Environmental, ecological and cultural impacts of tidal bores, burros and bonos

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ABSTRACT: A tidal bore is a series of waves propagating upstream as the tidal flow turns to rising. It forms during the spring tide conditions when the tidal range exceeds 4 to 6 m and the flood tide is confined to a narrow funnelled estuary with low freshwater levels. Tidal bores are locally called mascaret, pororoca, burro, bono, benak and aegir. A tidal bore is associated with a massive mixing of the estuarine waters that stirs the organic matter and creates some rich fishing grounds. Its occurrence is essential to many ecological processes and the survival of unique eco-systems. The tidal bores are also part of the cultural heritage in many regions: the Qiantang River bore in China, the Severn River bore in UK, the Dordogne River in France. In this contribution, the environmental, ecological and cultural impacts of tidal bores are detailed and discussed.

Keywords: Tidal bores, turbulence, turbulent mixing, theory, observation, environmental impact, ecological impact, cultural heritage, burro, bono.

1 INTRODUCTION

A tidal bore is a surge of waters propagating upstream as the tidal flow turns to rising and the flood tide rushes into a funnel shaped river mouth (Fig. 1). The bore forms during the spring tides when the tidal range exceeds 4 to 6 m and the rising tide waters are confined to the narrow funnelled estuary with low freshwater levels. It is estimated worldwide that over 400 estuaries are affected by a tidal bore, on all continents but Antarctica. A bore is a discontinuity of the water depth and it represents a hydrodynamic shock. The tidal bores have a significant impact on the environmental system and the ecology of the river mouth. Recent studies demonstrated in particular the significant impact of small tidal bores and of non-breaking undular surges on natural channels[13,14,15]. Surprisingly, the tidal bore remains a challenging research topic to theoreticians, and many hydrodynamic features remain unexplained.

The existence of a tidal bore is based upon a fragile hydrodynamic balance between the tidal flow range, the freshwater river flow conditions and the channel bathymetry. Some simple theoretical considerations show that this balance may be too easily disturbed by changes in boundary conditions and freshwater inflow. For examples, a number of tidal bores disappeared because of river training, dredging and damming. Man-made interventions led to the loss of several bores with often adverse impacts onto the eco-system: e.g., the mascaret of the Seine River (France) no longer exists after extensive training works and dredging; the Colorado River bore (Mexico) is drastically smaller after dredging. Although the fluvial traffic gained in safety in some case, the ecology of estuarine zones were adversely affected. The tidal bores of the Colorado (Mexico), Couesnon (France) and Petitcodiac (Canada) Rivers almost disappeared after construction of upstream barrage(s). At Petitcodiac, this yielded the elimination of several native fish species. The proposed construction of the Severn Barrage in UK is a major threat to one of the best documented tidal bores: the Severn River bore. The tidal bores do have a significant effect on the natural channels and their ecology. The tidal bore affected estuaries are the natural habitats of several fish species, for example in the Severn, Petitcodiac and Rokan Rivers, as well as the feeding grounds of larger predators. The tidal bores can be some major tourism attractions like in Canada, China, France and UK. Several tidal bores are regularly surfed by kayakers and surfers in Brazil, France and UK. The surfers’ aim is the distance and duration of the ride: how long can we ride the bore? But some bores are dangerous and have had a sinister reputation although they contribute to our cultural heritage.

The tidal bores were studied by hydraulic engineers and applied mathematicians for a couple of centuries. Major contributions included the works of Bazin[2], Barré de Saint Venant[3], Boussinesq[4], Benjamin And Lighthill[5], and Peregrine[6]. For example, in his milestone paper, Adhémar Jean Claude Barré de Saint Venant (1797–1886) applied his famous equations to the tidal bore of the Seine River[7].

The origin of the word ‘bore’ is believed to derive from the Icelandic ‘bara’ (“billow”) indicating a potentially dangerous phenomenon: i.e., a tidal bore with a breaking roller[8]. The French name is ‘mascaret’ and other local names of tidal bores include ‘le montant’ (Garonne River, France), ‘la barre’ (Seine River, France), ‘le mascarin’ (Vilaine, France), the ‘pororoca’ (Amazon River, Brazil), the ‘burro’ (Colorado River, Mexico), the ‘bono’ (Rokan River, Indonesia).

In this keynote, the author aims to share his enthusiasm and passion for the tidal bore. Some basic theoretical considerations are developed. Then the turbulence and turbulent mixing induced by a tidal bore are documented. The rumble noise of tidal bores is discussed based upon field observations, before the interactions between tidal bores and mankind are discussed.

2 THEORETICAL CONSIDERATIONS

2.1 Basic principles

A tidal bore may occur when the tidal range exceeds 4 to 6 m and the funnel shape of the river mouth amplifies the tidal wave. The driving process is the large tidal amplitude. The tides are forced oscillations generated by the attractions of the Moon.
and Sun, and have the same periods as the motion of the Sun and Moon relative to the Earth. Every fourteenth day at full moon or new moon, the attraction forces of the Sun and Moon reinforce one another, and these conditions give the spring tide conditions. The tidal range may be locally amplified further by a number of factors including when the natural resonance of the bay and estuary is close to the tidal period\[^7\, Zl\]. This coincidence implies that the general sloshing of the waters around the inlet or bay becomes synchronised with the lunar tides and amplify their effect, yielding often the best tidal bores a couple of days after the date of the maximum tidal range.

When the sea level rises with time during the flood tide, the tidal wave becomes steeper and steeper, until it forms an abrupt front: the tidal bore. After the formation of the tidal bore, there is an abrupt rise in water depth at the bore front and the flow singularity may be analysed as a hydraulic jump in translation\[^18\, Z1\]. The inception and development of a tidal bore may be predicted using the Saint-Venant equations and the method of characteristics. The flow properties immediately upstream and downstream of the tidal bore front must satisfy the continuity and momentum principles\[^39\, 12\]. Considering a tidal bore travelling in a river section, the bore front propagates upstream with a celerity \(U\) (Fig. 2). Yet the same tidal bore is seen by an observer running alongside the bore at a speed \(U\) as a quasi-steady flow situation called a hydraulic jump in translation. The integral equations of conservation of mass and momentum give a series of relationships between the flow properties in front of and behind the bore front:

\[
(V_1 + U) \times d_1 = (V_2 + U) \times d_1
\]

(1)

\[
\frac{1}{2} \times \rho \times g \times (d_2^2 - d_1^2) = \rho \times (V_1 + U) \times d_1 \times (\beta_1 \times (V_1 + U) - \beta_2 \times (V_2 + U))
\]

(2)

where \(\rho\) is the water density, \(g\) is the gravity acceleration, \(V\) is the flow velocity positive downstream towards the river mouth, \(d\) is the water depth, \(\beta\) is a momentum correction coefficient, the subscript 1 refers to the initial flow conditions and the subscript 2 refers to the new flow conditions (Fig. 2). Herein \(d_1\) and \(d_2\) are respectively the flow depths immediately before and after the tidal bore passage. Note that Equation (2) is based the assumption of hydrostatic pressure distribution in front of and behind
the bore front, and the friction losses are neglected. The combination of Equations (1) and (2) yields the classical result:

\[
\frac{d_2}{d_1} = \frac{1}{2} \left( \sqrt{1 + 8 \times Fr_1^2} - 1 \right)
\]  

(3)

where \( Fr_1 \) is the tidal bore Froude number:

\[
Fr_1 = \frac{V_1 + U}{\sqrt{g \times d_1}}
\]  

(4)

The tidal bore Froude number \( Fr_1 \) is always greater than unity and it is a measure of the strength of the bore. If the Froude number \( Fr_1 \) is less than unity, the tidal wave cannot become a tidal bore. Equations (1) and (2) form a system of two equations with five variables \( (d_1, d_2, V_1, V_2, U) \). Typically the upstream conditions \( (V_1, d_1) \) are known and one more boundary condition is required[2].
2.2 Undular tidal bores

The shape of the tidal bore is directly linked with its Froude number $F_{ri}$. An undular tidal bore is observed for a bore Froude number between 1 and 1.5 to 1.8. For larger Froude numbers, a breaking bore takes place. Practically the very large majority of tidal bore occurrences have an undular shape: i.e., the leading wave followed by a train of well-developed undulations called whelps (Fig. 3). For example, the Equipe Cousteau photographed the 'pororoca' 10 nautical miles before it reached the river mouth\cite{20}. There were more than 30 waves, each 2–3 m high with 20–30 m between crests, and extending behind the horizon with an estimated visibility of 20 nautical miles. Figure 3 shows show an example of an undular tidal bore. Immediately behind the bore front, the wave train presents a pseudo-periodic, undular profile, although the observations show also the development of "semi-chaotic" patterns with increasing time. The field observations indicate also the long-lasting effects of the wave motion, sometimes more than 20 to 30 minutes after the tidal bore passage. This aspect is well-known to surfers and kayakers who can experience some difficulties to come back ashore after surfing.

Considering an undular bore in the system of co-ordinates in translation with the bore front, the flow is quasi-steady and the free-surface profile is stationary. For a two-dimensional incompressible flow, the differential form of the equation of conservation of mass is:

$$\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial x} = 0$$

where $V_x$ is the longitudinal velocity component positive downstream and $V_y$ is the vertical velocity component positive upwards. Since the fluid is incompressible, the stream function $\psi$ exists and the velocity components equal $V_x = -\partial \psi / \partial y$ and $V_y = \partial \psi / \partial x$. The condition of irrotational flow motion is a Laplace equation in terms of the stream function: $\Delta \psi = 0$, and the boundary conditions are: (a) $\psi(y=0) = 0$ at the channel bed, (b) $\psi(y=d) = -q$ at the water free-surface where $q = (V_1 + U) \times d_1$ is the water flow rate per unit width in the quasi-steady flow analogy system of co-ordinates (Eq. (1)), and (c) the Bernoulli principle:

$$\frac{(V_x^2 + V_y^2)}{2} + g \cdot y + \frac{P}{\rho} = \text{const} \tan t$$

with $y$ the vertical elevation ($y = 0$ at the bed), $P$ the local pressure and $\rho$ the fluid density. With the sign convention that is selected, the flux $q$ is positive for a tidal bore propagating upstream. Using the continuity equation, the Navier-Stokes equation
for an ideal fluid in the y-direction yields:

$$V_x^2 \times \frac{\partial (V_y / V_x)}{\partial x} = -\frac{1}{\rho} \frac{\partial P}{\partial y} - g$$

(6)

When the streamline curvature is non-negligible, the pressure gradient departs from the hydrostatic pressure gradient ($\partial P/\partial y = -\rho \times g$) and Equation (6) gives an expression for the pressure deviation caused by the free-surface curvature. Let us assume a linear vertical velocity distribution:

$$\frac{V_y (y = d)}{V_x (y = d)} = \frac{\partial d}{\partial x}$$

(7)

After re-arranging, the variation of pressure field in response to the surface curvature gives a differential equation in terms of the flow depth $d$ and depth-averaged longitudinal velocity. For an ideal fluid in a horizontal channel, it yields:

$$\frac{\partial}{\partial x} \left( V_x^2 \times d + \frac{1}{2} \times g \times d^2 + \frac{1}{3} \times V_x^2 \times d \times \left( d \times \frac{\partial^2 d}{\partial x^2} - \left( \frac{\partial d}{\partial x} \right)^2 \right) \right) = 0$$

(8)

Note that a velocity correction coefficient was dropped in the uppermost left term for clarity. In the system of co-ordinates of the quasi-steady flow analogy, the integration of Equation (8) has a solution:

$$\left( \frac{\partial d}{\partial x} \right)^2 = 6 \times g \times \left( -M \times d - \frac{1}{3} \times d^3 + \frac{d}{g} - E \times d^2 \right) = 0$$

(9)

where $M$ and $E$ are respectively the momentum function and the specific energy. The $M$- and $E$-functions must be defined herein for the general case of a non-hydrostatic pressure distribution and non-uniform velocity profile:

$$M = \int_0^d \left( \frac{\rho \times g}{2 \times g} + \frac{V_x^2}{2 \times g} \right) \times dy$$

(10)

$$E = \int_0^d \left( y \times \frac{\rho \times g}{2 \times g} + \frac{V_x^2 + V_y^2}{2 \times g} \right) \times dy$$

(11)

The periodic wave solution of Equation (9) is called a cnoidal wave function because it takes the form of the square of the Jacobian elliptic function $cn^{10,11,25}$. Some typical free-surface profiles are presented in Figures 4 and 5. Figure 4 shows the water depth as a function of the time at a fixed location, while Figure 5 presents the water elevation as a function of the longitudinal distance at a given time. The measurements highlight the pseudo-periodic shape of the free-surface undulations. In Figures 4 and 5, the data are compared with a sinusoidal curve and cnoidal wave function. Herein, each function was fitted for each half-wave length between a crest/trough and the adjacent trough/crest. Altogether there is a reasonable agreement between the data and mathematical functions, although neither the linear wave theory nor the Boussinesq equations capture the asymmetrical wave shape nor the fine details of the free-surface profile shape. The findings are consistent with an earlier study of relatively large amplitude shallow water waves.$^{10}$

Noteworthy, the agreement between the free-surface data and cnoidal function is best achieved using the parameter of the elliptic function $m > 0.5$ between a wave crest and trough, while $m < 0.5$ between a wave trough and crest. For $m = 0$, the cnoidal wave function equals the sinusoidal profile and more generally the nonlinearity causes little departure from the linear wave theory for small values of $m$. As $m$ increases, the crest becomes more peaky and the trough shallower. The experimental observations highlight the asymmetry of the free-surface undulations, with some differences in wave shape between a crest and trough, and between a trough and the next wave crest. The undulation asymmetry was already noted in the stationary undular hydraulic jumps in terms of both the free-surface profile and the vertical distributions of pressure and velocity.$^{10}$

3 IMPACT OF TIDAL BORES

A tidal bore is a hydrodynamic shock with a sudden rise in water elevation. The flow singularity progresses upstream and may travel dozens of kilometres inland before vanishing. The development and advance of a tidal bore may be predicted by some simple theoretical considerations. The presence of a tidal bore indicates some macro-tidal conditions associated with an asymmetrical tide. The flood tide is usually shorter than the ebb tide period and the flood flow is much faster. Worldwide, it is believed that over 400 estuaries are affected by a tidal bore on all continents but Antarctica, and that number is likely an underestimate because it does not include the numerous tidal bores in small inlets, creeks and drainage canals in shallow-water bays (e.g. Baie du Mont Saint Michel, Bristol Channel) nor the small tributaries of large rivers (e.g., Seine, Hooghly, Garonne).

Limited quantitative information is available on the turbulence and mixing induced by the tidal bore because the field observations are difficult and most studies did not use a fine instrumentation under well-defined flow conditions. Some recent laboratory investigations provide some much needed details. The results demonstrate unequivocally that a tidal bore acts like a ‘gigantic’ mixer that stirs the matters and sediments, and advects upstream the suspended materials into the upper estuarine
Figure 4. Free-surface profile of an undular tidal bore: time-variation of the flow depth for the Dee River tidal bore on 22 September 1972 (Data: Lewis 1972) – Comparison with the linear wave theory (sinusoidal) and Boussinesq equation solution (cnoidal).

Figure 5. Free-surface profile of an undular tidal bore: longitudinal variation of the water elevation in an undular positive surge in the Oraison power plant intake channel (Data: Ponsy and Carbonnell 1966) – Comparison with the linear wave theory (sinusoidal) and Boussinesq equation solution (cnoidal).

regions. All the observations show further the significant impact of small tidal bores and of non-breaking undular bores. A key feature of a tidal bore is its rumble noise that can be heard from far away. Some detailed measurements show that the sounds generated by a breaking bore have a low-pitch comparable to the sounds generated by bass drums and locomotive trains, and the dominant source of the rumble noise is the collective oscillations of the bubble clouds entrained in the tidal bore roller[6].

The tidal bores do have a significant effect on the natural channels and their ecology. The tidal bore affected estuaries are the natural habitats of several fish species, as well as the feeding grounds of larger predators like sharks, crocodiles, seals and whales. A tidal bore is the result of delicate balance between the tidal conditions, the freshwater conditions and the estuarine bathymetry. This fragile balance can be easily disturbed: e.g., by a change in freshwater discharge or some variation in bathymetry (dredging, river training). Man-made interventions led to the disappearance of several tidal bores with often adverse impacts onto the eco-systems. The interactions between tidal bores and Mankind are complicated. The tidal bores can be some major tourism attractions like in Canada, China, France and UK. Several tidal bores are regularly surfed by kayakers and surfers in Brazil, France and UK. The surfers' aim is the distance and duration of the ride: how long can we ride the bore? But some bores are dangerous and have had a sinister reputation (Qiantang River, Seine River, Bamu and Fly Rivers) while hindering the local development and transportation. A tidal bore is an integral part of our environment and cultural heritage like in China where the tidal bore attracts half million of tourists during the Moon festival. But it is an endangered phenomenon that can be too easily affected adversely by human interventions.
REFERENCES


