A QUANTITATIVE CRITERION TO PREDICT THE OCCURRENCE OF TIDAL BORES

Daniele P. Viero [1]* & Andrea Defina [1]

(1) Dipartimento di Ingegneria Civile, Edile e Architettura, Università di Padova (Padova)

*email: daniele.viero@unipd.it

KEY POINTS

- *Tidal bores are fascinating phenomena that occurs in the estuary of many tidal rivers worldwide.*
- *Tidal bores have significant repercussions on ecology and morphodynamics of an estuary.*
- *Despite the interest, a predictive criterion for tidal bore occurrence is still missing.*
- *Tidal bore is assessed from a phenomenological standpoint, based on the results of a numerical study.*
- *The predictive criterion for bore occurrence performs well against both numerical and real data.*

1 INTRODUCTION

Tidal bores, one of the most fascinating and widely known phenomena observed in tidal rivers, are positive waves travelling upstream along the estuary of a river. Their occurrence is related to a relatively rapid rise of the tide, and often enhanced by the funnelling shape of the estuary. As the flooding tide advances upstream along an estuary, the swell due to the tide grows and its front steepens, thus promoting the formation of a sharp front wave, i.e., the tidal bore (*Bartsch-Winkler & Lynch,* 1988; *Chanson* 2011b).

Tidal bores play a significant role on the ecology and morphodynamics of an estuary, as well as on the social activities that take place in these environments. Turbulent mixing and dispersion are enhanced at the passage of a tidal bore (*Simpson et al.*, 2004; *Koch & Chanson*, 2009), and significant bed erosion and sediment resuspension take place (*Khezri &Chanson*, 2012; *Keevil et al.*, 2015); the bed material is suspended, aerated, advected upstream with the bore, and redeposited on the retreat of the tide (*Chanson et al.*, 2011; *Lubin et al.*, 2010; *Reungoat et al.*, 2014). This process has a positive and significant influence on the breeding of many small, estuarine invertebrates such as shrimps, molluscs and worms, which in turn feed several species of fish and provide important feeding grounds for wading birds and estuarine wildlife (*Chanson*, 2011a). Tidal bores provide opportunity for recreational activities such as surfing, thus acting as a major tourist attraction.

Given their importance and appeal, tidal bores have long been studied theoretically, numerically, experimentally, and with field investigations. However, possibly because of the many mechanisms and conditions that determine whether a tidal bore forms or not (e.g., freshwater river flow velocity and depth, bed slope and friction, the funnelling shape of the estuary, see for example *Shi et al.*, 2014), the prediction of bore occurrence through effective criteria, that are not just qualitative, remains a challenge (*Bonneton et al.*, 2016; *Hoitink & Jay*, 2016).

In the present study, a wide series of numerical simulations are first carried out in a markedly simplified framework. Then, a phenomenological analysis of numerical results is used to shed light on the main processes and parameters controlling the formation of tidal bores (*Viero & Defina*, 2018). Finally, a criterion for predicting bore formation on the basis of external parameters is proposed. Besides well interpreting the results provided by numerical simulations, it also performs surprisingly well when compared with available data from real estuaries.

2 NUMERICAL RESULTS AND PHENOMENOLOGICAL ANALYSIS

In this study, the problem is largely simplified by performing a wide series of numerical simulations in a rectangular channel of constant width, with a uniform subcritical flow forced downstream by rising the water level at a constant rate (Fig. 1). In the numerical simulations, the rate of downstream level rise resembles the

maximum rising rates typical of semi-diurnal tides of real estuaries where tidal bores form (*Friedrichs*, 2010; *Savenije*, 2012; *Bonneton et al.*, 2015). Most of simulations last less than 1-2 hours and, in few cases, extend up to 4 hours.
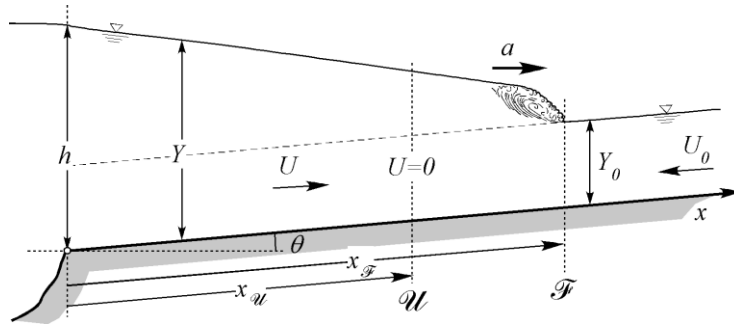

Figure 1. Schematic of the surge propagating upstream against a uniform flow of depth Y_0 and velocity U_0, with notations. $x_{\mathscr{F}}$ denotes the position of the foot of the front, i.e., the most upstream cross section where undisturbed water level is affected by the propagating tide; $x_{\mathscr{U}}$ denotes the position of the cross section where the flow reverse, i.e., the velocity is zero.

Although the framework assumed in the present study to assess the formation and development of a tidal bore is extremely simple, yet the problem is still complex, and the solution is far from being trivial. From the results of numerical simulations, we identified three distinctive behaviours in which, respectively, a tidal bore forms, a tidal bore does not form, or a weak bore forms; the latter has a weakly steep front and, after the bore formed, its fate is to rapidly vanish.

We denote with "$\mathscr{F}$" the foot of the front, and with "$\mathscr{U}$" the cross-section where the flow reverses (see Fig. 1). According to the results of numerical simulations, when the section $\mathscr{F}$ travels upstream faster than the section $\mathscr{U}$, no bore can form; otherwise, bores are found to form when $\mathscr{U}$ meets $\mathscr{F}$. When $\mathscr{U}$ meets $\mathscr{F}$, either the two sections align their velocities to move closely with the same speed (well-formed bore) or else, $\mathscr{F}$ speeds up and $\mathscr{U}$ slows down, so that the just formed bore progressively reduces its height until it vanishes (weak bore). This first basic criterion, relying on the position and speed of sections $\mathscr{U}$ and $\mathscr{F}$, allows to univocally determine if, in a simulated scenario, a well-formed or a weak bore has formed, or not.

3   PREDICTIVE CRITERION FOR TIDAL BORE FORMATION

For non-dimensionalization purposes, vertical lengths are scaled by the flow depth of the incoming uniform flow, Y_0, horizontal lengths are scaled by the ratio Y_0/s, where $s = \tan\theta$ is the bottom slope, velocity is scaled by the small wave celerity $c_0 = (gY_0)^{1/2}$, where g is gravity, and time is scaled by $\tau = Y_0/(c_0 s)$ (see *Viero et al.*, 2017). Non-dimensional variables are denoted with an asterisk (e.g., non-dimensional time is $t^* = t/\tau$).

A criterion to predict the bore formation on the basis of external parameters is here proposed. First, we observe that the growth rate of downstream level controls, to some extent, the flow rate entering the channel from the sea, while the speed of the wave front determine the spreading of these volumes over the channel reach. When the growth rate of the downstream level is large compared to the speed of the wave front, the water from the sea is compressed within a short space and the front is pushed upstream, thus promoting the formation of a bore. On the contrary, if the growth rate of the downstream level is not large, the small volumes of water from the sea are spread over a longer channel reach so that the free surface elevation gently reduces from the sea to the foot of the wave front and the bore does not form. Accordingly, given that during the early stage of the process the foot of the front moves with velocity $a_0 = c_0 - U_0$, the non-dimensional ratio $(dh^*/dt^*)/a_0^*$ is used to measure the strength of this formative mechanism.

Second, a competing mechanisms has been recently highlighted by *Viero et al.* (2017), who showed that the fate of a positive surge, propagating upstream against a subcritical uniform flow, is to gradually reduce its height and velocity until vanishing at a distance L_M, which is given approximately by

$$L_M^* = \frac{2F_0}{1 - F_0^2} \tag{1}$$

where F_0 is the Froude number of the incoming uniform flow. Using the non-dimensional ratio $1/L_M^*$ to measure the intensity of this competing mechanisms, the prevalence of the formative factor over the competing factor is expressed by the ratio

$$\left(\frac{dh^*/dt^*}{a_0^*}\right)\Big/\left(\frac{1}{L_M^*}\right) \tag{2}$$

which must be greater than a threshold value, say a non-dimensional parameter α, in order for the bore to occur. Therefore, noting that $a_0^* = 1 - F_0$, a predictive criterion for bore formation is readily obtained in the form

$$\frac{dh^*}{dt^*} \geq \alpha \frac{(1 - F_0)(1 - F_0^2)}{2F_0} \tag{3}$$

The criterion given by Eq. (3) identifies the rising rate of the downstream level and the Froude number of the freshwater incoming flow as the two main controlling factors of the process.

With $\alpha = 1$, the condition (3) is found to compare well with the results of the numerical model (see Fig. 2a). If the cases in which a weak bore forms are excluded, the criterion has a 100% success rate. The two dashed lines of Fig. 2a are obtained from Eq. (3) with $\alpha = 1.2$ (upper curve) and $\alpha = 0.65$ (lower curve), and they enclose a region on the $(F_0, dh^*/dt^*)$ diagram that contains most of conditions for a weak bore to form. This occurrence strengthen the proposed criterion.
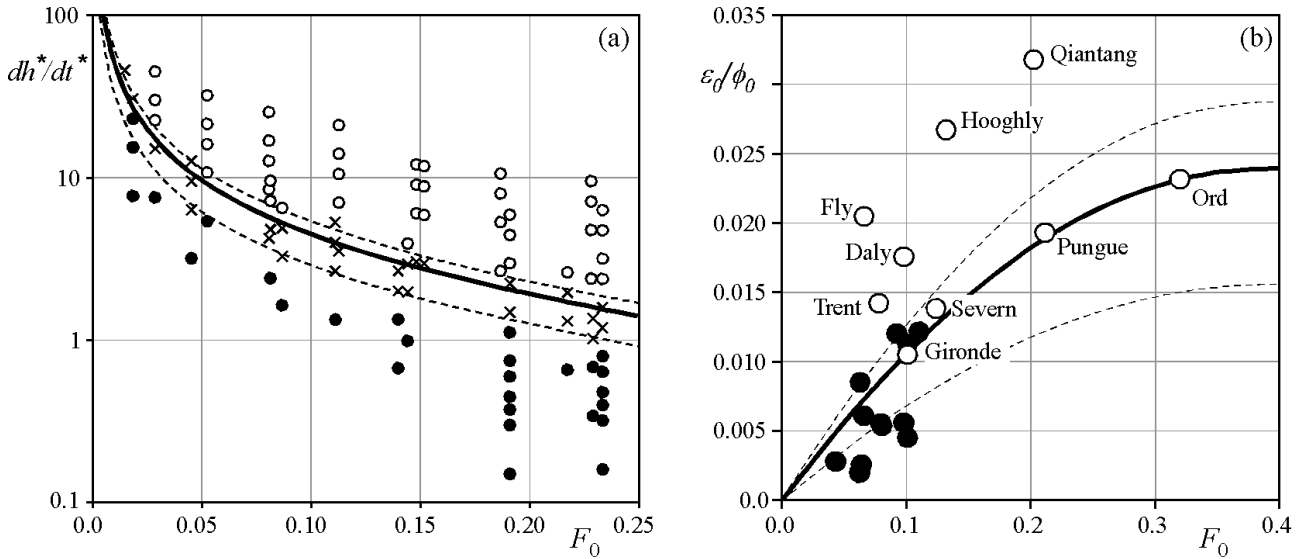

Figure 2. a) Comparison between numerical results and the theoretical criterion for tidal bore occurrence as given by Eq. (3). White and black circles denote conditions in which bores form and do not form, respectively; crosses denote conditions in which weak bores form. The solid curve is given by Eq. (3) with $\alpha = 1$; the two dashed lines are given by Eq. (3) with $\alpha = 1.2$ (upper curve), and $\alpha = 0.65$ (lower curve). b) Data of real estuaries where bores do form (white circles) and do not form (black circles) are plotted in the $(F_0, \varepsilon_0/\phi_0)$ diagram. The solid curve is given by Eq. (4) with $\alpha = 1$; the two dashed lines are given by Eq. (4) with $\alpha = 1.2$ (upper curve) and $\alpha = 0.65$ (lower curve).

3.1 Application of the present criterion to real estuaries

The framework within which the proposed criterion is sound, differs from that of real estuaries mainly because, in the present numerical simulations, the channel has not a funnel shape, and because water levels imposed at the sea do not vary gradually as for a real tide. However, although important, these aspects are not likely to affect dramatically the conclusions drawn above, at least from a qualitative point of view.

Based on a scaling analysis of the one-dimensional shallow water equations, *Bonneton et al.* (2016) showed that the global tidal dynamics is governed by three dimensionless parameters, namely *i)* the dimensionless tidal amplitude $\varepsilon_0 = A_0 / D_0$, with A_0 the tide amplitude and D_0 a characteristic water depth; *ii)* the friction parameter $\phi_0 = C_{f0} L_{\omega 0} / D_0$, with C_{f0} a characteristic and constant friction coefficient, and $L_{\omega 0} = (g\, D_0)^{1/2} / \omega_0$ the frictionless tidal-wave length scale (e.g., *Friedrichs*, 2010; *Lanzoni & Seminara*, 1998; *Savenije*, 2012), ω_0 being the tidal angular frequency; *iii)* the convergence ratio $\delta_0 = L_{\omega 0} / L_{b0}$ where $L_{b0} = -B/(dB/dx)$ is the convergence length, with B the channel width. Bore formation is weakly affected by the convergence ratio δ_0, possibly because most of real estuaries all have approximately the same δ_0 (*Bonneton et al.*, 2016).

In order to compare the prediction of our criterion with the available data for real estuaries, we rewrite condition (3) using the parameters suggested by Bonneton et al. (2015), i.e., ϕ_0 and ε_0

$$\frac{\varepsilon_0}{\phi_0} \geq \alpha \frac{\left(1 - F_0\right)\left(1 - F_0^2\right)}{4k} F_0 \qquad (4)$$

where k is a calibration factor. The predictive criterion (4), with $k = 2.1$, has been tested in predicting the occurrence of tidal bores in real estuaries for which data are available in the literature (Fig. 2b). The available experimental data do not distinguish strong from weak bores; however, it is interesting to observe that points pertaining to estuaries where very strong bores are observed, locate well above the plotted curves. Despite the obvious limitations of the theoretical and numerical frameworks used in this study, the predictions are found to compare favourably with field data, suggesting that the key features controlling the formation of tidal bores are retained in the proposed theory.

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