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# The Importance of Suppression of Turbulence by Stratification on the Estuarine Turbidity Maximum

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**ABSTRACT: A simple numerical model demonstrates that the reduction in turbulence due to stratification greatly enhances the trapping of suspended sediment that occurs at the estuarine turbidity maximum. In moderately and highly stratified estuaries the turbulent diffusivity decreases markedly between the region upstream of the salinity intrusion, where the turbulence is uninhibited by salt stratification, and the stratified regime within the salinity intrusion, where turbulence is reduced by the inhibitory influence of salt stratification. This reduction in turbulent diffusion results in a reduction in the quantity of sediment that can be carried by the flow, causing sediment to be trapped near the landward limit of the salinity intrusion. This trapping process occurs at the same location as that due to the estuarine convergence, but it appears to be many times more effective at trapping silt-size particles. A model is formulated that is similar to Festa and Hansen's (1978) model of the estuarine turbidity maximum, with the addition of a stratification-dependent eddy diffusivity. For silt-size sediment particles, the model indicates as much as a 20-fold increase in the trapping rate with inclusion of the stratification effect. It is likely that this mechanism is important in many partially mixed and highly stratified estuaries.**

## Introduction

The turbidity maximum is a region of locally-elevated suspended matter concentration that occurs near the landward limit of salt intrusion in estuaries (e.g., Glangeaud 1938; Postma 1967; Schubel 1968). Postma (1967) proposed that the turbidity maximum is maintained by the convergence in near-bottom flow associated with the estuarine circulation. He hypothesized that the strength of the turbidity maximum should depend on the amount of sediment originating from riverine or oceanic sources, the strength of the estuarine circulation, and the fall velocity of the sediment. Festa and Hansen (1978) verified Postma's hypothesis with a numerical simulation, which showed that the estuarine circulation results in elevated sediment concentrations at the landward limit of the salinity intrusion for finite fall velocities. Festa and Hansen's model was a significant step toward quantifying the mechanics of the turbidity maximum. However, the model did not account for variations in vertical diffusivity, K, between the unstratified and stratified portions of the domain, which will be shown in this paper to be a major factor contributing to the turbidity maximum.

Other studies have noted the important influence of tidal motions on the estuarine turbidity maximum. Many observational studies (Schubel 1968; Wellershaus 1981; Gelfenbaum 1983; Grabemann and Krause 1989) have indicated that the suspended sediment concentration in the turbidity maximum varies by an order of magnitude or more through the tidal cycle due to resuspension and deposition; hence tidal processes must also play an important role in the mechanics of the turbidity maximum. Schubel (1968) pointed out that the estuarine circulation traps the sediments in the upper portion of the estuary, but that tidal resuspension is responsible for the elevated concentrations in the water column. Uncles et al. (1985) found that tidal pumping of sediment may result in significant longitudinal transport in macrotidal estuaries, and Uncles and Stephens (1989) showed that the turbidity maximum in the Tamar Estuary was sometimes displaced landward of the salinity intrusion by tidal pumping.

Wellershaus (1981) helped to clarify the distinction between horizontal convergence of sediment (i.e., sediment trapping) and tidal resuspension. In a detailed study of the Weser Estuary, he showed that the estuarine convergence leads to the accumulation of a mobile pool of sediment on the seabed, which he designated the "mud reach." His observations indicate that the mud reach moves up and down the estuary as a result of changes in the position of the salt wedge. Tidal resuspension of the easily erodible sediments of the mud reach results in the formation of the turbidity maximum. Wellershaus pointed out that turbidity maxima occur in most estuaries in conjunction with mud reaches, and that their position is almost always in the vicinity of the estuarine convergence. A nu-

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merical simulation of estuarine sediment transport by Lang et al. (1989) included the effect of the mud reach by incorporating a longitudinally varying erosion parameter. The ability of this model to reproduce observed suspended sediment distributions is largely attributable to the prescribed variation of the erosion parameter, which is ultimately the consequence of the sediment deposition rate, and hence the horizontal convergence of sediment occuring in the water column. A model by Uncles and Stephens (1989) was integrated over many years, allowing the mud reach to form as a result of the convergence of sediment in the water column.

An important result of Wellershaus' (1981) work and these more recent model studies is that the turbidity maximum observed at a particular time depends on the tidal velocities and spatial distribution of erodible sediment, that is, it does not depend directly on the horizontal convergence process that actually produces the mud reach. It appears that the estuarine convergence controls the distribution of erodible sediment but on considerably longer timescales than the tidal fluctuations of suspended sediments. Wellershaus' findings reconcile the concept of estuarine convergence of sediment with the observation that the local manifestation of the turbidity maximum is largely the result of tidal resuspension. Still, the details of the trapping process are as yet poorly understood, due in part to the complexity of the interaction between the tidal flow, the suspended sediment, and the estuarine circulation and stratification.

One process that has received little attention, but which may be a very important ingredient in the convergence of sediment, is the suppression of turbulence by stratification, either by salinity or by the suspended sediment itself, leading to the rapid sinking of suspended material at the landward end of the salinity intrusion. Various authors (Hamblin 1989; Lang et al. 1989) indicate the importance of stratification-induced inhibition of turbulence in influencing the vertical distribution of sediment in the turbidity maximum zone. However, the role of this process in contributing to the actual trapping of sediment has not been indicated heretofore, although Uncles and Stephens (1989) hinted at such a role. Stratification has a profound influence on turbulent exchange, due to the stabilizing influence of the vertical buoyancy gradient (Richardson 1920). The stratification within even partially mixed estuaries is large enough to reduce substantially the strength of turbulent mixing. Since the sediment is held in suspension by an approximate balance between gravitational sinking and turbulent mixing (e.g., Dyer 1986), a reduction in vertical mixing will immediately result in sinking of sediment. Generally the salt stratification is responsible for the suppression of turbulence, but in highly turbid systems the stratification by suspended sediment also contributes, leading to rapid accumulation of sediment in fluid mud layers (Allen et al. 1980).

The purpose of this paper is to explore the significance of stratification-induced sinking of particles in the turbidity maximum zone. A simple numerical model is used to quantify the convergence of sediment in a quasi-steady regime, neglecting tidal advective influences and complicating aspects of the bottom boundary condition. Tide-generated turbulence is assumed to set the magnitude of the turbulent diffusivity, although the time variability of the turbulence is not considered, nor are tidal advection and tidal variations in salinity structure. Although the absence of tidal variability limits the detailed application of the model, it is found that the convergence process occurs rapidly enough that it may be significant even if it operates for a limited fraction of each tidal cycle.

## The Influence of Stratification on Suspended Sediment Flux

### EQUILIBRIUM SUSPENDED SEDIMENT DISTRIBUTIONS IN NEUTRAL FLOWS

In the absence of stratification, for example in the flow landward of the salinity intrusion, the turbulence in an estuary is characteristic of open channel flow, for which the vertical mixing is well described by a parabolic eddy diffusivity (e.g., Dyer 1986)

$$K = \beta\kappa u_* z(1 - z/h_0) \tag{1}$$

where $\beta \approx 1$ is a proportionality coefficient between eddy viscosity and diffusivity, $\kappa = 0.41$ is von Karman's constant, $u_* = (\tau_b/\rho)^{1/2}$ is the friction velocity (where $\tau_b$ is the bottom stress), z is elevation above the bed, and $h_0$ is the water depth. For all but the smallest particles in suspension, a balance is rapidly achieved between gravitational sinking and turbulent transport

$$Cw_s = -K\frac{\partial C}{\partial z} \tag{2}$$

where C is the concentration of sediment of a certain size and $w_s$ is the fall velocity of that sediment. This equation is readily integrated, yielding the Rouse profile

$$C = C_{ref}\left(\frac{(h_0 - z)}{z}\frac{h_{ref}}{(h_0 - h_{ref})}\right)^{-w_s/\beta\kappa u_*} \tag{3}$$

where the subscript refers to a reference level a small distance above the bed. The reference concentration, $C_{ref}$, is believed to depend on the shear stress and the bed characteristics (Smith and McLain 1977). In the case of fine, cohesive sediments that make up the turbidity maximum, the reference concentration may also depend on the time history of erosion (Sheng and Villaret 1989) as well as the total supply of erodible sediment in the bed.

The exponent $Ro = w_s/\beta\kappa u_*$ is called the Rouse parameter, signifying the relative magnitude of the fall velocity to the turbulent motion of the fluid. In Fig. 1 the vertical distribution of sediment is shown for different values of Ro. As Ro approaches 1 there is little sediment except in the lower portion of the boundary layer. For small values of Ro, the profile is nearly homogeneous in the vertical.

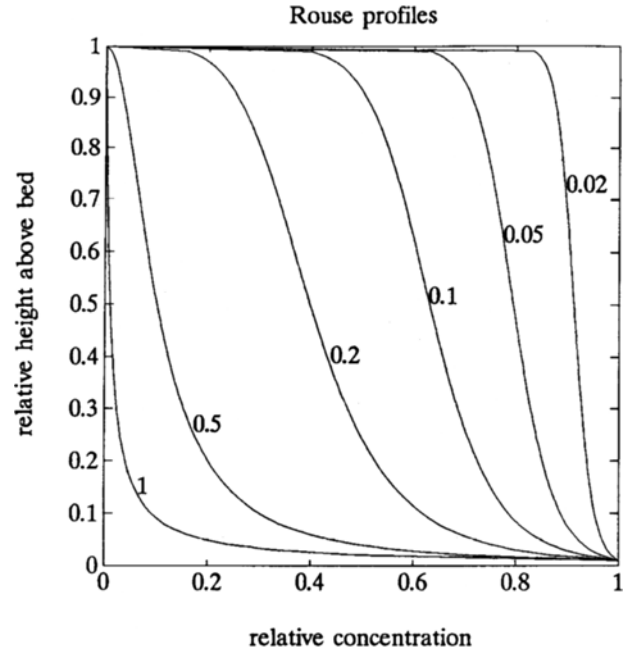


Fig. 1. Dimensionless vertical profiles of suspended sediment (Rouse profiles) for various values of the Rouse parameter $Ro = w_s/\beta\kappa u_*$. The magnitude of the suspended sediment is scaled by the near-bed concentration, which depends on the bed conditions and $u_*$.

## Suppression of Turbulence in Stratified Estuaries

Stratification, either by salinity or by the suspended sediment itself, reduces turbulent kinetic energy and hence reduces K. A popular parameterization for the modification of K was proposed by Munk and Anderson (1948):

$$K = K_0\left(1 + \frac{10}{3}Ri\right)^{-1.5} \tag{4}$$

where $K_0$ is the diffusivity for unstratified water (e.g., Eq. 1), and

$$Ri = -\frac{g}{\rho}\frac{\partial\rho/\partial z}{(\partial u/\partial z)^2} \tag{5}$$

is the gradient Richardson number. Typical values of Ri in stratified estuaries range from 0.5 to 10, yielding reductions of diffusivity by one or two orders of magnitude, based on Munk and Anderson's relationship. More recent developments in turbulence closure theory provide more accurate but far more complicated parameterizations of the influence of stratification on turbulence (e.g., Mellor and Yamada 1974), but Eq. 4 provides a reasonable estimate of the order of magnitude reduction in turbulence to be expected when stratification is encountered.

One important problem with a formulation of the Munk-Anderson type is that the turbulent mixing in the upper water column, where stratification is weak but there is no local source of turbulence, may be overestimated by the model. In the absence of wind stress there is little local production of turbulence in the upper layer of a stratified estuary, so turbulence is likely to be weak. Yet the Mund-Anderson formulation yields an increase in the turbulence in the upper layer to levels comparable to the bottom boundary layer. Fortunately, the distribution of salt and sediment depend only weakly on the diffusivity in the upper water column; they are most sensitive to its value in the bottom boundary layer and across the strongly sheared pycnocline.

## Settling of Sediment in Stratified Estuaries

The large reduction in turbulent diffusivity that occurs between the unstratified, riverine flow and the stratified, estuarine regime causes a commensurate decrease in the quantity of sediment that can be maintained in suspension. It is clear from Eq. 2 that a sharp decrease in K requires an equal increase in the vertical concentration gradient; that is, the concentration must decrease sharply in the vertical direction once within the stratified regime. This adjustment process will occur by sinking of the sediment in the upper part of the water column. The turbulence level in the upper part of the water column is nearly irrelevent, since the weak turbulence within the halocline causes the sediment concentration to decrease to a small value before it reaches the upper layer.

In fact the one-dimensional balance described by Eq. 2 does not apply at the estuarine front because advection and/or time-dependence will also enter into the balance. For the purpose of inves-

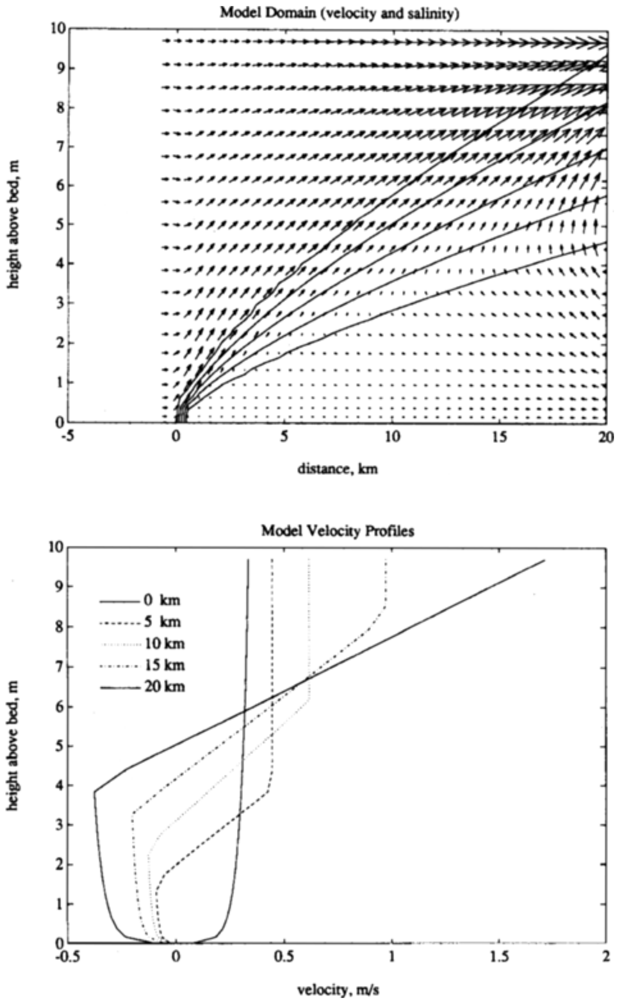


Fig. 2. Idealization of the flow and salinity structure of a salt wedge estuary, depicting the flow field that is used in the numerical simulations. Upper panel: The vectors indicate the longitudinal and vertical velocity, and the solid lines are isohalines. Note that the vertical velocity is scaled by the aspect ratio of the domain. Lower panel: horizontal velocity profiles at 5-km intervals.

tigating the full advection-diffusion problem, a two-dimensional model was constructed that incorporates the suppression of turbulence by stratification as well as horizontal and vertical advection. As will be seen in the model calculations that follow, the trapping that occurs due to the suppression of turbulence is far more effective than that which would occur in a regime with uniform diffusivity (e.g., Festa and Hansen's 1978 model).

## Simulation of the Turbidity Maximum

### Model Formulation

A model was constructed to test the influence of suppression of turbulence by stratification on the formation of a turbidity maximum. The simulations are based on an arrested salt-wedge regime (Officer 1976), in which the tidal motions are neglected except insofar as they result in enhanced turbulent mixing. The neglect of tides means that the large temporal variations of suspended sediment concentration due to resuspension are not included in the formulation, nor are tidal variations in mixing intensity. Although the neglect of tides limits the direct application of the model to actual estuaries, it allows the specific mechanism of turbulence suppression by stratification to be isolated. The model results indicate that the convergence process is rapid enough that the mechanism is important even if it only operates for the 2–4 hour periods during flood and ebb when significant resuspension occurs.

The model prescribes the velocity and salinity (Fig. 2), including a homogeneous upper layer, a halocline in which there are uniform gradients of salinity and velocity, and a bottom boundary layer which has constant salinity and a logarithmic velocity profile. Upstream of the salt wedge there is a homogeneous boundary layer flow. The flow is specified such that mass and salt are conserved. The vertical velocity, w, is determined from the continuity equation. No longitudinal diffusion is included in the model.

The model solves the equation for the time variation of suspended sediment concentration

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + w\frac{\partial C}{\partial z} = +w_s\frac{\partial C}{\partial z} + \frac{\partial}{\partial z}\left(K\frac{\partial C}{\partial z}\right) \quad (6)$$

The bottom boundary condition is zero flux, as in Festa and Hansen (1978). This boundary condition precludes the use of the model for long integrations in time, since the concentration tends to increase without bound. For timescales on the order of several hours however, the boundary condition is appropriate for representing the interval within the tidal cycle when bottom-generated turbulence prevents the settling of sediment. The landward boundary condition is that the sediment conform to the equilibrium profile (Eq. 3). The concentration of inflowing water in the lower layer at the seaward boundary was fixed at the same value as the landward boundary, meaning that there is a source of sediment from both the landward and seaward directions. For the estuarine circulation imposed in the model, the seaward source tended not to be significant, however, and the solution was not sensitive to the seaward boundary condition.

The turbulent diffusion coefficient was represented by Eq. 1 for the unstratified portion of the domain, and the Munk and Anderson (1948) parameterization (Eq. 4) was used to represent the attenuation of turbulence by stratification (Fig. 3).

Although, as noted above, it has deficiencies as a parameterization of turbulence within a stratified estuary, it is a widely used form that likely provides an appropriate order of magnitude reduction in turbulent intensity. A fixed value of $u_* = 1$ cm s$^{-1}$ was applied at all horizontal positions. This would correspond to tidal velocities of 20–30 cm s$^{-1}$. This value of $u_*$ is rather arbitrary; however, it is only important insofar as is specifies the Rouse parameter, $w_s/\beta\kappa u_*$, and since $w_s$ is varied, there was no need to vary $u_*$.

It is assumed that the turbulence is due predominantly to the tidal motions, so there is no variation in $u_*$ due to the estuarine circulation itself. In many estuaries that assumption is not valid, but that brings up another problem that is beyond the scope of this investigation.

To quantify the influence of the suppression of turbulence, "control" cases were run using the unstratified form for the diffusivity throughout the domain. The sediment distribution from these runs was compared to that generated from runs with the Munk-Anderson formulation for suppression of turbulence.

The dimensions and parameters were selected to represent a "typical" salt wedge estuary (Table 1). The initial condition for the model is that the concentration everywhere has a Rouse profile, with a value of $C = 1$ at the bottom. For each run the model was stepped in time for 4 h. This is a reasonable timescale over which tidal stirring may prevent settling, and it is enough time for the upper layer to transit the length of the domain. Note that the model does not achieve a steady concentration, due to convergence within the salt wedge. A steady state solution would require either a horizontal dispersion mechanism or settling, which would add to the complexity of the model without contributing any insight to the mechanism of focussing sediment.

The equations were cast in finite difference form, with a third-order scheme for advection in order to resolve accurately horizontal gradients in concentration (Leonard 1979). The concentration equation was solved explicitly, with a time step of 15 s determined by the diffusive stability constraint.

## Results of Model Simulations

The results of the simulations show the formation of a turbidity maximum whether or not the stratification effect is imposed (Figs. 4–6; Table 2); however, the suppression of turbulence by stratification has a dramatic influence on the intensity of the turbidity maximum, particularly for the intermediate values of $w_s$ (i.e., 0.03–0.1 cm s$^{-1}$). In the absence of the stratification effect (Figs. 4–7,

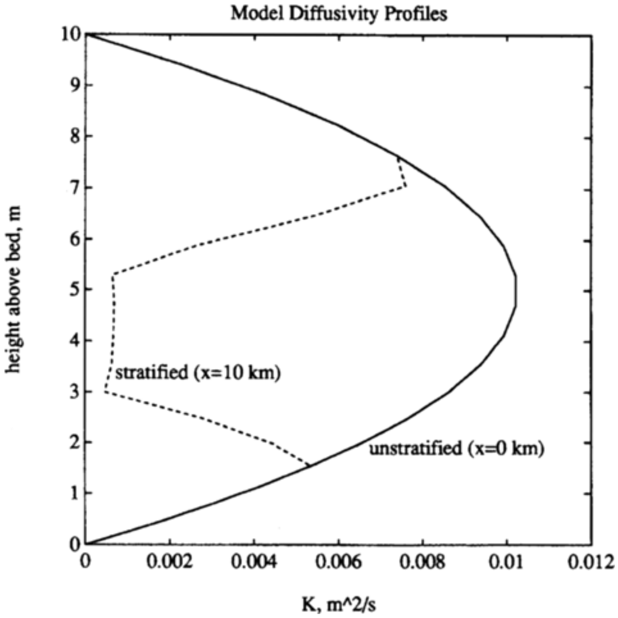


Fig. 3. Eddy diffusion coefficient, K, used in the model simulations for unstratified conditions (solid line, Eq. 1) and stratified conditions (dashed line, Eqs. 1 and 4). The region of small K in the stratified case occurs within the halocline, where the value of the gradient Richardson number becomes large.

upper panel), the concentration shows a broad, weak maximum for all but the highest value of $w_s$. When the stratification effect is imposed (Figs. 4–7, lower panel), the concentration in the upper water column decreases as the upper layer overrides the salt wedge, this results from the sinking of the particles within the halocline due to the reduction of K. These sinking particles are trapped in the lower layer and advected toward the toe of the salt wedge. For the finest sediment (Fig. 4), the maximum is quite broad, extending essentially the entire length of the salt wedge. As the velocities in the fall increase to those typical of silt (Figs. 5 and 6), there is a more pronounced horizontal gradient in sediment concentration in the upper layer as sediment falls into the lower layer, and the turbidity maximum becomes more localized at the toe

TABLE 1. Parameters and dimensions used in the numerical model.

| Parameter | Dimension |
|---|---|
| Water depth | 10 m |
| Horizontal length of domain | 20 km |
| Freshwater velocity | 0.3 m s$^{-1}$ |
| Upper layer velocity | 0.4–1.6 m s$^{-1}$ |
| Lower layer velocity | −0.1 m s$^{-1}$ |
| Maximum vertical velocity | 0.025 cm s$^{-1}$ |
| $u_*$ | 1 cm s$^{-1}$ |
| $w_s$ | 0.01–0.3 cm s$^{-1}$ |

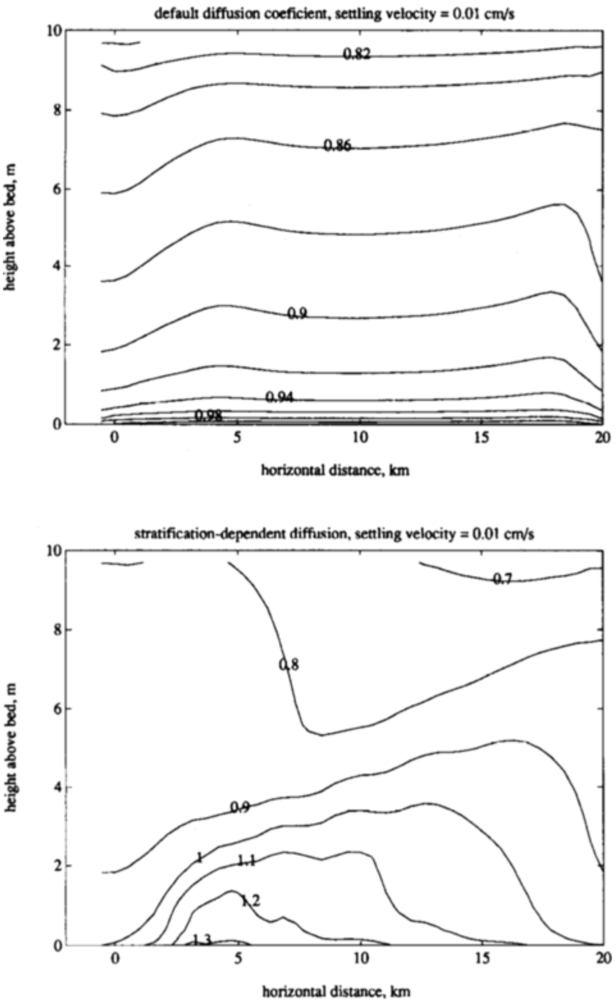


Fig. 4. Contours of suspended sediment concentration for $w_s = 0.01$ cm $s^{-1}$ (fine silt). The default case (upper panel) does not include the stratification effect, while in the lower panel the turbulent diffusion coefficient decreases due to stratification according to the Munk-Anderson formulation. There is a pronounced turbidity maximum in the stratification-dependent case, and there is a notable downstream decrease in concentration in the upper layer.

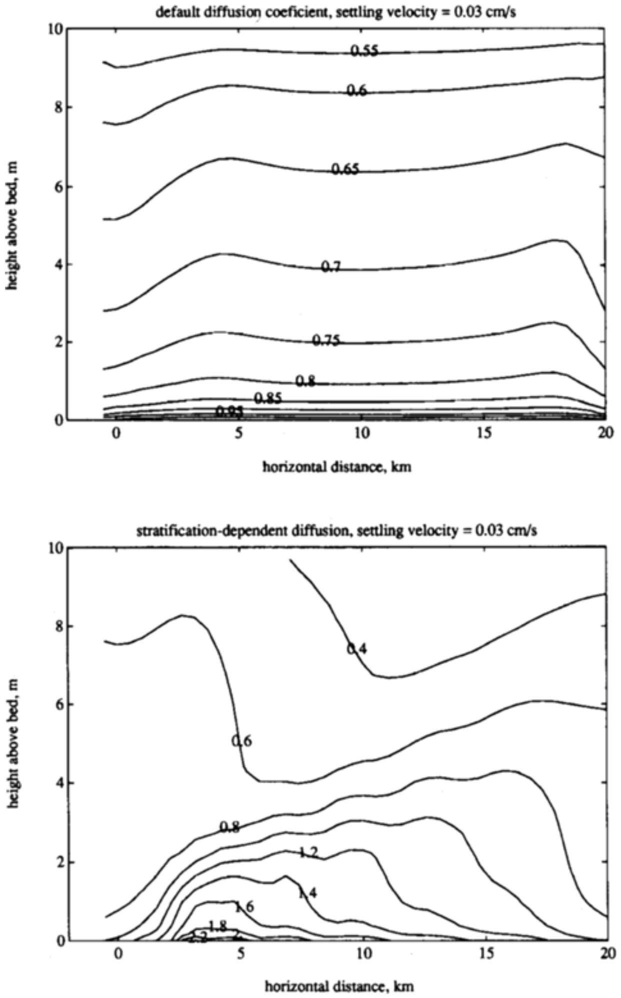


Fig. 5. Contours of suspended sediment concentration for $w_s = 0.03$ cm $s^{-1}$ (fine–medium silt). The upper panel corresponds to the default diffusion coefficient and the lower panel includes the suppression of turbulence by stratification.

of the salt wedge. For fall velocity corresponding to fine sand ($w_s = 0.3$ cm $s^{-1}$, Fig. 7), there is negligible sediment in the upper layer, and all of the trapping occurs close to the bottom where stratification effects are not very pronounced.

The pattern of sediment flux for $w_s = 0.03$ cm $s^{-1}$ and $w_s = 0.1$ cm $s^{-1}$ is shown in Fig. 8. (Note that the arrows are scaled differently for the two runs.) The recirculation of sediment discussed by Festa and Hansen (1978) is clearly evident. The recirculation zone is quite extended for the finer sediment, and it is tightly confined to the landward limit of the salinity intrusion for coarser sediment.

Summary statistics of the sediment distributions in various runs are included in Table 2. A concentration perturbation is defined as $C' = C - C_{ROUSE}$, where $C_{ROUSE}$ is determined from Eq. 3. For each of the runs, the mean concentration anomaly in the landward end of the salt wedge was calculated (defined to include the region from the seabed to the mid-point of the halocline, extending from 0 km to 10 km). For all of the runs, whether or not the stratification effect was included, there was a positive concentration anomaly. However, the anomaly was much more pronounced in the stratified cases. The last column in Table 2 provides a measure of the amplification of the trapping with the inclusion of the stratification effect. For silt-size particles, there is more than an order of magnitude increase in the turbidity anomaly, hence in the trapping effectiveness, when the suppression of turbulence by stratification is included. For the coarsest particles (fine sand), there is little effect.

The model results indicate that the focussing of sediment within the turbidity maximum is most

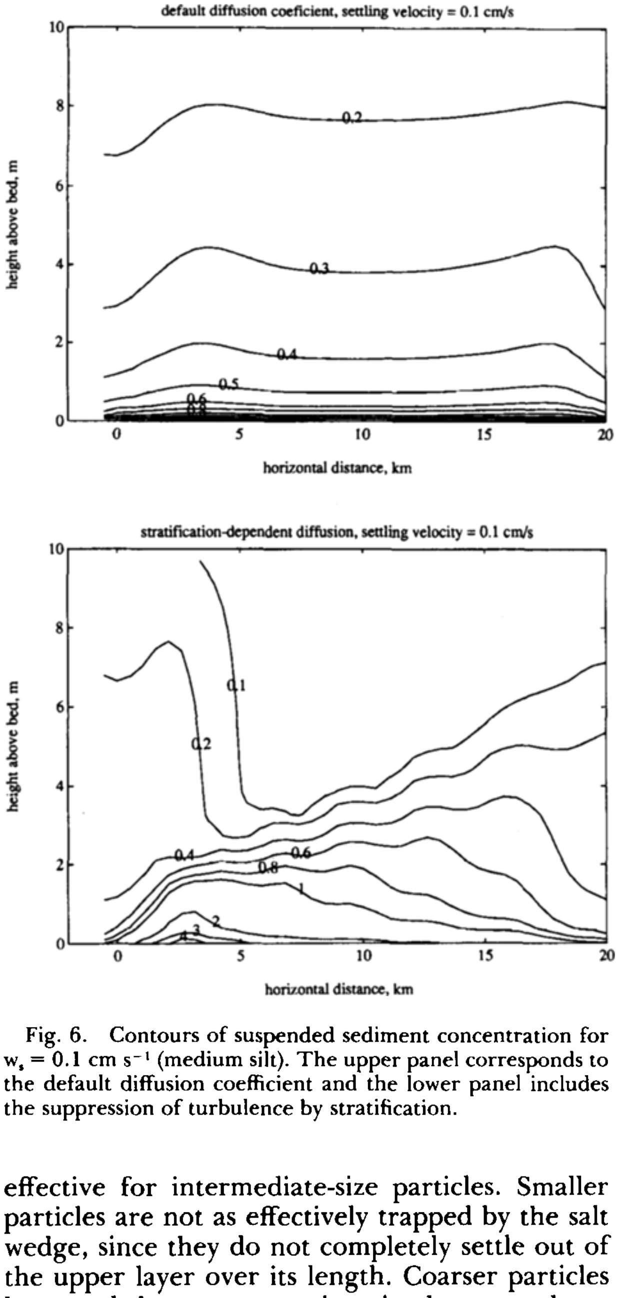


Fig. 6. Contours of suspended sediment concentration for $w_s = 0.1$ cm s$^{-1}$ (medium silt). The upper panel corresponds to the default diffusion coefficient and the lower panel includes the suppression of turbulence by stratification.

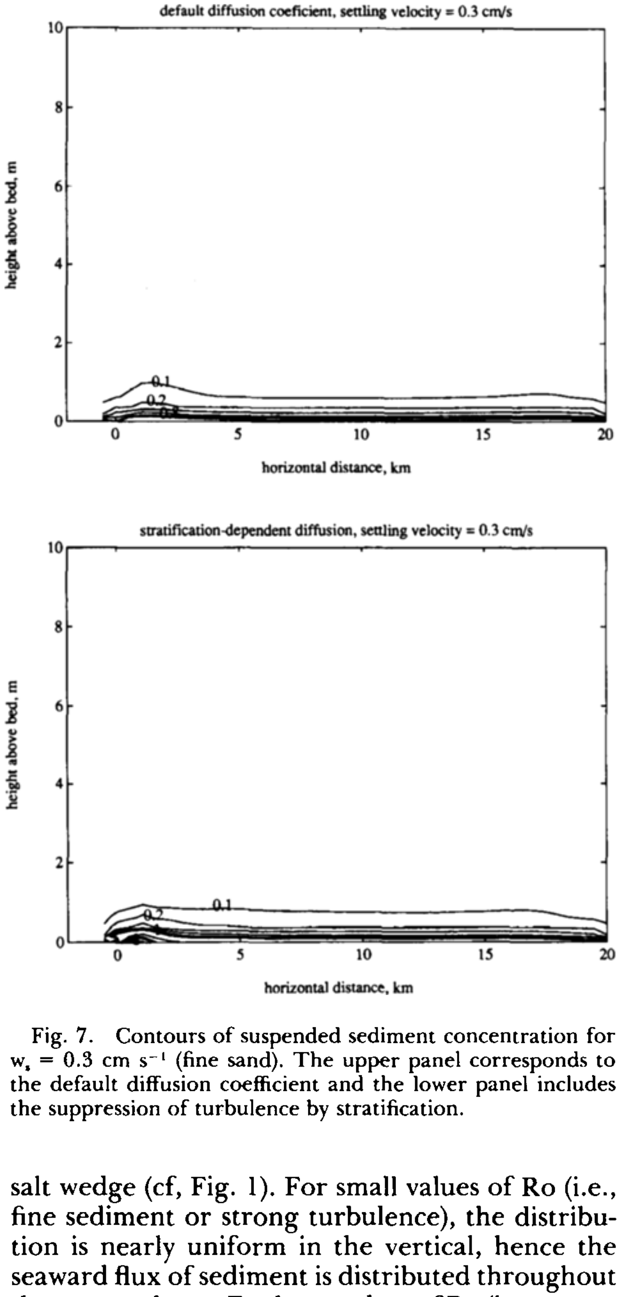


Fig. 7. Contours of suspended sediment concentration for $w_s = 0.3$ cm s$^{-1}$ (fine sand). The upper panel corresponds to the default diffusion coefficient and the lower panel includes the suppression of turbulence by stratification.

effective for intermediate-size particles. Smaller particles are not as effectively trapped by the salt wedge, since they do not completely settle out of the upper layer over its length. Coarser particles have such low concentrations in the upper layer that the only trapping occurs right at the nose of the salt wedge. The two dimensionless parameters describing the trapping process are the Rouse parameter, $Ro = w_s/\beta\kappa u_*$, and a dimensionless trapping length, $\ell = u_1h_1/w_sL$ (where $u_1$ and $h_1$ are velocity and thickness of the upper layer and L is the length of the salinity intrusion, chosen to be 20 km for these model runs). The parameter $\ell$ is the ratio of the advective lengthscale for sinking of sediment out of the upper layer to the length of the estuarine convergence zone. Table 3 indicates the values of these parameters.

The Rouse parameter, Ro, determines the vertical distribution of sediment as it impinges on the salt wedge (cf, Fig. 1). For small values of Ro (i.e., fine sediment or strong turbulence), the distribution is nearly uniform in the vertical, hence the seaward flux of sediment is distributed throughout the water column. For large values of Ro (i.e., coarse sediment or weak turbulence), the sediment and the sediment flux are confined to the near-bottom region. While the higher fall velocities mean that the sediment is more easily trapped, there is less flux due to lower concentrations in the upper water column.

TABLE 2. Results of the model simulations.

| Fall Velocity cm$^{-1}$ | $C'_{control}$ | $C'_{strat}$ | $C'_{strat}/C'_{control}$ |
|---|---|---|---|
| 0.01 | 0.011 | 0.222 | 19.50 |
| 0.03 | 0.030 | 0.597 | 20.07 |
| 0.10 | 0.062 | 0.909 | 14.62 |
| 0.30 | 0.055 | 0.201 | 3.67 |

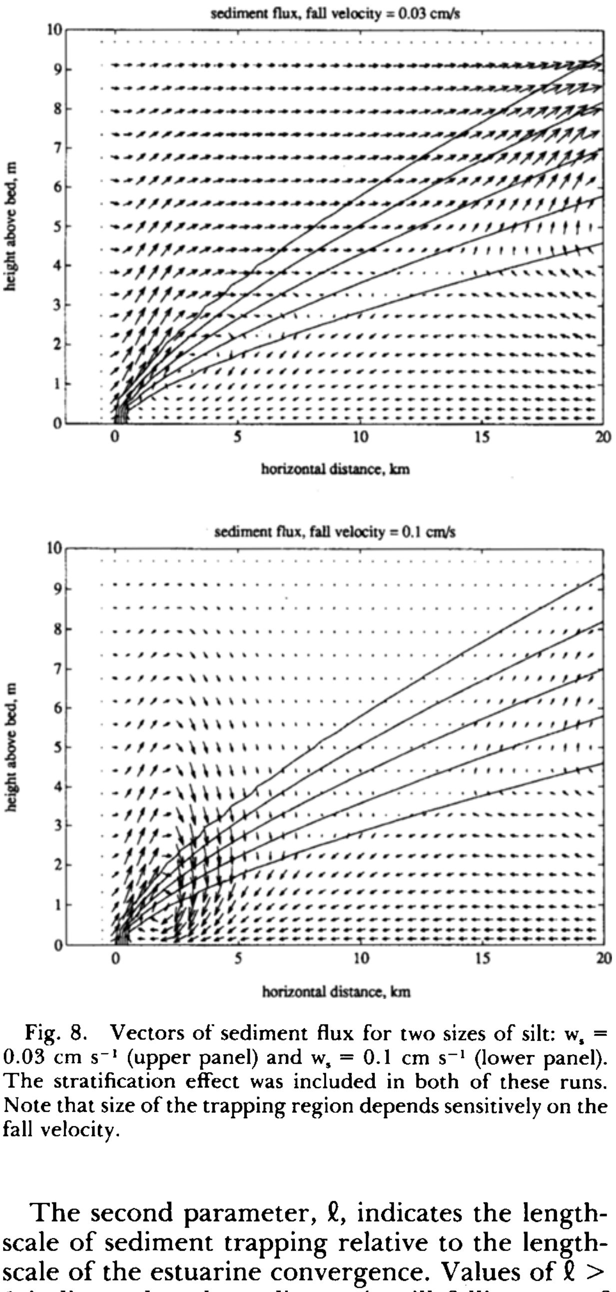


Fig. 8. Vectors of sediment flux for two sizes of silt: $w_s$ = 0.03 cm $s^{-1}$ (upper panel) and $w_s$ = 0.1 cm $s^{-1}$ (lower panel). The stratification effect was included in both of these runs. Note that size of the trapping region depends sensitively on the fall velocity.

The second parameter, $\ell$, indicates the length-scale of sediment trapping relative to the length-scale of the estuarine convergence. Values of $\ell >$ 1 indicate that the sediment is still falling out of the upper layer at the seaward end of the salt wedge, while $\ell \ll 1$ indicate that the trapping is confined to a small area around the toe of the salt wedge. The influence of $\ell$ is clearly evident in the distribution of sediment in the upper layer, which shows a gradual decrease in the downstream direction for fine sediment (Fig. 4) but an abrupt drop-off at the front of the salt wedge for coarser sediment (Fig. 5). For large values of Ro there is so little sediment in the upper layer that the seaward decrease in concentration is no longer evident (Fig. 6). However, the stratification effect still has some influence, as indicated in Table 2.

TABLE 3. Rouse parameter ($w_s/\beta\kappa u_*$) and dimensionless trapping length ($u_1h_1/w_sL$) for model runs.

| $w_s$, cm $s^{-1}$ | $w_s/\beta\kappa u_*$ | $u_1h_1/w_sL$ |
|---|---|---|
| 0.01 | 0.02 | 1.35 |
| 0.03 | 0.07 | 0.45 |
| 0.10 | 0.24 | 0.14 |
| 0.30 | 0.73 | 0.05 |

## Discussion

### Influence of Tidal Motions

Tidal currents exert a tremendous influence on the distribution of suspended sediment. Tidal resuspension of sediments is particularly important, but advection may also be important in the vicinity of the turbidity maxima due to strong horizontal gradients (Gelfenbaum 1983). Given the large variations of suspended concentrations at tidal time-scales, does a model of steady estuarine circulation have any relevance?

The validity of the model depends in a large part on the timescale of horizontal convergence of sediment relative to an appropriate timescale for resuspension. If the resuspension timescale is much shorter than the convergence timescale, then the mean estuarine convergence may not have an appreciable influence on the sediment distribution. In addition, tidal variations in the strength of the estuarine circulation (e.g., internal tidal motions) may be correlated with variations in suspended sediment concentration, altering the horizontal transport of sediment.

The model results presented here indicate that the convergence timescale is, in fact, quite short; significant convergence is obtained in several hours for the representative conditions used for the model simulations. Hence, this mechanism should operate even for the 1–3 h intervals that resuspension is often observed. The timescale for development of a turbidity maximum would be much greater in the absence of stratification effects, on the order of 20 times as long for silt-size particles based on the model results. The results of Festa and Hansen (1978) indicate an even longer timescale for development of the turbidity maximum, on the order of 100 d based on an estimate of the diffusive flux in their model. This very long timescale is due in part to the small fall velocities and large horizontal scales in their model. For the more typical fall velocities used in the present model and with the inclusion of the effect of stratification, a much more vigorous convergence is obtained, yielding significant fluxes even in a fraction of a tidal cycle.

Based on existing observations from the estuarine literature it is difficult to determine the spatial distribution of sediment through the course of the tidal cycle, but a general characterization is possible. Maximum suspended concentrations tend to occur during times of maximum tidal velocity due to resuspension (Schubel 1968; Wellershaus 1981). Spatial gradients due presumably to variations in erodibility (due to unconsolidated sediment in the mud reach) also contribute to the variability of the suspended sediment (Wellershaus 1981; Gelfenbaum 1983). The amount of resuspension depends on the magnitude of the near-bottom velocity, which tends to be higher during the flood due to the addition of the estuarine circulation and the tidal motion. By similar reasoning, near-bottom ebb motions tend to be weaker, except in the region landward of the salinity intrusion, where the ebb velocity should be slightly greater than the flood due to the net seaward flow.

The estuarine circulation is also modulated by the tidal current, due in part to the advection of the salt wedge up and down the estuary (e.g., Geyer and Farmer 1988), but also to the variation of shear resulting from tidal variations in bottom stress (Geyer and Farmer 1988; Simpson et al. 1990). The shear due to bottom stress acting on the tidal flow augments the estuarine shear during the ebb and reduces or reverses it during the flood, depending on the relative strength of the estuarine and tidal velocities. This modulation of shear also results in a modulation of stratification due to "tidal straining" of the horizontal salinity gradient (Simpson et al. 1990). Stronger stratification occurs during ebb flow and weaker stratification occurs during the flood due to this mechanism. This tidal variation of the estuarine shear and stratification can be altered by bathymetric variations, but it provides a generic description that is applicable to many estuarine systems.

A schematic of the variation of the estuarine regime and its influence on sediment trapping is shown in Fig. 9. The tidal variations of estuarine conditions and suspended sediment provide favorable conditions for trapping sediment during the ebb. Resuspension as well as transport of riverine sediment provide a strong seaward flux of sediment in the water impinging on the salt wedge. The strong stratification occurring during the ebb leads to reduced turbulence in the upper layer, causing sediment to fall into the saline layer, where it may settle or remain in suspension. In most estuaries, the ebb is strong enough to result in seaward flow in the lower layer, hence the trapping zone is advected seaward through the course of the ebb. Sediment will leak out of this trapping zone in the bottom boundary layer, but it will quickly be carried back in the seaward direction by the impinging freshwater flow.

The conditions during the flood tide do not favor trapping, since the convergence of suspended sediment becomes much weaker and stratification is reduced. However, the sediment that was trapped during the ebb and subsequently settled to the bottom is readily resuspended, so the turbidity maximum is regenerated during the flood. The sediment is advected landward toward the landward limit of the salinity intrusion. There is often a long period of slack water at the end of the flood, during which the sediment settles near the landward limit of the salt wedge. This sediment will again be resuspended as the salt wedge retreats during the ebb, repeating the cycle. The sediment is ulti-

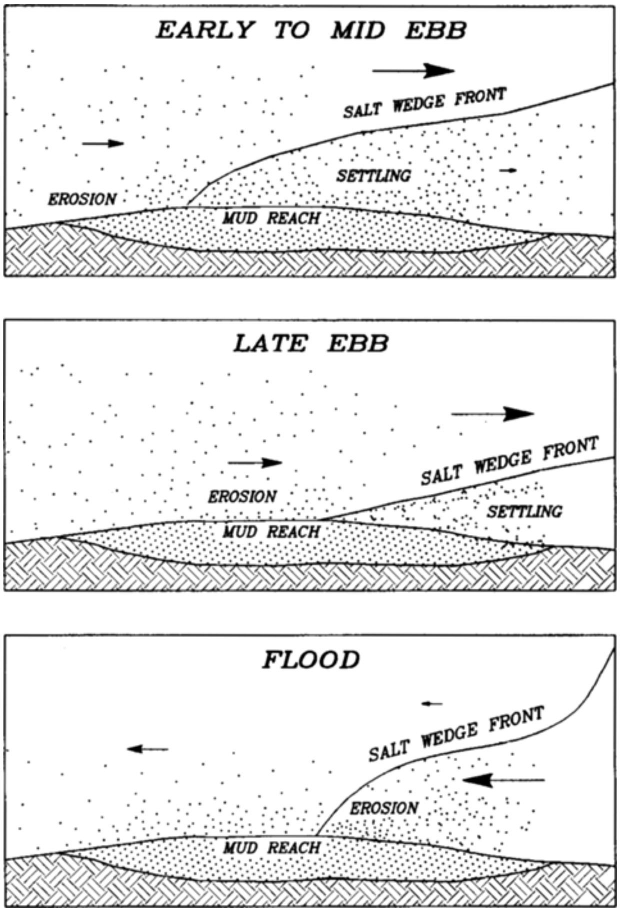


Fig. 9. Schematic of the variation of the estuarine regime through the tidal cycle. The "mud reach" is an area of easily eroded sediment that occurs, on average, near the landward end of the salinity intrusion. The distribution of suspended sediment during maximum tidal flow is largely the result of resuspension from this easily erodible pool of sediment. The salt wedge moves back and forth across the "mud reach" during the tidal cycle, causing a variation in the location of the trapping region. The trapping is likely to be most effective during the ebb, when stratification and shears are strongest. However, the pronounced resuspension during the flood will redistribute the sediment toward the landward end of the mud reach.

mately lost from the system either by net sedimentation, advection, or dispersion into side-channels, or longitudinal dispersion. In many estuaries, a large fraction of the sediment that is transported to the turbidity maximum is removed by dredging.

## Variations on Longer Timescales

When variations of the estuarine regime on timescales longer than a tidal cycle are considered, such as spring-neap variations in stratification (Haas 1977) or runoff variations, the problem becomes much more complicated. For example, a large amount of sediment may be trapped in the lower reach of an estuary during a period of high discharge, which would result in the trapping of a large quantity of fine sediment in that reach. A subsequent decrease in runoff would cause the salinity intrusion to move landward, but the sediment pool would not likely adjust immediately to the change in the hydrographic conditions. In fact there could be a significant lag in the adjustment, depending on the relative magnitude of resuspension flux to the initial supply of sediment to the turbidity maximum. Because of this lag in the adjustment of the "mud reach," one would expect that following a major change in hydrographic conditions, the position of maximum turbidity may be displaced from the estuarine convergence zone. This may explain some anomalous occurrences of the turbidity maximum where there is no obvious relationship to the salinity distribution.

## Comparison With Observations

### *Estimating Fall Velocity*

In virtually every estuary in which a turbidity maximum has been observed, there is a significant variation in turbidity (between a factor of 2 and more than 100) through the course of the tidal cycle that is generally recognized to be the result of resuspension and settling (Schubel 1968). This general observation provides a means of estimating the lower bound on fall velocities of the tidally-varying fraction of sediment, which generally dominates the signal. If this sediment settles during slack water, this indicates a clearing timescale of 1–3 h over a typical depth range of 2–10 m. The range of fall velocities based on these time and depth scales, assuming that the turbulence dies out completely, is $w_s = 0.02 - 0.3$ cm $s^{-1}$. This is the approximate range of fall velocities that were used in the model. In this range of fall velocities, the parameter $\ell$ is O(1) or less, hence there should be a marked decrease in the turbidity of the upper layer moving seaward across the salt wedge front.

### *Assessing the Influence of Stratification*

Most estuaries that exhibit pronounced turbidity maxima have strong stratification for at least a portion of the tidal cycle. Examples of estuaries with pronounced turbidity maxima that show significant ebb tide stratification include the Savanah River (Meade 1972), the Weser Estuary (Wellershaus 1981), the Columbia River during neap tides (Gelfenbaum 1983), the Huanghe (Wright et al. 1990), the Changjiang (Milliman et al. 1985), the Gironde (Allen et al. 1976), and the Amazon (Nittrouer et al. 1986; Kineke et al. 1991). Although most estuarine observations do not provide adequate information about the temporal and spatial distribution of sediment to quantify the convergence of sediment, there are several estuaries in which sediment, velocity, and water properties have been measured in enough detail to see whether they are qualitatively consistent with the model.

**The Weser Estuary.** Observations of the Weser Estuary by Wellershaus (1981) clearly illustrate the clearing of the upper layer during the ebb. At the landward end of the salt wedge, the suspended sediment in the upper layer reaches more than 500 mg $l^{-1}$, but it drops to less than 125 mg $l^{-1}$ by the 8 psu salinity contour, and down to 60 mg $l^{-1}$ at the 20 psu contour. Velocity data indicate near-surface currents of as much as 1.4 m $s^{-1}$ during the ebb, compared to near-bottom values of 0.6 m $s^{-1}$. This indicates that the surface water is rapidly advected over the deep water in the seaward direction, but the sediment must settle rapidly out of the upper layer in order to maintain the observed gradient in suspended sediment. Comparing the shear to the stratification near the toe of the salt wedge, the Richardson number is close to 0.25, which suggests active mixing within the halocline. Yet it is clear that the turbulence is not capable of maintaining the sediment in suspension in the near-surface waters. Almost all of the flux of sediment that impinges on the salt wedge from upstream is trapped within the region of strong salinity gradient, and most of the flux is trapped landward of the 10 psu contour.

High suspended sediment concentrations just upstream of the salt wedge were shown by Wellershaus (1981) to result from the resuspension of sediment that has been trapped in the convergence zone. The position of this pool of sediment upstream of the region where it is trapped during the ebb may be explained by landward advection during the flood followed by settling.

Interestingly, there is a sharp drop in suspended sediment concentration in the upper layer before the salinity stratification becomes strong, but where the stratification is dominated by the vertical gradient of suspended sediment itself. The region of high turbidity just upstream of the salt wedge acts in the same way as the salt wedge to trap sediment by suppressing turbulence. Stratification by suspended sediment is observed in many estuaries with large sediment supplies, including the Amazon (Kineke et al. 1991), the Changjiang (Milliman et al. 1985), the Huanghe (Wright et al. 1990), and the Demerara (Postma 1967).

**The Amazon Estuary.** The Amazon Estuary has a similar distribution of suspended sediment to the Weser, with very high concentrations at the landward end of the salt wedge and rapidly decreasing concentrations in the seaward direction in the upper layer. Observations during a spring tide (tidal velocities of 2 m $s^{-1}$) indicate concentrations up to 5,000 mg $l^{-1}$ in the near-surface waters just upstream of the salt wedge, dropping to less than 10 mg $l^{-1}$ in the upper layer of the salt wedge as the water is advected seaward. During neap tides (tidal velocities 1 m $s^{-1}$), concentrations are not as high on the landward side due to weaker resuspension, but again there is a marked seaward gradient in concentration, dropping to less than 10 mg $l^{-1}$ at the seaward end of the salt wedge. During the neap, fluid muds are observed, with concentrations of up to 40 gm $l^{-1}$ under the nose of the salt wedge. Extremely large vertical gradients of suspended sediment are observed at the halocline in this region. The combined effect of salt and suspended sediment stratification very effectively damps the turbulence within the pycnocline, and the salt wedge functions as a nearly perfect trap of sediment during the neap tide. Enhanced vertical mixing as well as stronger horizontal dispersion during spring tides lead to a less pronounced turbidity maximum, although the total mass of sediment in suspension is probably greater during spring tides due to resuspension throughout the water column.

**The Gironde Estuary.** Similar variations through the spring-neap cycle are observed in the Gironde Estuary (Allen et al. 1980). High concentrations of suspended sediment are observed throughout the water column during spring tides at the point just landward of the salt wedge, but during neap tides a fluid mud layer forms. The fluid mud layer becomes more concentrated through the course of the neap period, but it is re-eroded during the next spring period.

**The Columbia Estuary.** The Columbia River Estuary has a pronounced turbidity maximum during spring tides, when the estuary has relatively weak stratification, and the turbidity maximum appears to vanish during neap tides, when the estuary is strongly stratified (Gelfenbaum 1983; Jay and Smith 1990). At first, this appears to contradict the central thesis of this paper. The paradox is explained by distinguishing the resuspension process, which is a function of the tidal velocity and the local sediment availability, from the sediment trapping process, which depends on the estuarine convergence and the stratification as well as the suspended sediment supply. Based on the results of the present modeling study, the trapping of sediments in the Columbia River probably occurs principally during the neap tides. Rather than being maintained in the water column, however, they tend to settle on the bed during the neap tides and are remobilized during the spring tides. The trapping process determines the distribution of available sediment, hence it controls the location within the estuary where the turbidity maximum will occur. In the Columbia River Estuary the turbidity maximum is advected up to 20 km by tidal advection during spring tides. Large excursions such as this are likely to result in considerable horizontal dispersion of the sediment, counteracting the focussing that occurs during neap tides.

**Chesapeake Bay.** Chesapeake Bay is a partially mixed estuary with a broad turbidity maximum at the landward end of its salinity intrusion (Schubel 1968). There is a significant reduction in suspended sediment in the upper layer as the stratification increases, although bathymetric changes may also contribute to this variation. Tributary estuaries, such as the James and the Rapahonock, also exhibit a similar relationship between the salinity structure and turbidity near the landward limit of their salinity intrusions. However, these partially mixed embayments do not show as clear a manifestation of the influence of stratification, since these estuaries do not have abrupt transitions between unstratified and stratified conditions as is evident in salt wedge estuaries. Still, it is likely that stratification contributes to particle trapping in these systems, even though the influence is not as dramatic as in more strongly stratified systems.

## Summary and Conclusions

The results of a simple, kinematic model of suspended sediment transport in estuaries suggests that the suppression of turbulence by stratification may be an important mechanism for trapping of sediment at the turbidity maximum. Rates of trapping increase by as much as a factor of 20 when the suppression of turbulence by stratification is included in the model. Trapping is so effective that it may explain the formation of the turbidity maximum even if it operates for a small portion of each tidal cycle. The absence of tidal resuspension in the model is a major limitation that restricts its application to idealized cases. However, the model clearly indicates the dominant importance of suppression of turbulence by stratification in comparison to the trapping due solely to the estuarine circulation. With the inclusion of tidal variations there should still be enhancement of the trapping due to stratification effects, although the magnitude and location of the trapping should vary through the tidal cycle.

A variety of observations of turbidity and velocity in highly stratified and moderately stratified estuaries are consistent with the hypothesis of the model, although there was no attempt to make a quantitative comparison. The most easily observed indication of the stratification effect is an abrupt decrease in the concentration of suspended sediment in the upper layer as it overrides the salt wedge. Such a feature is observable in a variety of estuaries, including the Weser (Wellershaus 1981), the Amazon (Nittrouer et al. 1986), and possibly the Chesapeake (Schubel 1968). A more quantitative comparison of the model to observations would require inclusion of the tidal variations in the model formulation as well as careful consideration of the bottom boundary condition. More insight can also be gained by well-executed observational studies of the tidal variation of velocity, salinity, and suspended sediment distributions near the landward limit of the salinity intrusion.

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