Shear velocity structure and sediment resuspension associated with tidal bores

N. Bonneton, P. Bonneton, J.P. Parisot & A. Sottolichio
CNRS, UMR EPOC, University of Bordeaux, Talence, France

ABSTRACT: Tidal bores are nonlinear and nonhydrostatic phenomenona, which can be very intense and play a significant role in estuary and river ecosystems. We present results from the first intensive field study conducted in the Garonne river. We show that the flow reverse can be very intense, with currents varying from -1.1 m/s to 0.95 m/s in 3 s, being associated with a strongly vertically sheared horizontal velocity field. We also quantify the impact of high amplitude tidal bores on suspended sediments.

1 INTRODUCTION

In a shallow, gently sloping and narrowing river, the propagation of significant amplitude tidal wave may form a tidal bore. This tidal bore, characterized by a positive water depth surge, propagates with the tidal wave at the beginning of flood tide. High-amplitude tidal bores can be easily visually observed and are named *mascaret* in French.

This fascinating phenomenon has been qualitatively observed in many places worldwide. If tidal bores occur generally on macrotidal environments and under spring tides conditions, Bonneton et al. (2012) have shown that in the Garonne river, tidal bores form for a large occurrence percentage of tides, about 90 % for low river discharges and 65 % for high river discharges. The under-estimation of tidal bore occurrence in literature (see Chanson 2005) is

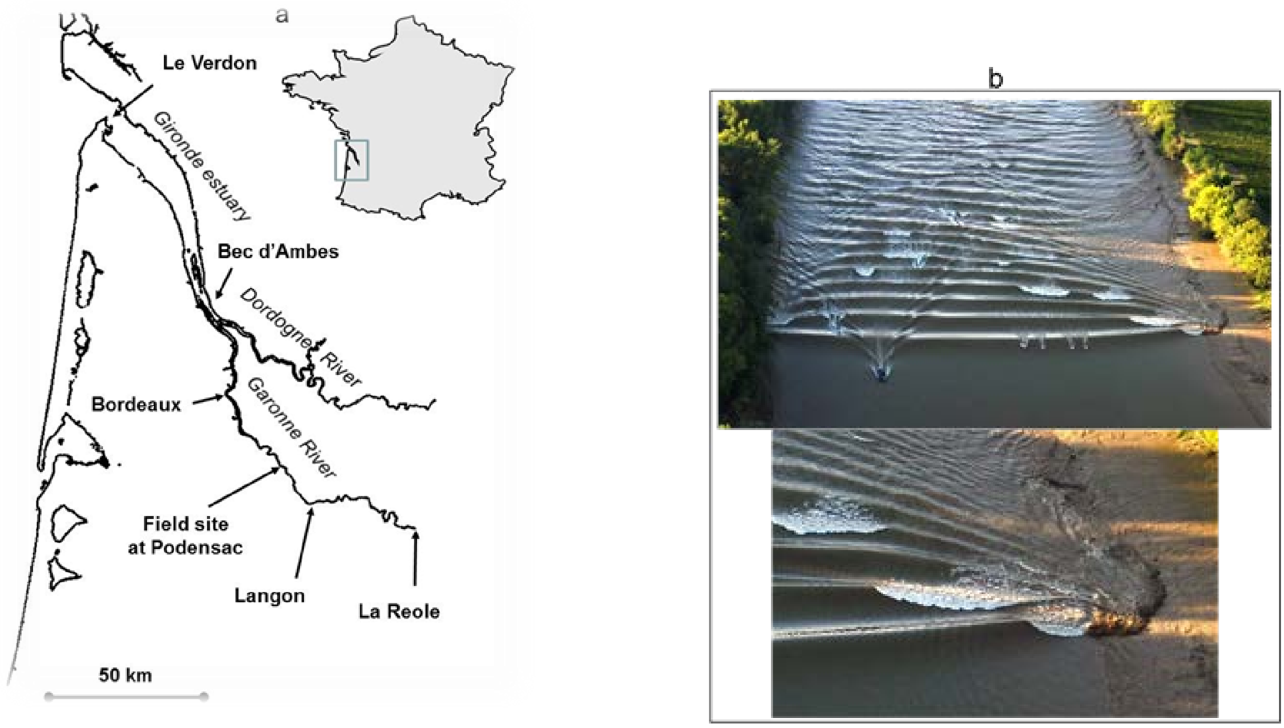

Figure 1. (a) Location map of the Gironde/Garonne/Dordogne system and the Podensac field site; (b) aerial photographs of the tidal bore at Podensac on the 10th of September 2010, 17h31 TU.

connected with the fact that observations were visual and qualitative in most cases. This leads us to conduct two field experiments to better understand tidal bore dynamics and impact on sediment transport and, more generally, on the river ecosystem behavior in the Gironde/Garonne/Dordogne system. These field experiments also aim to improve and validate Boussinesq-type models (see Bonneton et al. 2011a and Tissier et al. 2011) for tsunami-like applications.

In the present paper, we present the vertical structure of the velocity field associated with tide propagation in the Garonne river in three representative cases: without tidal bore (TB abbreviated form), with Low amplitude TB, and with High amplitude TB (i.e mascaret).

2 FIELD EXPERIMENTS

2.1 *Field Site*

Two field experiments were conducted in the Garonne river at Podensac, located 140 km upstream of the estuary mouth (see fig. 1a). This site was selected owing to the presence of a well-developed undular tidal bore during spring tides and also because of the straightness of the river at this location, which limits the complexity of the tidal bores structures. At Podensac, the observed TBs are undular, partially breaking (see fig. 1b). They are representative of most observed TBs in the Garonne river (see Bonneton et al. 2011b). Because of their strong interaction with the gently sloped river banks, the secondary waves (with first wave front height may exceed 1.3 m) have a completely different dynamics compared to those found in rectangular channel experiments. In order to observe TBs for a large range of tidal amplitudes and flow discharges, two field campaigns were conducted in 2010 around the spring and autumn equinox. The first campaign, TBG1 took place between the 24^{th} of February and the 5^{th} of April, for high freshwater discharges (around 700 m^3/s) and the second one, TBG2, between the 1^{st} of September and the 22th of October 2010, under low river flow (around $125 m^3/s$). The field site and field campaigns were detailed by Parisot et al. (2010) and by Bonneton et al. (2011b).

2.2 *Materials and Methods*

During TBG1 campaign instruments were moored along one section of the river. Two pressure sensors (Ocean Sensor System) sampled at 10 Hz were deployed in shallow water close to the rivers banks. One Acoustic Doppler Current Profiler (ADCP-RDI) associated with near bottom Acoustic Doppler Velocimeter (ADV Nortek) were deployed in the deepest part of the 150-m river cross-section and continuously sampled at 2 Hz. The ADCP bin size was equal to 0.2 m. For all instruments, data were acquired during 17 tides from the 24^{th} of February to the 5^{th} of March 2010.

During the second campaign, TBG2, 17 instruments (6 pressure sensors/Ocean Sensor System, 3 ADCP/RDI, 1 AWAC, 2 ADV/Nortek 2 altimeters ALTUS/Ifremer/Micrel, 3 turbidimeters (OBS-3A/Campbell) were set up along 3 sections of the river spaced at approximately 200 m intervals. For all instruments data were acquired during 27 tides from the 1^{st} to the 14^{th} of September 2010 and for one pressure sensor during 99 tides. Pressure sensors were sampled at 10 Hz, ADV at 32 Hz, ADCP and AWAC at 2 Hz and OBS-3A at 2 min. The ADCP bin sizes were respectively equal to 0.05 m and 0.2 m. The OBS-3A was positioned at 0.3 m above the bed.

The present paper focuses on tidal bores dynamics and mainly relies on turbidity, velocity (recorded from ADCP) and water depth time series.

3 RESULTS

3.1 *Tidal wave distortion and undular bore formation*

Figure 2 shows time series of water depth and depth-averaged horizontal velocity for a complete tidal cycle at the Podensac field site for three representative cases: without TB (fig. 2a and 2b), with Low amplitude TB (fig. 2c and 2d), and with High amplitude TB (fig. 2e and 2f). The tidal wave in the lower estuary (Le Verdon) is fairly symmetric. As the tide propagates upstream, the wave is deformed and a marked ebb-flood asymmetry occurs in the central estuary, which subsequently intensifies in the Garonne river at Bordeaux and also at Podensac (see fig. 2a, 2c and 2e). For the highest tidal range (fig. 2e), ebb tide duration is about 9 hours, whereas rising tide is only 3h 20 min. This asymmetry is due to friction and non-linear effects during tide propagation from the estuary mouth to Podensac field site (about 140 km). Water discharge plays a significant role on the damping of tidal wave in the estuary. For large water discharges, we recorded the same tidal amplitude value (5.1 m) at Le Verdon and at the field site location (fig. 2c), while for low water discharges, the tidal amplitude value increases from 4.9 m at Le Verdon to 6.3 m at our field site (fig. 2e). For the three cases, the 5 min-averaged depth-averaged horizontal velocity is about - 1 m/s (downstream) during ebb tide and strongly increases at the beginning of flood tide. For both high river discharge cases (fig. 2b and 2d), the flow remains negative for most of flood tide. By contrast, we observe for low water discharges cases, a velocity field reversal which may reach 1.5 m/s at the beginning of flood tide.

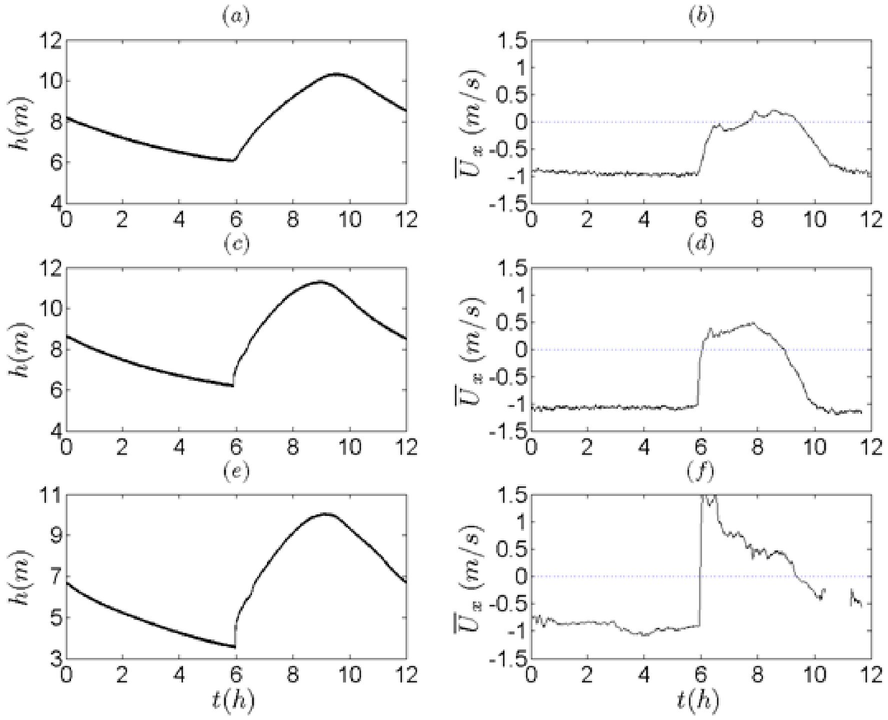

Figure 2. Water depth and depth-averaged horizontal velocity time series at the Podensac field site. (a and b): the 25th of February (TBG1), tidal range of 4.4 m (2.7 m at Le Verdon); (c and d): the 3rd of March (TBG1), tidal range of 5.1 m (5.1 m at Le Verdon); (e and f): the 9th of September (TBG2), tidal range of 6.3 m (4.9 m at Le Verdon), (f): sometimes missing data at flood tide by reason of high turbidity.

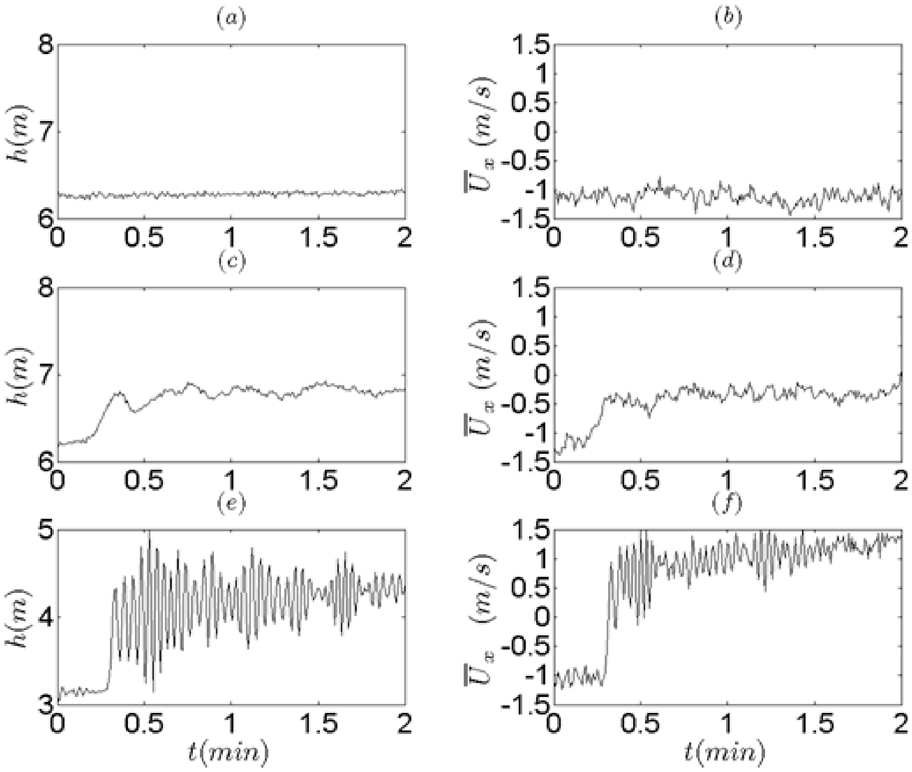

Figure 3. Water depth and depth-averaged horizontal velocity 2 min time series at the beginning of flood tide. (a and b): the 25th of February (TBG1), tidal range of 4.4 m (2.7 m at Le Verdon); (c and d): the 3rd of March (TBG1), tidal range of 5.1 m (5.1 m at Le Verdon); (e and f): the 9th of September (TBG2), tidal range of 6.3 m (4.9 m at Le Verdon).

Figure 3 shows a zoom of figure 2 over 2 minutes at the beginning of flood tide. Water depth and depth-averaged horizontal velocity are represented at 2 Hz. In the first case (fig. 3a and 3b) we observe a continuous flow variation whereas in the two others cases there is a rapid and intense flow variation associated with undular TB. For low TB amplitude (fig. 3b and 3c), water depth increases of 0.64 m in 21 s and is associated with a horizontal velocity variation of 1 m/s and a Froude number of 1.08. For higher tidal range of about 6.3 m, we observe a more intense phenomenon (see fig. 3e and 3f). The water depth variation reaches 1.2 m in 3 s, associated with a Froude number of about 1.26 and a 2.5 m/s velocity variation (from -1.1 m/s to 0.95 m/s) at flow reversal. The secondary waves associated to TB have a velocity variation and a period respectively equal to 1.2 m/s and 3 s. These strong velocity and water depth variations at the front of the bore might have a significant impact on sediment transport.

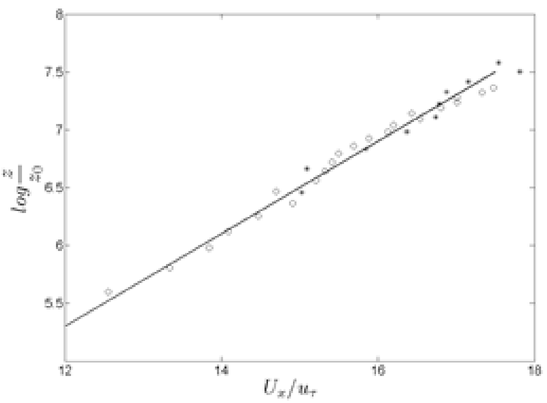

Figure 4. Logarithmic representation of non-dimensional ratio between 5 min-averaged depth-averaged $\overline{U}_\mathbf{x}$ and friction velocity u_τ 3 h before TB arrival. ○: the 3rd of March (TGB1); ∗: the 9th of September (TBG2); ▬: logarithmic boundary layer model.

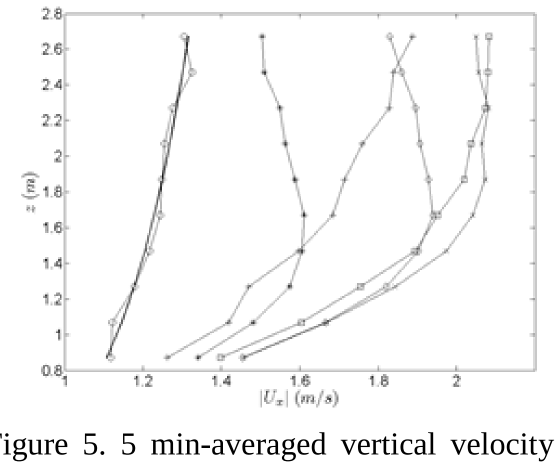

Figure 5. 5 min-averaged vertical velocity profiles $|U_x|$ at different times . ○: t_0 -3h ; *: t_0 + 4 min ; ◊: t_0 +6 min; x: t_0 + 8 min; □: t_0 + 10 min; +: t_0 + 20 min; ▬: Boundary layer model at t_0 -3h with t_0: time just before TB arrival.

3.2 *Vertical velocity profile and suspended sediment*

We analysed vertical velocity profile for both campaigns. For all TBG1 measurements and for ebb tide TBG2 measurements, boundary profiles are logarithmic, with a roughness length z_0 of about a few millimeters (z_0 = 5 mm for TBG1 and z_0 = 2 mm for TBG2). We can see in figure 4, 3 hours before TB arrival and for each campaign, logarithmic representation of 5 min-averaged vertically integrated $\overline{U}_\mathbf{x}$ non-dimensionalized by the friction velocity u_τ . The measurements are in good agreement with the following logarithmic boundary layer model:
$\overline{U}/u_\tau = 1/K\ .(\ln(z/z_0) - 1))$, with K the Karman constant equal to 0.4.
The remarkably stable $\overline{U}_\mathbf{x}$ value during ebb tide (see fig. 2b, 2d and 2f) involves a constant friction velocity u_τ equal to 0.07 m/s for ebb tide.
By contrast, for high TB amplitude, boundary profile is no longer logarithmic and velocity profiles become significantly sheared (see fig. 5) involving major implications in terms of sediment transport that are presently investigated.
Figure 6 presents for high TB amplitude, water depth and Suspended Particulate Matter (SPM) concentration time series from the last 3 hours of ebb tide to the beginning of flood tide. SPM concentration has been recorded 30 cm above the bed. It decreases during ebb tide and strongly increases as the TB passes. On the wave front, SPM increases by 11 g/l in 6 min.

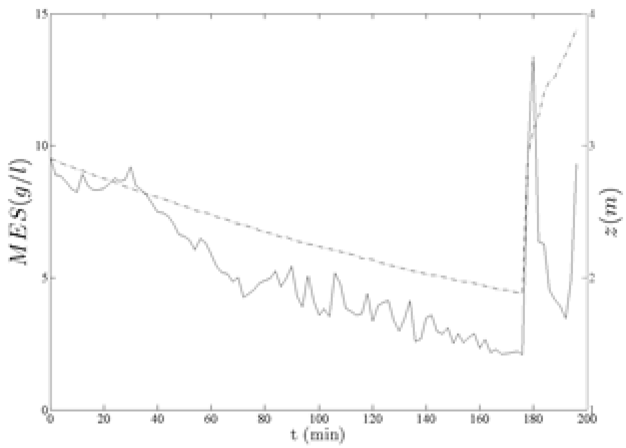

Figure 6. Time series of water depth h (dashed line) and suspended matter concentration (MES, continuous line). The 9th of September, [SPM] were recorded every 2 min at 0.3 m above the bed.

4 CONCLUSION

In the present paper, we present preliminary results of a first intensive field investigation of tidal bore dynamics, emphasing the vertical structure of horizontal velocity associated with tidal bores.

For high tidal bore amplitude, we found very intense velocity variations (from -1.1 m/s to 0.95 m/s in 3s), associated with significant vertically sheared velocity profiles. We have also brought to light the increase in Suspended Particulate Matter, involving high sediment resuspension. This suggests in that case strong impact of TB on sediment dynamics of the river.

Knowing that TB of variable intensity occur for a large majority of tides (Bonneton et al. 2012, 2011b), it is crucial to reassess their impact on sediment transport.

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