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Conditions for tidal bore formation in convergent alluvial estuaries

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ABSTRACT

Over the last decade there has been an increasing interest in tidal bore dynamics. However most studies have been focused on small-scale bore processes. The present paper describes the first quantitative study, at the estuary scale, of the conditions for tidal bore formation in convergent alluvial estuaries. When freshwater discharge and large-scale spatial variations of the estuary water depth can be neglected, tide propagation in such estuaries is controlled by three main dimensionless parameters: the nonlinearity parameter ε_0, the convergence ratio δ_0 and the friction parameter ϕ_0. In this paper we explore this dimensionless parameter space, in terms of tidal bore occurrence, from a database of 21 estuaries (8 tidal-bore estuaries and 13 non tidal-bore estuaries). The field data point out that tidal bores occur for convergence ratios close to the critical convergence δ_c. A new proposed definition of the friction parameter highlights a clear separation on the parameter plane (ϕ_0,ε_0) between tidal-bore estuaries and non tidal-bore estuaries. More specifically, we have established that tidal bores occur in convergent estuaries when the nonlinearity parameter is greater than a critical value, ε_c, which is an increasing function of the friction parameter ϕ_0. This result has been confirmed by numerical simulations of the two-dimensional Saint Venant equations. The real-estuary observations and the numerical simulations also show that, contrary to what is generally assumed, tide amplification is not a necessary condition for tidal bore formation. The effect of freshwater discharge on tidal bore occurrence has been analyzed from the database acquired during three long-term campaigns carried out on the Gironde/Garonne estuary. We have shown that in the upper estuary the tidal bore intensity is mainly governed by the local dimensionless tide amplitude ε. The bore intensity is an increasing function of ε and this relationship does not depend on freshwater discharge. However, freshwater discharge damps the tidal wave during its propagation and thus reduces ε and consequently limits the tidal bore development in the estuary. To take into account this process in the tidal-bore scaling analysis, it is necessary to introduce a fourth external parameter, the dimensionless river discharge $\mathcal{Q}_0$.

1. Introduction

Tidal bores are an intense nonlinear wave phenomenon which has been observed in many convergent alluvial estuaries worldwide (see example in Fig. 1). Up until the beginning of the 21*st* century, tidal bore characterization in natural environments was based essentially on qualitative observations (see Lynch (1982) and Bartsch-Winkler and Lynch (1988)). In the last decade several quantitative field studies have been devoted to the analysis of wave, turbulent and sediment processes associated with tidal bores (e.g. (Simpson et al., 2004; Wolanski et al., 2004; Uncles et al., 2006; Bonneton et al., 2011a, 2012; Chanson et al., 2011; Furgerot et al., 2013)). Most of these studies focused on well-developed tidal bores and small scale processes for some specific estuaries, but not on the tidal-bore occurrence conditions for any given alluvial estuaries.

The basic conditions for tidal bore formation are well-known (Bartsch-Winkler and Lynch (1988)): a large tidal range, a shallow and convergent channel, and low freshwater discharge. Yet, estuarine classification in terms of tidal bore occurrence cannot be

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Fig. 1. Illustration of a tidal bore propagating in the Garonne River. Aerial photograph taken at Podensac on September 10, 2010. Tidal wave amplitude at the estuary mouth $A_0 = 2.5$ m and freshwater discharge $q_0 = 128\ \mathrm{m^3/s}$.

established from simple criteria based on these hydrodynamic and geometric conditions. Nevertheless, bore formation criteria based on the tidal range, *Tr*, has been published (Bartsch-Winkler and Lynch (1988) and Chanson (2012)). For instance, in his numerous publications, *Chanson* asserts that *a tidal bore forms when the tidal range exceeds 4–6 m and the flood tide is confined to a narrow funneled estuary*. The tidal range used in this empirical criterion is not clearly defined. Thus, the criterion was tested based on two different definitions. Firstly, we defined the tidal range as the one at the estuary mouth Tr_0. In this case, field observations do not support the empirical criterion proposed by Chanson. For instance, Furgerot (2014) showed that in the Sée/Mont Saint Michel estuary, Tr_0 must be larger than 10 m for tidal bore formation and, on the other hand, Bonneton et al. (2015) observed tidal bores in the Gironde/Garonne estuary for Tr_0 smaller than 2 m. Alternatively, we consider a local tidal range *Tr* at a location in the estuary where tidal bore can form. Once again field observations do not support the *Tr*-criterion. For instance, Bonneton et al. (2012) showed that in the Seine estuary the local tidal range must be greater than 8 m for bore formation and, on the other hand, Furgerot et al. (2013) observed tidal bores in the Sée River when $Tr = 1$ m. These examples prove that such a simple criterion, based on a dimensional flow variable, cannot be relevant to determine tidal bore occurrence.

The objective of the present study is to analyze the conditions which control tidal bore formation in convergent alluvial estuaries. We develop a scaling analysis of the global tidal wave transformation as a function of both the tidal forcing at the estuary mouth and the large-scale geometric properties of the channel. From this analysis we proposed an estuarine classification, in terms of tidal bore occurrence, as a function of several dimensionless parameters.

2. Scaling analysis

A tidal bore can form when a large-amplitude tidal-wave propagates upstream a long shallow alluvial estuary. This large-scale tidal-wave transformation is largely controlled by a competition between bottom friction, channel convergence and freshwater discharge (e.g. Friedrichs (2010), Savenije (2012)). To determine the conditions favorable to tidal bore occurrence, a scaling analysis of this complex physical problem is required. Although such an analysis is common to study tidal wave propagation in estuaries (e.g. LeBlond (1978), Parker (1991), Friedrichs and Aubrey (1994), Lanzoni and Seminara (1998), Toffolon et al. (2006), Savenije et al. (2008)), only few studies have addressed tidal bore formation (Munchow and Garvine (1991) and Bonneton et al. (2015)). Thus, this paper aims to fill in this gap of research by clarifying which dimensionless parameters effectively control tidal bore occurrence in alluvial estuaries.

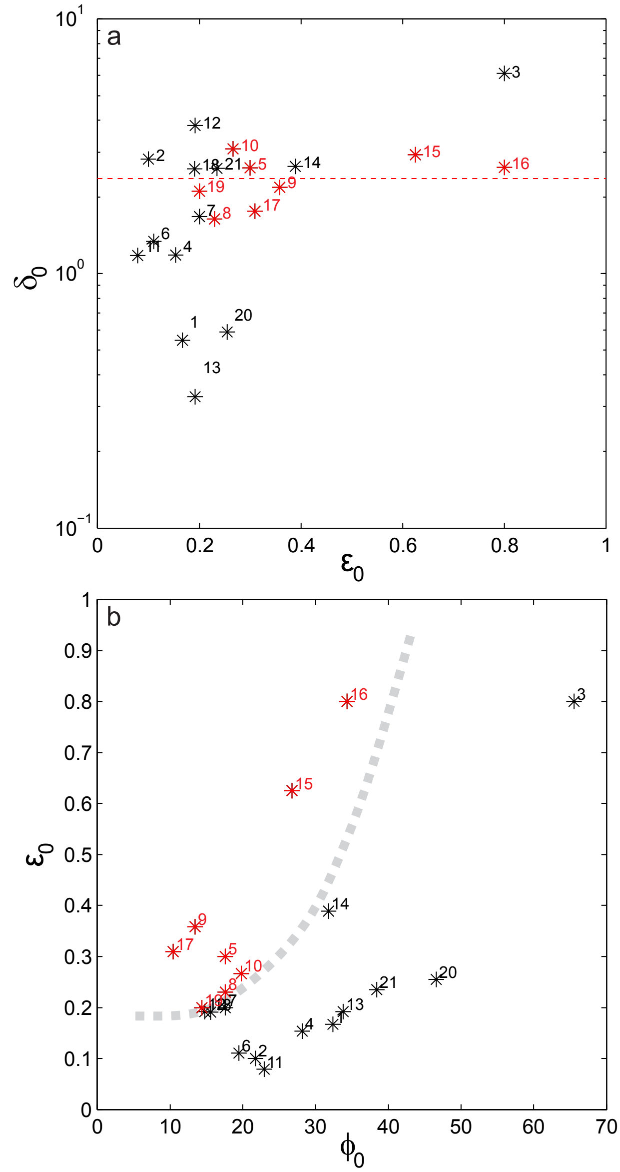

Fig. 2. Position of convergent alluvial estuaries (see Table 1) in the parameter space (ε_0, δ_0, ϕ_0). Red and black asterisks correspond to estuaries with and without tidal bore respectively. a, projection on the plane (ε_0,δ_0). The red dashed line corresponds to the mean value of δ_0 for the 8 tidal-bore estuaries; b, projection on the plane (ϕ_0, ε_0). The thick dashed line ($\varepsilon_c = f(\phi_0)$) divides the plane into two estuarine regimes: estuaries with and without tidal bore. This dashed line was drawn by eye and by drawing on the trend observed in Fig. 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Alluvial estuaries are characterized by movable beds made of sediments of riverine and marine origin. The shape of such estuaries is the result of feedback mechanisms between the flow field and the sediment transport processes. In tide-dominated environments, the self-formed tidal channels are generally funnel shaped with a width that tapers upstream in an approximately exponential fashion and with a fairly horizontal bottom (see Lanzoni and Seminara (1998), Davies and Woodroffe (2010), Savenije (2012)). Thus, an alluvial estuary geometry can generally be characterized by two characteristic length scales: the mean water depth D_0 and the convergence length L_{b0}, which is defined by