CHAPTER 121

FACTORS INFLUENCING ESTUARY SEDIMENT DISTRIBUTION

by

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Introduction

Many factors combine to determine the way in which sediments are distributed throughout an estuary.

Most fundamental are those which produce the natural rhythm of diurnal (or semi-diurnal), bi-monthly and seasonal fluctuations due to predictable variations in tide and weather. This group includes tidal discharge, fresh river flow and the resultant distribution of saline water. When considered together with such factors as the availability and properties of sediments within and beyond the landward and seaward limits of an estuary, they determine how the available material shall be eroded, transported and deposited during the course of the natural cycle.

Superimposed on these regular fluctuations are the effects of other factors which may or may not be predictable, are not necessarily regular in occurrence and may be either natural or man-made.

These include secular trends, such as long-term adjustments in land/sea levels or climatic conditions, which have a small but continuing effect on some of the factors in the first group. They also include sudden, short-term events like earthquakes or hurricanes which impose a shock to the system that may involve the movement of large quantities of material during the subsequent period of readjustment. Sometimes the influence of this group

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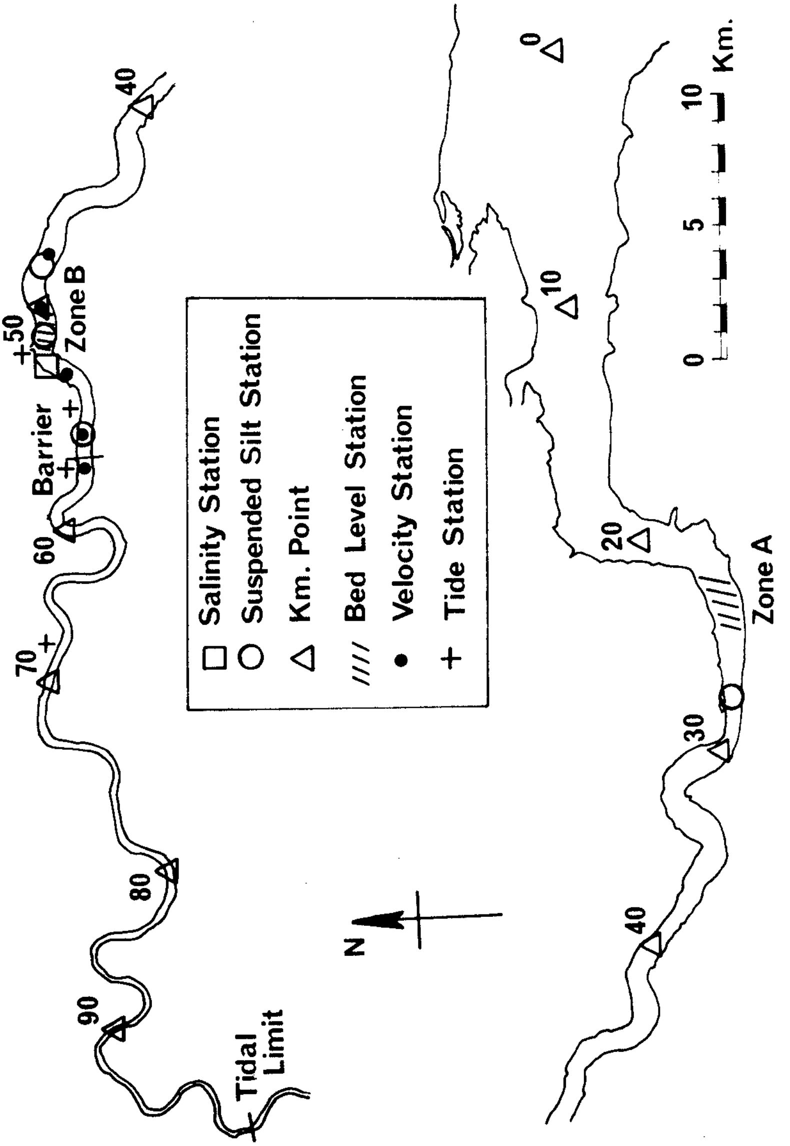


Fig. 1. KEY PLAN OF ESTUARY

of factors on sediment movement is indirect in that they necessitate the implementation of civil engineering works which, in turn, lead to a redistribution of sediment.

Finally, and most familiar to the coastal engineer, are those factors which create the recurring practical problems confronting him as estuaries are developed more and more intensively to meet the demands of modern industrial society - the construction of new jetties and container berths, channel dredging and training for navigation, sand and gravel winning for industry, the commissioning of water-cooled power stations, the discharge of sewage and industrial effluents, the control of water supply and tidal discharge by hydraulic structures, etc. Such developments usually affect the prevailing distribution of sediment in some way.

The tidal Thames in England (Fig 1) exemplifies a relatively well-documented estuary which for many years has been studied in the field, on physical and mathematical models and through laboratory tests on sediment. Using some of the results of these studies, the authors attempt to demonstrate how the above-mentioned factors interact: (a) in the short-term throughout a single tide, (b) during the slightly longer course of the bi-monthly spring-to-neap cycle, (c) as a result of annual seasonal variations and (d) in the longer term over a period of 30 years or more. Finally the paper illustrates the impact that civil engineering works can have on an estuary whose prevailing sediment distribution is already the result of the combined effect of the factors previously discussed.

Diurnal (or semi-diurnal) effects

Fig 2 depicts events on one (semi-diurnal) spring tide over an 8 km stretch of estuary (Fig 1).

The tidal range, which was 5.53 m at km point 0 (the mouth) about 50 km away, is amplified to 6 m (a), the

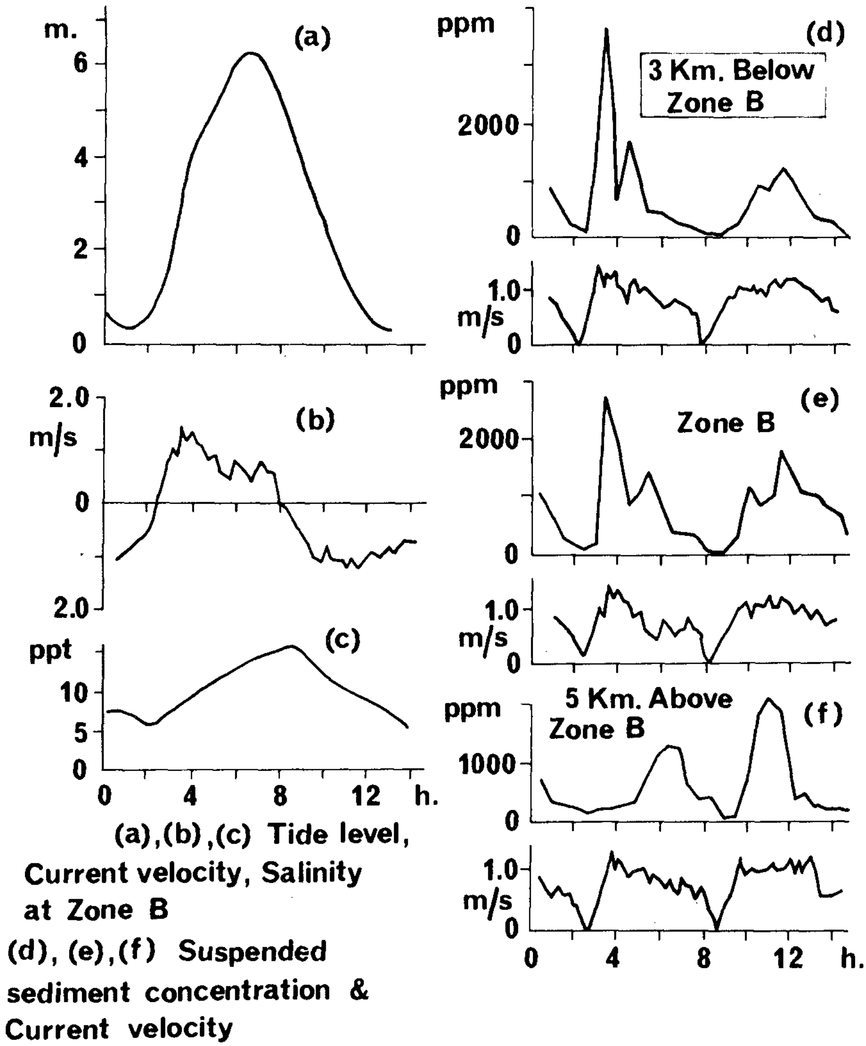


Fig. 2. SEMI-DIURNAL FLUCTUATION IN FACTORS AFFECTING SEDIMENT DISTRIBUTION

slightly shorter flood period giving marginally higher maximum current velocities on the flood than on the ebb (b). The vertically well-mixed conditions produce a rise in salinity of 10 parts per thousand at all depths from slack low tide to slack high tide (c). Because of the difficulties inherent in attempting direct measurement of changes in the level of the surface of a silty bed throughout a tide, measurements of variations in both the concentration of suspended sediment and current velocity at a number of depths at selected stations are used to infer how material is eroded, transported and deposited in a given reach of the estuary.

The records shewn on (d), (e) and (f), 1.5 m above the bed, typify the pattern of changes occurring throughout the lower 3 m of flow.

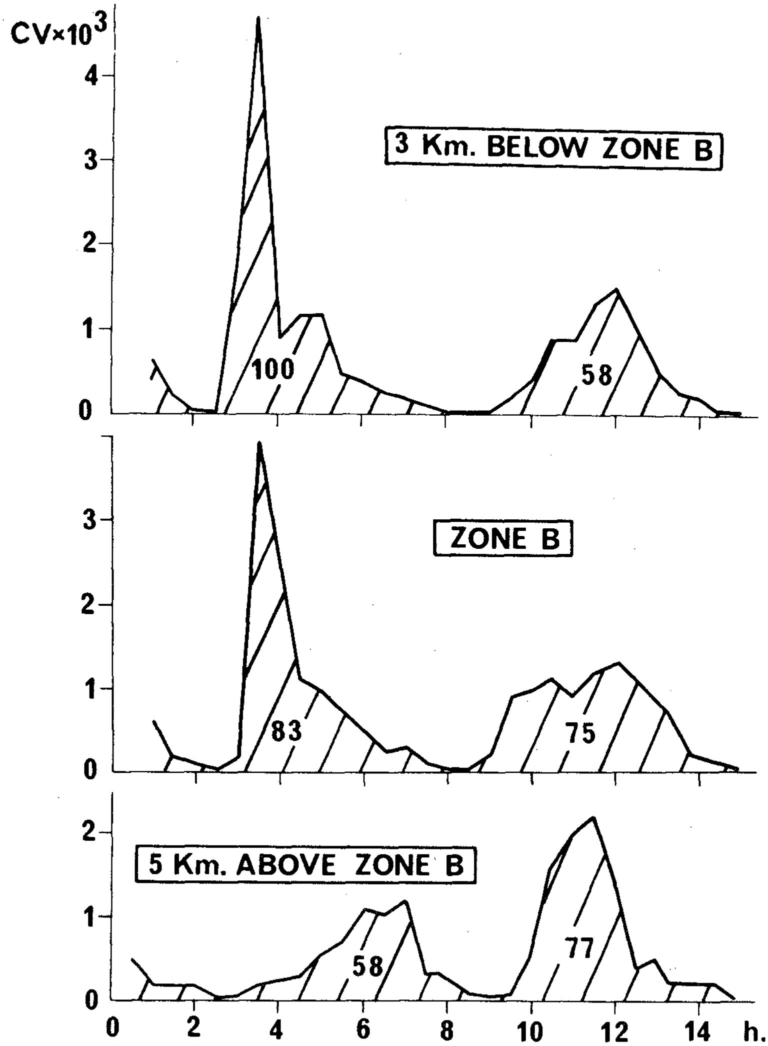
On the flood tide, material at the station 3 km seawards of Zone B (d) is entrained as soon as the critical shear for erosion is reached. The fact that the subsequent sharp decline in sediment concentration is not accompanied by a significant decrease in current velocity suggests that the material passes from the site up the estuary. Some of it deposits before arriving at Zone B, probably in the lee of bends, where flow is slow. If this were not the case, the concentration-time curve at Zone B would provide evidence of its arrival there. Instead, graph (e) shews that conditions at this site are similar to those shewn on graph (d), sediment entrainment occurring early on the flood tide followed by a reduction in concentration as material moves away up-estuary.

A second, smaller concentration peak occurs at both stations and, assuming that suspended sediment travels at the speed of the water transporting it, the evidence suggests that this material was eroded from the bed at a position more than 3 km below Zone B, passed through the lower silt station, deposited some of its load on the bed between there and the second station and passed on up the estuary.

At the third station, 5 km above Zone B (f), events are quite different. The suspended sediment concentration remains low even when the current velocity has exceeded 1 m/s, indicating little or no erosion of the bed locally. It is not until between 3 and 4 hours after low water that material arrives from further down the estuary, and the timing suggests that this could have originated at, and upstream of, Zone B. Some of this sediment passes on for a short distance before settling on the bed, the remainder deposits at the station due to the decrease in current velocity associated with the arrival of slack high tide.

On the ebb, concentrations at this station soon exceed 2000 ppm as the deposited sediment is re-entrained,and clearly more sediment passes down the estuary at this point than passed up on the preceding flood tide. The velocity-time curve shews that the sediment is transported seawards, concentrations remaining low for the rest of the ebb tide. At Zone B, conditions at the start of the ebb are similar, material being eroded from the bed as soon as the critical shear is reached. This moves away down-estuary, but halfway through the ebb tide the concentration-time curve (e), peaks suddenly, and this rise coincides with the arrival time of the suspended sediment which created the concentration peak at the station 5 km up-estuary. From this point until slack low water, the concentration at Zone B falls as current velocity falls, material depositing at and below the site.

At the third station 3 km seaward, sediment concentration rises and falls gradually as ebb current velocity increases and decreases (d), reaching only half the maximum value recorded at the other two stations - a further indication of deposition on the bed between here and Zone B.



C = Concentration (ppm) V = Velocity (m/s)

Fig. 3. SEMI-DIURNAL FLUCTUATION IN SEDIMENT FLUX

The data in (d), (e) and (f) are re-plotted on Fig 3 as sediment-flux curves for each of the three stations. These graphs illustrate more clearly the longitudinal sediment redistribution in the study area already inferred from the raw data on Fig 2 since the areas under the curves represent the quantity of sediment per unit area passing each station on each half tide.

To facilitate comparison, the flood tide sediment flux at the seaward station is regarded as 100 units. With this as the reference, Fig 3 demonstrates that within the 8 km of estuary used in the example, the amount of sediment deposited on the bed during the flood tide is more than twice that deposited on the ebb. Furthermore, whereas flood tide deposition is distributed relatively evenly both above and below Zone B, most of the ebb tide deposition occurs at Zone B and seawards. (Clearly the greater the number of measuring points per river section, the more reliable will be the result.)

Bi-monthly (spring-to-neap) effects

Figs 2 and 3 shew how sediment can be redistributed during the course of a single tide under a condition of low river flow. Fig 4 demonstrates the slightly longer-term variations that can occur during the bi-monthly spring-to-neap cycle, employing data collected near to Zone A and Zone B (Fig 1), two areas respectively 25 km and 50 km above the estuary mouth. The data are plotted both for summer (low river flow) and winter (high river flow) conditions. Graph (a) shews the cyclic variation in tidal range and indicates that tidal currents in both summer and winter must be similar since tidal ranges are similar. (River flow has negligible effect on currents at the monitoring stations.) (b) shews the steady, low summer river flow and the fluctuating, higher winter river flow. (c) and (d) shew the bi-monthly variation in mean suspended sediment concentration on both flood and ebb tides.

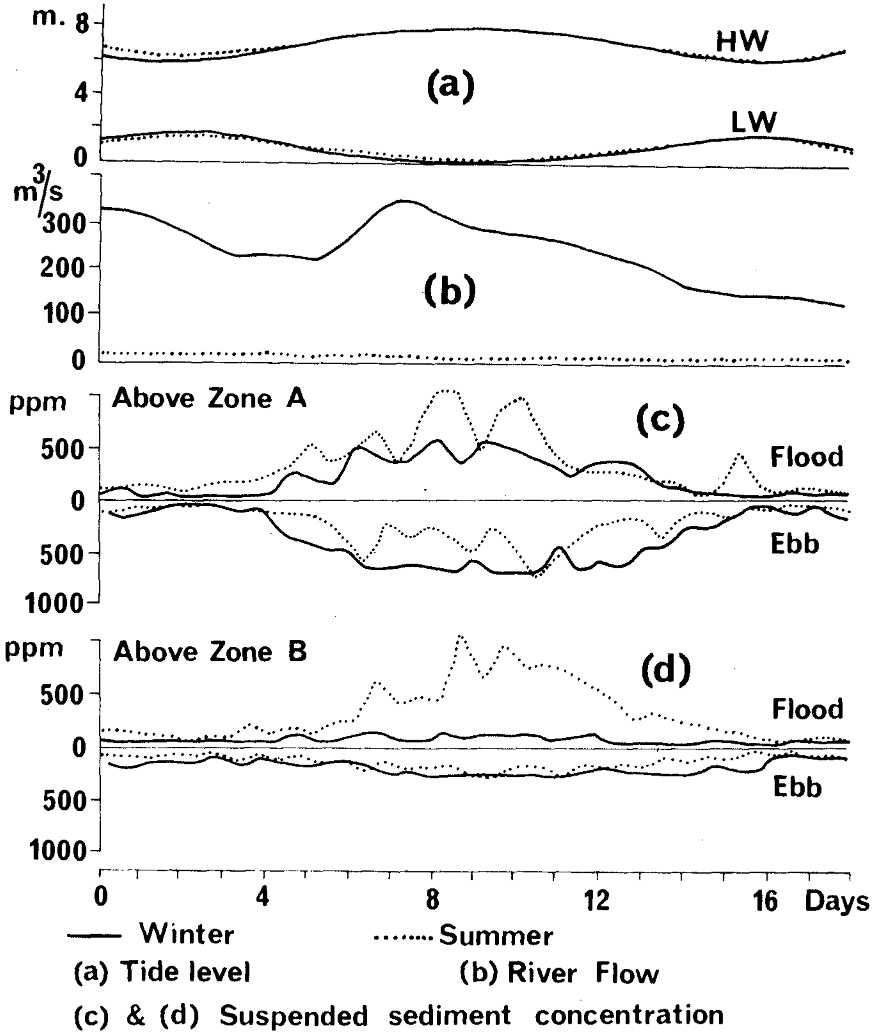


Fig. 4. BI-MONTHLY FLUCTUATION IN FACTORS AFFECTING SEDIMENT DISTRIBUTION

The most significant fact to emerge is that sediment concentration increases and decreases with tidal range, remaining low throughout the period of neap tides and increasing as the range exceeds the mean value. Significant sediment movement is therefore largely confined to spring tides.

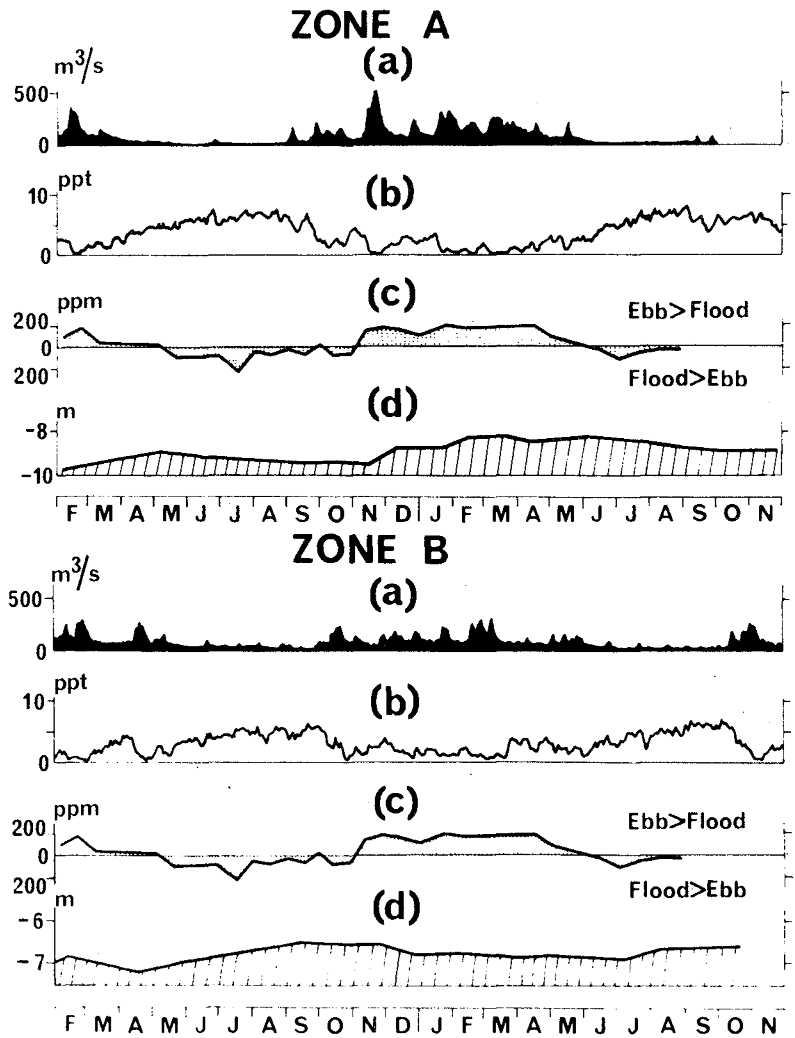
In the summer, spring tide concentrations are higher on the flood than on the ebb at the 2 stations just above Zone A and Zone B, suggesting a net landward movement of material up the estuary during this period. However, flood tide values are similar at the 2 stations indicating no net accretion of the bed between the sites. The transported material must therefore deposit further up the estuary. On the ebb, values are higher near Zone A than near Zone B indicating erosion of the bed between the stations.

In the winter the converse is true. Spring tide concentrations are higher on the ebb than on the flood at both stations, implying net deposition seaward of the lower station (from bed level data this in fact occurs at Zone A). However, at this time of the year both flood and ebb values are much greater near Zone A than Zone B, indicating considerable sediment movement, with deposition occurring between the two sites on the flood and erosion occurring on the ebb.

Annual seasonal effects

Continuing the study by extending the time-scale of cyclic variations from 2 weeks to 2 years, Fig 5 shews the relationship between fresh river flow, water salinity, concentration of suspended sediment and river bed level at Zone A and Zone B. The location of study zones and monitoring stations is given on Fig 1.

The significant feature is that for a given 2-year pattern of variations in river flow, salinity and suspended sediment concentration, bed levels in the two areas react in diametrically opposite ways.



(a) River flow (b) Salinity (c) Suspended sediment concentration (d) Bed level relative to Chart Datum

Fig. 5. SEASONAL FLUCTUATION IN FACTORS AFFECTING SEDIMENT DISTRIBUTION

High river flow (October-April), the consequent low salinity and the subsequent ebb-predominant, suspended sediment concentration result in accretion of the bed at Zone A. On the other hand, a similar combination of factors produces erosion of the bed at Zone B. Low river flow (May-September), the consequent high salinity and the subsequent flood-predominant, suspended sediment concentration result in erosion of the bed at Zone A whilst at Zone B, the result is accretion.

Clearly, material is redistributed seasonally along the estuary, the reduction in salinity associated with a prolonged period of high river flow leading to the release (through a reduction in cation bonding) of deposits at Zone B for transportation down-estuary. Conversely, during the period of low river discharge, the prevailing net landward movement of water and sediment in the lower layers of flow in the seaward reaches results in the gradual up-river transport of sediment.

Effects of secular trends

So far, the paper has described only those regular, largely predictable variations in natural phenomena which affect estuary sediment distribution. It now considers other, less regular, less predictable factors whose continuing effects, though small, can be of considerable significance when superimposed on existing regular fluctuations. The long-term land/sea level adjustment taking place in the southern North Sea provides a useful example.

Following an examination of 50 years of daily records of tide level, salinity and river flow, the authors confirm earlier findings (Ref 1, Ref 2) that mean tide level at the mouth of the Thames and tidal amplitude 70 km up-estuary have risen significantly during this century. In addition they shew this to be accompanied by a rising trend in saline penetration and a falling trend in river flow. Fig 6

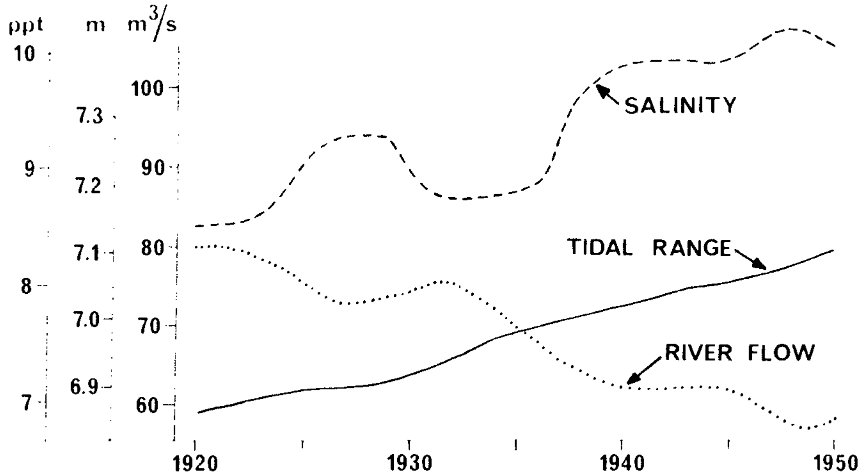


Fig. 6. SECULAR TREND IN FACTORS AFFECTING SEDIMENT DISTRIBUTION

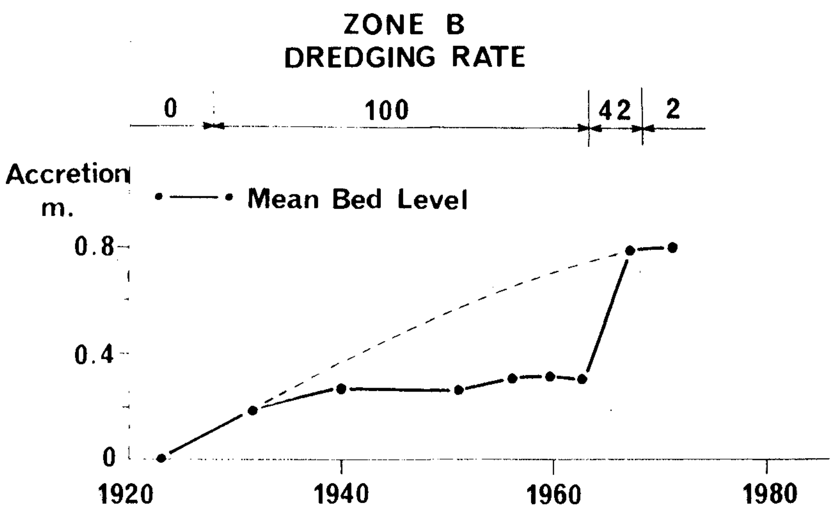


Fig. 7. RESPONSE OF BED LEVELS TO SECULAR TRENDS

illustrates this in the form of 15-year running means for all three parameters for the period 1920-1950.

The relative dependence of saline penetration on tidal range and river flow is currently being investigated. However, for present purposes, the significant fact is that for a period of at least 30 years, the main hydraulic factors controlling sediment movement themselves underwent a gradual change in a constant direction. The net effect on sediment distribution was to increase the thickness of the deposits on the estuary bed in the reaches immediately landward of the major deposition zone of the estuary - Zone B. Civil engineering works, including continuous channel maintenance dredging, masked this effect to some extent during the major part of the period, but when dredging was reduced, the readjustment of the estuary sediment distribution to the changing situation was rapid.

This effect is demonstrated by Fig 7, which shews changes in mean bed level (derived from soundings at approximately 30-m intervals on sections 175 m apart) between 1923 and 1971 for a 4-km - long reach located 3 km above Zone B. Annual dredging during the period of continuous channel maintenance is taken to be 100 units.

<u>Effects of civil engineering works</u>

Up to this point, the paper has been largely confined to a consideration of the interaction of those factors which affect estuary sediment distribution before they have been modified in any way by man's intervention. The authors now go a step further and examine what can happen to the sediment distribution when development schemes are carried out which modify the influence of those factors.

Two examples are cited - one familiar, the other perhaps less so. The first, jetty construction, usually affects only the local area but can be costly in terms of economic efficiency if badly located and ill-designed, as

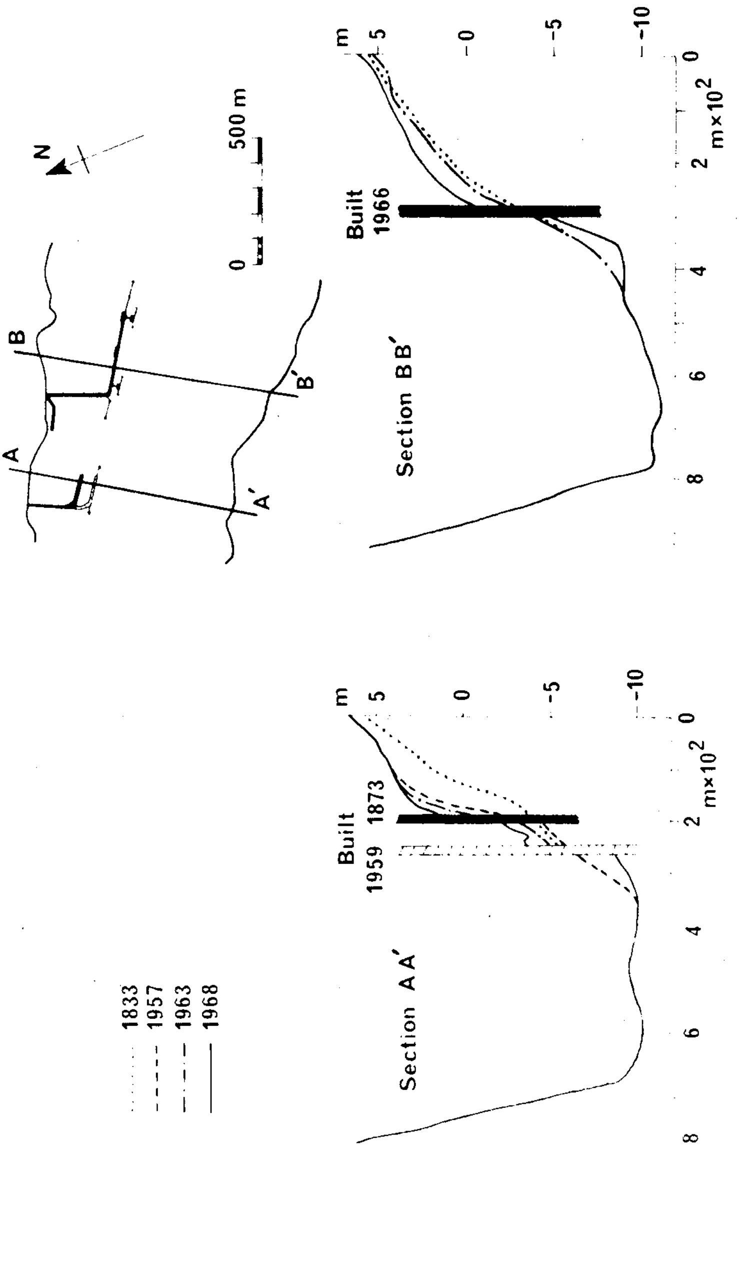


Fig. 8. EFFECT OF JETTY CONSTRUCTION ON SEDIMENT DISTRIBUTION

was often the case in the past and unfortunately still happens today.

Fig 8 demonstrates the response of bed levels in the Thames to the construction and extension of jetties about 35 km above the mouth. The bankside accretion which occurred between 1873 and 1957 following the building of the first jetty (Section A-A') amounted to a riverward movement of the low tide mark of about 80 m. This was relatively local in effect,not extending as far down-estuary as Section B-B' where the bankline had remained as before. However, once a jetty was built at B-B' and associated front face dredging carried out, bankside deposition began there also, and in 2 years (1966-1968) the bankline advanced about 50 m. Meanwhile, back at A-A', an extension into deeper water had been added in 1959 and dredging also undertaken along the front face. Deposition continued - at a reducing rate behind the original 1873 construction, but at a higher rate between it and the new extension.

Why did this deposition occur? Prior to jetty construction sediment was carried into the area on the flood tide, deposited round about slack high water, re-entrained on the ebb and transported seawards. A long-term balance was therefore maintained and bed levels near the side of the estuary changed very little from year to year. Jetty construction had the effect of marginally reducing current velocities near the bank and thus providing a longer period for deposition at high water. Furthermore the ebb current was less efficient in re-entraining sediment and so the former balance between deposition and scour was no longer maintained.

The civil engineering undertaking used as the second example of how such works modify the influence of the hydraulic factors responsible for estuary sediment distribution is tide control (Ref 3). It is more ambitious than

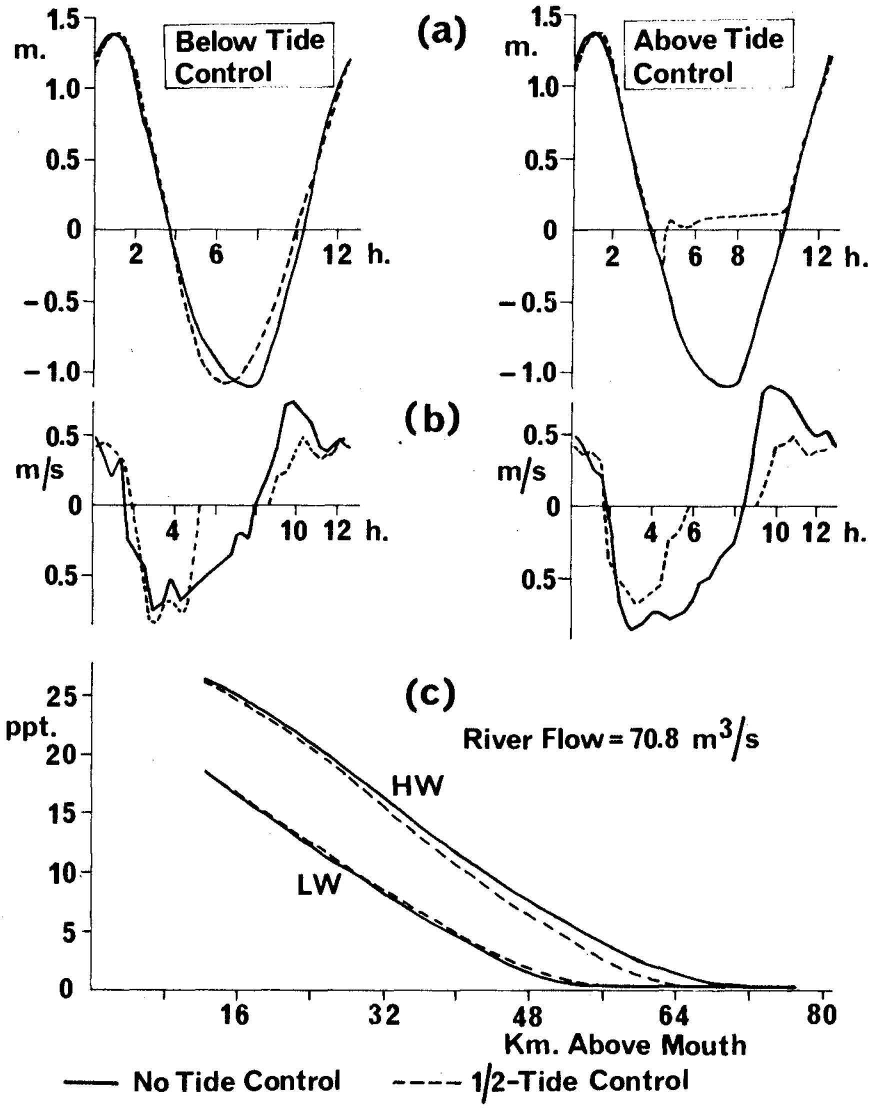


Fig. 9. EFFECT OF TIDE CONTROL ON WATER MOVEMENT

jetty construction, has more far-reaching effects and is therefore much less likely to be carried out without prior investigation into its likely impact on the estuary environment.

Physical and mathematical model studies of various forms of tide control have been made at Wallingford. Using physical model results, Fig 9 shows the effect on water movement of one form - half-tide control by a gated barrier located 55 km above the estuary mouth. The way the system operates is for the gates to be shut halfway through every ebb tide, remain closed throughout the low water period, be re-opened halfway through the following flood tide when water levels on either side of the structure are the same, and remain open throughout the high water period.

The effect is demonstrated by comparing tide levels (a), current velocities (b) and salinity (c) with and without half-tide control at stations above and below the structure. Below the structure, the response to tide control is for the ebb period to be shorter, the flood period correspondingly longer, maximum flood current velocities lower and maximum ebb current velocities higher. Above the structure, once the initial fall in flood tide level following gate closure has occured, levels increase slowly with incoming river flow until the gates are re-opened: current velocities on both flood and ebb tides are lower. The main effect of half-tide control on the longitudinal salinity distribution is to move the upstream limit of saline penetration about 5 km seawards (Ref 4).

Fig 10 demonstrates how these changes in water movement within the estuary affect the sediment distribution on the bed according to both the physical model (upper diagram) and the mathematical model (lower diagram).

The results take different forms. Those from the physical model are presented in the form of deposition/erosion

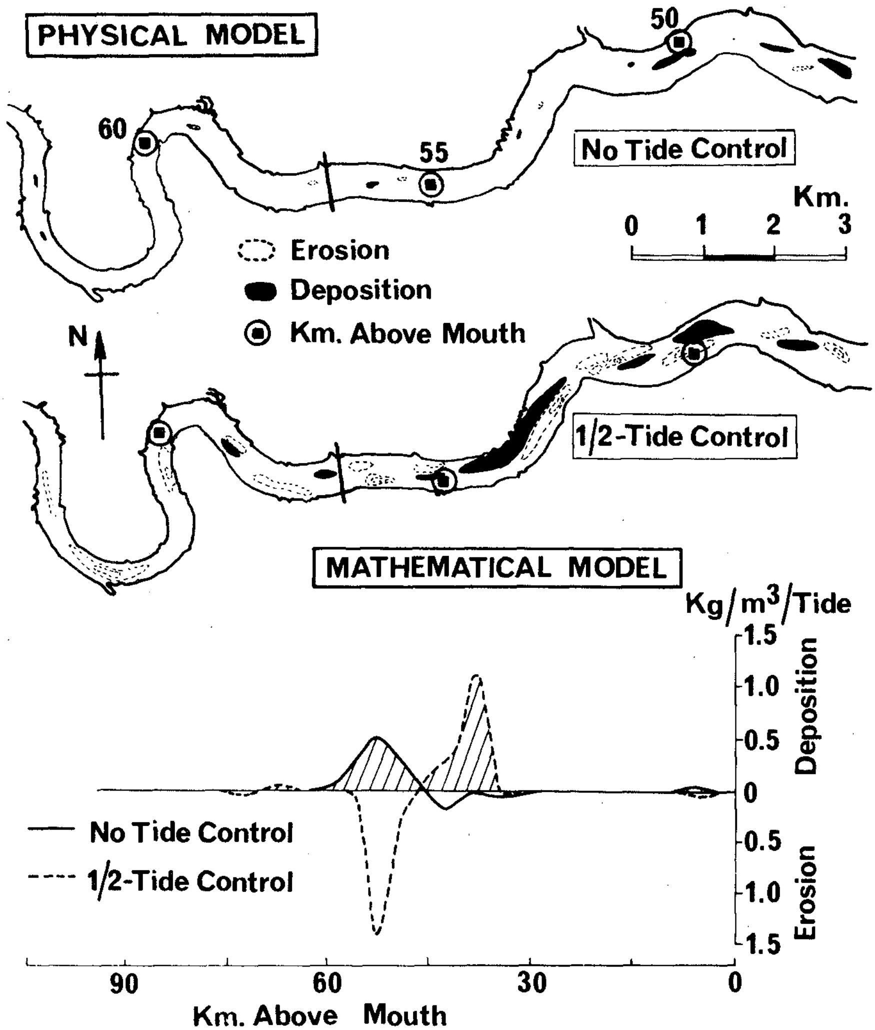


Fig 10. EFFECT OF TIDE CONTROL ON SEDIMENT DISTRIBUTION

charts which compare the negligible change in sediment distribution following construction but before operation of the tide control structure, with the considerable sediment redistribution resulting from continuous half-tide control. The mathematical model results illustrate longitudinal changes in the location of zones of erosion and deposition, indicating that tide control has the opposite effect to that of the rising trend in tidal range in that it produces a seaward migration of the major deposition zone.

Acknowledgements

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