Formation of Estuarine Turbidity Maxima in Partially Mixed Estuaries

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Abstract

In many estuaries and tidal channels particles are trapped at specific locations due to converging suspended sediment fluxes caused by the joint action of tide– and density–driven currents. These convergences can result in pronounced estuarine turbidity maxima (ETM). From observations in the York river, a tributary to the Chesapeake Bay (VA.), it can be concluded that during moderate stratified conditions usually one near–bed ETM is found. When the stratification is stronger, the ETM weakens and is pushed upstream, while during more mixed conditions a second, downstream ETM is produced.

In this contribution a simple model is developed and analysed to gain more understanding about ETM dynamics. It is shown that time–averaged sediment fluxes result from residual gravitational circulation and tidal velocity asymmetry. The predicted dependence of the location of the convergences in the time–averaged sediment fluxes on tidal forcing and fresh water discharge appears to coincide with the observations in the York river. However, it turns out that the strength of the ETMs can only be explained by allowing for bed erodability which is not uniform in the along–channel direction. Furthermore, it will be shown that more than one ETM can be found if a time–dependent (vertical) density profile is prescribed. This time–dependency models the fact that, when the stratification becomes too unstable, it will be eliminated by mixing processes.

1 Introduction

Estuaries are the connections between the marine and riverine environments where fresh river water and salty seawater meet. Vertical mixing processes, induced by e.g. tides and waves, cause the formation of a salt wedge. This results in an along–channel baroclinic pressure gradient which sets up a density–driven (also called gravitational) circulation, see e.g. Hansen & Rattray (1965); Nichols & Poor (1967). These models put emphasis on the convergence near the bed of the landward-directed gravitational circulation and seaward–directed river flow.

Another mechanism resulting in particle trapping is the occurrence of tidal velocity asymmetry and its interaction with the time–varying concentration field (Jay & Musiak, 1994). The relative importance of these mechanisms has been studied numerically by Burchard & Baumert (1998). They concluded that in the setting they choose the mechanism associated with tidal asymmetry was more important than the one resulting from the residual gravitational circulation.

The York river (VA.) seems to fit the conditions underlying the conceptual model of Nichols & Poor (1967) in some regards: the system is micro-tidal and partially mixed; the regions of highest turbidity are found above muddy deposits, near the transition from brackish to salt water. However, a second ETM is often located more seaward in the estuary, near the along–channel transition from stratified to mixed conditions (Lin & Kuo, 1999).

In section 2 an idealized model is developed and analysed to gain more understanding about ETM dynamics. Approximate analytical solutions of the equations are constructed by making an expansion of the physical variables in a small parameter Z/H, the ratio of the amplitude of the vertical tide and the undisturbed water depth. Using these expressions, the leading order contributions to the convergence of net sediment fluxes can be separated in two distinct contributions, one related to the convergence of sediment associated with gravitational circulation and the other one associated with tidal velocity asymmetry. This is shown in section 3 where the results are discussed and the conclusions are given.

2 Model formulation

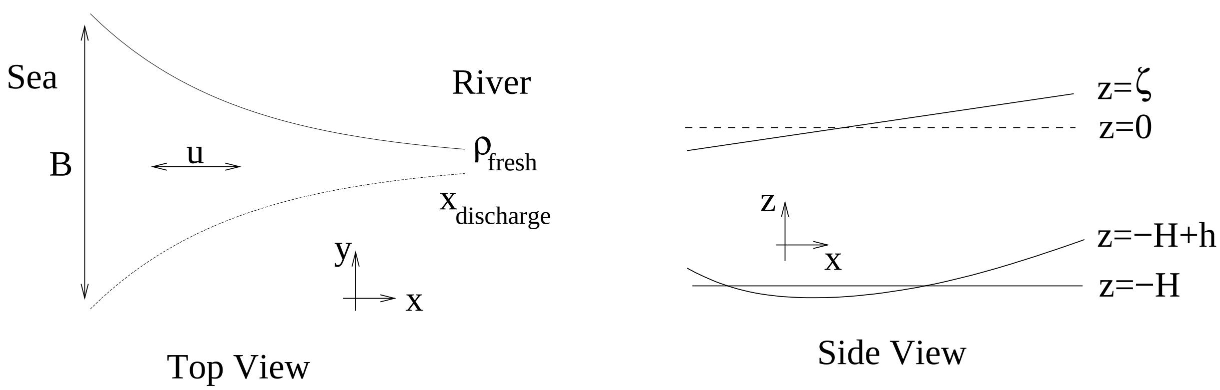


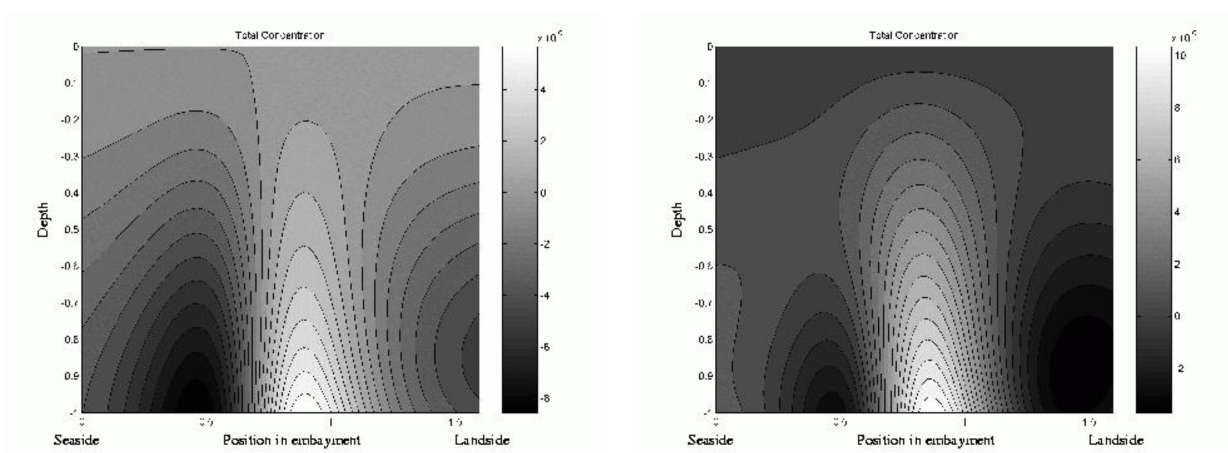
Figure 1: Geometry (left: top view, right: side-view) of the model estuary.

The geometry consists of an open channel with rectangular cross–section and a flat bed, whereas the width converges exponentially with a length scale L_b which is taken from observations. At the seaside the system is forced by a prescribed tidal elevation, whilst at the landside a river inflow is imposed. The water motion is modelled by the width–averaged shallow water equations. The width–averaged advection–diffusion equation is used to find the concentration profiles in the embayment. The density profile is prescribed diagnostically in both the horizontal and vertical direction. In estuaries with a significant river inflow the density is not constant in space and time. In order to model this behaviour in a diagnostic way the following density profile is used:

$$\rho = \rho_0(x) + \rho_1(z) + \rho_2(x, z, t) \qquad (1)$$

Here the first contribution on the right-hand side describes the observed gradual decrease of density from the sea to the river, the second term reflects the observation that systems like the York river are always stably stratified, whereas the last term models the time–dependency of the density. Since the stratification is depth–dependent, the eddy viscosity coefficients are influenced by it. Here we adopt formulations discussed by Van de Kreeke & Zimmerman (1988). Our main interest is in finding the ETM locations in the estuary where a maximum in the concentration occurs. Besides we are interested in the locations where the convergence in the flux of suspended sediment is maximum. In order to find these locations solutions of the model, discussed above, will be constructed. The analysis is based on the fact that the parameter $\epsilon = U/(\sigma L)$ which is, apart from a factor of 2π, the ratio of the tidal excursion (the distance traveled by a fluid particle in a tidal period) and the embayment length, is usually a small number. Note that an alternative expression for this parameter is $\epsilon = Z/H$. For example in the York estuary $\epsilon \sim 0.05$. Hence approximate solutions can be constructed by expanding the physical variables in power series of ϵ and solving the equations at various orders of ϵ. It turns out that only at order ϵ^2 a net sediment flux is obtained. This net sediment flux consists of a part due to residual circulation and a part due to tidal asymmetry. Some results will be discussed in the next section.

3 Results and Discussion



(a) (b)

Figure 2: Time mean concentration for (a) a depth and time independent density field and (b) a depth and time dependent density field. Here the depth is scaled with $H = 10$ m and the length with $L = 70$ km.

In figure 2 the time averaged concentration fields are plotted for two different diagnostically prescribed density fields. It turns out that to get an estuarine turbity maximum, it is essential for the density profile to have an inflection point. This situation is shown in figure 2(a) where a density profile without any depth dependency and an inflection point around $L = 60$ km is prescribed. Here the mechanism is due to an along–channel baroclinic pressure gradient which sets up a density–driven circulation. If a depth– and time dependency is added to the diagnostically prescribed density profile (so both ρ_1 and ρ_2 are unequal to zero in (1)), it is possible to find situations in which more than one ETM is observed. Hence another mechanism resulting in particle trapping is the occurrence of tidal velocity asymmetry and its interaction with the time–varying concentration field. Usually a strong ETM is found around $L = 60$ km and a weaker one near the entrance of the estuary.

From these and other numerical experiments it can be concluded that during generally stratified conditions, one near–bed ETM is found. If the density stratification is assumed to be time–dependent as well (influence of tide), situations occur where two distinct ETMs occur. Hence due to the phase lag between stratification and velocity another mechanism resulting in net convergence of suspended sediment is at work. The physical interpretation of this mechanism is presently under investigation. This seems to be consistent with field measurements where during more mixed conditions two instead of one ETMs are observed. However, the positions of the ETMs found in the model do not correspond very well with the observations. Therefore, the dependence of the stratification on time and place will be studied in more detail.

Furthermore, the strength of the ETMs is usually under–estimated. Therefore, an along–channel variable erosion will be studied in the near future as well.

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