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F Toublanc, I Brenon, T Coulombier. Formation and structure of the turbidity maximum in the macrotidal Charente estuary (France): Influence of fluvial and tidal forcing. *Estuarine, Coastal and Shelf Science*, 2016, 169, pp.1 - 14. 10.1016/j.ecss.2015.11.019 . hal-01459347

HAL Id: hal-01459347

<https://hal.science/hal-01459347>

Submitted on 7 Feb 2017

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Formation and structure of the turbidity maximum in the macrotidal Charente estuary (France): influence of fluvial and tidal forcings

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Abstract

Understanding estuarine sediment dynamics, and particularly turbidity maximum dynamics, is crucial for the management of these coastal systems. Various processes impact the formation, movement and structure of the turbidity maximum. Several studies have shown that tidal asymmetry and density gradients are responsible for the presence of this suspended sedimentary mass.

The Charente estuary is a highly turbid system (with suspended sediment concentrations mostly in excess of 5 g/L) that remains poorly understood, despite its strong impact on local activities. In this study, a three-dimensional hydrosedimentary model is developed to represent the sediment dynamics of this estuary. Model validation demonstrates good accuracy, especially on reproducing semi-diurnal and spring-neap variability. Several simulations are performed to evaluate the influence of tides and river discharge on the turbidity maximum. Mean and maximum suspended sediment concentrations (*SSC*) and sediment stratification, are calculated. *SSC* transects are also used to visualise the suspended sediment distribution along the estuary.

The turbidity maximum generally oscillates between the river mouth and the Rochefort area (20-30 km upstream). The model shows strong variations at different time scales, and demonstrates that *SSC* is mainly driven by deposition/resuspension processes. Spring-neap comparisons show that the turbidity maximum is not well-defined during neap tides, for low and mean runoff conditions. Simulations of spring tides and/or high runoff conditions all result in a compact suspended sedimentary mass.

Performing simulations without taking density gradients into account demonstrates that tidal asymmetry is the main mechanism leading to the formation of the turbidity maximum. However, density gradients contribute to maintaining the stability of the turbidity maximum. Vertical stratification traps sediments at the bottom. Longitudinal stratification ensures a sharper edge at the downstream limit of the suspended sedimentary mass, preventing a massive export of sediments.

Keywords: Estuary, Turbidity maximum, Numerical Modelling, Sediment dynamics, Tidal asymmetry, Density gradient

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1. Introduction

Because of their unique location at the interface between land and sea, estuaries are critical ecosystems subject to strong anthropogenic pressures. Macrotidal estuaries characterized by the presence of fine cohesive sediments frequently exhibit the formation of a highly turbid zone. This compact suspended sedimentary mass is called a turbidity maximum, and it is sensitive to variations in the tidal and fluvial regime. Understanding the dynamics and characteristics of turbidity maxima is important for the ecology as well as the economy of nearby coastal areas. For example, fine cohesive sediments are noted carriers of pollutants that endanger water quality (Eyre and McConchie, 1993). They are also related to strong siltation rates near harbours or other infrastructure, necessitating regular dredging. For instance, Owens et al. (2005) report that 50×10^6 tons/year of sediment are dredged from coastal areas in the UK. They also show that dredging reaches 4 to 5×10^6 m^3 /year in the Elbe river and Hamburg harbour in Germany.

Turbidity maximum processes have been studied in several estuaries (Allen et al., 1980; Brenon and Le Hir, 1999; Cancino and Neves, 1999; Dyer, 1997; Sottolichio et al., 2000; Uncles and Stephens, 1993; Uncles et al., 2006). The suspended sediment concentration in the turbidity maximum varies on several time scales (following the ebb-flood cycle, spring-neap cycle, seasonal variations, and so forth). On the 12 h scale of a semi-diurnal tidal cycle, slack waters tend to favour sedimentation and deposition, whereas flood and ebb phases favour erosion and resuspension, with mobile bed sediments feeding the turbidity maximum (Allen et al., 1980). Fluctuations on the larger time scale of a spring-neap tidal cycle, induced by changes in the current velocities intensities, are also important (Allen et al., 1980; Dyer, 1997). From spring to neap tides, current velocities decrease and sedimentation takes place. The turbidity maximum zone is then reduced, and fluid mud appears (or is supplemented) at the bottom. Seasonal variations related to river discharge also occur. For example, floods can induce a seaward movement of the turbidity maximum (Allen and Castaing, 1973; Uncles et al., 2006).

The formation of a turbidity maximum in an estuary is mainly attributed to two processes: density circulation and tidal asymmetry (Allen et al., 1980). Density gradients may generate two-layer circulation (density circulation), with freshwater moving seaward at the surface and saltwater moving landward at the bottom. A turbidity maximum can appear at the density nodal point, where the flow becomes entirely seaward-oriented (Allen et al., 1980; Dyer, 1997). Tidal asymmetry, characterized by uneven current velocities and slack waters (Aubrey and Speer, 1985; Friedrichs and Aubrey, 1988), can generate a turbidity maximum at the tidal nodal point. According to Allen et al. (1980) and Dyer (1997), the tidal nodal point is often located upstream from the density nodal point. Uncles and Stephens (1993) showed that positions of the turbidity maximum sometimes corresponds to the freshwater-saltwater interface.

The relative importance of both processes depends on estuary characteristics. Li (1994) suggested that turbidity maximum dynamics are mainly driven by the tides. This behaviour was confirmed by Brenon and Le Hir (1999) and Sottolichio et al. (2000) in the Seine and Gironde estuaries, respectively. However, both studies showed that density gradients are essential to the stability of the turbidity maximum by maintaining a compact sedimentary mass in suspension and preventing strong sediment export.

35 The Charente estuary (Figure 1), located on the French Atlantic coast, is a useful site in which to study estuarine
36 dynamics. In the recent years, the area has experienced droughts and also hosts a broad spectrum of economic
37 activities (oyster farming, agriculture, tourism, port operations, and so forth), making this estuary particularly sensitive
38 to water quality and siltation issues. Local features, such as the inversion of tidal asymmetry as a function of the
39 spring-neap tidal cycle (Toublanc et al., 2015) are also interesting. More generally, although numerous studies have
40 investigated large macrotidal estuaries, smaller systems such as the Charente remain poorly understood. However,
41 many of these small estuaries strongly influence their surroundings. This study focuses on the turbidity maximum and
42 suspended sediment dynamics in the Charente, at different time scales and under various fluvial and tidal regimes.
43 Several indicators are used to quantify the impact of these forcings on the horizontal and vertical distribution of
44 *SSC* (suspended sediment concentration), and to identify the mechanisms that drive the formation of the turbidity
45 maximum. Changes in its structure are also investigated numerically, to delineate the processes controlling sediment
46 escape to the connected bay.

47 2. Study site

48 The Charente estuary (45°96N, 1°00W, Fig. 1) is located on the French Atlantic Coast. The river flows into the
49 Marennes-Oléron Bay, in the southern part of the pertuis Charentais. The river's catchment is 10550 m^2 and its length
50 is 365 km. A dam is located in Saint-Savinien, 50 km from the river mouth. The mean river discharge is estimated
51 to be 70 m^3/s . Discharge can reach extreme values of 600 to 700 m^3/s during flood events, and drop to less than 10
52 m^3/s during the summer. Exceptional floods can have caused discharges of up to 1000 m^3/s . The river is shallow,
53 with a maximum depth of 10 m below mean sea level, and the estuary mouth is funnel-shaped.

54 The Marennes-Oléron Bay's total surface area covers nearly 150 km^2 , with 60% composed by intertidal areas.
55 The sediments in the estuary and in the eastern part of the Marennes-Oléron Bay are entirely cohesive, with a very
56 fine grain size (Strady et al., 2011). In the western part of the bay, sediments are sandier (Tesson, 1973; Bertin et al.,
57 2005). The mud ratio decreases and the mean grain size tends to increase upstream, but the latter remains less than 20
58 μm and the mud ratio is always greater than 80% (Coulombier et al., 2013).

59 The estuary and the bay are affected by semidiurnal tides. At the river mouth, the mean and maximum tidal
60 ranges are 4.5 m and 6.5 m, respectively. This macrotidal regime is also characterized by the influence of quarter-
61 diurnal constituents (M4, MS4 and MN4), which are strongly amplified shoreward by resonance along the Bay of
62 Biscay shelf (Le Cann, 1990). Bertin et al. (2012) verified this phenomenon numerically and showed that the largest
63 amplification by resonance occurred for the MS4 constituent. In combination with the internal tidal distortion of the
64 estuary, these externally generated overtides result in fortnightly inversions of the tidal asymmetry (Toublanc et al.,
65 2015). Depending on the timing of the spring-neap tidal cycle, and the position in the estuary, the estuary can be
66 dominated either by the flood or the ebb.

67 Prior to this study, few data were available on the turbidity maximum of the Charente estuary, including only

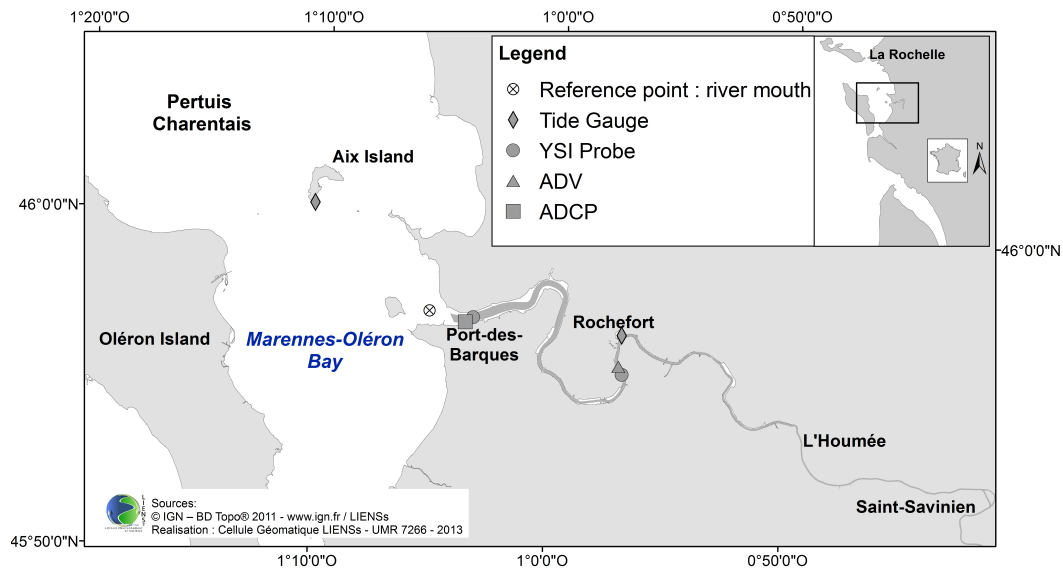


Figure 1: The Charente River, from the Saint-Savinien dam to the mouth, including locations of sampling stations

68 intermittent observations and no numerical modelling. Ravail et al. (1988) recorded SSC up to 10 g/L at the river
 69 mouth, Auguet et al. (2005) measured concentrations greater than 5 g/L at the surface in Rochefort. Local actors often
 70 reported strong suspended sediment concentrations around Rochefort (20 km upstream from the mouth): bathymetric
 71 surveys performed by public services revealed at several occasions the presence of a highly concentrated suspended
 72 sedimentary mass in front of the Rochefort harbour. Schmidt et al. (2010) and Le Moine et al. (2012) reported the
 73 presence of fluid mud in the proximity of the Saint-Savinien dam. Despite these observations, the spatio-temporal
 74 evolution of the turbidity maximum has not been studied yet in the Charente estuary.

75 The characteristics and movements of the turbidity maximum are very important to management of the area. This
 76 is especially true in Rochefort where the harbour is often dredged to compensate for strong sediment accumulation:
 77 reports estimate that $160,000\text{ m}^3/\text{year}$ of sediment is dredged. Tourism, as well as oyster and mussel farming in the
 78 Marennes-Oléron Bay also strongly depend on outflows from the Charente river.

79 3. Materials and methods

80 3.1. Numerical modelling

81 The numerical model MARS-3D (Modelling for Applications at Regional Scales) used in this study has been
 82 described in previous work (Lazure and Dumas, 2008). It is a finite differences model that solves the Navier-Stokes
 83 equations under hydrostatic and Boussinesq assumptions when used in 3D mode.

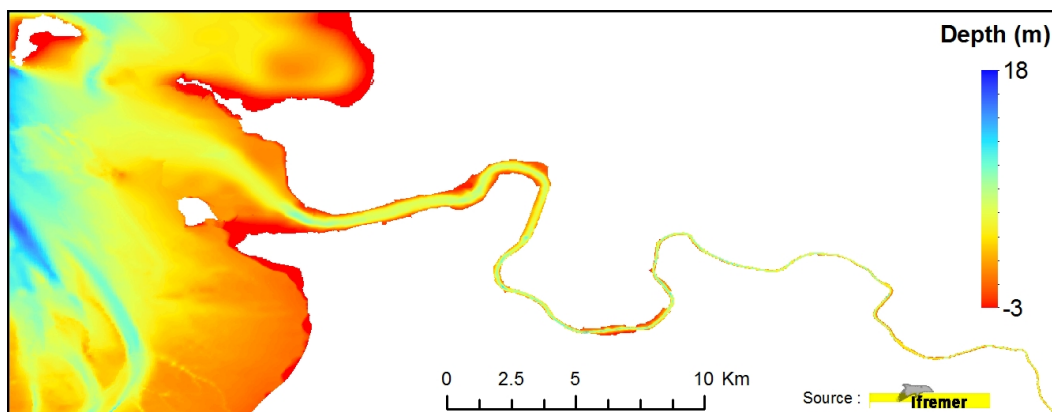


Figure 2: Bathymetric data used for numerical modelling

84 The configuration presented here consists of two nested grids. The first one, with 100 m horizontal resolution, is
 85 forced by tides computed using the SHOM CST-France model (Le Roy and Simon, 2003). It runs in 2D and provides
 86 open boundary conditions at the seaward limit for the second grid. This grid has a 30 m horizontal resolution and
 87 runs in 3D with 8 sigma levels. Daily river discharges are prescribed. Bathymetric data (Fig. 2) were provided by
 88 several organizations (SHOM, Ifremer, EPTB Charente). Upstream of L’Houm e, the grid resolution is insufficient
 89 to accurately represent the dynamics of the river. Consequently, an artificial canal is created, with bathymetric values
 90 extracted from the real data. This allows us to prescribe the estimated daily discharge at the Saint-Savinien dam.

91 Atmospheric forcing is provided by the ARPEGE model from M t e-France (15 kilometres, 6 hours). The model
 92 includes the wind speed 10 meters above the sea surface, the atmospheric pressure and the temperature 2 meters above
 93 the sea surface.

94 A two equation k-kl turbulence closure model is used (Warner et al., 2005b). This model, which resembles the
 95 Mellor-Yamada level 2.5 scheme (1974; 1982), solves the vertical eddy viscosity and diffusivity by calculating the
 96 turbulent kinetic energy and the turbulence length scale. The horizontal eddy viscosity and diffusivity are computed
 97 by using the Smagorinsky method, to take the local shear conditions into account (1963).

98 Considering the relative homogeneity of the sediment and its granulometry measured along the estuary, one sedi-
 99 mentary class is used in the model. Settling velocity is variable (between 0.05 and 1 mm/s) and depends on concen-
 100 tration, salinity and turbulence, according to a semi-empirical formulation (Le Hir et al., 2001). The concentration
 101 and turbulence dependence for settling is crucial to take into account the flocculation processes that occur in areas of
 102 strong SSC with cohesive sediment (Blake et al., 2001; Milligan et al., 2001, 2007). The sedimentary module *mud-*
 103 *sand* in MARS-3D was fully described by Le Hir et al. (2011) and takes into account suspended sediment transport
 104 (no bedload transport) associated with fine sediments. Consolidation processes are not considered in this study. In the
 105 absence of relevant measurements at the Saint-Savinien dam that would allow us to establish a runoff/concentration
 106 relationship, a fixed input of 0.05 g/L is prescribed at the upstream boundary. This value was chosen according to

107 upstream data presented by Modéran et al. (2012). Moreover, cores and surface sediments sampled on the estuarine
108 banks show little variation in the mud fraction and mean grain size. Thus, variations in river flow do not necessarily
109 imply a strong fluvial sediment input, because the sediment characteristics remain very similar.

110 3.2. *In-situ measurements for model validation*

111 Model validation is performed using in-situ data recorded for different periods and at different locations, as shown
112 in Figure 1.

113 Sea surface elevation and current velocities are validated using continuous tide gauge data from Rochefort and
114 the Aix Island (from the REFMAR portal) and ADCP data (Sentinel-RDI instruments, 1200 kHz, 5-minute sampling
115 frequency, February to April 2011) at the river mouth (Port-des-Barques). Current velocities are also validated using
116 ADV measurements (Argonaut-ADV, Sontek) carried out at Rochefort (November 2012 to August 2013, 30 seconds
117 averaged every 5 minutes), approximately one meter above the sediment bed.

118 Simulated salinity levels are compared to datasets obtained from multi-parameter probes (YSI 6600V2) located
119 at the mouth, surface (February to March 2011, 10-minute sampling frequency) and bottom (October to December
120 2012, 5-minute sampling frequency). Turbidity data were also recorded with the same probes (5-minute sampling fre-
121 quency), at the mouth (approximately two meters above the bed) and at Rochefort (approximately one meter above the
122 bed). Salinity and turbidity probes were laboratory calibrated using standard solutions (12880 *microSiemens.cm*⁻¹,
123 and formazin at 1000 and 4000 NTU, respectively). Wet sediments collected from the intertidal banks of the Charente
124 were diluted at several concentrations in a 40 L black bucket to calibrate the turbidity sensors. Validation of suspended
125 sediment concentrations was performed after filtration on GF/C filters (Coulombier et al., 2013).

126 4. Results

127 This section focuses on the results obtained by numerical modelling. The *SSC* levels are analysed and displayed
128 for various fluvial and tidal conditions. Prior to this analysis, the performance of the model is validated to several
129 variables (water surface elevation, current velocities, salinity levels and *SSC*).

130 4.1. *Model validation*

131 Mean absolute (MAE) and root mean square (RMSE) errors are calculated to compare the modelled and observed
132 water surface elevation, current velocities and salinity levels. Model accuracy is also evaluated using the skill pa-
133 rameter (Eq. 1) developed by Willmott (1981) and used in several recent estuarine dynamics studies (Li et al., 2005;
134 Ma et al., 2011; Warner et al., 2005a; Xing et al., 2012). This parameter takes into account the modelled (X_{mod}) and
135 observed (X_{obs}) deviations around the observed mean ($\overline{X_{obs}}$) to estimate model performance, and varies between 0 (no
136 agreement) and 1 (perfect agreement), as follows:

$$Skill = 1 - \frac{\Sigma |X_{mod} - X_{obs}|^2}{\Sigma (|X_{mod} - \overline{X_{obs}}| + |X_{obs} - \overline{X_{obs}}|)^2} \quad (1)$$

137 All calculations are presented in Table 1. The stations used for validation are shown in Figure 1.

Table 1: Model - data comparison calculations for water surface elevation, current velocities and salinity

Variable	Location	MAE	RMSE	Skill (no unit)
Water surface elevation (<i>cm</i>)	Aix Island	9.92	12.3	0.9974
	Port-des-Barques	12.66	15.38	0.9976
	Rochefort	13.26	16.73	0.9969
Current velocities (u;v) (<i>cm/s</i>)	Port-des-Barques (averaged)	12.4 ; 7.06	16.2 ; 8.78	0.9802 ; 0.9344
	Rochefort (bottom)	10.04 ; 12.47	12.48 ; 15.79	0.9255 ; 0.9473
Salinity (<i>psu</i>)	Port-des-Barques (surface)	2.71	3.39	0.9708
	Port-des-Barques (bottom)	1.91	2.26	0.9620
	Rochefort (bottom)	2.23	2.75	0.9506

138 Water surface elevations are well reproduced by the model (skill > 0.99 for all locations). Figure 3 shows a
 139 graphical representation of the results at the estuary mouth and at Rochefort. A period of two tidal cycles (24 h) is
 140 shown for the water surface elevation at Port-des-Barques, close to the estuary mouth.

141 In MARS-3D, bottom friction is calculated using a roughness length z_0 , derived from the Nikuradse coefficient
 142 (Nikuradse, 1950). The hydrodynamic results showed in Figure 3 and Table 1 required adjusting this parameter, which
 143 was reduced within the estuary. This issue was particularly important in the Rochefort area, because of fluid mud in
 144 the channel, which can cause a significant increase in current velocities, the physical roughness of the sediment bed
 145 being very low. Hamm and Walther (2009) and Walther et al. (2007) showed that hydrodynamic models often fail to
 146 reproduce this effect and overestimate low water levels. King and Wolanski (1996) made similar observations. After
 147 calibration of our model, the Chézy coefficient corresponding to the roughness length is estimated to reach 100 to 110
 148 $m^{1/2}/s$, depending on the water depth. These values are within the range of those obtained in other studies: according
 149 to Winterwerp and Van Kesteren (2004), Chézy values of 110 $m^{1/2}/s$ were found in the Yangtze and the Amazon
 150 rivers, due to the presence of fluid mud.

151 Current velocities are better reproduced in the direction of flow (zonal in Port-des-Barques, meridional in Rochefort
 152 (Figure 3)) than in the perpendicular direction. However, the model still agrees well with observational data (skill >
 153 0.92). The highest errors occurred at Rochefort, both for current velocities and water surface elevation. Model per-
 154 formance on salinity is within the range of the two previous parameters (skill > 0.95). Errors mainly occur during the
 155 transition from spring to neap tide (and vice versa).

156 Concerning sediment dynamics, French (2010) noted that it was difficult to validate modelled suspended sediment

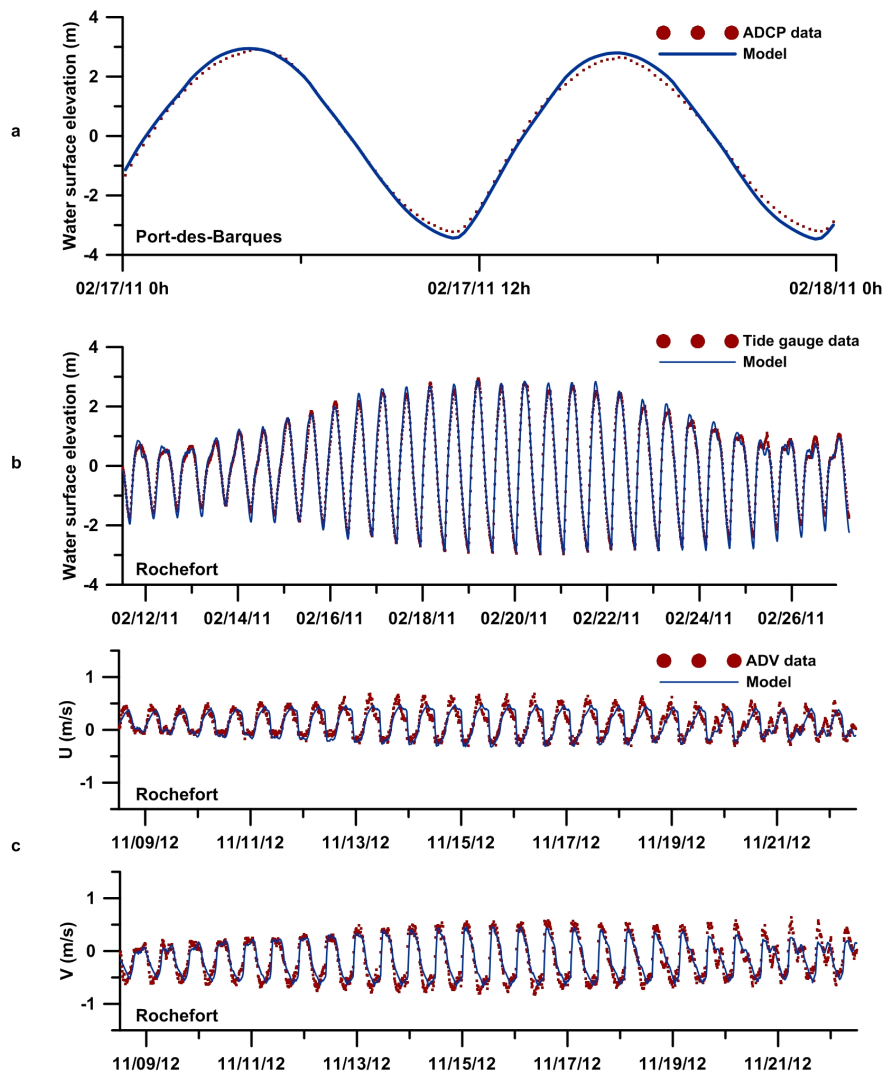


Figure 3: Measured and modelled water surface elevations at the river mouth (Port-des-Barques) over 24 h (a) and at Rochefort over 14 days (b). Measured and modelled current velocities at Rochefort (c)

157 concentrations, compared to tidal levels and velocities. This difficulty arises from the complexity inherent in the large
 158 parameter sets of suspended sediment models. A brief description of the sediment module in MARS-3D is available
 159 in the appendix, and demonstrates that there are a lot of variables to take into account and to calibrate. In the Charente
 160 estuary, this difficulty was enhanced by the high levels of turbidity observed. Over 4000 NTU, turbidity sensors
 161 saturate and fail to properly measure sediment concentrations. Validation is thus impossible with classical parameters
 162 such as MAE and RMSE. Nonetheless, a series of tests was conducted to calibrate the model with data comparisons
 163 from two locations: Port-des-Barques and Rochefort (not shown). Several parameters were adjusted including the
 164 minimum and maximum settling velocities, the sedimentary stock available at the beginning of the simulation, the
 165 skin roughness length, and the erosion constant. The skin roughness length is associated with sediment grain-size
 166 characteristics and used to estimate the threshold shear stress for the initiation of sediment motion. It differs from the
 167 bedform roughness length previously mentioned, which is used to take into account the effect of bedforms on flow
 168 (Le Hir, 2008).

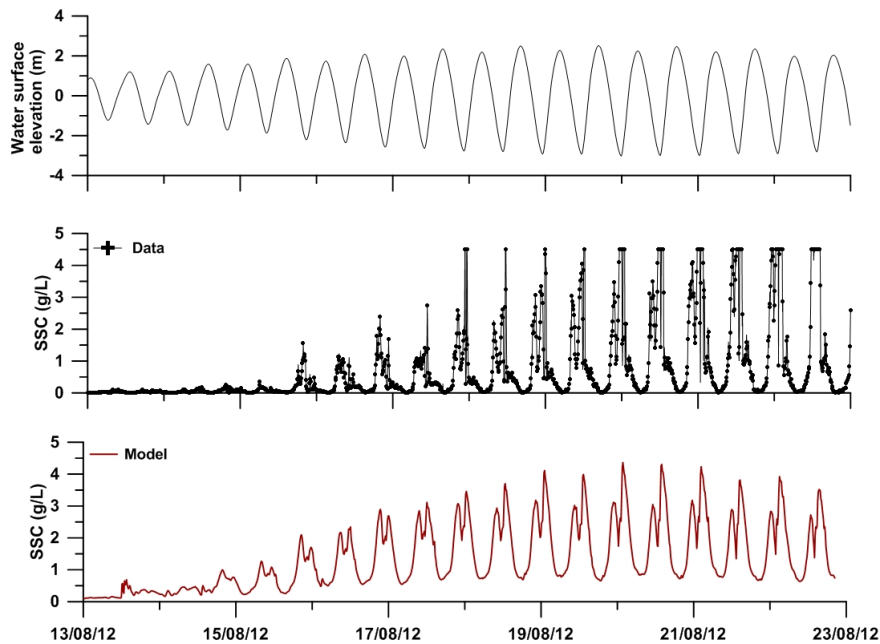


Figure 4: Measured (using a YSI probe) and modelled suspended sediment concentrations at the river mouth

169 Following this calibration/validation, the turbidity maximum is well reproduced by the model, and its position
 170 and movements are coherent with field observations. The background concentration is higher in the model than in
 171 observations. This difference could be explained by the tendency of numerical models in sigma coordinates to smooth
 172 the *SSC*, the volume integrated in the modelled cell being more important than the volume of the measurement cell
 173 (Sottolichio et al., 2014). A different tuning of the settling velocity could also improve the results, but the values for
 174 the maximum and minimum settling velocities were chosen to obtain satisfying results, both at the river mouth and
 175 at Rochefort. Higher *SSC* are obtained during neap tides in the model. This period in the tidal cycle favours the

176 presence of the fluid mud. As shown by Ross and Mehta (1989), density stratification caused by fluid mud and its
 177 interface with the water column (lutocline) can reduce mixing and suppress resuspension. This is not yet taken into
 178 account in the model and could explain the differences obtained during neap tides.

179 The skill parameter equals 0.62 at the river mouth and 0.74 at Rochefort. These results are within the range
 180 of those obtained in recent studies on 3D hydrosedimentary modelling of estuaries: Cheng et al. (2013) obtained
 181 skill values of 0.66 and 0.88 for surface and bottom SSC , respectively; Van Maren et al. (2015) obtained skill values
 182 greater than 0.6. Figure 4 shows that the order of magnitude of suspended sediment concentrations and the spring-neap
 183 variability are well reproduced. Particularly, the transition from neap to spring tides occurs gradually, following the
 184 same pattern as the observations. We also note that the ebb/flood asymmetry, which is a crucial feature in this study, is
 185 well-represented: during spring tide, the SSC is higher during the flood than during the ebb, and the high water slack
 186 favours deposition more than the low water slack. Thus, the model is suitable for the study of sediment dynamics
 187 conducted here, because it reproduces well the two main timescales considered (semi-diurnal and spring-neap tidal
 188 cycles).

189 4.2. Semi-diurnal variability

190 In this section, the evolution of suspended sediment concentrations during a 12 h spring tidal cycle is presented.
 191 The river discharge is set at $50 \text{ m}^3 \cdot \text{s}^{-1}$. Four indicators are used to discuss the modelling results: \overline{SSC} , which rep-
 192 represents the mean suspended sediment concentration in the estuary (from the river mouth to the upstream limit of the
 193 domain); $\overline{\Delta SSC}$, the mean bottom-surface difference in SSC , which is used to evaluate the overall vertical SSC
 194 stratification; SSC_{max} , the spatial maximum suspended sediment concentration and ΔSSC_{max} , the spatial maximum
 195 bottom-surface difference in SSC . For the last two parameters, the distance from the estuary's mouth is also calcu-
 196 lated. These values are extracted from the model at four times: low water, three hours after low water (or mid-flood),
 197 high water, and three hours after high water (or mid-ebb) (Table 2).

Table 2: Indicators \overline{SSC} , $\overline{\Delta SSC}$, SSC_{max} , ΔSSC_{max} (g/L) and distances from the river mouth for SSC_{max} and ΔSSC_{max} (km)

	Low water	Low water + 3 h	High water	High water + 3 h
\overline{SSC}	3.78	2.41	1.21	0.620
$\overline{\Delta SSC}$	1.29	1.44	1.41	0.425
SSC_{max}	9.07	9.80	14.7	2.87
Distance	-3.76	2.97	13.3	11.4
ΔSSC_{max}	5.27	8.24	14.4	2.26
Distance	-4.31	2.97	13.3	11.4

198 The variations in SSC are also shown in Figure 5. The results are displayed using a logarithmic colour scale to
 199 include the over the entire range of concentrations. This logarithmic scale is particularly important for the results

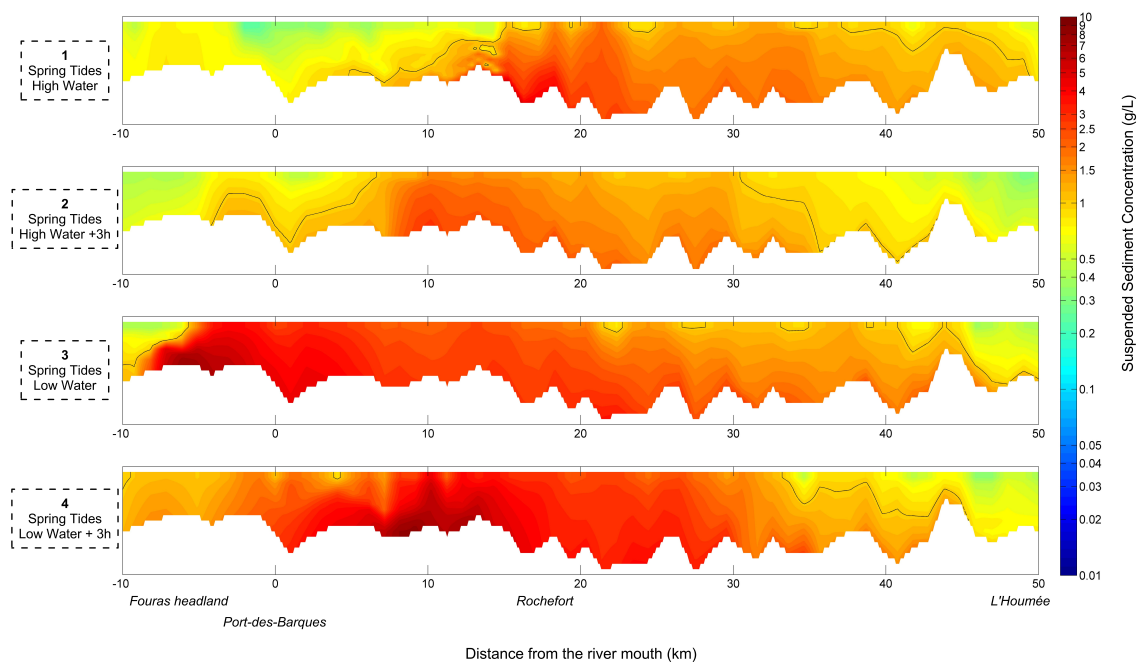


Figure 5: Transects of modelled suspended sediment concentrations for a tidal cycle of spring tides and mean river discharge - The black line represents the 1g/L contour

200 shown in the later sections, including neap tides results. The contour line corresponding to a concentration of 1 g/L is
 201 drawn in black and hereafter to denote the "limit" of the turbidity maximum.

202 At low water, the mean \overline{SSC} is close to 4 g/L and $\overline{\Delta SSC}$ is 1.29 g/L. SSC_{max} and ΔSSC_{max} are both obtained
 203 approximately 4 kilometres downstream from the reference point chosen as the river mouth (see Figure 1). As the tidal
 204 cycle progresses, \overline{SSC} decreases by more than 35% in 3 hours, while $\overline{\Delta SSC}$ remains stable. SSC_{max} and ΔSSC_{max}
 205 are obtained 3 km upstream from the mouth, and their values increase between low water and mid-flood. Transects
 206 3 and 4 (Figure 5) show that the turbidity maximum extension is close to 60 km and does not vary significantly.
 207 Suspended sediment concentrations remain high during this phase of the tidal cycle.

208 Between mid-flood and high water, the mean \overline{SSC} is halved. \overline{SSC} is three times higher at low water than at high
 209 water. However, $\overline{\Delta SSC}$ remains nearly constant, suggesting that stratification is high. Strong SSC_{max} and ΔSSC_{max}
 210 values (more than 14 g/L) that occur 13 km from the river mouth support this assumption. An overall decrease in
 211 \overline{SSC} is also observed in transect 1 (Figure 5), even though strong concentrations still exist close to the bottom. The
 212 turbidity maximum extension is almost 45 km.

213 Between high water and mid-ebb, \overline{SSC} is nearly halved, and $\overline{\Delta SSC}$ is reduced by 70%. The \overline{SSC} and ΔSSC
 214 maxima reach their lowest values (Table 2). The difference in distance between high water and mid-ebb is 2 km,
 215 compared to 7 km between low water and mid-flood. The turbidity maximum extension at mid-ebb (Transect 2,
 216 Figure 5) is estimated to be between 35 and 40 km.

217 From mid-ebb to low water, mean SSC and ΔSSC increase sixfold and threefold, respectively. Maximum values
 218 also increase and occur 15 km downstream from their mid-ebb location.

219 These results suggest that the most dynamic periods in the tidal cycle are the first hours of flood and the last hours
 220 of ebb. These periods are associated with strong increases in $SSCs$ in the estuary, and with the highest differences
 221 in distance for SSC_{max} and ΔSSC_{max} . In contrast, from mid-flood to mid-ebb, suspended sediment concentrations
 222 decrease significantly.

223 4.3. Spring-neap variability

224 The indicators presented in the previous section (\overline{SSC} , $\overline{\Delta SSC}$, SSC_{max} and ΔSSC_{max}) are extracted from mod-
 225 elling results and presented in Table 3, for spring and neap tides. \overline{SSC} and $\overline{\Delta SSC}$ are calculated over two tidal cycles
 226 (approximately 24 h). The corresponding distances from the mouth are indicated for SSC_{max} and ΔSSC_{max} , as well
 227 as the time in the tidal cycle when these values are reached. Figure 6 shows the distribution of SSC for high and low
 228 water during spring and neap tides.

Table 3: The indicators \overline{SSC} , $\overline{\Delta SSC}$, SSC_{max} , ΔSSC_{max} (g/L), and their associated distances from the mouth (km) and times during the tidal cycle at mean, high and low river discharge ($50 \text{ m}^3/\text{s}$, $400 \text{ m}^3/\text{s}$, $5 \text{ m}^3/\text{s}$)

	Mean river discharge		High river discharge		Low river discharge	
	Spring tides	Neap tides	Spring tides	Neap tides	Spring tides	Neap tides
\overline{SSC}	1.63	0.183	1.29	0.307	1.22	0.091
$\overline{\Delta SSC}$	1.11	0.080	0.880	0.141	0.697	0.037
SSC_{max}	14.7	1.81	12.0	2.74	5.58	1.14
Distance	13.3	29.8	3.09	22.1	11.7	22.3
Tide hour	HW	LW	LW+3	LW	LW+4	HW+5
ΔSSC_{max}	14.4	1.44	10.6	2.22	4.21	0.887
Distance	13.3	29.8	1.64	22.1	12.2	22.3
Tide hour	HW	LW	LW+3	LW	LW+4	HW+5

229 The indicators \overline{SSC} , SSC_{max} and ΔSSC_{max} are reduced by an order of magnitude between spring and neap tides.
 230 Maxima occur at high water during spring tides and at low water during neap tides. The $\overline{\Delta SSC}$ is less than 0.1 g/L
 231 during neap tides, and close to 1 g/L during spring tides.

232 These values show a large reduction of the suspended sedimentary mass between spring and neap tides, which is
 233 also shown in Figure 6. The 1 g/L contour line (in black) is non-existent during the high water period of neap tides and
 234 barely visible at low water (approximately 45 km from the river mouth). It appears to be difficult to define a turbidity
 235 maximum zone under these conditions. For spring tides, the highest $SSCs$ are obtained close to the downstream

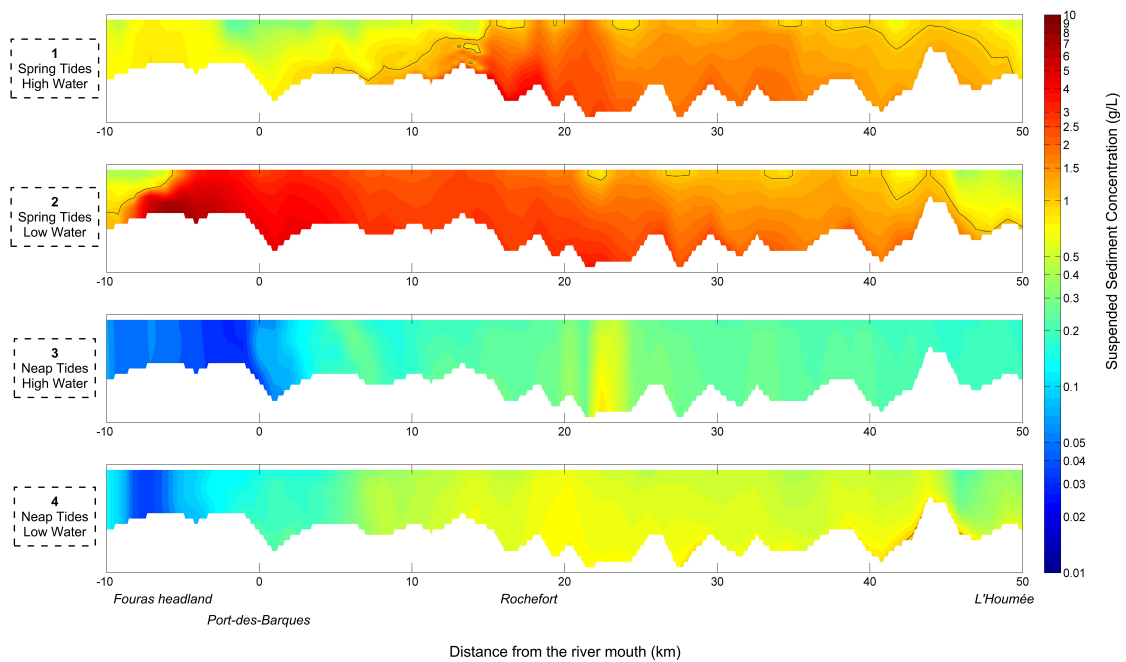


Figure 6: Transects of modelled suspended sediment concentrations for high and low water during spring and neap tides under mean river discharge. The black line indicates the 1 g/L contour.

236 limit of the sedimentary mass in suspension. During neap tides, the highest concentrations occur in the middle of the
 237 estuary (approximately 22 km from the river mouth during high water) or further upstream (low water).

238 4.4. Runoff variability

239 To estimate the impact of river discharge on the turbidity maximum dynamics and characteristics, the same indi-
 240 cators are presented in Table 3, for a high runoff of $400 \text{ m}^3/\text{s}$ and a low runoff of $5 \text{ m}^3/\text{s}$. Figures 7 and 9 show the
 241 corresponding transects along the estuary, as in the previous sections.

242 4.4.1. High runoff

243 The spring tide mean SSC decreases between the $50 \text{ m}^3/\text{s}$ and the $400 \text{ m}^3/\text{s}$ simulations (by more than 20%).
 244 Similar results are obtained for $\overline{\Delta SSC}$, SSC_{max} and ΔSSC_{max} (which decrease between 18% and 26%). In contrast,
 245 during neap tide the SSC increases by more than 50% when the river runoff increases. Transects 3 and 4 (Figure 7)
 246 demonstrate this difference, especially at low water: while the 1 g/L contour line was almost non-existent in Figure
 247 6, it is well defined in Figure 7.

248 The SSC_{max} and ΔSSC_{max} both occur three hours after low water during spring tide (three hours sooner than
 249 mean runoff conditions), and relatively close to the mouth (3.09 km and 1.64 km, respectively). Both maxima occur
 250 22 km from the river mouth during low water during neap tides (and at the same time as the mean runoff).

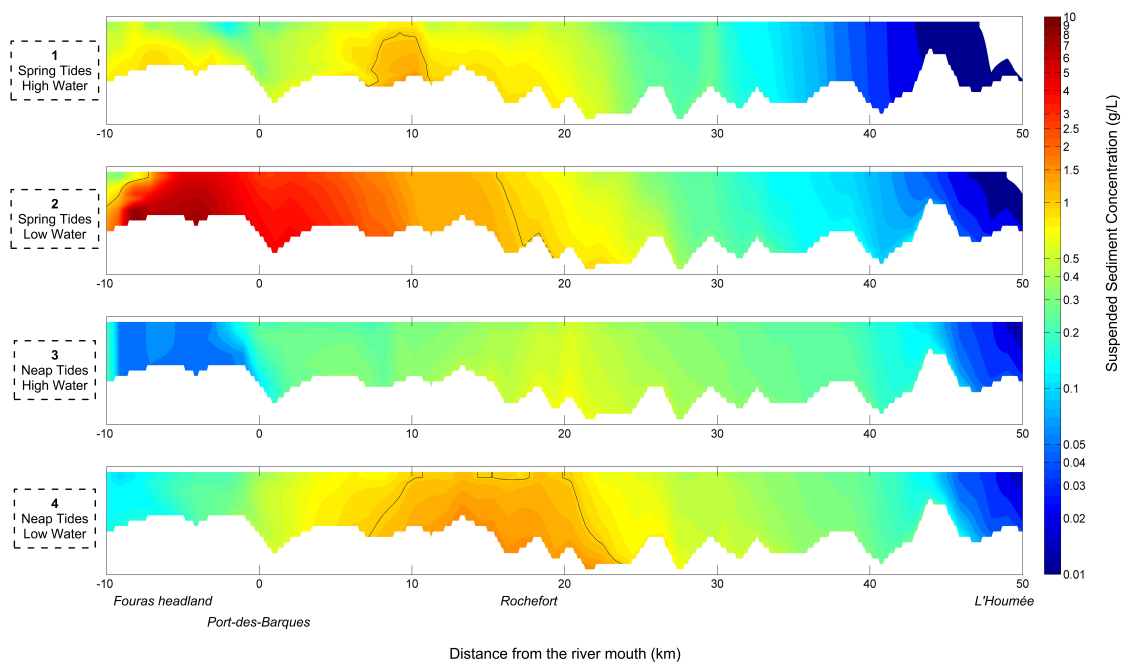


Figure 7: Transects of modelled suspended sediment concentrations for high and low water during spring and neap tides under high river discharge. The black line indicates 1 g/L contour.

251 The transects also show changes in the upstream area. At low water during spring tide, the turbidity maximum is
 252 denser, as shown by a downstream shift in the 1 g/L contour line, and the maximum *SSC* reaches 8.7 g/L, compared
 253 to 7.8 g/L in mean runoff conditions. The extension of the turbidity maximum is close to 30 km, compared to 60 km
 254 for the mean runoff simulation. The *SSC* does not exceed 0.01 g/L at the most upstream position for all transects.

255 At low water during spring tides, the downstream "limit" of the turbidity maximum shifts seaward by a few
 256 kilometres. If the limit is considered to be point of maximum *SSC*, this constitutes a 2.1 km difference. However, the
 257 turbidity maximum does not seem to be fully advected from the estuary into the bay. *SSC* measurements confirm this
 258 behaviour (Figure 8): river discharge is increasing from 150 m³/s to 400 m³/s and *SSC* decreases at Rochefort while
 259 it stays high at the river mouth. Moreover, *SSC* values greater than 1 g/L are recorded during neap tides.

260 4.4.2. Low runoff

261 Estuarine turbidity consistently decreases when the river runoff is very low (5 m³/s). All of the values in the
 262 final two columns of Table 3 (representing low runoff conditions) are lower than those for mean runoff. The transects
 263 (Figure 9) confirm this behaviour graphically.

264 The *SSC* and ΔSSC maxima occur at different times during the tidal cycle: 4 hours after low water for spring tide
 265 and five hours after high water for neap tide. Positions and extensions are similar to those for mean river discharge. For
 266 high water during spring tides (Figure 9, transect 1), *SSC* is however higher upstream during low runoff conditions.

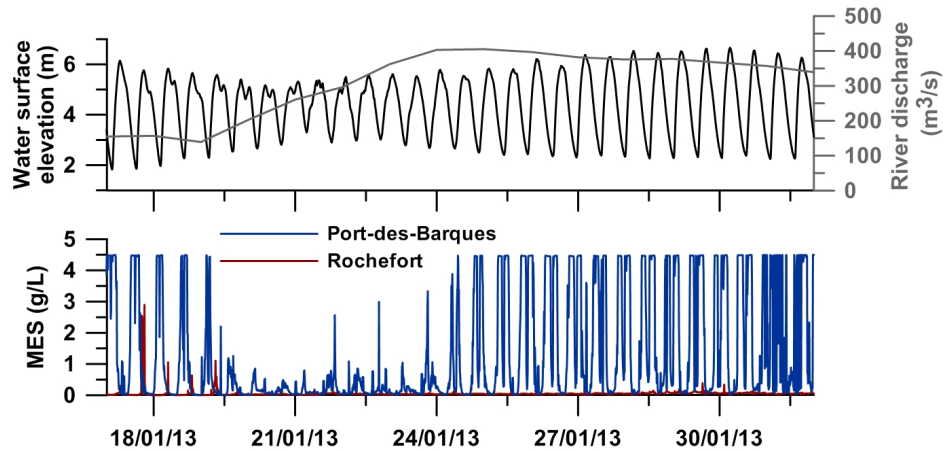


Figure 8: Observed SSC at the river mouth (Port-des-Barques) and Rochefort under flood conditions

267 During neap tide, the same remark made for mean runoff holds true for low runoff conditions: it is difficult to define
 268 a suspended sedimentary mass.

269 5. Discussion

270 5.1. Flood/ebb variability: deposition and resuspension

271 The semi-diurnal tidal cycle induces variations in current velocities, which directly impact the bed shear stress.
 272 Along with the nature and state of the sedimentary bed, bed shear stress is one of the parameters that control erosion
 273 processes (Mehta and Parchure, 2000; Tolhurst et al., 2000). The results of this study demonstrate the impact of these
 274 current variations on the turbidity maximum over a tidal cycle during spring tides.

275 The difference between high and low water slack is particularly important. The latter is short and current velocities
 276 remain high within the estuary (more than 1 m/s). Around high water, current velocities are weaker for a longer period
 277 of time, allowing sedimentation. This behaviour affects SSC and ΔSSC . The \overline{SSC} is three times higher at low water
 278 that at high water.

279 At high water, the maximum SSC is high (over 10 g/L) and so is stratification. Calculating a stratification
 280 ratio ($\overline{\Delta SSC} / \overline{SSC}$) allows comparison between the results. This ratio is greater than 1 at high water, showing that
 281 suspended sediments are not well distributed throughout the water column; the transects in Figure 5 confirm this
 282 result. In contrast, the stratification ratio is 0.34 at low water. Three hours after high water (mid-ebb), \overline{SSC} is halved,
 283 suggesting that deposition occurred for the last three hours, causing an overall decrease in estuarine SSC .

284 The \overline{SSC} decreases between low water and mid-flood as well, but it remains higher than around high water: \overline{SSC}
 285 is almost four times greater at mid-flood than at mid-ebb. This difference also suggests that deposition occurred, but
 286 for a shorter period of time. Sediments also begin to become resuspended due to the increase in current velocities,
 287 because SSC_{max} , ΔSSC_{max} and ΔSSC increase three hours after low water. The turbidity maximum extension,

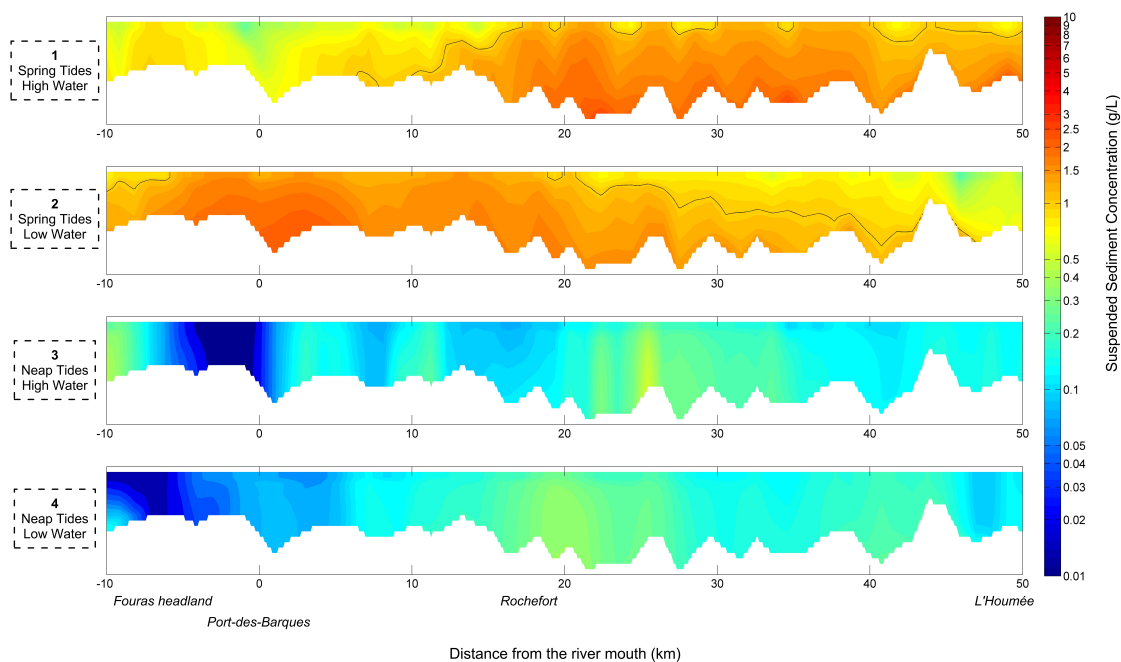


Figure 9: Transects of modelled suspended sediment concentrations for high and low water during spring and neap tides under low river discharge. The black line indicates the 1 g/L contour.

288 defined by the 1 g/L limit, is greater at low water and mid-flood (60 to 55 km) than at high water and mid-ebb (40 to
 289 45 km).

290 Sediments are maintained in suspension by strong velocities at the end of the ebb and at the beginning of the flood,
 291 making this period in the tidal cycle more dynamic than the high water slack. This behaviour has been observed in
 292 other estuaries including the Tamar, the Humber-Ouse (Uncles and Stephens, 1993; Uncles et al., 2006), the Gironde
 293 (Sottolichio, 1999) and the Seine (Brenon and Le Hir, 1999).

294 The SSC variations in the Charente turbidity maximum are mainly driven by the successive phases of deposition,
 295 advection and resuspension, caused by current velocity fluctuations. Uncles et al. (1996) showed, that the turbidity
 296 maximum in the Tamar estuary primarily results from local resuspension, and that seasonal variability is partly due
 297 to the migration of mud deposits that move the bed-source of sediments. These observations can be transposed to the
 298 Charente estuary, where both the modelling results presented in this study and field measurements (Coulombier et al.,
 299 2013) show the same type of behaviour.

300 5.2. Fortnightly and seasonal variability: does the turbidity maximum always exist ?

301 Results show a strong variability in the dynamics and characteristics of the turbidity maximum in the Charente
 302 estuary. The spring-neap tidal cycle and the fluctuations in river runoff cause significant variations in suspended
 303 sediment concentrations throughout the estuary.

304 The mean SSC decreases nearly ninefold between spring and neap tide. Bottom shear stress is significantly
305 reduced during neap tide because of the decrease in current velocities. As shown in the previous section, these
306 fluctuations strongly impact resuspension and deposition processes. Turbulence and tidal mixing keep sediments in
307 suspension during spring tide, whereas weak neap tide currents favour sedimentation (Dyer, 1997).

308 For mean runoff, it is difficult to define a turbidity maximum during neap tides, because no clear high concentration
309 area stands out. The maximum SSC (1.8 g/L) occurs approximately 30 km upstream, at low water, and probably
310 results from local resuspension due to bathymetric variations as opposed to tidal straining. Dual frequency echo
311 sounding performed during average tidal conditions (Coulombier et al., 2013) showed the presence of a turbidity
312 maximum, confirmed by high SSC recorded from mid-depth to the bottom, meaning that the turbidity maximum
313 was not extended throughout the water column. These observations testify of an intermediate state between spring
314 and neap tide, when the turbidity maximum still exists but begins to weaken. In contrast, echo sounding performed
315 during spring tide showed no interface in the water column with high SSC recorded throughout the water column
316 and over the entire area covered during the survey (from the river mouth to approximately 5 km downstream from
317 L'Houmée). Modelling results are coherent with these observations. In the Loire estuary, Marchand (1993) mentions
318 that during neap tide, the turbidity maximum settles and induces the formation of a mud layer at the bottom, which
319 can cover a large area (20 km in the case of the Loire). The dual frequency echo sounding mentioned before also
320 showed a net interface near the bottom at Rochefort, interpreted as a fluid mud patch of high concentration, with a
321 thickness reaching 1.5 m in the deepest part of the channel. Fluid mud at the bottom can significantly reduce friction
322 and tidal dissipation, which was taken into account in our model. This phenomenon has also been observed at the
323 Amazon outlet (Gabioux et al., 2005; Kineke et al., 1996). Other highly turbid macrotidal estuaries are likely to
324 display this type of behaviour, and Marchand (1993) highlights its negative effect on water quality, which is essential
325 to the ecology of these areas.

326 The same behaviour is observed for low runoff conditions (Figure 9), which often prevail during the summer; even
327 lower concentrations exist in the water column (mean SSC is less than 0.1 g/L and maximum SSC is less than 1.5
328 g/L). A shift in the time occurrence of maximum SSC and ΔSSC is also observed. They occur one hour earlier
329 during neap tide (five hours after high water), and two hours earlier during spring tide (four hours after low water).
330 In the absence of significant river discharge, the sediment dynamics of the estuary are essentially driven by the tidal
331 forcing. Toubanc et al. (2015) showed that tidal asymmetry inversions occur in the estuary, following the spring-neap
332 tidal cycle. For spring tide, the estuary is flood-dominant (shorter flood, stronger flood velocities). During neap tide,
333 it is ebb-dominant (shorter ebb, stronger ebb velocities). These inversions could explain the difference we find in this
334 study, with higher SSC during the ebb for neap tides, and higher SSC during the flood for spring tides.

335 High runoff simulations show that a turbidity maximum can also appear during neap tide. The joint action of high
336 river discharge and the tides leads to the formation and maintenance of a well-defined suspended sedimentary mass,
337 with significant longitudinal SSC gradients, in contrast to the mean and low runoff simulations. During spring tide,
338 SSC_{max} and ΔSSC_{max} occur three hours earlier (mid-flood) than for the mean runoff simulation (high water). This

339 difference can be explained by the tidal damping caused by a strong river discharge. Because the hours defined as for
340 low and high water are extracted from predictions, they cannot reflect the shift in the estuarine dynamics due to runoff
341 variability. As explained by Horrevoets et al. (2004), high runoff induce higher low water levels upstream, especially
342 when the cross-section is narrow. Friction is modified and the estuarine flow is more quickly by the river discharge
343 than for mean conditions. Godin (1985) indicated that in the downstream part of the estuary, low water will be slowed
344 and high water will be accelerated. The three-hour shift observed during spring tide and high runoff conditions could
345 correspond to this river discharge effect.

346 Although *SSC* levels vary between the mean and low runoff simulations, the position and extension of the turbidity
347 maximum between low and high water during spring tide are similar. These results suggest that, for this range of river
348 discharge, turbidity maximum dynamics are mainly driven by the tides. In the following subsection, the relative
349 importance of the tides and the density gradients are discussed further.

350 5.3. *Impact of density gradients on turbidity maximum characteristics*

351 Two principal mechanisms dictate the formation of a turbidity maximum in an estuary: tidal asymmetry and
352 density circulation (Allen et al., 1980; Brenon and Le Hir, 1999; Uncles et al., 1998). The characteristics and dynamics
353 of this sedimentary mass often result from the joint action of these two phenomena. Uncles and Stephens (1993)
354 explain that the position of the turbidity maximum sometimes corresponds to the position of the saline intrusion, and
355 varies according to changes in tidal and fluvial forcings. The transects for mean and high river runoff conditions
356 (Figures 6 and 7) show that, even if the turbidity maximum shifts seaward when the runoff is high, it does not seem to
357 be exported from the estuary.

358 Maintenance of the turbidity maximum within the limits of the estuary could be explained by interactions be-
359 tween this sedimentary structure and salinity gradients, which are also subject to variations in the tides and the river
360 discharge. Figure 10 shows the *SSC* along with modelled salinity levels for different tidal and fluvial conditions.

361 The saline intrusion limit, defined by the 1 psu contour line, is located upstream of the maximum *SSC* zone for
362 the mean runoff simulation. However, the downstream limit of 1g/L corresponds to the area where the salinity levels
363 change rapidly, i.e when the horizontal salinity gradient is stronger, especially at low water. Under a strong runoff, the
364 saline intrusion moves downstream and the horizontal salinity gradient is stronger. The association with the turbidity
365 maximum is clearer than for mean runoff conditions. Given these observations, we hypothesize that density gradients
366 associated with the salinity variations play a crucial role in maintaining the turbidity maximum inside the estuary.
367 In the Gironde estuary, according to Sottolichio et al. (2000), density gradients are essential to the stability of the
368 turbidity maximum and prevent a massive export of sediments. Brenon and Le Hir (1999) showed that tidal influence
369 is predominant in the Seine estuary, but that density gradients also play a significant role in shaping the structure of the
370 turbidity maximum and keeping fine sediments in the estuary. The relative importance of both mechanisms was also
371 studied by Allen et al. (1980) and Uncles et al. (1998), who consider that tidal asymmetry is predominant at low to
372 mean runoff conditions and that sediment trapping strongly depends on density circulation at high runoff conditions.

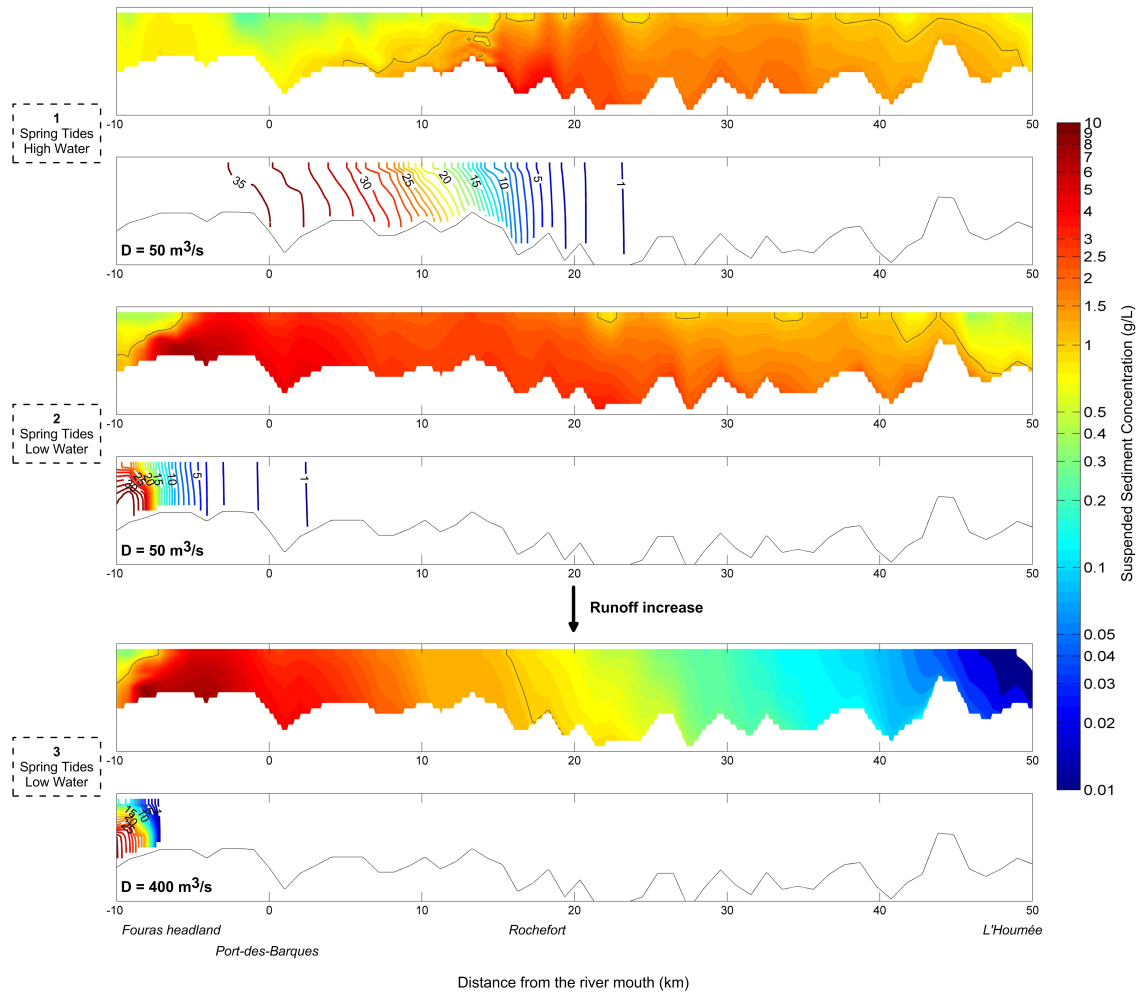


Figure 10: Transects of modelled suspended sediment concentrations and salinity for high and low water during spring tide under mean river discharge conditions (1 & 2) and for low water under high river discharge conditions (3).

373 Simulations that do not consider the density gradients related to salinity are presented in Figure 11. The results
 374 show that even when the density gradients are not taken into account, the turbidity maximum stays within the estuary
 375 for both mean and high river runoff conditions. However, density gradients seem to play a significant role in defining
 376 the extension and concentration of the turbidity maximum. At low water, the downstream end of the turbidity max-
 377 imum is sharper when density gradients are considered, and the longitudinal *SSC* gradient is much stronger (3.75
 378 *g/L/km* versus 1.25 *g/L/km* for the high runoff simulation).

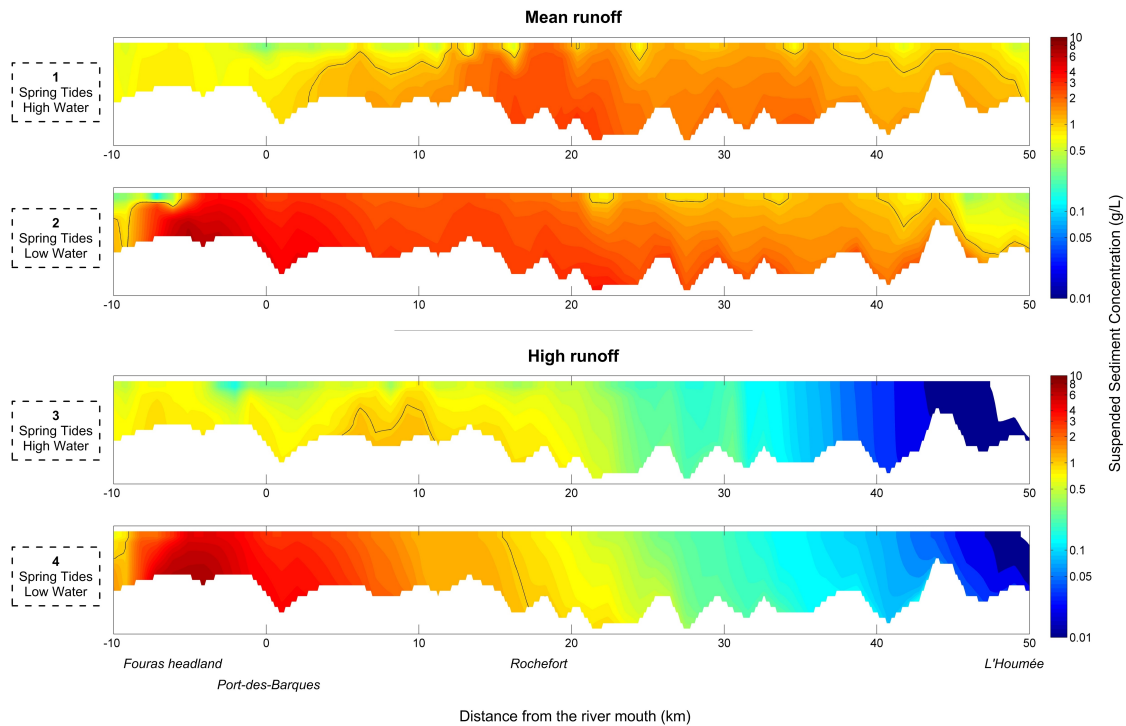


Figure 11: Transects of modelled suspended sediment concentrations for high and low water during spring tide, at mean (transects 1 & 2) and high (transects 3 & 4) river discharges. Density gradients are not taken into account.

379 Vertical density gradients also impact the structure of the turbidity maximum. For the mean runoff simulation,
 380 the downstream 1*g/L* limit is closer to the bottom when density gradients are considered, both at high and low
 381 water. Without these gradients, suspended sediments are better distributed throughout the water column, and the
 382 maximum concentrations are reduced. This behaviour is also observed for high runoff conditions. Figure 10 shows
 383 that salinity stratification is strong in this area, which reduces turbulent mixing and traps sediments near the bottom.
 384 This phenomenon was investigated and proved numerically by Geyer (1993) and Burchard and Baumert (1998). Blake
 385 et al. (2001) observed the same behaviour in the ACE Basin.

386 As in other macrotidal and/or highly turbid estuaries (Gironde,(Sottolichio et al., 2000); Humber-Ouse, (Uncles
 387 et al., 1998, 2006) and Seine (Brenon and Le Hir, 1999)), tidal asymmetry is the dominant mechanism leading to the
 388 formation of a turbidity maximum, but its structure and sediment trapping inside the estuary also depend on density

389 circulation.

390 **6. Conclusion**

391 The Charente estuary is a highly turbid macrotidal system characterized by strong *SSC* variations throughout the
392 semi-diurnal and the spring-neap tidal cycles. River discharge also strongly influences *SSC*.

393 The results of this study show that tidal forcing dominantly governs the dynamics and characteristics of the turbid-
394 ity maximum in the Charente estuary. Resuspension and deposition cycles are the main source and sink for suspended
395 sediments. Conditions during spring tide ensure that sediments are eroded and trapped in a highly turbid area for all
396 river runoff situations. However, weak neap tide currents are insufficient to maintain a well-defined sedimentary mass
397 in suspension. In this case, the river discharge can play a key role in the formation of the turbidity maximum; when
398 runoff is high, a compact suspended sedimentary mass is obtained. Under low and mean runoff during neap tide,
399 strong sedimentation is likely to induce the formation of a fluid mud layer at the bottom, or to reinforce its presence.

400 The turbidity maximum is not advected out of the estuary during high runoff conditions. Simulations without
401 density gradients show that the core of the turbidity maximum remains within the estuary, although its structure and
402 stability are significantly modified. The downstream end of the suspended sedimentary mass is less sharp, which
403 could lead to greater sediment export, especially at low water during spring tides. Preliminary sediment fluxes results
404 suggest a 12% net sediment export increase, after a 14 day simulation. Sediments are also more distributed throughout
405 the water column, suggesting that vertical density stratification traps sediment at the bottom. Thus, tidal asymmetry
406 is mostly responsible for the formation of the turbidity maximum, but density gradients help define its shape and the
407 vertical and longitudinal *SSC* stratifications.

408 Bed consolidation was not taken into account in the model and is a perspective for future research. This mechanism
409 could be particularly important for the transition between neap and spring tides. As mentioned before, neap tides
410 favour sedimentation, generating deposits that may not be resuspended for several days. In this situation, consolidation
411 could occur, making it more difficult for currents to erode sediments during the neap to spring transition. The impact
412 of fluid mud also merits further investigation. For this study, friction does not vary through time. The development of
413 coupling between deposits and the roughness length could be considered to improve model performance. Moreover,
414 the reduction of mixing caused by density stratification in the lutocline could favour the stabilisation of fluid mud and
415 suppress resuspension. Future developments of sediment component of the model could include this phenomenon.

416 **Acknowledgments**

417 The authors gratefully acknowledge funding from the Conseil Général of Charente Maritime, the Poitou-Charentes
418 Region, the CNRS, the FEDER and the University of La Rochelle. We also acknowledge the REFMAR portal for the
419 tide gauge data provided, as well as Ifremer for bathymetry and the MARS-3D code.

420 Appendix A. Sediment dynamics modelling

421 The sediment module implemented in MARS-3D solves an advection/diffusion equation, taking into account
422 erosion and deposition processes. A full description is available in previously cited studies (Le Hir et al., 2001; Le
423 Hir et al., 2011). A brief summary follows.

424 For pure mud, the erosion law of Partheniades-Ariathurai is chosen to calculate the erosion flux:

$$E_{mud} = E_{0,mud} \left(\frac{\tau}{\tau_{cem}} - 1 \right) \quad (A.1)$$

425 τ_{cem} is the critical shear stress for erosion and $E_{0,mud}$ is a constant.

426 The deposition flux is following the Krone law:

$$D = W_s C \left(\frac{1 - \tau}{\tau_{cd}} \right) \quad (A.2)$$

427 τ_{cd} is the critical shear stress for deposition, C is the suspended sediment concentration, and W_s is the settling
428 velocity. W_s is determined through a semi-empirical relationship with C (Le Hir et al., 2001), to take into account
429 flocculation processes:

$$W_s = W_{min}(1 + \alpha_1 C + \alpha_2 C^2) \text{ if } C \leq C_{W_{max}} \quad (A.3)$$

$$W_s = (1 - \beta_1 C^{\beta_2})^{4.65} R \text{ if } C_{W_{max}} < C \leq C_{W_{cr}} \quad (A.4)$$

$$R = \frac{W_{min}(1 + \alpha_1 C_{W_{max}} + \alpha_2 C_{W_{max}}^2)}{(1 - \beta_1 C_{W_{max}}^{\beta_2})^{4.65}} \quad (A.5)$$

430 W_{min} and W_{max} are the minimum and maximum settling velocities, respectively. $C_{W_{max}}$ is the concentration at
431 which $W_s = W_{max}$. α_1 and α_2 are constants chosen to reach a given maximum settling velocity at $C_{W_{max}}$. Beyond this
432 value of C , hindered settling velocity occurs. β_1 and β_2 are chosen to take into account this behaviour. $C_{W_{cr}}$ is a critical
433 value of concentration, which corresponds conceptually to the gel point (concentration from which the water-sediment
434 mixture is classified as fluid mud). Turbulence is also taken into account according to Van Leussen (1994).

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