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Settling dynamics of cohesive sediments in a highly turbid tidal river

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8 1. Introduction

9 The accumulation of cohesive sediments is one of the most prominent issues in many tidal estu-
10 aries, as it has major implications on estuarine morphodynamics and on water quality and dredging
11 strategies to support harbor activities. Cohesive sediments have the ability to aggregate into flocs,
12 which drastically affects sediment dynamics (Manning et al., 2010; Mehta, 2013; whitehouse, 2000;
13 Winterwerp, 2002; Xu et al., 2010). The settling velocity of flocs can be a couple of orders of magni-
14 tude larger than that of primary particles. In this sense, flocculation largely influences fine-grained
15 sediment transport through increased settling velocity and hindered settling, resulting in stronger
16 deposition and promoting the formation of estuarine turbidity maxima (ETM) (Burchard et al.,
17 2018; Horemans et al., 2020; Winterwerp, 2002). The strong cohesiveness of aggregated sediments
18 due to organic content may also reduce bed sediment erodibility (Malarkey et al., 2015; Parsons
19 et al., 2016). Factors enhancing flocculation include salinity (Gibbs, 1983; Liu et al., 2018; Mietta
20 et al., 2009; Zhang et al., 2021), the suspended sediment concentration (Mikkelsen and Pejrup,
21 1998; Verney et al., 2009), biological processes (Eisma, 1986; Deng et al., 2021; Fall et al., 2021;
22 Furukawa et al., 2014) and the turbulent characteristics of the flow (Gratiot and Manning, 2004;
23 Mikes et al., 2004; Verney et al., 2011; Winterwerp, 2002).

24 The effects of flocculation on sediment settling dynamics and deposition processes are highly
25 affected by hydrological conditions and may thus vary over different time scales. Settling variations
26 over the semidiurnal tidal cycle and the fortnightly cycle have been reported up to one or two orders
27 of magnitude (Guo et al., 2017; Pejrup and Mikkelsen, 2010; van Leussen, 1999; Van der Lee, 2000;
28 Manning et al., 2006). On a seasonal timescale, river runoff drives salinity intrusion, the rate
29 of organic matter and suspended matter concentration, resulting in seasonal variation in settling
30 velocities (Xia et al., 2004). In addition, settling velocity is challenging to study experimentally
31 due to the fragile nature of flocs.

32 The most used techniques in recent decades have been settling tubes, such as Owen tubes
33 (Owen, 1971). Although settling columns are inexpensive and easy to deploy in highly turbid
34 environments, they also have many disadvantages, such as (1) they may destroy larger flocs during
35 sampling (Dyer et al., 1996; Eisma et al., 1991), (2) flocculation due to differential settling may occur
36 in the tube (Eisma, 1986), (3) subsampling contamination due to incomplete removal of fine-grained
37 sediment and (4) changes in temperature may generate convection inside the tube (Puls and Kühl,
38 1996). Since then, new settling columns have been developed to overcome these inconveniences, with
39 sidewall withdrawal tubes to avoid subsampling contamination, thermal insulation and autonomous
40 sampling systems (Cornelisse, 1996; van Leussen, 1996). The Sedigraph instrument also measures
41 the settling velocity of fine grain sediment, however it is designed for laboratory granulometric
42 analyses and too-high concentrations required for such analyses may lead to hindered settling effects
43 and the underestimation of settling velocities (Stein, 1985).

44 Recently, considerable improvements have been made in settling velocity measurement, and
45 various in-situ instruments have been developed based on optic (Kineke et al., 1989; Gratiot et al.,
46 2015; Murray et al., 1996; Zaneveld et al., 1982), video (Fennessy et al., 1994; Heffler et al., 1991;
47 Sanford et al., 2005; Smith and Friedrichs, 2011; Sternberg et al., 1996; Van Leussen and Cornelisse,
48 1993), holographic (SEQUOIA; Graham and Nimmo Smith, 2010; Owen and Zozulya, 2000; Watson
49 et al., 1998, 2004) and laser (Agrawal and Pottsmith, 2000; Mikkelsen and Pejrup, 2001) methods
50 among others (Mantovanelli, 2005). The advantage of these new techniques is that they additionally

51 provide floc size information. A laser-based instrument is an indirect method of estimating settling
52 velocity, as it uses scattering theory for regularly shaped spherical particles to estimate particle
53 sizes and then computes the in situ mean effective density and mean settling velocity (Mikkelsen
54 and Pejrup, 2001). Such methods may induce error when nonspherical particles are studied. Video
55 and holographic-based methods can simultaneously measure particle size and settling velocity in
56 a fully automated manner (Graham and Nimmo Smith, 2010; Manning and Schoellhamer, 2013).
57 The density may then be estimated with the Stokes equation, giving additional information on the
58 particles inside the water column. Major limitations of such methods are the heavy time cost of
59 data postprocessing, the complex deployment of an imposing structure, a unique positioning close
60 to the seabed, and a range of application limited by a concentration lower than a few grams per liter
61 for the most advanced ones (Fennessy et al., 1994; Owen, 1971). Indeed, holographic systems are
62 generally limited to concentrations smaller than tens of $mg.L^{-1}$ (SEQUOIA), laser instruments are
63 capable of being used up to $800 mg.L^{-1}$ (Mikkelsen and Pejrup, 2001), Owen tubes are appropriate
64 for use up to $5 g.L^{-1}$ (Owen, 1971), and one of the most advanced methods found in the literature is
65 the INSSEV system, which is able to function with concentrations up to $8.5 g.L^{-1}$ (Fennessy et al.,
66 1994). However, the INSSEV must be positioned close to the seabed. A comprehensive review
67 of the different techniques, their advantages and disadvantages was proposed by Mantovanelli and
68 Ridd (2006) and pursued by Wendling et al. (2015).

69 In the highly turbid Garonne Tidal River, the surface concentration may reach $7 g.L^{-1}$ and
70 tens of grams per liter close to the riverbed. Recently, an optical settling column was specially
71 designed for this type of hyper turbid environment, namely, the System for the Characterization
72 of Aggregates and Flocs (SCAF) (Wendling et al., 2015; Gratiot et al., 2015). The SCAF was
73 successfully used under laboratory conditions for a wide range of natural sediment concentrations
74 ($20-30,000 mg.L^{-1}$; Le et al. (2020)). It was also used in the field during reservoir flushing in the
75 Arc River in the Alps (Legout et al., 2018). This new instrument benefits from easy handling and
76 straightforward data postprocessing. However, this new patented equipment has never been used
77 in the field in a hyperturbid environment that is subjected to tidal forcing.

78 Understanding and predicting settling and deposition processes is a key factor to achieve realistic
79 simulations of suspended sediment fluxes and concentration (Diaz et al., 2020; van Maanen and
80 Sottolichio, 2018). Various theoretical (process-based or empirical) formulations for predicting
81 settling velocities have been developed. A power law relating the settling velocity to SSC below
82 the hindered settling regime has been outlined by various authors (Dyer et al., 1996; Jones and
83 Jago, 1996; Pejrup and Edelvang, 1996; Puls et al., 1988). This type of formulation was based
84 on the hypothesis that SSC is the driving parameter of flocculation, and therefore on the settling
85 velocity variation. Van der Lee (2000) reported that the variations in settling velocity were related
86 to the tidal phase in the Dollard Estuary and proposed a formulation based on the time from
87 high water. Further investigations highlighted the dominant role of turbulence-induced aggregation
88 and floc breakup processes in settling velocity variations (Spearman et al., 2011). For example,
89 Verney et al. (2011) confirmed the major dependency of floc sizes on the Kolmogorov microscale.
90 Other studies defined a shear stress parameter that is included in the formulation of the settling
91 velocity to consider the influence of the turbulence (Dyer and Manning, 1999; Manning et al., 2007;
92 Pejrup and Mikkelsen, 2010; Winterwerp et al., 2006). However, studies on the settling dynamics
93 of cohesive sediments in tidal rivers, which are barely affected by salinity, therefore characterized

94 by less favorable flocculation conditions, are rare.

95 The aim of this study is to explore the variability of the settling velocity along different time
96 scales in a tidal river that is characterized by low salinity and low rate of organic matter and to
97 investigate simple empirical formulations of the settling velocity, which are necessary for numerical
98 modeling purposes. A series of field measurements have been conducted in the Garonne Tidal River
99 (Gironde Estuary, France). A specific protocol was designed to use the SCAF device in a highly
100 turbid river subjected to semidiurnal tidal forcing. This new instrument allowed us to evaluate
101 for the first time the values of settling velocities and their variations over different time scales in
102 such environment. The role of the ETM in those variations is discussed, and different empirical
103 formulations are proposed to predict the settling velocity variations observed in the Garonne Tidal
104 River.

105 2. Study site

106 The Garonne Tidal River is one of the two tributaries of the Gironde Estuary located on the
107 southwest coast of France (Fig. 1). From the confluence with the Dordogne River to the tidal
108 intrusion limit, the Garonne Tidal River extends over 95 km. The Garonne tidal river is subjected
109 to a semidiurnal macrotidal forcing, with a tidal amplitude ranging from 1.7 m to 6.2 m at the
110 confluence (Jalón-Rojas et al., 2018). In addition, during its propagation into the tidal river, the
111 tidal wave becomes asymmetric with shorter (longer) flood (ebb) duration and stronger (weaker)
112 flood (ebb) currents. This hypersynchronous behavior results in intense tidal pumping, leading to
113 massive sediment trapping and a highly concentrated ETM (Allen et al., 1980). During periods
114 of low river discharge, the suspended matter is advected landward into both tidal rivers. In the
115 Garonne Tidal River (GTR), a large ETM occurs at river flows lower than $300 \text{ m}^3 \cdot \text{s}^{-1}$, with surface
116 concentrations of few grams per liter (Jalón-Rojas et al., 2015, 2021).

117 Little is known regarding the floc size distribution or settling velocity of suspended sediment
118 in the Garonne Tidal River, as most of the previous studies were focused on the downstream part
119 of the Gironde Estuary, which is mainly composed of a mud-sand mixture (Allen, 1971; Manning
120 et al., 2004; Sottolichio et al., 2011). Gibbs et al. (1989) showed a progressive increase in the mean
121 diameter of suspended sediment particles from the Garonne Tidal River to the mouth of the Gironde
122 Estuary. According to this study, the mean diameter ranges from $5 \mu\text{m}$ to $20 \mu\text{m}$ in the Garonne
123 Tidal River, and a floc size maximum is reached 30 km seaward from the ETM (i.e., close to the
124 mouth of the estuary). More recent studies have shown that sediment in the Gironde Estuary is
125 characterized by low organic content with no seasonal variation (Abril et al., 2002; Etcheber et al.,
126 2007).

127 The Garonne Tidal River is therefore characterized by a pronounced and well-documented es-
128 tuarine turbidity maxima largely stretching in fresh waters during the dry season. Such highly
129 concentrated ETM occurs in a region barely affected by salinity and variation in organic content
130 and where no settling velocity data are available, which makes this system an ideal site for this
131 study. Although different process-based models of the Gironde Estuary and the Garonne Tidal
132 River have been developed over the past decades, all of which adequately reproduce the ETM in
133 the lower estuary, they still face challenges in reproducing the realistic SSC in tidal rivers (Diaz
134 et al., 2020; Lajaunie-Salla et al., 2017; van Maanen and Sottolichio, 2018). Such models were based

135 on a strong hypothesis on the settling velocity and did not rely on in situ measurements in the tidal
136 river.

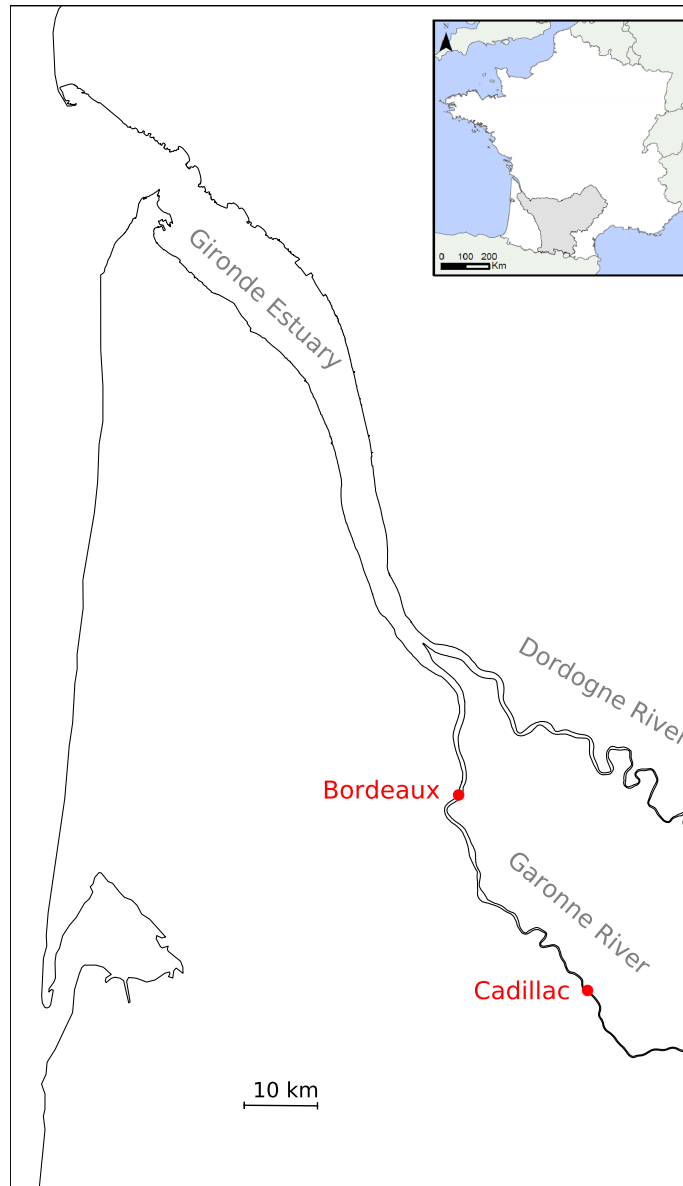


Figure 1: Map of the Gironde Estuary and the Dordogne and Garonne Tidal Rivers with locations of the field measurement sites (Bordeaux and Cadillac).

137 3. Materials and Methods

138 3.1. Laboratory experiments

139 The SCAF device was developed by the French Institute of Environmental Geosciences to effi-
140 ciently measure the sediment settling velocity in a highly turbid environment (Wendling et al., 2015;
141 Gratiot et al., 2015). This settling column is equipped with 16 infrared emitters and 16 diamet-
142 rically opposed photosensors. It measures the variation in light attenuation with time and depth

143 to estimate the settling velocity of suspended sediments, based on the fact that the absorbance
144 $A = -\log(I/I_{max})$ of a suspension of particles is the sum of the individual absorbance of each
145 particle, where I is the light intensity and I_{max} the light intensity through clear water. During the
146 settling, particles with the highest settling velocity will progressively fall below a given level, leading
147 to a progressive decrease of the absorbance. The settling velocity of each particle size class is then
148 given by the slope of a specific iso-absorbance value in a depth-time graph. The post-processing
149 is adapted from the method proposed by Piro et al. (2011). A more complete description of the
150 measurement principle can be found in Wendling (2015) and Gratiot et al. (2015).

151 The SCAF estimates a flocculation index (FI) as follow: $FI = (w_b - w_s)/w_s$, where w_b is the
152 settling velocity measured with six lower IR sensors of the settling column and w_s is the settling
153 velocity with six upper IR sensors of the settling column. In case of non-cohesive sediments, the
154 slope of iso-absorbances with time is constant along the depth of the settling column, meaning w_b
155 is equal to w_s and so FI is zero. For cohesive sediments, flocculation may occur during settling
156 resulting in an increased settling velocity with depth and time, leading to w_b greater than w_s and
157 FI greater to 0. The FI values reported in previous studies typically range from 0 to 10 (Wendling,
158 2015; Le et al., 2020; Legout et al., 2018). Negative values of FI could be due to hindered settling
159 effects.

160 Prior to field measurements, different tests were conducted in the laboratory to design an ex-
161 perimental protocol adapted to the use of the SCAF in a turbid environment subjected to tidal
162 forcing.

163 Even though the SCAF was previously used successfully with highly concentrated suspensions,
164 up to 30 g.L^{-1} (Le et al., 2020), the range of concentrations in which the instrument is able
165 to measure the settling velocity may be highly dependent on the mud composition. Therefore,
166 we tested the SCAF with 7 suspensions of different concentrations ranging from 0.2 to 15 g.L^{-1}
167 prepared with natural mud from the Garonne Tidal River. Only for the two more concentrated
168 suspensions (10 g.L^{-1} and 15 g.L^{-1}) were the sensors saturated during the first few seconds of
169 measurement (9 and 28 seconds, respectively). These laboratory tests validated the use of the
170 SCAF for settling measurements of surface waters in the Garonne Tidal River, knowing that the
171 surface concentration value of 15 g.L^{-1} is much higher than the surface concentration reported in
172 the literature thus far (Sottolichio and Castaing, 1999; Jalón Rojas, 2016).

173 The second limiting factor in designing our protocol was the settling time: the longer the
174 water sample is allowed into the settling column, the wider the range of particles considered in the
175 median settling velocity estimation. Previous studies using the SCAF selected settling times of 5 h
176 or more to catch the settling of very fine particles (Legout et al., 2018). Such a long settling time
177 was not appropriate to study variations throughout the semidiurnal tidal cycle. This limitation
178 is compounded by tidal asymmetry, which triggers very short flood periods in the Garonne Tidal
179 River (up to 4 h at Bordeaux station during spring tides). Therefore, we carried out settling
180 tests of different duration, namely, 1 h, 1 h30, 2 h, 2 h30 and 3 h, to determine the optimal time
181 resolution. Figure 2 presents the settling velocity distributions for the five experiments where the
182 settling time varies from 1 h to 3 h. Our results demonstrate that the median and quartile values
183 were very similar for all experiments, with median settling velocity values ranging from 0.068 to
184 0.073 mm.s^{-1} . The minimum settling velocity decreased with increasing settling time, as expected.
185 Thus, we decided to consider a settling time of 1 h 30 h to be able to collect water samples at least

186 every two hours. This sampling interval allowed us to catch the main stages of the semidiurnal tidal
187 cycle: low water, mid-flood, high water and mid-ebb, even when the tide is strongly asymmetric
188 with a flood duration of 4 hours.

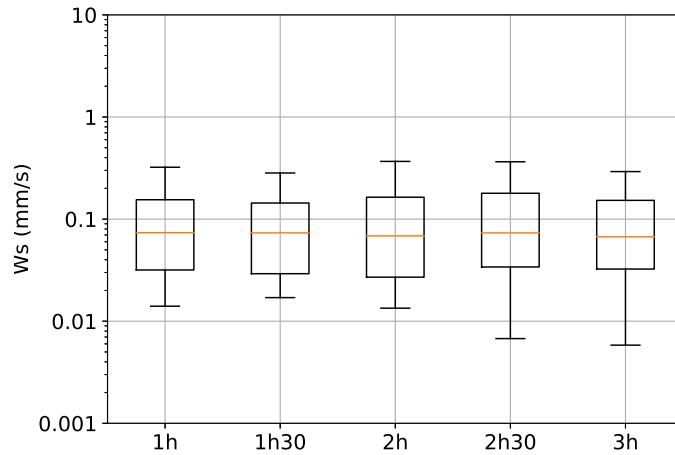


Figure 2: Distribution of the settling velocity for the five settling time tests under laboratory conditions

189 3.2. Field campaigns

190 Nine field campaigns were carried out in the Garonne Tidal River to evaluate the variations in
191 sediment settling velocities in surface waters over different time scales (tidal cycle, fortnightly cycle,
192 spring-to-summer transition). A summary of the tidal range and river flow conditions during the
193 field experiments are given in Table 1. Figure 3 shows timeseries of (a) water elevation at Bordeaux
194 and Cadillac and (b) daily averaged river flow at Tonneins (i.e., first station upstream of the tidal
195 propagation limit) with shadowed areas representing the presence of the ETM at Bordeaux (gray)
196 and Cadillac (blue).

Table 1: Experimental conditions

Location	Date	Tidal range (m)	River Flow ($m^3.s^{-1}$)	SSC ($g.L^{-1}$)
Fixed station				
Bordeaux	May 18th, 2021	3.9	680-770	0.53
	May 25th, 2021	5.10	350-420	2.07
	June 24th, 2021	5.15	250-300	4.16
	July 5th, 2021	3.9	230-300	2.24
	August 25th, 2021	5.10	120	7.80
	August 30th, 2021	3.6	85	4.64
Cadillac	June 25th, 2021	5.25	270-330	0.18
	July 2nd, 2021	3.9	230-260	0.04
	August 23rd, 2021	5.15	100	2.07
Longitudinal sections				
From	May 24th, 2021	5.1	390-440	
Bordeaux	June 18th, 2021	4.25	140-160	
to	July 19th, 2021	4.15	215-240	
Cadillac	August 19th, 2021	4.1	105	

197 Field measurements were conducted in two different locations, at Bordeaux and Cadillac (Fig.1),
 198 located 25 and 62 km from the river confluence, respectively, and 95 km and 132 km from the mouth,
 199 respectively. At these locations, water levels and surface turbidity are continuously recorded by
 200 automatic networks, allowing the monitoring of the upstream shift of the ETM during the whole
 201 period (<https://data.shom.fr> et <https://magest.oasu.u-bordeaux.fr/>). In addition, the tidal wave
 202 reaches its maximum amplitude along the estuary between these two stations (Bonneton et al.,
 203 2015). The measurements took place at Bordeaux on May 18th and 25th, 2021, on June 24th,
 204 2021, on July 05th, 2021 and on August 25th and 30th, 2021, and at Cadillac on June 25th, 2021,
 205 on July 2nd, 2021, and on August 23rd, 2021 (Tab.1). This period corresponds to the spring-to-
 206 summer transition, when the ETM shifts from the lower estuary toward the tidal rivers because
 207 the river flow decreases to its minimum annual value (Fig. 3). At both stations, vertical profiles
 208 of velocity, salinity, temperature and turbidity were measured. Velocity profiles were continuously
 209 recorded at 4 Hz by a Nortek Signature 500 kHz ADCP, with a vertical resolution of 0.5 m. Velocity
 210 profiles were then averaged over 10 min intervals. Salinity, temperature and turbidity profiles
 211 were recorded every 30 min with an NKE MPx multiparameter probe. This optical turbidity
 212 sensor was calibrated in the laboratory with sediments from the Garonne River to deduce the
 213 suspended sediment concentration (SSC). Calibration relationships are known to change with flocculation
 214 characteristics such as particle size, density and composition (Boss et al., 2009; Downing, 2006;
 215 Druine et al., 2018). Filtration was conducted in the field to estimate the SSC of surface waters
 216 every hour. These field SSC measurements satisfactorily fitted the laboratory calibration used to
 217 convert turbidity data. Some of these samples were also used to estimate the settling velocity with
 218 the SCAF at approximately high water, high water + 2 hrs, high water + 5 hrs, low water and low
 219 water +2 hrs.

220 During boat surveys along the GTR between Bordeaux and Cadillac on May 24th, 2021, June
 221 18th, 2021, July 19th, 2021 and August 19th, 2021 complementary bed sediment samplings were
 222 carried out with a Berthois cone, which is a weighted metallic cone that is dragged with a rope at
 223 the rear of the boat.

224 Dispersed particle size distributions (PSDs) of the sediments used in the settling column and
 225 riverbed sediments were measured after 60 seconds of stirring and sonication at their maximum
 226 level with a Malvern laser-diffraction instrument operating in the range 0.01-2000 μm .

227 3.3. Data bases

228 The daily river discharge for the Garonne River at Tonneins station and the water elevation
 229 at Cadillac were retrieved from the Banque Hydro database (www.hydro.eaufrance.fr). The water
 230 elevation at Bordeaux was extracted from the SHOM database (www.data.shom.fr/).

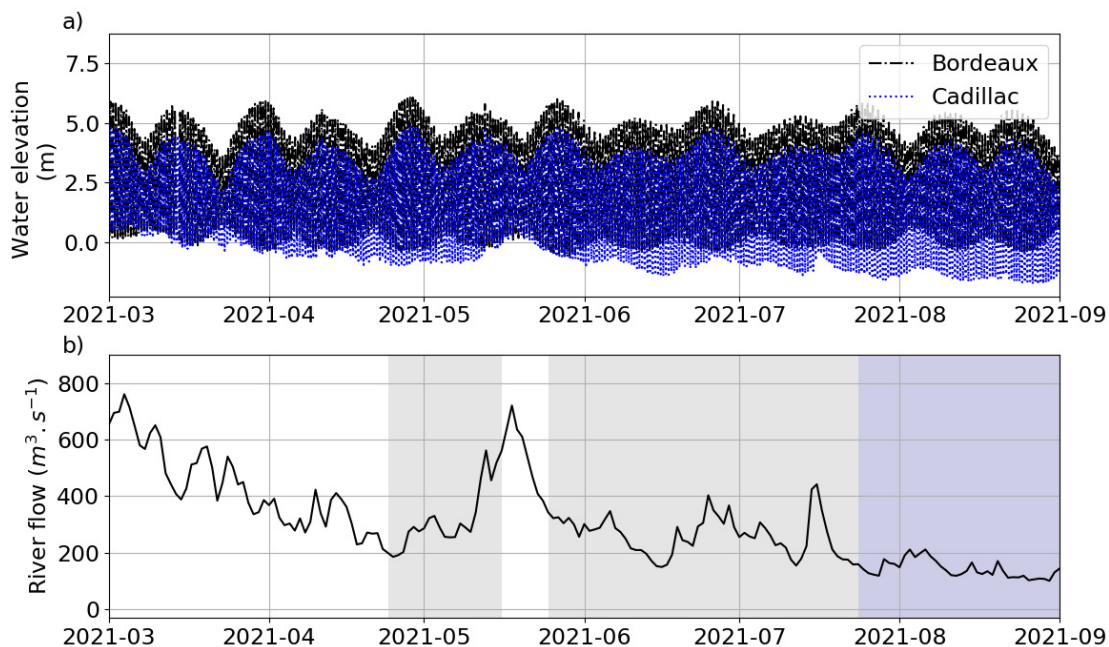


Figure 3: Time series of a) water elevation (m) at Bordeaux and Cadillac and b) daily averaged river flow ($\text{m}^3 \cdot \text{s}^{-1}$) at Tonneins. The shadowed areas correspond to the presence of the ETM at Bordeaux (gray) and Cadillac (blue).

231 4. Results

232 This section presents the observations of sediment settling dynamics in the surface waters of the
 233 Garonne Tidal River over different time scales. First, variations along the semidiurnal tidal cycle
 234 are presented, and then the data collected during neap and spring tides are compared. Finally,
 235 variations over the spring-to-summer transition are investigated. In this study, the settling velocity
 236 of suspended sediment is expressed as the median settling velocity w_{50} , and the median diameter
 237 D_{50} values refer to the dispersed particles (after sonication). The velocity data are projected into
 238 a local coordinate system with the x-axis directed along the riverine channel with positive values
 239 for inflow, the y-axis directed laterally toward the right bank, and the z-axis directed upward. The

240 velocities shown in the figures refer to the velocity component along the channel axis (x-axis). Most
241 of the data presented in this section were collected at Bordeaux. Data collected at Cadillac were
242 mostly not representative due to a very low SSC (below 60 mg.L^{-1}), i.e., out of the concentration
243 range of the SCAF and the Malvern instruments. Only seven samples appeared to be significant
244 (five of which are presented in Figure 5), and they are discussed in subsection 5.2.

245 4.1. Variations throughout the semidiurnal tidal cycle

246 Over the complete set of data, the settling velocity ranged from 0.018 to 0.268 mm.s^{-1} , and the
247 median diameter ranged from 4.74 to $14.38 \text{ }\mu\text{m}$. Settling velocities were lower at Bordeaux than
248 at Cadillac, with values ranging from 0.018 to 0.144 mm.s^{-1} and from 0.067 to 0.268 mm.s^{-1} ,
249 respectively. Median diameters were higher at Cadillac than at Bordeaux, with average values of
250 11.62 and $7.17 \text{ }\mu\text{m}$, respectively. Two examples of data collected along a tidal cycle at Bordeaux
251 and Cadillac are presented in Figures 4 and 5, with timeseries of (a) water level in meters, profiles
252 of (b) velocity, (c) suspended sediment concentration and (d) salinity, median diameter of dispersed
253 particles from surface waters and settling velocity of suspended sediments from surface waters. A
254 distinct pattern was observed at Bordeaux along every tidal cycle, with a decreasing settling velocity
255 during the rising tide and an increasing settling velocity during the falling tide (Fig. 4 f). The
256 range of settling velocity (i.e., quartile values) also varied during the tidal cycle, with a wider range
257 at the end of the ebb and a narrower range at the end of the flood. A similar pattern was found for
258 the median diameter. At Cadillac, the pattern was flattened compared to Bordeaux, with relatively
259 similar settling velocities from mid-flood to mid-ebb and an increase at the end of the ebb (Fig. 5
260 f).

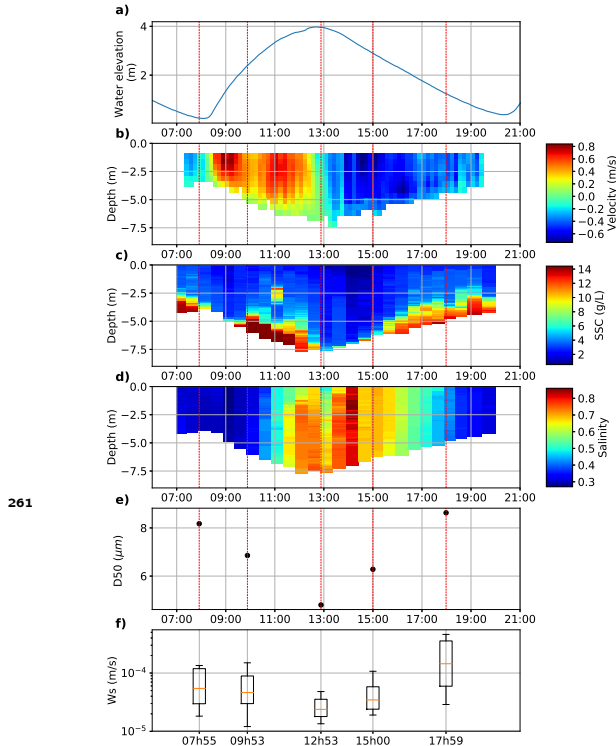


Figure 4: Time series of a) water elevation in meters, b) velocity profiles in meters per second, c) suspended sediment concentration in grams per liter, d) salinity, e) median diameter of surface suspended sediments in microns, and f) settling velocity distribution of surface suspended sediments in meters per second. Data collected at Bordeaux on August 30th.

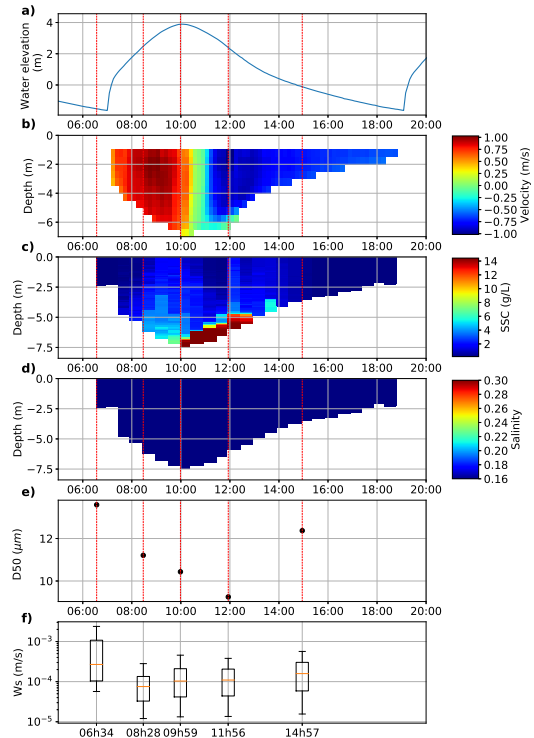


Figure 5: Time series of a) water elevation in meters, b) velocity profiles in meters per second, c) suspended sediment concentration in grams per liter, d) salinity, e) median diameter of surface suspended sediments in microns, and f) settling velocity distribution of surface suspended sediments in meters per second. Data collected at Cadillac on August 23rd.

262 This tidal pattern suggests that sediment processes and transport mechanisms taking place
 263 along the tidal cycle, such as erosion, deposition and advection, determine the settling velocity and
 264 the median diameter. To precisely distinguish advection from local vertical processes (erosion and
 265 deposition), simultaneous measurements at two close stations are needed. However, the evolution
 266 of the median settling velocity along with the depth-averaged SSC and velocity (Fig. 6) provides
 267 insight into the processes involved. Throughout the tidal cycle, the variation in SSC with flow ve-
 268 locity at Bordeaux displayed the same specific pattern for all hydrological conditions. At the end of
 269 the outflow, the decrease in SSC associated with a decrease in velocity indicates a deposition mech-
 270 anism (1). The deposition lasted from the beginning of the inflow until a velocity of approximately
 271 $0.4 \text{ m}\cdot\text{s}^{-1}$ was reached. Then, the increasing velocity increased with an increase in SSC, suggesting
 272 resuspension (2). Another phase of decreasing SSC and velocity evokes deposition (3). When the
 273 outflow reached $-0.4 \text{ m}\cdot\text{s}^{-1}$, both SSC and velocity increased again, probably due to resuspension
 274 (4). At the end of the outflow, the SSC increased or remained equal while the velocity decreased,
 275 which is likely associated with advection and/or diffusion mechanisms (5). The associated patterns
 276 of settling velocity revealed that it was higher at the end of the resuspension/advection/diffusion
 277 phases and lower at the end of the deposition phases. Higher values of settling velocity at the

278 end of resuspension phases could be attributed to bigger particles being eroded from the bed and
 279 maintained in suspension by higher turbulence and/or higher flocculation promoted by higher SSC.
 280 In the other hand, lower value during high water slack time may be attributed to sorting processes
 281 due to lower turbulence and so deposition of the bigger particles.

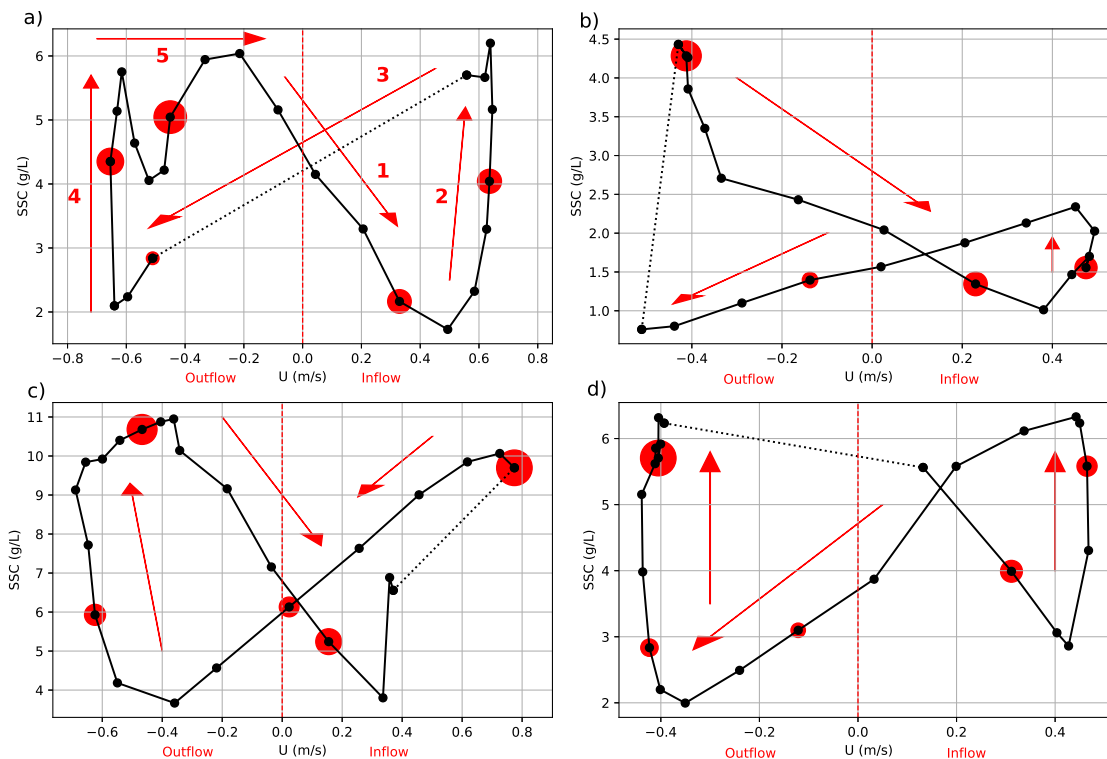


Figure 6: Variation in the depth-averaged SSC with the depth-averaged velocity for the data collected at Bordeaux on a) June 24th, b) July 5th, c) August 25th and d) August 30th. The red dot size represents the relative order of magnitude of the median settling velocity of surface suspended sediment.

282 4.2. Variations throughout the fortnightly cycle

283 Even if the settling velocity followed the same pattern along the tidal cycle for all the mea-
 284 surement conditions, differences can be observed when we discriminate neap tide from spring tide
 285 observations. Figure 7 shows the variations in the settling velocity distribution of surface sediments
 286 in relation to the time to high water for (a) spring and (b) neap tides. The median settling velocity
 287 was slightly higher during spring tides than during neap tides, with mean values of $0.072 \text{ mm}\cdot\text{s}^{-1}$
 288 and $0.06 \text{ mm}\cdot\text{s}^{-1}$, respectively. The range of settling velocity was also wider during spring than
 289 during neap tide. This is likely the result of higher resuspension and vertical mixing during spring
 290 tide, as revealed by the higher SSC and tidal currents in spring (Fig.6 a and c) than at neap tides
 291 (Fig.6 b and d). Regarding the median diameter, the comparison between neap and spring tide is
 292 not straightforward. Similar values of D50 were observed in July for both conditions. In May, the
 293 median diameter during neap tide was slightly larger than during spring tide, with mean values of
 294 $12.25 \mu\text{m}$ and $10.66 \mu\text{m}$, respectively, while in August, the opposite trend was observed, with mean
 295 values of $6.95 \mu\text{m}$ and $8.25 \mu\text{m}$, respectively. This pattern may be explained by the river flood
 296 (approximately $700 \text{ m}^3\cdot\text{s}^{-1}$, Fig. 3) that occurred in May at neap tide, which might have brought

297 some particles with higher dispersed D50 from landward sources.

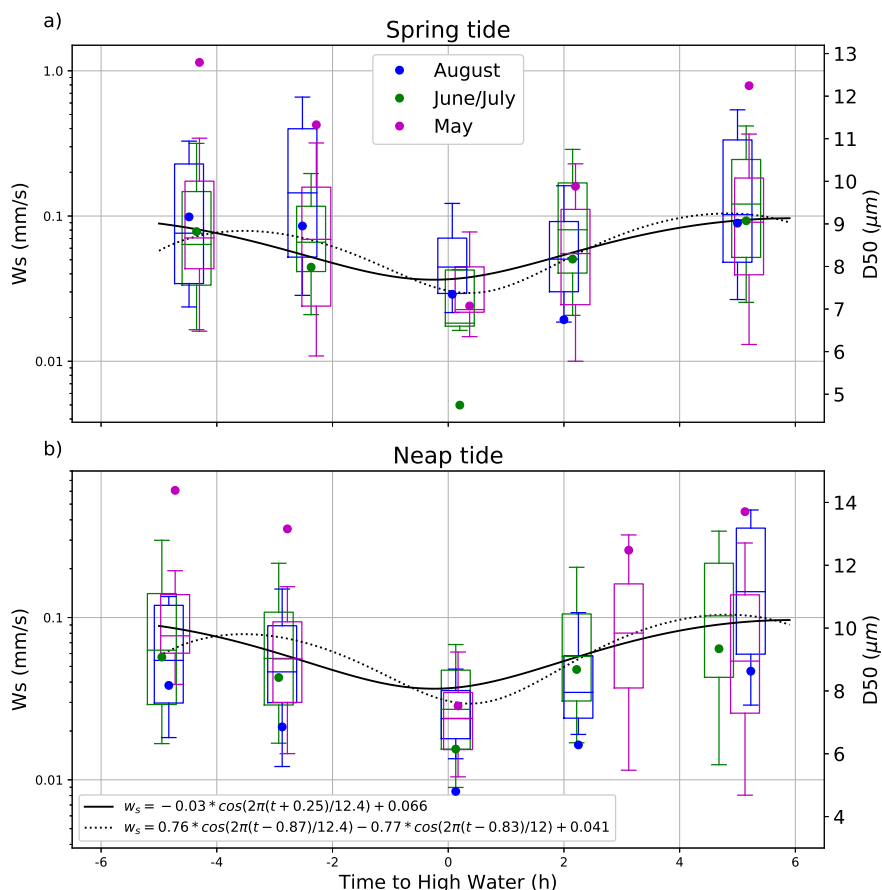


Figure 7: Settling velocity distribution in millimeters per second (colored box plots) and median diameter in microns (colored dots) of surface suspended sediments as a function of the time to high water during a) spring tides and b) neap tides. Data presented in this figure have been collected at Bordeaux. The colors correspond to the period of measurement: magenta for May, green for the end of June and the beginning of July and blue for August. The full and dotted black lines represent two relations of the median settling velocity variation with the time to high water, which are discussed in Section 5.2.

298 4.3. Seasonal variations

299 Observations were carried out during four consecutive months to study the variations in sediment
 300 settling dynamics during the transition period of decreasing river flow that promotes the shift of
 301 the ETM from the lower estuary to the tidal river. In May, the river flow was impacted by a spring
 302 freshet, while it decreased in the following months to less than $200 \text{ m}^3 \cdot \text{s}^{-1}$ in August (Fig. 3).
 303 The settling velocities slightly increased between May and August, with tidally averaged settling
 304 velocities of 0.059 and $0.072 \text{ mm} \cdot \text{s}^{-1}$, respectively (Fig. 7). Note that the increase between May
 305 and August was more pronounced at spring tides than at neap tides. This enhanced increase during
 306 spring tide might be due to higher resuspension and vertical mixing in August due to higher tidal
 307 current intensity and/or more available sediment on the bed.

308 In Figure 7, in contrast to the increase in settling velocity, a decrease in the median diameter of
 309 the dispersed particles can be observed between May and August, with tidally averaged D50 values

310 of 11.5 and 7.6 μm , respectively. This tendency is even clearer in Figure 8, which represents the
 311 particle size distribution of dispersed particles collected in surface waters at Bordeaux in the same
 312 period. A clear shift of the particle size distribution can be noticed between May (in blue) and
 313 the following months (in red and black). In July, after the installation of the ETM (see discussion
 314 in Section 5), the quantity of small particles ($< 10 \mu m$) increased, and the second tiny peak at
 315 approximately 500 μm (sand fraction) flattened.

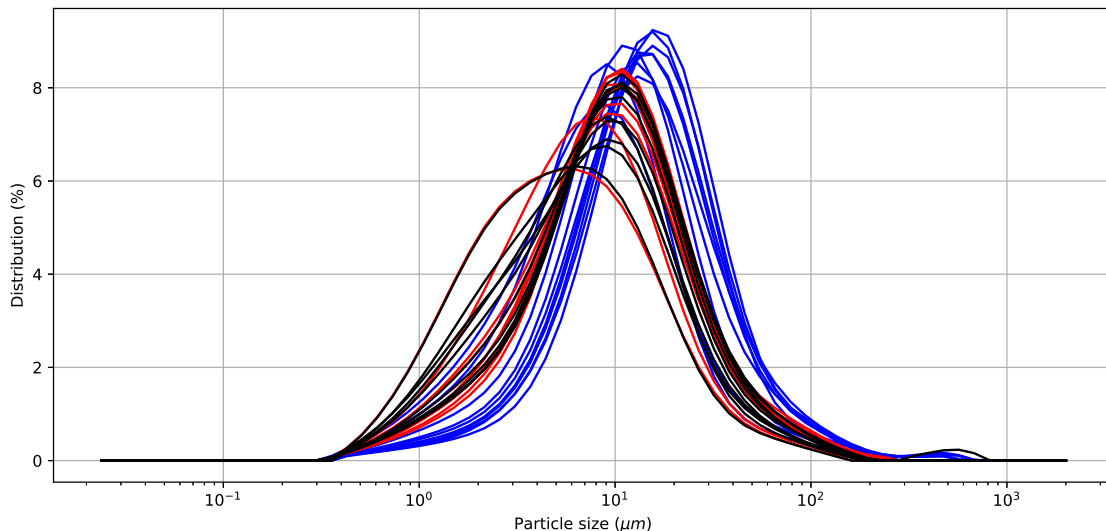


Figure 8: Particle size distribution of the dispersed surface particles collected in May (blue), June and July (red) and August (black) at Bordeaux.

316 5. Discussion

317 5.1. Influence of the ETM

318 The influence of the upward displacement of the ETM into the Garonne Tidal River on settling
 319 dynamics was evaluated through field measurements carried out in late spring and the beginning
 320 of summer (Fig. 3). As expected, the ETM progressively moved upward from the Gironde Estuary
 321 to the Garonne Tidal River with decreasing river flow: (1) in April, the river flow decreased to 200
 322 $m^3 \cdot s^{-1}$, and the ETM appeared in Bordeaux; (2) in May, a freshet ($Q = 700 m^3 \cdot s^{-1}$) momentarily
 323 moved the ETM downward, which moved back to Bordeaux in June; and (3) the ETM finally
 324 reached Portets and Cadillac in July (Fig. 3). In the Gironde Estuary, the ETM is associated with
 325 the presence of a fluid mud layer at the bottom. During the dry season, when the river flow is lower
 326 than $500 m^3 \cdot s^{-1}$, ETM moves upstream, and fluid mud forms in the tidal rivers (Sottolichio and
 327 Castaing, 1999). The variation in the particle size distribution of bed sediments along the Garonne
 328 Tidal River for different river flow conditions is shown in figure 9. Bed sediment samplings carried
 329 out between May and August 2021 (Fig. 9) seem to confirm the formation of fluid mud in the
 330 Garonne Tidal River with decreasing river flow. In May, the bed surface of the GTR is composed
 331 of mud, sand and pebbles/rocks depending on location, while in June, the GTR is mostly covered
 332 by mud. In July, a slight increase in river flow was sufficient to remove some patches of mud (at
 333 km 12 and km 23). In August, the river flow lowered to $100 m^3 \cdot s^{-1}$, and a fluid mud layer covered

334 almost the entire portion between Bordeaux and Cadillac. The shift in the particle size distribution
 335 observed between May and the following months (Fig. 8) was likely induced by the displacement
 336 of the ETM and the arrival of a fluid mud layer on the bed of the Garonne River.

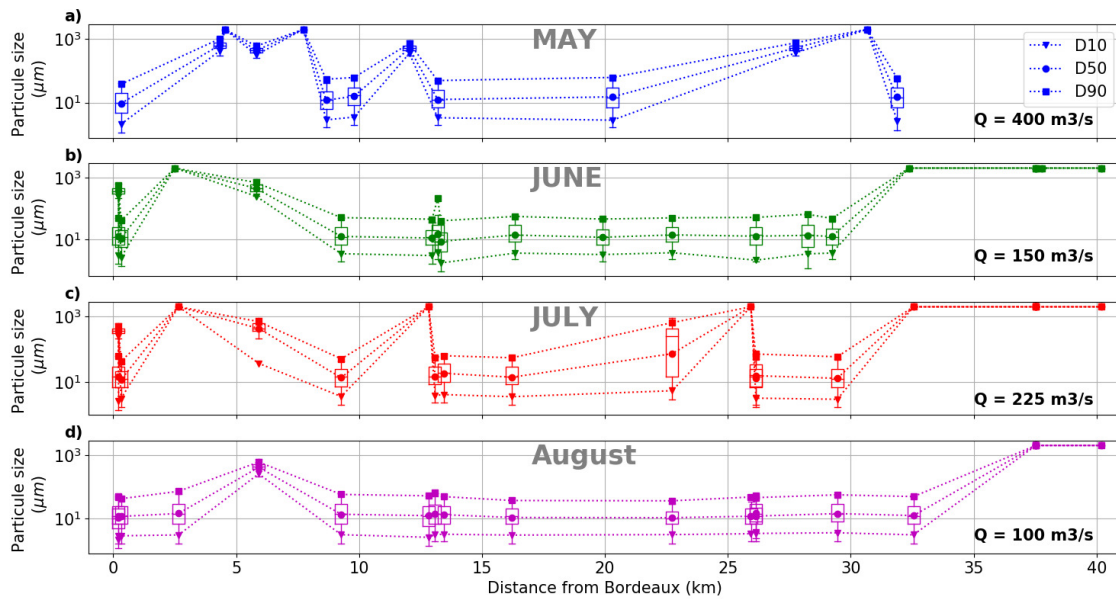


Figure 9: Particle size distributions of bed sediments along the Garonne Tidal River: from Bordeaux to Cadillac.

337 The increase in settling velocity when the median diameter of dispersed particles decreases may
 338 indicate higher flocculation of particles. In Figure 10, the flocculation index (FI), which indicates
 339 the tendency of sediments to flocculate in quiescent water (i.e., in the settling column) is represented
 340 as a function of SSC. The flocculation appeared to be strongly correlated with the SSC, with a linear
 341 increase in FI with SSC. In May (before ETM arrival in Bordeaux), the SSC is reduced, as is the
 342 FI, with a mean value of 1.34. In August (after ETM installation in Bordeaux), the SSC increased,
 343 and the FI varied from 2 to 12, with a mean value of 5.8 (Fig. 10). The settling velocity variations
 344 seemed also correlated with the FI and SSC, as higher settling velocities were observed at high SSC
 345 and FI, and vice versa (Fig. 10 and 12). Therefore, the increase in SSC induced by the upward
 346 displacement of the ETM should have favored flocculation and the increase in settling velocities.
 347 The influence of SSC on the settling velocity is further detailed in Subsection 5.2.

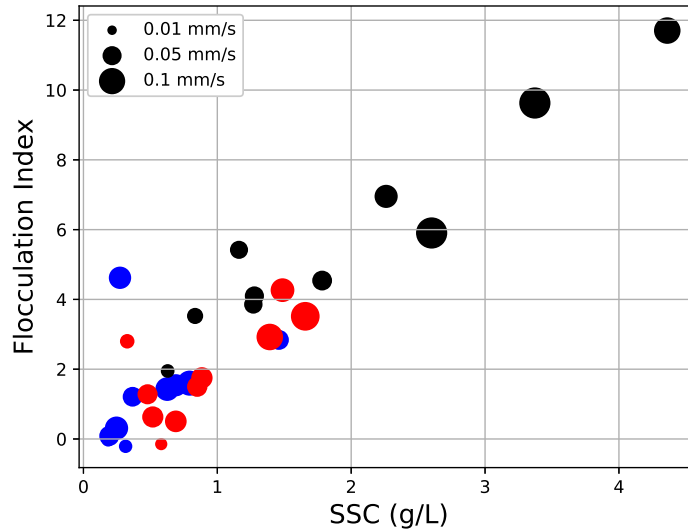


Figure 10: Flocculation index (FI) variations with the surface sediment concentration. Sediments collected in May (blue), June and July (red) and August (black) at Bordeaux. The size of the dot is proportional to the median settling velocity.

348 In the Garonne Tidal River, the ETM is generated upstream of the salt intrusion limit by tidal
 349 pumping during low river discharge (Allen et al., 1980; Jalón-Rojas et al., 2015, 2021). Figure
 350 11 illustrates the median settling velocity of surface sediments as a function of the surface water
 351 salinity. In the tidal river where the salinity remained below 0.8, the effect of salinity on suspended
 352 sediment dynamics and more precisely on flocculation appeared to be limited. Salinity is well known
 353 to promote flocculation in estuaries, whereas in this study, the median settling velocity does not
 354 correlate with salinity. This can be partly explained by the fact that higher salinity values are
 355 encountered during high water slack times when the deposition process occurs. The deposition
 356 process may counteract salinity-induced flocculation in surface waters. Further investigations are
 357 needed to more deeply analyze the effects of salinity on flocculation. In the lower Gironde Estuary
 358 (i.e., downstream of the salt intrusion limit) salinity may be a key parameter for flocculation and
 359 settling dynamics (Gibbs et al., 1989; Mikeš and Manning, 2010). Additional in situ measurements
 360 downstream of the lower estuary are required to gain a better understanding of this issue.

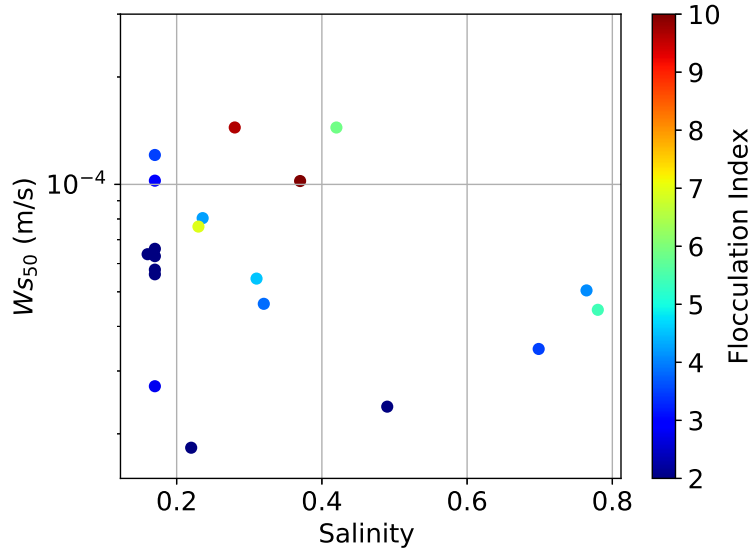


Figure 11: Median settling velocity variations with salinity and flocculation index. Data collected at Bordeaux.

361 5.2. Settling velocity prediction

362 The settling process is a key aspect of mud dynamics that depends on the sediment composition,
 363 water properties, sediment concentration, and turbulence characteristics of the ambient water,
 364 among others. All these parameters vary in time and space. The prediction of settling velocities
 365 is therefore challenging, and different complex empirical formulations have been proposed in the
 366 literature (Manning and Dyer, 2007; Soulsby et al., 2013). In this section, our results are compared
 367 with simple empirical formulations that consider SSC and tidal phase as parameters correlating
 368 with the settling velocity. In the absence of any more reliable parameterization, the predictive
 369 capabilities of these formulations are assessed, since they are of potential utility for operational
 370 simulations.

371 5.2.1. Relationship with SSC

372 The settling velocity is supposed to be well correlated with SSC based on the hypothesis that
 373 an increase in SSC induces an increase in floc collision frequency, which favors floc growth (Pejrup,
 374 1988). In addition, bed erosion can increase SSC and the resuspension of larger flocs, which could
 375 also explain the correlation between SSC and settling velocity. Figure 12 presents the variations
 376 in median settling velocity with SSC in surface waters. From those data, a power law relation
 377 between the settling velocity and SSC measured at Bordeaux was estimated: $ws = 0.068 * SSC^{0.4}$
 378 (Fig. 12 a). This power law indicated that variations in SSC explained only 41% of the variation
 379 in the settling velocity (Tab. 2), which suggests that SSC variations are not sufficient to explain
 380 the settling velocity variations. This idea is reinforced by the fact that for similar SSC values, the
 381 settling velocities measured in August were lower than those in June/July (Fig. 12 b), whereas the
 382 flocculation index was equivalent for both periods (Fig. 10), and the particle size distributions were
 383 comparable (Fig. 8).

384 Figure 12 a) also compares our data with the formulations by Ross (1988) and Mehta (1986)
 385 obtained with laboratory experiments. Even if the Ross (1988) formulation gave settling velocities

386 of the same order of magnitude as the data presented in this study, the influence of SSC on the
 387 settling velocity was more important as the slope became steeper. This could be due to differences
 388 in sediment and water composition (e.g., binding efficiency, salinity). The hindered regime reached
 389 approximately 2 g.L^{-1} in Ross (1988) experiments, while it seems that sediment at Bordeaux did
 390 not reach hindered settling at 4 g.L^{-1} . Likewise, hindered settling has been shown to start for
 391 concentrations greater than 13 g.L^{-1} in the Gironde Estuary Sottolichio et al. (2011). This could
 392 mean that flocculation was less important in the Garonne Tidal River than in the study by Ross
 393 (1988) .

394 When data are discriminated by periods of measurement (Fig. 12 b), the covariance between
 395 SSC and settling velocity varies on a seasonal time scale. In May, the covariance between the
 396 settling velocity and SSC was poor, suggesting that variations in SSC were not significantly driving
 397 the variation in settling velocity (Tab. 2). In June/July and August, the slope was steeper,
 398 showing a stronger influence of the variations in SSC on the variations in settling velocity, and
 399 both parameters were significantly correlated. This reinforces the fact that the ETM installation
 400 modified the settling behavior of the particles, as discussed in Subsection 5.1, and SSC had a larger
 401 influence on the settling velocity inside the ETM than outside. Similar observations were made in
 402 the 'Groot Gat' tidal channel, with varying relations between SSC and settling velocity throughout
 403 the seasons (Van der Lee, 2000).

404 Spatial variability in settling behavior was also observed. The comparison of data collected at
 405 Bordeaux and Cadillac reveals that Cadillac data did not fit any of the relations between settling
 406 velocity and SSC obtained with data from Bordeaux. At Cadillac, particles were slightly larger than
 407 at Bordeaux (refer to Section 4), which could partly explain the higher settling velocity observed
 408 at Cadillac. Such observations seem to indicate a local source of sediment. However, more data
 409 are needed to precisely investigate the spatial variability of the settling dynamics. Similarly, van
 410 Leussen (1999) also found a variety of relationships linking settling velocity and SSC in the Ems
 411 estuary from measurements at five locations. In conclusion, power laws to estimate the settling
 412 velocity from SSC were shown to be seasonal and site-specific even in the same estuary.

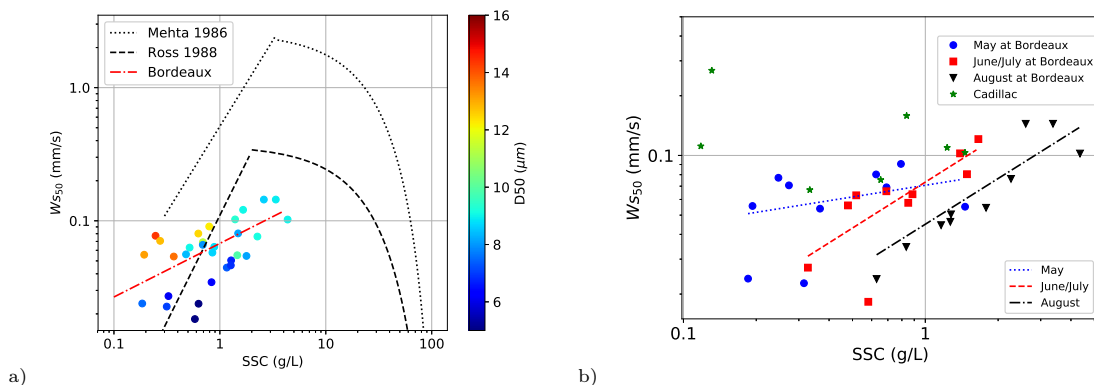


Figure 12: a) Median settling velocity variation with sediment concentration and median diameter. Data collected in surface waters at Bordeaux. b) Median settling velocity variation with sediment concentration for each period of measurement at Bordeaux: May in blue, June/July in green and August in black. Data collected at Cadillac are in red. Data collected in surface waters at Bordeaux.

413 5.2.2. Relationship with tidal cycle

414 A variation in the settling velocity throughout the tidal cycle was observed in this study for
 415 every condition of tidal (spring/neap tide) and riverine forcing (Fig. 7), suggesting that tidal pro-
 416 cesses may be one of the major drivers of the settling velocity. Sediment processes and transport
 417 mechanisms taking place along the tidal cycle, such as (a) erosion, which resuspends new particles
 418 in the water column, increasing the median settling velocity; (b) deposition, during which larger
 419 particles settle, decreasing the median settling velocity; and (c) advection, which brings particles
 420 from sources other than local, potentially modifying the settling velocity distribution. The coun-
 421 terclockwise hysteresis observed during both flood and ebb tides are similar to those obtained in
 422 the Fraser Estuary (Kostaschuk et al., 1989). This lag during the accelerating phase is generally
 423 attributed to an enhanced resistance to erosion by bed sediments. In our study, a critical current
 424 of 0.4 m.s^{-1} seems to be necessary to resuspend bed sediments, while in the Weser Estuary, a
 425 current of 0.2 m.s^{-1} seems to be sufficient to resuspend sediments (Grabemann and Krause, 1989).
 426 However, in the Weser Estuary, the u-c relationship does not display a counterclockwise hysteresis,
 427 as the measurement site is more affected by advection and depletion than local resuspension and
 428 deposition. These different patterns highlight the diversity of the relative importance of advection
 429 and mixing on SSC variability in different estuaries even if generic biophysical laws govern fine-scale
 430 processes of flocculation and sedimentation. To consider the observed variations in the settling ve-
 431 locity along the tidal cycle in the prediction law for further numerical work, a simple formulation
 432 relating the settling velocity to the tidal phase as proposed by Van der Lee (2000) was fitted to the
 433 data:

$$434 \quad ws = a * \cos\left(\frac{2\pi}{T}(t + \phi)\right) + c \quad (1)$$

435 where $T = 12.4 \text{ h}$ is the period of the M2 tidal harmonic (i.e., major harmonic at Bordeaux), t
 436 is the time to high water, and a , ϕ and c are constants determined by the fit to the data collected
 437 at Bordeaux. The range of settling velocity was estimated to be $a = -0.03 \text{ mm.s}^{-1}$, the phase
 438 lag to high water was $\phi = 0.25 \text{ hours}$, and the average settling velocity was determined to be c
 439 $= 0.066 \text{ mm.s}^{-1}$. This relation is represented in Figure 7 with a full black line. The tidal phase
 440 fitted the settling velocity variations only at 41% in a similar manner as the SSC variation. A
 441 second formulation was developed taking into consideration the second major tidal harmonic S2 at
 442 Bordeaux (Ross and Sottolichio, 2016):

$$443 \quad ws = a_1 * \cos\left(\frac{2\pi}{T_1}(t + \phi_1)\right) + a_2 * \cos\left(\frac{2\pi}{T_2}(t + \phi_2)\right) + c \quad (2)$$

444 where $a_1 = 0.76 \text{ mm.s}^{-1}$, $T_1 = 12.4 \text{ h}$, $\phi_1 = -0.87 \text{ h}$, $a_2 = 0.77 \text{ mm.s}^{-1}$, $T_2 = 12 \text{ h}$, $\phi_2 = -0.83$
 445 h , and $c = 0.041 \text{ mm.s}^{-1}$. This new formulation better fit the data ($r^2 = 0.56$), as it created
 446 a slight asymmetry (Fig. 7 dashed line), and the covariance of the tidal phase and the settling
 447 velocity slightly increased with this new formulation (Tab. 2). When discriminating data by
 448 periods, the formulation with the two harmonics produced better covariance and better predictive
 449 capacity for each period. The predictive capacity of formulations based on tidal phase were better
 450 than those obtained with power laws, particularly for data collected in May (i.e., before the arrival
 451 of the ETM). Formulation depending on the tidal phase could therefore be more appropriate for
 452 numerical simulation once calibrated through campaigns of measurements. In this respect, the

453 SCAF device offers fast operational readiness and easy handling, in contrast to video systems or
 454 LISST instruments.

Table 2: Different formulations for settling velocity prediction

Period	Equation	Covariance	Prediction
all	$ws = 0.068 * SSC^{0.4}$	0.41	0.41
May	$ws = 0.071 * SSC^{0.19}$	0.15	0.05
June/July	$ws = 0.073 * SSC^{0.77}$	0.74	0.74
August	$ws = 0.045 * SSC^{0.77}$	0.69	0.62
all	$ws = -0.03 * \cos(2\pi(t + 0.25)/12.4) + 0.066$	0.41	0.41
all	$ws = 0.76 * \cos(\frac{2\pi}{12.4}(t - 0.87)) - 0.77 * \cos(\frac{2\pi}{12}(t - 0.83)) + 0.041$	0.56	0.56
May	$ws = 0.83 * \cos(\frac{2\pi}{12.4}(t - 0.14)) - 0.83 * \cos(\frac{2\pi}{12}(t - 0.13)) + 0.03$	0.76	0.57
June/July	$ws = 0.70 * \cos(\frac{2\pi}{12.4}(t - 0.84)) - 0.71 * \cos(\frac{2\pi}{12}(t - 0.77)) + 0.043$	0.90	0.80
August	$ws = -0.74 * \cos(\frac{2\pi}{12.4}(t - 4.22)) + 0.76 * \cos(\frac{2\pi}{12}(t + 4.1)) + 0.056$	0.64	0.54

455 5.3. Comparison to other studies

456 The settling velocities measured during this study were one order of magnitude lower than the
 457 values measured by Manning et al. (2004) at the mouth of the Gironde estuary ($1-3 \text{ mm.s}^{-1}$) and
 458 in other estuaries, such as the Elbe Estuary (Dyer et al., 1996) and the Tamar Estuary (Manning
 459 et al., 2006). This could partly be explained by the fact that previous studies generally measured
 460 settling velocities close to the bed, where stronger turbulence may resuspend larger particles, and
 461 at the mouth of the estuaries, where the bed is mostly composed of sand and salinity may favor
 462 flocculation. The order of magnitude difference between the present study and the Manning et al.
 463 (2004) study may also come from the different methodology employed: settling column vs. video
 464 system, as the video system did not account for the smaller particle size (less than $20 \mu\text{m}$). According
 465 to Dyer et al. (1996), measurements made with settling columns such as the Owen tube may give
 466 settling velocity one order of magnitude smaller than the direct measurement with video systems.
 467 In addition, optic systems that rely on isoabsorbances, such as the SCAF instrument, are more
 468 sensitive to fine particles, which may lead to underestimation of the settling velocity, as larger flocs
 469 are less efficiently considered by such instruments. Coupling different techniques, such as SCAF,
 470 video, and laser type, would provide the most efficient strategy. However, settling velocities reported
 471 in this work are of the same order of magnitude as those measured in the Yangtze Estuary (Guo
 472 et al., 2017) and those measured with natural mud from the Lower Mekong River (Le et al., 2020).
 473 This suggests that the findings of this work can be extrapolated to other tidal rivers. For instance,
 474 the magnitude and dynamics of the settling velocity can vary significantly between the lower and
 475 upper estuary. In tidal rivers, the ETM can play a key role in enhancing flocculation and therefore
 476 settling velocities despite the low salinity. The seasonal patterns of the ETM can provide a hint on
 477 the seasonal variability of settling velocities in this estuarine region.

478 Moreover, a similar dependence on tide has been observed for settling velocities in the Dollard
 479 Estuary, with a phase lag of the minimum settling velocity of 1 h and 9 min after high water (Van der
 480 Lee, 2000). This similarity reinforces the fact that using constant values of settling velocities in a
 481 numerical model may not be appropriate, and a better representation of the sediment dynamics

482 can be given using a settling velocity formulation depending on the tidal phase, particularly in tidal
483 rivers.

484 6. Conclusion

485 This study presents the very first values of the settling velocity of cohesive sediments in surface
486 waters measured in the Garonne Tidal River. Settling velocities are hard to measure in situ;
487 however, the new SCAF instrument has shown great potential despite its "quasi in situ" method.
488 The ergonomic and handy design of the SCAF device allows easy-going measurement of settling
489 velocity on a relatively short time scale and in a highly turbid environment. However, the SCAF
490 instrument does not provide information on the size or shape of the particles, which limits data
491 interpretation on floc density. The present results outlined a time and space variability of settling
492 velocities of cohesive sediments. Settling velocity dynamics can vary notably from the lower to
493 upper tidal river. In tidal rivers, settling velocity varies over different time scales. The major
494 variations occur during the tidal cycle, where the median settling velocity of surface sediments may
495 be four times higher at the end of the ebb tide than at high tide. On a longer timescale, ETM may
496 affect settling velocities in two ways: (1) by increasing SSC, which favors flocculation, and (2) by
497 promoting fluid mud in the bed, which modifies the particle size distribution of sediment. In tidal
498 rivers, salinity seems too low to promote flocculation, unlike in lower estuaries. Simple formulations
499 to predict settling velocities are hard to establish due to the large range of influencing factors and
500 their variability in time and space. In the absence of process-based reliable parameterization, a
501 simple empirical formulation based on tidal variation may allow a satisfactory representation of
502 settling velocity and consequently on suspended sediment dynamics in numerical works than with
503 a classical power law related to SSC.

504 Data in this study are publicly available at <https://data.mendeley.com/datasets/6rrzthht5b/1>.

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