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FIELD MEASUREMENTS IN THE TIDAL BORE OF THE GARONNE RIVER AFTER A RECENT FLOOD

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Abstract

A tidal bore is a natural phenomenon associated with the rising flood tide. Composed of surface waves, it may occur in estuaries and propagate up rivers. The present study was conducted in the Garonne River (France) in the Arcins channel. Using an ADV unit and further recording equipments, experimental data are collected during a flat undular bore with a bore Froude number close to unity. Velocity analysis and sediment characterisation revel a slight rise in water elevation starting about 70 s prior to the front and a flow reversal about 50 s after the bore front. The turbulent transport of suspended sediment is presented in term of mass flux per unit area highlighting a negative (upriver) sediment mass transfer.

Keywords: Tidal bores, Field measurements, Garonne River, Flow reversal, Sediment characteristics.

1. Introduction

A tidal bore is a series of waves propagating upstream as the tidal flow turns to rising (Fig. 1). The bore forms during spring tide conditions when the tidal range exceeds 4 to 6 m and the flood tide flow is restrained into a narrow funneled estuary. The bore front is a flow singularity and hydrodynamic shock (Lighthill 1978, Liggett 1994). In a system of reference following the bore front, the integral form of the continuity and momentum equations gives a series of relationships between the flow properties in front of and behind the bore (Lighthill1978):

$$(V_1+U)\times A_1 = (V_2+U)\times A_2 \quad (1)$$

$$\rho\times(V_1+U)\times A_1\times(\beta_1\times(V_1+U)-\beta_2\times(V_2+U)) = \iint_{A_2} P\times dA - \iint_{A_1} P\times dA + F_{fric} - W\times\sin\theta \quad (2)$$

where V is the flow velocity and U is the bore celerity for an observer standing on the bank, A is the channel cross-sectional area measured perpendicular to the main flow direction, , the subscript 1 refers to the initial flow conditions and the subscript 2 refers to the flow conditions immediately after the jump. Neglecting the flow resistance (F_{fric} = 0) and for a flat horizontal channel (θ = 0), Equations (1) and (2) give a relationship between the ratio of conjugate cross-section areas A_2/A_1 as a function of the bore Froude number $Fr_1 = (U+V)/(g\times A_1/B_1)^{1/2}$ (Chanson 2012).

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A number of previous field studies in Brazil, Australia, UK and France emphasised the intense turbulent mixing induced by the bore (Kjerfve and Ferreira 1993, Simpson et al. 2004, Wolanski et al. 2004, Chanson et al. 2011). In the present study, some field measurements were conducted in the Garonne River (France) at Arcins on 7 June 2012, a few weeks after a major flood of the Garonne River (Fig. 1, Table 1). The results provided a detailed characterisation of the unsteady flow features in the undular tidal bore as well as of the suspended sediment flux properties.

Figure 1. Tidal bore in the Arcins channel on 5 June 2012 at 17:34 looking downstream

Table 1. Tidal bore properties in the Arcins channel (Garonne River, France) in 7 June 2012

Date and time	Tidal bore properties			
	Bore type	Fr_1	U (m/s)	A_1 (m^2)
7/06/2012 at 06:44	Undular (very flat)	1.02	3.9	158.9
7/06/2012 at 18:47	Undular	1.19	4.6	152.3

2. Garonne River tidal bore

2.1. ***Local configuration***

A well preserved macro-tidal environment is the Gironde estuary, Garonne River and Dordogne River in south-western France. A number of visual observations highlighted the rapid evolution of the tidal bore shape and appearance in response to the estuarine bathymetry (Chanson 2011). The present study was conducted in the Garonne River (France) in the Bras d'Arcins (Arcins channel)

The Bras d'Arcins is located between Île d'Arcins (Arcins Island) and the right bank close to Lastrene (44°47'58"N, 0°31'07"W). The Arcins channel is about 1.8 km long, 70 m wide and about 1.1 to 2.5 m deep at low tide (Fig. 1). More details could be found in Chanson et al. (Chanson et al. 2011). Measurements were done a few weeks after a major flood. The river bed might have been scoured from the soft sediments during the April-May 2012 floods of the Garonne River.

Although the tides are semi-diurnal, the tidal cycles have slightly different periods and amplitudes indicating some diurnal inequality (Fig. 2). Figure 2 presents the water elevation observations at Bordeaux that are compared with the water elevations recorded on-site prior to and shortly after the passage of the tidal bore on 7 June 2012. In Figure 2, all the water elevations are presented in m NGF IGN69. The field measurements were conducted under spring tide conditions on 7 June 2012 morning and evening. The tidal range data are summarised in Table 2

Table 2. Tidal bore field measurements in the Arcins channel, Garonne River (France)

Date (1)	Tidal range (m) (2)	ADV system (3)	Sampling rate (Hz) (4)	Sampling duration (5)	Start time (6)	Tidal bore time (7)	End time (8)	ADV sampling volume (9)
7/06/2012	5.68	Sontek microADV (50 Hz)	50	2h 58 min (10,694 s)	06:01	06:44	09:00	About 11.58 m from right bank waterline (at low tide), 1.03 m below water surface.
	5.5	Visual Obst^{n}	N/A	N/A	N/A	18:47	N/A	N/A

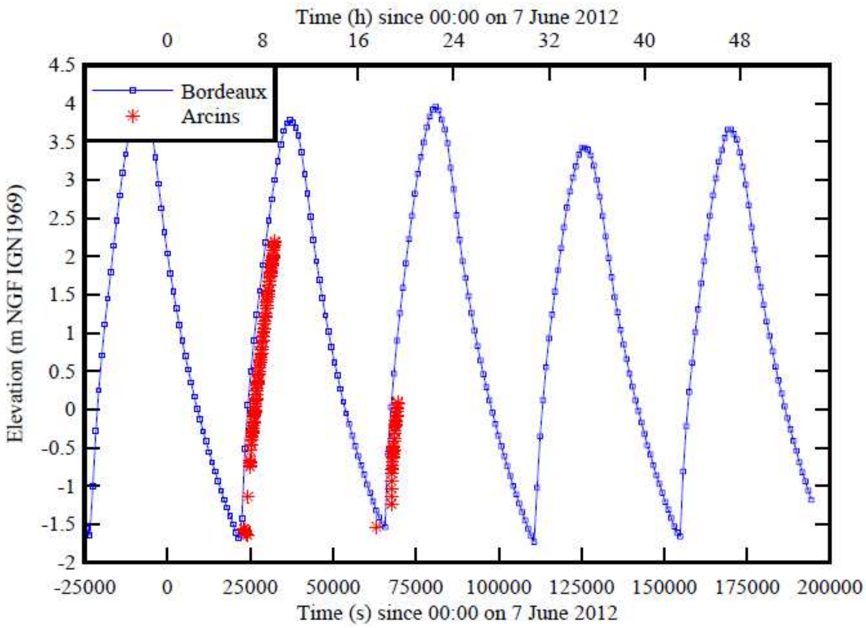

Figure 2. Water elevations at Bordeaux (44°52'N, 0°33'W) (Data: Vigicrue, Ministère de l'Environnement et du Développement Durable) and observations in the Arcins channel on 7 June 2012

2.2. *Experimental apparatus and properties*

To perform sediment transport analyses, a series of measurement were collected including :

-free surface elevation,
-cross section,
-free surface velocity,
-temperature,
-sediment concentration,
-turbulent velocity under surface,
-rheological and granulometry properties.

The following give details for accuracy and signal treatment from probes.

2.2.1. *Cross section measurement*

The cross section of the Arcins channel at the field study location was surveyed. Several positions were defined along a cross line through the Arcin channel, where the velocity measurements were done. Results are compared with earlier surveys at the same cross line in 2010. The results are presented in Figure 3. No significant modification was observed except a lower depth of the river bed about 10 to 20cm lower.

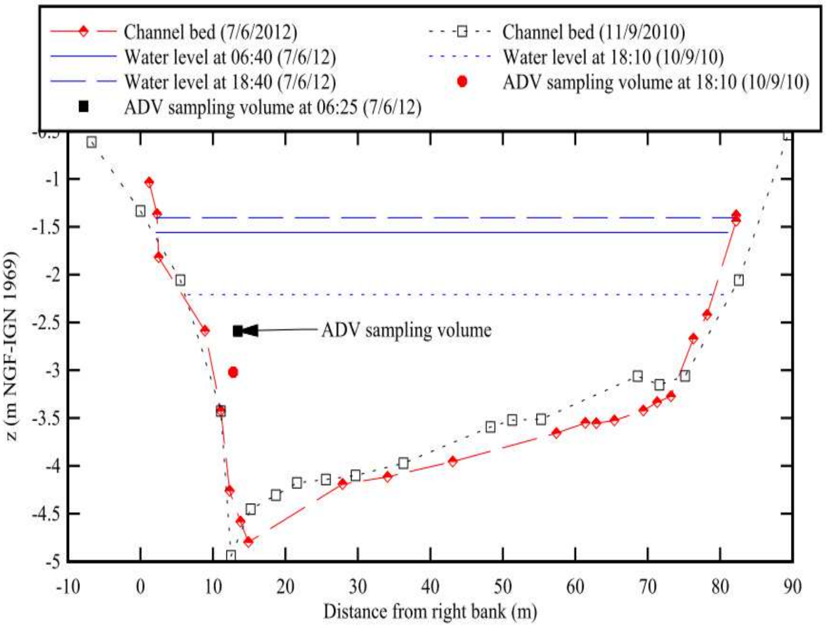

Figure 3. Surveyed (distorted) cross-section looking upstream - Comparison between the 2010 and 2012 surveys at the same cross-section

2.2.2. *Velocity and elevation measurements*

The free surface elevations were measured manually using a video camera (50Hz) recording the water level. During the investigations, the turbulent velocities were measured with a Sontek^{TM} microADV (16MHz, serial number A1036F-3D side-looking head) on 7 June 2012 morning. The system was fixed at the downstream end of a 23.55 m long heavy, sturdy pontoon. It was mounted vertically, the emitter facing towards Arcins Island, and the positive direction head was pointing downstream. The sampling volume was about 1.03 m below the free-surface for the duration of the study. All the ADV data underwent a post-processing procedure to eliminate any erroneous or corrupted data from the data with the software WinADV^{TM} version 2.028 following the same method as Chanson et al. (2011).

The calibration of the ADV in terms of suspended sediment concentration (SSC) was accomplished by measuring the signal amplitude of known, artificially produced concentrations of material obtained from the bed material sample, diluted in tap water and thoroughly mixed.

The accuracy of the ADV velocity measurements was 1% of the velocity range (± 2.5 m/s) (Sontek 2008). The accuracy of the water elevation was 0.5 cm prior to the tidal bore and 1-2 cm during the tidal bore passage. The mass of wet sediment was measured with an accuracy of less than 0.01 g, and the SSC was estimated with an accuracy of less than 0.00025 g/l.

2.2.3. *Sediment properties*

The bed material was basically a cohesive mud mixture and the granulometry data were nearly independent of the sample and mixing technique (table 3).

Some Garonne River bed material was collected next to the pontoon. The soil sample granulometry was measured with a Malvern™ laser Mastersizer after mixing (mechanical or ultrasound), The rheological properties of mud samples were tested with a rheometer Malvern™ Kinexus Pro quipped with either a plane-cone (∅ = 40 mm, cone angle: 4°) or plane-disk (∅ = 20 mm) configuration.

Table 3. Characteristics of sediment sample sin the Arcins channel, Garonne River (France)

Sediment sample (1)	Location (2)	Type (3)	Mixing (4)	d_{50} (5)	d_{10} (6)	d_{90} (7)
7/06/2012	Low tide	Silt	Mech (10min)	11.86	3.06	50.80
			Mech (20min)	11.11	2.93	42.19
			Mech (30min)	12.23	3.10	49.74
			Ultras (18 min)	13.68	3.19	51.91
8/06/2012	mid ebb tide	Silt	Mech (10min)	13.06	3.75	51.53
			Mech (20min)	11.05	3.47	38.51
			Mech (30min)	13.06	3.74	52.15
			Ultras (14 min)	15.76	3.56	62.97

The rheometry test results showed some basic differences between the two sediment samples (Table 3). The sediment sample collected on 7 June 2012 appeared to be more cohesive and less homogeneous. The magnitude of the shear stress during unloading was smaller than the shear stress magnitude during loading for a given shear rate. Quantitatively the findings were consistent with the qualitative observations: that is, a more cohesive sediment mixture was collected on 7 June 2012 associated with larger yield stress and apparent viscosity. On average, the apparent viscosity was between 18 and 36 Pa.s, and the yield stress was about 75 to 271 Pa for the sediment sample collected on 7 June 2012 at low tide. For the sediment sample collected on 8 June 2012 at mid-ebb tide, the apparent viscosity was between 2.9 and 13 Pa.s, and the yield stress was about 15 to 74 Pa on average. Further the present data were not dissimilar with the sediment characteristics of samples collected at Arcins on 11 September 2010 (Chanson et al. 2011).

After calibration, within the experimental conditions, the relationship between acoustic backscatter amplitude (Ampl) and suspended sediment concentrations (SSC) showed a decreasing backscatter amplitude with increasing SSC. For the laboratory tests with low suspended loads (SSC ≤ 8 kg/m3), the best fit relationships were:

$$\mathrm{SSC} = \frac{-8.735}{1 - 35253 \times \exp(-0.1053 \times (\mathrm{Ampl} - 92))} \quad (1)$$

3. **Observations**

On 7 June 2012, the tidal bore in the Arcins channel formed first at the downstream end of the channel and extended across the entire channel width as an undular bore. When the bore propagated upstream, its shape evolved constantly in response to the local bathymetry (Table 4). The tidal bore was charact erised first by its front following with a pseudo-chaotic surface motion several minutes. At the sampli ng location, the front elevation Δd rose rapidly in the first 10-15 seconds. For the next 40 minutes, the water elevation rose further by 1.22 m and 1.33 m on 7 June 2012 morning and afternoon respectively.

In the system of reference in translation with the bore front, the momentum principle yields a dimensionless relationship between the ratio of conjugate cross-section areas A_2/A_1 and the upstream

Froude number Fr_1 (Chanson 2012) with the tidal bore Froude number Fr_1:

$$\frac{A_2}{A_1} = \frac{1}{2} \times \frac{\sqrt{\left(2 - \frac{B'}{B}\right)^2 + 8 \times \frac{B'/B}{B_1/B} \times Fr_1^{\,2}} - \left(2 - \frac{B'}{B}\right)}{\frac{B'}{B}} \tag{2}$$

where the tidal bore Froude number is defined as :

$$Fr_1 = \frac{V_1 + U}{\sqrt{g \times \frac{A_1}{B_1}}} \tag{3}$$

The present results are shown in Figure 4 with the ratio of conjugate cross-sectional areas A_2/A_1 as a function of the tidal bore Froude number Fr_1. The results highlighted the limitations of the Bélanger equation, based upon a rectangular channel, in natural irregular channels for which the cross-sectional properties may have a significant impact on the definition of the bore Froude number.

Table 4. Characteristics of tidal bore on 7 June 2012 in the Arcins channel, Garonne River (France)

Type	Fr_1	U m/s	V_1 m/s	d_1 m	A_1 m^2	B_1 m	Δd m	ΔA m^2	B_2 m	B m	B' m	A_1/B_1	B_2/B_1	Fr
Undular (flat)	1.02	3.85	0.68	2.72	158.9	79	0.45	36.71	84.3	81.6	82.4	2	1.067	1.15
Undular	1.19	4.58	0.59	2.65	152.3	78.7	0.52	42.24	84.3	81.2	81.8	1.04	1.071	1.19

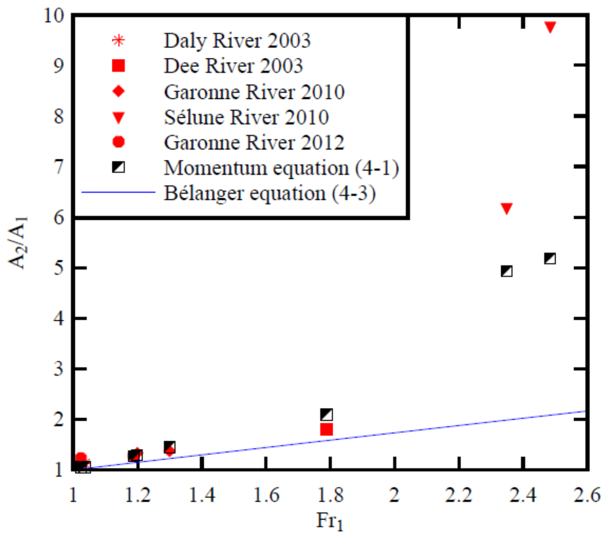

Figure 4. Dimensionless relationship between the conjugate cross-sectional area ratio A_2/A_1 and tidal bore Froude number Fr_1

Concerning the water depth, some unusual features observed herein: (a) a slow rise of water level immediately prior to the bore front in the morning and (b) some unexpected water level drop about 10 minutes after the front. On 7 June 2012 morning, the free-surface depth data highlighted a gentle rise of 0.04 m in about 70 s immediately prior to the bore front discontinuity (Fig 5). The surface velocity observations highlighted the sudden flow reversal associated with the passage of the tidal bore. However, next to the ADV, the video observations indicated that the surface flow direction reversed about 6 s after the bore front on 7 June 2012 morning.

On 7 June 2012 morning, the instantaneous velocity data showed the drastic impact of the tidal bore propagation (1). Figure 6 presents the time-variations of the ADV velocity components, with the longitudinal velocity component V_x positive downstream towards Bordeaux, the transverse velocity component V_y positive towards the Arcins Island, and the vertical velocity component V_z positive upwards. The time-variations of the water depth at the survey staff are shown together with the surface velocity data. The turbulent velocity data showed the marked effect of the passage of the bore front at t = 24,180s. The longitudinal velocity component data showed some rapid flow deceleration associated with the passage of the bore front although with some delay. The surface velocity data exhibited a general pattern similar to the ADV data. The tidal bore passage was observed about t ≈ 24,180 s with the sudden rise in free-surface elevation of the bore front. A time delay between the bore front passage and longitudinal flow reversal was observed about 50 s after the bore front. his unusual flow reversal differed from a number earlier observations including Wolanski et al. (2004), Simpson et al. (2004), Chanson et al. (2011) and Mouaze et al. (2010) in the field. All these studies showed the flow reversal at the same time as the bore passage. However a few field studies reported some usual delay between the bore front arrival and the flow reversal.

The Reynolds stress levels were basically larger than those during the ebb tide, with normal stresses between 2 and 3.5 times larger on average than before the bore front. Similarly the tangential stresses were significantly larger on average after the bore, while the fluctuations in tangential stresses were on average 10% larger than those at the end of ebb tide.

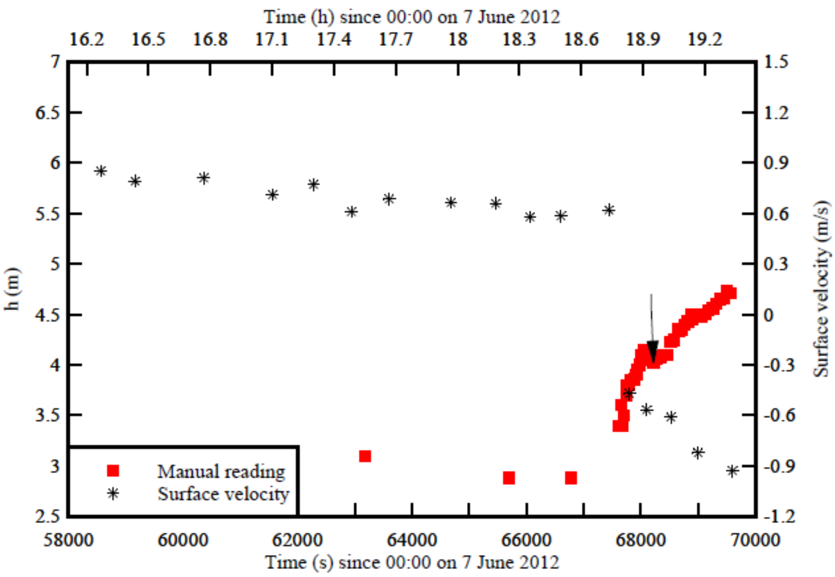

Figure 4. Time variations of the water depth next to ADV unit and free-surface velocity in the channel centre during the field experiments -

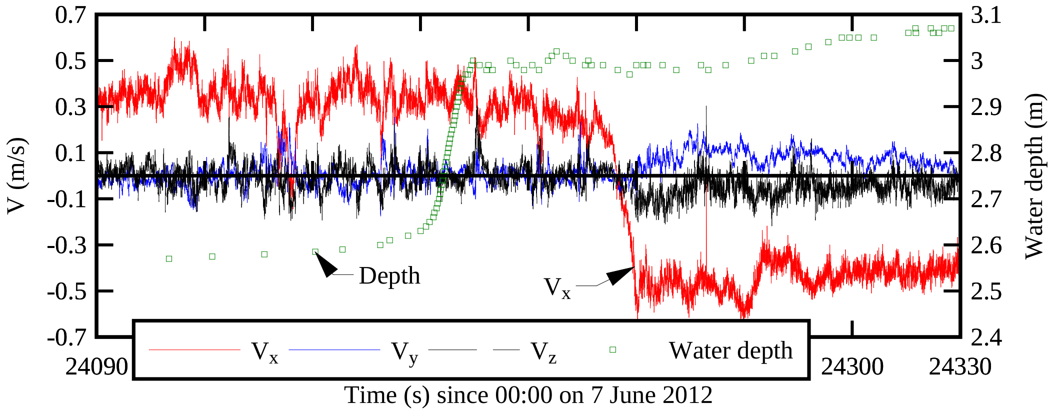

Figure 6. Time variations of velocity and water depth during the tidal bore on 7/06/2012 morning

The results highlighted that the flow reversal was characterised by a very significant increase in all the shear stress components (Fig. 6). That is, the magnitude of shear stresses during the flow reversal was about 2 to 10 times larger than that during the end of ebb tide. The sudden increase in shear stress was caused by the flow reversal rather than the bore front passage.

4. Discussion

The turbulent velocity fluctuations were based upon a low-pass filtering of the instantaneous velocity component V using the variable interval time average VITA (Piquet 1999, Koch and Chanson 2008). The upper limit frequency was about the Nyquist frequency (25 Hz herein) and a lower limit was abou t 0.16-0.25 Hz, corresponding to the period of 4-6 s of the bore undulations on 7 June 2012 morning. The results yielded an optimum threshold: F_{cutoff} = 0.5 Hz.

The present data showed large and rapid turbulent Reynolds stress fluctuations during the tidal bore and flood flow. During the tidal bore and flood flow, the amplitudes of instantaneous Reynolds stresses were significant, with normal stress magnitudes up to 120 Pa and tangential stress magnitudes up to 30 Pa.

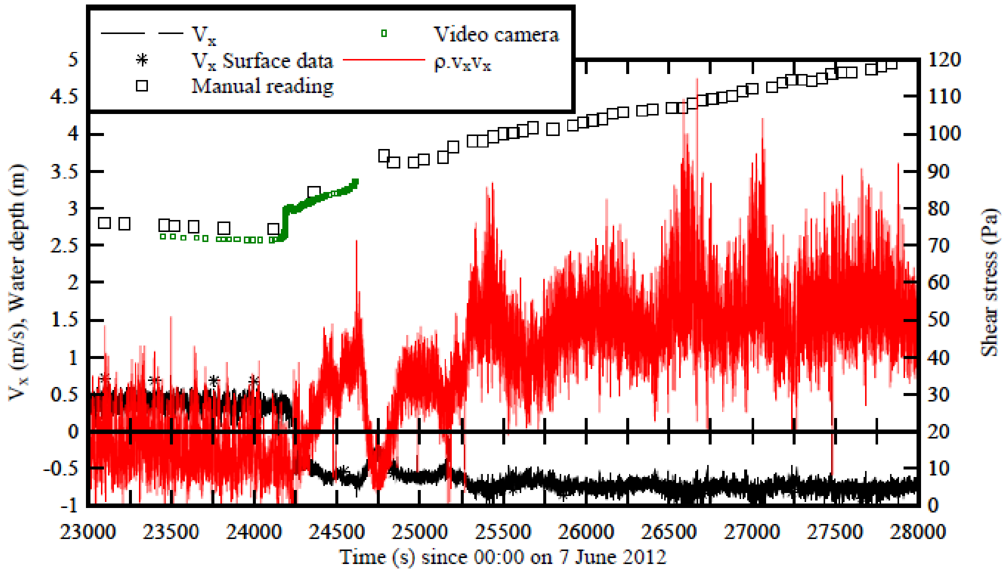

Figure 7. Time-variations of Reynolds stresses, water depth and longitudinal velocity component during the tidal bore passage on 7 June 2012 morning - Post-processed ADV data, sampling rate: 50Hz

5. Conclusion

Some field observations were conducted in the tidal bore of the Garonne River on 7 June 2012 in the Arcins channel. The tidal bore was a flat undular bore with a bore Froude number close to unity (Table 1). A feature of the study was some effect of recent floods (April-May 2012) of the Garonne River. At the end of ebb tide, the current was strong, the water level was relatively high and the water was predominantly freshwater. The field observations highlighted a number of unusual features on the morning of 7 June 2012. These included (a) a slight rise in water elevation starting about 70 s prior to the front, (b) a flow reversal about 50 s after the bore front as illustrated in Figure 2, (c) some large fluctuations in suspended sediment concentration (SSC) about 100 s after the bore front and (d) a transient water elevation lowering about 10 minutes after the bore front passage. The measurements of water temperature and salinity showed nearly identical results before and after the tidal bore: there was no evidence of saline or thermal front.

The sediment material was cohesive with a median particle size of about 13 µm, and the mud exhibited a non-Newtonian behaviour. The rheometry results suggested that the quantitative characterisation of the material was closely linked with the testing protocol and configuration. The suspended sediment flux data indicated a downstream positive flux during the end of the ebb tide. The arrival of the tidal bore and flow reversal was characterised by a rapid reversal in suspended sediment flux during the flood tide. After the passage of the bore, the net sediment mass transfer per unit area was negative (i.e. upriver) and its magnitude was twice as large as the ebb tide net flux. Overall the sediment concentration and data highlighted some very significant suspended sediment load.

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