CHAPTER 40

SUSPENDED SEDIMENT IN A TIDAL ESTUARY

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ABSTRACT

A brief description is given of work being carried out in the Mersey Estuary, England. This work is part of a sedimentation study of the area, and has necessitated many days' field observations at stations distributed along and across the Estuary. Attention is drawn to the factors influencing the sediment movement and the variables, such as velocity, suspended solids, salinity and temperature that must be measured in order to define the sedimentation complex adequately.

A study is made of the effect of variations in temperature and tidal range upon the mean concentration of suspended solids observed at stations in the Estuary; the relationship proposed is of the form

$$\bar{\bar{C}} = A + (B+CT)R + DT$$

where A, B, C and D are constants, R is the tidal range and T is the water temperature. The vertical distribution of suspended sediment is discussed and examples given which do not conform to existing theory. Variations in the vertical distributions of sediment along the Estuary are examined and explained theoretically by reference to the existing bed conditions and hydraulic characteristics of the Estuary.

INTRODUCTION

The River Mersey has been of considerable interest to Engineers for many years. The processes which control the Estuary regimen have not been clear and over the past 40 years a number of people, [1,2,3,4], have examined the River and commented on its regimen. The last investigation in 1957 conducted by the Hydraulic Research Station at Wallingford, England, [5], went a long way in explaining the processes at work in the Estuary. Much of this understanding was obtained by the use of a hydraulic scale model. The Mersey Docks and Harbour Board, who have sponsored many of the past investigations, felt that a more complete understanding of the Estuary area was desirable and could only be obtained by working with the Estuary itself. For this reason, a research team from the University of Liverpool is engaged on a research programme, which started in 1964, and is designed to study the mechanism of sediment movement in the area.

DESCRIPTION OF AREA AND METHODS OF MEASUREMENT

Observations have been carried out over a large part of Liverpool Bay and within the River system itself. (Fig.1.). Bed sediment samples have been taken over an area of approximately 150 sq. miles of Liverpool Bay on lines 1 mile apart and at intervals of ½ to 5 miles, depending on the bottom topography. The Estuary area itself has been sampled along lines approximately 1000 ft. apart in the Narrows area, extending to 5,500 ft. in the shallow water areas higher up the Estuary. In all, some 1,000 samples have been collected, of which 327 have been from the Mersey Estuary itself.

Together with the bed sampling programme, an echo sounding survey of certain areas of Liverpool Bay and the Mersey Estuary has been made in order to provide information on movement of sand waves. Further background information has also been provided by a "sparker" survey run in the main shipping channel and in the Upper Estuary. In the near future it is hoped that 3 ft. - 4 ft. core samples will be taken on the beaches and that these will provide useful data on beach movements.

Observations on current velocities and directions, suspended silt contents, salinities and temperatures have been made at 5 - 10 ft. intervals throughout the water depth and at 20 - 30 min. intervals threughout the tide.[6.] (The stations at which these observations have been made are shown in Fig. 1.). The suspended sand concentration has also been determined at half hourly intervals at 2 or 3 positions in the vertical.

All of these observations are continued for one half a tide cycle, i.e. the flood or ebb tide, although longer periods of observations such as 1, 3, 5 and 10 complete tide cycles have been worked. The half-tide method of working has been used partly because of the size of the research team and the availability of vessels, crews, etc., and partly because a wide coverage of all the parameters involved in the problem was required. This wide coverage is obtained by the half-tide method of working (some 350 half tide obs. have been taken to date) and has the practical advantage that long working periods are avoided. However, in order to have some comparisons available, several longer period obs. have been made as also have simultaneous observations at two or more stations. The results of two half-tide measurements having almost the same range but for different times of the year at position D are given in Fig. 2. The quantity of water flowing per foot width on the two days can be seen to compare very well indeed and shows how dependable are the half-tide measurements.

Half-tide measurements along the lines described above have been made throughout the year for spring to neap tides at each of the stations shown in Fig. 1. However, on section, A-E located in the Narrows section has been worked more thoroughly than the others. This section has a hard sandstone bed which proves to be extremely useful when examining and explaining the sediment transport characteristics of the Estuary.

FACTORS AFFECTING SEDIMENT MOVEMENT

The field investigation is intended to cover as many as possible of the variables involved in the control of the Estuary regimen. Those that are present in the Mersey Estuary include the following:

1. The effect of the tide.

This is the prime factor which controls silt and sand movements in any estuary. In the Mersey Estuary spring tides of 32 ft. range occur with corresponding maximum velocities of 10 ft. per second at positions such as C. (Fig.1). The tide is the agency by which bottom sediments are eroded and transported along the Estuary. The magnitude of this tidal influence is shown in the section dealing with the regression analysis of suspended silt content.

2. Density gradient effects.

This is produced by the density difference between the sea and river waters and can be present even in a "well mixed" estuary like the Mersey. 4,5.

The density gradient has the effect of superimposing a second circulation on that produced by the tide. Since this secondary circulation produces a nett upstream flow near the bed, the density gradient provides a means whereby sediment can move progressively upstream near the estuary bed.

3. The effect of mixing of salt and fresh water.

If fine sediment of a silt and clay nature is present in the river water, then a change of electrolytic environment may cause the silt and clay particles to flocculate. This is likely to occur at the upstream limit of the density intrusion wedge and to cause shoaling at this position. In a tidal system like the Mersey, the position of the intrusion limit is dependent on the fresh water discharge. Consequently any shoaling due to this action will be spread over a lenth of the Estuary; the position of deposition at any instant being dependent on the fresh water flow and tidal range.

4. Fresh water discharge.

Much of the fine sediment and organic material may be supplied to an estuary from the upper river. If organic material being supplied to an estuary can combine with the clay particles present in the estuary, then by virtue of the density circulation these materials will also be contained within the (estuary) system. In the Mersey Estuary there is evidence available to indicate that this "trapping" process is occuring at the present time.

One further effect of the fresh water discharge observed in the Mersey, is to produce salinities which are lower than those suggested by the ratio of the total fresh water discharge to tidal volume. Salinities are produced which correspond to roughly a week's cumulative fresh water discharge.

5. Effect of the seasons.

A change of season is accompanied in an estuary by two distinct effects. The quantity of fresh water supplied to the river varies as also does the water temperature. The effect of the fresh water discharges has already been discussed in section (4). Consider now the effect of changes in temperature.

An increase of temperature causes a reduction in the water viscosity and gives a consequent increase in the settling rate of particles carried in suspension. This low viscosity in the summer will also encourage the collision of particles carried in suspension and thus the flocculation of the fine material. Any buoyancy action supplied by the fine material to the coarser fraction will thus also be reduced in the summer. An increase in the settling rate of the fine material implies that the estuary deposits have longer to consolidate. When this is considered, together with the shorter consolidation time due to the lower water viscosity, it implies that the estuary deposits will possess a higher shear strength during the summer period, i.e. the deposits have a greater resistance to erosion. Since the fresh water discharge is likely to be lowest during the summer, then the supply of fine material to the estuary will be least at this time. The nett result of a change of season from winter to summer is that less material would be expected in snspension during the summer period. This is indeed found to be the case, in the Mersey Estuary, and the results are elaborated in the following section.

6. Wave action and littoral drift.

These are the factors which produce alterations in beach profiles and consequently are important in any estuary stndy. In the Mersey, the littoral drift along the Welsh and Lancashire coasts has been shown to be small.[5] The effect of direct wave action, however, will be more important in this Estuary. Extensive sand banks exist behind the West revetment and even in comparatively good weather, waves are observed breaking on these banks. As the predominant wave direction is westerly, these waves provide one of the means whereby material can pass over the revetment and into the main shipping channel.

7. Sediment distribution.

A knowledge of the composition of the sea, estnary and river bottom is essential if an understanding of sediment movement is to be obtained. The quantity and quality of material found in suspension is dependent on the composition of the bed material as also is the vertical distribution of the sediment. This point is illustrated by the last section of this present paper. The type of bed sediment may well determine which of the factors already discussed are of importance when considering a particnlar estuary. Beds composed of coarse grained material will be influenced more by wave action and littoral drift effects, whereas fine sediments will be more influenced by floccnlation and density effects. Ultimately, it is the distribution of bottom sediments that determines the estuary sediment movements and shoaling characteristics.

VARIATIONS IN SILT CONTENT

The main emphasis of this particular project is on the sedimentation processes. Therefore great interest centres around the amount of solids in suspension and the variation of this throughout the estnary with the various parameters such as tidal range, season of year, fresh water discharge, etcetera.

The method used to determine the snspended solids content is a light extinction meter, developed by the British Transport Docks Board. Jackson,[7] nsed this technique in the River Humber when examining silt contents close to the shore and at a number of fixed positions only, so that it was possible to nse electrical recorders. Measnrements near dock entrances in the Mersey have similarly been made with the aid of recorders. However, for positions in mid-river, when half-tide measurements have been made, the underwater probe has been mounted alongside the current meter so that simultaneous measurements of velocity and snspended solids are possible at any depth. Calibration of each instrument has been achieved by taking bottle or pumped samples in the river at the same time as reading the instrument; subsequent laboratory analysis giving the actual suspended solids. The calibration is dependent on grain size and shape, but was found to be substantially the same, for all the river positions worked.

Measurements of silt content at various levels throughout the depth and at various stations in the river have enabled the vertical profiles of silt to be studied and movements of silt along the Estuary to be understood. By integrating these throughout the depth the mean silt content $\bar{C}$ at any time for the station is obtained. Fig. 2 shows the variation of $\bar{C}$ throughout an ebb tide for Position D. If now the mean value of $\bar{C}$ throughout the ebb or flood tide is calculated ($\bar{\bar{C}}$) it is to be expected that this would vary with tidal range. The results of such calculations for measurements taken at Positions B, C and D are shown in Fig. 3. These three positions are close together in the centre of the river, and have approximately the same depth of water so it is reasonable to consider them as one. The results show that $\bar{\bar{C}}$ increases with the height of high water (H) * and that this increase is approximately linear. A regression line through the winter results gives the equation of best fit as:

$$\bar{\bar{C}} = -2981 + 127.5H ,$$

and the coefficient of correlation as 0.91. If this is written in terms of tide range (R) then

$$\bar{\bar{C}} = -1066 + 63.8R. \qquad (a)$$

Jackson also found a linear relationship between average silt content and range in the River Humber but the governing equation proposed gave a positive silt content even at zero tide range. The Mersey results indicate that at small tidal ranges there should be little or no silt in suspension; according to equation (a), for ranges less than about 17 ft. $\bar{\bar{C}}$ is zero, and measurements at Position A for tide ranges of about 15 ft. have confirmed this. This is very reasonable since on physical grounds a minimum velocity is required before the material can be brought into suspension.

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* It is more usual to correlate parameters with tidal range, but in the Mersey Estuary it is found that tidal velocities, quantities, etcetera, are almost the same for two tides, having the same high water level (h.w.l.) but whose low water levels (l.w.l.) differ considerably. For example:

7th October 1964 h.w.l. = 30.6 ft. L.B.D., l.w.l. = 4.0 ft. L.B.D.
range = 26.6 ft.

27th September 1965 h.w.l. = 30.8 ft. L.B.D., l.w.l. = -0.2 ft. L.B.D.
range = 31.0 ft.

This better correlation is probably because the Estuary has only a small plan area at low water but large at high water. Since the mean tide level is 15 ft. L.B.D., h.w.l. and ("mean") range are related by the relationship $2(H-15) = R$.

Perhaps the more striking and interesting fact which emerges from the results, is the difference between summer and winter values. Fig. 2 compares the variation in $\overline{C}$ at Position D for two tides having almost identical range; one observed at the end of the summer when the water temperature (T) was 14.4 °C and the other early in March when the temperature was 2.8 °C. The increase in silt content in the winter is more than four times.

Similarly Fig. 3 shows that there is considerably greater quantites of silt in suspension in the winter than the summer. Jackson found similar results near shore when a four-fold increase was observed. So this work confirms the work of Jackson and draws attention to this very important phenomena. However, in the case of the work on the Humber, the rate of increase of silt content with range apparently did not change from summer to winter and the relationship proposed was

$$\text{(mean) } C = 457 - 38T + 25R. \qquad \text{(b)}$$

Fig. 3 clearly indicates that for the positions in the Narrows of the Mersey the rate of increase in silt content is much greater in the winter. The results have been gathered together over a period of nearly two years. Clearly a great deal of time, effort and money is needed to obtain each result and this is the reason for the comparatively small number available. Combining all the results including the autumn and spring values (some 36 values in all), and assuming the equation for silt content to be of the form

$$\overline{\overline{C}} = A + (B + CT)R + DT \qquad \text{(c)}$$

the equation of best fit is found to be

$$\overline{\overline{C}} = -1626 + (93.8 - 6.03T)R + 108.9T \qquad \text{(d)}$$

where T = the water temperature in °C, (varying between 5°C in winter to about 14°C in summer).

R = the tidal range in feet and $\overline{\overline{C}}$ = mean silt content in p.p.m.

Correlation of the great increase in silt content in winter with the decrease in temperature may be objected to by arguing that the increase is due to the storm condtions that occur more frequently in the winter. These disturb the mud through wave action, and allow the material to be brought into suspension more easily. While this is no doubt an important influence in many cases, in the Mersey the area of the mud banks is not subject to the worst of the storm conditions as they are situated upstream of the Narrows and are shielded from the large waves occuring in Liverpool Bay. The physical explanation for the increase in silt content in winter is far from fully understood, but the correlation with temperature as equation (d) is good and therefore lends support to the explanation given in section (5) of "Factors affecting sediment movement" above.

With more results available further refinements should be included in the analysis. There is good physical reason for expecting the mean silt content to be higher (for the same actual range) if the tide range is decreasing than when it is increasing. Observations taken by the Delft Hydraulics Laboratory [8] off the coast of British Guiana, show this phase lag in the variation of mean daily silt content compared with the tidal range and velocity. Similarly it is to be expected that other things being equal the silt content for a given temperature will be less when the temperature is decreasing than when it is increasing and this is also suggested by observations taken in the autumn and spring.

The fresh water discharge is another important parameter but it is difficult to include for at least two reasons; firstly accurate measurement is very difficult and secondly there appears to be a "build-up" of fresh water in the Estuary, so that even if daily flows are known in the non-tidal portion it is not possible to state the fresh water discharge at all positions of the tidal estuary. In an attempt to allow for the fresh water and also any flocculation effects, the mean salinity was included as an extra (linear) term in equation (d). However, the results showed that it's effect was small compared with the temperature and range effects and further results are needed to examine this factor in more detail.

VERTICAL DISTRIBUTION OF SEDIMENT

It is still not possible to describe the vertical distribution of sediment under idealized conditions by an exact mathematical relationship. Various mathematical forms are used by engineers at present. Those due to Rouse, Hunt, Einstein and Chien [9] are well known. In 1958 a study by Tanaka and Sugimoto [10] produced the following relationship.

$$\frac{C_y}{C_a} = \left[\frac{\sqrt{d} + \sqrt{d-y}}{\sqrt{d} - \sqrt{d-y}} \times \frac{\sqrt{d} - \sqrt{d-a}}{\sqrt{d} + \sqrt{d-a}}\right]^Z \qquad (1)$$

where $Z = \frac{w}{Ku_*}$; Cy : Concentration at level y
Ca : " " " a
w : fall velocity of particle
K : Von-Karman Constant
u_* : Shear Velocity = $\sqrt{gdS}$ in a channel
S : Water Surface Slope
d : Water depth

More recent work (1964) by the Russians Ananian and Gerbashian [11] using the fundamental equations for two phase movement produced the equation

$$\frac{C_\eta}{C_a} = e^{-\frac{(\eta - \eta_\circ)}{A}} \quad \text{and } A = \frac{0.0017u_m^2}{gd}\left[\frac{\rho_s - (1 + K_1)\rho}{\rho_s - \rho}\right] \qquad (2)$$

where u_m : Mean water velocity; $\eta = \frac{y}{d}$; $\eta_\circ = \frac{\Delta}{d}$;
ρs : Density of solid particles; $\Delta = 2 - 3$ D;
ρ : Water Density; D = grain diameter.
$K_1 = f(w)$, a function of the fall velocity of the particles;

However, the relationship probably most widely used and of comparitively simple form, is that of Vanoni [12] later derived by Einstein [13] from an energy consideration, i.e.

$$\frac{C_y}{C_a} = \left[\left(\frac{d}{y} - 1 \right) \Big/ \left(\frac{d}{a} - 1 \right) \right]^{Z} \qquad (3)$$

Under laboratory experimental conditions the above equations still show variations from the experimental data and this has been attributed to several causes. These include changes in the turbulent characteristics once sediment is being carried by the flow, changes in bed configuration, a change in the fall velocity of the particles, and the use of non-uniform sediment.

Under site conditions Nordin [14] has found that equation 3 applies to the actual concentrations found in a river provided the exponent Z was altered to allow for an apparent fall velocity produced by the concentration gradient.

However, these equations for equilibrium conditions of steady flow all indicate that the sediment distribution is one that decreases continuously from bed to surface.

Observations taken in the Mersey Estuary have shown vertical suspended sediment profiles that do not conform to any of the equations mentioned previously. It is possible to have a profile which decreases from bed to surface, but which has a discontinuity in the upper layers of water. It is also possible to have an inverted profile, i.e. the sediment concentration is greater in the upper layers of water than in those nearest the bed. The vertical distribution then appears to show none of the characteristics of equation 3.

At first sight, the discrepancies may be dismissed by the fact that we are dealing with a major tidal system involving large changes of depth and hydraulic conditions in a comparatively short time. However, although the system is tidal, the conditions regarding instantaneous suspended sediment must be similar to that of an equilibrium state, at any one moment.

Consider the river observations taken at position AD on the 5th May, 1965, Fig. 4. These show the vertical distribution of silt, (here taken as all material 63) at various times after L.W. The absicca and ordinate have been chosen to conform with equation 3. The discontinuity is seen at approximately mid-depth, and it would appear that equation 3 may be quite reasonable if the exponent Z was different above and below this discontinuity.

However, Bowden [4], Price and Kendrick [5], and Abbot [15], in the past have shown that the Mersey Estuary has an important salinity current even though the estuary may be classed as well-mixed on a tidal volume to fresh water flow basis. Over a tidal cycle there is a nett movement of water landward near the bed and seaward at the surface. Thus the conditions above and below the level of zero nett motion will mean that the instantanious equilibrium steady state condition mentioned above should be modified to account for the density effect.

One of the authors has attempted to do this, using the work of Agnew [16]. By combining the theoretical velocity distribution obtained in a tidal estuary with an assumed mixing length distribution, the variation in the concentration of sediment with depth under equilibrium steady state conditions can be calculated. The expression is given thus:-

$$\frac{C_y}{C_h} = \left[\frac{\left(\frac{d}{y} - \alpha\right) + \sqrt{\left(\frac{d}{y} - \alpha\right)^2 - \beta^2}}{\left(\frac{d}{a} - \alpha\right) + \sqrt{\left(\frac{d}{a} - \alpha\right)^2 - \beta^2}}\right]^Z \qquad (4)$$

where $Z = \frac{\chi w}{K\sqrt{gdS_1}}$ $\qquad \alpha = \frac{P_1}{S_1}$ $\qquad \beta = \sqrt{\frac{P_1^2}{S_1^2} + \frac{D_1}{S_1}}$

χ is the Ratio of coefficients of momentum and sediment transfer.

i.e. $\chi = \frac{\varepsilon_m}{\varepsilon_s}$, $\qquad S_1 = I - A_b - F_b - \frac{1}{2}(\Delta A + \Delta F) - D$

$P_1 = \frac{1}{2}\left[I - A_b - F_b - 2D\right]$ $\qquad D_1 = -\frac{1}{2}(\Delta A + \Delta F) + D$

$I = \frac{\partial d}{\partial x}$ the water surface slope due to the tidal component.

$A_b = \frac{1}{g}\frac{\partial u_b}{\partial t}$, an inertia effect: u_b is the water velocity near the bed.

$F_b = \frac{\partial}{\partial x}\left[\frac{U_b^2}{2g}\right]$, a Kinetic effect. $\qquad \Delta A = A_s - A_b$

$A_s = \frac{1}{g}\frac{\partial U_s}{\partial t}$, U_s is a surface velocity. $\Delta F = F_s - F_b$

$F_s = \frac{\partial}{\partial x}\left[\frac{U_s^2}{2g}\right]$ $\qquad D = \frac{d}{2\rho}\frac{\partial \rho}{\partial x}$ $\qquad \rho$ = water density.

Equation (4) applies below the level of zero nett motion which is determined as $\delta = \frac{h}{d}$

The distribution above the position of zero nett motion is then given by the equation

$$\frac{C_y}{C_h} = \left[\frac{\sqrt{S_1+D_1\eta} + \sqrt{S_1}}{\sqrt{S_1+D_1\eta} - \sqrt{S_1}} \times \frac{\sqrt{S_1+D_1\delta} - \sqrt{S_1}}{\sqrt{S_1+D_1\delta} + \sqrt{S_1}}\right]^a \left[\frac{\sqrt{S_1+D_1} - \sqrt{S_1+D_1\eta}}{\sqrt{S_1+D_1} + \sqrt{S_1+D_1\eta}} \times \frac{\sqrt{S_1+D_1} + \sqrt{S_1+D_1\delta}}{\sqrt{S_1+D_1} - \sqrt{S_1+D_1\delta}}\right]^b \qquad (5)$$

where $a = \frac{\chi w\sqrt{1-\delta}}{K\sqrt{gdS_1}}$ $\qquad b = \frac{\chi w\sqrt{1-\delta}}{K\sqrt{gd(S_1+D_1)}}$ $\qquad \eta = \frac{y}{d}$

As the water surface slope S_1 is considerably greater than the density slope D_1, except near L.W. then the expression for b is approximately equal to a, i.e. $Z\sqrt{1 - \delta}$

Thus below the position of nett motion equation (4) is subjeot to the exponent Z; above this position the exponent is approximately, $Z\sqrt{1 - \delta}$

In the middle reaches of an estuary δ will have a value of approximately 0.50. The exponent in the upper layers then becomes approximately $\frac{Z}{1.41}$. Thus the conoentration in the upper layers will be greater than that given by the single continuous curve of equation 3. This is shown clearly in Fig. 5, where the modification that occurs to equation (3) when equations (4) and (5) are used is shown. An arbituary value of $Z = \frac{1}{4}$ has been chosen, and the tidal conditions correspond to maximum ebb velocities.

An examination of actual river results Fig. 4, shows the effect. In those layers above approximately mid-depth, the exponent is seen to be reduced, i.e. more sediment is evident in the upper layers.

Consider now the other "discrepancy" from the ideal case; that of an inverted profile. In order to explain this case, consider first the mechanism of erosion in a tidal estuary. The tidal velocities scour sediment from the river bed and then the turbulent components of the flow carry the sediment into suspension. Scour and settling ooour at this point until an equilibrium vertical profile is reached. The suspended sediment is then transported by the tidal currents along the estuary. If conditions were identical along the estuary length, and diffusion was negligible, then the concentration would be constant with time at every point. If the estuary bed is hard and non-erodable then the equilibrium conditions will no longer apply as the bed is non-contributing. The tidal currents will then distort the equilibrium vertical profile such that the surface sediment will travel further than the bed material. This then means that in areas where the bed is hard it will be possible to have an inverted sediment profile. Thus the vertical suspended sediment profile is very much a function of the presence of erodable material on the river bed.

This inverted profile can be illustrated by reference to the Mersey. Here there is an upper estuary connected via a narrow section which has a hard bed to an outer Bay. The bed of the Narrows section can therefore be considered to be non-contributing. (In fact, it is possible to have this area contributing since some deposition of sediment occurs at the end of the ebb tide. This material is then available for re-distribution and suspension on the flood tide. However, the quantity of material is generally small compared with that available on the bed in the upper estuary).

By plotting the vertical variations of sediment against time, it is possible to see the changes in silt content and their implications. Results for Position C on the 6th November 1964 are shown in Fig. 6a. Notice the inversion taking place at 2½ hours after H.W. The full vertical profile at 2½ hours after H.W. is shown in Fig. 6b.

In Fig. 6a, the bed concentration is seen to rise to a maximum at

V_{max} and then start to decrease. This is due to material being eroded at the station by the tidal velocities - notice the vertical profile is "normal" i.e. increasing with increasing depth. However, at V_{max} the surface curve continues to increase whilst the bed decreases until a point is reached where the surface concentration is greater than the bed concentration. Shortly after this there is a general increase in concentration at all depths. Eventually the surface concentration starts to decrease while that at the bed is still increasing, nntil as L.W. is approached the concentration near the bed decreases as material settles on the bed.

The explanation for this variation in silt content is as follows. The increase and decrease of silt content to V_{max} is material being eroded from Position C, whilst this erosion is occuring, material is being eroded in the upper estuary and is being transported towards Position C which it reaches in the surface layers first. Thus, if the concentrations are of the right magnitude an inverted profile will resnlt, in fact, depending on the magnitude of the concentration and the velocity distribution, any type of profile can result, i.e. greater at mid-depth or quarter depth, etcetera. As the flow decelerates the concentration being produced in the upper estuary reduces but at C that material eroded early in the tide, say at V_{max} is just passing C, and the concentration continues to increase. As the reducing concentration advances on Position C, its effect is felt in the surface layers first, gradually spreading to the bed. However, at about 5 - 5½ hours ebb, a concentration maximum will occur as the tidal velocities reduce to zero and all the material in suspension settles out. The positions of the silt peaks will natnrally be dependent on the positions of the erosion areas and the observation point.

This type of sediment distribution may be illustrated nsing the ideas already discussed. Suppose that sediment is eroded from the upper estuary and forms vertical silt profiles conforming to a mathematical relation, (for ease of working, Eq. 3 has been used), and that this sediment is then allowed to drift along the estuary with no diffusion.

In order to perform the computation the velocity pattern along the estuary at various stages of the tide must be known. The velocity pattern at surface and bed has been extracted from field data taken at positions along the centre line of the estuary. In this way the velocity pattern for a standard tide of 28.0 ft. H.W. L.B.D. has been prodnced and is shown in Fig. 7. From these graphs the drift of a particle released at various stages of tide has been computed and the results are shown in Fig. 8.

For the purposes of this illustration, between sections AB and C the river will be considered to behave as a uniform channel with a two dimensional tide superimposed. If the silt pattern at Position C is formed by material drifting along the channel with no dispersion, then the silt peaks evident at surface and bed will have been produced (at the same instant of time) at the erosion area. Thus by assuming that these two peaks were produced at the same time, the vertical silt profile can be specified by the use of equation 3, i.e. a Z value can be computed which when used in equation 3 gives the concentration at surface and bed corresponding to the magnitude of the silt peaks at Position C. The variation of Z with time at Position AB is now required. This can readily be obtained if the distribution of u_* throughout the tide is known. Observations in various parts of the river using the vertical velocity profiles, have given an estimate of this u_* variation. Using the estimated river variation of u_* throughout the tide, the tidal variation of Z can be computed. Once the bed concentration throughout the tide is specified then the surface concentration can be computed by use of equation 3, and the appropriate Z values.

Silt present on the bed at Position C is also eroded during the tide. The total silt pattern at Position C is then the summation of that eroded from C together with the drifting material from AB. The bed concentration at Position C is known from field data. Thus by using the Z values of AB (since the river was assumed to act as a uniform channel) the surface concentration of sediment can be calculated. The complete computation is shown in Table 1.

Table No.1.

TIME (hrs. after H.W.)	u_* f.p.s.	η_b%	η_s%	Z_{AB}	POSITION AB		POSITION C	
					C_b ppm	C_s ppm	C_b ppm	C_s ppm
0	0	7.3	95	∞	0	0	20	0
0.5	0.057	7.4	95	0.85	75	1	35	0
1	0.186	7.6	95	0.26	340	83	140	34
1.5	0.25	7.9	95	0.194	860	300	185	65
2	0.242	8.3	95	0.20	580	198	200	69
2.5	0.202	9.0	94	0.24	380	112	105	31
3	0.151	9.7	94	0.32	250	50	0	0
3.5	0.11	10.7	93	0.44	160	20	0	0
4	0.076	12	92	0.64	100	6	0	0
4.5	0.0485	13.3	91	1.0	60	1	0	0
5	0.03	15	90	1.6	35	0	0	0
5.5	0.016	16.7	89	3	25	0	0	0
6	0.005	18.4	88	10	10	0	0	0
6.5	0.001	19.6	87	50	5	0	0	0
7	0	20	87	∞	0	0	0	0

The final silt pattern at position C is built up by combining the concentration at position C with the "water drift concentration" as given by Table 1, and Fig. 8. Thus at the surface material eroded at half hours ebb at AB, reaches C at just after 2 hours ebb, whereas the bed material eroded at the same time reaches C at just after 3 hours ebb. Material near the bed, eroded from AB at maximum velocity ($1\frac{1}{2}$ hours ebb) reaches C at nearly 6 hours ebb. However, by this time the velocity has dropped to such a level that the silt can no longer be carried in suspension - River results have indicated that this occurs when the velocity near the bed falls to about 1 fps. i.e. around 5 - $5\frac{1}{2}$ hours. This means that the full concentration will not reach position C and must be modified to reach a zero at 7 hours ebb. The surface and bed concentrations for position C are then added to the drifting silt pattern to give the final silt pattern shown in Fig. 9.

The shape of the overall silt pattern is seen to be almost identical with the actual one observed at position C. The calculated surface concentrations for material eroded from position C also show a very good agreement with the observed surface concentrations.

CONCLUSIONS

1. Measurements of many variables are needed in order to define and understand the sedimentation processes in any estuary.
2. Large variations in suspended silt content have been shown to occur with change of season. These have been correlated with temperature in the Mersey Estuary.
3. The nett circulation pattern existing in an estuary can modify the vertical sediment profiles and prevent the removal of material from the estuary even when the vertical salinity gradient is small.
4. The total silt pattern at any position is the summation of that eroded locally, together with the material drifting from upstream. The contribution due to drifting, can be predominant if there is a limited supply of silt on the bed.

ACKNOWLEDGMENTS

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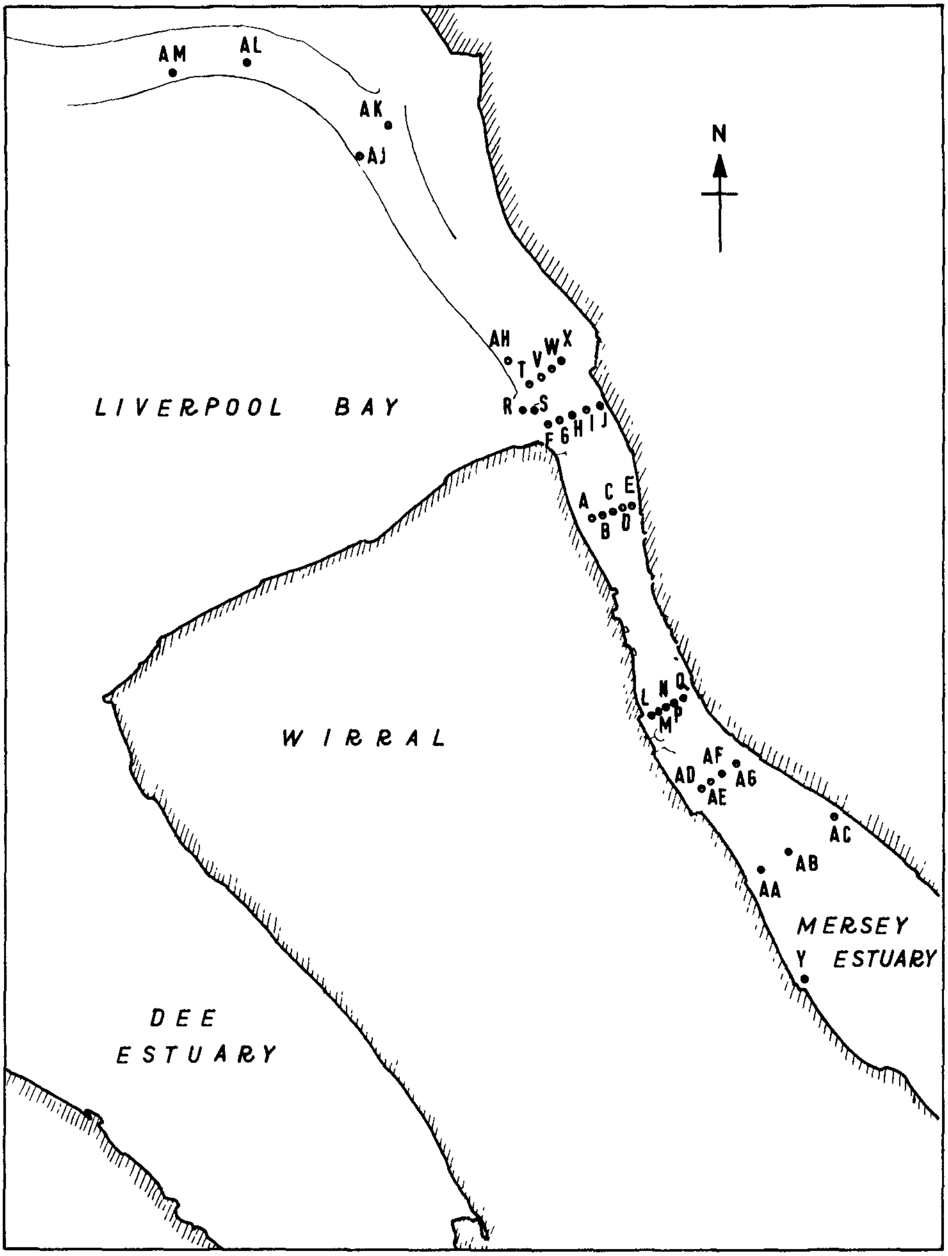

Fig. 1. Observation Stations - Liverpool Bay and Mersey Estuary.

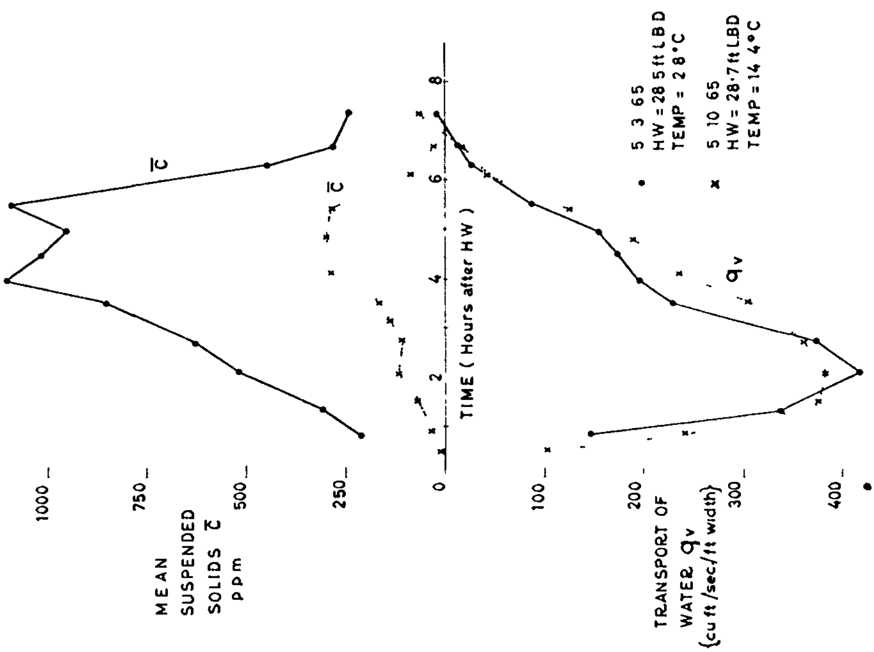

Fig. 2. Variation of $\overline{C}$ with season.

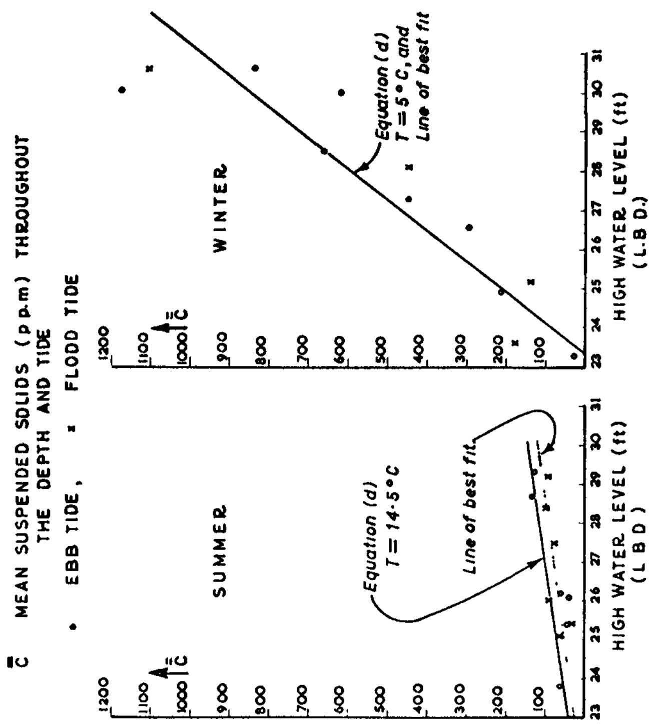

Fig. 3. Variation of $\overline{\overline{C}}$ with h.w.l. for summer and winter conditions (position B, C and D, Egremont section).

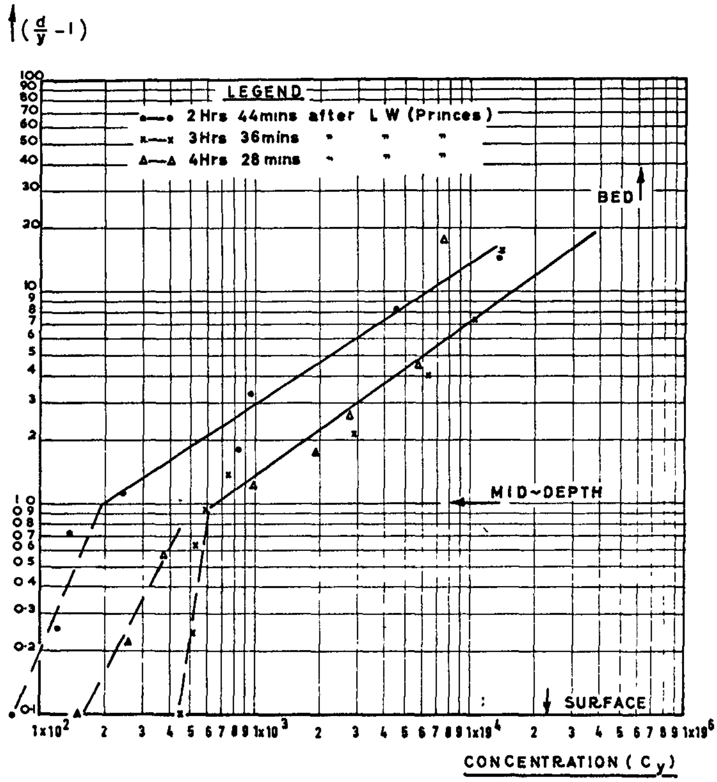

Fig. 4. Vertical silt profiles - position AD, 5·5:65 (flood tide).

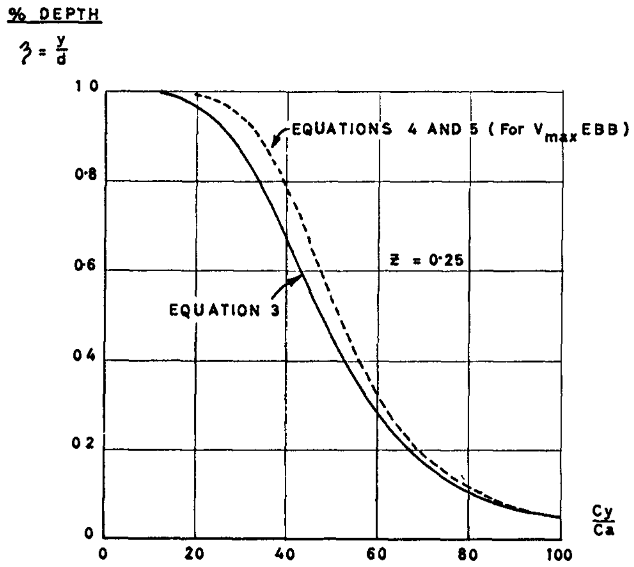

Fig. 5. Theoretical vertical silt profiles.

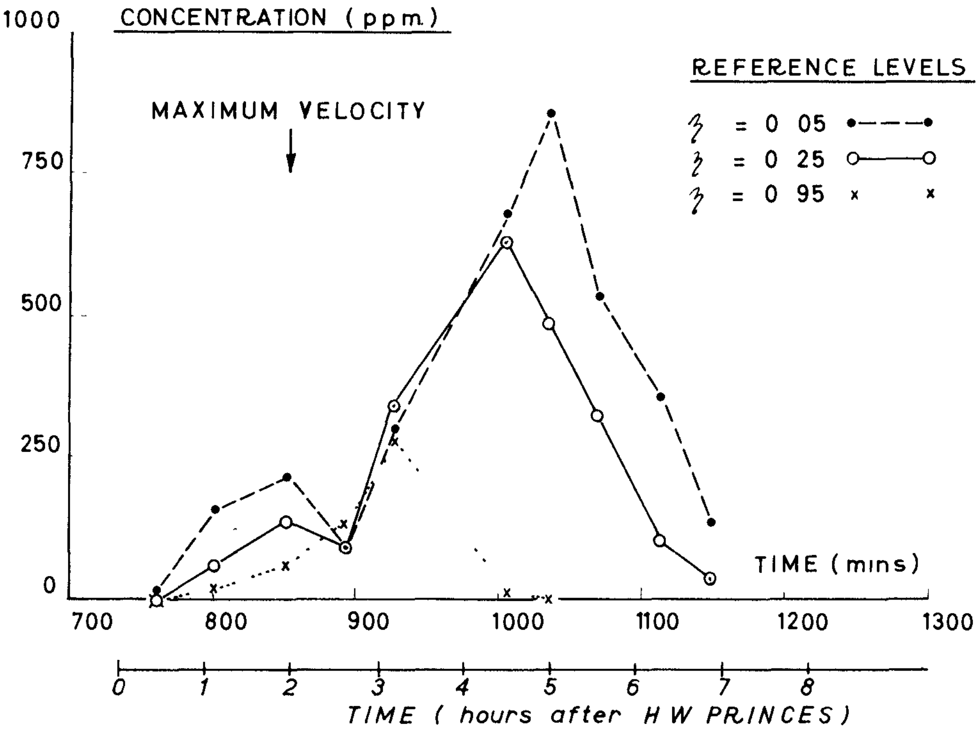

Fig. 6a. Variation of silt concentration with depth and time position C - 6:11:64 (ebb tide).

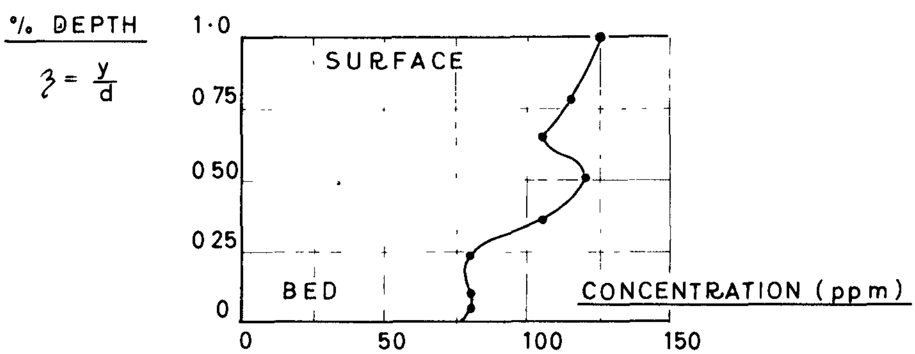

Fig. 6b. Vertical silt profile at 2-1/2 hours after high water position C - 6:11:64 (ebb tide).

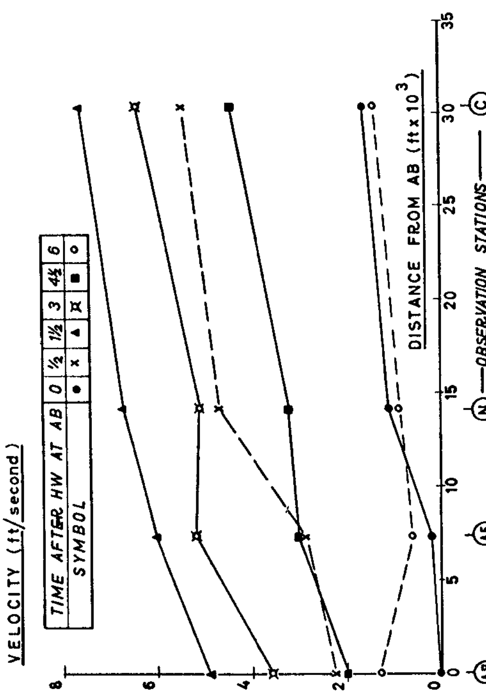

Fig. 7a. Variation of surface velocity along the estuary. (28·0 ft HW Ebb tide)

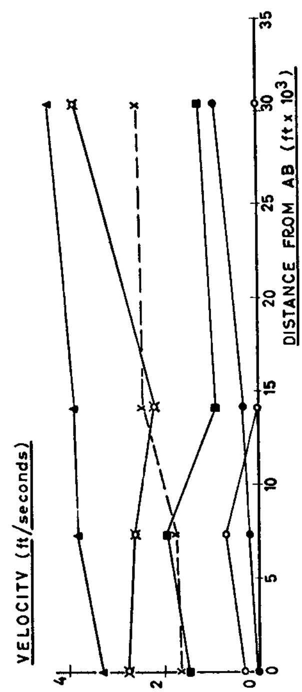

Fig. 7b. Variation of velocity near the bed along the estuary.

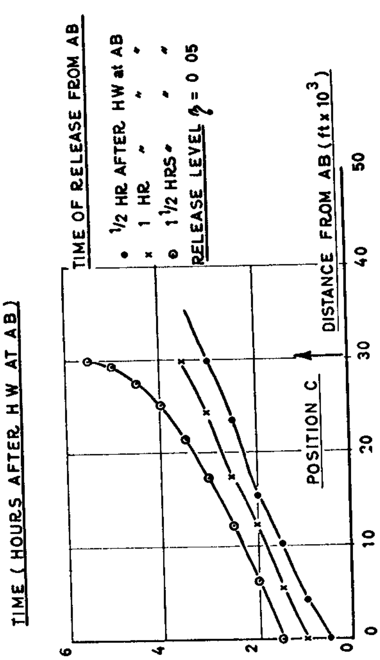

Fig. 8a. Drift of particle released just above the bed from position AB.

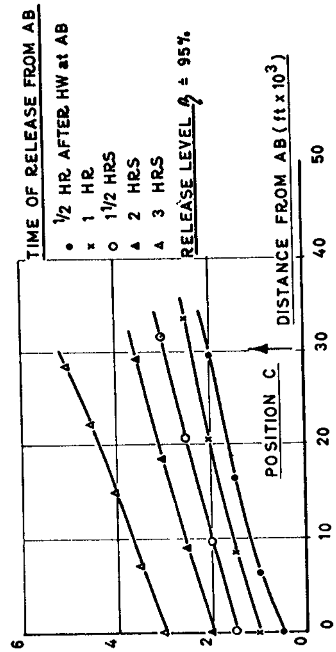

Fig. 8b. Drift of particle released just below the surface from position AB.

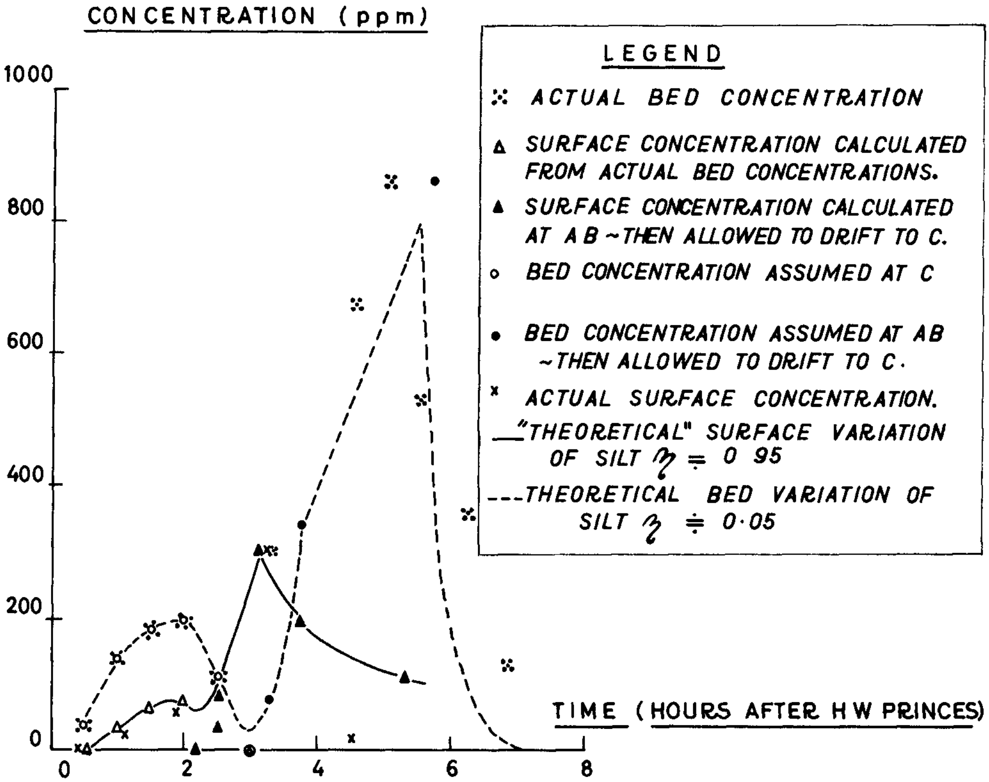

Fig. 9. Surface and bed variations of silt content with time at position C - 6:11:64 (ebb tide).