



Settling dynamics of cohesive sediments in a highly turbid tidal river

Sophie Defontaine, Isabel Jalón-Rojas, Aldo Sottolichio, Nicolas Gratiot, Cédric Legout

► To cite this version:

Sophie Defontaine, Isabel Jalón-Rojas, Aldo Sottolichio, Nicolas Gratiot, Cédric Legout. Settling dynamics of cohesive sediments in a highly turbid tidal river. *Marine Geology*, 2023, 457, pp.106995. <10.1016/j.margeo.2023.106995>. <hal-04093832>

HAL Id: hal-04093832

<https://hal.science/hal-04093832v1>

Submitted on 10 May 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY 4.0 - Attribution - International License

1 Settling dynamics of cohesive sediments in a highly turbid tidal river

2 Sophie Defontaine ⁽¹⁾, Isabel Jalon-Rojas ⁽¹⁾, Aldo Sottolichio ⁽¹⁾, Nicolas Gratiot ⁽²⁾, Cédric
3 Legout ⁽²⁾

4 ⁽¹⁾ *Univ. Bordeaux, CNRS, Bordeaux INP, EPOC, UMR 5805, F-33600 Pessac, France*

5 ⁽²⁾ *Univ. Grenoble Alpes, CNRS, IRD, Grenoble INP, IGE, 38000 Grenoble, France*

6 Abstract

An optical settling column was used in the Garonne Tidal River to estimate the settling velocity of suspended matter in surface waters over a period characterized by contrasting hydrological conditions. A time and space variability of settling velocity was observed during this study. The settling velocities of surface suspended matter ranged from 0.018 to 0.268 $mm.s^{-1}$, and the median diameter of dispersed particles varied from 4.74 to 14.38 μm . The data revealed the physical processes influencing the sediment settling dynamics throughout different time scales in a highly turbid tidal river. On tidal and fortnightly time scales, resuspension, deposition and advection mechanisms were the major drivers of the settling velocity variability, while it is likely that the estuarine turbidity maxima (ETM) was responsible for seasonal variations. The findings of this work suggest that in tidal rivers, salinity is too low to promote flocculation, whereas ETM can play a key role in enhancing this process. The stronger variability in settling velocity occurs on a tidal timescale, with median values up to four times higher at the end of the ebb tide than at high water. These variations cannot be correlated to salinity or sediment concentration. On a seasonal timescale, flocculation appears to be strongly correlated with the presence of the ETM and associated fluid mud layer. A simple correlation based on tidal variations seems to be a better predictor than the relationships based on the sediment concentration.

7 **Keywords:** sediment dynamics, settling velocity, cohesive sediment, ETM, SCAF, tidal river

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 ($20\text{-}30,000 mg.L^{-1}$; 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.

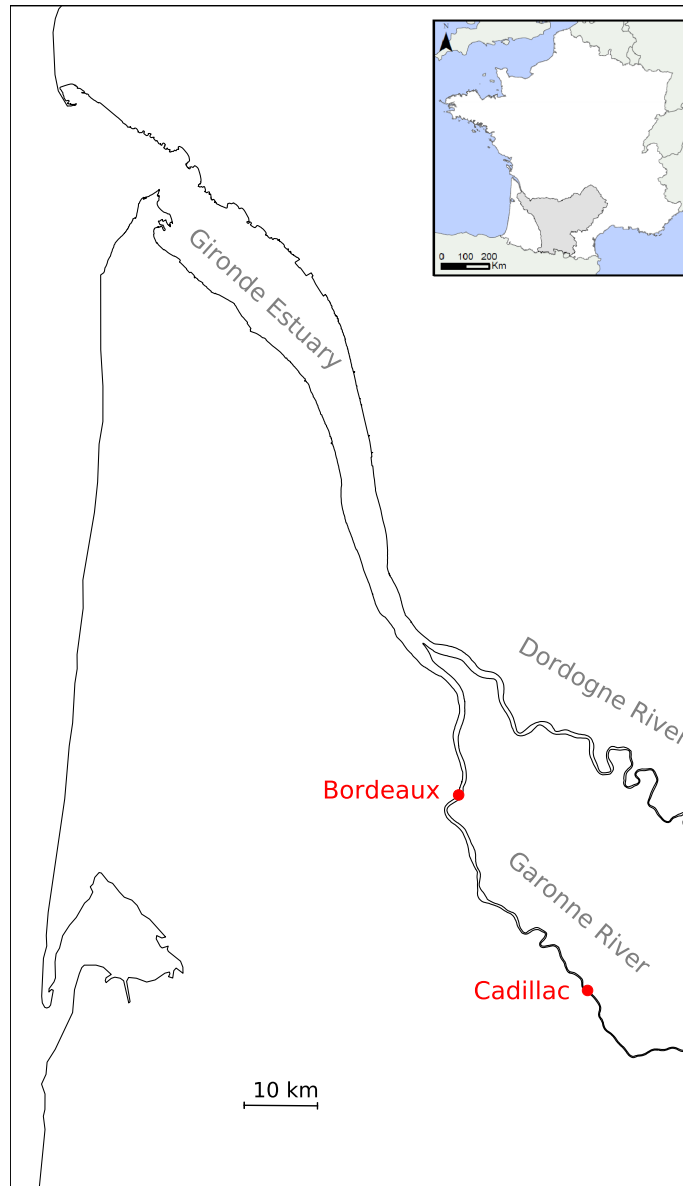


Figure 1: Map of the Gironde Estuary and the Dordogne and Garonne Tidal Rivers with locations of the field measurement sites (Bordeaux and Cadillac).

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

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

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

Prior to field measurements, different tests were conducted in the laboratory to design an experimental protocol adapted to the use of the SCAF in a turbid environment subjected to tidal forcing.

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

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

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

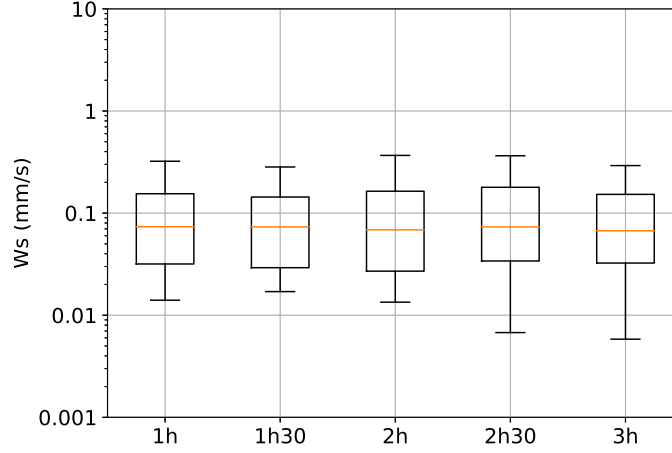


Figure 2: Distribution of the settling velocity for the five settling time tests under laboratory conditions

3.2. Field campaigns

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

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

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

Dispersed particle size distributions (PSDs) of the sediments used in the settling column and riverbed sediments were measured after 60 seconds of stirring and sonication at their maximum level with a Malvern laser-diffraction instrument operating in the range $0.01\text{-}2000\text{ }\mu\text{m}$.

3.3. Data bases

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

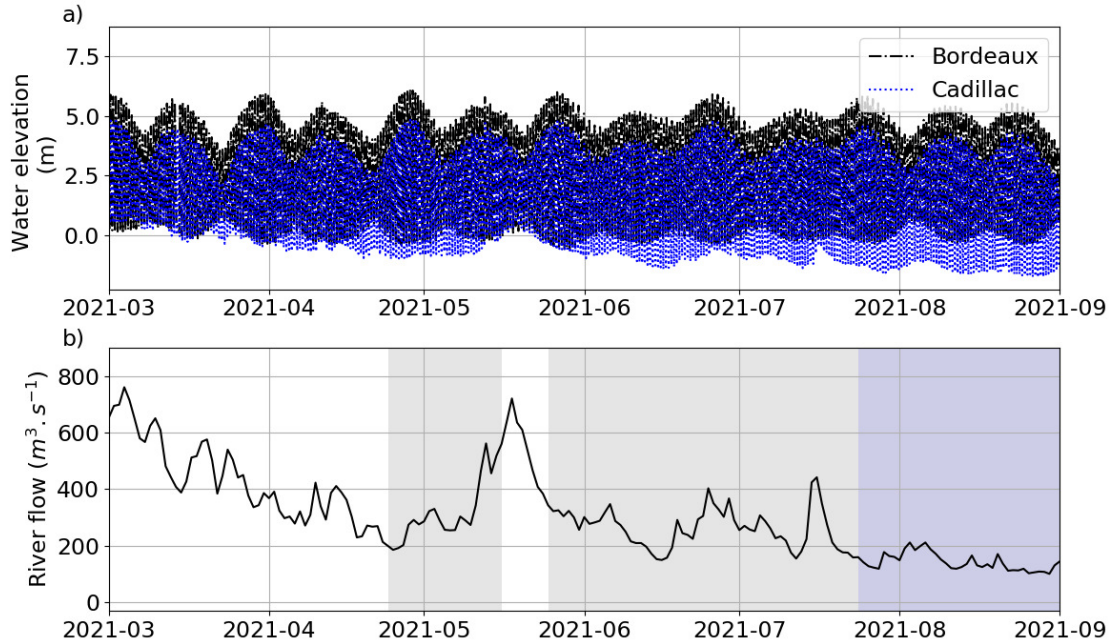


Figure 3: Time series of a) water elevation (m) at Bordeaux and Cadillac and b) daily averaged river flow ($\text{m}^3.\text{s}^{-1}$) at Tonneins. The shadowed areas correspond to the presence of the ETM at Bordeaux (gray) and Cadillac (blue).

4. Results

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

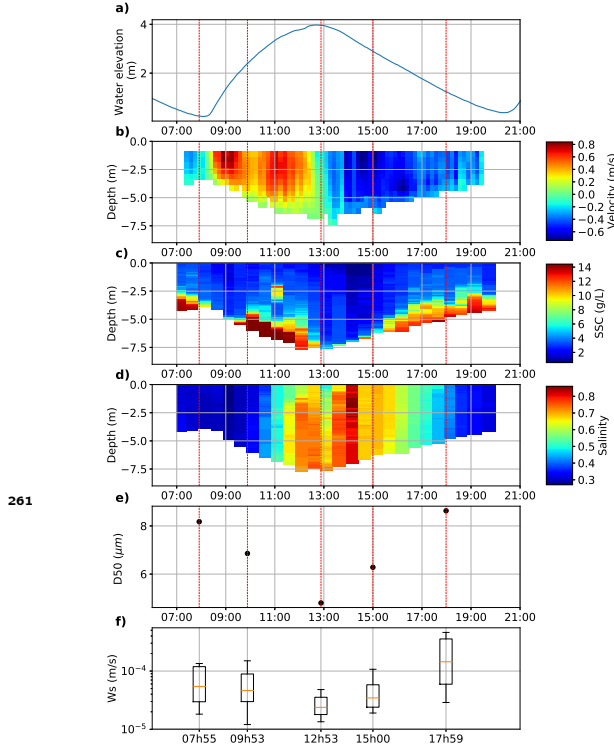


Figure 4: Time series of a) water elevation in meters, b) velocity profiles in meters per second, c) suspended sediment concentration in grams per liter, d) salinity, e) median diameter of surface suspended sediments in microns, and f) settling velocity distribution of surface suspended sediments in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

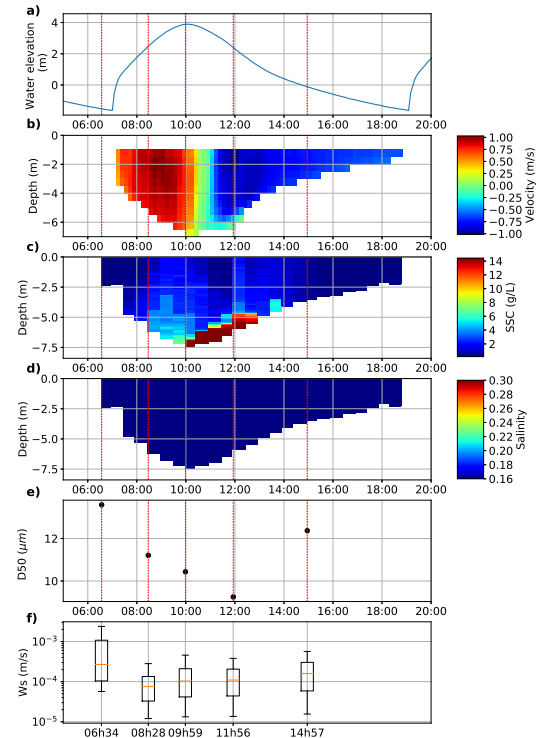


Figure 5: Time series of a) water elevation in meters, b) velocity profiles in meters per second, c) suspended sediment concentration in grams per liter, d) salinity, e) median diameter of surface suspended sediments in microns, and f) settling velocity distribution of surface suspended sediments in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

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

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

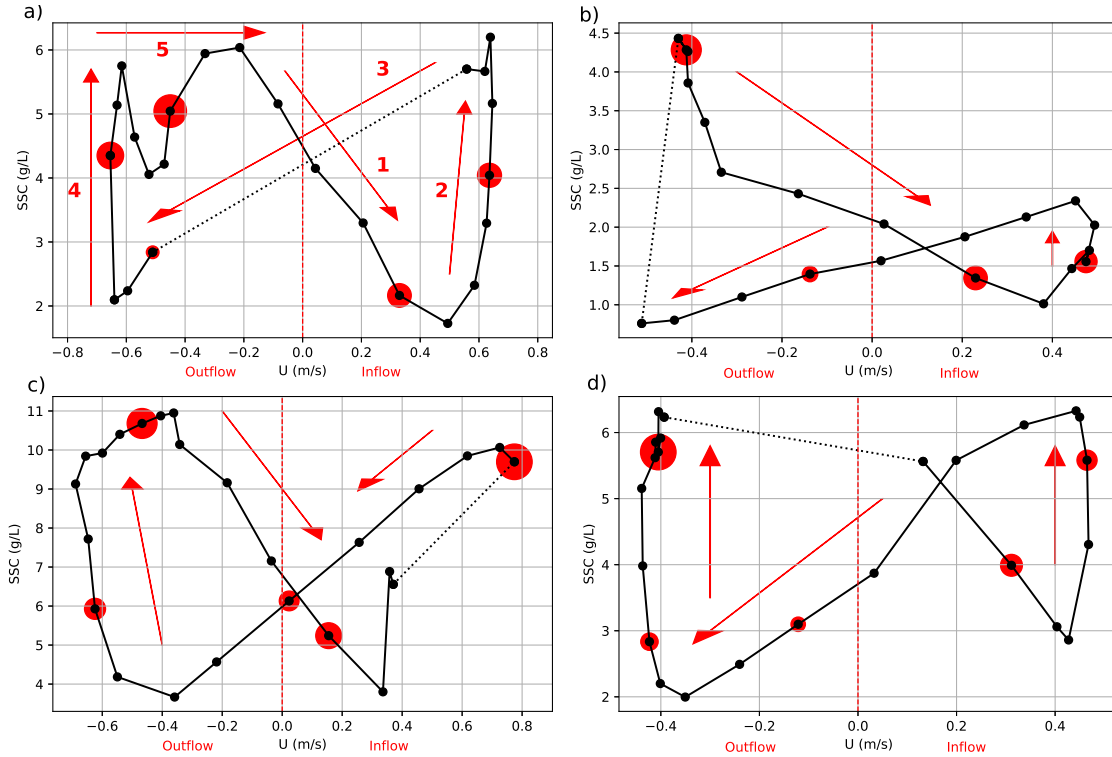


Figure 6: Variation in the depth-averaged SSC with the depth-averaged velocity for the data collected at Bordeaux on a) June 24th, b) July 5th, c) August 25th and d) August 30th. The red dot size represents the relative order of magnitude of the median settling velocity of surface suspended sediment.

4.2. Variations throughout the fortnightly cycle

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

297 some particles with higher dispersed D50 from landward sources.

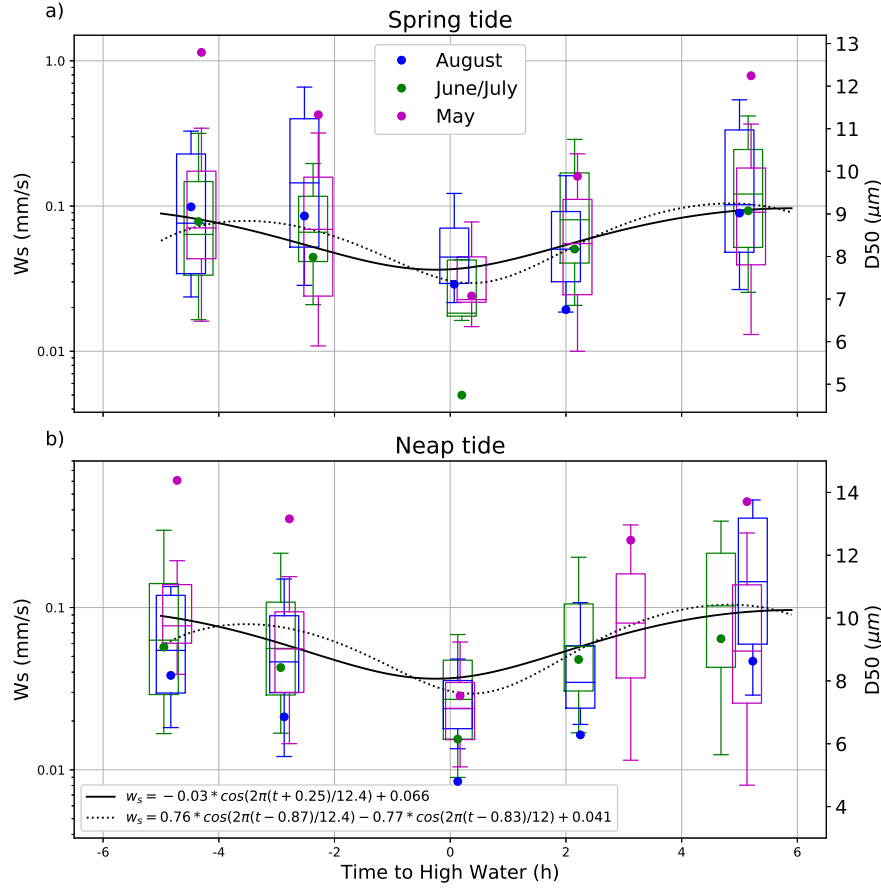


Figure 7: Settling velocity distribution in millimeters per second (colored box plots) and median diameter in microns (colored dots) of surface suspended sediments as a function of the time to high water during a) spring tides and b) neap tides. Data presented in this figure have been collected at Bordeaux. 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 D_{50} 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.

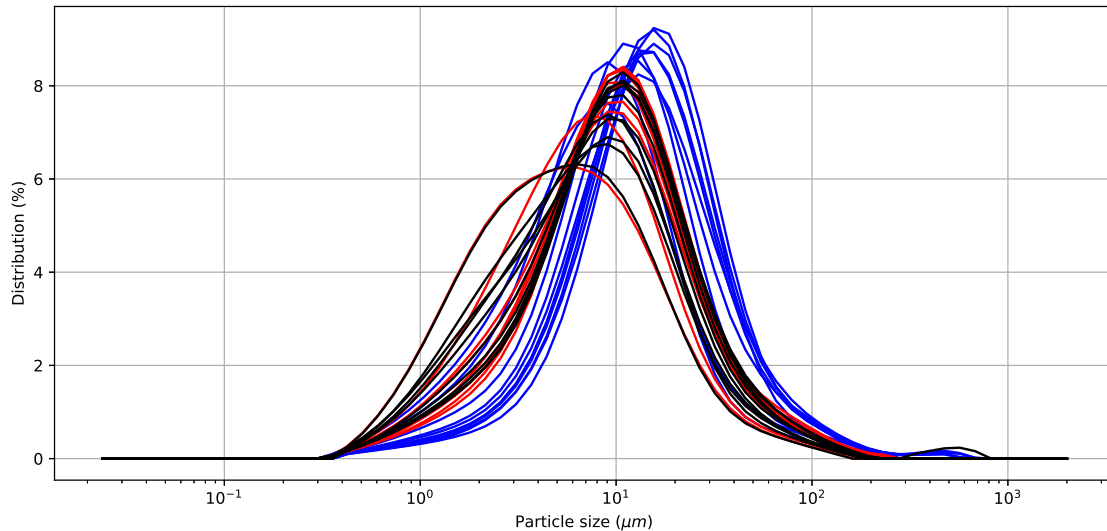


Figure 8: Particle size distribution of the dispersed surface particles collected in May (blue), June and July (red) and August (black) at Bordeaux.

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 $m^3.s^{-1}$, and the ETM appeared in Bordeaux; (2) in May, a freshet ($Q = 700 m^3.s^{-1}$) 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 $m^3.s^{-1}$, 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 $m^3.s^{-1}$, and a fluid mud layer covered

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

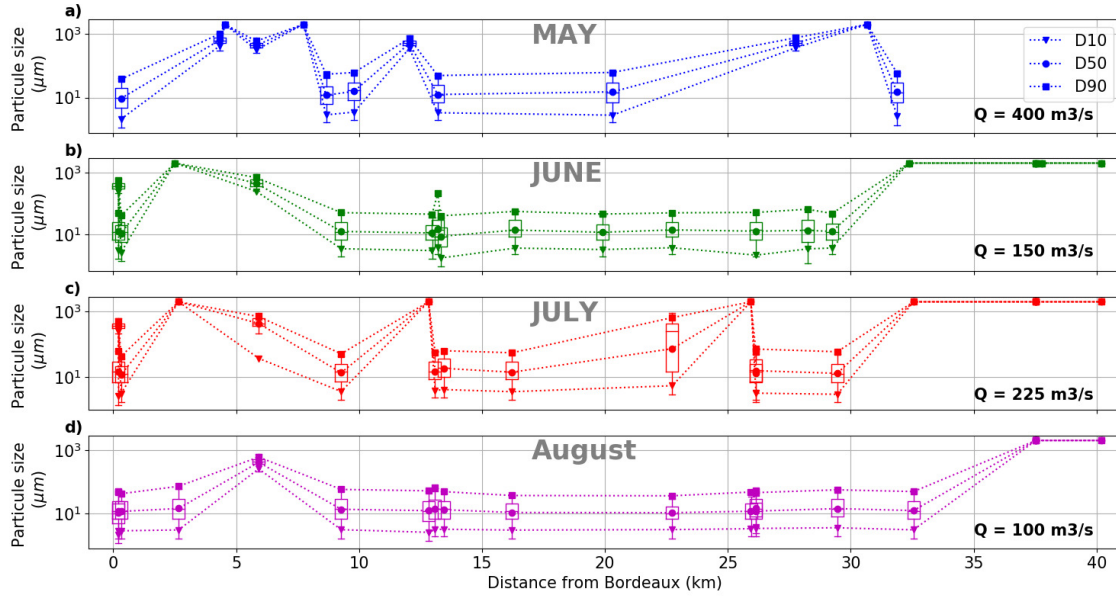


Figure 9: Particle size distributions of bed sediments along the Garonne Tidal River: from Bordeaux to Cadillac.

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

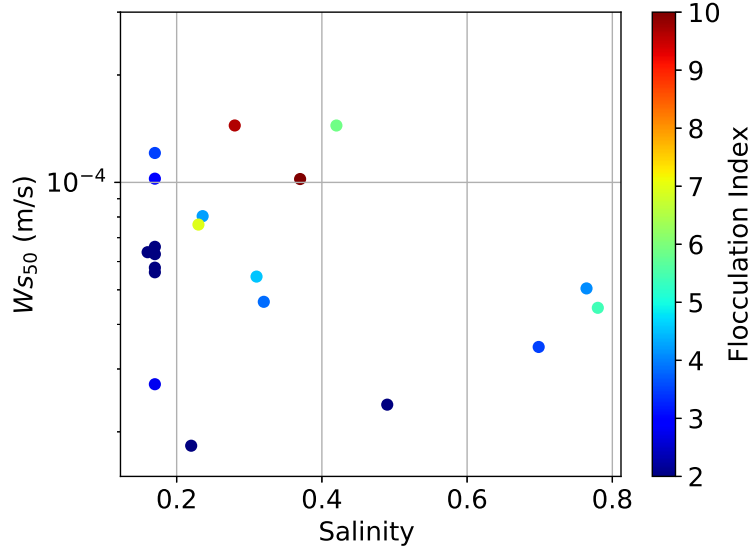


Figure 11: Median settling velocity variations with salinity and flocculation index. Data collected at Bordeaux.

5.2. Settling velocity prediction

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

5.2.1. Relationship with SSC

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

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

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

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

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

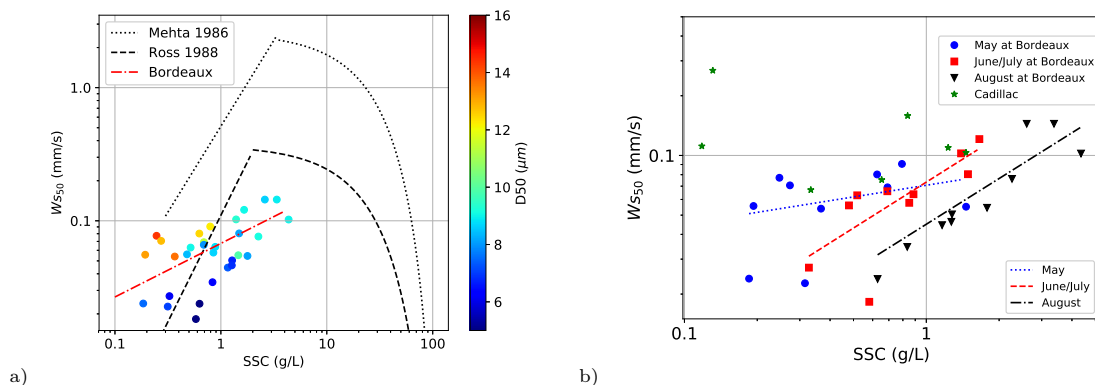


Figure 12: a) Median settling velocity variation with sediment concentration and median diameter. Data collected in surface waters at Bordeaux. b) Median settling velocity variation with sediment concentration for each period of measurement at Bordeaux: May in blue, June/July in green and August in black.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

SCAF device offers fast operational readiness and easy handling, in contrast to video systems or 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

5.3. Comparison to other studies

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

Moreover, a similar dependence on tide has been observed for settling velocities in the Dollard Estuary, with a phase lag of the minimum settling velocity of 1 h and 9 min after high water (Van der Lee, 2000). This similarity reinforces the fact that using constant values of settling velocities in a 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>.

505 7. Acknowledgments

506 This study was supported by the EMPHASE project (ANR-FRQ). The authors acknowledge
507 Marie-Claire Perello for the Malvern grain-size analysis and Sabine Schmidt for lab support. The
508 authors are grateful to Marine Vandenhove, Maurizio d'Anna, Mario Humbert, Marion Chapalain,
509 Carla Labarthe and Guillaume Detandt for their support during fieldwork.

510 Abril, G., Nogueira, M., Etcheber, H., Cabéçadas, G., Lemaire, E., Brogueira, M., 2002. Behaviour
511 of organic carbon in nine contrasting european estuaries. *Estuarine, coastal and shelf science* 54,
512 241–262.

513 Agrawal, Y.C., Pottsmith, H.C., 2000. Instruments for particle size and settling velocity observa-
514 tions in sediment transport. *Marine Geology* 168, 89–114.

515 Allen, G.P., 1971. Relationship between grain size parameter distribution and current patterns in
516 the gironde estuary (france). *Journal of Sedimentary Research* 41, 74–88.

517 Allen, G.P., Salomon, J., Bassoullet, P., Du Penhoat, Y., De Grandpre, C., 1980. Effects of tides
518 on mixing and suspended sediment transport in macrotidal estuaries. *Sedimentary Geology* 26,
519 69–90.

520 Bonneton, P., Bonneton, N., Parisot, J.P., Castelle, B., 2015. Tidal bore dynamics in funnel-shaped
521 estuaries. *Journal of Geophysical Research: Oceans* 120, 923–941.

522 Boss, E., Slade, W., Hill, P., 2009. Effect of particulate aggregation in aquatic environments on the
523 beam attenuation and its utility as a proxy for particulate mass. *Optics express* 17, 9408–9420.

524 Burchard, H., Schuttelaars, H.M., Ralston, D.K., 2018. Sediment trapping in estuaries. *Annual*
525 *review of marine science* 10, 371–395.

526 Cornelisse, J.M., 1996. The field pipette withdrawal tube (fipiwitu). *Journal of Sea Research* 36,
527 37–39.

528 Deng, Z., He, Q., Chassagne, C., Wang, Z.B., 2021. Seasonal variation of flocculation influenced
529 by the presence of algae in the changjiang (yangtze river) estuary. *Marine Geology* 440, 106600.

530 Diaz, M., Grasso, F., Le Hir, P., Sottolichio, A., Caillaud, M., Thouvenin, B., 2020. Modeling mud
531 and sand transfers between a macrotidal estuary and the continental shelf: Influence of the sedi-
532 ment transport parameterization. *Journal of Geophysical Research: Oceans* 125, e2019JC015643.

533 Downing, J., 2006. Twenty-five years with obs sensors: The good, the bad, and the ugly. *Continental*
534 *Shelf Research* 26, 2299–2318.

535 Druine, F., Verney, R., Deloffre, J., Lemoine, J.P., Chapalain, M., Landemaine, V., Lafite, R.,
536 2018. In situ high frequency long term measurements of suspended sediment concentration in
537 turbid estuarine system (seine estuary, france): Optical turbidity sensors response to suspended
538 sediment characteristics. *Marine Geology* 400, 24–37.

539 Dyer, K., Cornelisse, J., Dearnaley, M., Fennessy, M., Jones, S., Kappenberg, J., McCave, I., Pejrup,
540 M., Puls, W., Van Leussen, W., et al., 1996. A comparison of in situ techniques for estuarine floccu-
541 lation settling velocity measurements. *Journal of Sea Research* 36, 15–29.

542 Dyer, K., Manning, A., 1999. Observation of the size, settling velocity and effective density of flocs,
543 and their fractal dimensions. *Journal of sea research* 41, 87–95.

544 Eisma, D., 1986. Flocculation and de-flocculation of suspended matter in estuaries. *Netherlands*
545 *Journal of sea research* 20, 183–199.

546 Eisma, D., Bernard, P., Cadée, G., Ittekkot, V., Kalf, J., Laane, R., Martin, J.M., Mook, W.,
547 Van Put, A., Schuhmacher, T., 1991. Suspended-matter particle size in some west-european
548 estuaries; part i: Particle-size distribution. *Netherlands journal of sea research* 28, 193–214.

549 Etcheber, H., Taillez, A., Abril, G., Garnier, J., Servais, P., Moatar, F., Commarieu, M.V., 2007.
550 Particulate organic carbon in the estuarine turbidity maxima of the gironde, loire and seine
551 estuaries: origin and lability. *Hydrobiologia* 588, 245–259.

552 Fall, K.A., Friedrichs, C.T., Massey, G.M., Bowers, D.G., Smith, S.J., 2021. The importance of
553 organic content to fractal flocculation properties in estuarine surface waters: Insights from video, list,
554 and pump sampling. *Journal of Geophysical Research: Oceans* 126, e2020JC016787.

555 Fennessy, M., Dyer, K., Huntley, D., 1994. Inssev: An instrument to measure the size and settling
556 velocity of flocs in situ. *Marine geology* 117, 107–117.

557 Furukawa, Y., Reed, A.H., Zhang, G., 2014. Effect of organic matter on estuarine flocculation:
558 a laboratory study using montmorillonite, humic acid, xanthan gum, guar gum and natural
559 estuarine flocs. *Geochemical Transactions* 15, 1–9.

560 Gibbs, R., Tshudy, D., Konwar, L., Martin, J.M., 1989. Coagulation and transport of sediments in
561 the gironde estuary. *Sedimentology* 36, 987–999.

562 Gibbs, R.J., 1983. Coagulation rates of clay minerals and natural sediments. *Journal of Sedimentary*
563 *Research* 53, 1193–1203.

564 Grabemann, I., Krause, G., 1989. Transport processes of suspended matter derived from time series
565 in a tidal estuary. *Journal of Geophysical Research: Oceans* 94, 14373–14379.

566 Graham, G.W., Nimmo Smith, W.A.M., 2010. The application of holography to the analysis of size
567 and settling velocity of suspended cohesive sediments. *Limnology and Oceanography: Methods*
568 8, 1–15.

569 Gratiot, N., Coulaud, C., Legout, C., Mercier, B., Mora, H., Wendling, V., 2015. Unit for measuring
570 the falling speed of particles in suspension in a fluid and device comprising at least one measuring
571 unit and one automatic sampler. Patent-Publication number WO2015055963 A 1.

572 Gratiot, N., Manning, A., 2004. An experimental investigation of flocc characteristics in a diffusive
573 turbulent flow. *Journal of Coastal Research* , 105–113.

574 Guo, C., He, Q., Guo, L., Winterwerp, J.C., 2017. A study of in-situ sediment flocculation in the
575 turbidity maxima of the yangtze estuary. *Estuarine, Coastal and Shelf Science* 191, 1–9.

576 Heffler, D., Syvitski, J., Asprey, K., 1991. The flocc camera. Principles, methods, and application
577 of particle size analysis , 209–221.

578 Horemans, D.M., Dijkstra, Y.M., Schuttelaars, H.M., Meire, P., Cox, T.J., 2020. Unraveling the
579 essential effects of flocculation on large-scale sediment transport patterns in a tide-dominated
580 estuary. *Journal of Physical Oceanography* 50, 1957–1981.

581 Jalón Rojas, I., 2016. Évaluation des changements hydro-sédimentaires de l’estuaire de la Gironde
582 en lien avec les pressions sur le milieu. Ph.D. thesis. Bordeaux.

583 Jalón-Rojas, I., Dijkstra, Y., Schuttelaars, H., Brouwer, R., Schmidt, S., Sottolichio, A., 2021.
584 Multidecadal evolution of the turbidity maximum zone in a macrotidal river under climate and
585 anthropogenic pressures. *Journal of Geophysical Research: Oceans* 126, e2020JC016273.

586 Jalón-Rojas, I., Schmidt, S., Sottolichio, A., 2015. Turbidity in the fluvial gironde estuary (south-
587 west france) based on 10-year continuous monitoring: sensitivity to hydrological conditions. *Hy-*
588 *drology and Earth System Sciences* 19, 2805–2819.

589 Jalón-Rojas, I., Sottolichio, A., Hanquiez, V., Fort, A., Schmidt, S., 2018. To what extent multi-
590 decadal changes in morphology and fluvial discharge impact tide in a convergent (turbid) tidal
591 river. *Journal of Geophysical Research: Oceans* 123, 3241–3258.

592 Jones, S., Jago, C., 1996. Determination of settling velocity in the elbe estuary using quisset tubes.
593 *Journal of Sea Research* 36, 63–67.

594 Kineke, G., Sternberg, R., Johnson, R., 1989. A new instrument for measuring settling velocities
595 in situ. *Marine Geology* 90, 149–158.

596 Kostaschuk, R., Luternauer, J., Church, M., 1989. Suspended sediment hysteresis in a salt-wedge
597 estuary: Fraser river, canada. *Marine Geology* 87, 273–285.

598 Lajaunie-Salla, K., Wild-Allen, K., Sottolichio, A., Thouvenin, B., Litrico, X., Abril, G., 2017.
599 Impact of urban effluents on summer hypoxia in the highly turbid gironde estuary, applying a
600 3d model coupling hydrodynamics, sediment transport and biogeochemical processes. *Journal of*
601 *Marine Systems* 174, 89–105.

602 Le, H.A., Gratiot, N., Santini, W., Ribolzi, O., Tran, D., Meriaux, X., Deleersnijder, E., Soares-
603 Frazão, S., 2020. Suspended sediment properties in the lower mekong river, from fluvial to
604 estuarine environments. *Estuarine, Coastal and Shelf Science* 233, 106522.

605 Van der Lee, W.T., 2000. Temporal variation of flocc size and settling velocity in the dollard estuary.
606 *Continental Shelf Research* 20, 1495–1511.

607 Legout, C., Droppo, I., Coutaz, J., Bel, C., Jodeau, M., 2018. Assessment of erosion and settling
608 properties of fine sediments stored in cobble bed rivers: the arc and isère alpine rivers before and
609 after reservoir flushing. *Earth Surface Processes and Landforms* 43, 1295–1309.

610 van Leussen, W., 1996. The rws field settling tube. *Journal of Sea Research* 36, 83–86.

611 van Leussen, W., 1999. The variability of settling velocities of suspended fine-grained sediment in
612 the ems estuary. *Journal of sea research* 41, 109–118.

613 Liu, D., Edraki, M., Berry, L., 2018. Investigating the settling behaviour of saline tailing suspensions
614 using kaolinite, bentonite, and illite clay minerals. *Powder Technology* 326, 228–236.

615 van Maanen, B., Sottolichio, A., 2018. Hydro-and sediment dynamics in the gironde estuary
616 (france): Sensitivity to seasonal variations in river inflow and sea level rise. *Continental Shelf*
617 *Research* 165, 37–50.

618 Malarkey, J., Baas, J.H., Hope, J.A., Aspden, R.J., Parsons, D.R., Peakall, J., Paterson, D.M.,
619 Schindler, R.J., Ye, L., Lichtman, I.D., et al., 2015. The pervasive role of biological cohesion in
620 bedform development. *Nature communications* 6, 1–6.

621 Manning, A., Dyer, K., 2007. Mass settling flux of fine sediments in northern european estuaries:
622 measurements and predictions. *Marine Geology* 245, 107–122.

623 Manning, A., Dyer, K., Lafite, R., Mikes, D., 2004. Flocculation measured by video based in-
624 struments in the gironde estuary during the european commission swamiee project. *Journal of*
625 *Coastal Research* , 58–69.

626 Manning, A., Friend, P., Prowse, N., Amos, C., 2007. Estuarine mud flocculation properties de-
627 termined using an annular mini-flume and the labsfloc system. *Continental Shelf Research* 27,
628 1080–1095.

629 Manning, A., Schoellhamer, D.H., 2013. Factors controlling flocc settling velocity along a longitudinal
630 estuarine transect. *Marine Geology* 345, 266–280.

631 Manning, A.J., Bass, S.J., Dyer, K.R., 2006. Flocculation properties in the turbidity maximum of a
632 mesotidal estuary during neap and spring tidal conditions. *Marine Geology* 235, 193–211.

633 Manning, A.J., Baugh, J.V., Spearman, J.R., Whitehouse, R.J., 2010. Flocculation settling char-
634 acteristics of mud: sand mixtures. *Ocean dynamics* 60, 237–253.

635 Mantovanelli, A., 2005. A new approach for measuring in situ the concentration and settling velocity
636 of suspended cohesive sediment. Ph.D. thesis. James Cook University.

637 Mantovanelli, A., Ridd, P.V., 2006. Devices to measure settling velocities of cohesive sediment
638 aggregates: A review of the in situ technology. *Journal of Sea Research* 56, 199–226.

639 Mehta, A.J., 1986. Characterization of cohesive sediment properties and transport processes in
640 estuaries, in: *Estuarine cohesive sediment dynamics*. Springer, pp. 290–325.

641 Mehta, A.J., 2013. An introduction to hydraulics of fine sediment transport. volume 38. World
642 Scientific Publishing Company.

643 Mietta, F., Chassagne, C., Manning, A.J., Winterwerp, J.C., 2009. Influence of shear rate, organic
644 matter content, pH and salinity on mud flocculation. *Ocean Dynamics* 59, 751–763.

645 Mikeš, D., Manning, A.J., 2010. Assessment of flocculation kinetics of cohesive sediments from the
646 seine and gironde estuaries, france, through laboratory and field studies. *Journal of Waterway,
647 Port, Coastal, and Ocean Engineering* 136, 306–318.

648 Mikes, D., Verney, R., Lafite, R., Belorgey, M., 2004. Controlling factors in estuarine flocculation
649 processes: experimental results with material from the seine estuary, northwestern france. *Journal
650 of coastal research* , 82–89.

651 Mikkelsen, O., Pejrup, M., 1998. Comparison of flocculated and dispersed suspended sediment in
652 the dollard estuary. Geological Society, London, Special Publications 139, 199–209.

653 Mikkelsen, O., Pejrup, M., 2001. The use of a lisst-100 laser particle sizer for in-situ estimates of
654 floc size, density and settling velocity. *Geo-Marine Letters* 20, 187–195.

655 Murray, P., McCave, I., Owen, T., Mason, M., Green, M., 1996. A robust in situ settling velocity
656 box for coastal seas. *Journal of Sea Research* 36, 101–107.

657 Owen, M., 1971. The effect of turbulence on the settling velocities of silt flocs, in: *Proceedings of
658 the Fourteenth Congress of IAHR*, pp. 27–32.

659 Owen, R.B., Zozulya, A.A., 2000. In-line digital holographic sensor for monitoring and character-
660 izing marine particulates. *Optical Engineering* 39, 2187–2197.

661 Parsons, D.R., Schindler, R.J., Hope, J.A., Malarkey, J., Baas, J.H., Peakall, J., Manning, A.J., Ye,
662 L., Simmons, S., Paterson, D.M., et al., 2016. The role of biophysical cohesion on subaqueous
663 bed form size. *Geophysical research letters* 43, 1566–1573.

664 Pejrup, M., 1988. Flocculated suspended sediment in a micro-tidal environment. *Sedimentary
665 Geology* 57, 249–256.

666 Pejrup, M., Edelvang, K., 1996. Measurements of in situ settling velocities in the elbe estuary.
667 *Journal of Sea Research* 36, 109–113.

668 Pejrup, M., Mikkelsen, O.A., 2010. Factors controlling the field settling velocity of cohesive sediment
669 in estuaries. *Estuarine, Coastal and Shelf Science* 87, 177–185.

670 Piro, P., Carbone, M., Penna, N., Marsalek, J., 2011. Characterization of the settling process for
671 wastewater from a combined sewer system. *Water research* 45, 6615–6624.

672 Puls, W., Kuehl, H., Heymann, K., 1988. Settling velocity of mud flocs: results of field measurements
673 in the elbe and the weser estuary, in: *Physical processes in estuaries*. Springer, pp. 404–424.

674 Puls, W., Kühl, H., 1996. Settling velocity determination using the bigdan settling tube and the
675 owen settling tube. *Journal of Sea Research* 36, 119–125.

676 Ross, L., Sottolichio, A., 2016. Subtidal variability of sea level in a macrotidal and convergent
677 estuary. *Continental Shelf Research* 131, 28–41.

678 Ross, M.A., 1988. Vertical structure of estuarine fine sediment suspension. Ph. D. Thesis, Coastal
679 and Oceanographic Eng. Department, University of Florida .

680 Sanford, L., Dickhudt, P., Rubiano-Gomez, L., Yates, M., Suttles, S., Friedrichs, C., Fugate, D.,
681 Romine, H., 2005. Variability of suspended particle concentrations, sizes, and settling velocities
682 in the chesapeake bay turbidity maximum. *Flocculation in natural and engineered environmental*
683 *systems* , 211–236.

684 SEQUOIA, . LISST-HOLO 2, SUBMERSIBLE DIGITAL HOLOGRAPHIC CAMERA.

685 Smith, S.J., Friedrichs, C.T., 2011. Size and settling velocities of cohesive flocs and suspended
686 sediment aggregates in a trailing suction hopper dredge plume. *Continental Shelf Research* 31,
687 S50–S63.

688 Sottolichio, A., Castaing, P., 1999. A synthesis on seasonal dynamics of highly-concentrated struc-
689 tures in the gironde estuary. *Comptes Rendus de l’Académie des Sciences-Series IIA-Earth and*
690 *Planetary Science* 329, 795–800.

691 Sottolichio, A., Hurther, D., Gratiot, N., Bretel, P., 2011. Acoustic turbulence measurements of
692 near-bed suspended sediment dynamics in highly turbid waters of a macrotidal estuary. *Conti-*
693 *nenal Shelf Research* 31, S36–S49.

694 Soulsby, R., Manning, A., Spearman, J., Whitehouse, R., 2013. Settling velocity and mass settling
695 flux of flocculated estuarine sediments. *Marine Geology* 339, 1–12.

696 Spearman, J.R., Manning, A.J., Whitehouse, R.J., 2011. The settling dynamics of flocculating mud
697 and sand mixtures: part 2—numerical modelling. *Ocean Dynamics* 61, 351–370.

698 Stein, R., 1985. Rapid grain-size analyses of clay and silt fraction by sedigraph 5000d: comparison
699 with coulter counter and atterberg methods. *Journal Of Sedimentary Research* 55.

700 Sternberg, R., Ogston, A., Johnson, R., 1996. A video system for in situ measurement of size and
701 settling velocity of suspended particulates. *Journal of Sea Research* 36, 127–130.

- 702 Van Leussen, W., Cornelisse, J.M., 1993. The determination of the sizes and settling velocities of
703 estuarine flocs by an underwater video system. *Netherlands Journal of Sea Research* 31, 231–241.
- 704 Verney, R., Lafite, R., Brun-Cottan, J.C., 2009. Flocculation potential of estuarine particles: The
705 importance of environmental factors and of the spatial and seasonal variability of suspended
706 particulate matter. *Estuaries and coasts* 32, 678–693.
- 707 Verney, R., Lafite, R., Brun-Cottan, J.C., Le Hir, P., 2011. Behaviour of a floc population during
708 a tidal cycle: Laboratory experiments and numerical modelling. *Continental Shelf Research* 31,
709 S64–S83.
- 710 Watson, J., Chalvidan, V., Chambard, J., Craig, G., Diard, A., Foresti, G., Forre, B., Gentili, S.,
711 Hobson, P., Lampitt, R., Maine, P., et al., 1998. High-resolution in situ holographic recording
712 and analysis of marine organisms and particles (holomar), in: *IEEE Oceanic Engineering Society.*
713 *OCEANS’98. Conference Proceedings (Cat. No. 98CH36259)*, IEEE. pp. 1599–1603.
- 714 Watson, J., Player, M., Sun, H., Hendry, D., Dong, H., 2004. eholocam-an electronic holo-
715 graphic camera for subsea analysis, in: *Oceans’ 04 MTS/IEEE Techno-Ocean’04 (IEEE Cat.*
716 *No. 04CH37600)*, IEEE. pp. 1248–1254.
- 717 Wendling, V., 2015. Développement d’un système de caractérisation des agrégats et des flocs en
718 suspension. Ph.D. thesis. Université Grenoble Alpes.
- 719 Wendling, V., Gratiot, N., Legout, C., Droppo, I.G., Coulaud, C., Mercier, B., 2015. Using an
720 optical settling column to assess suspension characteristics within the free, flocculation, and
721 hindered settling regimes. *Journal of Soils and Sediments* 15, 1991–2003.
- 722 Whitehouse, R., Soulsby, R., Roberts, W., Mitchener, H., 2000. *Dynamics of estuarine muds.*
723 Thomas Telford Publishing.
- 724 Winterwerp, J., Manning, A., Martens, C., De Mulder, T., Vanlede, J., 2006. A heuristic formula
725 for turbulence-induced flocculation of cohesive sediment. *Estuarine, Coastal and Shelf Science*
726 68, 195–207.
- 727 Winterwerp, J.C., 2002. On the flocculation and settling velocity of estuarine mud. *Continental*
728 *shelf research* 22, 1339–1360.
- 729 Xia, X., Li, Y., Yang, H., Wu, C., Sing, T., Pong, H., 2004. Observations on the size and settling
730 velocity distributions of suspended sediment in the pearl river estuary, china. *Continental Shelf*
731 *Research* 24, 1809–1826.
- 732 Xu, F., Wang, D.P., Riemer, N., 2010. An idealized model study of flocculation on sediment
733 trapping in an estuarine turbidity maximum. *Continental Shelf Research* 30, 1314–1323.
- 734 Zaneveld, J.R.V., Spinrad, R.W., Bartz, R., 1982. An optical settling tube for the determination
735 of particle-size distributions. *Marine Geology* 49, 357–375.
- 736 Zhang, Y., Ren, J., Zhang, W., Wu, J., 2021. Importance of salinity-induced stratification on
737 flocculation in tidal estuaries. *Journal of Hydrology* 596, 126063.