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1 Hydrodynamics and SPM transport in an engineered tidal estuary: the  
2 Adour river (France)

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14 **Abstract**

15 The present paper reports on a series of field experiments aiming to characterise the functioning  
16 of a man-engineered strongly forced salt-wedge estuary : the lower estuary of the Adour river,  
17 France. Bottom-moored velocity measurements and surface boat surveys have been performed  
18 under low river discharge conditions, for both neap and spring tides, in order to provide a well-  
19 documented reference framework to understand the dynamics of water masses, turbulence and  
20 suspended particulate matter (SPM) transport in the lower estuary. An additional campaign has  
21 been carried out in high river discharge conditions. This first documented *in-situ* study of the  
22 Adour lower estuary demonstrates its variability in terms of hydrological regimes, from salt-wedge to  
23 partially mixed regimes depending on tidal and discharge conditions. Turbulent properties showed  
24 a significant response to the variations of salinity structure, with higher values when stratification  
25 is minimal. At spring tide, a tidal variation between mixing conditions on the ebb and the flood  
26 is revealed by ADCP measurements, with higher values extended up to the surface during the  
27 ebb. The link between turbulent mixing and suspended sediment concentration is straightforward  
28 during the ebb. During the flood, the suspended sediment concentration (SSC) seems related to  
29 the salt-wedge entrance re-suspension and stratification-induced turbulence damping. No stable  
30 Estuarine Turbidity Maximum (ETM) has been observed during the field experiment in the lower  
31 Adour estuary.

32 *Keywords:* Salt-wedge estuary, estuarine circulation, stratification, turbulence, suspended  
33 particles transport, Adour river.

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## 34 1. Introduction

35 Estuaries are complex transfer areas of water masses and suspended particulate matters (SPM)  
36 between ocean, land and continental waters [12]. They constitute unique habitats for a large variety  
37 of living organisms and essential nurseries for many marine species. In the overall context of climate  
38 change and growing anthropogenic pressure, a key issue of the preservation of estuarine ecosystems  
39 is to improve our knowledge of the hydro-dynamical processes controlling the dynamics and renewal  
40 of water masses in estuaries and their ability to transport, expel or retain sediments, contaminants,  
41 nutrients and living organisms.

42 Many studies investigated estuarine dynamics from *in-situ* measurements [16, 46, 10, 44] and/  
43 or numerical modelling [32, 5, 41, 9]. From a physical point of view, estuaries are exchange areas  
44 between fresh brackish continental water and salty marine waters, mainly driven by river run-off,  
45 tides and wind forcing. Density gradients generated by the continental waters inter-playing with  
46 marine waters, and interactions between tides and estuarine morphology have been shown to be  
47 the major mechanisms governing the estuarine dynamics. Those mechanisms are known as : (i)  
48 gravitational circulation induced by horizontal density gradient, (ii) tidal pumping generated by an  
49 ebb-flood asymmetry, (iii) tidal straining caused by advection. The vertical salinity gradient plays  
50 also an essential role by influencing the turbulent mixing inside the water column. Note that a  
51 wide number of additional processes can also act on the estuarine dynamics and mixing, including  
52 bed morphology [16], lateral circulation [13, 14, 31, 32, 45], wind [43, 40], Earth rotation [32, 56],  
53 internal waves [54, 14, 15] and sediment load [61].

54 A growing interest in classifying estuaries developed along the years, in order to gain a unified  
55 view of the physics of estuaries. Different classification schemes have been proposed based on water  
56 balance, geomorphology [39], vertical salinity structure [7] or hydrodynamics [24, 56, 21]. One of  
57 the commonly used classification has been proposed by Cameron and Pritchard [7]. It is based on  
58 water column stratification, in which estuaries can be classified as salt-wedge, strongly stratified,  
59 weakly stratified or well mixed. However, the horizontal and vertical salinity gradients can show  
60 important variations in time (e.g. from neap to spring tide, or from wet to dry season) and space  
61 within a given estuary, such as stratification might not be systematically used to classify estuaries.  
62 Therefore this type of qualitative classification has been progressively forsaken, to be replaced by  
63 more quantitative methods. One recent approach has been proposed by Geyer and MacCready [21],  
64 discussing the respective contributions of tide and river flow in mixing and stratification processes.  
65 It is based on two dimensionless parameters. The former is the freshwater Froude number  $Fr_f$  [17]  
66 which express the ratio between the river flow inertia and the buoyancy due to salinity gradient. The  
67 second is the mixing parameter  $M$  which quantifies the effectiveness of tidal mixing in stratified  
68 estuaries. Geyer and MacCready proposed a mapping of various estuaries based on those two  
69 parameters, demonstrating the efficiency to discriminate different classes of estuary. For example,  
70 salt-wedge estuaries, such as the Mississippi, The Fraser and the Ebro rivers are located near the  
71 top of the  $Fr_f/M$  diagram (i.e. high values of  $Fr_f$ ); while partially stratified estuaries are on the  
72 center of the diagram (e.g. James river and San Fransisco Bay) and fjords and well mixed estuaries  
73 are on the bottom part (e.g. Puget Sound). This research effort for a quantitative classification of  
74 estuaries needs to be deepened and sustained, in particular by providing relevant in-situ data from  
75 additional and contrasted case studies.

76 In addition to the hydrodynamic structure, a major issue of estuarine dynamics is to understand

77 the fate of the sediment load. Under the competing effects of turbulent suspension and gravitational  
78 settling, strong variations of Suspended Particulate Matter (SPM) concentrations are observed in  
79 both time, along the tidal cycle, and space, along the estuary [58, 18]. In the past decades, many  
80 studies, see e.g. [9, 52, 4], have revealed the presence and the mechanisms responsible for the  
81 generation of a zone of high turbidity, the so-called Estuarine Turbidity Maximum (ETM) in salt-  
82 wedge estuaries. Three major mechanisms have been highlighted in the formation of ETM. First,  
83 the estuarine circulation, due to longitudinal salinity gradient, associated with the river run-off drive  
84 a convergent SPM transport at the salt intrusion limit, that can lead to the formation of an ETM.  
85 Second, the asymmetry between the ebb and flood duration and peak velocities can also contribute  
86 to the formation of an ETM. Third, damping of turbulent mixing, due to stable stratification, can  
87 also be responsible for a sinking of particles from the upper part of the water column to the lower  
88 part. Those particles will then be advected upward by the lower layer. In addition, a recent study  
89 [23] also revealed that energetic wave conditions can influence the ETM mass by increasing the  
90 mass by a factor of 3 during mean tides. The presence or the absence of an ETM in a given estuary  
91 is a major concern when trying to understand and predict the dispersion or the retention of SPM  
92 and related biochemical issues.

93 A significant research effort has thus been engaged during the last two decades to perform field  
94 observations of turbulence, mixing and stratification in order to provide a basis for theoretical  
95 analysis and numerical modelling of estuarine dynamics and sediment transport [49, 50, 48, 5, 21].  
96 The present study has been specifically designed to advance knowledge on hydrodynamics and  
97 sediment transport in a man-engineered channel-shape estuary, subjected to strong tidal and fluvial  
98 forcing, with few intertidal area and small watershed; as very few is known about such estuaries.  
99 The selected field site is the Adour river estuary, located at the bottom of the Bay of Biscay. It is  
100 a highly developed estuary with several kilometres of its downstream part completely channelised  
101 in order to secure the Bayonne harbour operations. This specific morphology is reinforced by a  
102 man-engineered reduction of the section at the last reach, in order to ease the expulsion of water  
103 and sediment. The dynamics of estuarine water masses and sediments is further affected by human  
104 interventions aiming to facilitate the navigation by dredging activities and wave protection. In  
105 addition to this very specific morphology, the Adour estuary is also subjected to important fluvial  
106 and tidal forcing, due to the location nearby the Pyrénées (heavy rainfall and snow melt freshet) and  
107 the Atlantic ocean. Despite serious economic and environmental issues related to water quality and  
108 sediment supply, very little is known about the functioning of the Adour estuary and the influence  
109 of human interventions on its internal dynamics. Most known studies have focused on the dynamics  
110 of the turbid plume and its area of influence in ocean waters [2, 11, 8, 37, 28].

111 The aim of our study is to gain a detailed insight on the behaviour of the current and salinity  
112 structure within the Adour river and their influence on particle matters dynamics. The present  
113 paper reports therefore on the first field experimentation conducted in the lower Adour estuary,  
114 where the marine waters play a primary role and the hydrological system remains simple enough  
115 to be monitored. The methods and instrumentation are presented in section 2. The results are  
116 detailed in section 3 and discussed in section 4. The last section is devoted to the conclusion.

## 117 2. Study site and data set

### 118 2.1. Study site

119 The Adour river originates in the Pyrenées mountains at an altitude of 2200 m, and flows about  
120 300 km before pouring into the Bay of Biscay (SW of France). The catchment area is of about  
121 17000 km<sup>2</sup>. The annual average river discharge is of about 300 m<sup>3</sup>.s<sup>-1</sup>, and can reach up to more  
122 than 3 000 m<sup>3</sup>.s<sup>-1</sup> during extreme flood events. The Adour river is characterised by a turbulent  
123 pulsed transport with about 75 % of annual solid flux exported within 30-40 days [38]. The estuary  
124 is exposed to a mesotidal regime, with a tidal range varying between 1 m to 4.5 m. The tidal regime  
125 is mostly composed of semi-diurnal components (M2: 1.22 m, S2: 0.42 m, N2: 0.25 m, K2: 0.12  
126 m). The tide wave propagates until St Vincent-de-Paul (70 km upstream), and the saline intrusion  
127 limit is nearby Urt village (22 km upstream). The lower Adour river estuary (i.e. the lower 6 km),  
128 which is our zone of primary interest, is a fully man-engineered channel of 150 m to 400 m width.  
129 The main channel depth is maintained by dredging to about 10 m depth along the dock in the  
130 Bayonne harbour, to ease navigation. The estuary mouth has been straightened and channelised  
131 by embankments in order to accelerate water flow and to facilitate the sediment expulsion out of  
132 the estuary. In addition, a 700 meters long jetty has been constructed at the north side of the river  
133 mouth to protect the Bayonne harbour from swells mainly coming from the northwest sector (Fig.  
134 1).

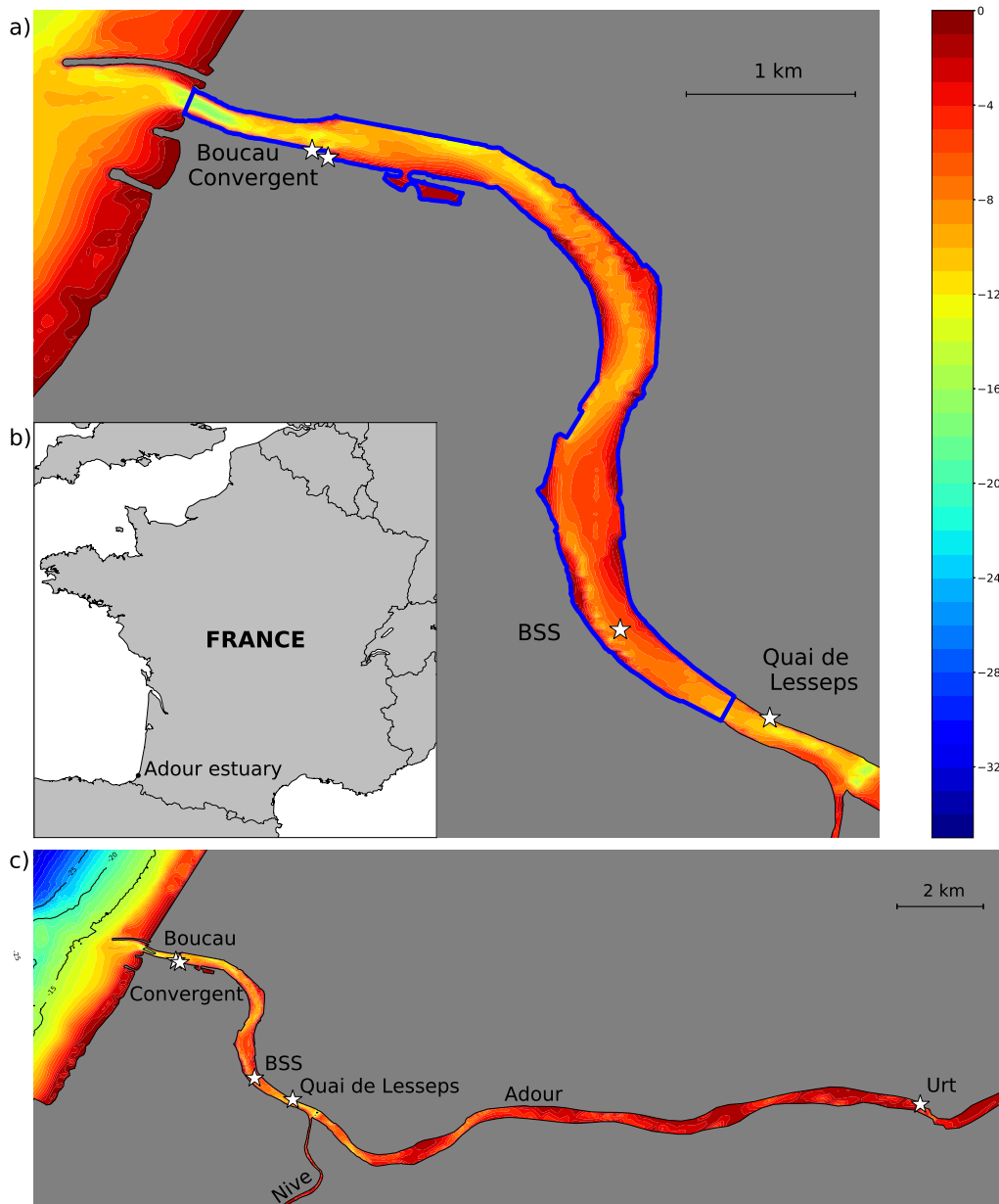


Figure 1: a) The study area, i.e. the last 6km of the estuary , with the Bayonne Harbor in blue. b) The location of the Adour estuary along the French coast. c) The Adour estuary from the entrance to Urt village. BSS white star is the boat survey station location. Boucau, Convergent, Quai de Lesseps and Urt white stars are the tide gauges locations. Colors represent the bathymetry in meter below the chart datum.

135 *2.2. Field experiments*

136 The objective of the present field experiments is to study the tidally-driven hydrodynamics  
 137 inside the lower estuary, including salt-wedge, stratification, mixing and SPM dynamics. The field  
 138 campaigns are based on a series of operations aiming to investigate the effect of river discharge and  
 139 tidal range on the estuarine dynamics. For the sake of simplicity, the experimental results will be  
 140 organized and named following the forcing conditions: LD/HD will refer to low/high river discharge  
 141 and ST/NT will refer to spring/neap tide conditions, respectively, while the year is added at the

142 end. For instance, LD-ST17 will refer to data recover in low discharge and spring tide conditions  
 143 in 2017. A summary of conditions during the boat survey measurements is given in Table 1, while  
 144 each type of measurement is described herebelow. The measurements have been undertaken only  
 145 in the last 6km of the estuary, in between the mouth and the confluence with the Nive river (Fig.  
 146 1 b)).

	<b>Conditions</b>		
	Date	T.R. (m)	Disch. (m <sup>3</sup> /s)
<b>LD-ST17</b>	Sept, 19-20 2017	3.2-3.8	84-86
<b>LD-NT17</b>	Sept, 28-29 2017	1.2-1.3	112-128
<b>LD-ST18</b>	Sept, 25 2018	3.3	103
<b>HD-ST18</b>	June, 12 2018	3.2	1421

Table 1: Experimental conditions. LD/HD refer to low/high discharge conditions, respectively. ST/NT refer to spring/neap tide, respectively. T.R. and Disch. are the tidal range and river discharge, respectively.

### 147 2.2.1. Bottom moored measurements

148 A bottom-moored station has been deployed, at about 5 km from the entrance of the estuary,  
 149 at the same location than the boat survey station (BSS on Fig. 1), in September 2017. Velocity  
 150 profiles were recorded by a Flowquest ADCP (600 kHz) every 15 min (time averaged 5-min burst  
 151 data at 4Hz), with a vertical resolution of 0.5m. The ADCP was located at 0.56 m above the bed.  
 152 Velocity profiles recorded during LD-NT17 are presented in figure 4.

### 153 2.2.2. Fixed boat surveys

154 The fixed boat surveys were dedicated to the vertical structure of velocity, salinity, temperature  
 155 and turbidity. Measurements were performed from an anchored boat (BSS on Fig. 1).

156 The salinity, temperature and turbidity measurements were carried out by a Seabird C19plus  
 157 CTD sensor or a YSI 6920 probe. For each experiment, five-litre water samples have been taken  
 158 to calibrate the instruments. Forty kilograms weights were attached to the measurements line in  
 159 order to ensure the verticality. Probes measurements were recorded at 4Hz for the Seabird C19plus  
 160 and 1Hz for the YSI 6920. Temperature data will not be discussed in this paper, due to negligible  
 161 contributions in the density variations compared to salinity effect.

162 In addition to water properties measurements (1 profile every 15 min), high-frequency velocity  
 163 profiles were recorded, for LD-ST18 and HD-ST18 only, by a Nortek Signature 1000 current profiler  
 164 (ADCP) secured along the hull. The ADCP was continuously sampling at a rate of 8Hz with 20 to  
 165 30 cm cells.

### 166 2.2.3. Longitudinal sections

167 Longitudinal transects were realised across the control area (from 1 km to 5.5 km, from the  
 168 entrance of the estuary) with an OSIL Minibat under-water towed vehicle, equipped with a multi-  
 169 parameter probe. Salinity, temperature, pressure and turbidity have been recorded by the Minibat.  
 170 Deployments have been carried out during LD-ST17 and LD-NT17 experiments (see Fig. 3 and  
 171 5, respectively). While the Minibat provides useful spatial information, its deployment remains a  
 172 very delicate operation in such a shallow and vertically sheared navigation channel. The transects

173 were surveyed following the centre axis of the estuary, i.e. not always in the main channel due to  
 174 navigation constraints near the docks.

#### 175 2.2.4. Water levels

176 The tide gauge data presented hereafter have been collected either by Convergent or Bayonne-  
 177 Boucau tide gauges, due to episodic malfunctioning. Both are operated by the Service Hydro-  
 178 graphique et Océanographique de la Marine (SHOM) and located near to the entrance of the  
 179 estuary (Fig. 1). In this paper, those data will be presented in water elevation above the local  
 180 chart datum (in m C.D.).

### 181 2.3. Data processing

#### 182 2.3.1. Velocity measurements

183 For each profiler, the velocity data are projected into a local coordinate system with the x axis  
 184 directed along the channel with positive values landward, the y axis directed laterally towards the  
 185 right bank, and the z axis directed upward. For simplicity, the generic term "velocity" generally  
 186 refers later on to the x-component of velocity, otherwise clarification will be given.

187 High frequency velocity data from LD-ST18 and HD-ST18 are used to analyse turbulence prop-  
 188 erties. The 8Hz, 1s averaged, ADCP data of opposing beams ( $b_i$ ) have been split into a mean ( $\overline{b_i}$ )  
 189 and a fluctuating part ( $b'_i$ ), using a sampling interval of 10 min. An additional high-pass filter is  
 190 applied to remove low frequency fluctuations due to ship motion. The along-beam velocities have  
 191 been used to estimate the components of Reynolds stress [34, 60, 46], as follows :

$$-u'w' = \frac{\overline{b_3'^2} - \overline{b_1'^2}}{4\sin(\theta)\cos(\theta)} \quad (1)$$

$$-v'w' = \frac{\overline{b_2'^2} - \overline{b_4'^2}}{4\sin(\theta)\cos(\theta)} \quad (2)$$

192 where  $\theta$  represent the angle of each beam from the axis of the instrument ( $\theta = 25^\circ$  for Nortek  
 193 Signature 1000 ADCP).

194 The eddy viscosity is classically computed following the flux-gradient hypothesis:

$$\nu_t = -\frac{\overline{u'w'}}{\partial\overline{u}/\partial z} \quad (3)$$

195 The rate of Turbulent Kinetic Energy (TKE) production is expressed as a product of stress and  
 196 shear :

$$P = -\rho\overline{u'w'}\frac{\partial\overline{u}}{\partial z} - \rho\overline{v'w'}\frac{\partial\overline{v}}{\partial z} \quad (4)$$

#### 197 2.3.2. Richardson number

198 The non-dimensional Richardson number  $Ri$  is often used to quantify the stability of the density  
 199 stratification in sheared flow [53]. A threshold value of 0.25 is commonly applied to distinguish stable  
 200 stratification from unstable situation due to the breakdown of stratification by turbulent mixing.  
 201 For high values of  $Ri$ , the buoyancy forces driven by the vertical density gradient are expected to



202 overcome and suppress turbulent mixing. The Richardson number formulation is here calculated  
203 from the ratio between density and mean velocity gradients:

$$204 \quad Ri = -\frac{g}{\rho_0} \frac{\partial \rho / \partial z}{(\partial \bar{u} / \partial z)^2} \quad (5)$$

204 where  $\rho_0$  is the depth-averaged density. For the calculation of the Richardson number, density  
205 is estimated according to UNESCO formula and density profiles are interpolated over the ADCP  
206 regular measurement positions. It should be noted that in figure 2, the top of the water column is  
207 missing in some salinity and SSC profiles due to the malfunctioning of our multi-parameters probe.

### 208 2.3.3. Turbidity and SSC

209 Turbidity profiles from boat surveys during LD-NT17, LD-ST18 and HD-ST18 have been con-  
210 verted into suspended sediment concentration (SSC) using a series of five-litre water samples and  
211 pre-weighted glass fiber filters.

## 212 3. Results

213 The presentation of the field results will first focus on salinity structure and circulation, based on  
214 the time evolution of the vertical profiles of the measured parameters (Figs. 2, 4 and 6 for LD-ST18,  
215 LD-NT17 and HD-ST18 cases, respectively) together with longitudinal sections (Figs. 3 and 5 for  
216 LD-ST17 and LD-NT17 cases, respectively). The LD-ST18 and HD-ST18 data are also depicted as  
217 temporal contour plots in Figures 7 and 8, respectively. For these cases, additional turbulence data  
218 over the whole water column, including estimates of eddy viscosity and rate of TKE production,  
219 are then presented from hull-mounted ADCP measurements, to analyse the competition between  
220 turbulence and stratification. SPM dynamics is finally explored in the view of previous observations  
221 on estuarine dynamics.

### 222 3.1. Estuarine salinity structure and circulation

223 Figures 2, 4, and 6 present the tidal evolution of velocity, salinity and Suspended Sediment  
224 Concentration (SSC) profiles, during the dry season, for spring (LD-ST18) and neap (LD-NT17)  
225 tide conditions, and during the wet season for spring tide (HD-ST18) respectively. Figures 3 and  
226 5 display vertical salinity and turbidity structure along the last 6 km of the estuary, from Minibat  
227 measurement during LD-ST17 and LD-NT17 experiments, respectively.

228 The data analysis is first focused on the spring tide condition during the dry season (Fig. 2  
229 and 3). The ebbing tide is characterised by a horizontal salinity gradient (Fig. 2 (c) and Fig. 3  
230 (b)), with a homogeneous water column flowing out the estuary. As the ebb progresses, the water  
231 column becomes fresher and flows faster. At low water (11:36), the seaward current shows a strongly  
232 sheared structure, with a nearly linear profile across the water column. Progressively, the water  
233 column slows down and the salinity still decreases homogeneously along the water column. As the  
234 tide rises, the salinity at the top of the water column goes on decreasing, while, at the bottom of  
235 the water column the salinity increases. Salinity profiles are not homogeneous anymore, and the  
236 salinity gradient increases. The current reversal occurred around 13:30 (i.e. almost 2 h lagged from  
237 the low water time). The velocity profile reveals a typical salt-wedge profile, when the salty marine  
238 waters flow into the estuary. A fast landward salty bottom layer is observed in the lower 3m, while

239 an oppositely fresh upper layer is still flowing seaward with a sheared profile. The salinity reaches  
 240 its minimal value in the surface layer, when the salt-wedge starts entering the estuary. The salty  
 241 bottom layer, which is rather well-mixed, increases both in thickness and salinity as the tide rises.  
 242 At the end of the flood tide, the full water column is salty and flows upstream, blocking the fresh  
 243 water inside the upper part of the estuary. The continental waters blocked into the upper part of  
 244 the estuary during the flood, are then released during the ebb. This mechanism, named "pulsed  
 245 plume mechanism", has already been highlighted by Dailloux [8].

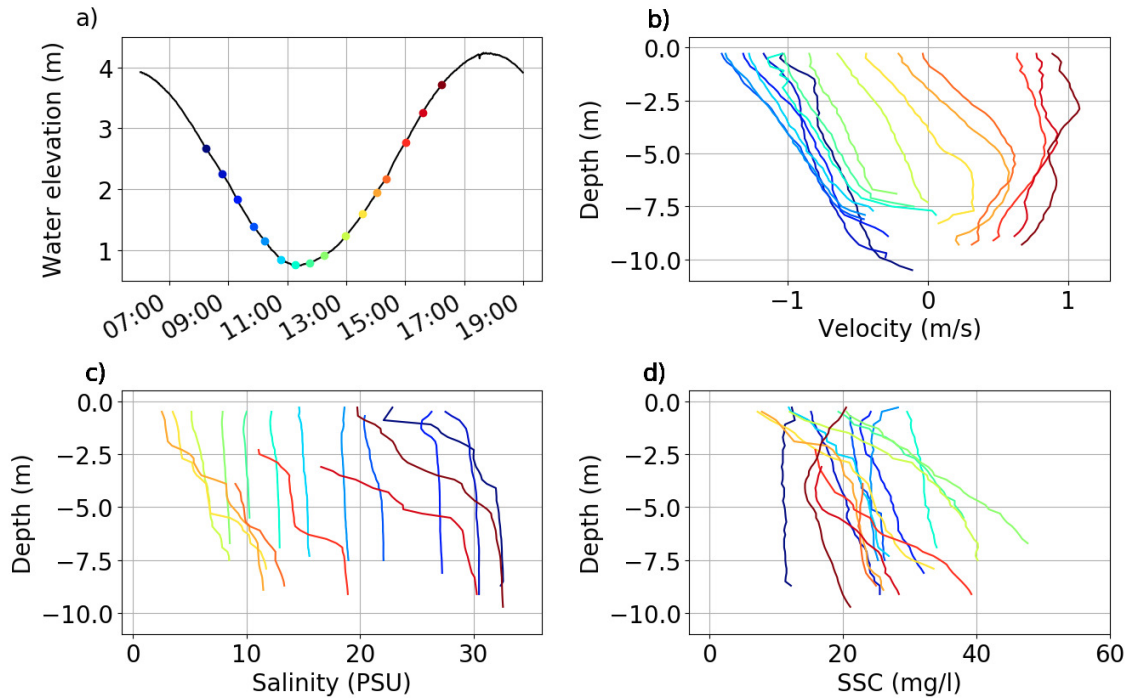


Figure 2: Tidal dynamics from LD-ST18 fixed boat surveys during low discharge spring tide conditions. (a) Water level and timing of measurements. (b), (c), and (d): velocity, salinity and SSC profiles. Note that the same data is presented in contour plots in Figure 7.

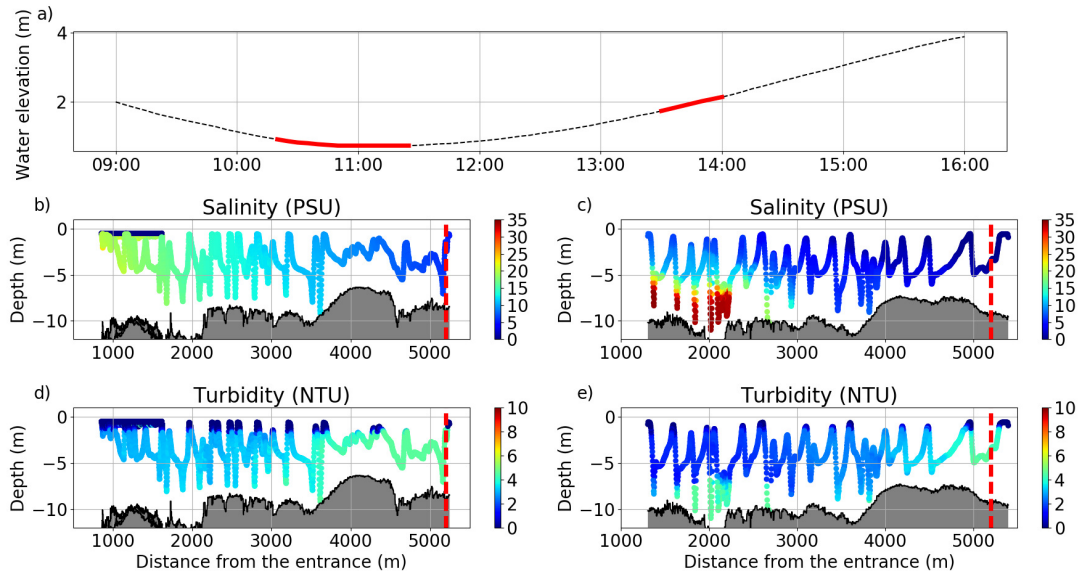


Figure 3: Longitudinal and vertical structure across the lower estuary from Minibat measurement during LD-ST17 experiment. (a): Water elevation with measurement periods highlighted in red. (b) and (c): salinity data for falling and rising tide. (d) and (e): turbidity data for falling and rising tide. The bed of the estuary is represented in grey. The red dashed line represents the BSS location.

246 The contrast between spring tide and neap tide (Fig. 4 and 5) is straightforward, as during neap  
 247 tide the salinity stratification is maintained all along the tidal cycle and the velocity magnitudes are  
 248 reduced. At the end of the flood (11:00), a sharp pycnocline separates a two-layer flow, with denser  
 249 marine water flowing upstream underneath fresh continental waters. The bottom saline layer grows  
 250 thicker until post-high tide slack water (14:00). Unlike spring tide, at neap tide the pycnocline is not  
 251 able to reach the surface. The current reversal is lagged of almost 3h from the high water (10:49).  
 252 As flow reverses seaward, the pycnocline thickens and deepens, while the surface and the bottom  
 253 salinity remain relatively constant. This time the ebbing shear velocity profiles are associated with  
 254 a vertical stratification. This permanent stratification leading to an inhibition of the salt-wedge  
 255 flushing during neap tide is generally associated with stagnant waters and hypoxia [29, 3].

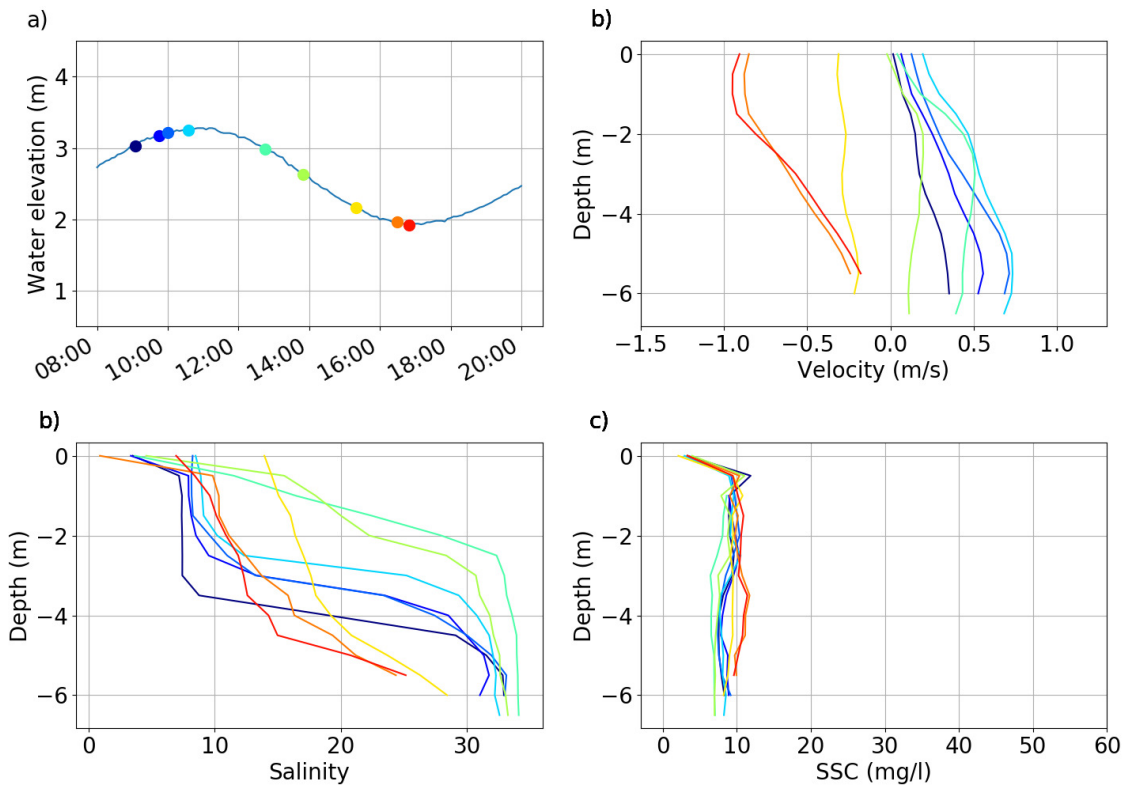


Figure 4: Tidal dynamics from LD-NT17 fixed boat surveys during low discharge neap tide conditions. (a) Water level and timing of measurements. (b), (c), and (d): velocity, salinity and SSC profiles.

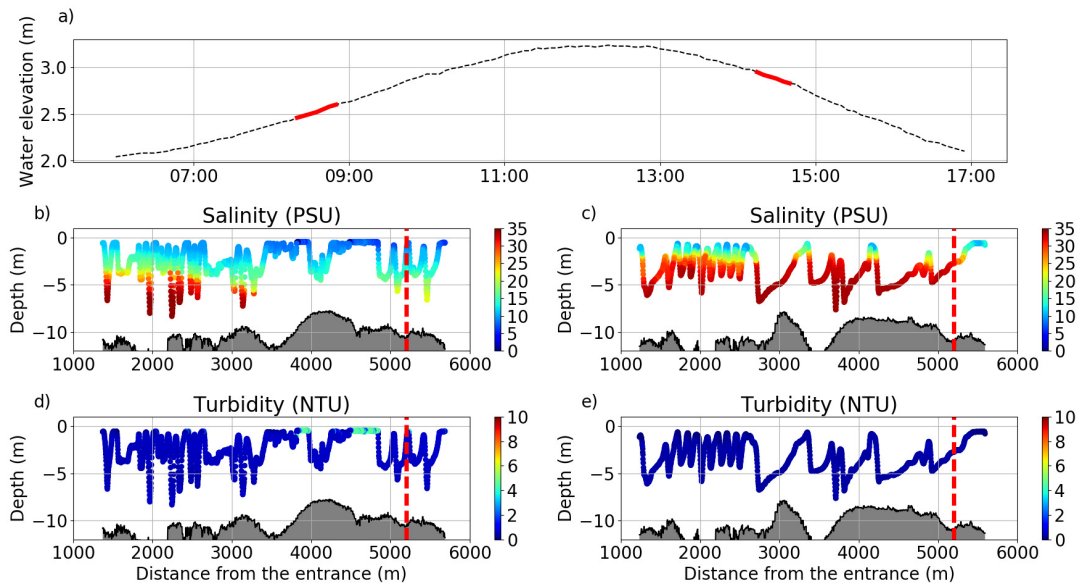


Figure 5: Longitudinal and vertical structure across the lower estuary from Minibat measurement during LD-NT17 experiment. (a): Water elevation with measurement periods highlighted in red. (b) and (c): salinity data for falling and rising tide. (d) and (e): turbidity data for falling and rising tide. The bed of the estuary is represented in grey. The red dashed line represents the BSS location.

256 A dedicated experiment (HD-ST18) was carried out during a high discharge event in order to  
 257 explore the role of river runoff on the hydro and sediment dynamics compared to the reference  
 258 low river discharge dataset presented hereabove. Figure 6 depicts the time evolution of velocity  
 259 profiles, salinity and Suspended Sediment Concentration (SSC) profiles during high river discharge  
 260 conditions. The comparison with low discharge conditions presented in Figure 2 shows the drastic  
 261 influence of river run-off on the estuarine dynamics. Similar maximal magnitudes are reached during  
 262 the ebb, but the velocity profile is almost constant, and the water column is homogeneously fresh.  
 263 As tide rises, the water column shows a piston-like behaviour, i.e. marine water impounding river  
 264 water into the estuary with a quasi uniform velocity along the vertical. The current reversal (13:00)  
 265 occurs much later for the high discharge case, i.e. almost three hours after the low water (09:58),  
 266 than for the low discharge case. The piston-like behaviour remains active all along the flow reversal  
 267 and during the most part of the flood tide. This greatly differs from the low discharge case for  
 268 which a vertical shear of velocity is systematic at the early stage of flood tide. At the very end of  
 269 the flood (16:00), the salt-wedge is finally able to reach the measurement area. A 2 m thick bottom  
 270 salty layer propagates upstream at about 0.5 m/s. The high river discharge is again responsible for  
 271 a significant time lag compared to low discharge conditions for which the salt-wedge was able to  
 272 reach boat survey station about 2 h earlier. A remarkable observation, at the salt-wedge arrival, is  
 273 the rapid seaward reversal of the overlying fresh water layer. The water column forms, therefore,  
 274 a two-layer vertical structure with strong vertical shear in velocity and a sharp pycnocline. Note  
 275 that the seaward/landward velocity maxima are reached in the upper parts of the pycnocline and  
 276 of the salt-wedge, respectively.

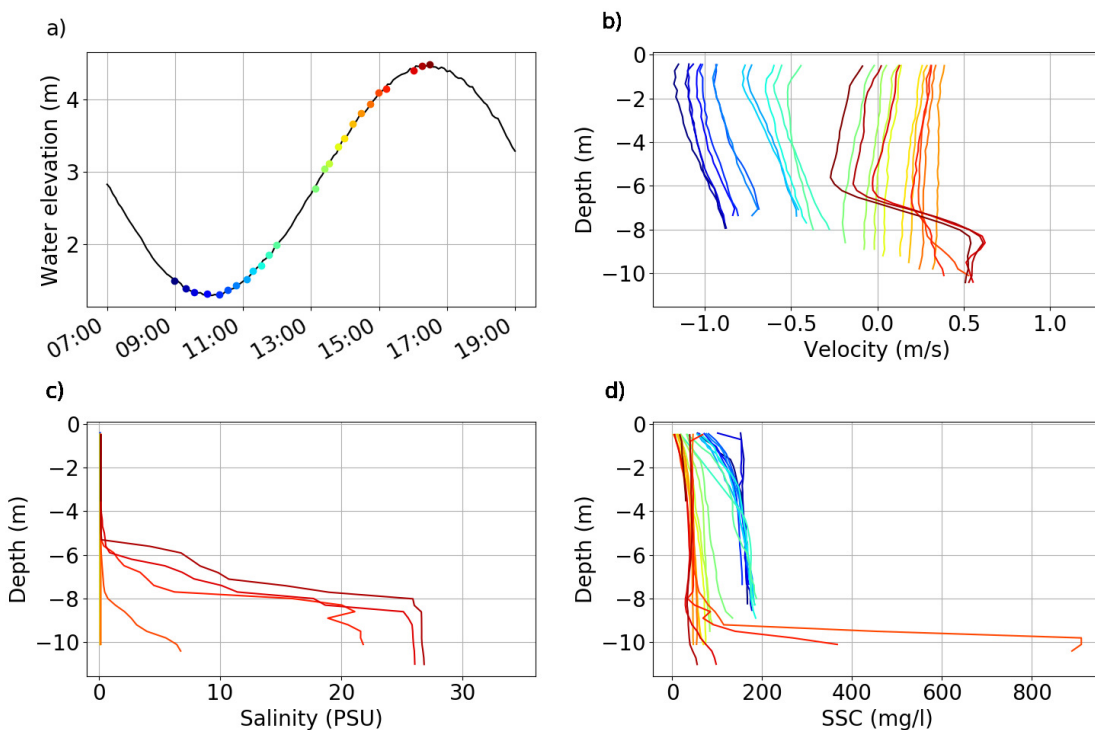


Figure 6: Tidal dynamics from HD-ST18 fixed boat surveys during high discharge spring tide conditions. (a) Water level and timing of measurements. (b), (c), and (d): velocity, salinity and SSC profiles. Note that the same data is presented in contour plots in Figure 8.

277 *3.2. Turbulence properties*

278 The previous section revealed the complex vertical salinity structure and circulation taking  
279 place into the Adour estuary. This first result needs to be further investigated by a turbulent  
280 properties analysis, to get a better understanding of the interaction between stratification and  
281 turbulent mixing. The representation of Richardson number profile as  $\log_{10}(Ri/0.25)$  is used in  
282 figures 7 and 8 to easily estimate the stability of the water column: stable (unstable) flows are  
283 expected for positive (negative) values. In addition, high-resolution high-frequency velocity profiles  
284 are used to infer turbulent properties of the flow. Figures 7 and 8 shows the tidal evolution of the  
285 vertical distribution of turbulent properties at the survey station BSS for the low (LD-ST18) and  
286 high (HD-ST18) river discharge experiments respectively.

287 Figure 7 depicts the data recovered during spring tide and low discharge conditions (LD-ST18).  
288 At 08:15, the water column is slightly stratified and the production of turbulence is focused in a  
289 very thin layer above the bed related with weak turbulent diffusion in most of the water column. As  
290 the water column becomes homogeneous and ebb current accelerates during the estuary flushing,  
291 the turbulence spreads into the water column aside from in the 2 m surface layer. The turbulent  
292 mixing overcomes the buoyancy forces and water column becomes fully unstable ( $\log_{10}(Ri/0.25) <$   
293  $0$ ). Maximal values of  $P_{tke}$  and  $\nu_t$  are associated with maximum ebb currents. The eddy viscosity  
294 is maximal in the bottom 4 m and reaches typical values (about  $1.5 \cdot 10^{-2} \text{ m}^2 \cdot \text{s}^{-1}$ ) measured in  
295 estuary for similar velocity and stratification conditions [46]. Those measurements also confirms  
296 that the eddy viscosity decreases toward the surface [35]. The slack water and the subsequent flow  
297 reversal are associated with a drastic drop of turbulence production. After 13:00, the sign change of  
298 the Richardson number indicates the shift toward a stable stratified situation which further reduces  
299 the eddy viscosity. At the salt-wedge entrance (around 13:30), a stable stratification develops with  
300 no turbulent mixing except an increase of TKE production and eddy viscosity at the tip of the  
301 salt-wedge. High values of Richardson number are associated to the edges of the pycnocline. Burst  
302 of turbulent production seems to develop in the upper layer between 14:00 and 14:30, which may  
303 correspond to a local destabilisation of the sheared layer. As the tide rises, the water column turns  
304 on stable up to the surface with no more turbulent mixing.

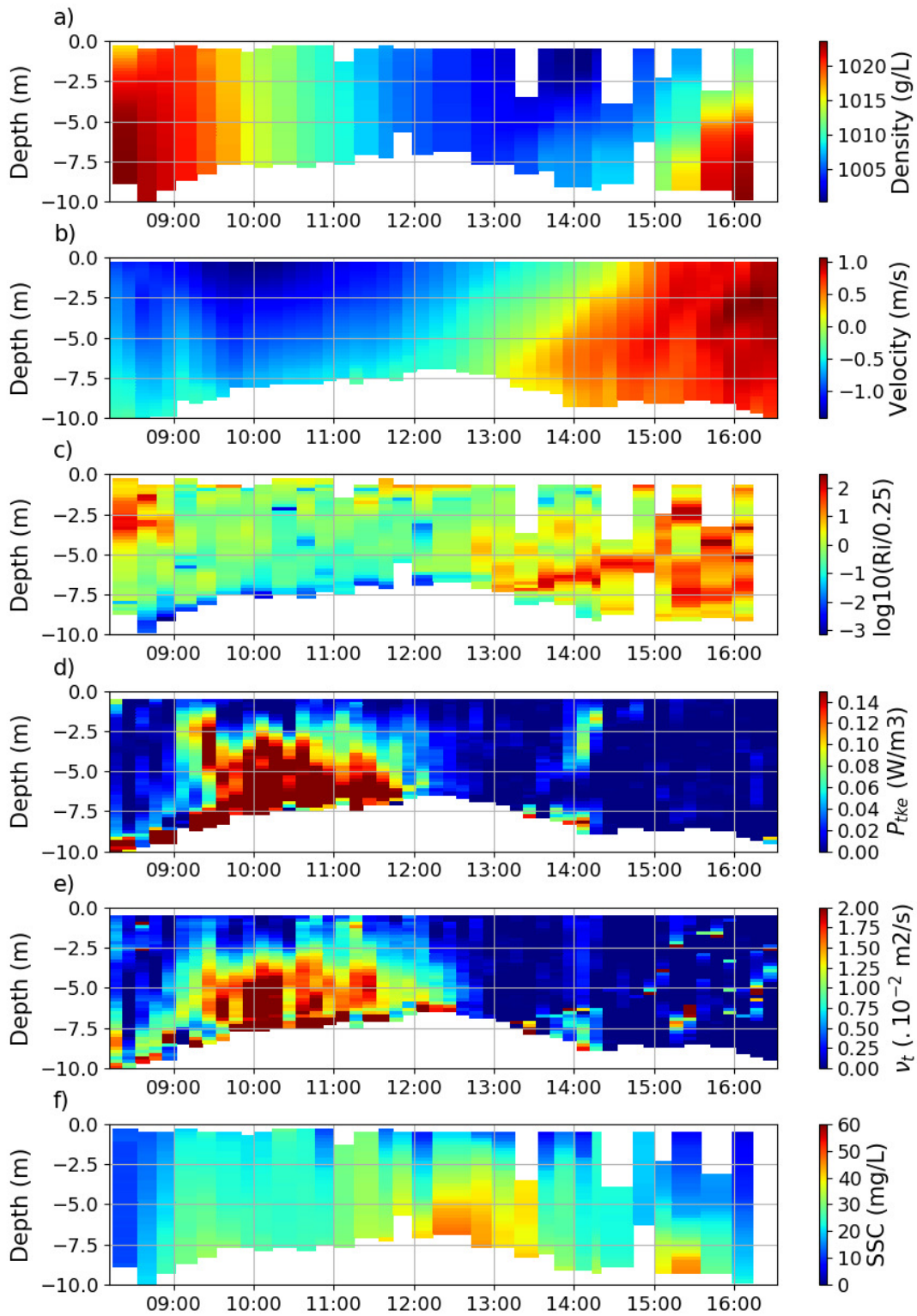


Figure 7: Tidal evolution during LD-ST18 experiment : (a) vertical structure of density, (b) time-averaged velocity, (c) Richardson number, (d) production rate of TKE, (e) eddy viscosity, and (f) suspended sediment concentration.

305 In addition, Ri calculations (not shown here) have been carried out for neap tide conditions  
306 based on profiles shown in figure 4. As expected, the nearly permanent vertical salinity stratification  
307 promotes stability throughout the water column.

308 Figure 8 presents similar data than figure 7, but applied on data collected under high river  
309 run-off conditions. It is first recalled that Richardson number should be considered with respect to  
310 the corresponding velocity and density profiles: nearly neutrally stratified conditions (i.e. unstable  
311 conditions) may appear stable in terms of Richardson number when the velocity shear is very weak.  
312 This is for instance the case in the surface layer (Fig. 8). During high discharge conditions, the  
313 lower estuary is filled with fresh water for most of the tidal cycle, the only exception being the salt-  
314 wedge arrival just before high tide (15:00). Therefore, the turbulent properties variations drastically  
315 differ from the low discharge case shown in figure 7. At the end of the ebb tide (before 10:00), the  
316 water column is fully fresh and has an almost constant velocity. High rate of TKE production and  
317 eddy viscosity are measured at the peak of ebb currents. The strong discharge is able to maintain  
318 the instability and a significant TKE production until 12:00 (i.e. more than two hours after low  
319 tide). Then, slack water (around 13:00) is associated to a strong drop of turbulence production and  
320 eddy viscosity, which remains very weak until the arrival of the salt-wedge. However, the piston  
321 effect is clearly visible at rising, with nearly vertically uniform velocity profiles during most of the  
322 rising tide. The consequence, in term of stability, is that the lower estuary remains unstable all  
323 the time until the salt-wedge is able to reach the measurement station (15:00). A first moderate  
324 rise of TKE production is observed near the bottom to a depth of 3m, which indicates that the  
325 tip of the salt-wedge is a mixing zone. From that moment, one notes the development of a 1 to  
326 2 m high pycnocline, both strongly stratified and very sheared. Corresponding positive values of  
327 Richardson number indicates the stability of the sheared layer. Peaks of Richardson number are  
328 observed near the edges of the pycnocline, associated to more stable areas, whereas the core of the  
329 sheared zone is very close to the instability threshold. The TKE production strongly rises near  
330 the bottom, but remains confined near the bottom layer by the effect of overlying stratification.  
331 It can be noticed that, even if the velocity of entering marine waters is much lower than for the  
332 low discharge case, a much stronger turbulent mixing is observed in the bottom layer. The salt-  
333 wedge arrival (15:00) is a striking example of a dynamical competition between turbulent mixing  
334 and stratification: turbulent diffusion is very active near the bottom and below the pycnocline, but  
335 totally vanishes in the overlying fresh water layer.



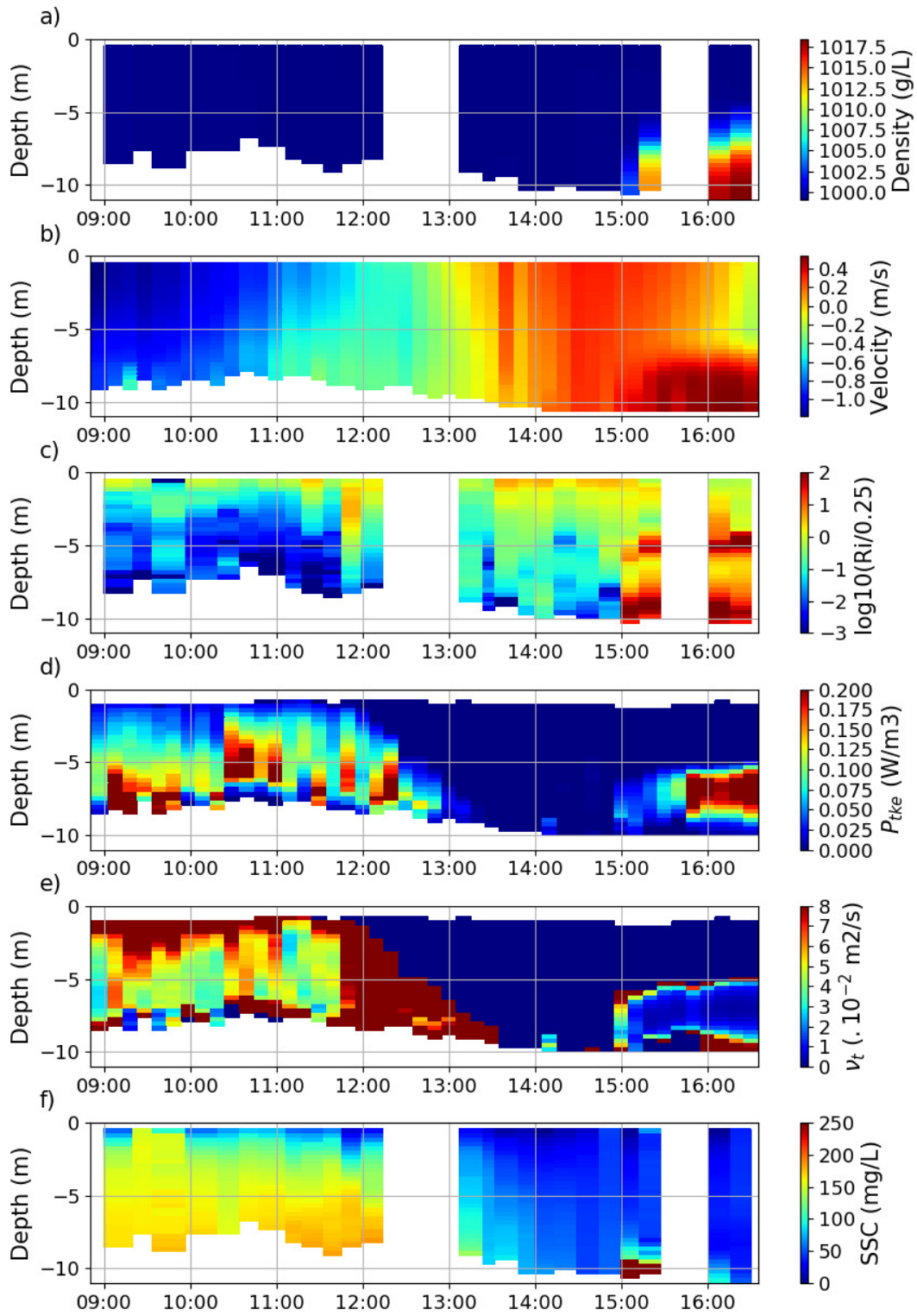


Figure 8: Tidal evolution during HD-ST18 experiment : (a) vertical structure of density, (b) time-averaged velocity, (c) Richardson number, (d) rate of TKE production, (e) eddy viscosity and (f) suspended sediment concentration. Note the difference in range compared to Figure 7.

### 336 3.3. Suspended sediment dynamics

337 This section is dedicated to the response of the sediment load to the complex hydrodynamics of  
338 the lower Adour estuary presented above. Figures 2 (d), 4 (d) and 6 (d) represent the SSC profiles  
339 collected during LD-ST18, LD-NT17 and HD-ST18 respectively. Figures 7 (f) and 8 (f) display  
340 same data as presented in Figures 2 (d) and 6 (d) under timeseries color plots. Figures 3 (d), (e)  
341 and 5 (d), (e) show Minibat turbidity data collected during LD-ST17 and LD-NT17 respectively.

342 First, a focus on the low river discharge reference case allow us to study the effect of tidal cycle  
343 on sediment dynamics, such as erosion, advection and deposition mechanisms. In Figures 2 and 7,  
344 it can be noticed that at mid-ebb, the full water column is flowing out the estuary and the vertical  
345 velocity gradient is increasing. It results in a sufficient bottom shear stress to re-suspend sediment  
346 around 08:30. The sediments are maintained in suspension and are able to reach the surface of  
347 the water column by the turbulent mixing appearing at 09:00. Figure 3 shows that a horizontal  
348 gradient of SSC associated to the horizontal gradient of salinity develops, with SSC increasing as  
349 the water becomes fresher. These sediments in suspension are advected seaward by the flow, at  
350 a velocity that can reach  $1.5 \text{ m.s}^{-1}$  in the surface. Approaching the slack water period (12:00),  
351 the ebbing velocity is less than 0.6 m/s (green profiles on Fig. 7) and the vertical gradient of  
352 velocity decreases. Consequently the re-suspension capacity of the flow decreases. The turbulence  
353 maintaining the sediment in suspension also drops down, and so the SSC develops a vertical gradient,  
354 which might be associated to settling. It progressively leads to an overall SSC decrease. Around  
355 14:00, sediments accumulated at the bottom of the water column are advected landward by the  
356 entrance of the marine waters into the estuary, while sediments located at the surface are still  
357 advected seaward. At 15:00, an area of high turbidity is generated at the tip of the salt-wedge  
358 front. This trend is generally attributed to the accumulation of sediments due to the convergence  
359 of sediment fluxes from the river and the ocean. This peak of SSC is contained near the bottom by  
360 the pycnocline. Another striking feature is the decrease of SSC in the layer of fresh continental water  
361 flowing above the salt-wedge (Fig. 7 and 3). This observation should likely be attributed to the  
362 stratification-induced damping of turbulence, leading to particles sinking, as previously observed in  
363 other systems [59, 18]. At 16:00, velocity profiles are much more homogeneous and the turbulence  
364 is damped by the stability of the two-layer flow, and so the SSC decreases.

365 The tidal range has also a striking effect on the above mentioned sediment dynamics, as shown  
366 by the comparison between Figures 2 and 4. During neap tides, the SSC remains very low, about 10  
367  $\text{mg.L}^{-1}$  all over the tidal cycle and quite homogeneous over the water column, while during spring  
368 tides, the SSC is generally stronger (up to  $45 \text{ mg.L}^{-1}$ ) and slightly more variable throughout the  
369 tidal cycle. This very low SSC can be explained by a permanent stratification and a reduced  
370 velocity. Low velocities impede the re-suspension of sediments and the permanent stratification  
371 damps down the turbulence. The sediments can therefore not remain in suspension. During neap  
372 tides the flushing capacity is drastically reduced by the absence of re-suspension and advection and  
373 the strong deposition.

374 The riverine forcing also influences the sediment dynamics, as highlighted by Figures 6 and 8.  
375 During high river discharge, the ebbing currents are reinforced and the flow is much more turbulent,  
376 resulting in a stronger re-suspension and seaward advection. Consequently, SSC values are much  
377 more higher than those observed during low discharge conditions. In Figure 8, it can be noticed  
378 that during the ebb, the SSC is quite homogeneous in the water column, with values about 150

379  $mg.L^{-1}$ . These reinforced re-suspension and advection result in a very good flushing capacity of  
 380 the estuary. At 11:30, both flow and turbulent mixing reduce in intensity. The particles are not  
 381 anymore maintained in suspension and a progressive sedimentation can be observed. The SSC  
 382 shows a pattern similar to the one of turbulent properties. Between 15:00 and 17:00, the piston-  
 383 like behaviour occurs pushing slowly the full low SSC water column landward. Similarly to the  
 384 low discharge conditions, the salt-wedge passing (15:00) corresponds to the higher measured SSC.  
 385 However, during high river discharge, the SSC is able to reach up to  $850 mg.L^{-1}$  in the bottom  
 386 layer. The increased river flow reinforces the convergence mechanism. These sediment in suspension  
 387 are also contained by the pycnocline and advected landward, while the surface waters containing  
 388 little sediments are advected seaward. Around one hour after the salt-wedge front passing, the SSC  
 389 at the bottom of the water column has decreased to about  $100 mg.L^{-1}$ . This high turbidity area  
 390 is thus supposed to follow the up estuary motion of the salt-wedge leading front.

## 391 4. Discussion

392 This article presents a set of field observations carried out to improve the knowledge about  
 393 circulation and sediment transport into the lower Adour estuary. These results provide the first  
 394 in-situ characterisation of the hydrological functioning of the Adour lower estuary, but also give rise  
 395 to a number of questions. Discussion points have been organised under three main topics: estuarine  
 396 salinity structure and circulation, sediment dynamics and connection to plume dynamics.

### 397 4.1. Estuarine circulation

398 The present *in-situ* dataset revealed the high variability of the Adour lower estuary, in terms  
 399 of hydrological functioning. A salt-wedge generally develops during the flood tide in the Adour  
 400 lower estuary. This salt-wedge depends on river discharge, by being more steeply marked during  
 401 the wet season due to intense river forcing. In addition, the tidal forcing is also an important driver  
 402 of the Adour estuary (mesotidal system) with a significant effect of the spring/neap cycles on the  
 403 estuarine salinity structure. Under low discharge conditions, the neap tides are associated to fully  
 404 vertically stratified estuary along the tidal cycle, while during spring tide the salt-wedge shape is  
 405 lost during the ebb, and an horizontal salinity gradient takes place. Such a versatility in the salinity  
 406 circulation in response to the fluctuations of tidal and fluvial forcing can not be properly accounted  
 407 for by usual descriptive estuary classifications, such as, e.g. the well-know scheme of Cameron and  
 408 Pritchard [7]. More physical insight is provided by the recent quantitative scheme of classification  
 409 developed by Geyer and MacCready [21].

410 The scheme of classification developed by Geyer and MacCready [21] investigates the respective  
 411 contribution of tidal mixing and stratification by the means of a two parameters space : the freshwa-  
 412 ter Froude number  $Fr_f = U_R/(\beta g s_{ocean} H)^{1/2}$  and the mixing parameter  $M = \sqrt{(C_D U_T^2)/(\omega N_0 H^2)}$ ,  
 413 where  $U_R$  is the net velocity due to river flow (i.e. the river volume flux divided by the estuarine  
 414 section),  $\beta$  is the coefficient of saline contraction,  $g$  is the acceleration due to gravity,  $s_{ocean}$  is the  
 415 ocean salinity,  $H$  is the water depth,  $C_D$  is the bottom drag coefficient,  $U_T$  is the amplitude of the  
 416 tidal velocity,  $\omega$  is the tidal frequency and  $N_0 = (\beta g s_{ocean}/H)^{1/2}$  is the buoyancy frequency for  
 417 maximum top-to-bottom salinity variation in an estuary. The former dimensionless parameter  $Fr_f$   
 418 compares the net velocity due to river flow and the maximum possible front propagation speed,  
 419 while the latter  $M$  assesses the role of tidal mixing and the influence of stratification on the vertical

420 mixing. Due to spring/neap variations and wet/dry seasons changes, estuaries are not represented  
421 by a point in this classification scheme, but rather by rectangles covering the range of observed  
422 regimes. An adaptation of the Geyer and MacCready's regime diagram [21] is proposed in Figure 9,  
423 with the  $M$  and  $Fr_f$  ranges reached by some well-documented estuarine systems in order to easily  
424 compare with the Adour estuary.

425 Of particular interest is to know the extent to which the variability of the Adour estuary can  
426 be described by such approach and to evaluate how it can compare to other typical systems  
427 selected for their contrasted dynamics. For the calculation of both parameters, we considered  
428  $\beta = 7.710^{-4} PSU^{-1}$ ,  $H$  to be a characteristic value of the water depth  $H = 10m$ , the salinity of  
429 ocean  $s_{ocean} = 34.5$  PSU. A first remark should be made on the uncertainty on the estimation of  
430 the mixing parameter  $M$ . This parameter shows a strong sensitivity to both  $U_T$  and  $C_D$  values,  
431 which are not straightforward to estimate. In Geyer et al 2014 [21],  $U_T$  is defined as the amplitude  
432 of the depth-averaged tidal velocity, while it has been estimated as the rms velocity 3m above the  
433 bed in Geyer et al 2000 [20] and considered equivalent to the maximal velocity in Li et al 2014  
434 [33]. For the present study, the reference value of  $U_T$  is provided by rms depth-averaged velocity  
435 measured at the BSS bottom moored station (Fig. 1). The bottom drag coefficient  $C_D$  can also  
436 be strongly spatially variable inside an estuary, and relatively challenging to estimate. In Geyer et  
437 al. 2014 [21] authors consider that  $C_D$  generally varies between 1 to  $2.5 \cdot 10^{-3}$  inside an estuary,  
438 while Geyer et al. 2010 [17] mentioned a value of  $C_D$  generally about  $3 \cdot 10^{-3}$  inside estuaries. For  
439 the Adour estuary, two point currentmeters deployed in the bottom layer have been used by Sous  
440 et al [47] to estimate a  $C_D$  value about  $1.5 \cdot 10^{-3}$  between Convergent and BSS stations, which is  
441 used here as a reference for the estimation of  $M$ . Using data collected inside the Adour estuary,  $U_R$   
442 estimation ranges from 0.05 to  $0.75 m.s^{-1}$ , therefore  $Fr_f$  should range from 0.03 to 0.46 for low to  
443 high discharge conditions, respectively. The mixing parameter  $M$ , based on reference values for  $U_T$   
444 and  $C_D$ , ranges from 0.36 to 0.66 for neap to spring tide conditions, respectively (Fig. 9, solid line  
445 rectangle). In order to illustrate the  $M$  sensitivity to  $U_R$  and  $C_D$  parameters, estimating now  $U_T$   
446 as the maximal entering velocity together with a  $C_D$  value of  $3 \cdot 10^{-3}$  will shift the Adour's system  
447 toward higher ranges of mixing parameter values (0.68 to 1.13), see dashed line rectangle in Figure  
448 9. In addition, the values of the mixing parameter might be further increased with data from neap  
449 tide conditions combined to high river run-off, which are not documented by the present dataset.

450 Keeping in mind these limitations, the estuarine parameter space diagram proposed by Geyer  
451 and MacCready [21] confirms the variability of the hydrological functioning of the Adour estuary  
452 in comparison with other typical systems (Fig. 9). Noted that the large area covered by the  
453 Adour river in this diagram is due to the highly contrasted hydrological conditions encountered  
454 during our measurements. Others systems may have been observed only during mean hydrological  
455 conditions, leading to reduced rectangles. Based on collected data, presented in this paper, we  
456 can analyse the observed dynamics of the Adour estuary. Under high tidal mixing conditions  
457 (i.e. high  $M$  value), the Adour river dynamics is quite similar to those of Fraser [19], Changjiang  
458 [33] and Merrimack rivers [41], which are all considered as time-dependent salt-wedge estuaries.  
459 Those energetic and stratified estuaries are characterised by strong tidal and fluvial velocities (Fig.  
460 10). It results in a strengthened stratification during the flood, that weakens during the ebb tide,  
461 where the turbulence develops in the full water column. Under low tidal mixing conditions (i.e.  
462 low  $M$  value), the Adour tends to show a behaviour similar to the Ebro river. This latter has a

463 similar shape and river discharge than the Adour, but the microtidal regime (associated to a small  
 464  $M$ ) results in a stagnant salt-wedge under low river run-off ejected out of the estuary when the  
 465 river discharge exceeds  $500 \text{ m}^3 \cdot \text{s}^{-1}$  [25]. Measurements undertaken during neap tide and low river  
 466 discharge in the Adour estuary reveal a similar pattern with an almost stagnant salt-wedge and  
 467 strong stratification. Unfortunately, observations were not carried out during neap tide and high  
 468 river discharge (around  $1500 \text{ m}^3 \cdot \text{s}^{-1}$ ), but we can expect an absence of the salt-wedge or at least  
 469 a strong reduction of the saline intrusion. The role of river discharge is however clearly identified  
 470 for spring tides, corresponding to fluctuations along the  $Fr_f$  axis in Figure 9 for large value of  $M$ .  
 471 Under low river discharge conditions (i.e. low  $Fr_f$  value), the influence of tidal mixing is more  
 472 important, leading to a smoother vertical stratification and a strongly stratified regime. During the  
 473 ebb, the peak of turbulence can be sufficient to break down the vertical stratification and generate  
 474 an horizontal stratification. This horizontal stratification is a typical attribute of partially mixed  
 475 regime. When the river discharge increases (i.e. higher  $Fr_f$  values), the vertical stratification  
 476 appears to be stronger, with a sharper pycnocline and a salt-wedge restricted in the lower part of  
 477 the water column.

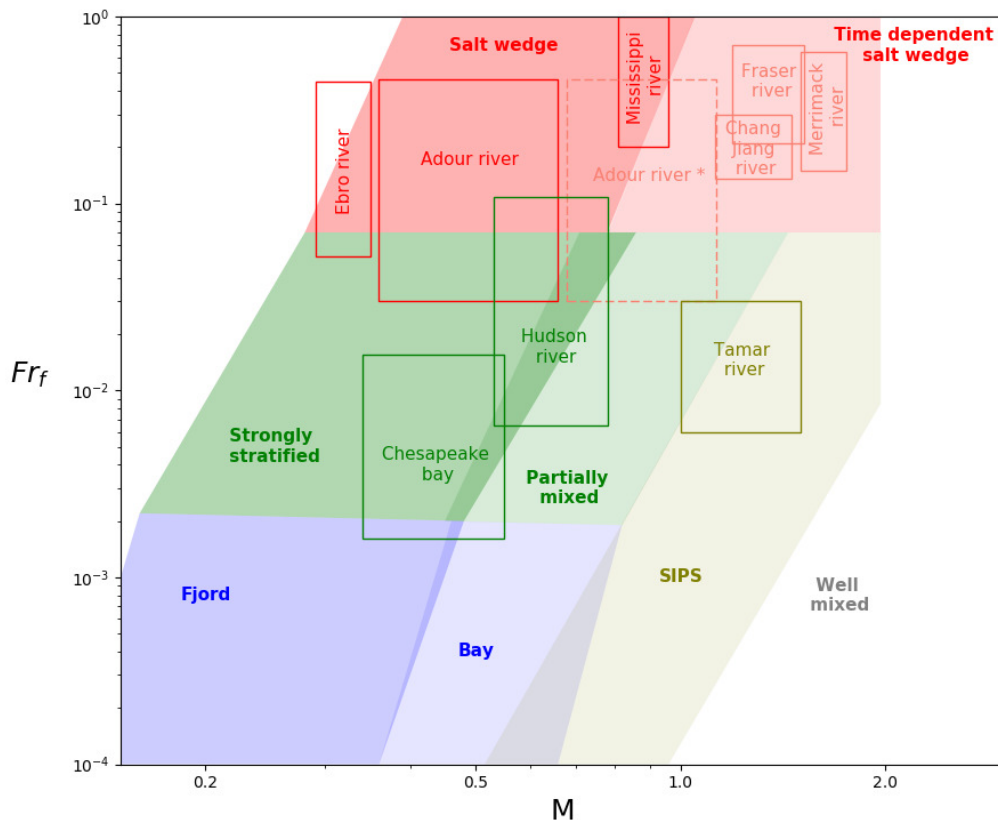


Figure 9: Estuarine classification based on the freshwater Froude number and mixing number, adapted from [21], Fig 6. (\*) The dashed rectangle represent the location of the Adour river using other estimations of  $U_t$  and  $C_D$ .

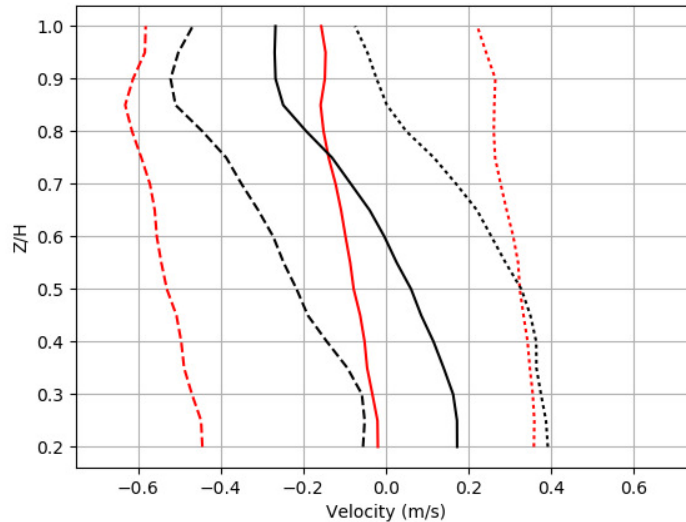


Figure 10: Tidally averaged velocity profiles for neap (full black line) and spring (full red line) tides with low river discharge. Flood (dotted lines) and ebb (dashed lines) average velocity profiles for neap/spring low river discharge conditions. Data from bottom moored station located at BSS location (Fig. 1)

478 The lateral dynamics, which has not been explored in the present data analysis, may play an  
 479 additional important role in the estuarine circulation and salinity structure. Both local curvature of  
 480 the lower estuary and cross-sectional bathymetric gradient are expected to favor a degree of three-  
 481 dimensionality in the estuarine flow structure [31, 44]. This calls for further dedicated experimental  
 482 campaign to better understand the contributions of along-channel and lateral components in mixing  
 483 processes, and their dependencies on tidal range and river discharge.

#### 484 4.2. Suspended sediment dynamics

485 The present study allows to analyse the impacts of physical processes taking place inside the  
 486 Adour estuary on the observed sediment transport. Since the Glangeaud's pioneering description of  
 487 an Estuarine Turbidity Maximum (ETM) in the Gironde estuary in 1938 [22], a series of numerical  
 488 and experimental studies have revealed the importance of ETM in estuarine sediment dynamics  
 489 [4, 27, 55, 6] among others. ETM have strong impacts on the marine and estuarine ecosystems,  
 490 being a major driver of sediments, contaminants and nutrients from continent to ocean. ETM  
 491 formation is primarily driven by the hydrodynamical functioning of the estuary. In salt-wedge  
 492 systems, and in particular in the presence of strong tidal forcing, two key mechanisms have been  
 493 identified in the ETM dynamics: the residual gravitational circulation and the tidal asymmetry.  
 494 Burchard and Baumert [4] demonstrated that tidal asymmetry is of a bigger importance in the  
 495 ETM formation than gravitational circulation in macrotidal salt-wedge estuaries. The gravitational  
 496 circulation plays a part in sustaining and stabilising the ETM mass. In the Charente estuary, which  
 497 shows similarities with the Adour in terms of dimension and salt-wedge regime but with a stronger  
 498 tidal forcing, the tidal asymmetry is mostly responsible for the formation of the turbidity maximum,  
 499 while the density gradient has an influence on its shape and its stratification [52]. More recently,

500 Olabarrieta et al. [36] have highlighted the role of density gradient-driven subtidal flows in the  
501 sediment import and trapping into the estuary associated to near-bed flood tide dominance.

502 Based on the present dataset, no stable ETM has been observed in the lower Adour estuary.  
503 Further insight is provided by analysing the main expected ETM drivers. First, the tidal asymmetry  
504 in the Adour estuary has been studied based on the water elevations collected by tidal gauges  
505 along the estuary. Figure 11 outlines that a slight tidal asymmetry of less than 20 minutes exists  
506 in the lower estuary. Provided time lag appears too weak to generate an ETM when compared  
507 to the Charente estuary, where tidal asymmetry can reach almost 3.8h at the river mouth [52, 51].  
508 A strongest asymmetry can be noticed in the upper part of the estuary (i.e. 20 km upstream at  
509 Urt village). Such mechanism might generate an ETM in this reach of the estuary. Extended  
510 measurements until Urt village or a dedicated numerical study are foreseen as further work to  
511 estimate the impact of this tidal asymmetry on the sediment transport in the upper estuary. The  
512 second ETM driving process is the residual estuarine circulation. In most cases, no residual estuarine  
513 circulation has been observed in the lower estuary. The mean ebbing velocities are stronger than  
514 the mean flooding velocities, resulting in a good flushing of water masses and suspended sediment.  
515 The only exception is observed during very low river flow and tidal forcing conditions, as revealed  
516 by the residual [tidally-averaged](#) velocity profiles depicted in Figure 10, black solid line. In such  
517 conditions, a residual circulation is observed, but its effect in generating a well-developped ETM is  
518 likely compensated by limited resuspension due to reduced velocities. Note however that the bottom  
519 moored current profilers are not able to resolve the bottom 1.5 m (structure size and blanking zone),  
520 which can hide near-bed processes.

521 Moreover, it should be noted that riverine input of sediment is very low compared to other  
522 tidal estuaries, based on SSC obtained in the present conditions. Even during high river discharge,  
523 during the ebb, when the water column is full of fresh riverine waters flowing out the estuary, the  
524 SSC is about  $150 \text{ mg.L}^{-1}$ . This very low supply in sediment even during high river discharge might  
525 be related to the marshy meadows located along the Adour river, which could be responsible for  
526 particle trapping.

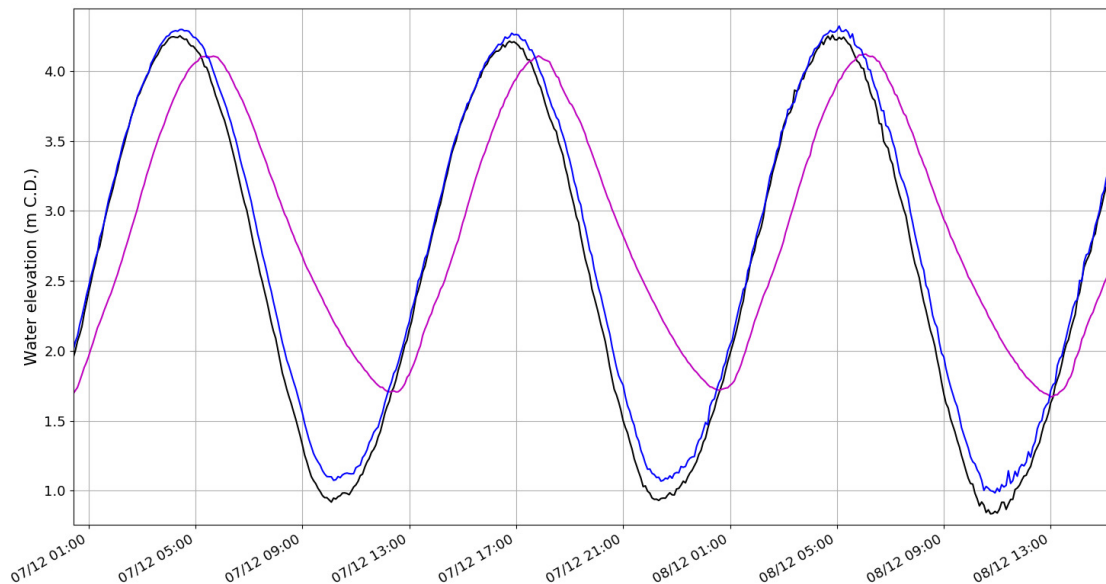


Figure 11: Water elevation data collected at Urt village (22 km from the estuary mouth, in magenta), at Convergent (700 m from the estuary mouth, in black) and Quai de Lesseps (5.6 km from the estuary mouth, in bleu) tide gauges, during spring tide.

527 The observed influence of tidal range on the lower estuary has also a strong effect on the ejected  
 528 plume. At spring tide during the dry season, continental waters are blocked inside the estuary by  
 529 the marine waters entrance for about three hours. This mechanism drives the pulsed behaviour  
 530 of the plume of the Adour estuary already highlighted by Dailloux [8]. By contrast, at neap tide  
 531 during low discharge conditions or under high discharge conditions, a layer of continental water is  
 532 flowing seaward all along the tidal cycle at the top of the water column, almost constantly feeding  
 533 the plume leaving the estuary with fresh water. The pulsed behaviour of the Adour estuary may  
 534 take place only when the tidal forcing is able to overcome the riverine forcing, and so the riverine  
 535 waters are blocked into the estuary by the marine water entrance.

#### 536 4.3. Impacts of engineering works

537 The Adour estuary exhibits a strong variability of salinity, which has never been reported in the  
 538 literature. This is highlighted by direct measurements in a range of conditions and confirmed by  
 539 the Geyer and MacCready classification diagram [21]. Part of the observed variability is directly  
 540 imposed by the fluctuations of the external forcing, i.e. a mesotidal regime associated with seasonal  
 541 variations of river discharge driven by the oceanic climate and the close proximity to the Pyrenées  
 542 mountains. However, such conditions may not entirely explain the observed variability of estuarine  
 543 salinity circulation when comparing the Adour to other systems. It can be hypothesised that the  
 544 artificial channelisation of the lower estuary coupling with strong dredging activities act to enhance  
 545 the fluctuations in hydrological regimes. The Adour estuary is fully artificial since 1578, when the  
 546 mouth of the estuary has been fixed in front of the Bayonne city by diking, under the decision  
 547 of King Charles IX. In 1810, Napoleon decided to reduce the entrance of the estuary to 150 m  
 548 in the aim of protecting the channel from sand accumulation by focusing the ebb energy. For a  
 549 wider lower estuary, which would be likely the case in a more natural context, the  $U_R$  value would



550 consequently decrease and so the  $Fr_f$ . This reduction of river flow velocity should reduce the  
551 stratification within the estuary which should promote the development of strongly stratified or  
552 partially mixed regimes. These engineering works are complemented by dredging activities from  
553 1896. Nowadays, the quantity of sediments to be dredged in the lower estuary per year is about  
554  $525000\text{ m}^3$ . The dredger of  $1200\text{ m}^3$  capacity operates almost everyday, except from June to  
555 September. This is also supposed to have a significant impact on the stratification, by maintaining  
556 the channel deeper. In the absence of dredging, the depth reduction would strengthen the river flow  
557 and decrease the tidal propagation speed, resulting in an enhanced mixing. Following the Geyer  
558 and MacCready classification [21], this would result in an increase of both parameters likely leading  
559 to a more systematic time-dependent salt-wedge regime. Such assumptions can certainly not be  
560 directly assessed from the present or former dataset, and would require prospective scenarios with  
561 dedicated numerical modelling to be further discussed. The potential changes on estuarine salinity  
562 structure might have significant consequences on biogeochemical processes controlled by mixing,  
563 residence time and water properties. Such issues should obviously not only concern the Adour  
564 system and call for a more extensive assessment of the impact of artificialisation and urbanisation  
565 of estuarine systems on the physical processes controlling the hydrodynamics and finally affecting  
566 the entire ecosystem.

567 The question arises then on the role of estuary engineering (channelisation and dredging) on  
568 the absence of observed ETM in the lower reach of the estuary, in particular when compared to  
569 other tidal estuaries. First, the width reduction at the estuary mouth certainly enhances the good  
570 flushing capacity of the lower Adour by reinforcing the ebbing currents. Such hypothesis might be  
571 impossible to confirm due to the lack of available data collected before those engineering works,  
572 a numerical study could be necessary to discuss further this issue. In addition, it is hypothesized  
573 that the artificialization of the river mouth tends to maintain a low marine sediment input, thus  
574 participating to the absence of ETM. At the river mouth, along the Northern jetty, a sand pit has  
575 been artificially created and maintained by dredging operations, in order to avoid sand accumulation  
576 in the estuary entrance under storm conditions. Dubranna's numerical study [11] highlighted that  
577 the transport of sediment from the coastal area into the estuary is strongly limited by this man-  
578 engineered retention pit. Grasso and al [23] have shown the important contribution of energetic wave  
579 conditions to the ETM mass, by sediment resuspension action. However, it has been demonstrated  
580 that both jetties located at the estuary entrance, efficiently protect the port against incoming  
581 swell and sea waves with a reduction factor of 85 % compared to the offshore wave energy [1].  
582 All together, these interventions may also contribute to the absence of ETM in the Adour lower  
583 estuary. Nevertheless, the impacts of the artificialisation of the lower estuary on its hydrodynamics  
584 and sediment transport can not be quantified by the present study, and would require further  
585 investigations.

586 The plume generated by the brackish fresh waters flowing out the estuary is also influenced by  
587 the engineering works at the entrance of the estuary. As already mentioned the width reduction at  
588 the entrance of the estuary might be responsible for an intensification of the plume. In addition,  
589 the Northern jetty also affects the dispersion of the plume orienting the plume in the southwest  
590 direction. Such issue was not part of the scope of this study, however this could be the aim for  
591 additional research. Additional measurements upstream in the Adour estuary would be necessary  
592 to confirm such hypothesis.

## 593 5. Conclusion

594 This study aimed to investigate the hydro-sedimentary behaviour of the lower Adour estuary  
595 by means of field experiments. A series of hydrodynamical processes are documented through  
596 bottom-moored, hull-mounted and vertical profiling instrumentation. It has been shown that its  
597 functioning is strongly influenced by both river and tidal forcing, resulting in a wide range of density  
598 stratification. The stratification variations show different time scales : from flood to ebb tides, from  
599 neap to spring tides, even from dry to wet seasons. It has been demonstrated that stratification is  
600 strengthened during the flood tide and weakened during the ebb tide. During low river discharge,  
601 neap tides promote stable salt-wedge in the lower estuary, while spring tides allow full flushing of  
602 the salt-wedge. On the other hand, wet season has a tendency to constrain the salt-wedge in a thin  
603 bottom layer, enhancing the vertical stratification. This strong variability in the flow structure has  
604 a huge influence on the flushing capacity of the estuary.

605 The tidal evolution of the gradient of Richardson number has revealed the straight influence  
606 of the salinity structure on the turbulent mixing. Flood tide is generally associated with reduced  
607 turbulence production and stable stratification, while ebb tide is characterised by strong turbulent  
608 mixing. Through stratification and mixing characteristics of the Adour estuary, a recent classifica-  
609 tion scheme has been applied to compare it to others salt-wedge estuaries. Based on the Geyer and  
610 MacCready classification [21], the Adour estuary varies from salt-wedge to partially mixed estuary.

611 Density effects, salt-wedge displacement and the competition between stratification and mixing  
612 processes have a strong impact on the suspended matter displacement : longitudinal convergence at  
613 the salt tip, sinking of particles due to stratification induced turbulence damping, and re-suspension  
614 due to the salt-wedge passing. However, both major mechanisms associated with ETM generation  
615 have not been observed in the lower estuary : tidal asymmetry and residual estuarine circulation.

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