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Hydro- and sediment dynamics in the Gironde estuary (France): Sensitivity to seasonal variations in river inflow and sea level rise

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A B S T R A C T

Understanding estuarine hydrodynamics and sediment dynamics is of key importance to provide the foundation for sound management of these coastal systems. Turbidity maxima, which are zones of elevated suspended sediment concentration (SSC), are of particular interest as they control biogeochemical cycling and affect the overall environmental quality of the estuary. These turbidity maxima, however, are complex dynamic features that respond to changes in forcing conditions. In this study we use a 3D numerical model to investigate the response of hydrosedimentary dynamics to variations in river inflow and sea level rise in the Gironde estuary, which is one of the largest estuarine systems in Europe. Yearly simulations and comparisons with satellite data and measurements of salinity and SSC show that the model reproduces variations in salinity intrusion and the migration of the turbidity maximum driven by seasonal fluctuations in river inflow. Numerical experiments indicate that the formation of this dynamic turbidity maximum is mainly driven by tidal asymmetry. Density gradients play a secondary role by maintaining the stability of the suspended sediment mass. The model also simulates the presence of a secondary turbidity maximum which is more stable, consistent with observations. Evaluation of the sediment budget shows that sediment export mainly occurs during spring tides and when river discharge is high. Simulations including sea level rise suggest that salinity levels in the middle estuary will increase and rising water levels cause tidal amplification, strengthening of tidal currents and enhanced SSC levels in the upper estuary. On the other hand, the locations of the salinity front and the turbidity maximum remain relatively stable under rising water levels. Overall, our simulations suggest that decadal changes in river inflow can potentially have a larger effect on turbidity maximum dynamics than sea level rise.

1. Introduction

Estuaries are found along many parts of the world's coastline. These environments form the transition between riverine systems and the sea, creating highly energetic and dynamic sedimentary environments with large spatial and temporal gradients in physical properties, such as salinity and suspended sediment concentration (SSC) (Dyer, 1997). A characteristic feature in estuarine systems is the formation of a turbidity maximum. These turbidity maxima are zones of locally-elevated suspended matter concentration and understanding their dynamics and behaviour is of key importance for estuarine and coastal environmental issues. Indeed, the estuarine turbidity maximum plays a role in the long-term infilling of an estuary as well as it plays a notable role in biogeochemical cycles. Moreover, seaward fluxes are directly conditioned by residence times of suspended matter within the estuarine zone (Dyer, 1986).

Following the paradigm proposed by Dyer (1988), two main mechanisms can induce a turbidity maximum in tidal estuaries. Firstly, the transition between fresh and saline water leads to a density-driven residual circulation, with a seaward flow at the surface and a landward flow near the bottom that traps suspended material at the landward limit of the salinity intrusion (Postma, 1967). Secondly, the asymmetry of the tidal wave, in which the flood phase is shorter than the ebb phase, causes upstream tidal pumping (Uncles et al., 1984). The inequality between flood and ebb currents drives a net landward transport of suspended matter because of a more intense resuspension during the flood phase, and a more massive settling during high water slack, which is longer than low water slack (Allen et al., 1980). This tidal pumping of particles becomes ineffective once the river flow starts to dominate. Other processes that contribute to the formation of a turbidity maximum are suppression of turbulence by vertical density stratification (Simpson et al., 1990; Geyer, 1993) and tidal velocity asymmetry due to changes in vertical mixing during the tidal phase (Jay and Musiak, 1994). These mechanisms may apply to many

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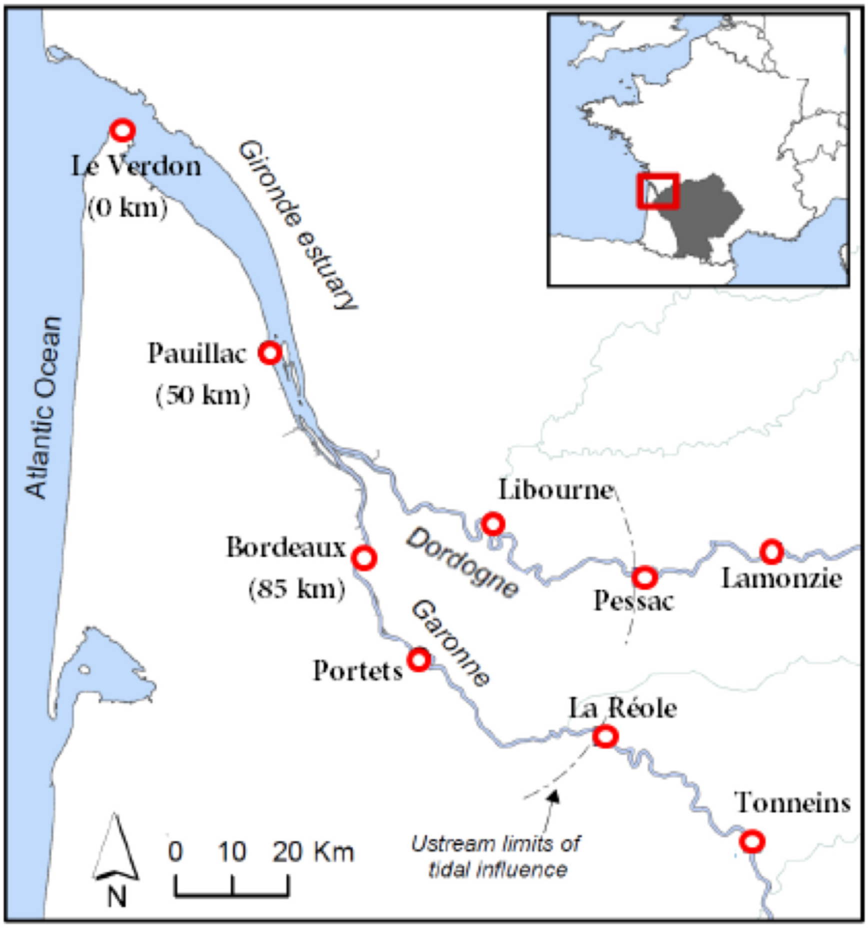

Fig. 1. Location map of the Gironde estuary. The grey area in the insert shows the watershed of Garonne and Dordogne rivers.

estuaries, and their relative importance is dependent on the characteristics of each environment, including shape and bathymetry, river flow, and particle behaviour. Even if many of these mechanisms can act together, we here focus on the two mechanisms of Dyer's paradigm, which is a first order approach on the identification of key factors (Brenon and Le Hir, 1999).

Here we study one of the largest estuaries in Europe, the Gironde located in southwest France (Fig. 1) where a well-developed turbidity maximum appears, and we take advantage of existing field data to compare to a numerical model. The Gironde estuary is a partially mixed to well-mixed macrotidal estuary with a relatively strong river discharge. Investigations into sediment dynamics in the Gironde estuary have highlighted the complexity of the formation of the turbidity maximum. Early observations pointed out that the high-concentration zone was always located close to the freshwater-saltwater interface (Allen, 1972), suggesting that density effects play a major role. However, Allen et al. (1980) later demonstrated that the origin of the turbidity maximum is tidally-induced. In addition to this tidally-induced turbidity maximum which shifts along the estuary depending on river flow, a secondary high turbidity zone in the Gironde exists which remains at a more steady location. Sottolichio and Castaing (1999) described both turbidity maxima based on suspended sediment distributions obtained from water sampling along transects. However, because of the large spatial scales involved these in-situ measurements can provide only limited quantitative information on the geometry and dynamics of these turbidity maxima. Satellite remote sensing can help to obtain a more complete picture of sediment dynamics in the whole estuary. Doxaran et al. (2009) used MODIS satellite data covering a 1-year period (Jan 2005 – December 2005) and they also detected the existence of two distinct turbidity maxima (Fig. 2). Although this type of satellite data improves our understanding of spatial distributions and movements, it remains difficult to use these images to elucidate underlying mechanisms and to make predictions on how sediment dynamics might change in the future under changing boundary conditions.

Both exploratory models (e.g. Huijts et al., 2006, 2009; Talke et al., 2009a; Chernetsky et al., 2010) and simulation models (e.g. Brenon and Le Hir, 1999; Cancino and Neves, 1999; Le Normant, 2000; Burchard et al., 2004; Park et al., 2008; Toublanc et al., 2016) (following the model classification by Murray, 2003) have been successfully applied to study hydrosedimentary processes in estuarine systems. For the Gironde, Sottolichio et al. (2001) conducted numerical modelling exercises to assess the mechanism responsible for the turbidity maximum formation. A 2DH model reproduced the right position of the turbidity maximum under tidal asymmetry effects only, confirming the main role of the tide. The use of a 3D model suggested that density stratifications cause a sharper seaward limit of the turbidity maximum. Sottolichio et al. (2001) pointed out that the conclusions presented in their paper were preliminary, as the parameterizations of particle behaviour and sediment processes were simplified and sedimentary patterns were only partly validated because of the lack of consistent data. Furthermore, they stressed the need to perform longer term simulations to evaluate trends in estuarine sediment budget.

Similar to Sottolichio et al. (2001), modelling efforts usually address estuarine dynamics over a relatively short time scale. Multiple simulations may then be carried out with different river flows to study the effect of freshwater discharge on the location of the salinity front and turbidity maximum (Brenon and Le Hir, 1999; Lin and Kuo, 2003). Simulations of salinity and turbidity over a complete year or longer, however, are still scarce, even though they allow for a more detailed