A quantitative criterion to predict the occurrence of tidal bores

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ABSTRACT

Tidal bores are positive waves travelling upstream along the estuary of many rivers worldwide, with important implications on ecology, morphology, and social activities. A predictive criterion for tidal bore formation is proposed and applied to real estuaries.

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 [1, 2].

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 this environment. Turbulent mixing and dispersion are enhanced at the passage of a tidal bore [3], and significant bed erosion and sediment resuspension take place; the bed material is suspended, aerated, advected upstream with the bore, and redeposited on the retreat of the tide [4]. 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 [2]. Tidal bores provide opportunity also for recreational activities such as surfing, thus acting as a major tourist attraction.

Given its importance and appeal, tidal bore has 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, etc.; see, for example, [5]), the prediction of bore occurrence through effective criteria, that are not just qualitative, remains a challenge [6].

In this study, a phenomenological analysis of numerical results is carried out to shed light on the main processes and parameters controlling the formation of tidal bore [7]. The problem is largely simplified by performing a wide series of numerical simulations [8] 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 [9].

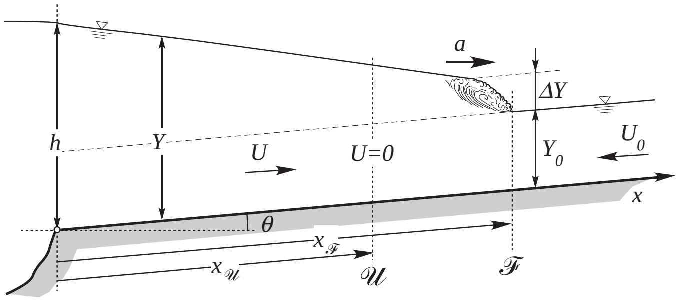

Figure 1: Schematic of the surge propagating upstream against a uniform flow of depth Y_0 and velocity U_0, with notations. ΔY is the bore front height, $x_{\mathscr{F}}$ denotes the position of the foot of the front, i.e., the most upstream cross section where undisturbed water level is affected by 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 solutions are far from being trivial.

From the results of numerical simulations, we identify three distinctive behaviours, in which a tidal bore forms, a tidal bore does not form, and a weak bore forms; the latter has a weakly steep front and, after the bore formed, its fate is to rapidly vanish. With reference to Fig. 1, we denote with "$\mathscr{F}$" the foot of the front, and with "$\mathscr{U}$" the cross-section where the flow reverses. When the section $\mathscr{F}$ travels upstream faster than the section $\mathscr{U}$, no bore can form; otherwise, bores were 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 a common speed (well-formed bore) or, alternatively, $\mathscr{F}$ speeds up and $\mathscr{U}$ slows down, so that the bore just formed progressively reduces its height until it vanishes (weak bore). This first basic criterion allows to univocally determine if, in a simulated scenario, a well-formed or a weak bore has formed, or not.

More importantly, a further criterion is proposed in order to predict the formation of tidal bore on the basis of external parameters. First, we observe that the growth rate of downstream level controls, to some extent, the flow rate (and thus the volume of water) entering the channel from the sea, whereas the speed of the wave front determine the spreading of this volume 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, this way promoting the formation of a bore. In the opposite case, the small volume of water from the sea is 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 $a_0 = \sqrt{gY_0} - U_0$, the non-dimensional ratio $(dh/dt)/a_0 s$ is used to measure the strength of this first formative mechanism (g is gravity, Y_0 and U_0 are respectively the uniform flow depth and velocity, $s = \tan\theta$ is the bottom slope, and t denotes time; a dimensional analysis is carried out in [10, 11]).

Secondly, a competing mechanisms has been recently highlighted by [11], 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 by

$$L_M = \frac{Y_0}{s} \frac{2F_0}{1 - F_0^2} \tag{1}$$

where F_0 is the Froude number of the incoming uniform flow. Using the non-dimensional ratio $Y_0/L_M s$ to measure the intensity of this competing mechanisms, the prevalence of the formative over the competing mechanism is expressed by the ratio

$$\left[\frac{dh/dt}{a_0 s}\right] / \left[\frac{Y_0}{L_M s}\right] \tag{2}$$

which must be greater than a threshold value, say α, in order for the bore to occur. The predictive criterion for bore formation is thus obtained in the form

$$\frac{1}{c_0 s} \frac{dh}{dt} \geq \alpha \frac{(1 - F_0)(1 - F_0^2)}{2F_0} \tag{3}$$

which 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.

Suitably rearranged in terms of significant non-dimensional parameters according to [6], the criterion (3) is tested in predicting the occurrence of tidal bores in real estuaries for which sufficient data are available in the literature. Despite the obvious limitations of the theoretical framework 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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