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## Fortnightly tidal asymmetry inversions and perspectives on sediment dynamics in a macrotidal estuary (Charente, France)

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### Abstract :

Tidal asymmetry is a phenomenon that characterises estuarine hydrodynamics and has a strong impact on sediment dynamics. Extensive research has been dedicated to studying tidal dynamics in semidiurnal macrotidal estuaries, highlighting several general principles. The ratio of flood to ebb peak velocities and differences in ebb and flood durations are often used to characterise the asymmetry encountered in estuaries.

In the Charente estuary (French Atlantic coast), water surface elevation data obtained using an ADCP (Acoustic Doppler Current Profiler) and a tide gauge show that the duration asymmetry undergoes inversions during the spring-neap tidal cycle. A two-dimensional hydrodynamics model is used to investigate the connection between spring-neap inversions of the tidal asymmetry and the harmonic composition of the tide. Different constituents (M<sub>2</sub>, S<sub>2</sub>, M<sub>4</sub> and MS<sub>4</sub>) are considered at the open boundary. The results show that M<sub>4</sub> and MS<sub>4</sub> play a key role in the occurrence of these inversions. The influence of the morphology is also discussed and modifications of the bathymetry are performed to evaluate its impact. In the Charente estuary, the existence of both externally and internally generated overtides thus results in a spatially and fortnightly variable tidal asymmetry.

The modelled barotropic tidal currents are used to estimate the possible impact on sediment dynamics. The results suggest that asymmetry inversions tend to create sediment accumulation in an intermediate zone between the river mouth and Rochefort, located approximately 20 km upstream.

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## Highlights

► We investigate tidal asymmetry inversions in the Charente estuary. ► Both M4 and MS4 overtides play a key role in duration and velocity asymmetries. ► Overtides are generated externally by interaction with the continental shelf. ► Interaction with the estuarine morphology also generates overtides internally.

**Keywords** : Estuary, Tidal asymmetry, Duration asymmetry, Ebb/flood dominance, Morphology, External/internal overtides, Sediment transport

## 1. Introduction

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Investigating estuarine hydrodynamics is essential to understand these systems. Sanitary and/or economical issues are associated with these areas. At the interface between land and ocean, estuaries are indeed subject to important anthropic pressure. Many activities (such as fisheries, harbours and leisure) are strongly dependent on water quality and

5 on sediment-related issues, such as siltation. Estuarine hydrodynamics and sediment dynamics are greatly determined  
6 by the interaction between the morphology of the area and the forcing variables, such as the river discharge and the  
7 tide. The resulting sediment transport and siltation can then provoke morphological changes that modify the estuarine  
8 dynamics. Understanding the constant interactions between the morphology and the hydro-sedimentary dynamics of  
9 estuaries is thus crucial to the management of these systems.

10 Although general principles can be deduced from the numerous studies conducted on estuarine hydrodynamics,  
11 each system has its peculiarities. This work focuses on the tidal asymmetry observed in the Charente estuary (Fig.  
12 1). In this paper, we address tidal asymmetry in terms of duration (difference between ebb and flood durations) and  
13 peak velocity (ratio of flood to ebb peak velocities). Tidal distortion is commonly observed in estuaries, and it has  
14 been the object of many studies (Aubrey and Speer, 1985; Bolle et al., 2010; Dronkers, 1986; Fortunato and Oliveira,  
15 2005; Friedrichs and Aubrey, 1988; Prandle, 2003). Depending on several characteristics (bathymetry, geometry and  
16 tidal regime), estuaries can be ebb-dominant if the ebb peak velocity is higher than the flood peak velocity, or flood-  
17 dominant in the opposite case. Duration asymmetry can be associated with these dominances with shorter falling tides  
18 for ebb dominance (or rising tides for flood dominance), particularly if the mean water depth is greater than the tidal  
19 range.

20 This asymmetry not only characterises the hydrodynamics of the system, but also impacts the sediment dynamics.  
21 Current velocities have a direct impact on the bed shear stress, which is one of the control parameters for erosion  
22 processes, with the nature and state of the sedimentary bed (Mehta and Parchure, 2000; Tolhurst et al., 2000). Conse-  
23 quently, ebb or flood dominance is often completed by a dominance in terms of net sediment transport (Aubrey and  
24 Speer, 1985; Dronkers, 1986; Friedrichs and Aubrey, 1988; Fry and Aubrey, 1990). Ebb-dominated estuaries tend to  
25 export sediment, whereas flood-dominated estuaries generate upstream sediment transport (Allen et al., 1980; Dyer,  
26 1997). On a long-term scale, sediment export or import could lead to morphological changes of sufficient importance  
27 to change the tidal asymmetry dominance (Dyer, 1997). Tidal asymmetry is also a driving mechanism controlling the  
28 formation and dynamics of the turbidity maximum in macrotidal estuaries (Allen et al., 1980). MacCready and Geyer  
29 (2010) investigated tidal asymmetry in vertical mixing, and the effect of the baroclinic pressure gradient. This phe-  
30 nomenon is not discussed in this paper, because a 2D vertically averaged model is used in the present work. Given the  
31 mixing conditions and the shallow depths in the Charente estuary, this approximation was considered to be adequate  
32 for the study proposed here.

33 Nonlinear interactions between the tide and the estuary provoke the growth of harmonics and compound tides of  
34 the main astronomical tidal constituents. Friedrichs and Aubrey (1988) studied the interaction between the M2 and  
35 M4 harmonic constituents of the tide to determine the direction of the asymmetry (flood- or ebb-dominated) and the  
36 degree of tidal distortion. Shorter rising tides correspond to a relative sea surface phase ( $2\varphi_{M2} - \varphi_{M4}$ ) between  $0^\circ$  and  
37  $180^\circ$ . For shorter falling tides, the relative phase is between  $180^\circ$  and  $360^\circ$ . The degree of tidal distortion caused by the  
38 estuary is indicated by the ratio of the two constituents' amplitudes ( $a_{M4}/a_{M2}$ ). The same parameters can be calculated  
39 for the velocity to provide an indication in terms of ebb/flood dominance. In a study by Friedrichs and Aubrey (1988),

40 shorter falling tides correspond to ebb dominance, and shorter rising tides to flood dominance. The estuaries or inlets  
41 used in their study are mostly short (18 km maximum), and the geometry of the model inlet is rectangular. Thus, the  
42 parameters indicated above may not apply to all estuarine systems.

43 Non-linear tidal distortion is determined by two effects related to the estuary's morphological characteristics: (1)  
44 the frictional effects of the interaction between the tidal currents and the channel bottom, and (2) intertidal storage  
45 occurring in the presence of tidal flats or marshes (Boon and Byrne, 1981; Speer and Aubrey, 1985; Friedrichs and  
46 Aubrey, 1988; Speer et al., 1991). To evaluate the impact of the frictional effects, the ratio of the M2 offshore  
47 amplitude and the channel depth at mean sea level ( $a/h$ ) can be calculated (Speer and Aubrey, 1985; Friedrichs and  
48 Aubrey, 1988). This ratio gives an indication of the relative shallowness of the estuary (Speer et al., 1991). If  $a/h$  is  
49 greater than 0.3, the frictional influence is greater at low water than at high water, causing flood dominance (Speer  
50 and Aubrey, 1985). The water level propagation is slowed at low water, leading to shorter rising tides and greater  
51 flood velocities. If  $a/h$  is less than 0.2, the channels are deep compared to the degree of asymmetry, the estuary is  
52 expected to be ebb-dominant (Friedrichs and Aubrey, 1988), ebb duration is shorter, and ebb velocities are usually  
53 stronger. For intermediate values of  $a/h$ , the system can be flood- or ebb- dominated, depending on the intertidal  
54 storage (Friedrichs and Aubrey, 1988). The intertidal storage effect is evaluated by calculating the ratio of the water  
55 volume stored between high and low water in intertidal areas, divided by the channel volume of water at mean sea  
56 level ( $V_s/V_c$ ) (Friedrichs and Aubrey, 1988). When  $V_s/V_c$  is large in relation to  $a/h$ , the intertidal area is sufficiently  
57 large to slow the propagation of high water, causing longer flood durations and greater ebb velocities.

58 Many examples of flood-dominated systems can be found in the literature: Nauset Inlet, USA (Aubrey and Speer,  
59 1985); Gironde estuary, France (Castaing and Allen, 1981); and Mandovi and Zuari estuaries, India (Manoj et al.,  
60 2009). Ebb-dominated systems are also represented throughout the world: Dyfi estuary, UK (Brown and Davies,  
61 2010); Johor estuary, Malaysia (Hasan et al., 2013); and Okatee Creek, USA (Huang et al., 2008). Ebb-dominant  
62 and flood-dominant channels can also be observed in estuaries (Yangtze, China (Wang et al., 2008)). All these sys-  
63 tems show no clear fortnightly dependent asymmetry inversions. Boon (1988) and Wang et al. (1999) have shown  
64 that spring-neap variability can modulate the amplitude ratio between M2 and M4 and the phase difference. Their  
65 results suggest that inversions following the spring-neap tidal cycle could occur, based on the evolution of the phase  
66 difference. They also showed that asymmetry is enhanced during spring tides. However, these studies do not show  
67 actual inversions in the sense of ebb and flood durations or peak velocities. It is therefore difficult to conclude whether  
68 systematic fortnightly asymmetry inversions occur in other coastal systems.

69 A large reduction of the cross-sectional area of the channel at the entrance of a bay can provoke a long-term  
70 asymmetry inversion from ebb to flood dominance (Boon and Byrne, 1981). In contrast, a weakly flood-dominant  
71 estuary could become ebb-dominant, due to the large import of sediment associated with strong flood currents, leading  
72 to an increase in the intertidal flats area (Boon and Byrne, 1981; Friedrichs and Aubrey, 1988; Speer and Aubrey,  
73 1985). Along the border between Belgium and the Netherlands, deepening of the channels caused by dredging in  
74 the Scheldt estuary also caused a reduction in flood dominance, and an evolution towards ebb dominance (Bolle

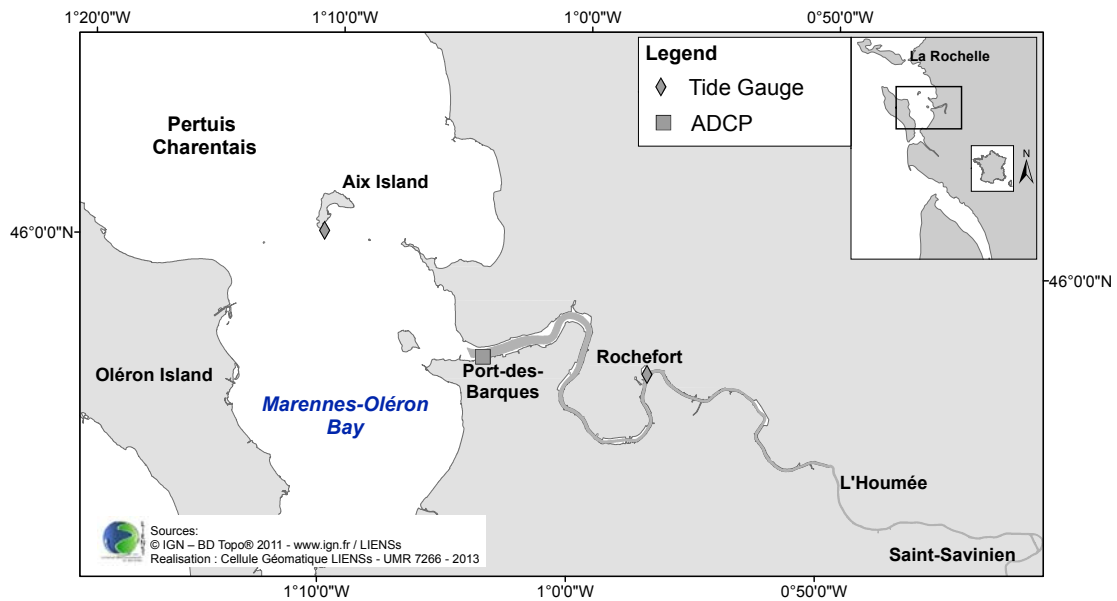


Figure 1: Charente River, from the Saint-Savinien dam to the mouth.

75 et al., 2010). Spring-neap asymmetry alternation has also been observed in the Skagit River (Nidziedo and Ralston,  
 76 2012) and the Murray Mouth coastal lagoon (Jewell et al., 2012), both of which are under the influence of mixed  
 77 diurnal/semidiurnal tides.

78 These inversions are all consequences of significant long-term changes in estuarine characteristics or a mixed tidal  
 79 regime, which is not the case in the Charente estuary. The objective of this study is to understand the tidal dynamics  
 80 encountered in the area, that are leading to short-term inversions of the tidal asymmetry. The impact on barotropic  
 81 tidal currents is investigated, and possible effects on sediment dynamics are discussed. In situ measurements and the  
 82 MARS-3D hydrodynamic model (Lazure and Dumas, 2008) are used for this purpose.

## 83 2. Study site

84 The French Atlantic Coast is under the influence of a semidiurnal tide. The Charente estuary (45°96'N, 1°00'W  
 85 ; Fig. 1), located to the south of La Rochelle (France) is small, shallow and characterised by the presence of large  
 86 intertidal flats (Fig. 2b). The river flows into the Marennes-Oléron Bay, in the southern part of the Pertuis Charentais.

87 The bay's total surface is approximately 150 km<sup>2</sup>, with 60% composed of intertidal areas. The sediments in the  
 88 estuary and in the eastern part of the Marennes-Oléron Bay are exclusively cohesive, with a very fine grain size (Strady  
 89 et al., 2011). In the western part of the bay, the sediments are sandier (Tesson, 1973; Bertin et al., 2005).

90 The Charente tidal regime is macrotidal, with mean and maximum tidal ranges of 4.5 metres and 6.5 metres,

91 respectively. The mean river discharge is  $70 \text{ m}^3/\text{s}$ . The lowest values are less than  $10 \text{ m}^3/\text{s}$  and floods can reach 600-  
92  $700 \text{ m}^3/\text{s}$ . The river catchment area is  $10,000 \text{ km}^2$  and the river length is 365 km. A dam is located at Saint-Savinien,  
93 50 km from the river mouth. This dam regulates the river discharge to avoid flooding and ensure the distribution of  
94 freshwater to the surrounding marshes and cultures.

95 The river is connected to the Marennes-Oléron Bay, in which the tide is already distorted. By applying a modified  
96 version of the Battisti and Clarke (1982) theory to the Bay of Biscay shelf, Le Cann (1990) showed that the quarter-  
97 diurnal tidal constituents (M4, MS4 and MN4) are strongly amplified shoreward, because of resonance occurring on  
98 the shelf. This behaviour was verified numerically by Bertin et al. (2012), who showed that the largest amplification  
99 by resonance occurred for MS4.

100 Water quality within the estuary represents a very important issue, because the Charente River is a source of fresh  
101 drinking water for the area. Extensive oyster farming in the Marennes-Oléron Bay and leisure activities are also  
102 strongly dependent on the Charente water quality and water level. According to Ravail et al. (1988), in summer, 90%  
103 of the freshwater input in the bay comes from the Charente river.

### 104 **3. Materials and methods**

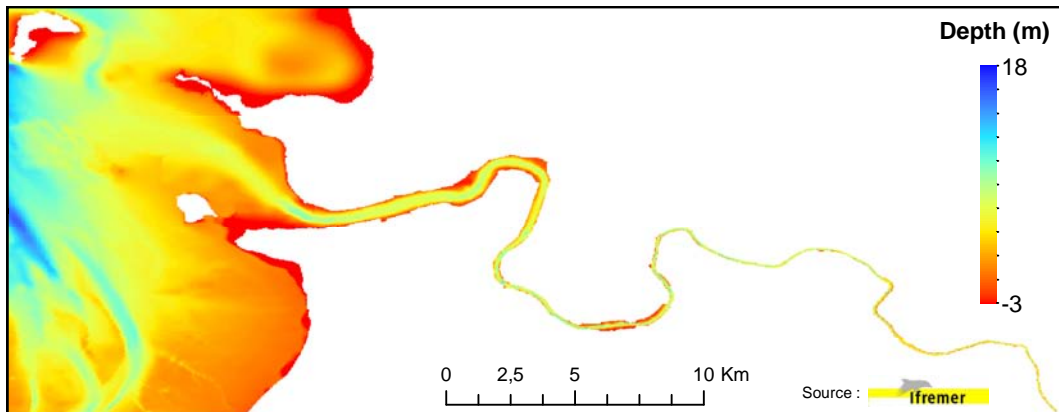
#### 105 *3.1. Numerical modelling*

106 The MARS-3D (Model for Applications at Regional Scale) numerical model used in this study was fully described  
107 by Lazure and Dumas (2008). MARS-3D is a finite differences model that, when run in 2D, resolves the shallow water  
108 (or Saint-Venant) equations.

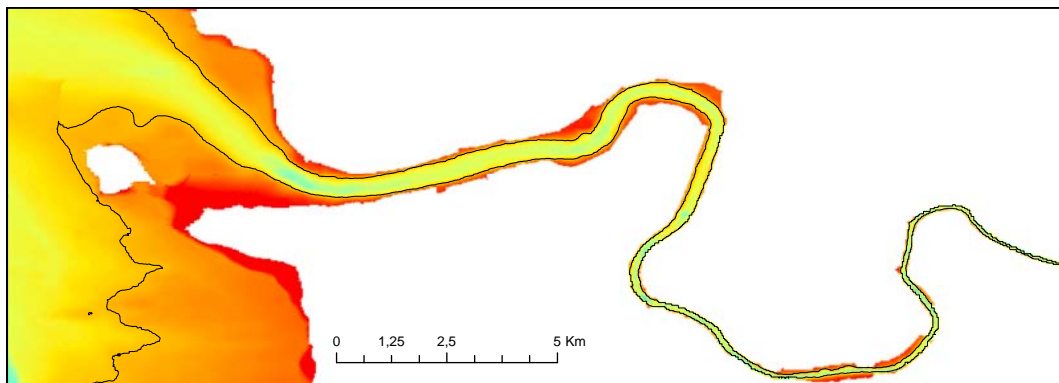
109 MARS-3D was used to determine the behaviour of the estuary in response to different hydrodynamic conditions.  
110 In particular, the effect of the harmonic composition of the tide at the boundaries was investigated.

111 A 2D configuration was developed to determine the impact of the tidal harmonic composition. Only the tide,  
112 computed from the SHOM CST-France model (Le Roy and Simon, 2003), and the actual daily river discharge were  
113 considered for the open boundary conditions. To specifically determine the impact of the harmonic composition of  
114 the tide, no atmospheric forcing was considered for this configuration. The roughness length was set at a relatively  
115 low value (0.1 mm), to represent accurately the variations of current velocities and water level. Indeed, the presence  
116 of fluid mud in the estuary tends to reduce friction and favour tidal propagation. The horizontal grid resolution is  
117 30m (1405 x 766 grid points). Bathymetric datasets from 2003, 2007 and 2010 (Fig. 2a) were provided by several  
118 organizations (SHOM, Ifremer and EPTB Charente). Fig 2b shows only the bathymetry in the downstream part of the  
119 estuary, with the 2 metres below the mean sea level isobath displayed in black. With a mean tidal range of 4.5 meters,  
120 this figure shows the intertidal areas that are alternatively exposed and submerged most of the time.

121 Four configurations are used for this study, corresponding to four different harmonic compositions of the tide at  
122 the system's open boundaries (Table 1). For each case, elevations are determined from the SHOM CST-France model  
123 with the harmonic composition considered. Nesting is not used here.



(a) Bathymetric data used for numerical modelling.



(b) Bathymetry in the downstream part of the Charente River. Dark line: isobath at 2 metres below the mean sea level.

Figure 2: Bathymetry of the Charente estuary.

124 N2 is not prescribed at the offshore boundary. This choice was justified by a test in which N2 was added (data not  
 125 shown); the results showed no significant differences from the tidal asymmetry behaviour obtained in configuration D  
 126 of this study.

### 127 3.2. *In situ measurements*

128 Fixed ADCP measurements (Sentinel-RDI, 1200 kHz, 5-minute sampling frequency) were performed in 2011  
 129 (from February 11 to April 8) at the mouth of the estuary, close to Port-des-Barques (Fig. 1). Tide gauge recordings  
 130 are available at Rochefort and at Aix Island. For this period, the river discharge corresponds to average conditions and  
 131 does not vary significantly (50 to 65  $m^3/s$ ). With these discharges, the estuarine Richardson number (Fischer, 1972)  
 132 ranges from 0.02 to 0.64, corresponding to well-mixed to partially mixed conditions. Highly stratified conditions  
 133 occur for a very high river discharge and during neap tides. Depth was corrected using a Demerliac filter, to compare  
 134 the data to the water levels obtained from the model without atmospheric forcing. Due to the ADCP emersion during  
 135 low waters of spring tides, comparisons with velocities are not available.

Table 1: Model configurations

Configuration	A	B	C	D
Semi-diurnal constituents	M2	M2,S2	M2,S2	M2,S2
Quarter-diurnal constituents	-	-	M4	M4,MS4

136 **4. Results: data and numerical analysis**

137 *4.1. Observations*

138 Water levels and durations of ebb and flood were obtained from ADCP measurements at the mouth, and from  
 139 tide gauge recordings at Rochefort (Fig. 3). Ebb durations correspond to the time between a water level maximum  
 140 and its following minimum. The time between a water level minimum and its following maximum gives the flood  
 141 duration. The dots representing these durations are plotted above the corresponding water level variations at each  
 142 location. Dashed lines indicate the duration asymmetry inversions.

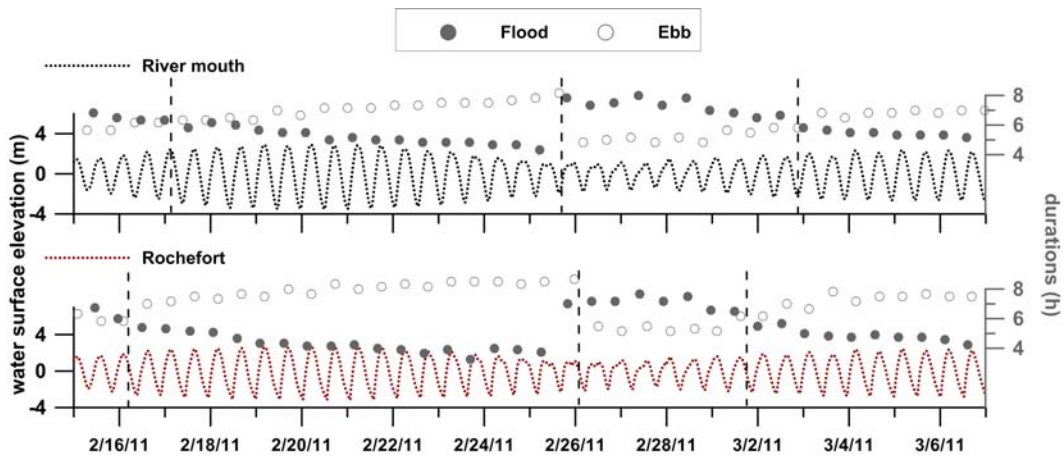


Figure 3: Surface elevation (left) and ebb and flood durations (right) at the river mouth (top) and Rochefort (bottom).

143 Inversion from a shorter flood to a shorter ebb occurs almost simultaneously at both locations: approximately at  
 144 the beginning of neap tides (February, 25 to 26). Inversion from a shorter ebb to a shorter flood occurs earlier during  
 145 neap tides at Rochefort. The level of distortion also differs between the two areas. When the flood is the shortest  
 146 (between February 16 and February 26), the difference in durations is much greater at Rochefort (up to 4.8 hours)  
 147 than at the river mouth (3.8 hours). In contrast, when the ebb is the shortest (between February 26 and March 2),  
 148 the maximum difference in durations occurs at the river mouth (up to 3.2 hours), compared to 2.5 hours at Rochefort.  
 149 Based on the tide gauge measurements at Rochefort, these inversions, in terms of durations, occur for a large set of  
 150 river discharges, suggesting that baroclinic effects are not preponderant in this case.



151 *4.2. Analytical analysis*

152 The amplitudes and phases of the principal tidal constituents at Aix Island are summarised in Table 2. These  
 153 results were obtained from a 419-day harmonic analysis performed using T.Tide (Pawlowicz et al., 2002). Given  
 154 the proximity of Aix Island to the estuary (approximately 5 km), the results are considered representative of the  
 155 tidal dynamics at the mouth. According to Friedrichs and Aubrey (1988), the relative sea surface phase  $2\varphi_{M2} -$   
 156  $\varphi_{M4}$  is  $188.36^\circ$  and the amplitude ratio  $a_{M4}/a_{M2}$  is 0.14, suggesting that the ebb should be shorter in this area (Table  
 157 2). However, these calculations should be treated with caution as the geometry (funnel-shaped) and length (50 km  
 158 between the mouth and the Saint-Savinien dam) of the Charente estuary differ from the setting used by Friedrichs and  
 159 Aubrey (1988) (rectangular and short).

Table 2: Amplitudes and phases of the main tidal harmonic constituents (Aix Island)

Harmonic constituents	Amplitude (cm)	Phase (deg)
M2	179.80	97.41
S2	64.32	130.78
N2	37.62	77.99
M4	25.44	6.46
MS4	9.27	98.41

160 Considering the geometric and tidal characteristics of the area, the two dimensionless parameters  $a/h$  and  $V_s/V_c$   
 161 were also calculated. At the Charente River mouth,  $a/h$  is evaluated at 0.23, with an M2 offshore amplitude of  
 162 1.75 metres and an average channel depth of 7.6 metres. This  $a/h$  value is insufficient to form conclusions about the  
 163 asymmetry dominance encountered. The intertidal storage ratio ( $V_s/V_c$ ) is estimated at 1, which is large in comparison  
 164 to  $a/h$ . These results suggest again that the tidal response of the estuary should be ebb-dominant. However, based  
 165 on the in situ measurements at the river mouth presented in the previous paragraph, it appears that in the Charente  
 166 estuary, the tidal asymmetry follows the spring-neap tidal cycle. The flood is shorter than the ebb during spring tides,  
 167 and the opposite occurs during neap tides. These short-term inversions are observed systematically, and the level of  
 168 distortion is modulated by the river flow and the tidal range.

169 *4.3. Numerical analysis*

170 To evaluate the impact of each component on the tidal asymmetry observed in the estuary, the results obtained  
 171 from numerical modelling are compared using two criteria: ebb/flood durations and maximum ebb/flood velocities.  
 172 No comparison of the absolute water surface level is performed because the objective is to study the distortion of the  
 173 wave, and critical constituents needed to more precisely reproduce its variations are missing. However, comparisons of  
 174 the modelled (configuration D) and observed amplitudes and phases of the main constituents considered are presented  
 175 in Table 3.

Table 3: Observed and modelled tidal amplitudes and phases of the main constituents at Aix Island

Constituent		M2	S2	M4	MS4
Amplitude (cm)	Model	177.5	62.50	25.60	10.23
	Data	179.8	64.32	25.44	9.27
	Difference	2.3	1.82	0.16	0.96
Phase (deg)	Model	96.95	129.95	10.38	103.82
	Data	97.41	130.78	6.46	98.41
	Difference	0.46	0.83	3.92	5.41

176 These comparisons are not performed between the ADCP data and the modelled results at the mouth because the  
 177 classical tools used for harmonic analysis appear to be unsuited for the Charente estuary. The results show that the  
 178 amplitudes and phases of the quarter-diurnal constituents may change over time, which is likely due to the highly  
 179 variable geometry of the flow section, with certain areas being inundated only during strong spring tides. In this  
 180 context, wavelet analysis represents a possible solution to this issue (Flinchem and Jay, 2000; Grinsted et al., 2004).  
 181 Such an analysis should be considered for further research but is beyond the scope of this study.

182 The numerical model can also be validated by comparing water surface elevations to the ADCP measurements  
 183 (Port-des-Barques, Fig. 1) and tide gauge recordings (Rochefort). The current velocities obtained with the ADCP are  
 184 averaged over the water column for comparison with the modelled barotropic velocities. For this validation, all 114  
 185 harmonic constituents available in CST-France are prescribed at the boundary. The mean absolute errors (MAE) and  
 186 root mean square errors (RMSE) are calculated, in addition to a skill parameter (Equation 1), developed by Willmott  
 187 (1981). This dimensionless parameter has been used in several estuarine studies (Li et al., 2005; Ma et al., 2011; Xing  
 188 et al., 2012) to estimate their model's accuracy. A perfect agreement between model and observations corresponds to  
 189 skill = 1.

$$Skill = 1 - \frac{\sum |X_{mod} - X_{obs}|^2}{\sum (|X_{mod} - \bar{X}_{obs}| + |X_{obs} - \bar{X}_{obs}|)^2} \quad (1)$$

190 The results show a good agreement between the modelled and observed water levels (Fig. 4). The skill parameter  
 191 is 0.980 at Rochefort and 0.997 at the river mouth (Port-des-Barques). The RMSE and MAE values are 17.6 and 14.0  
 192 cm at the mouth and 38.7 and 33.2 cm at Rochefort, respectively. When compared to the mean tidal range, these  
 193 errors are all less than 9 %. Errors on current velocities are calculated along the longitudinal (U) and meridional (V)  
 194 directions. Skills are greater than 0.9 for both U and V, with RMSEs of 14.9 and 10.2 cm/s.

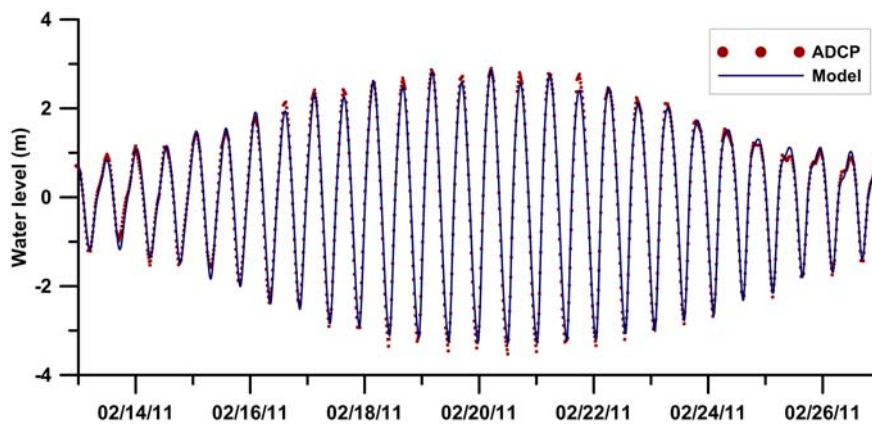


Figure 4: Comparison between modelled and observed water levels at the river mouth (Port-des-Barques)

#### 195 4.3.1. Duration asymmetry

196 Water surface elevations at the mouth over a full spring-neap tidal cycle are obtained for each configuration (Fig. 5)  
 197 and the corresponding ebb and flood durations are presented. Asymmetry inversions are indicated by dashed vertical  
 198 lines. Configurations A and B show almost no asymmetry inversion, with differences between ebb and flood durations  
 199 below 0.5 and 0.78 hours, respectively. Adding M4 to the harmonic composition at the open boundary leads to an  
 200 asymmetry inversion on February 27, the precise day of the lowest tidal range. The maximum difference between the  
 201 ebb and flood durations is 2.5 hours for spring tides and -2.25 hours for neap tides. A second inversion from a shorter  
 202 ebb to a shorter flood occurs on March 4, as the tidal range is increasing. If MS4 is considered (in configuration D),  
 203 both inversions occur sooner and the maximum (ebb-flood) duration reaches 2.5 hours during spring tides, compared  
 204 with 2 hours during neap tides.

205 At the upstream station, Rochefort (Fig. 1), the first difference is the response of the system to the basic con-  
 206 figuration A (Fig. 6). When the tide is almost undistorted at the mouth, it is clear at Rochefort that an M2 incident  
 207 tide induces a shorter flood (flood-ebb duration up to 2 hours). Configuration B produces the same type of results  
 208 but with the modulation of the spring-neap tidal cycle, the level of distortion being stronger for high tidal ranges.  
 209 Configurations C and D reproduce the asymmetry inversions observed at the mouth. However, ebbs are only shorter  
 210 than floods by one hour maximum during neap tides, compared to a maximum duration difference of 4 hours during  
 211 spring tides (when the flood is the shortest). When compared to the results at the mouth, the period during which ebbs  
 212 are the shortest is also decreased by more than two days (Fig. 5).

213 Regarding the duration asymmetry, the mouth appears to be driven by an alternation between periods of shorter  
 214 floods and shorter ebbs, with comparable levels of distortion. In contrast, the area of Rochefort is largely characterised  
 215 by shorter floods. During neap tides, floods are only slightly longer than ebbs, and for a brief period of time.

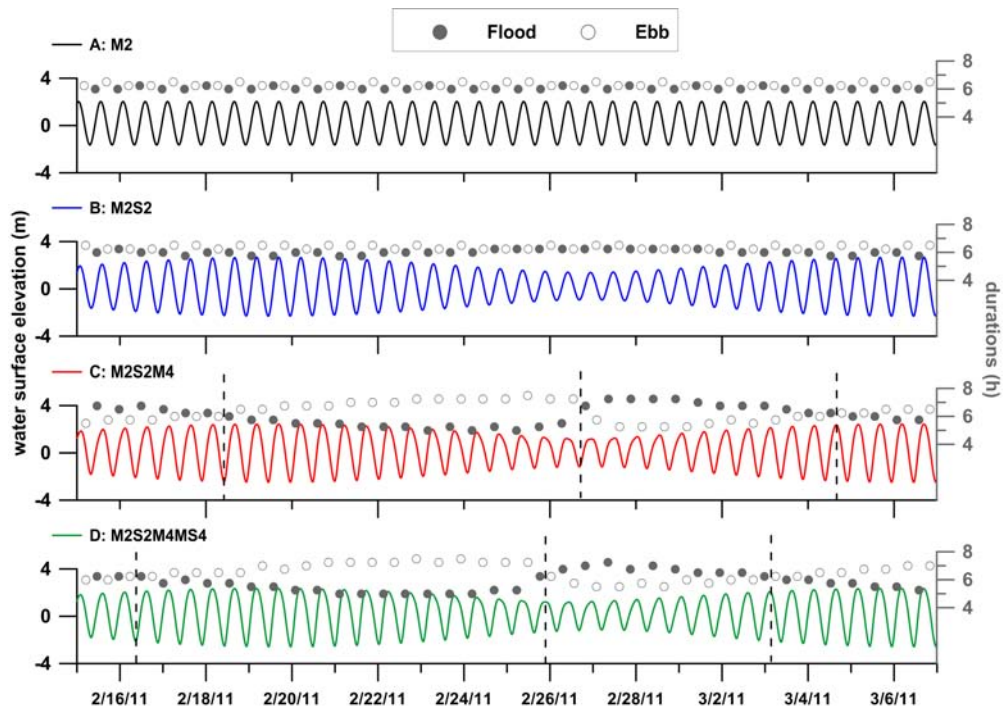


Figure 5: River mouth: water surface elevation (left) and ebb and flood durations (right) for each harmonic composition of the tide at the model boundary.

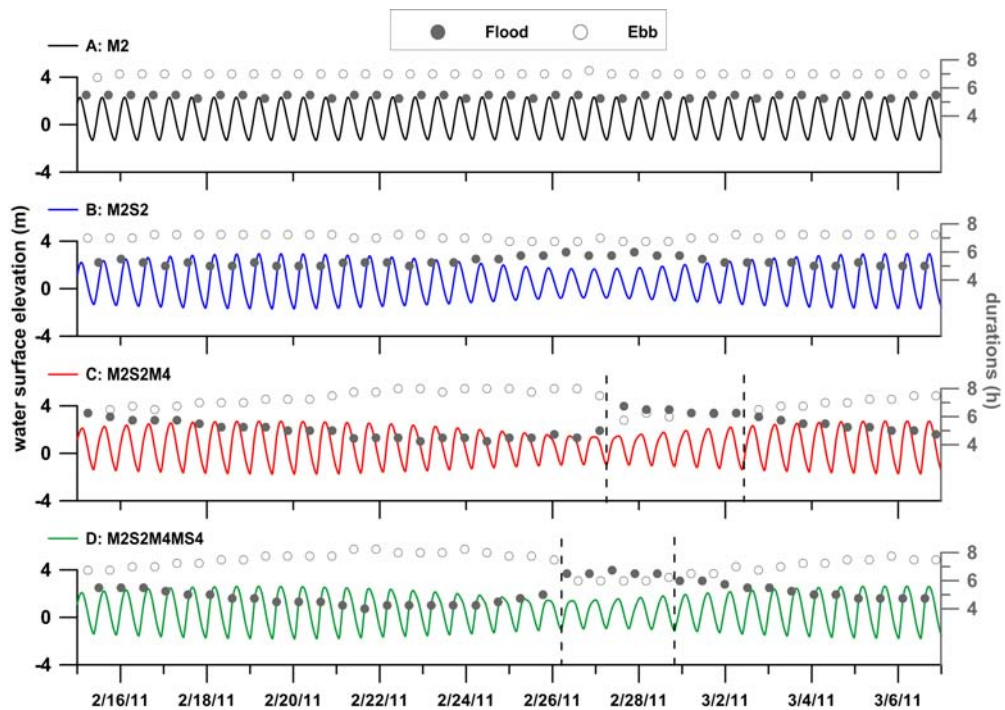


Figure 6: Rochefort: water surface elevation (left) and ebb and flood durations (right) for each harmonic composition of the tide at the model boundary.

216 4.3.2. Barotropic velocity asymmetry

217 Tidal asymmetry in ebb and flood durations can be associated with an asymmetry in current velocities, causing  
 218 shorter rising tides and longer falling tides to be combined with stronger flood currents and weaker ebb currents. In  
 219 the opposite case (shorter falling tides), ebb currents are expected to be stronger. Figs. 7 and 8 present the same water  
 220 level series as in Figs. 5 and 6, but with the addition of the ratio of the maximum flood velocity to the maximum ebb  
 221 velocity.

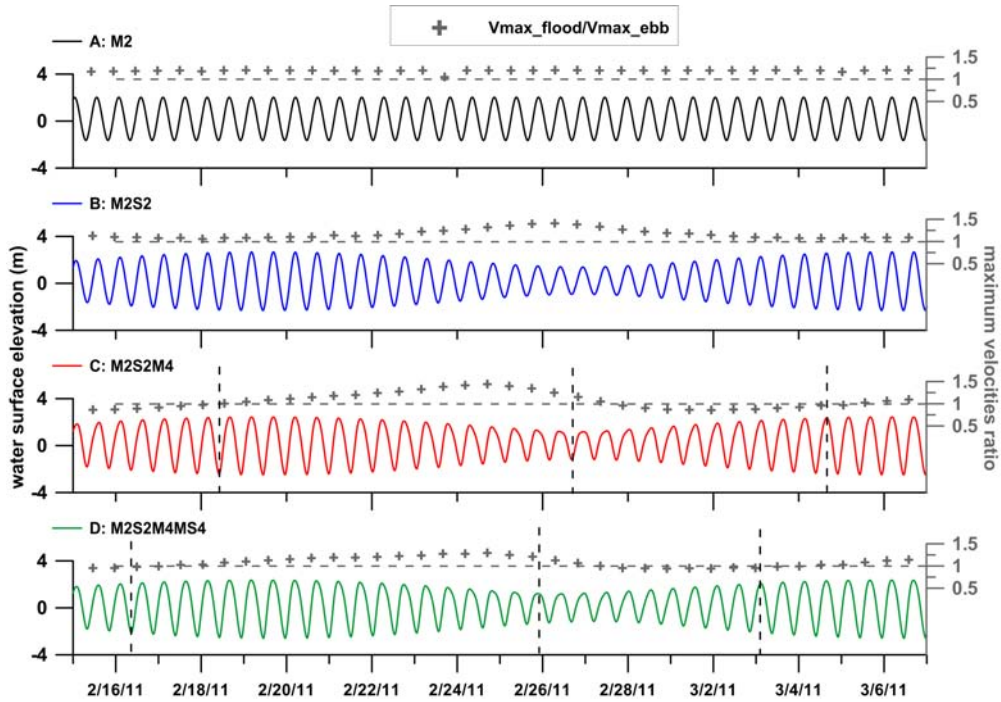


Figure 7: River mouth: water surface elevation (left) and velocity ratio  $V_{max_{flood}}/V_{max_{ebb}}$  (right).

222 A peak velocities ratio greater than 1 signifies that flood currents are stronger than ebb currents, indicating flood  
 223 dominance. Ebb dominance occurs for a velocities ratio less than one. Dashed lines mark the asymmetry inversions  
 224 observed with ebb and flood durations in the previous section. At the river mouth, the velocities ratio largely follows  
 225 the same pattern as the duration asymmetry. Configuration A shows a constant slight flood dominance. Configuration  
 226 B shows almost no asymmetry during spring tides, and flood dominance during neap tides. The quarter-diurnal  
 227 constituents are considered in configurations C and D ; thus, asymmetry inversions that are almost in phase with  
 228 duration asymmetry inversions are observed. However, when duration asymmetries are almost equivalent between  
 229 ebb and flood dominance, velocity asymmetry is much stronger for flood dominance than it is for ebb dominance.

230 At Rochefort, the velocity asymmetry is ebb-dominated for the simplest M2 tidal forcing, whereas duration asym-  
 231 metry is flood-dominated (Fig. 6). The same opposition is obtained for the M2,S2 tidal forcing, with a stronger ebb  
 232 dominance during neap tides. As in the previous paragraph, configurations C and D show velocity asymmetry inver-  
 233 sions but with higher phase differences compared with the duration asymmetries. Moreover, ebb dominance during

234 neap tides is stronger than flood dominance during spring tides, in contrast to the results at the river mouth.

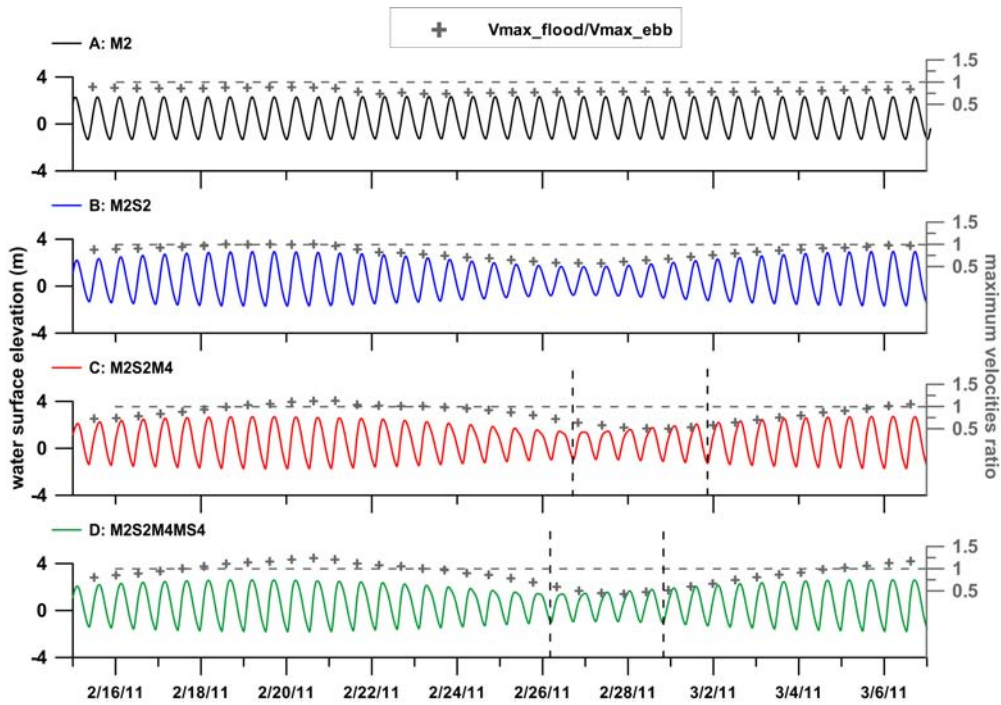


Figure 8: Rochefort: water surface elevation (left) and velocity ratio  $V_{max_{flood}}/V_{max_{ebb}}$  (right).

235 *4.3.3. Summary and comparison with measurements*

236 The best agreement with the ADCP data is observed with the last configuration (M2, S2, M4 and MS4 tidal  
237 forcing), although differences remain for the exact moments of inversion.

238 The calculated ebb/flood durations and flood/ebb maximum velocities at the two locations are presented in Table  
239 4. The difference between the values calculated and 1 (corresponding to a symmetric tide) gives an indication of the  
240 degree of tidal distortion. In the following paragraphs, the ebb/flood durations ratios and flood/ebb peak velocities  
241 ratios will be abbreviated DR and PVR, respectively.

242 At the mouth, the duration asymmetries are of the same order of magnitude, and display a good agreement with the  
243 ADCP data. Both the duration and velocity asymmetries are greater for shorter floods/flood dominance: the maximum  
244 DRs (1.5 for configuration D) and the maximum PVRs (1.3) are more distant from 1 than the minimum DRs (0.72)  
245 and the minimum PVRs (0.92).

246 The Rochefort area is characterised by a contrast between duration and velocity asymmetries. The duration asym-  
247 metries show a stronger duration difference when the flood is the shortest, which is confirmed by calculations per-  
248 formed with tide gauge data: the maximum DR is 2.32, compared to a minimum of 0.67. In contrast, the PVRs show a  
249 stronger ebb dominance: for configuration D, the minimum PVR is 0.43, compared to a maximum PVR of 1.38. This  
250 result is largely explained by the presence of intertidal flats in the area, which constrain the ebb flow for low water

Table 4: Dimensionless parameters used to characterise the tidal asymmetry at the river mouth and at Rochefort, for all model configurations

River mouth					
Configuration	A	B	C	D	ADCP data
Harmonics	M2	M2,S2	M2,S2,M4	M2,S2,M4,MS4	
Minimum ebb/flood durations ratio	1	0.89	0.7	0.72	0.6
Maximum ebb/flood durations ratio	1.08	1.14	1.5	1.5	1.88
Minimum flood/ebb peak velocities ratio	1.1	1.05	0.83	0.92	-
Maximum flood/ebb peak velocities ratio	1.21	1.41	1.44	1.3	-
Rochefort					
Configuration	A	B	C	D	Tide Gauge data
Harmonics	M2	M2,S2	M2,S2,M4	M2,S2,M4,MS4	
Minimum ebb/flood durations ratio	1.23	1.04	0.85	0.85	0.67
Maximum ebb/flood durations ratio	1.38	1.45	1.88	2.06	2.32
Minimum flood/ebb peak velocities ratio	0.74	0.58	0.5	0.43	-
Maximum flood/ebb peak velocities ratio	0.89	1	1.15	1.24	-

251 levels. The maximum flood velocity is reached between 1.5 and 2 hours after the beginning the flood, compared to  
 252 3.5-5 hours for the maximum ebb velocity. During spring tides, even if the flood duration is shorter, the ebb currents  
 253 are then equivalent or stronger than the flood currents (Fig. 9, left) because the flow is limited to the channel when the  
 254 water level drops. During neap tides (Fig. 9, right), tidal flats slow the flood tide when the water level reaches their  
 255 height: friction induces a decrease in flood velocities.

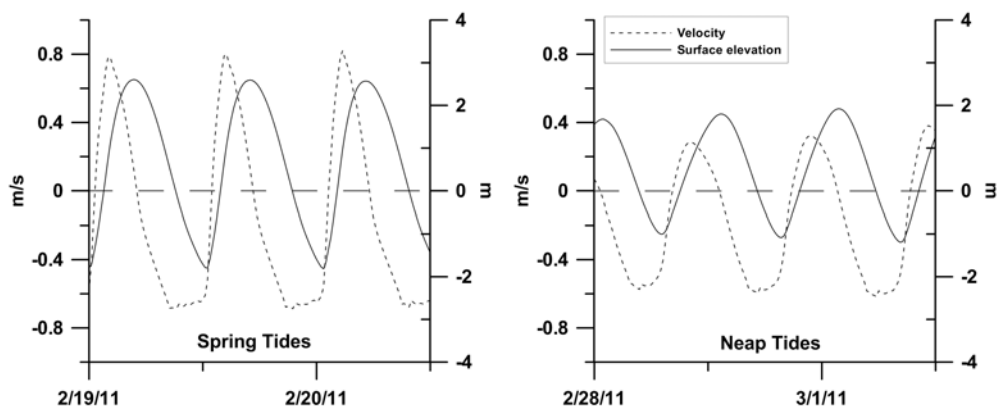


Figure 9: Current velocity (positive: flood, negative: ebb) and water surface elevation at Rochefort for spring (left) and neap tides (right).



## 256 5. Discussion

257 The results obtained from both observations and numerical modelling show that the spring-neap tidal cycle and  
258 the localisation greatly impact the tidal asymmetry observed in the Charente estuary. The most striking feature of the  
259 observed processes resides in the high-amplitude asymmetry changes: from ebb to flood dominance, and vice versa.  
260 In the following sections, we explore the possible causes of this peculiar behaviour and discuss its possible impact on  
261 the estuarine sediment dynamics.

### 262 5.1. Impacts of the incident tide and morphology on the Charente tidal asymmetry

#### 263 5.1.1. The key role of quarter-diurnal constituents

264 The first part of the study demonstrated the essential role played by quarter-diurnal constituents in the tidal asym-  
265 metry inversions observed in the Charente estuary. Interaction between the M4 harmonic and the principal M2 con-  
266 stituent had previously been demonstrated (Aubrey and Speer, 1985; Friedrichs and Aubrey, 1988). However, the  
267 introduction of the M4 harmonic into the model is necessary but not sufficient to reproduce the asymmetry observed  
268 in the estuary. When the MS4 harmonic is considered, asymmetry inversions are reproduced in phase with obser-  
269 vations. In the Charente estuary, tidal asymmetry thus results from the combination of the well-known estuarine  
270 distortion of the semidiurnal tide and the incidence of a tidal wave already composed of high-amplitude harmonics,  
271 which develop from the interaction with the continental shelf (Le Cann, 1990; Bertin et al., 2012).

272 The influence of the low-frequency constituent MsF could also be considered as a possible explanation for these  
273 inversions. The interaction between M2 and S2 inside the estuary indeed generates this constituent, with an MsF  
274 amplitude close to 12 cm. However, if the asymmetry inversions were related to MsF, they would occur in phase with  
275 the spring-neap tidal cycle. In the Charente case, they occur as the tidal range decreases and increases.

276 As shown in this paper, tidal asymmetry inversions are linked to the presence of significant quarter-diurnal con-  
277 stituents in the incident tide, with amplitudes exceeding 0.1 m. This unusual development of quarter-diurnal con-  
278 stituents before the tidal wave reaches shallow waters and inner estuaries was shown to result from interactions with  
279 the continental shelf in the Bay of Biscay by Le Cann (1990). Only a few areas of the world ocean (Fig. 10) are  
280 characterised by distorted incident tides (e.g. Patagonian Shelf, North Sea, Yellow Sea), where small coastal systems  
281 such as the Charente estuary likely remain unstudied. Further research in these areas could augment the present study,  
282 by comparing morphological differences within the estuaries and/or bays, as well as the possible impacts on tidal  
283 propagation associated with these differences.

#### 284 5.1.2. Locally- vs remotely-generated overtides

285 The idea of a combination of two "types" of overtides (externally and internally generated) is reinforced by har-  
286 monic analyses performed on the modelling results (Table 5) using T\_Tide (Pawlowicz et al., 2002). As stated previ-  
287 ously, it is difficult to use classical harmonic analysis approaches in the Charente estuary. The flow section is highly  
288 variable, which induces significant errors when harmonic analyses are performed on in situ data. However, the model



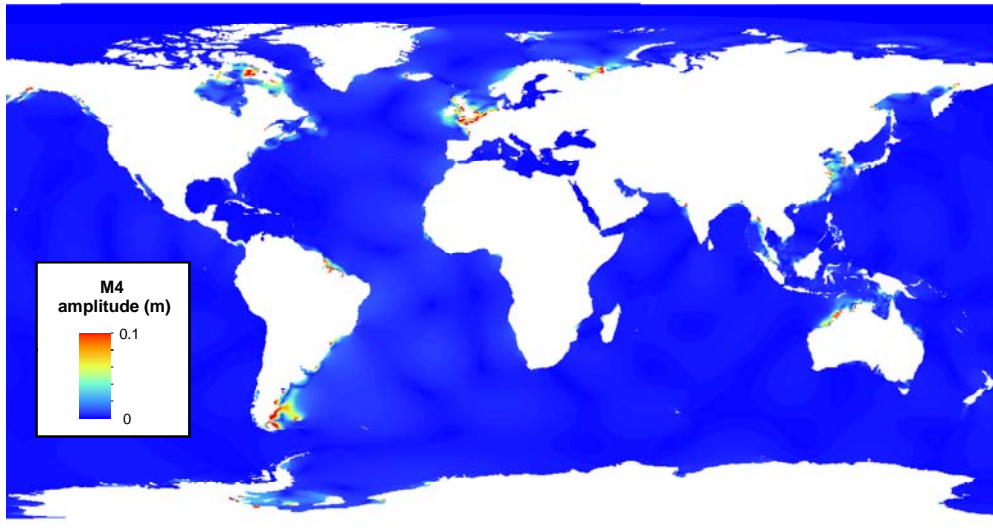


Figure 10: M4 amplitude (m) in the world ocean, extracted from FES 2004

289 configurations used here are idealised, in comparison to the complexity of in situ data, since the harmonic composition  
 290 of the tide at the boundary is limited to 4 constituents. Thus, the utilisation of harmonic analyses is possible, as long  
 291 as the results are compared the results between two model configurations that are close and simplified in terms of tidal  
 292 composition at the open boundary.

293 The amplitudes and phases of M4 in cases A and C illustrate the existence of externally and internally generated  
 294 overtides. At the river mouth, the differences in M4 amplitude are higher than at Rochefort (Table 5 (top)), due to a  
 295 greater distortion of the tide by the interaction with the estuary when moving upstream. At Rochefort, 66% of the M4  
 296 amplitude is due to internal tide-estuary interactions, compared to 13% at the river mouth. The M4 phase differences  
 297 between cases A and C, both at Rochefort ( $56.5^\circ$ ) and at the river mouth ( $45^\circ$ ), also indicate that the overtides are  
 298 generated both internally and externally. The same observations can be made on the MS4 compound harmonic, that  
 299 results from the interactions between M2 and S2, by comparing the amplitudes and phases differences between cases  
 300 B and D. (Table 5 (bottom)). At the river mouth, 23 % of the MS4 amplitude is generated internally, compared to 63  
 301 % at Rochefort. The phase difference is smaller at the river mouth ( $4.5^\circ$ ) than at Rochefort ( $13.5^\circ$ ).

302 The Charente estuary exhibits the following temporally and spatially dependent tidal asymmetries. (1) At the  
 303 mouth, asymmetry follows the spring-neap variations, with corresponding duration and velocity asymmetries (Fig. 5  
 304 and Fig. 7). (2) Upstream, asymmetry is still subject to spring-neap modulations ; however, velocity asymmetry is  
 305 mostly ebb-dominated (Fig. 8), whereas the flood duration is shorter than ebb duration most of the time (Fig. 6).  
 306 In the Rochefort area, tidal flats provoke strong variations in the flow section from high water to low water. The  
 307 flow is strongly constrained at low water values and larger peak ebb velocities can thus be observed, even if the  
 308 ebb is longer than the flood (Dronkers, 1986; Brown and Davies, 2010). Depth variations must also be considered.

Table 5: Amplitudes and phases of M2, S2, M4 and MS4 at the river mouth and at Rochefort for different model configurations

Model Configuration		Amp (cm)		Phase (deg)	
		A	C	A	C
River mouth	M2	180.57	178.85	101.14	100.88
	M4	3.69	28.18	73.73	28.80
Rochefort	M2	172.69	163.42	122.38	122.65
	M4	15.77	23.97	159.41	102.78

Model configuration		Amp (cm)		Phase (deg)	
		B	D	B	D
River mouth	M2	180.48	179.66	100.80	101.56
	S2	64.98	63.28	134.64	134.47
	MS4	3.08	13.54	121.05	116.60
Rochefort	M2	170.08	163.35	122.84	123.50
	S2	56.30	53.08	159.92	157.53
	MS4	11.80	18.73	204.99	191.27

309 At the river mouth, the mean channel depth is approximately 7.5 metres. Deeper areas are found upstream, with  
310 depths varying between 7 and 11 metres. Around Rochefort, the mean channel depth is close to 9 metres. As shown  
311 by several studies (Brown and Davies, 2010; Friedrichs and Aubrey, 1988; Moore et al., 2009; Wang et al., 2002)  
312 deeper channels favour ebb dominance, whereas shallower waters often lead to flood dominance. The combination  
313 of average depths and intertidal flats at the mouth would thus favour asymmetry inversions following the tidal range.  
314 Deeper upstream areas, which are also associated with intertidal flats, would lead to ebb dominance most of the time,  
315 even if asymmetry inversions were observed.

316 To more precisely evaluate the impact of the estuary's morphology, two tests involving different bathymetry mod-  
317 ifications are conducted. For the first test, the mean water level is increased by a metre. This modification provokes  
318 an increase in both the channel depth and the intertidal flats depth. For configuration D (M2, S2, M4 and MS4 at the  
319 open boundary), the results show that velocity asymmetry inversions no longer occur at the river mouth: the estuary  
320 is always flood-dominant at this location. The peak velocities ratio increases by 11 %. Ebb durations are also longer  
321 than for the original bathymetry. At Rochefort, the peak velocities ratio still increases during spring tides and reaches  
322 values larger than one (flood dominance). However, its maximum value is 1.05 compared to 1.24 (12.5 % drop on  
323 average), and the period of flood dominance is reduced (3 tidal cycles compared to 12). An increase in the mean water  
324 level (equivalent to a global deepening of the estuary) thus tends to eliminate velocity asymmetry inversions in the  
325 estuary. For configuration A (M2 at the open boundary), this modification enhances the dominances observed with

326 the original bathymetry (flood dominance at the mouth, ebb dominance at Rochefort), which is consistent with the  
327 previous results.

328 For the second test, only the tidals flats are deepened: the intertidal areas above the mean sea level are now at  
329 mean sea level. Simulations are performed only with the M2 constituent at the open boundary, to observe the possible  
330 impact of this modification on the flood dominance at the river mouth and the ebb dominance at Rochefort. At the  
331 river mouth, both flood and ebb velocities are enhanced by this modification but the peak velocities ratio globally  
332 decreases (9.6 % drop). The calculated maximum and minimum peak velocities ratios over the simulated period are  
333 1.11 and 1.04, respectively. With the original bathymetry (Table 4), these values were 1.21 and 1.10. These results  
334 indicate that flood dominance is reduced at the river mouth, when the tidal flats are slightly deepened. At Rochefort,  
335 the difference is less obvious than at the river mouth: the calculated maximum and minimum ratios are 0.93 and 0.75,  
336 compared to 0.89 and 0.74 for the original bathymetry (Table 4). On average, there is a 2.2 % increase in the peak  
337 velocities ratio. Ebb dominance is thus slightly reduced by this modification of tidal flats depth.

338 Fortunato and Oliveira (2005) studied the influence of intertidal flats on tidal asymmetry. They showed that the  
339 depth of the tidal flats maximising ebb dominance is at mean water level or slightly above, and depends on the tidal  
340 amplitude and the extent of the tidal flats. At the mouth of the Charente estuary, intertidal areas are large (up to 75  
341 % of the width), and mostly at depths below the mean water level. When the depths above the mean water level are  
342 reduced to this value, flood dominance remains, but decreases significantly. In contrast, when the tidal flats and the  
343 channel are deepened over the entire area, flood dominance is enhanced. Fortunato and Oliveira (2005) showed that  
344 when the tidal flats are below the mean water level, tidal amplitude strongly influences tidal asymmetry: if the flats  
345 are not exposed at low tide, the estuary tends to be flood-dominant. With the original bathymetry, intertidal flats at the  
346 river mouth are exposed for all tidal ranges, which is not the case after increasing the mean water level.

347 At Rochefort, tidal flats are mostly at depths above the mean water level, and they can represent up to 50 % of the  
348 width. When they are deepened to be at the mean water level, ebb dominance is slightly reduced but the modification  
349 is smaller than at the river mouth. This result is consistent with the study of Fortunato and Oliveira (2005). However,  
350 when all the bathymetry is deepened, ebb dominance is enhanced. In this case, the deepening of the channel, which  
351 tends to promote ebb dominance, appears to be playing a greater role than the modification of intertidal depths.

352 The modifications made on the Charente estuary morphology provoke significant changes to the tidal asymmetry.  
353 These results confirm that tidal asymmetry is the consequence of complex interactions between the incident tide,  
354 which is already distorted in this case, and the morphology of the estuary. Both the intertidal flats and the channel  
355 depth have an impact on tidal distortion.

## 356 5.2. *Perspectives on sediment dynamics*

### 357 5.2.1. *Net sediment transport*

358 Brown and Davies (2010) proposed two ratios to determine the ebb or flood dominance of sediment transport over  
359 a cross-section: (1) the ratio of the peak flood velocity to the peak ebb velocity  $u_p$  and (2) the ratio of the flood and

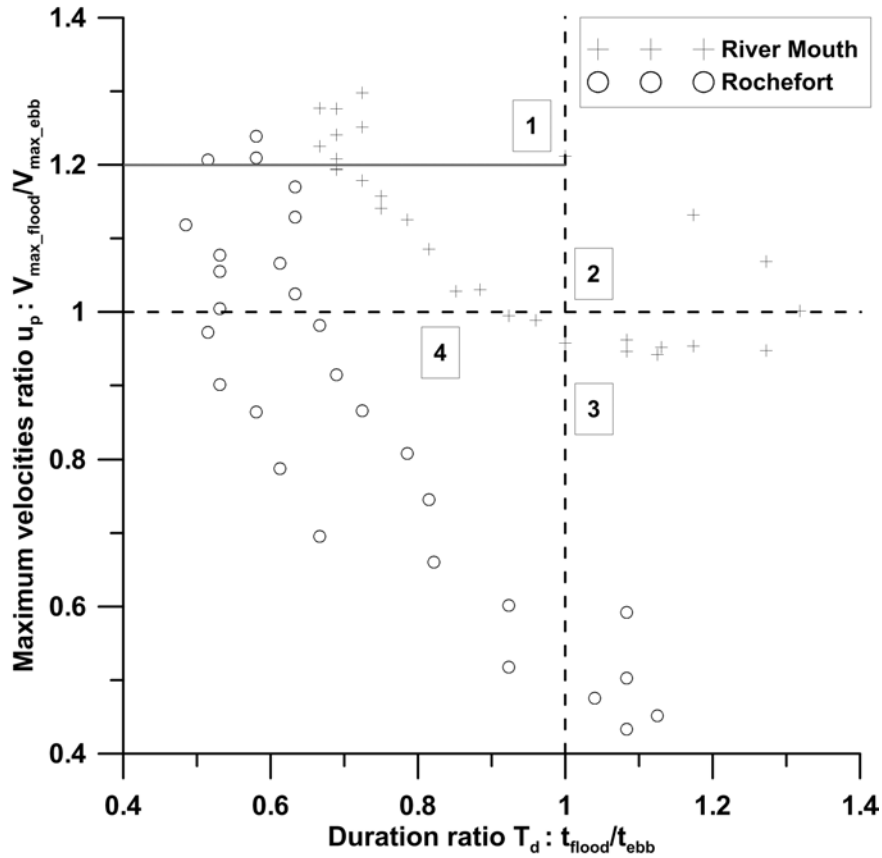


Figure 11: Peak flow velocities ratio against the duration ratio at the river mouth and Rochefort.

ebb durations during which the velocity is greater than a threshold for sediment movement  $T_d$ . Ebb dominance is obtained for values of  $u_p$  less than 1 and values of  $T_d$  greater than 1. However, Brown and Davies (2010) also show that ebb dominance can be obtained for  $u_p < 1.2$  and  $T_d < 1$ . In this case, ebb current velocities are higher than ( $u_p < 1$ ) or close to flood current velocities ( $1 < u_p < 1.2$ ). Combined with longer ebb duration ( $T_d < 1$ ), this configuration results in ebb-dominant net transport. Charente sediments are a very fine, exclusively muddy sediment, with a mean median grain size of  $9 \mu m$  close to the mouth (Strady et al., 2011). Moreover, as shown in Fig. 9, periods of slack water with very low velocities are short. In this paper, the velocity threshold is therefore considered to be exceeded for all ebb and flood durations, because very fine sediments in fluid mud can be easily resuspended in the water column by entrainment (Mehta, 1991). Calculations are performed over a full spring-neap tidal cycle to equally represent all possibilities, and  $u_p$  is plotted against  $T_d$  (Fig. 11).

Zone 1 is representative of the typical flood asymmetry, with short and rapidly rising tides. Zone 2 is populated by points with longer rising tides but higher flood velocities. Typical ebb-dominant asymmetry corresponds to zone 3, and zone 4 is characterised by longer falling tides but higher ebb velocities. Following the criteria of Brown and Davies (2010), points located in zone 1 below the solid line ( $u_p < 1.2$  and  $T_d < 1$ ) and in zones 3 and 4 ( $u_p < 1$  and  $T_d$

374 < 1) are representative of ebb-dominant sediment transport.

375 At Rochefort, sediment transport is thus ebb-dominated in 90% of the cases, compared to 65% at the river mouth.  
376 We could argue that the subdivision of zone 1 should also be applied to zone 3. Longer rising tides ( $T_d > 1$ ) with com-  
377 parable flood and ebb peak velocities ( $u_p > 0.8$ ) would then lead to flood-dominant sediment transport. This consid-  
378 eration would enhance the difference between Rochefort and the river mouth, with the latter becoming ebb-dominant  
379 only 38% of the time. These results are obtained by only considering the 2D modelled velocities. Consequently,  
380 all the processes associated with estuarine sediment dynamics are not considered. Further investigation, through 3D  
381 numerical modelling for example, remains needed to confirm these estimations.

### 382 5.2.2. *Morphological implications*

383 In terms of net sediment transport, the Rochefort area appears to be ebb-dominated most of the time, inducing  
384 net sediment export (Fig. 11). In contrast, the river mouth is more equally divided between periods of ebb and  
385 flood dominance. Flood dominance and net import at the mouth, which are associated with ebb dominance and net  
386 export at Rochefort suggest that the intermediate zone between those two locations is prone to sediment accumulation.  
387 According to Figs. 7 and 8, this configuration occurs mostly during the transition from spring to neap tides.

388 These modelling results are consistent with measurements of sediment accretion on the mudflats in the estuary,  
389 because small variations are observed near the mouth (8 cm per month) whereas upstream measurements show an  
390 accretion rates up to 40 cm per month during summer (Coulombier et al., 2013). Sediment fluxes calculated with 3D  
391 hydrodynamic modelling and turbidity measurements also suggest alternations between net import and net export at  
392 the river mouth, which are largely determined by the spring-neap variations of the tide (Toublanc et al., 2013).

393 A switch from flood to ebb dominance caused by sedimentary infilling and flat formation and/or extension has  
394 been discussed by many authors (Speer and Aubrey, 1985; Fortunato and Oliveira, 2005; Moore et al., 2009). In the  
395 Charente estuary case, we can wonder whether the accumulation of sediment observed and suggested by this study  
396 could lead to a change in tidal propagation and, therefore, in net sediment transport. The relative equilibrium reached  
397 at the river mouth suggests that the possible morphological changes induced by tidal asymmetry in sediment transport  
398 are not sufficiently large to alter the system dynamics. However, strong siltation (estimated up to 1 meter in a month)  
399 was observed farther upstream, close to the dam, and remains an issue of concern for the management of the area.

### 400 5.2.3. *Turbidity maximum*

401 As demonstrated by Allen et al. (1980), tidal asymmetry is a driving mechanism leading to the formation of a  
402 turbidity maximum in macrotidal estuaries. Because tidal asymmetry in the Charente estuary is strongly dependent  
403 on the spring-neap tidal cycle, turbidity maximum dynamics should also be partly determined by this cycle. Previous  
404 work has demonstrated that neap tides favour sedimentation and the depletion of the turbidity maximum, whereas  
405 spring tides favour resuspension and turbidity maximum extension (Allen et al., 1980; Dyer, 1997). In addition to  
406 these dynamics, which are related to the strength of current velocities, fortnightly asymmetry inversions could also

407 play a key role in the turbidity maximum. The transition from spring to neap tides is characterised by ebb-dominant  
408 current velocities at Rochefort, in contrast to flood-dominant velocities at the river mouth (Figs. 7 and 8), which could  
409 lead to turbidity maximum concentration and trapping in an intermediate zone, where current velocities would be  
410 neither ebb- nor flood-dominated. Inversely, the transition from neap to spring tides would favour the extension and  
411 downstream movement of the turbidity maximum, due to ebb dominance at both locations.

## 412 **6. Conclusion**

413 A temporally and spatially dependent asymmetry is observed in the Charente estuary and is reproduced by the  
414 model developed in this study. Parameters such as  $V_s/V_c$  and  $a/h$  (Friedrichs and Aubrey, 1988) cannot fully rep-  
415 resent the tidal asymmetry, because no time-dependent factor is considered. Moreover, considering only the relative  
416 importance of M2 and M4 in phase and amplitude ignores the strong impact of S2 and of the compound constituent  
417 MS4, which is demonstrated in this paper. Modifying the bathymetry of the estuary also alters the response in terms  
418 of asymmetry dominance. These results confirm that both the incident tide and the estuarine morphology play a sig-  
419 nificant role in the Charente tidal asymmetry. To our knowledge, no other studies have observed such a fortnightly  
420 dependent tidal asymmetry in other macrotidal estuaries under the influence of a semidiurnal tide. Time-dependent  
421 asymmetry inversions have been studied with mixed tidal regimes (Jewell et al., 2012; Nidzieko and Ralston, 2012)  
422 or after major morphological changes (Boon and Byrne, 1981; Bolle et al., 2010).

423 Net sediment transport calculations suggest that accumulation occurs between the river mouth and Rochefort,  
424 which is confirmed by observations. This result could lead to major changes in the management of dredgings, because  
425 this accumulation would most likely happen during the transition from spring to neap tides. Further investigation is  
426 needed to determine the possible impact of this behaviour on the long-term morphological evolution of the Charente  
427 estuary.

428 A better understanding of the impact of asymmetry inversion on sediment dynamics could be achieved by applying  
429 the different configurations developed in this study to a nested 3D hydro-sedimentary model. Net sediment transport  
430 calculations at different locations and turbidity maximum modelling would allow a confirmation of the tendencies  
431 noted in this paper. The effects on mixing and stratification could also be investigated.

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