. For the same reason some of the surveys took more than one day to complete and there is some latitude in the fortnightly spacing of the profiles. From these profiles 37 were selected and analysed in detail.

22. In the landward reach the longitudinal section was surveyed along the centre line of the channel, but from a point about $8\frac{1}{2}$ miles downstream of the Dock Entrance to Wallend Buoy this became increasingly difficult because of the increasing width of the trained channel and its greater instability. In this seaward reach the longitudinal survey was therefore carried out by following a definite course, i.e. on shore marks, so that it could be readily repeated from one survey to the next. In this way each profile was surveyed, as near as possible along the same line, although not everywhere exactly in the centre of the channel.

23. The conditions under which each profile was surveyed were marked on it according to the following key:-

A - Good visibility, course reliable

B - Poor visibility, course questionable

C - Off course due to obstacles

D - Sea conditions: calm

E - Sea conditions: light swell

F - Sea conditions: heavy swell

G - No bed ripples

H - Small bed ripples } Average bed level
J - Large bed ripples } plotted

These ripples are evidently the same as the "dunes" in Report No. E 280. The conditions under which the profile shown in Fig 2 was surveyed on 22nd April 1964 were good visibility (A) and a heavy swell (F), except between the 7th and 11th mile where the swell was light (E). The bed was covered with small ripples (H), except between the 5th and 7th mile where there were no bed ripples (G).

24. In order to measure the extent of the repeatability of the longitudinal section in the seaward reach, it was surveyed on two consecutive days, when any differences could be expected to be due to error rather than bed changes. The main survey was carried out on 14th October 1963 and the stretch between $8\frac{1}{2}$ and 15 miles repeated on the 15th, one day later. On the first day visibility was good (A), the sea was calm (D) and small bed ripples were present (H). On the second day conditions were the same from $8\frac{1}{2}$ to $12\frac{1}{2}$ miles, but from there seaward to Wallend Buoy ($15\frac{1}{2}$ mile) visibility was poor (B) and there was a light swell (E). Small bed ripples were also present there (H). When the two surveys had been plotted and superimposed upon each other it could be seen that they did not exactly coincide everywhere with each other, but that on the whole discrepancies were small as compared with the considerably larger changes which occur naturally from one fortnight to the next. However, in comparing these profiles with each other the fact that there are small, unavoidable errors inherent in them has been taken into account.

25. Each completed longitudinal survey was plotted by the Port of Preston Authority to a horizontal scale of 2 inches to 1 mile and a vertical scale of 1 inch to 10 feet on a separate sheet of transparent paper, so that the profiles could readily be superimposed upon each other. Parts of some of the superimposed profiles are shown later in this report. Fig 2 shows, as an example, one of the plotted profiles in full. In addition each profile was recorded in the form of a table of x - y co-ordinates at an interval of 1/40 of a mile, y being the level reduced to Ribble Datum (M.L.W.S. at sea) which is 12.50 ft below Ordnance Datum (Newlyn), x the distance from the Dock Entrance. From the tabulated co-ordinates the mean bed level for various stretches along the profile for each of the 37 selected surveys was calculated and the resultant curves plotted. As far as is known, such a series of profiles has not been surveyed before at such a short interval of time and it has proved to be of the utmost value in analysing the complicated changes which are continually

taking place on the bed of the Ribble estuary.

Contour maps of the seaward reach

26. The Port of Preston Authority publishes annually a contour map, scale 6 inches to 1 mile, of the seaward reach of the shipping channel from Lytham to the sea. It is based on annual cross sectional surveys of the navigable channel between the training walls and the sea area westwards of the end of the walls, and on less frequent surveys of the sandbanks outside the training walls. Copies of these maps for 1947, 1949, 1950, 1952 and then for every year to 1964 were sent to H.R.S. and form the basis of the description of the changes at the seaward end of the training walls given in Part IV of this report. Owing to the considerable and increasing instability in this seaward reach the Port of Preston Authority has carried out several additional cross-sectional surveys of this area since 1962 and prepared large scale contour maps from them. Copies of these additional maps were also made available to H.R.S.

Cross sections

27. Cross sections, spaced about one mile apart, were surveyed along the whole length of the shipping channel on five separate occasions during the investigation. These were on 17th-18th October 1963 during a period of high fresh water flow, 30th January-4th February 1964, 3rd September 1964 one day before the radio-active tracer experiment, 14th-15th December 1964 during a period of very high fresh water flow and on 19th January 1965 at the end of this period. Each cross section starts at the top of the south training wall and ends at the top of the north training wall.

Dredging records

28. It was recognised that, except for a limited period after the injection of the radioactive tracer in September 1964, it was not practicable to stop dredging while the field investigation was in progress. It was therefore particularly important that adequate dredging records should be kept, both as to quantity and location. The Port of Preston Authority kept these records in such a way that the series of profiles could be used as a framework for plotting the information. Plotted underneath each longitudinal section, to the same horizontal scale as the profile, and to a vertical scale of 1 inch equals 20 000 cubic yards, was the amount of material dredged since the previous survey in each of the one mile stretches between the Dock entrance and the first mile, first and second mile, second and third mile, and so on. Fig 2 shows, for example, the dredging output for the period from the previous survey on 7th and 8th April 1964 to the 22nd April 1964.

29. How accurate are these dredging figures? The Port of Preston Authority informed the Hydraulics Research Station in a letter dated 30th December 1964 that "the dredging figures represent hoppe cubic yards. When a suction dredger has finished pumping the level of sand in the well is measured relative to the top of the coaming and from a table the master obtains the approximate number of cubic yards of sand in the well. The tables have been calculated from the dimensions of the hopper well, and are quite accurate. The accuracy of

the system, however, depends on how carefully the master measures the cargo". In 'A History of the Ribble Navigation' the author James Barron, M.I.C.E. (Engineer to the Port of Preston Authority from 1901 to 1933) says that "the cubic yards dredged as returned by the captains are invariably excessive" (page 302). He therefore reduced some of the quantities of material dredged to about three-quarters of the captains' booked output. No such adjustment has been made to the dredging figures given in this report and the figures quoted are the actual figures given on the profiles (see Fig 2), but in reading them Mr. Barron's remark should be kept in mind. However, the conclusions reached in this report remain the same whether the true dredging figures are only about three-quarters of the quoted figures or not.

Daily fresh water flows

30. The Port of Preston Authority supplied tables showing the average daily fresh water flows in millions of gallons per day (M.G.D.) for the two year period from 1st January 1963 to 31st December 1964. The figures are based on an interim stage/discharge curve derived from gaugings at Samlesbury Primary Gauging Station by the Lancashire River Authority. Samlesbury is about 5 miles upstram of Preston on the non-tidal part of the river Ribble. The River Authority has been recording the fresh water flow there since 6th April 1960, i.e. for only the last five years so far, and the figures from that day onwards were also made available to the Hydraulics Research Station.

31. It was hoped that during the time of surveying the bed profile of the tidal Ribble at fortnightly intervals, i.e. from 1st July 1963 to 18th January 1965, there would be one or several periods both of very high and very low fresh water flows, so that the effect of these variations on bed levels could be adequately studied. Also the hydraulic observations which H.R.S. was to make at Stations A, B, C and D were planned to be carried out during a period of high fresh water flow and to be repeated during a period of low fresh water flow. The radioactive tracer experiment, too, at Station C was to be carried out during a period of low fresh water flow. Although 1963 and 1964 turned out to be years of apparently rather low fresh water flow - the records are not as yet extensive enough to be very definite about this - there occurred two periods of sustained high fresh water flow during each of which bed levels in the upper reaches of the trained shipping channel reacted as expected.

32. During the first of these periods, namely from 8th to 27th November 1963, there were twenty consecutive days with average flows higher than 1000 M.G.D. and a peak flow of 6470 M.G.D. during a freshet on 21st November. On two thirteen hour periods during these days (20th/21st and 27th/28th) the Hydraulics Research Station's observations were carried out.

33. During the second period, namely from 6th to 15th December 1964, there were ten consecutive days with average daily flows higher than 1000 M.G.D. and a maximum flow of 11350 M.G.D. on 12th December, the highest average daily flow since records were begun on 6th April 1960. Although this second period of high fresh water flows lasted only half as long as the first one in November 1963, bed levels in the upper reach of the shipping channel changed even more

dramatically than during the first (see later in this report). This was evidently due to the very high intensity of the freshets, not only on the 12th itself, but also on three other days when flows greater than 5000 M.G.D. were recorded. During the longer, earlier period there was only a single day when flow exceeded 5000 M.G.D.

34. As to low flows there were several periods, both in 1963 and in 1964, during which the average daily flow fell to less than 200 M.G.D., but not a single day when the flow was less than 100 M.G.D., as had occurred in 1960, 1961 and 1962. One of these periods of low fresh water flows occurred from 23rd June to 6th July 1964, when there were fourteen consecutive days with average daily fresh water flows of less than 200 M.G.D. On two thirteen hour periods during these days (23rd and 24th) the Hydraulics Research Station's observations were repeated.

35. The radioactive tracer was injected at Station C on 4th September 1964 during another period of average daily fresh water flows of less than 200 M.G.D. The period began on 30th August and ended, after eleven consecutive days with flows less than 200 M.G.D., on 9th September, so that after injection there remained another five days for tracking the material during low flows, enough to get a significant answer. Tracking was continued for six weeks after injection altogether, a period which included a further seven days with flows of less than 200 M.G.D. and only three days with flows greater than 1000 M.G.D. These three days were consecutive and occurred on the 8th (3450 M.G.D.), 9th (2880 M.G.D.) and 10th (2229 M.G.D.) October 1964, 33 days after injection.

III. THE PATTERN OF DREDGING

36. Table 1 sets out in tabular form the dredging outputs as plotted underneath each fortnightly profile, covering the period from 1st July 1963 to 18th January 1965. From this table the annual dredging output for each mile for the year 1963/64 has been obtained by summing the fortnightly figures from 13-9-1963 to 14-9-1964. This particular pair of dates was chosen to make up a year as nearly as possible. These annual figures, together with percentages, are shown by themselves in Table 2 and can be compared with the dredging outputs in each mile of channel for every year since 1949, which are shown in Table 3. These three tables bring out the present pattern of dredging in the tidal Ribble and the extent by which it has changed in the last fifteen years.

37. Table 1 shows that the total quantity dredged in 1963/64 was 2320798 cubic yards. However, it also shows that this large amount - it is large in absolute terms and very large relative to the size of the estuary - was not distributed uniformly along the whole length of the channel, but that it was concentrated into two main areas of dredging effort, one at the landward and the other at the seaward end of the channel. The landward area extended from the Dock Entrance to the 6th mile, but the bulk of the dredging took place between the Dock Entrance and the first mile. Here, in this narrow, one mile stretch amounts varying from about 9000 to nearly 60 000 cu.yds per fortnight had to be dredged unremittingly throughout the year. Between the 1st and 3rd and the 4th and 6th mile, too, dredging had to be carried out continuously throughout the year, but the quantities dredged were less, not rising above 18 000 cu.yds. per mile per fortnight. In the one mile stretch between the 3rd and 4th mile smaller quantities were dredged, intermittently, the several periods of no dredging adding up to about half a year.

38. At the seaward end heavy and continuous dredging took place between the 14th and 15th mile, more than 60 000 cu.yds being dredged during many fortnights with smaller amounts less regularly on either side of this stretch. In contrast, practically no dredging took place between the 6th and 9th mile and no dredging at all between the 10th and 13th mile, whilst there was some moderate dredging between the 9th and 10th mile.

39. Table 2 brings out the non-uniform distribution of the dredging effort in the Ribble estuary very clearly. It shows that of the total of 2¼ million cu.yds. dredged in 1963/64, 1045028 cu. yds. or 45.0% were dredged between the Dock Entrance and the 6th mile and 1195605 cu. yds. or 51.5% between the 13th and 16th mile.

40. Table 3 shows that the total annual dredging outputs since 1949 were of the same sort of magnitude as that of 1963/64, but had undergone a change in their distribution along the channel. Apart from 1963 itself the total

annual dredging output exceeded 2 million cu. yds. on three occasions and was around $1\frac{1}{2}$ million cu.yds. perannum during the rest of the period. With regard to its distribution Table 3 shows that as far as the landward area is concerned massive dredging has always been taking place between the Dock Entrance and the 6th mile, but that the seaward area - 13th to 16th mile - has only more recently become an area of heavy dredging. Within the seaward area the maximum dredging effort shifted from the 13th-14th to the 14th-15th mile stretch. Finally Table 3 shows that there was a third area of large scale dredging around the 8th mile which has gradually become less important until in 1963/64 little dredging was carried out there.

41. The non-uniform distribution of the present dredging effort points to two quite distinct problem areas, one at the seaward end of the shipping channel (13th-16th mile) and the other at its landward end (Dock Entrance-6th mile). These two areas will be dealt with in turn, the seaward area first.

IV. DIVIDED FLOOD AND EBB CHANNEL DEVELOPMENT AT THE SEAWARD END OF THE TRAINING WALLS

42. As was described in Section II of this report, the Port of Preston Authority publishes annually a contour map of the seaward reach of the shipping channel. Part of the latest map of this series, that for 1964, from the 11th mile to the sea, is shown on Fig 3, side by side with the same stretch of the 1963 map. The maps show how depths in the trained channel decrease from more than 18 ft below Ribble Datum at the 12th mile to less than 6 ft between the 13th and 15th mile and that the increasing depth contours of the open sea are not reached until well seaward of the 15th mile. As to widths, the shipping channel is 1250 ft wide between training walls at the 12th mile and 1400 ft at the 13th mile, but then the north training wall disappears under Salters Spit which encroaches upon the channel, reducing its width to a minimum of 250 ft between the low water contours at a point 1000 ft seaward of the 14th mile in 1963. Clearly conditions in the shipping channel, both as to depth and width, are very unsatisfactory between the 13th and 15th mile and this is fully borne out by the massive dredging figures for 1963/64 in this stretch, showing that a determined effort was made to improve conditions in the channel here.

43. Outside, to the south of the training walls, the maps of Fig 3 show a blind channel, called the South Gut, which has outflanked the shipping channel from the seaward, having reached the outside of the south training wall between the 13th and 12th mile. It is separated from the main channel by the low south training wall and by a number of drying sand banks, which are up to about 1500 ft wide (in 1963) and higher than the training wall. Between the 15th and 13th mile the blind channel is both wider and deeper than the main channel. Currents have been observed to flow (mainly during the early part of the flood) from the South Gut across the south training wall into the main channel and caused some breaches in the wall in this stretch which have recently been repaired.

44. A comparison of the two maps shows that, while the general configuration of the banks and channels has remained the same between 1963 and 1964, some detailed changes in depths and widths of both channels have taken place during this period. In describing these changes it must be remembered that very heavy dredging took place in this stretch of the shipping channel in 1963/64, amounting to 131 760 cu. yds. between the 13th and 14th mile and as much as 1045 545 cu. yds. between the 14th and 15th mile (Table 1). If the whole of the quantity dredged between the 14th and 15th mile in 1963/64 had gone to increase the dimensions of the channel, its width between the drying

contours would have increased from the minimum of 250 ft in 1963 to a uniform 1000 ft or so in 1964 and the 6 ft contour would have appeared along the whole of its length. In fact, a comparison of the two maps shows that no such increase in depth took place. On the contrary, there was a small patch of the 6 ft contour present in the channel in 1963 (where the $3^{o}05'$ grid line intersects the channel), which had disappeared in 1964. However, the width between the drying contours did indeed increase to about 1000 ft along much of the stretch between the 14th and 15th mile. This was brought about by the removal of a sand bank along the inside of the south training wall, which in 1963 jutted out into the channel opposite the port buoy at the 14th mile, and by the cutting back of Salters Spit on the north side, further seaward. Evidently the massive dredging of 1963/64 between the 14th and 15th mile had succeeded in improving the width and hence the alignment of the shipping channel quite considerably, but it is also very clear that this improvement fell far short of the full dredging effort expended. In short, what is becoming apparent is that a major part of the dredging effort had to be used merely to counteract another factor - accretion - which is evidently operating in this area.

45. In order to get some idea of the magnitude of accretion in this stretch, the volume changes in the channel between 1963 and 1964 were measured by superimposing the two contour maps upon each other, and it was found that the increase in volume amounted to about 400 000 cu. yds., so that of the just over one million cu.yds. which were dredged between the 14th and 15th mile, about 40% went to improve the channel dimensions and the remaining 60% were used up in countering accretion. Similar measurements and calculations were carried out for the stretch between the 13th and 14th mile where just over 130 000 cu. yds. were dredged in 1963/64. Here there was less need to increase the width of the channel and a comparison of the two maps shows that it was depth which increased in this stretch. The maps show that a patch of the 6 ft contour, about half a mile long, had appeared in 1964, just upstream of the 14th mile. Further upstream, too, depths increased a little. In contrast, between the 12th and 13th mile, where no dredging took place, the 24 ft contour disappeared from the 1964 map. The increase in volume was about 90 000 cu. yds., so that of the 130 000 cu. yds. dredged in this stretch as much as 69% went to improve the channel and only 31%, representing 40 000 cu. yds., to counteract accretion.

46. The description of changes between 1963 and 1964 cannot be completed without drawing particular attention to changes in the South Gut. A comparison of the two maps of Fig 3 shows that while length and alignment of this blind channel outside the training walls did not appreciably alter, it considerably increased its width. Halfway between the $3^{o}04'$ and $3^{o}05'$ grid lines the distance between the 12 ft contours increased from 300 ft in 1963 to 500 ft in 1964. The corresponding increase in the distance between the 6 ft contours was from 700 to 1100 ft and between the drying contours (Ribble Datum) from 1200 to 1800 ft. The increase in volume of the South Gut was also measured by superimposing the two maps and it was found that the increase amounted to about 900 000 cu. yds. between 1963 and 1964. Thus, while the

shipping channel between the 13th and 15th mile improved only moderately, in spite of a massive dredging effort, and would probably have deteriorated beyond the already unsatisfactory 1963 conditions without this major effort, the blind channel outside the training walls increased in volume without any dredging at all. In short, between 1963 and 1964, erosion took place in the South Gut and accretion would have become manifest in the shipping channel but for dredging. Also the amount by which the shipping channel might have accreted without dredging - 640 000 cu. yds. - is of the same order of magnitude as the quantity of material - 900 000 cu. yds. - which was eroded from the South Gut.

47. Is there a connection between erosion in the South Gut and accretion in the main channel between the 13th and 15th mile? In order to study this matter further, Fig 4 was prepared to bring out the pattern of changes in this seaward area. On it are shown, side by side, part of the contour maps (the same stretch as that of the 1963 and 1964 maps of Fig 3) of 1947, 1953, 1957 and 1962. 1947 was the first of the series of maps surveyed and it was found that an interval of time between maps of about five years would bring out the changes more clearly than a shorter interval. (If 1952 could have been chosen, instead of 1953, the interval between the maps of Fig 4 would have been exactly five years throughout, but in 1952, unfortunately, the area outside the main channel was not surveyed). In addition Table 4 was prepared (from Table 3) setting out the annual dredging figures since 1949 for the 13th to 14th and 14th to 15th mile stretches separately and together, and their totals for the intervals between the maps of Fig 4.

48. The four maps of Fig 4 very clearly show how serious deterioration in the main channel between the 13th and 15th mile, despite heavy dredging (see Table 4), went hand in hand with an extensive development of the South Gut, which lengthened, widened and deepened. In 1947 the South Gut was already present, but it had not yet advanced to the outside of the south training wall itself. In the main channel the 6 ft contour was still continuous as far as the 15th mile. By 1953 the drying contour of the South Gut had advanced about 2700 ft in an upstream direction and had become wider. One tip of it had crossed the south training wall, closely followed by the 6 ft contour, which had advanced about 1600 ft to within 100 ft of the wall and also become wider. In the main channel accretion had occured in two places, but had not yet affected the 6 ft contour, which was still continuous. The two places of accretion were on either side of the 6 ft contour where it crosses over from the deep water along the north wall, upstream of the 13th mile, to the deep water along the south wall on either side of the 14th mile. In the area of accretion to the south-east of the 6 ft contours, the width of the sandbank along the south training wall at the point where the South Gut had broken in had increased from 350 to 600 ft. In the area of accretion to the north-west of the 6 ft contour an isolated patch of the drying contour in 1947 between the port buoy at the 14th mile and the north training wall had

increased in size, until by 1953 it had joined up with Salters Spit, with the result that the encroachment of Salters Spit on the channel extended further upstream and a further length of the north training wall became covered up by sand. Although the processes of erosion in the South Gut and accretion in the main channel had thus started well before 1953, depths along the centre line of the shipping channel were hardly affected as yet and this is reflected in the dredging figures which show (Table 4) that practically no dredging was carried out between the 13th and 15th mile during the period 1949-1953.

49. Between 1953 and 1957 (Fig 4) erosion in the South Gut and accretion in the main channel continued. The drying contour of the South Gut advanced a further 2000 ft to within 150 ft of the south training wall at the 12th mile, and at the 13th mile, where it had previously broken into the main channel, it had enlarged the area of break in and scoured passages through the sandbank there. The width of both the drying and 6 ft contours continued to increase and in addition a patch of the 12 ft contour, up to 500 ft wide and 3300 ft long had appeared by 1957, showing that the South Gut was not only lengthening and widening, but also increasing in depth. While this substantial enlargement of the South Gut took place, accretion continued in the main channel and by 1957 the 6 ft contour was no longer continuous. In this way shoaling seriously reduced depths in the shipping channel for the first time between 1953 and 1957 and this was at once reflected in the dredging figures for that period. Table 4 shows that some 1,700 000 cu. yds. were dredged between 1954 and 1957, the bulk of it between the 13th and 14th mile where the 6 ft contourhad disappeared.

50. In the period 1958 to 1962 dredging more than doubled (Table 4) but in spite of this increasing effort the main channel continued to shoal most seriously. By 1962 the 6 ft contour had disappeared between the 13th and 15th mile, except for a small patch just seaward of the 14th mile where the channel had norrowed to 200 ft. In addition a large sandbank had formed right across the main channel between the 13th and 14th mile (where the $3^{o}04'$ grid line crosses the trained channel), dividing the shipping lane most awkwardly into two shallow branches. In the South Gut erosion continued between 1957 and 1962, but at a somewhat reduced rate. The tip of the blind channel retreated a little (in 1957 it was just across the $3^{o}02'$ grid line, but in 1962 it was once more short of it by 500 ft) and the width between the drying contours between the $3^{o}03'$ and $3^{o}04'$ grid lines decreased from 1200 ft in 1957 to 1000 ft in 1962. The width between the 6 ft contours, too decreased. On the other hand the maximum distance between the drying contours between the $3^{o}04'$ and $3^{o}05'$ grid lines continued to increase slightly and the 12 ft contour considerably increased its length, from the 3300 ft in 1957 to 4900 ft in 1962. Also the drying contour broke into the main channel at a number of further places. In all it appears that while erosion continued in the South Gut, its further enlargement between 1957 and 1962 was less substantial than it had been during

the earlier periods, i.e., it appeared that erosion had slowed down a little in the South Gut. In short, it seems that while accretion in the main channel between the 13th and 15th mile was at its height between 1957 and 1962, erosion in the South Gut was already past its peak during that period.

51. This detailed analysis of changes since 1947 makes it very clear that erosion in the South Gut did indeed go hand in hand with accretion in the main channel between the 13th and 15th mile. If it could be said that material which "departed" from the South Gut "arrived" in the shipping channel, works could be designed and built to prevent accretion in the main channel; but if this relationship is not correct such works would be useless. The field work which has been carried out in the Ribble estuary so far is not in itself sufficient to establish the mechanism of accretion and erosion in this seaward trouble spot , but on the basis of the annual contour maps a pattern of changes appears to exist, similar to that which has been observed to occur periodically at the seaward end of other estuaries.

52. Drawing on such observations made in other estuaries, the seaward end of the Ribble shows many of the symptoms which are typical of what had been called a "divided flood and ebb channel" development. Very briefly, there is a powerful tendency in estuaries for flood and ebb currents to flow in separate courses, the flood currents periodically scouring a separate course from the seaward. As it develops such a flood channel is "blind" at its upstream end, but it increasingly outflanks the main channel by continually lengthening, deepening and widening its bed, while the main channel seriously deteriorates until, eventually, the flood channel may become the main channel itself.

53. In a buoyed channel the presence of this kind of development can often be diagnosed by merely observing the direction in which the buoys are pointing during the rising tide. Normally they will point upstream during the flood, in a direction parallel to the axis of the channel. Similarly, during the ebb they will point downstream in the opposite direction, but still parallel to the channel's axis. Such observations indicate that the flood and ebb currents act along the same line and so ensure that sand, travelling along the bed under the action of the flood currents in an upstream direction, will trace back its steps during the ebb, with the desirable result that the net displacement of material moving along the bed under the action of the tides is practically zero. And this is true, even if the flood currents flow for a shorter time than the ebb currents - as they usually do - as the higher velocities of the shorter flood are balanced by the longer duration of the slower ebb.

54. In a stretch where a separate channel is developing, buoys marking the fairway will no longer point upstream during the flood, but across the channel in a direction at right angles to the prevailing direction of the flood currents. This indicates the presence of cross-currents, flowing in a direction from the developing, new channel towards the deteriorating, main channel. During the ebb such cross-currents do not develop to the same extent, so that the movement of sand, travelling under the action of these cross-currents out of the new channel

into the main shipping channel, is not compensated by sand returning from the main channel to the new one. The result is that shoaling will occur in the main shipping lane, while the new channel continues to become deeper, i.e. it develops at the expense of the fair way.

55. A typical case for which a great deal of information was collected is shown on the contour map in Fig 5 of part of the main shipping lane of the Outer Elbe, seaward of Cuxhaven. In the stretch shown on this map a separate flood channel has formed between lightships Elbe 3 and 4 along the south side of the main channel and is in the process of outflanking the fairway. In this area cross currents flow during the flood from the developing separate flood channel - still closed at its upstream end- across the long and narrow bank dividing flood and main channel, especially at its upstream end, into the fairway. They are due to the impounding effect which such partially formed, blind channels have. As the tide begins to flow the incoming tidal wave is more strongly reflected in the blind than in the main channel, so that water levels rise more rapidly in the flood channel than in the fairway. The result is that the water surface slopes downwards in a direction from the separate channel to the main channel and therefore water begins to flow in that direction.

56. The most ominous development shown on Fig 5 is the formation of a continuously growing sandbank, spreading from the north bank between lightships Elbe 3 and 4 right into the main navigation channel, causing quite intolerable conditions for shipping there. As float observations in the prototype and a model investigation showed, this growing sandbank was fed with sand which was transported during the flood by the cross currents referred to above from the shoal areas opposite lightship Elbe 4 into the fairway. During the ebb this material was then transported seaward and incorporated in the sandbank. In this way as the new separate channel developed, conditions in the shipping channel deteriorated more and more.

57. The solution suggested after a full field and model investigation was that a guide wall should be built from Kugelbake (see Fig 5) along the Mittelgrund (middleground) which separates the two channels. It was hoped in this way to suppress the cross currents which were carrying the sand into the shipping channel. The height of the wall was to be kept as low as possible for economic reasons and the length to seaward was to be decided in the light of how effective it proved as it was built. In fact the low training wall was found to be insufficient to suppress the cross currents and a later investigation showed a higher wall to be necessary.

58. If the contour maps of the Ribble and the Elbe are compared, the pattern of changes in the seaward stretch of the Ribble between the 13th and 15th mile seems very similar to that in the Outer Elbe. The South Gut is most probably a developing flood channel so that cross currents are carrying material from it into the shipping channel: the present south training wall, like the original wall in the Elbe scheme, is presumably too low to suppress these currents. If this is indeed so, the ultimate solution would be to raise the

the height of the south training wall considerably. This would prevent material from being scoured from the South Gut channel into the shipping channel: as the South Gut appears to be a flood channel, there would tend to be a net movement of material into it from seawards and it would be reduced in size and perhaps eventually disappear. If the training wall was raised, such a development could be hastened by dumping material dredged from this stretch of the shipping channel into the South Gut. If the South Gut could be considerably reduced, or eliminated altogether, the concentration of flood and ebb currents in the main shipping channel should help to maintain considerably improved conditions.

59. However, any proposal to raise the height of the training wall in this seaward stretch could not be considered in isolation from the rest of the estuary.

V. ALTERNATION OF ACCRETION AND EROSION IN THE SHIPPING CHANNEL AT THE LANDWARD END OF THE TRAINING WALLS

60. Fig 6 shows particle size distributions of the bed material along the trained channel at Stations A, B and C. The material from the 11th mile seaward consists mainly of fine and medium grained sand which moves predominantly along the bed. The material further upstream is rather finer and is a particularly mobile and troublesome bed material present in many estuaries. It moves close along the bed under condition of fairly steady flow, but is also quite easily scoured into suspension under more turbulent condition. This is brought out by the particle size distribution of the suspended load at Station A also included in Fig 6, which shows that the predominant particle sizes of material found on the bed are also to be found in suspension. When changes are caused by bed movement, material eroded along one stretch of the channel can usually be traced accreting elsewhere in the channel and it is not very difficult to link departure and arrival zones. On the other hand where suspended load transport is involved material eroded from the channel may travel much further, seemingly to disappear, although it can be deposited on banks in almost any stretch of the estuary. In the same way material arriving in suspension to settle in the channel may have come from widely dispersed sources on the banks or seaward.

61. Material of grain size 64 to 256 microns, present in the upper part of the Ribble estuary, can be transported in both these ways and it is necessary to distinguish the local changes to and fro along the channel caused by bed load transport from the more complicated changes caused by deposition and removal of suspended load.

62. The changes at the landward end of the estuary were analysed by detailed comparisons of the longitudinal section surveyed at fortnightly intervals from 1st July 1963 to 18th January 1965. These fortnightly profiles were plotted on transparent paper so that they could be superimposed upon each other. In this way accretional and erosional trends could be studied. In addition the x-y co-ordinates were tabulated at an interval of 1/40 mile for each survey, the mean bed level for various mileages along the profile for each survey was calculated and the resultant curves plotted. This further helped to sort out the pattern of changes along the bed of the trained channel. The data are set out in Tables 5 to 8.

63. In Fig 7 the mean bed levels for the one mile stretches between the 1st and 2nd mile, 6th and 7th mile, $7\frac{1}{2}$ and $8\frac{1}{2}$ mile and $10\frac{1}{2}$ and $11\frac{1}{2}$ mile have been plotted. The bed of the trained channel in the upper stretch of the

estuary - the first eight miles or so from the Dock Entrance downstream - is shown to have been subject to very large up and down changes, i.e. the bed was continually eroding or accreting. Fig 7 also shows that by the 11th mile, where Fig 6 has shown the bed material no longer to include the highly mobile very fine sand, the fluctuations in level were much smaller and that the bed level tended to remain much more steady. Between 11-11-63 and 27-11-63 the mean bed level between the 1st and 2nd mile fell from + 4.25 (4.25 ft above Ribble Datum) by 1.7 ft to + 2.55. Between 30-11-64 and 14-12-64 it fell from + 3.75 by 3.7 ft to + 0.05. Between the 6th and 7th mile the mean bed level rose from - 1.10 by 2.35 ft to + 1.25 in the period between 25-9-63 and 14-10-63. Between the $7\frac{1}{2}$ and $8\frac{1}{2}$ mile the mean bed level fell from - 0.85 by 2.85 ft to - 3.70 in the period between 9-1-64 and 23-1-64. These are very large changes in a very short time.

64. Although the bed was rising and falling continually in this way from fortnight to fortnight, longer periods of overall accretional or erosional trends can be distinguished. Thus, between the 1st and 2nd mile, the bed tended to fall from 25-9-63 (point marked "a") to 27-11-63 (point marked "b") and then to rise again - in spite of smaller fluctuations - from 27-11-63 (b) to 22-4-64 (c). It remained at roughly the same level - again in spite of individual fluctuations -from 22-4-64 (c) to 30-11-64 (d) and then fell dramatically in one fortnight from 30-11-64 (d) to 14-12-64 (e). The overall trends were: (a) to (b) fall: 2.75 ft; (b) to (c) rise: 2.1 ft; (d) to (e) fall: 3.7 ft.

65. If the second graph (6th and 7th mile) on Fig 7 is compared with the first one (1st and 2nd mile) it can be seen that, on the whole, when the first curve rises the second curve falls and vice versa. i.e. the two curves appear to be complementary to each other. Thus when curve one fell from (a) to (b) curve two tended to rise and when curve one rose from (b) to (c) curve two fell. Furthermore when the first curve was fluctuating about the same level, the second curve also remained at a steady level. Finally when curve one fell dramatically from (d) to (e) curve two rose dramatically from - 0.45 by 2.30 ft to + 1.85. There is thus an inverse correlation between the two graphs i.e. while there is a period of erosion at the 1st mile, the bed at the 7th mile is accreting, and, conversely, when accretion is taking place at the 1st mile, the bed is eroding at the 7th mile.

66. This striking pattern is brought out more fully in Fig. 8 in which, for the stretch between the Dock Entrance and the 7th mile, longitudinal profiles at periods (a) and (b), (b) and (c) and (d) and (e) were respectively superimposed upon each other. Fig 8 very clearly shows how, during each period selected, erosion in one stretch of the upstream compartment went hand in hand with accretion in the adjacent reach. Thus in the period between 25-9-63 and 27-11-63 there was erosion in the stretch between the Dock Entrance and the 3rd mile, lowering bed levels by up to about 4 ft and accretion in the stretch between the 3rd and 7th mile, raising bed levels, near the 7th mile, by up to 4 ft. During the next period (27-11-63 to 22-4-64) accretion and erosion was reversed the bed acc[illegible]ting in the stretch between the Dock Entrance and the

3rd mile (up to about $3\frac{1}{2}$ ft) and eroding in the stretch between the 3rd and 7th mile (up to about 2 ft). Finally, during the third period selected (30-11-64 to 14-12-64, i.e. only a fortnight), there was massive erosion in the stretches between the Dock Entrance and the $3\frac{1}{2}$ mile (up to 7 ft) and accretion in the stretch between the $4\frac{1}{2}$ and 7th mile (up to 4 ft).

67. If the graph of mean bed levels on Fig 7 for the one mile stretch between the $7\frac{1}{2}$ and $8\frac{1}{2}$ mile is compared with the other two, it is evident that the picture of complementary accretion and erosion which has been shown to exist between the first and second curves does not extend to the third curve. Nor do there appear to be any long continued overall accretional or erosional trends, as there were in the first and second curves. Rather, the third curve shows at the 8th mile a succession of accretional and erosional changes at fortnightly intervals, which are even more violent then at the 1st and 7th mile (first and second curve) and there is little evidence of any trends of longer duration. Thus the mean level of the bed between the $7\frac{1}{2}$ and $8\frac{1}{2}$ mile fell from - 0.85 to -3.70 in one fortnight (9-1-64 to 23-1-64) a fall of 2.85 ft, and this occurred after major changes during the previous four fortnights. Another example is the steep rise in the period between 1-6-64 and 25-6-64 when the bed at the 8th mile rose from - 2.45 by 2.15 ft to - 0.30.

68. However, if attention is concentrated on some of the most violent short term changes in the third curve, and the direction of the change, i.e. whether accretion or erosion took place, compared with what took place during the same period at the first and second curve, it can be seen that when the bed rapidly accreted at the 8th mile, it also did so at the 1st and 7th mile, though by much smaller amounts. Thus when the bed rose from - 2.45(point marked "5") by 2.15 ft to -0.30 (point marked "6") the bed also accreted at the 1st and 7th mile (see Fig. 7). Similarly when the bed at the 8th mile rapidly eroded from - 0.85 (3) by 2.85 ft to - 3.70 (4) there was also erosion at the 1st and 7th mile (Fig. 7) though again the actual amounts were smaller. There are several further fortnightly periods when either accretion or erosion occured at all three sections.

69. These short periods of widespread accretion or erosion along the whole of the upper compartment, like the longer periods of complementary erosion and accretion between the 1st and 7th mile, are very significant. This additional factor of overall accretion or overall erosion is brought out more fully in Fig 9 in which for the stretch between the Dock Entrance and the 13th mile, profiles (3) & (4), (5) & (6) and (1) & (2) were respectively superimposed upon each other. Fig 9 very clearly shows how during each short period selected, either accretion or erosion predominated along the whole of the stretch. Thus in the period between 9-1-64 and 23-1-64 (Profiles 3 & 4) there was widespread erosion everywhere and little compensating accretion. At the 8th mile the erosion amounted to a fall in bed levels of up to 5 ft, elsewhere it was around 1 ft and less. During the period from 1-6-64 to 25-6-64 (Profiles 5 & 6) there was widespread accretion and little erosion anywhere else (except apparently between the Dock Entrance and the 1st mile,

but this was due to dredging). At the 8th mile, and also at the 9th mile, the accretion amounted to a rise of up to 4 ft, elsewhere it was again around 1 ft.

70. In addition profiles (1) and (2) were superimposed upon each other, showing the changes in the period between 25-9-63 and 14-10-63. During this period accretion predominated between the 3rd and 13th mile, particularly at the 6th, 7th and 8th mile. But in this case there was also some erosion, namely between the Dock Entrance and the 2½ mile. However accretion by far outweighed erosion and this is therefore another of these short periods in which either accretion or erosion predominated in the whole of the upper compartment.

Fluctuation in bed levels related to changes in fresh water flow.

71. In Fig 10 the long and short term changes in bed levels in the landward compartment of the Ribble estuary have been correlated with changes in fresh water flow. In this figure the three mean bed level graphs at the 1st, 7th and 8th mile have been reproduced from Fig 7 and in addition fresh water flow has been plotted as follows. For each period between two profiles the number of days with fresh water flow less than 200 M.G.D. - low fresh water flow - have been counted from the records made by the Lancashire River Authority and plotted above the zero line. Similarly the number of days with fresh water flow greater than 1000 M.G.D. - high fresh water flow - have been plotted below the zero line. In addition, the number of days with fresh water flow greater than 2000 M.G.D. - very high fresh water flow - have also been counted and the part of the high fresh water columns corresponding to that number of days blacked in. In this way periods of long sustained high or low fresh water flow can be seen at a glance.

72. A comparison of the rise and fall of mean bed levels with periods of high and low fresh water flow shows quite good correlation as far as the first (1st & 2nd mile) and second (6th & 7th mile) curves are concerned. Thus during the period from 25-9-63 to 27-11-63 (64 days), when the mean bed level between the 1st and 2nd mile fell from (a) to (b) (from +5.30 by 2.75 ft to + 2.55), there was not a single day with fresh water flow less than 200 M.G.D., but 32 days during which the fresh water flow was more than 1000 M.G.D. Moreover these 32 days included 16 days with fresh water flow greater than 2000 M.G.D. Clearly the sharp drop in bed levels fell within a period of high fresh water flow. Similarly, the spectacular drop in bed levels from (d) to (e) (from +3.75 by 3.7 ft to +0.05) during the period from 30-11-64 to 14-12-64) fell into another period of high fresh water flow. During this latter period six days of very high fresh water flow were measured, the maximum occurring on 12-12-64 when 11350 M.G.D. were recorded, by far the highest flow during the whole period under observation. Evidently it was this extremely high flow and the very high flows during the preceeding days which account for the dramatic erosion in the first three miles seaward of the docks. The corresponding rise in mean bed level at the 7th mile (second curve) is equally exceptionally large.

73. As far as the accretional phase in the stretch between the Dock Entrance and the 3rd mile is concerned, during which the bed rose from (b) to (c), days with low fresh water flow - when tidal flow predominated over upland flow - were

much more numerous during this period than days with high fresh water flow. The same applies to the next period, (c) to (d), when the overall level of the bed between the Dock Entrance and the 3rd mile did not change much. During this period many days with low fresh water flow occurred, but there were also a few days of high fresh water flow. In short the fresh water flow in the period between (c) and (d) was erratic and so are the bed levels. On the whole it is the shorter periods of very high fresh water flow which strikingly correlate with erosion near the Dock Entrance. At other times, when the fresh water flow is more normal, the bed is more steady or slowly climbs back to higher levels.

74. Referring again to Fig 8, the erosion in the stretch between the Dock Entrance and the 3rd mile and related accretion in the stretch between the 3rd and 7th mile during the period from 25-9-63 to 27-11-63 is seen to have occurred after high fresh water flow. Similarly the accretion between the Dock Entrance and the 3rd mile and related erosion between the 3rd and 7th mile during the period from 27-11-63 to 22-4-64 occurred after mainly low fresh water flow; and finally the very substantial erosion between the Dock Entrance and $3\frac{1}{2}$ mile and accretion between the $4\frac{1}{2}$ and $7\frac{1}{2}$ mile during the period from 30-11-64 to 14-12-64 occurred after very high fresh water flow.

75. Thus, in the summer when fresh water flow is normally low, heavy accretion occurs immediately seaward of the dock, with erosion further downstream. In the winter, especially after freshets, the situation is reversed; the material is eroded immediately downstream of the Dock Entrance and accretion occurs further seaward. During the summer shipping is much hindered in the stretch immediately seaward of the dock and it is then that massive dredging is most needed. When freshets clear the deposits in the stretch immediately seaward of the Dock Entrance there may be short periods during which no dredging at all may be necessary. But the beneficial effect of the freshets is soon lost and the bed begins to rise again.

76. The dredging figures in Table 1 for the stretch between the 1st and 2nd mile show that no dredging took place in the periods between 11-11-63 and 27-11-63 and between 30-11-64 and 14-12-64 when fresh water flow was at its height, but high fresh water flow is not reflected in low dredging figures in the stretch between the Dock Entrance and the 1st mile. Rather dredging was on a very large scale there throughout 1963/64. This is because the stretch immediately seaward of the Dock entrance was overdredged to create a pit into which material could move without interfering with shipping.

77. This account of the correlation between fluctuations in fresh water flow and bed levels is based on the 1963/64 profiles surveyed at fortnightly intervals. Profiles surveyed at half yearly intervals, at the end of high winter and low summer flows exist for earlier periods and they show the same relationship; indeed the connection between fresh water flow and bed level changes in the landward reach of the Ribble estuary is well established.

78. Fig 11 shows a comparison of flood and ebb current velocities measured

one foot above the bed at Stations A, B and C during periods of high and low fresh water flow (see Section II of this report), and helps to explain why the changes in bed levels are related to changes in fresh water flow and why the effects of changes in fresh water flow are confined to the upper part of the estuary. Although there are other factors involved in bed load transport, an approximate picture can be obtained by considering the areas under the velocity curves, if it is borne in mind that very little material moves at under 1 ft per second but that above a threshold velocity of this order the amount of material transported increases as a non-linear function of the velocity. This has been indicated by open and closed vertical hatching of the areas under the velocity curves - open hatching between 1 and 2 ft/sec to bring out that transport may still be fairly small and closed hatching above 2 ft/sec to show that the important bed transport occurs above this velocity. The areas below 1 ft/sec have been left clear to indicate that transport below this velocity can be ignored.

79. It will be observed that, although the change from high to low fresh water flow makes considerable changes at Stations A and B, it has very little effect at Station C. By the 11th mile down the river, the fresh water flow is too small, proportionally to tidal discharge, to make any appreciable difference to the balance between flood and ebb currents.

80. At Station A (1st mile) the opposite is true. During periods of high fresh water flow the flood currents can only make their way upstream for a short period and at low velocities, the ebb currents predominate strongly both in velocities and duration, so that the net drift of material is heavily downstream. With low fresh water flow, the balance is dramatically reversed. The ebb currents are greatly reduced and the very high velocity flood currents will carry a heavy load into the area.

81. The contrast is slightly less obvious at Station B (7th mile). During high fresh water flow, although flood currents are much greater than at A, the ebb is still dominant. This is nevertheless an accumulation area presumably because these ebb currents have to remove not only material carried in by the flood currents but also the heavy load carried down by the ebb from further upstream. It is probable that salinity currents also tend to prevent the ebb load from being carried further downstream. During periods of low fresh water flow flood currents again predominate at B and carry the accumulated bed material back upstream.

82. It will be recalled that it was hoped to find out if the fresh water flow made a sufficient difference to flow conditions further downstream to produce an upstream movement of bed material into the estuary from the seaward during low fresh water flow. The velocity curves of Fig 11 by themselves, already give a clear indication that strongly biassed alternate ebb and flood bed drifts are confined to the upper compartment and that it is unlikely that changes in this area are dependent on supplies from the sea along the channel bed.

Fluctuations in bed levels not related to changes in fresh water flow.

83. While the complementary accretion and erosion pattern between Stations A and B are closely related to changes in the volume of fresh water flow, the short periods of overall accretion and erosion indicated by the third graph on Fig 7 do not fit into this pattern. Thus a marked fall of bed levels in the period between (3) and (4) (see Fig 10) occurred during a fortnight in which there was not a single day with either high or low fresh water flow. Similarly the rapid rise of bed levels from (5) to (6) fell into a period when there were only three days (out of a total of 24 days) of low fresh water flow. Thus there are periods of short-term overall accretion or erosion in the upstream compartment of the Ribble estuary which are largely independent of the state of the fresh water flow. Fig 9 shows periods of more widespread alternation between accretion and erosion which are independent of either high or low fresh water flow.

The two circulation systems

84. The analysis of all the profiles collected shows considerable bed changes in the first eight miles or so of the trained channel below the Dock Entrance where a high proportion of the bed material is very mobile, very fine sand between 64 and 128 microns grain size. By the 11th mile, where the bed is much coarser these changes have largely disappeared. Within the stretch from the Dock Entrance to the 8th mile, two quite distinct, but interlocking, circulation systems exist by which the bed material is redistributed. The simpler of the two systems is related to variations in fresh water flow. During high fresh water flow, when the ebb flow is augmented and the flood flow weakened, there is a 'departure' area between the Dock Entrance and the 3rd mile from which bed material is scoured and carried seaward. The mode of transport is probably close along the bed, and the material stays in the channel. Between the 4th and 7th mile there is an 'arrival' area where the ebb currents are no longer sufficiently strong to carry away the bed load being brought down from upstream, as well as the normal bed load brought in by the flood, and where accumulation therefore tends to take place.

85. During low fresh water flow the balance of ebb and flood currents is altered in these two areas. The ebb is very much weakened at the 7th mile and the balance of drift is now in an upstream direction. The stretch between the 4th and 7th mile becomes a 'departure' area and material is now scoured away and carried back upstream. In the stretch between the Dock Entrance and the 3rd mile the ebb currents are now weak while the flood currents are considerably strengthened, so that the material which is carried back upstream stays there.

86. In this system of bed load transport, then, there appears to be a limited amount of material which tends to accumulate at one end or the other of the stretch affected according to the volume of the fresh water flow. This circulation system is confined to the upper reaches where the river discharge is sufficiently important relative to tidal discharge to affect the velocity pattern.

By the 11th mile where tidal flow is dominant and fresh water flow has a negligible effect on velocities this type of bed change no longer occurs.

87. The second circulation system is not linked to changes in fresh water flow. The profiles show that there are short periods during which the whole of the upper compartment becomes an area of 'departure'. Material is scoured from the bed along the whole eight miles below the Dock Entrance and fairly large quantities leave the area altogether, perhaps travelling mainly in suspension. Scour is particularly heavy at the 8th mile, but elsewhere in the compartment a layer about one foot thick is eroded from the bed. In fact, in short periods fairly large quantities of material are being carried completely out of the upper estuary. The destination of this material, the 'arrival' area, is not known: it could be elsewhere in the Ribble estuary or right out to sea.

88. In the same way there are short periods during which this process is reversed. The whole of the upper compartment becomes an 'arrival' area and there is accretion all along its length, again with the change most marked at the 8th mile. Again, the source of this large quantity of material must be outside the upper compartment and the mode of transport is likely to be in suspension.

89. The question arises whether these two overlapping systems of accretion and erosion are self balancing or whether there is a tendency to progressive deterioration in the upper estuary. The bed movement between the first and seventh miles in sympathy with variations in fresh water flow, although it produces considerable local changes in depths, brings no new material into the channel, but merely redistributes what is already on the bed. At first sight the other periods of more general accretion along the whole stretch of the channel, alternating with other periods of general erosion, also appear to be self-balancing, at least over a long period. Fig 7 shows how mean bed levels at four, mile-long stretches fluctuated over the 37 fortnightly surveys carried out between 1963 and 1965. The general trend of the graphs indicates that despite the rapid short-term changes there is no progressive tendency towards rise of bed levels.

90. Unfortunately this at-first-sight favourable overall picture takes no account of the massive amount of dredging which was carried out between the Dock Entrance and the 6th mile during the period of the surveys and for many years before. Using the data in Table 1 the mean depth removed from the one mile stretch between the 1st and 2nd mile for each fortnight covered by the surveys have been calculated and are given in Table 9. The calculations are based on the assumption that the average width of dredging between the 1st and 2nd mile is 150 ft. In Fig 12, the actual mean bed levels between the 1st and 2nd mile are again plotted (full line) and the dredged depths from Table 9, have been added to show how levels could have risen cumulatively (dashed line) if no material had been removed by dredging. This graph slopes quite steeply upwards and therefore indicates a strong tendency to rapid progressive deterioration: in short there is a serious unbalance between accretion and

erosion in the upper stretch of the trained channel, which is only kept in check by continuous dredging.

91. Fig 12 also shows that without dredging bed levels between the 1st and 2nd mile could have reached a value of more than 9 ft above Ribble Datum, as compared with a maximum height of a little over 5 ft under actual conditions. However it is improbable that in the absence of dredging the bed of the channel would have risen to this extent. Rather some of the material arriving would have been re-circulated by increased natural erosion. The mean bed levels would tend to balance, as Fig 7 shows they do at the 8th mile, where practically no dredging takes place and where the rises and falls of bed levels are rather larger than further upstream. Undoubtedly the level at which natural balance would occur would be higher than the dredged level.

92. If one temporarily discounts the local redistribution of bed material caused by changes in fresh water flow and makes due allowance for dredging, the major problem in the landward stretch of the shipping channel is seen to be the arrival of very large supplies of sediments from an outside source. The sediments can raise the bed, as at the eight mile, by amounts greater than two feet in one fortnight. Although the accretion is likely to be self-regulating if the bed is allowed to rise to a sufficient height (as it already is at the eighth mile), it will always tend to continue to fill up the dredged channel. If the amount of dredging carried out is to be reduced, it is necessary first to trace the source of this material and then to consider how it can be discouraged from settling in the channel.

<u>The source of the fine material dredged from the landward end of the shipping channel.</u>

93. The radioactive tracer experiment, described fully in the supplementary report No. EX 280, was designed to check whether these large supplies of fine sands being removed from the upstream reach of the channel by dredging were being carried into the estuary along the bed of the channel from a source further to the seaward. A radioactive tracer was injected on to the bed of the channel at the 11th mile in September 1964. To make conditions as favourable as possible for an upstream movement of the tracer the injection was made during a period of low fresh water flow when upstream drift could be expected to be at its maximum. The particle size of the tracer was purposely matched to the fine sand in the dredged stretch from the 1st to the 6th mile and not to the coarser sand on the bed of the 11th mile itself. The subsequent excursion of the tracer showed a dispersion, largely confined to the channel, and of up to two miles in each direction , but no net drift upstream that would account for the large amounts dredged from the channel. This confirms the conclusion drawn from the velocity measurements shown on Fig. 11 that there is no net drift of material upstream at the 11th mile. The particle size analyses also show the bed material at the 11th mile as predominantly coarse (Fig 6) and the bed material in the dredged stretch as predominantly much finer. All these factors indicate that the problem material is not coming from a seaward source through

the low water channel itself.

94. Alternative sources have not been fully investigated and indeed are more difficult to investigate precisely, but experience of similar estuaries indicates only one likely source. Fresh water flow can be ruled out as negligible, even apart from the fact that increased fresh water flow tends to favour erosion rather than accretion. Several investigations, particularly in the Lune and Wyre, north of the Ribble, and in the Wash estuaries have shown that accretion at the rates experienced in the Ribble is often associated with a heavy suspended load picked up from silt banks outside the main low water channel. This material can settle in the upper part of the channel but not further seaward. In the Ribble such silt banks are very extensive particularly in the stretch seaward of the 7th mile (see Fig 1) where the estuary widens out and where there is a broadening belt of silt and sand banks between the edge of the salt marsh and the channel. These banks are subjected to surface scour from wave and tidal action and are interlaced by typical meandering creeks which indicate extensive side erosion in their downstream stretches. Suspended load samples here show high concentrations, although seaward samples (at Station D, seventeen miles seaward of the Dock Entrance, outside the training walls) show very low concentrations. It appears most likely that this is the source of the troublesome material.

VI. CONCLUSIONS AND RECOMMENDATIONS

The effect of permanently reducing fresh water flow

95. The investigation has confirmed the observations that the bed levels of the trained channel in the Ribble estuary between the Dock Entrance and the 3rd mile tend to rise under conditions of low fresh water flow. It has also been shown that this rise in levels goes hand in hand with an equivalent lowering of the channel bed between the 4th and 7th mile. Similarly, under conditions of high fresh water flow this situation is reversed and the channel bed is lowered between the Dock Entrance and 3rd mile and rises between the 4th and 7th mile. It follows that if the fresh water flow were permanently reduced by the river regulating reservoir on the Upper Ribble at Rathmell near Hellifield the resulting velocity patterns would tend to produce levels between the Dock Entrance and the 3rd mile higher than the present levels, and those between the 4th and 7th mile lower.

96. It has been demonstrated, however, both by the radioactive tracer experiment and by the comparison of velocity patterns in Fig 11 that this process does not in itself, bring about any net increase in the bed material in the channel. No additional material would travel up to the stretch between the 4th and 7th mile of the channel from the seaward to replace the bed material which has moved upstream. The effect of alterations in fresh water flow is merely to produce a local redistribution of material already present on the bed of the channel between the Dock Entrance and the 7th mile. The very large amount of material which Table 9 and Fig 12 show to be arriving in the first eight miles of the channel are not coming up the channel itself, and must therefore be coming from an outside source. The indications are that this material is arriving in suspension and that it is being picked up from the wide area of silt banks and mud flats where the estuary opens out seaward of the 7th mile. The rate at which this new material arrives in the landward reaches of the channel appears, from the investigation, to be quite independent of any variations in the rate of fresh water flow. The rate of arrival must be governed by the rate of departure from the supply area, i.e. probably by the amount of side erosion and wave action in the mud flat area under particular tidal and weather conditions.

97. Table 9 and Fig 12 show that the amounts of material arriving in the upstream stretch of the channel are very high. Under natural conditions, without dredging, these high amounts of silt and very fine sand would not continue to accumulate on the channel bed indefinitely. As the graph of mean bed levels at the 8th mile where no dredging is carried out shows, after a certain amount of accretion has altered local velocity patterns, there tends

to be an equivalent erosion phase and the bed rises and falls in level between definite limits (Fig 8). These fluctuations in bed levels tend to take no more than a fortnight and the rise and fall to be about two feet. There are few stable periods in between. In the dredged stretch of the estuary(Dock Entrance to 6th mile) it appears that the bed is very rarely allowed to rise to the regime levels at which natural erosion occurs and that almost the whole of the material arriving in the upper channel from outside is already being removed by dredging.

98. On the one hand this indicates the difficulty of using natural erosional forces to reduce the amount of maintenance dredging. On the other hand, since the channel is already being dredged below regime levels, any further deepening of the channel canneither increase the amount of sediments arriving from outside nor reduce much further the amount of natural erosion which is presumably minimal. The supply of sediments from outside is, over a long period of time, unlimited, but it cannot arrive at a tide to tide, or month to month rate greater than at present. It follows that if capital dredging were carried out along the first seven miles or so of trained channel sufficient to compensate for the loss of depths in the first three miles due to reduction in fresh water flow, there should be very little increase in the amount of subsequent maintenance dredging required to keep the improved depths. The channel would need to be dredged to a profile similar to that taken up during conditions of low fresh water flow to allow for the balance of bed load transport that occurs under these conditions.

99. There is supporting evidence for this conclusion that a deeper channel from the Dock Entrance to the 7th mile or so could be maintained by an amount of dredging similar to that at present, in Mr. Barron's book on the Ribble Navigation to which reference has already been made. On page 252 Mr. Barrom reproduces a graph of the mean bed levels of the trained channel between the Dock Entrance and the 8th mile at monthly intervals for the thirty years from 1906 to 1935 which shows how the bed of the upper reaches was deepened 4 ft by capital dredging between August 1919 and May 1926. Commenting on the result Mr. Barrom said (page 251): "It required an onslaught on the river bed in these six and a half years to have the desired effect, but the depth then gained has been retained ever since with the ordinary amount of maintenance ... This shows that once obtained the extra depth can be kept by the same amount of maintenance as before...".

100. The conclusion about a reduction in fresh water flow, then, which has been drawn from the evidence analysed in this report, is that the permanent abstraction of fresh water flow from the Upper Ribble will not involve the Port of Preston Authority in expenditure for maintenance dredging appreciably greater than at present, provided that the need for capital dredging to counteract the initial local accretion is accepted.

Reduction in maintenance dredging in the stretch between the Dock Entrance and the 6th mile.

101. Since depths in the upper stretch of the trained shipping channel are below natural regime depths, natural erosional forces cannot be harnessed to reduce the amount of dredging carried out. The only alternative is to try to reduce the amount of material reaching the upper channel either by blocking its path or by tackling the supply area.

102. Before 1840, when the Ribble training works were begun, the low water channel meandered through a broad area of silt and sand banks on a continually changing course. This meandering action was in itself the main erosional mechanism which kept the estuary in balance. In the course of its meanderings it cut down the central silt banks and kept the material in them in continual circulation. Most estuaries tend to accumulate supplies of silts and fine sands. Probably, over a geological time scale, they are washed out of the seaward sand by wave action and carried down from the land by the rivers. These fine sands and silts are trapped by the tidal action in the estuary and are continually re-worked to and fro. They settle on the bed under calm conditions and build up in layered deposits. They are cut back into suspension by side erosion during the fluctuations of the channel and by bed scour. If the erosional forces are reduced in some stretches, the accretional phase of the circulation goes on unchecked and the material becomes consolidated as salt marsh. This occurred in the Ribble in the middle of the 19th century when the powerful erosional mechanism of meandering was suppressed by training the low water channel. There was then a considerable advance in salt marsh, right to the training walls up to the 7th mile. Beyond the 7th mile, where the estuary widens out, there was some advance of saltings along the margins but there still remains a large area of unconsolidated silt banks, where smaller scale erosional forces like meandering drainage creeks, scar erosion and surface scour due to wave action keep the surface of the silt banks and mud flats continually changing and the silt in circulation. These processes have been studied in various estuaries (Ref 2 and 3). In the Wash it was shown that silt picked up from marginal mud flat areas was the source of heavy concentrations of suspended load entering the Wash rivers and causing siltation at their upstream ends.

103. The field investigation carried out in the Ribble estuary has not been particularly directed towards studying the flanking shoal areas. However, from experience in other estuaries it appears that the mud flat area seaward of the 7th mile is the only possible source of the material being dredged between the Dock Entrance and the 6th mile, and hence the best way of improving conditions permanently would be by raising the height of the training walls substantially from about the 7th mile seawards. This would help immediately by preventing suspended load being washed into the channel in appreciable quantities and eventually, by causing a further consolidation of the silt area into new saltings, it would permanently reduce the supply of silt and fine sand.

Reduction in dredging at the seaward end of the training walls

104. In the stretch between the 13th and 15th mile, the other area of heavy dredging, the bed material is coarser and moves principally as bed load. The analysis of the evidence in Section IV suggested that a separate flood channel, the South Gut, had developed which was outflanking the trained shipping channel. Shoaling in the main channel was caused by cross currents between the two channels, which carried material from the flood channel into the shipping channel during the rising tide. There is some evidence that the cycle of changes taking place in this stretch is reaching a phase in which the shoaling will be rather less than it has been in the recent past and the repair of gaps in the south training wall should help to reduce the amount of dredging. However, the long term solution appears to be a raising of the height of the training walls, designed to suppress the cross currents and hence to prevent the transfer of material from the South Gut into the trained shipping channel.

Details of raising the training walls

105. In putting forward the single solution -raising the height of the training walls - for both problem areas, there are a number of technical details which should be briefly mentioned. In the first place it would not be necessary to raise the walls all along their lengths from the Dock Entrance, but only from the 7th mile or so onwards, for where the saltings have already advanced to the edge of the training wall, as they have done along the first seven miles, no further changes can be expected. Also, the raising of both walls would have to be carried out in such a way that it did not decrease the width of the trained channel. The gap in the south training wall to admit the River Douglas and that in the north wall opposite Lytham could be left. The seaward end of the north wall should be extended so as to prevent Salters Spit (see Fig 3) from encroaching on the channel. It would be desirable to extend both walls to the 16th mile, to have a more powerful effect both on suppressing the South Gut and on consolidating the silt and fine sand supplies outside the trained channel further upstream into permanent saltings. Once the south wall between the 13th and 15th mile has been raised the area of the flood channel behind it should be used as a dumping ground for dredged material so as to speed up the process of eliminating that channel from the vicinity of the shipping channel.

106. However, there remains the question, to what height the training walls should be raised? In the Outer Elbe it was tackled initially by float tracking and a model study, but ultimately a pragmatic approach had to be adopted in which both the final length and final height of the guide wall was decided in the light of the actual results obtained. This leads to the consideration of a similarly pragmatic approach being adopted in the Ribble estuary.

107. Unfortunately, this is the kind of problem on which a very large amount of further expenditure on field and model investigations could be incured with a very small reward in firm, quantitative results. It is known that raising training walls will cause a further advance in salt marsh, but in the present state of knowledge it is not really possible to say what the ultimate extent of that advance will be. In the same way, although it is clear that raising the

training walls should prevent sand from being carried across from the South Gut into the main channel in the 13th to 15th mile stretch, the Outer Elbe experience, where very extensive field and model experiments were carried out on a similar problem, showed that it was only by pragmatic experiment in the prototype that the minimum works to achieve the necessary suppression of cross currents could be designed and built.

108. If the Port of Preston Authority is prepared to give serious consideration to the raising of their training walls, a limited amount of further field observations might be advisable, but they should be kept to the minimum. A model experiment is not recommended. Any raising of the walls would be better carried out in stages. If the ultimate increase in the height of the walls necessary were to be of the order of, say, 15 ft from the 7th mile to about the 15th mile, this might be carried out in three stages of 5 ft each. Careful observations of changes brought about by the first stage would make it easier to assess the minimum works necessary to suppress shoaling in the channel and give early indications of any side effects.

109. Short of engineering works on this scale it will be difficult to bring about any substantial reduction in the amount of maintenance dredging carried out. Conditions in the seaward stretch may, nevertheless, tend to improve somewhat in the coming years and should be helped by the repair of the breaches in the training walls.

REFERENCES

1. Inglis, C.C. and Kestner, F.J.T. The long-term effects of training walls, reclamation and dredging on estuaries. Proc. Instn.Civ.Engrs., Vol. 9, pp. 193-216, March 1958.

2. Inglis, C.C. and Kestner, F.J.T. Changes in the Wash as affected by training walls and reclamation works. Proc. Instn. Civ. Engrs., Vol. 11, pp 435-466, December 1958.

3. Kestner, F.J.T. The supply and circulation of silt in the Wash. I.A.H.R. Congress, London, September 1963.

TABLE 1. DREDGING OUTPUT IN EACH MILE OF CHANNEL FROM 1st JULY 1963 TO 18th JANUARY 1965 - CUBIC YARDS

No. of Profile	Date of Previous Profile	Date of Profile	Dock	Entrance - 1st Mile	1st-2nd Mile	2nd-3rd Mile	3rd-4th Mile	4th-5th Mile	5th-6th Mile	6th-7th Mile	7th-8th Mile	8th-9th Mile	9th-10th Mile	10th-11th Mile	11th-12th mile	12th-13th Mile	13th-14th Mile	14th-15th Mile	15th-16th Mile	Total D.E. -16th Mile
12/63 1		1-7-63																		
2	1-7-63	15-7		30890	7960	2500	0	2080	3020	0	0	5900	26980	0	0	0	0	0	0	
3	15-7	30-7		32005	6570	11310	2900	2865	13340	0	0	3000	4140	0	0	0	8800	0	0	
4	30-7	14-8		20945	7470	15190	0	930	7915	0	0	0	0	0	0	0	26400	0	0	
5	14-8	27-8		13500	320	9500	0	4830	9500	0	0	0	0	0	0	0	12000	0	0	
6	27-8	13-9		17160	2800	14380	0	5550	5185	0	0	1000	6130	0	0	0	17255	40450	0	
7	13-9	25-9		800	0	0	0	0	0	0	0	0	400	0	0	0	0	0	0	
8	25-9	14-10		21240	0	700	2700	800	11310	0	0	0	2900	0	0	0	0	5600	0	
10	14-10	28-10		24400	620	4600	10970	1225	17750	0	0	0	3755	0	0	0	0	27450	1300	
11	28-10	11-11		21695	5500	6800	800	1620	850	0	0	0	465	0	0	0	0	35650	0	
13	11-11	27-11	p	16925	0	1400	0	1000	1400	0	0	0	22300	0	0	0	0	46600	0	
14	27-11	12-12	a	37330	460	4360	0	7500	3950	0	0	0	4790	0	0	0	0	77770	4100	
15	12-12	23-12	a	15400	465	1200	2900	4850	1710	0	0	0	0	0	0	0	0	23000	0	
12/64 1	23-12	9-1-64	a	17400	100	100	0	5850	6615	0	0	0	450	0	0	0	0	18150	1400	
2	9-1-64	23-1	a	25000	1240	0	950	6750	5665	0	0	0	1500	0	0	0	0	63450	2800	
3	23-1	10-2		24300	5180	6050	950	5150	6185	0	0	0	1000	0	0	0	0	11500	6300	
4	10-2	25-2		32300	8920	4200	0	8100	7500	0	0	0	1815	0	0	0	0	49145	1200	
5	25-2	11-3	a	30800	9860	3450	0	850	6440	0	0	0	0	0	0	0	0	84260	0	
6	11-3	24-3	p	9700	1140	800	0	0	3250	0	0	0	0	0	0	0	0	60080	0	
7	24-3	8-4	a	9000	3630	1200	0	950	8700	0	0	0	1560	0	0	0	0	42470	0	
8	8-4	22-4	a	21300	8910	5690	450	2960	3635	0	0	0	3265	0	0	0	0	64160	0	
9	22-4	6-5		18900	10700	8230	1150	950	10720	0	900	0	5920	0	0	0	0	45950	0	
10	6-5	20-5		19800	7250	7090	2200	5200	6815	0	0	0	4565	0	0	0	4400	27800	0	
11	20-5	1-6		16800	12500	420	0	0	2350	0	0	0	0	0	0	0	10680	64200	0	
12	1-6	25-6		59100	13260	5130	1780	1500	2200	0	0	0	2980	0	0	0	22880	85190	1200	
13	25-6	20-7	a	58100	9020	550	0	870	1800	0	0	0	11300	0	0	0	19000	42290	0	
14	20-7	4-8	a	24100	8710	4140	3950	1700	13610	0	0	0	2700	0	0	0	21360	45550	0	
15	4-8	18-8	a	25500	420	3200	11850	0	2470	0	900	0	400	0	0	0	30100	58250	0	
16	18-8	2-9	a	28600	6693	7115	0	950	4715	0	0	0	6300	0	0	0	19770	50250	0	
17	2-9	14-9	a	31300	5450	9400	0	2500	17820	0	0	0	0	0	0	0	3570	16780	0	
13.9.63 - 14.9.64 i.e. year 1963/64			p	589790	120028	85825	40650	61275	147460	0	1800	0	78365	0	0	0	131760	1045545	18300	2320798
18	14-9	1-10	a	45300	5400	4550	0	1000	7320	0	4500	0	650	0	0	0	17800	35300	0	
19	1-10	15-10	a	33700	5630	5600	950	0	5235	0	0	0	0	0	0	0	16250	29050	2200	
20	15-10	26-10		25700	2900	950	0	1950	3370	0	0	0	0	0	0	0	20460	29470	3800	
21	26-10	17-11	a	35900	2460	3970	0	0	900	0	0	0	2460	0	0	0	19320	70030	2600	
22	17-11	30-11	a	22500	1450	3950	1000	600	12100	0	1400	0	1400	0	0	0	6600	21460	1300	
25	30-11	14-12	a	19700	0	1200	0	1600	2910	0	0	0	1900	0	0	0	4420	26600	1400	
12/65 1	14-12	18-1-65		0	2950	0	1000	14450	13100	0	0	0	6665	0	0	0	6810	15000	0	

p: part pumped ashore.   a: all pumped ashore

TABLE 2.

DISTRIBUTION OF DREDGING OUTPUT IN THE YEAR 1963/64

Mileage	Cubic Yards	%	%	%
0 - 1	589790	25.4		
1 - 2	120028	5.2		
2 - 3	85825	3.7		
3 - 4	40650	1.8		
4 - 5	61275	2.6		
5 - 6	147460	6.4		
0 - 6	1045028		45.0	
6 - 7	0	0.0		
7 - 8	1800	0.1		
8 - 9	0	0.0		
9 - 10	78365	3.4		
10 - 11	0	0.0		
11 - 12	0	0.0		
12 - 13	0	0.0		
6 - 13	80165		3.5	
13 - 14	131760	5.7		
14 - 15	1045545	45.1		
15 - 16	18300	0.8		
13 - 16	1195605		51.5	
0 - 16	2320798			100.0

TABLE 3

ANNUAL DREDGING OUTPUT IN EACH MILE OF CHANNEL FROM 1949 TO 1963. CUBIC YARDS.

Year	0 - 1	1 - 2	2 -3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 11	11 - 12	12 - 13	13 - 14	14 - 15	15 - 16	Total 0 - 16
1949	236660	9800	72810	14400	408680	196550	3480	29295	350500	64560	57640	100860	18760	0	0	48870	1618715
1950	99470	34090	157170	133600	419180	360560	6800	66400	343290	195940	155220	78080	0	0	0	17360	2083170
1951	6910	43090	92850	52740	272200	294170	8790	127040	334720	294740	188830	53890	4360	0	6760	93060	1873149
1952	9670	2610	62300	58590	137720	252140	0	77410	361380	92820	118370	4500	1500	4500	0	139720	1323230
1953	165025	66050	96500	77950	128985	224425	1330	60815	128700	211436	30380	19960	26800	50830	21920	197530	1508680
1954	24965	4750	34650	41075	130840	277735	0	87630	44755	185005	0	2820	10430	259580	257225	13800	1362270
1955	52700	5620	16480	45670	275215	316100	465	71120	12930	203535	400	2540	16530	246000	110575	45460	1421340
1956	214109	60475	85450	73765	253300	254245	0	16725	1500	105765	1675	3280	3865	299230	26685	11300	1418469
1957	169005	23165	36580	26225	238400	312315	0	34130	1960	118330	2210	0	16390	473325	23970	0	1476005
1958	69535	156630	84690	14075	273230	222860	1400	42460	1400	41605	5105	0	4910	907150	222080	106390	2155910
1959	597780	247085	110910	23190	247870	155060	1270	36340	800	6550	480	0	525	277310	50840	1500	1760970
1960	166055	14980	45160	5400	252160	182810	0	65775	0	53580	0	1300	900	702945	185550	0	1674505
1961	21620	0	7310	9685	219845	195805	0	74480	0	17895	0	0	0	337520	545165	30410	1494025
1962	172185	17710	10400	2900	87850	137205	0	51100	44850	49755	0	0	0	509725	846910	101800	2037190
1963	484126	142726	123610	13500	57515	122040	0	5000	33900	135225	0	0	0	378500	852615	43450	2258455

TABLE 4

DISTRIBUTION OF DREDGING OUTPUT AT THE SEAWARD END OF THE TRAINING WALLS FROM 1949 TO 1963 - CUBIC YARDS.

Year	Period	13 - 14	14 - 15	13 - 15
1949		0	0	0
1950		0	0	0
1951		0	6760	6760
1952		4500	0	4500
1953		50830	21920	72750
	1949-53	55330	28680	84010
1954		259580	257225	516805
1955		246000	110575	356575
1956		299230	26685	325915
1957		473325	23970	497295
	1954-57	1278135	418455	1696590
1958		907150	222080	1129230
1959		277310	50840	328150
1960		702945	185550	888495
1961		337520	545165	882685
1962		509725	846910	1356635
	1958-62	2734650	1850545	4585195
1963		378500	852615	1231115

TABLE 5

MEAN BED LEVELS BETWEEN 1st & 2nd MILE (ABOVE OR BELOW RIBBLE DATUM)

No. of Profile	Date of Profile	Bed levels between 1st and 2nd mile Feet and Inches 1	$1\frac{1}{4}$	$1\frac{1}{2}$	$1\frac{3}{4}$	2	Σ	Mean ft
12/63/1	1-7-63	6.0	6.0	6.0	4.9	4.6	27.25	5.45
2	15-7	2.3	5.6	5.6	4.9	4.3	22.25	4.45
3	30-7	3.9	5.6	5.6	4.9	4.3	23.75	4.75
4	14-8	5.0	5.9	5.0	5.0	4.0	24.75	4.95
5	27-8	6.0	3.0	5.6	5.0	4.0	23.50	4.70
6	13-9	6.0	6.0	5.9	5.3	4.0	27.00	5.40
7	25-9	7.3	4.9	5.9	4.9	4.0	26.50	5.30
8	14-10	4.6	5.0	4.6	4.0	3.0	21.00	4.20
10	28-10	4.6	5.9	4.6	3.6	3.6	21.75	4.35
11	11-11	4.3	5.6	4.9	3.9	3.0	21.25	4.25
13	27-11	2.3	3.0	2.9	2.6	2.3	12.75	2.55
14	12-12	3.3	4.3	3.6	2.9	2.6	16.25	3.25
15	23-12	4.3	3.9	4.0	2.9	2.3	17.00	3.40
12/64/1	9-1-64	4.0	4.6	4.0	3.0	3.0	18.50	3.70
2	23-1	5.0	4.0	3.9	2.6	2.0	17.25	3.45
3	10-2	5.0	5.0	5.0	4.0	3.3	22.25	4.45
4	25-2	1.6	4.6	4.6	3.0	3.0	16.50	3.30
5	11-3	1.6	4.0	4.6	3.0	3.0	16.00	3.20
6	24-3	3.3	5.0	4.9	2.6	3.0	18.50	3.70
7	8-4	4.6	5.0	4.9	3.3	3.0	20.25	4.05
8	22-4	6.0	5.3	5.0	4.0	3.0	23.25	4.65
9	6-5	5.6	5.6	5.3	3.9	3.3	23.25	4.65
10	20-5	4.6	5.0	5.0	3.3	3.3	21.00	4.20
11	1-6	5.0	5.0	3.6	4.0	2.6	20.00	4.00
12	25-6	5.9	5.3	3.0	3.0	3.3	20.25	4.05
13	20-7	4.3	5.3	5.0	3.0	3.6	21.00	4.20
14	4-8	6.0	0.0	5.6	3.0	3.3	17.75	3.55
15	18-8	5.9	-3.0	4.9	2.9	3.0	13.25	2.65
16	2-9	1.0	0.0	5.3	4.0	3.6	13.75	2.75
17	14-9	3.0	5.0	3.0	2.0	3.9	16.75	3.35
18	1-10	5.3	5.0	3.6	3.9	3.0	20.50	4.10
19	15-10	4.3	4.6	4.6	3.9	3.3	20.25	4.05
20	26-10	5.0	5.0	4.0	3.3	3.0	20.25	4.05
21	17-11	5.6	1.3	4.9	3.6	3.0	18.00	3.60
22	30-11	4.9	3.9	3.9	3.6	3.0	18.75	3.75
25	14-12	0.0	2.0	-0.6	-1.3	0.0	0.25	0.05
12/65/ 1	18-1-65	-1.0	0.3	0.0	-1.6	-0.9	- 3.00	-0.60

TABLE 6

MEAN BED LEVELS BETWEEN 6th & 7th MILE (ABOVE OR BELOW RIBBLE DATUM)

No. of Profile	Date of Profile	Bed levels between 6th & 7th Mile Feet and Inches 6	$6\frac{1}{4}$	$6\frac{1}{2}$	$6\frac{3}{4}$	7	Σ	Mean ft
12/63/1	1-7-63	0.0	1.0	0.9	0.3	-1.0	1.00	0.20
2	15-7	-1.3	-0.9	0.0	-1.3	-1.6	-4.75	-0.95
3	30-7	-1.9	0.0	0.0	0.0	-2.6	-4.25	-0.85
4	14-8	-1.0	0.0	0.6	-2.9	-3.0	-6.25	-1.25
5	27-8	1.3	-0.3	1.0	1.6	-1.6	2.00	0.40
6	13-9	-0.3	1.0	0.3	-1.9	-2.0	-2.75	-0.55
7	25-9	-1.0	0.9	-0.9	-2.6	-2.0	-5.50	-1.10
8	14-10	2.3	1.9	1.6	0.9	0.0	6.25	1.25
10	28-10	1.6	1.0	1.3	0.0	- 0.9	3.00	0.60
11	11-11	1.3	1.0	1.0	0.0	0.0	3.25	0.65
13	27-11	2.0	1.9	1.6	2.0	0.0	7.25	1.45
14	12-12	1.6	1.0	1.0	0.3	0.0	3.75	0.75
15	23-12	1.0	0.9	0.9	0.9	-0.6	2.75	0.55
12/64/1	9-1-64	1.0	1.0	0.9	-0.3	0.0	2.50	0.50
2	23-1	0.6	0.0	0.6	0.6	-1.0	0.50	0.10
3	10-2	1.3	0.9	1.0	0.0	-0.6	2.50	0.50
4	25-2	1.0	1.0	0.9	0.0	-0.6	2.25	0.45
5	11-3	0.0	0.6	0.0	-0.3	-1.0	-0,75	-0.15
6	24-3	0.9	0.3	0.0	-1.0	-1.0	-1.00	-0.20
7	8-4	1.0	0.6	0.0	-1.0	-1.3	-0.75	-0.15
8	22-4	0.6	0.9	1.0	0.0	-0.9	1.50	0.30
9	6-5	0.3	0.3	0.0	-1.0	-1.0	-1.50	-0.30
10	20-5	1.3	0.6	0.9	-1.0	-0.3	-1.25	-0.25
11	1-6	1.0	0.0	0.3	0.3	-2.0	-0.50	-0.10
12	25-6	0.9	1.0	-0.3	-1.0	-0.3	0.25	0.05
13	20-7	1.0	-0.3	0.9	-2.0	-3.0	-3.50	-0.70
14	4-8	-0.6	-0.6	0.0	-3.3	-1.0	-5.25	-1.05
15	18-8	0.0	0.3	-0.9	-2.3	-1.0	-3.75	-0.75
16	2-9	-1.0	-0.6	1.0	-2.0	0.0	-2.50	-0.50
17	14-9	-0.3	1.9	-0.6	-0.9	-1.3	-1.00	-0.20
18	1-10	0.0	1.3	-1.0	-0.3	-2.0	-2.00	-0.40
19	15-10	0.6	1.3	0.6	0.0	-0.6	1.75	0.35
20	26-10	0.3	0.3	0.0	-1.3	0.0	-o.75	-0.15
21	17-11	0.0	1.0	-0.6	-2.0	-1.0	-2.50	-0.50
22	30-11	0.0	0.0	-0.6	-1.0	-0.9	-2.25	-0.45
25	14-12	2.3	2.6	2.6	2.6	-0.6	9.25	1.85
12/65/ 1	18-1-65	2.0	2.3	2.0	1.9	1.3	9.25	1.85

TABLE 7

MEAN BED LEVELS BETWEEN $7\frac{1}{2}$ & $8\frac{1}{2}$ MILE (BELOW RIBBLE DATUM)

No. of Profile	Date of Profile	Bed levels between $7\frac{1}{2}$ & $8\frac{1}{2}$ mile Feet and Inches $7\frac{1}{2}$	$7\frac{3}{4}$	8	$8\frac{1}{4}$	$8\frac{1}{2}$	Σ	Mean ft
12/63/1	1-7-63	-0.3	-2.6	-1.0	-4.6	-2.6	-10.75	-2.15
2	15-7	0.0	-0.6	-0.6	-2.3	-1.6	- 4.75	-0.95
3	30-7	0.3	-1.6	-4.0	-3.0	-1.3	- 9.50	-1.90
4	14-8	0.0	-2.0	-3.0	-0.9	-2.6	- 8.25	-1.65
5	27-8	-0.6	-2.0	-6.6	-6.0	not surv.	-15.00	-3.75
6	13-9	-1.0	-2.3	-2.6	-2.9	not surv.	- 8.50	-2.13
7	25.9	-1.0	-3.9	-4.9	-3.3	-0.3	-13.00	-2.60
8	14-10	0.0	-0.9	-1.6	-2.0	-0.3	- 4.50	-0.90
10	28-10	0.0	-0.6	0.0	-2.6	-1.0	- 4.00	-0.80
11	11-11	0.0	0.0	-0.9	-1.0	-1.0	- 2.75	-0.55
13	27-11	0.0	-1.6	-3.0	-3.9	-0.9	- 9.00	-1.80
14	12-12	0.0	-0.3	-1.0	-2.0	-1.0	- 4.25	-0.85
15	23-12	-1.0	-2.6	-3.0	-3.9	not surv.	-10.25	-2.56
12/64/1	9-1-64	0.0	0.0	-0.3	-2.9	-1.3	- 4.25	-0.85
2	23-1	-1.3	-3.9	-5.6	-5.0	-3.0	-18.50	-3.70
3	10-2	-0.6	-3.0	-3.0	-4.0	-1.6	-12.00	-2.40
4	25-2	-0.3	-1.0	-2.6	-4.6	-2.3	-10.50	-2.10
5	11-3	-0.9	-2.0	-2.0	-3.3	-3.0	-11.00	-2.20
6	24-3	-0.6	-1.0	-1.0	-2.0	-2.6	- 7.00	-1.40
7	8-4	-0.3	-1.3	-1.9	-2.0	-2.0	- 7.25	-1.45
8	22-4	0.0	-1.0	-1.3	-3.0	-2.0	- 7.25	-1.45
9	6-5	-0.6	-2.0	-3.6	-3.0	-1.6	-10.50	-2.10
10	20-5	-0.3	-2.3	-2.6	-4.0	-1.3	-10.25	-2.05
11	1-6	0.0	-3.6	-3.3	-4.6	-1.0	-12.25	-2.45
12	25-6	0.6	-1.3	-0.6	0.0	-0.3	- 1.50	-0.30
13	20-7	-2.0	-1.0	0.0	-1.0	-0,6	- 4.50	-0.90
14	4-8	-0.6	-0.3	-2.0	-1.0	-0.6	- 4.25	-0.85
15	18-8	0.0	0.3	-3.9	-2.3	-0.9	- 6.50	-1.30
16	2-9	-3.3	-3.9	-2.3	-3.6	0.0	-12.75	-2.55
17	14-9	-2.3	-1.0	-2.0	-2.6	-0.6	- 8.25	-1.65
18	1-10	-2.6	-4.3	-4.6	-3.0	0.0	-14.25	-2.85
19	15-10	-1.0	-0.9	-2.0	-3.0	0.3	- 6.50	-1.30
20	26-10	-1.6	0.0	-3.9	-3.0	-1.0	- 9.25	-1.85
21	17-11	-2.6	-1.9	-2.6	-3.0	-1.3	-11.00	-2.20
22	30-11	-2.3	-0.9	-2.0	-3.0	-3.6	-11.50	-2.30
25	14-12	-1.9	-1.3	-2.9	-3.0	-1.0	- 9.75	-1.95
12/65/1	18-1-65	-0.3	0.3	-0.3	-1.6	-0. 3	- 2.00	-0.40

TABLE 8

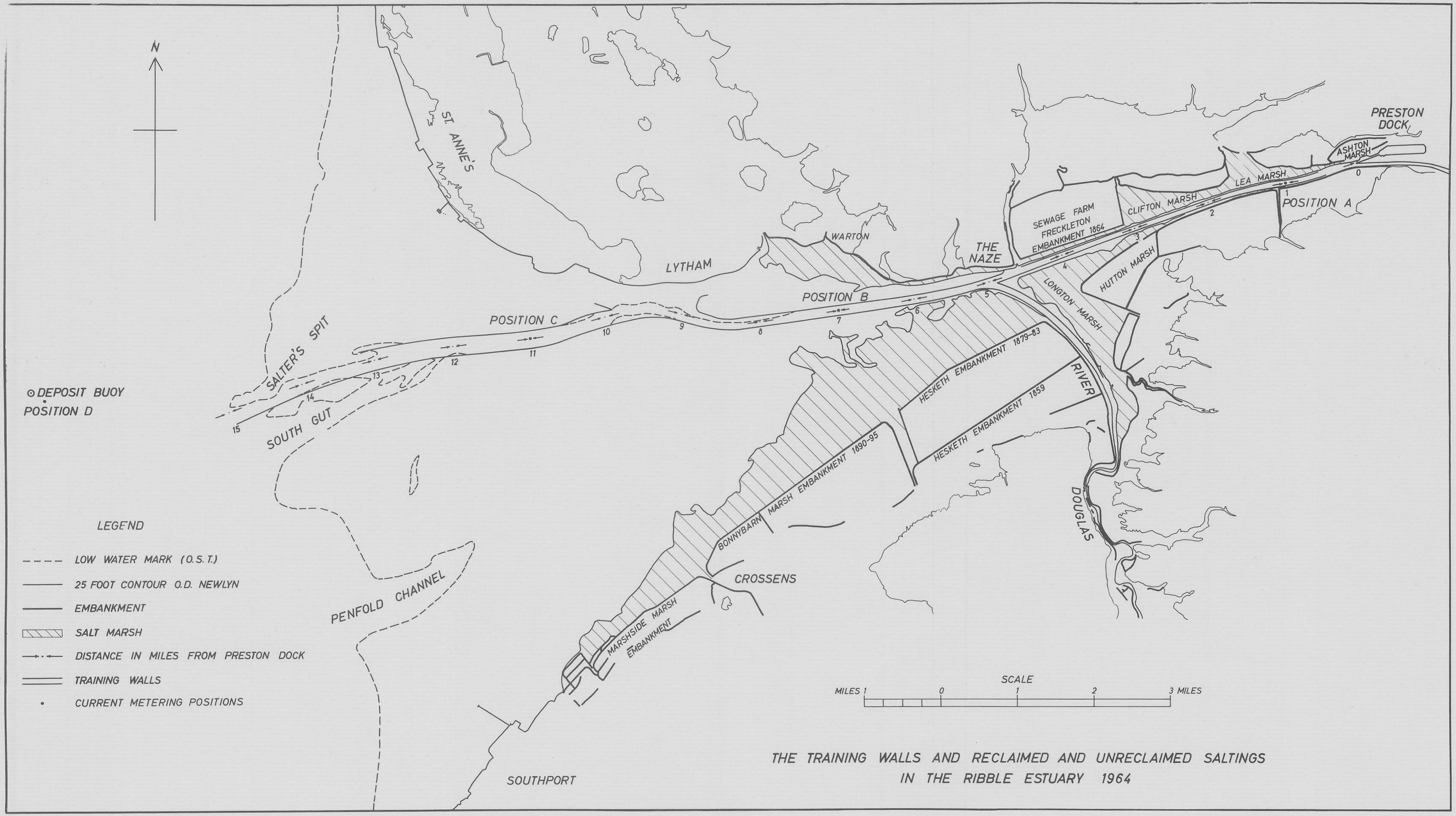
MEAN BED LEVELS BETWEEN 10½ & 11½ MILE (BELOW RIBBLE DATUM)

No. of Profile	Date of Profile	Bed levels between 10½ and 11½ mile Feet and Inches 10½	10¾	11	11¼	11½		Mean ft.
12/63/1	1-7-63	-10.3	-8.9	-9.6	-10.9	-12.6	-51.75	-10.35
2	15-7	-10.0	-9.0	-9.0	-10.0	-13.3	-51.25	-10.25
3	30-7	-10.0	-8.6	-8.6	- 9.9	-13.0	-49.75	- 9.95
4	14-8	-10.0	-9.0	-9.0	-10.6	-13.0	-51.50	-10.30
5	27-8	not surv.	not surv.	not surv.	not surv,	not surv.		
6	13-9	not surv	not surv.	not surv.	not surv.	not surv.		
7	25-9	-10.0	-8.9	-8.0	-10.6	-14.9	-52.00	-10.40
8	14-10	- 9.6	-8.0	-8.9	-10.0	-12.9	-49.00	- 9.80
10	28-10	- 9.3	-8.9	-8.6	- 9.3	-12.9	-48.50	- 9.70
11	11-11	- 9.6	-8.3	-9.0	- 9.9	-12.3	-48.75	- 9.75
13	27-11	- 8.3	-8.6	-9.0	- 9.3	-12.0	-47.00	- 9.40
14	12-12	- 8.0	-8.3	-9.3	-10.3	-13.0	-48.75	- 9.75
15	23-12	not surv.	notsurv.	not surv.	not surv.	not surv.		
12/64/1	9-1-64	- 9.0	-9.0	-9.3	-10.0	-13.0	-50.25	-10.05
2	23-1	- 9.0	-9.6	-9.0	- 9.3	-13.0	-49.75	- 9.95
3	10-2	- 9.0	-8.3	-8.3	- 8.9	-11.0	-45.25	- 9.05
4	25-2	- 9.6	-8.3	-8.0	-10.0	-12.6	-48.25	- 9.65
5	11-3	- 9.0	-9.0	-8.0	- 9.6	-12.3	-47.75	- 9.55
6	24-3	- 9.3	-9.0	-8.9	- 9.0	-12.3	-48.25	- 9.65
7	8-4	- 9.9	-9.0	-9.0	-10.0	-12.6	-50.25	-10.05
8	22-4	- 9.6	-8.3	-8.9	- 9.0	-12.0	-47.50	- 9.50
9	6-5	- 9.3	-8.3	-8.6	- 9.0	-12.3	-47.25	- 9.45
10	20-5	- 9.0	-8.3	-8.0	- 8.9	-11.9	-45.75	- 9.15
11	1-6	- 8.6	-8.6	-9.0	- 9.9	-12.6	-48.25	- 9.65
12	25-6	- 9.0	-7.9	-8.0	- 9.6	-12.0	-46.25	- 9.25
13	20-7	- 8.9	-8.0	-8.6	- 9.6	-12.6	-47.25	- 9.45
14	4-8	- 9.0	-8.0	-8.9	- 9.0	-12.6	-47.25	- 9.45
15	18-8	- 9.0	-8.3	-9.0	-10.0	-13.0	-49.25	- 9.85
16	2-9	- 9.0	-8.0	-8.0	- 9.3	-12.3	-46.50	- 9.30
17	14-9	not surv.	not surv.	not surv.	not surv.	not surv.		
18	1-10	- 9.0	-8.3	-8.6	- 9.0	-12.6	-47.25	- 9.45
19	15-10	- 8.6	-8.0	-9.0	- 9.9	-12.3	-47.50	- 9.50
20	26-10	- 8.9	-7.3	-8.6	- 9.6	-13.0	-47.00	- 9.40
21	17-11	- 8.9	-9.0	-8.9	- 9.3	-12.6	-48.25	- 9.65
22	30-11	not surv.	not surv.	not surv.	not surv.	not surv.		
25	14-12	- 8.3	-7.9	-8.9	- 9.9	-13.0	-47.50	- 9.50
12/65/1	18-1-65	- 7.6	-7.0	-8.3	- 9.6	-12.3	-44.50	- 8.90

TABLE 9

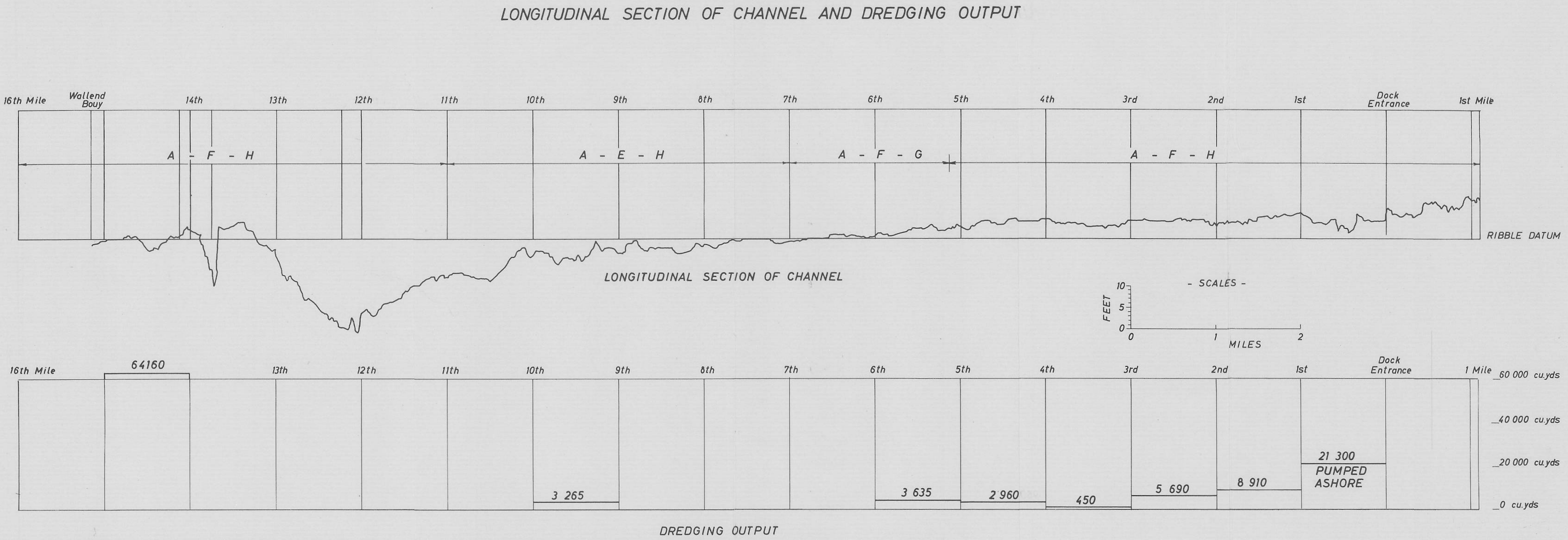
MEAN DEPTHS REMOVED BY DREDGING BETWEEN 1st AND 2nd MILE

No. Of Profile	Date of Previous Profile	Date of Profile	Dredging Output Between 1st & 2nd Mile Cubic Yards	Actual Mean Bed Levels Between 1st & 2nd Mile Feet	Calculated Dredged Depths Between 1st & 2nd Mile Feet	Accumulated Dredged Depths Between 1st & 2nd Mile Feet	Inferred Mean Bed Levels Between 1st & 2nd Mile without Dredging Feet
12/63/1		1-7-63		5.45		0.00	5.45
2	1-7-63	15-7	7960	4.45	0.27	0.27	4.72
3	15-7	30-7	6570	4.75	0.22	0.49	5.24
4	30-7	14-8	7470	4.95	0.25	0.74	5.69
5	14-8	27-8	320	4.70	0.01	0.75	5.45
6	27-8	13-9	2800	5.40	0.10	0.85	6.25
7	13-9	25-9	0	5.30	0.00	0.85	6.15
8	25-9	14-10	0	4.20	0.00	0.85	5.05
10	14-10	28-10	620	4.35	0.02	0.87	5.22
11	28-10	11-11	5500	4.25	0.19	1.06	5.31
13	11-11	27-11	0	2.55	0.00	1.06	3.61
14	27-11	12-12	460	3.25	0.02	1.08	4.33
15	12-12	23-12	465	3.40	0.02	1.10	4.50
12/64/1	23-12	9-1-64	100	3.70	0.00	1.10	4.80
2	9-1-64	23-1	1240	3.45	0.04	1.14	4.59
3	23-1	10-2	5180	4.45	0.18	1.32	5.77
4	10-2	25-2	8920	3.30	0.30	1.62	4.92
5	25-2	11-3	9860	3.20	0.34	1.96	5.16
6	11-3	24-3	1140	3.70	0.04	2,00	5.70
7	24-3	8-4	3630	4.05	0.12	2.12	6.17
8	8-4	22-4	8910	4.65	0.30	2.42	7.07
9	22-4	6-5	10700	4.65	0.36	2.78	7.43
10	6-5	20-5	7250	4.20	0.25	3.03	7.23
11	20-5	1-6	12500	4.00	0.43	3.46	7.46
12	1-6	25-6	13260	4.05	0.45	3.91	7.96
13	25-6	20-7	9020	4.20	0.31	4.22	8.42
14	20-7	4-8	8710	3.55	0.30	4.52	8.07
15	4-8	18-8	420	2.65	0.01	4.53	7.18
16	18-8	2-9	6693	2.75	0.23	4.76	7.51
17	2-9	14-9	5450	3.35	0.19	4.95	8.30
18	14-9	1-10	5400	4.10	0.18	5.13	9.23
19	1-10	15-10	5630	4.05	0.19	5.32	9.37
20	15-10	26-10	2900	4.05	0.10	4.42	9.47
21	26-10	17-11	2460	3.60	0.08	5.50	9.10
22	17-11	30-11	1450	3.75	0.05	5.55	9.30
25	30-11	14-12	0	0.05	0.00	5.55	5.60
12/65/1	14-12	18-1-65	2950	-0.60	0.10	5.65	5.05



THE TRAINING WALLS AND RECLAIMED AND UNRECLAIMED SALTINGS IN THE RIBBLE ESTUARY 1964

FIG 1



Dredging outputs shown are the amounts in cu.yds dredged in each mile between the date of this section and the date of the previous section i.e. 7 & 8/4/64

Date of Section 22/4/64 NO. 12/64/8

FIG 2

CONTOUR MAPS OF THE SEAWARD REACH SURVEYED IN 1963 AND 1964

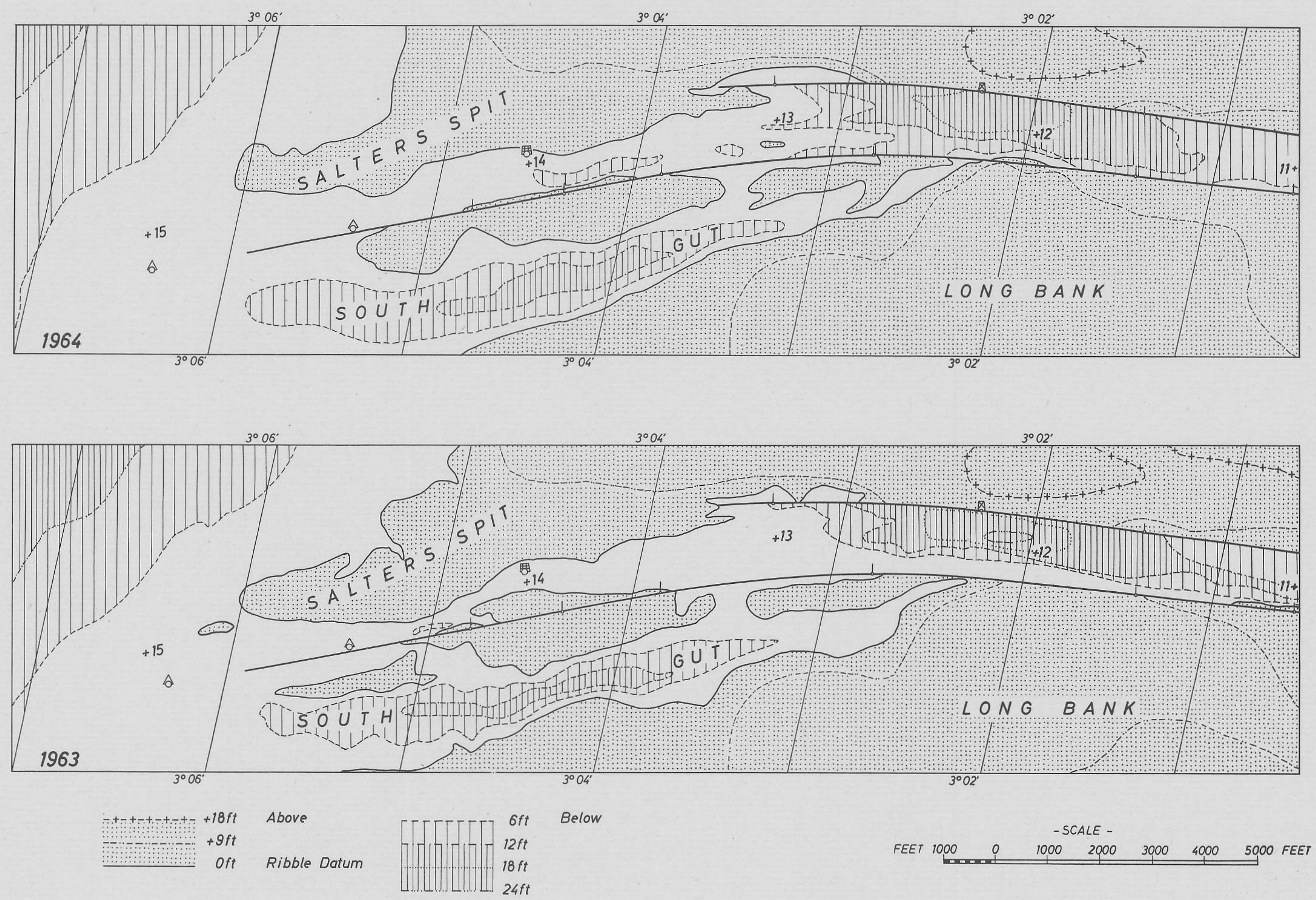


FIG 3

CONTOUR MAPS OF THE SEAWARD REACH SURVEYED IN 1947, 1953, 1957 AND 1962

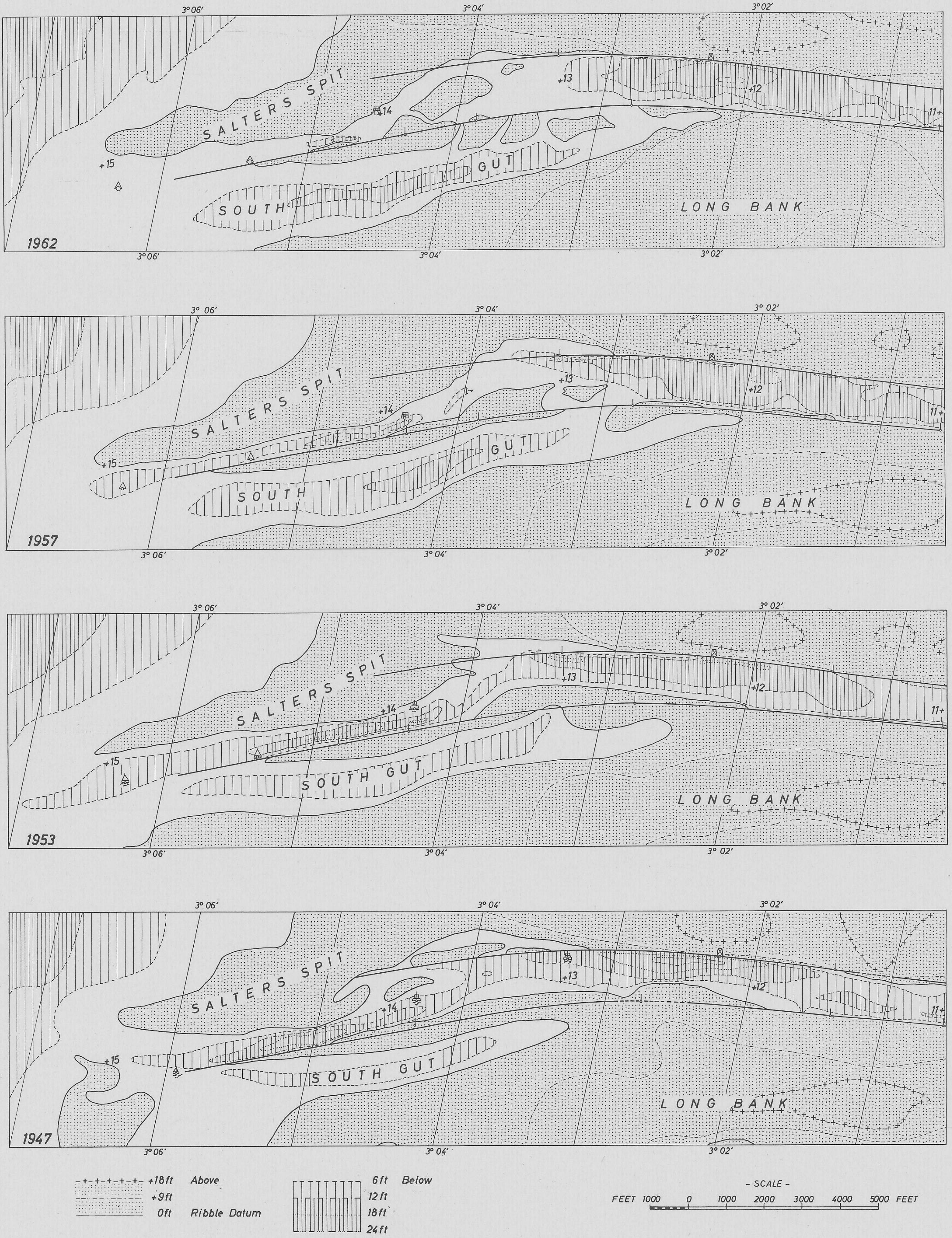


FIG 4

OUTER ELBE
Divided Flood and Ebb Channel

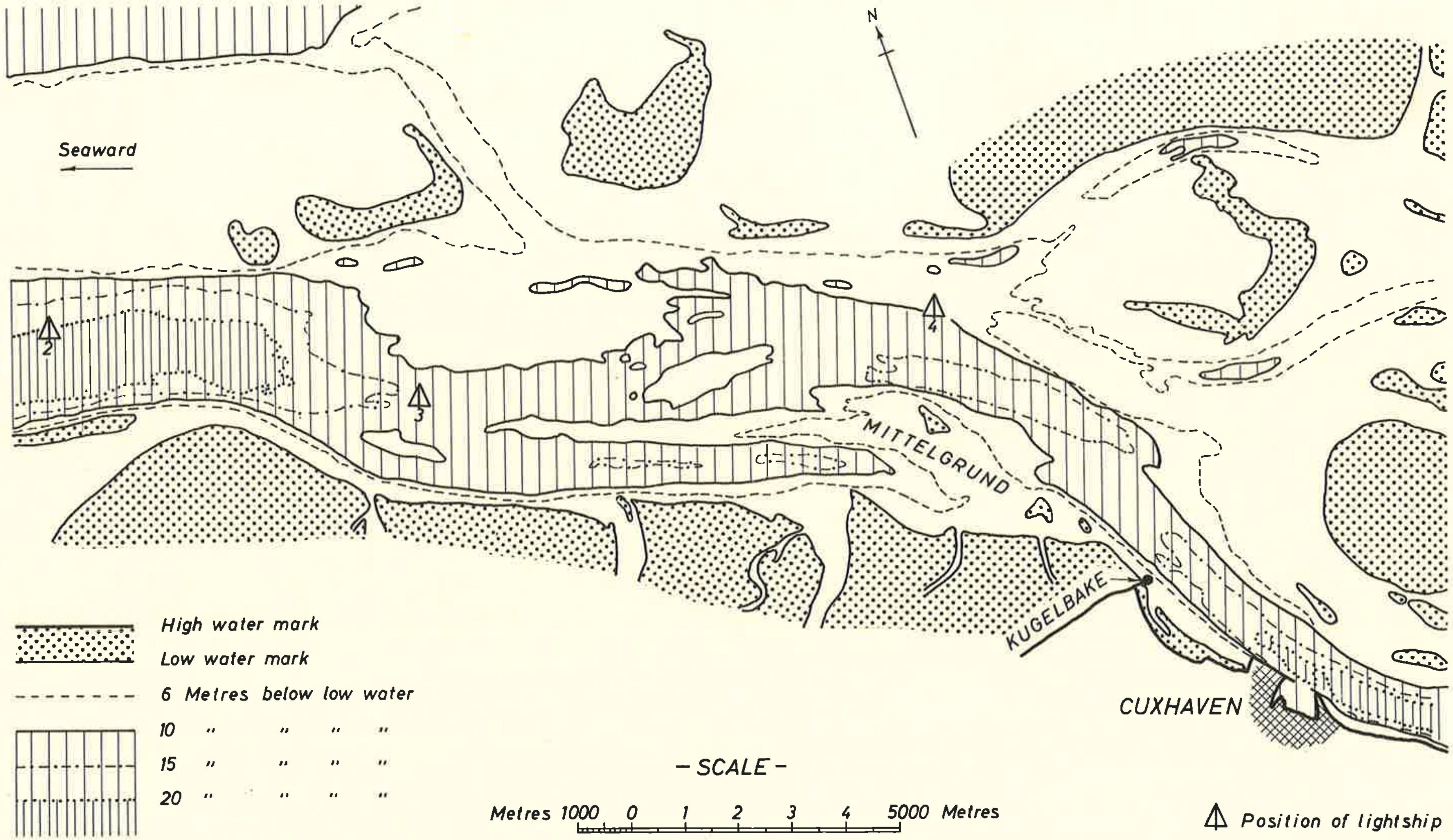


FIG 5

PARTICLE SIZE DISTRIBUTIONS

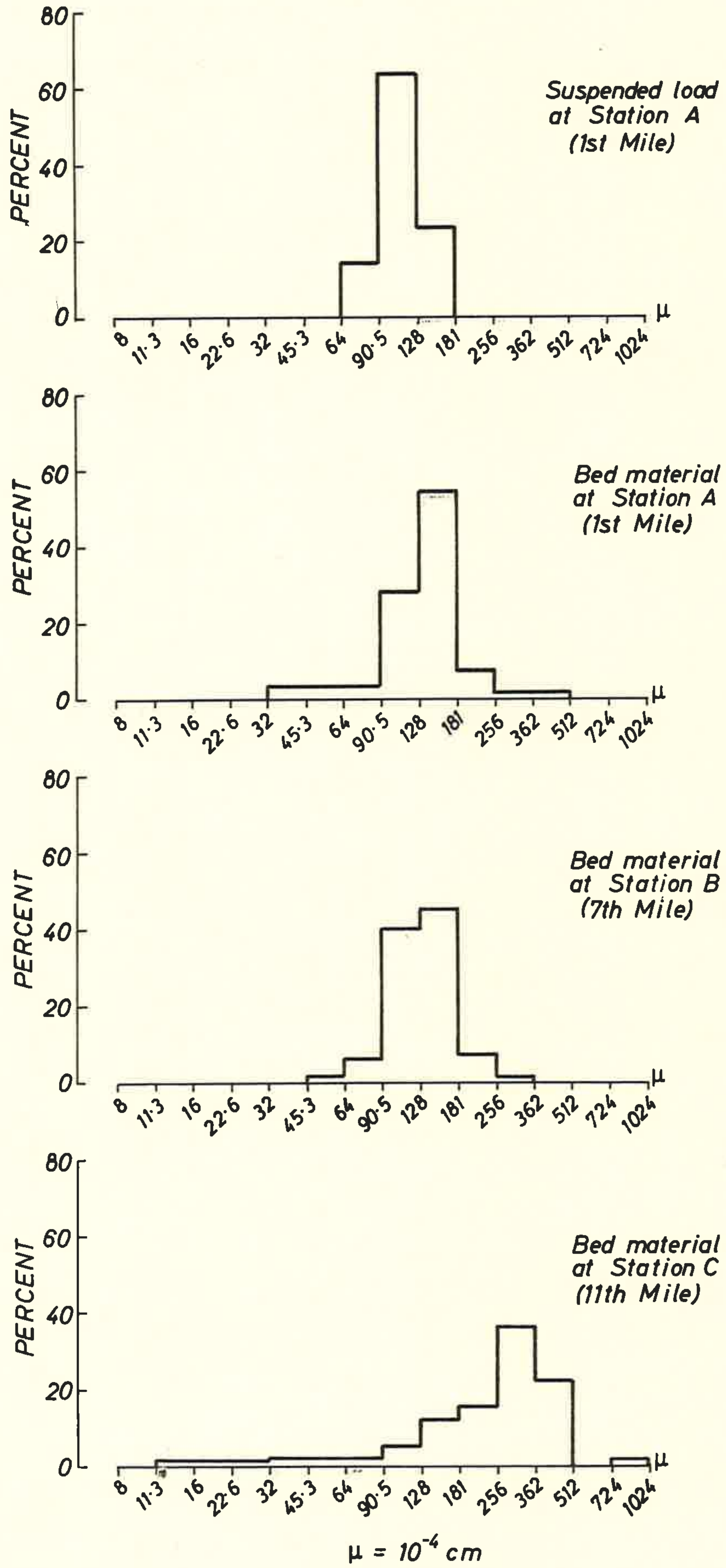
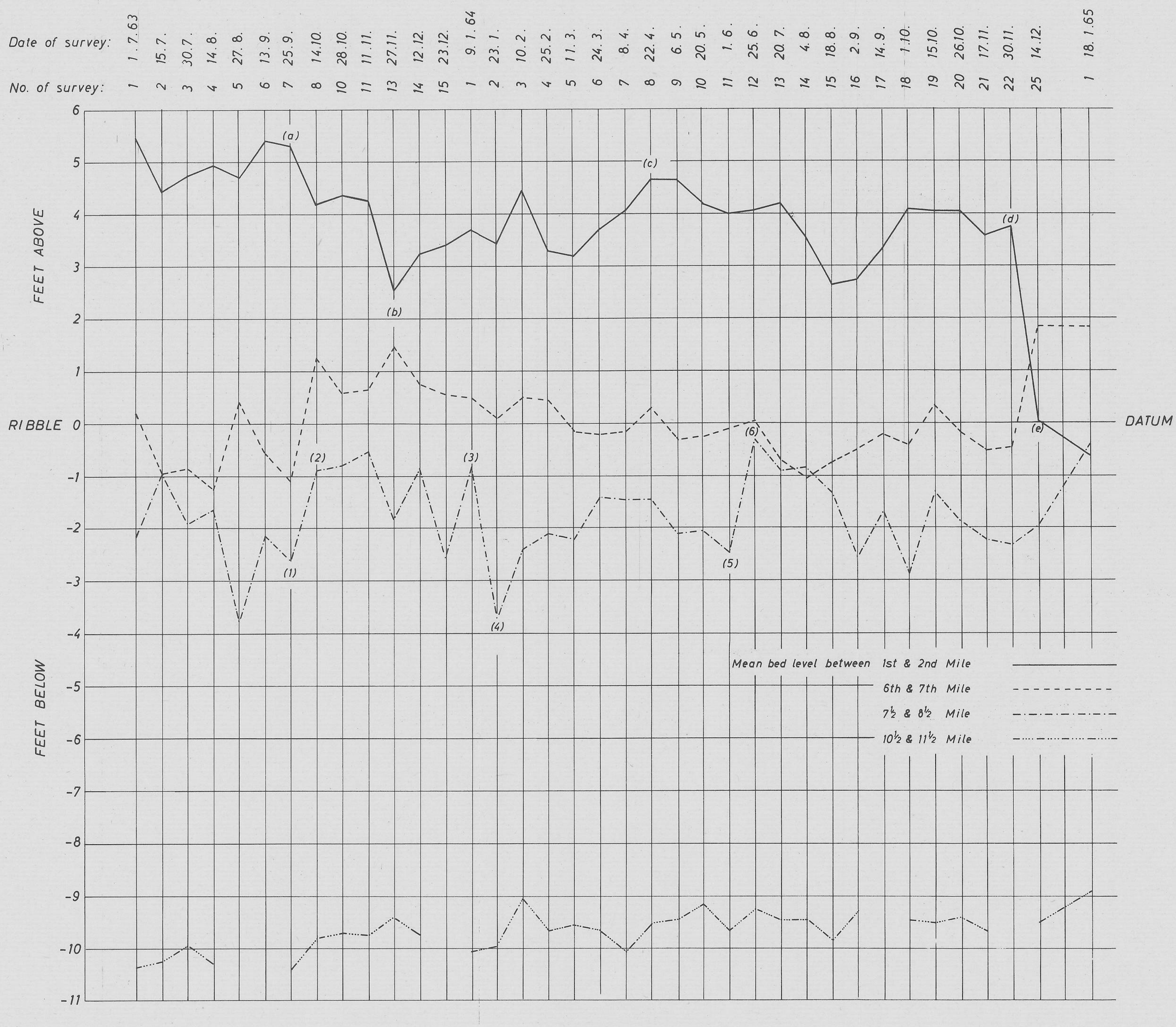


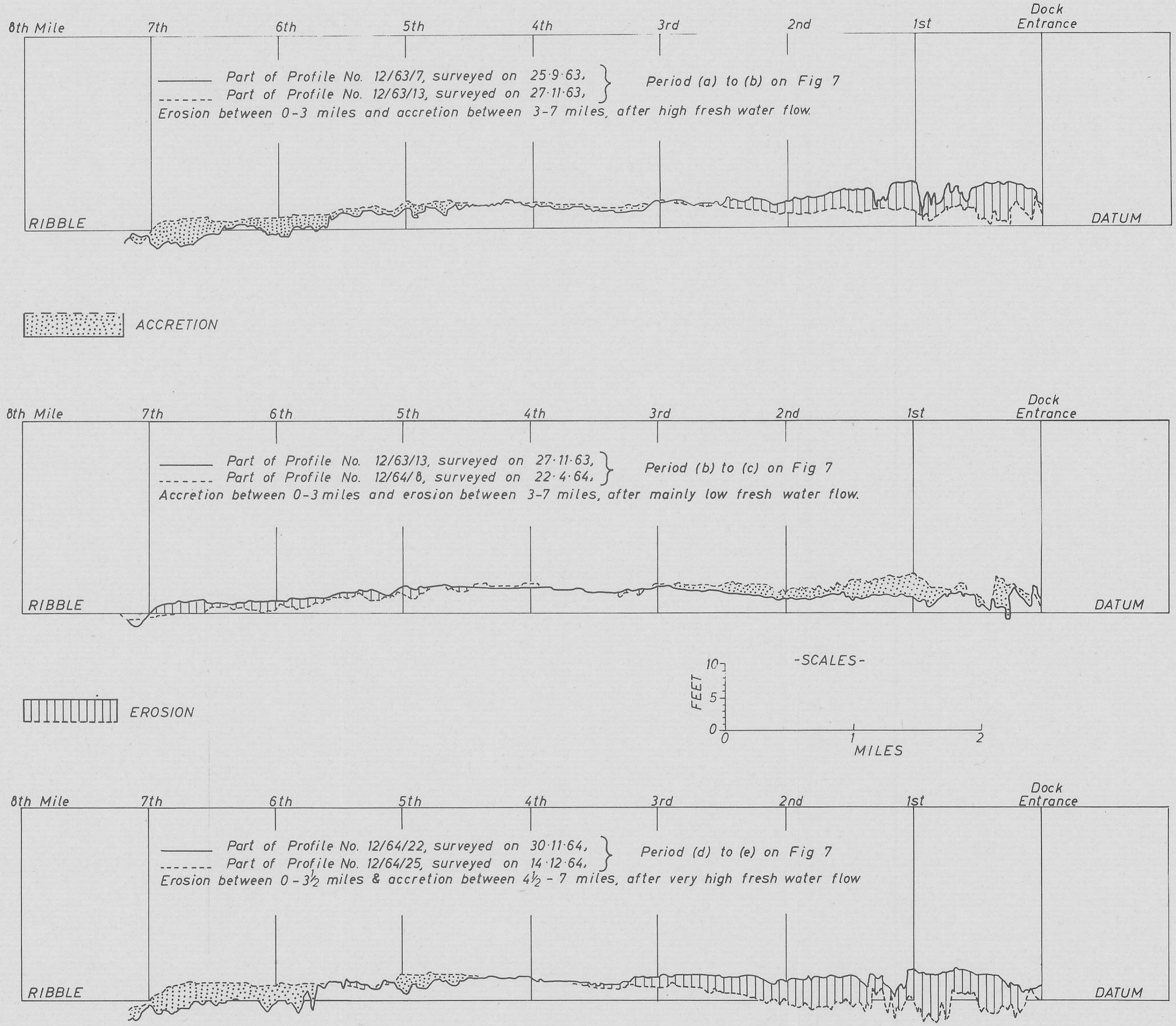
FIG 6



FLUCTUATIONS IN MEAN BED LEVELS

FIG 7

PROFILES SUPERIMPOSED I



Local alternation between erosion and accretion as a result of high and low fresh water flow.

FIG 8

PROFILES SUPERIMPOSED II

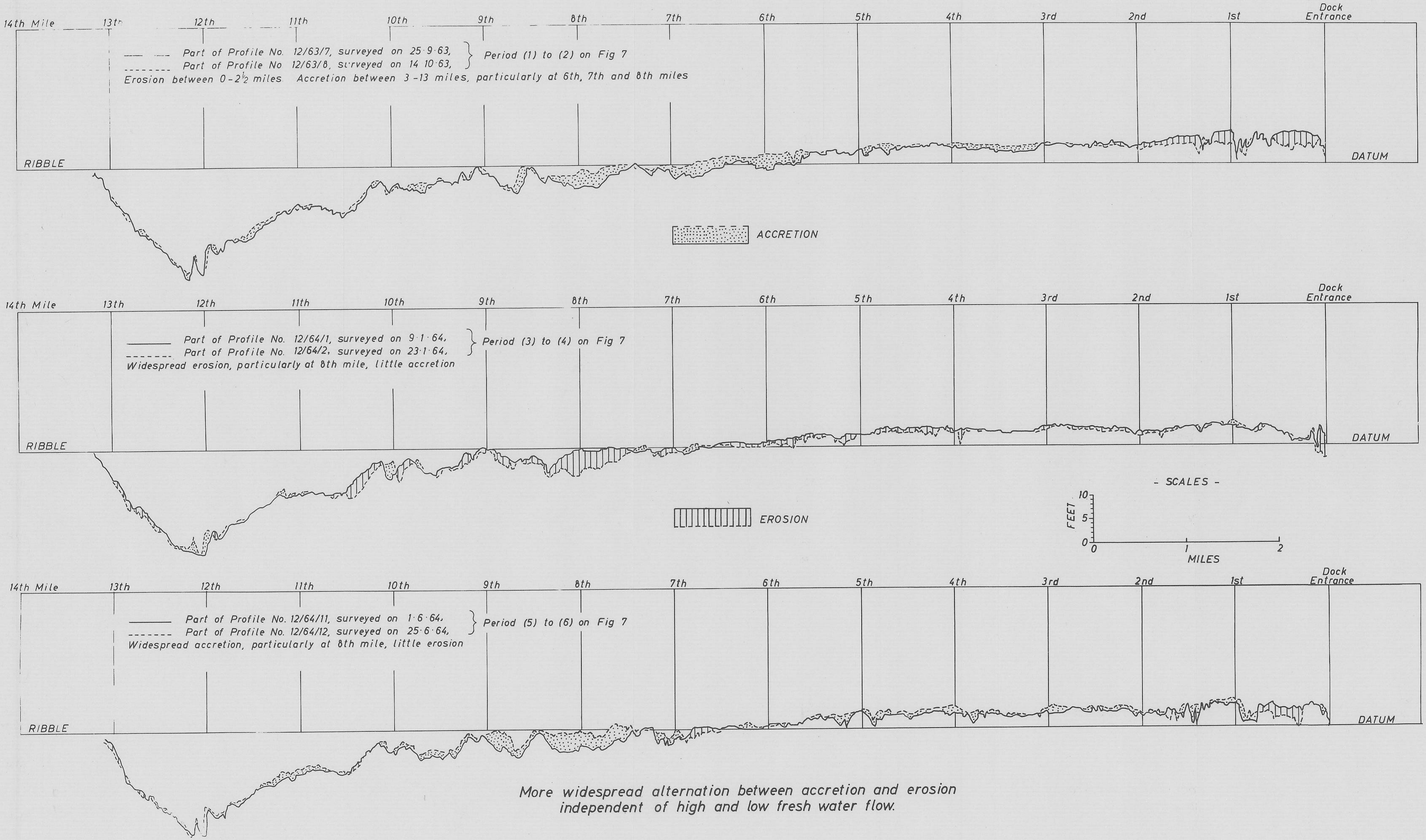
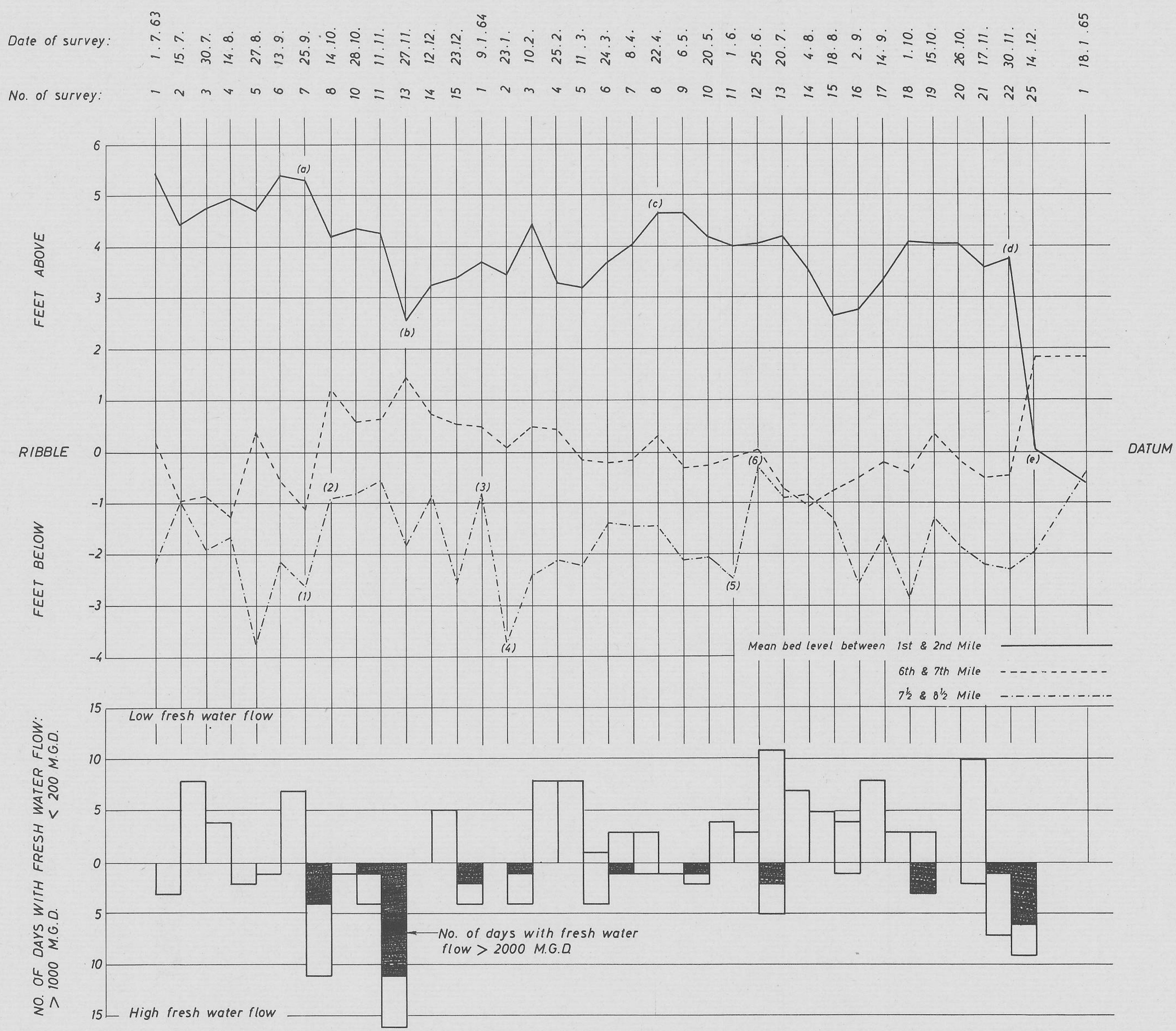
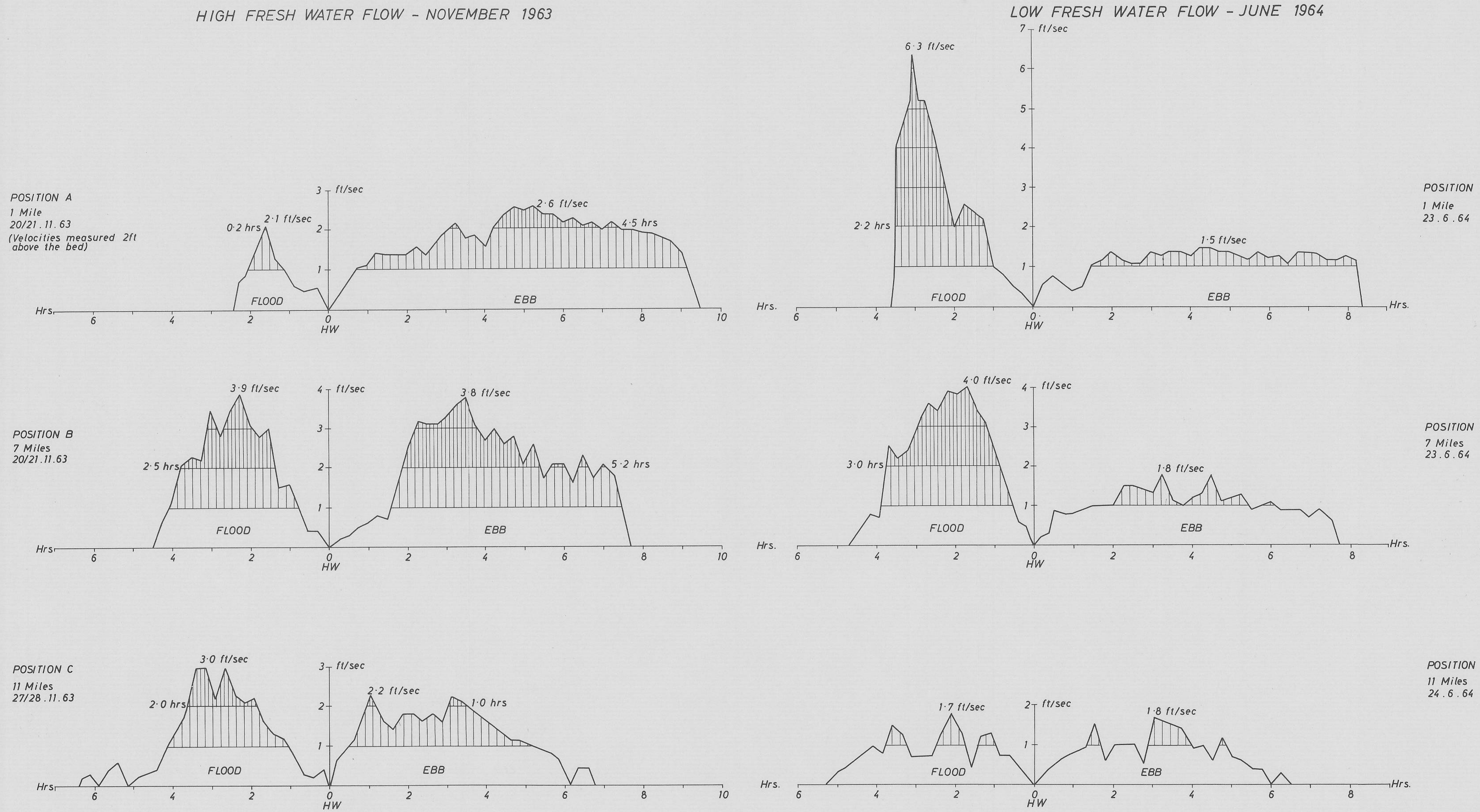


FIG 9



FLUCTUATIONS IN MEAN BED LEVELS AND CHANGES IN FRESH WATER FLOW

FIG 10



COMPARISON OF VELOCITIES

Measured 1ft above bed

FIG 11

INFERRED RISE OF BED LEVELS WITHOUT DREDGING, MILE 1 TO 2

FIG 12

D 42479/1/R.23 80 7/65 XL & CL