SEASONAL MONITORING OF SEDIMENT DYNAMICS IN A HIGHLY TURBID ESTUARY (CHARENTE ESTUARY, FRANCE): SOURCE AND SINK OF THE TURBIDITY MAXIMUM.

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Abstract

Sediment dynamics is still poorly understood in the highly turbid Charente estuary. In order to answer management and scientific questions, a seasonal monitoring was deployed from the river mouth to the up-estuary intrusion of saline waters. Continuous field measurements were produced with the means of 2 velocimeters stations and 3 stations of SSC measurement. And occasional field measurements were produced with the means of sediment accretion measurements with poles, surface sediment samples, sediment cores, and 2 bi-frequency (33-200Khz) surveys combined with continuous turbidity measurements to estimate the turbidity maximum (TM) extension. The measurements have shown that cyclic sediment deposition and reworking occurred at different timescales, from tidal to seasonal scales. Sediment transport is strongly linked to tidal amplitude and river runoff. At a seasonal scale, low river flows favor strong sedimentation. Fine and unconsolidated sediment accretion can increase up to 50cm a month during Summer. Sediment accumulation on the river bank and suspended sediments are rapidly exported with Autumn strong river flows.

Key words: Deposited sediments, stratification, instrumentation, maximum turbidity zone,tidal cycle, runoff

1. Introduction

As an interface between land and seas, estuaries play a key role on coastal environment. Fine sediment dynamics drives the evolution of these areas, and is therefore essential to understand and manage estuaries. Sediment concentrations vary greatly between different estuaries and depend upon coast and estuarine morphology, river flow, tidal range, waves, type of sediments (e.g. Uncles et al., 2006, Manning et al., 2010). Numerous descriptions of turbidity maximum are available (e.g, Mitchell et al., 2003, Doxaran et al., 2009, Uncles and Stephens, 2010). Mobile bed sediments, present due to continuing tidal erosion and deposition, form the source of the TM (Allen et al., 1980). Strong currents provoked by river runoff can modify sediment balance and drive sediments seaward. On the other hand, low freshwater and spring tides tend to move the TM landward. Continuous monitoring of sediment concentrations is frequently use to understand the sediment dynamics of estuaries (Ruhl et al., 2001, Mitchell et al., 2003, Lawler, 2005). However, the narrow link between low consolidate sediments, tides, freshwater flow, suspended sediments and the turbidity maximum (TM) dynamic is still unexplored on several estuaries. As the study site is narrow, shallow and turbid, it is not an easy system to explore and instruments are often threatened and limited. Due to its small dimensions and strong sedimentation, the Charente estuary is however a great system to understand sediment transport in estuarine environments. The purpose of this monitoring was to provide field data for estuarine model validation. A 3D numerical model (MARS3D, Ifremer) was developed (Toublanc et al., 2013), but data analysis bring into account several key-processes for a general understanding. The narrow link between low consolidate sediments, tides, freshwater flow, suspended sediment concentration (SSC), and TM evolution was explored.

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2. Materials and Methods

2.1. *Study location*

The study was performed at the Charente estuary (45°70'N, 1°00'W), in the south of La Rochelle, France. The river catchment area is about 10 000 km², total river length is 381 km. Oceanographic conditions vary from typically marine to fluvial, with a complete range of salinity. Tides are semi-diurnal, mean tidal range is about 5 m, and spring range is 6.5 m. Influence of spring-neap tidal cycles leads to continuous change on estuarine currents and bed sediment resuspensions. Recent research highlighted the influence of tidal asymmetry inversion (with longer flood than ebb or the opposite) that could also influence sediment dynamics (Toublanc et al., 2012).

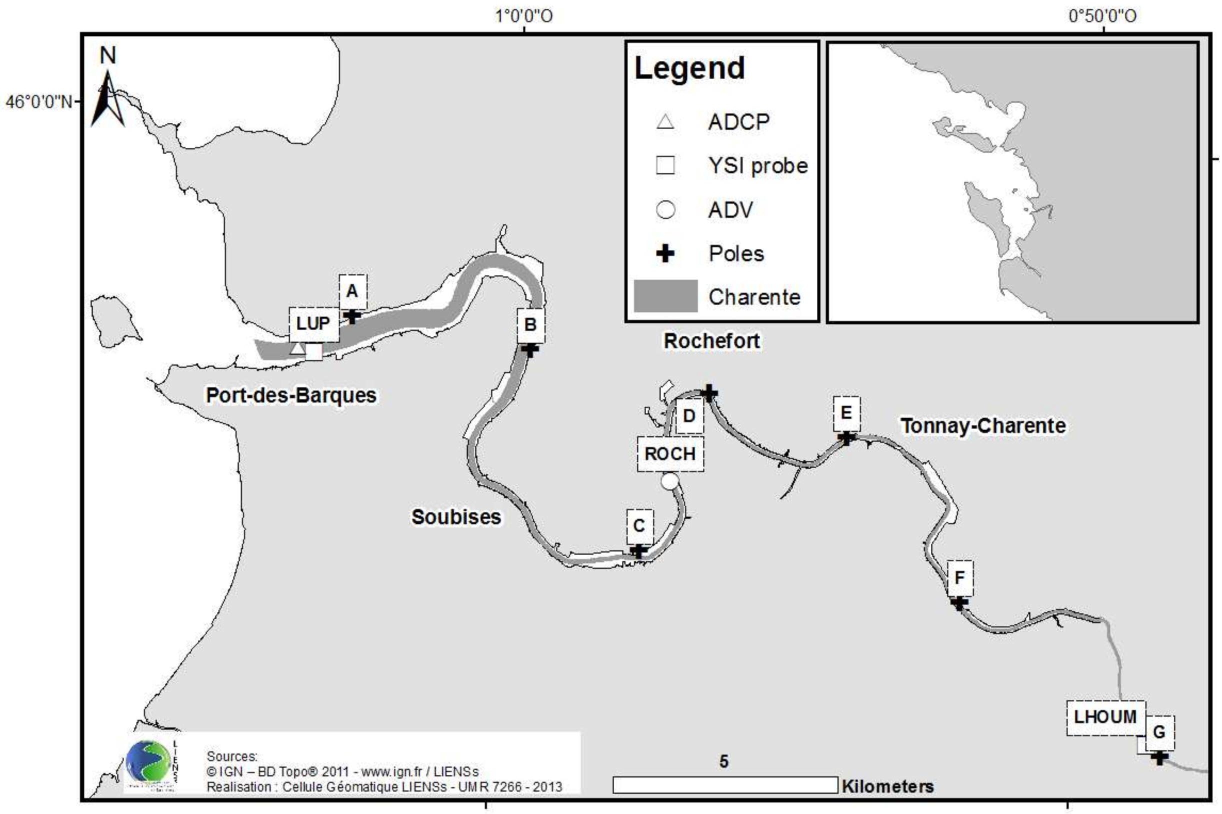

Figure 1: Study area, position of instruments and sediment monitoring

Sediment concentration is unanimously high up to 10g.L^{-1}(e.g: Ravail et al., 1988, Kervella, 2009, Modéran et al., 2012), but spatial turbidity dynamics has never been studied at a full year scale. The estuarine zooplankton community, driven by river flow and tide, appeared to be structured by suspended sediment concentration (Modéran et al., 2010, Modéran et al., 2012). At the river mouth, the Marennes-Oléron Bay is a large oyster-producing area under the influence of estuarine waters, particularly in Summer (Ravail et al., 1988). A large part of surface muds in the Marennes-Oléron bay came from the Charente river (Kervella, 2009). The Charente banks are highly anthropized, with cities, factories and a river dam at 50km from the river mouth. The St-Savinien dam stops tidal influence and prevents flooding of the downstream areas during great tides. Despite these numerous uses of the estuarine area, only few studies are available, many questions remain, and problems such as water and sediment pollution or mudding are often highlighted by users. Field experiments were performed at several places along the saline area of the estuary. The river dam at St-Savinien was considered as the upstream limit for field measurements.

2.2. *Hydrodynamics measurements*

Currents were monitored continuously from 08 November 2012 to 20 February 2013, and keep working at the conference date. Hydrodynamic measurements were performed with two 10-MHz Acoustic Doppler Velocimeters (Argonaut-ADV, Sontek) deployed on self-made tripods. The ADV was programmed to average 30 seconds of measurement every 5 minutes. The velocity probe was deployed 1 meter above the sediment surface at Rochefort (Figure.1) and was visited every month for maintenance. A 1200-KHz Acoustic Doppler Profiler (Sentinel, Teledyne RDI) sampled the water column from the 11 February to 8 April 2011 at the river mouth. This profiler averaged 200 pings, and stored 5min averages. These data from the bottom up to the surface were provided by IFREMER. Reference water levels were provided by Refmar. Freshwater runoffs were provided by the Charente general council.

2.3. *Suspended sediments monitoring*

Temperature, salinity and turbidity were measured at a 5min interval from 30 May 2012 to 20 February 2013 using a multi-parameter probe (YSI 6600V2 with 6026 optic turbidimeter). 3 monitoring stations were moored: near the river mouth (“LUP”), at Rochefort (“ROCH”) and near the limit of the saline intrusion (“LHOUM”). “LUP” and “LHOUM” floated around 2 meters above the river bed on a mooring line design with “Mooring Design & Dynamics matlab package” (Dewey, 1999). “ROCH” was fixed 1 meter above the bed on a tripod bottom mooring.
Salinity and turbidity were laboratory calibrated using 12880Us.cm^{-1} & formazine 1000 and 4000 NTU standard. Laboratory calibrations of turbidity sensors for SSC were performed in a 40L black bucket using wet sediments collected from intertidal banks. SSC were validated by filtration through GF/C filters with field samples. Times-series data were processed with Matlab routines and intercalibration of probes were checked. No significant differences were noticed (paired T-student test with simultaneous field-measurements, $p<0.01$). A strong approximation remains for sediment concentration and sediment flux, as YSI turbidity probe can only measure up to 4000 NTU. During measurements, probe saturation has occurred up to 80% a day, particularly during spring tide and high runoff. Surface sediment budget (kg.m^{-2}) was computed with the following formula:

$$Q(t) = \sum \Delta t \; U \; SSC \; dt \tag{1}$$

Where *U* is current magnitude (m/s), *SSC* is suspended sediment concentration (kg/m^3),*dt* is the time step (300s). Sediment budgets were computed for Δt defined as flood and ebb tide. Due to strong lateral and vertical variation of SSC, sediment budget wasn’t computed on the estuarine section.The SPM retention percentage (Purnachandra et al., 2011) was calculated for different runoff step using the following formula:

$$SSC\ retention\ (\%) = \frac{(SSCspring - SSCneap)}{SSCspring} \times 100 \tag{2}$$

Surveys were performed with a bi-frequency 33/200 kHz sonar (Navisoud 620, Reson). Five transects were made from accretion station “F” to the river mouth (Figure.1). A multi-parameter probe (YSI 6600V2 with 6026 optic turbidimeter) was mounted 1 meter under the boat, a second probe was used to make vertical profiles as sounding signal changed.

2.4. *Estuarine banks*

Sedimentation rates were measured with accretion poles deployed at 7 stations from the river mouth to the fresh water area of the estuary (Figure.1). Poles data indicate relative elevation changes including subsurface processes (Thomas, 2004) at a centimetric accuracy. Three poles were deployed at each station; accretion was measured alternatively during neap/spring tide and function of the river flow.

3. Results

3.1. *Field observations*

. Numerous previous surveys (26/07/2011, 17/11/2011, 03/04/2012) presented a large sound-barrier up to 5 meters thick in front of the sounding zone of the Rochefort-harbor (Figure.1). Every observation of this phenomenon happens during high tide of average amplitude, which is in concomitance with TM estimated position.

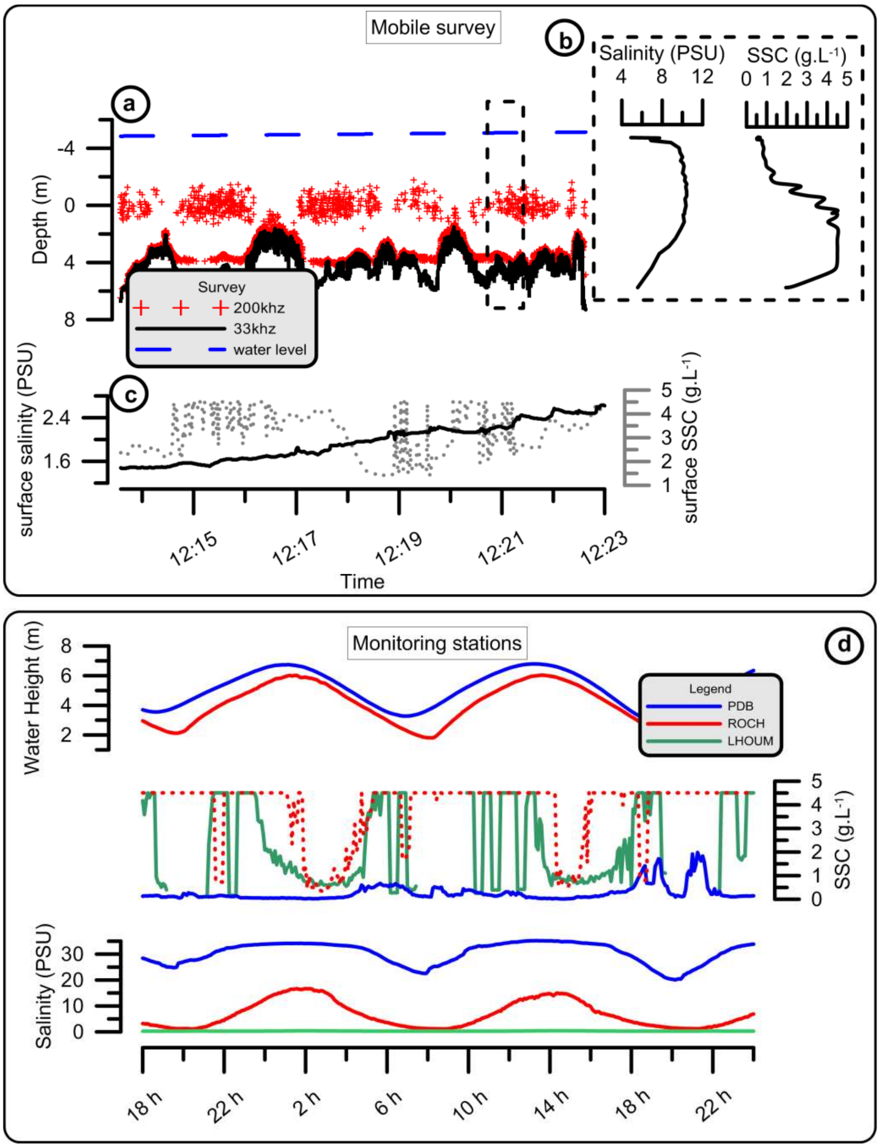

Figure 2: Survey data and associated turbidity probe, time-series of monitoring station, 12 October 2012.

Desmazes et al. (2010) have used bi-frequency method to describe fluid-muds dynamic in the Loire estuary. To confirm the bi-frequency sounding pertinence for turbidity monitoring, 2 surveys were performed in neap and spring tides, the 12 and 17 October 2012. The first survey during neap tide extended from Rochefort to the river mouth at low tide and from the river mouth to station “F” during the flood. A net sound barrier occurred at mid-depth between Rochefort and Soubise (Figure.1) at low tide. Surface SSC did not present extreme values, but a strong stratification was noticed. Turbidity profiles confirmed the occurrence of a TM in this area. At high tide, the phenomena occurred 6km upstream and extended

from Rochefort to station “F” (Figure.2-a).A net interface was noticed 1 meter above the river bed, classed as low consolidated sediments or fluid-muds.The vertical profiles across the mid-depth sound-barrier confirmed several hypotheses (Figure.2-b). Turbidity maximum occurred at 4 meters depth, which is in concomitance with the 200 KHz survey. On the deeper part of the sounding profile, a net interface appeared 1 meter above the river bed: this phenomenon could be due to water stratification and the associated lutocline or to deposited fluid mud. Parallel to the SSC increase with depth, a salinity decrease can be observed. The strong SSC in the estuary increases water density. Affected by density and bottom friction, the slow TM was surrounded by the saline flow tide. This observation could be explained by an instrument artifact as high SSC can cause an underestimated conductivity (Sottolichio et al., 2011). However, sediment concentration decrease in the deeper part of the profile did not cause conductivity shift; the observed stratification is therefore credible. The 200 KHz survey could finally be modified by water stratification and strong sediment concentrations. The TM position around Rochefort is confirmed by monitoring station « ROCH » (Figure.2-d) where the probe saturation is reached for all the flood tide. On the opposite, the saline water at “PDB” station remains clear even during low tide.
The second survey during a spring tide did not present any of these characteristics: SSC reached a maximum and salinity was constant from the surface to the river bed. No net sound-barrier appeared on the 33/200 KHz survey. These homogeneous water columns suggest strong water-bodies mixing including fluid-muds reworking.

3.2. *Flow and suspended sediment monitoring*

Three turbidity stations (“LUP”, “ROCH”, and “LHOUM”) were deployed along the estuary between June 2012 and February 2013. Additional data were provided by 2 probes deployed on the boat during survey. Any temporal synchronization appeared between TM occurrence at ROCH and LUP. The maximum concentration often occurred at ROCH before LUP station, both during flood and ebb.

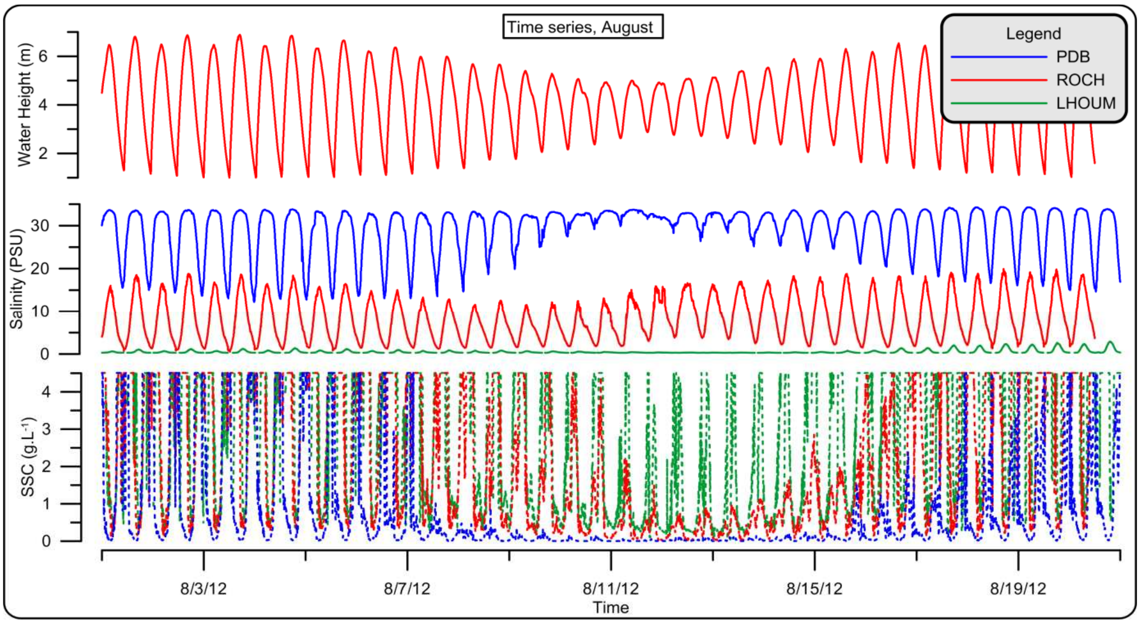

Figure 3: time series of water height in August, salinity and suspended sediment concentration (SSC) at PDB, ROCH and LHOUM.

Maximum turbidity punctually exceeds 5g.L^{-1} at every location of the estuary. Mean suspended sediment concentrations at low runoff (<40m^{-3}.s^{-1}) were 0.20g.L^{-1}, 1.82g.L^{-1} and 1.54g.L^{-1} during neap tide from the river mouth to the upper estuary (Figure.3). During spring tide mean concentration at low runoff increased at least twofold (1.67, 3.43 and 3.27g.L^{-1}) as this result is underestimated by probe saturation. SSC was generally lower at LUP than at ROCH. Concentration differences between stations were greatest during transitional period between spring and neap tide as sediment concentration decreased at the river mouth few days before the decrease at Rochefort.

Table 1: SSC evolution with river runoff, June 2012-February 2013

		Mean tidal SSC (g.L-1)			**SSC Retention %**			**SSC budget (kg/m²/tide)**
	River runoff (m3/s)	LHOUM	ROCH	LUP	LHOUM	ROCH	LUP	ROCH
Low	0-40	2,58±0,83	2,84±0,86	1,03±0,77	44	46	88	
Transition	40-100	0,1537±0,18	2,69±1,16	1,59±0,86	80	-50	56	-782287
Hight	>100	0,103±0,13	0,09±0,11	1,62±0,74	-25	34	48	-228135

Salinity constantly increased in Summer at every station. Maximum marine water intrusion occurred in September as salinity was 4 PSU at the upper station LHOUM. As the runoff increased to 20 $m^3.s^{-1}$, the saline water intrusion in the upper estuary progressively decreased fourfold. The November flood definitely exported marine water downstream. As the runoff constantly increased, sediment concentrations at ROCH were significantly higher than in Summer (Table. 1). Over than 200 $m^3.s^{-1}$ runoff exported marine water downstream from ROCH. During winter month, river runoff constantly increased (Figure.4) up to 500 $m^3.s^{-1}$ in February: turbidity did not exceed 2 $g.L^{-1}$ at ROCH and LHOUM and was generally lower than 0.5 $g.L^{-1}$.

Two currentmeters (“PROF” and “CROCH”, Figure.1) were deployed near the estuary channel (Figure.1). Maximum velocities were measured during ebb tide of spring tide. Current speed at CROCH tends to increase with river runoff (20 days Lanczoc filter, p>0.05).

3.3. *Sediment deposition*

Sediment level was measured for various tidal amplitudes between July 2012 and March 2013 (Figure-4).

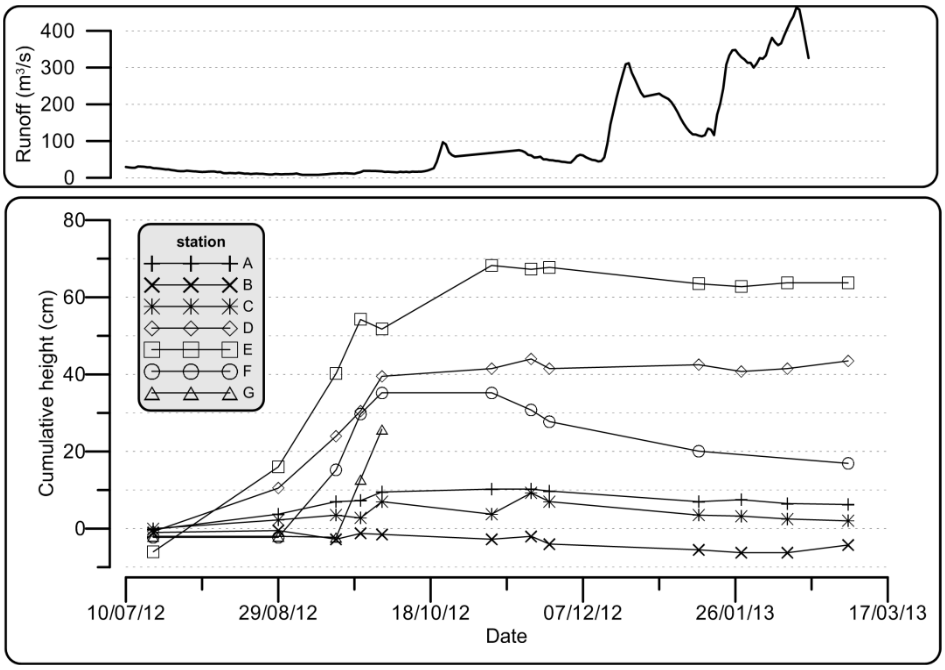

Figure 4: River runoff and relative sediment level at 7 station of the Charente Estuary

Maximum relative accumulation occurred in August during lower runoff at the upstream poles (≈40 cm a month). The river mouth seems more stable, with a maximum accumulation of 8 cm a month. Comparison between mean relative sediment level variation and mean runoff between 2 measurements confirmed that river runoff has a direct effect on bank evolution of the estuary (Figure.4).
During summer low runoff, sediment accumulations on the river bank are fluid and unconsolidated. Such sediment accumulations did not occur from the first autumn flood (≈100 $m^3.s^{-1}$) to the last measurement. However, poles data from station D to F during flood flow did not present significant erosion. During November measurement, these poles had slide 2 meters from their initial position towards the river channel. This observation suggests a general mud slide of the river bank. Two phenomena could therefore be the source of bank-water sediment exchanges: a strong summer sedimentation and the fall erosion of the channel slope.

4. Discussion

4.1 *Different patterns*

To identify the main factors that control temporal variation of sediment transport, correlations between sediment concentrations and several parameters were tested (runoff, tidal range, duration of theflood/ebb tide, salinity, mean sediment concentrations at other stations…). For ROCH and LUP stations, a multiple linear regression was computed for sediment concentration. This statistical analysis highlights the main factors that affect sediment transport at each station deployed during field work. Sedimentary processes seem quite different at each station.
At the river mouth (LUP), the parameters used were the river runoff and mean water height. The significance level of the model (Pr> Fisher's F) is better than 0.001 and r^2=0.53. More than half of the variance is explained by tidal regime, and slightly by the river runoff. The same observation was made by Uncles et al.(2006) for TM position.

Table 2: Multiple linear regression of tidal mean SSC at the estuarine mouth (LUP). R^2=0.53, n=371. The equation of the model is: log (SSC+1) = -1.39+0.24×Hmax+0.0012×Runoff

Parameter	Coefficient	Standardized coefficient	Standard Deviation	Student's t	Pr > |t|	Lowerbound (95%)	Upperbound (95%)
Intercept	-1,391	n/a	0,088	-15,796	< 0,0001	-1,564	-1,218
Hmax	0,244	0,719	0,013	19,260	< 0,0001	0,219	0,269
Runoff	0,001	0,463	0,000	12,404	< 0,0001	0,001	0,001

At Rochefort (ROCH), several models were tested, including salinity intrusion, river runoff, water height, and season. The seasonal impact of river runoff at ROCH is stronger than at LUP: sediment concentration strongly decreases as the runoff increases (Table. 1). Time series observation and linear regression confirm a threshold effect of fresh water on sediment dynamics. For statistical purpose, a focus was made on low-runoff data's (<20$m^{-3}.s^{-1}$). A significant link was found between maximum water height and mean tidal sediment concentration (R^2=0.54, n=188). Runoff did not have a linear effect on sediment dynamics. SSC first increased between 40 and 100 $m^{-3}.s^{-1}$ (Table. 1); as the freshwater-saltwater interface did not reach the station anymore (16 October), SSC decreased under 0.5$g.L^{-1}$ and net sediment budget decreased fourfold (Table. 1).
The positive relationship between runoff and SSC at both stations also highlights the seaward shift of sediment oscillation in Winter. A similar link was noticed by previous studies, especially between saline intrusion and TM position (Uncles and Stephens, 1993, Uncles et al., 2006, Cook et al., 2007). However, the threshold effect of runoff on sediment dynamics observed on the upstream stations (ROCH and LHOUM) and the non-synchronization with the river mouth put forward different patterns. Even if ROCH and LUP sediment transports are linked, 2 turbidity maximum processes could be considered. At the river mouth (LUP), spring tides bring a TM when salinity was less than 20 PSU. Strongly correlated to the tide,

this TM is linked to its sediment source: the upstream TM (ROCH). At the station ROCH, salinity and turbidity peak occurrence are not synchronized. This upstream TM appeared only with low runoff due to tidal pumping of the brackish waters. The bimodal trend is similar to Patchineelam and Kjerfve (2004) observation of a traditional mobile TM and a sediment resuspension area. This phenomenon could also be compared to the seasonal spread of SSC and formation of 2 TM described by Doxaran et al. (2009) in the Gironde Estuary.

4.2 *Siltation and erosion*

The upper estuary seems to be its most dynamic part, as the maximum sediment deposition occurred from station D to G during Summer (Figure.4).The maximum sediment accumulation occurred in September and can be linked to the maximum saline intrusion. During this low runoff period, the estuary constantly shifts landward and leads to strong trapping of suspended sediment. According to Toublanc et al. (2013) estimation, the saline waters intrude 45 km from the river mouth. What favors summer siltation of the upper estuary? Survey data of the 12 October partly answer the question. Between 8h and 13h, TM moved 5km landward. The strong SSC measured at mid depth is associated with a salinity inversion (Figure.2). Such an inversion could be due to the presence of nearly stationary underlying sediments, slower than tidal flows (Uncles et al., 2006, Sottolichio et al. 2011). Bottom friction and higher viscosity could slow the TM and favor the siltation of the area. Maximum sediment accumulation on the river banks then occurred in the area where the TM was detected by bi-frequency survey. The observed mud patch (Figure.2) had disappeared during spring-tide survey (17 October) and the TM extended from ROCH to PDB. During this spring tide, mean concentration increased twofold and no stratification appeared. Spring tide acts on a wide length and available sediments are then concentrated during neap tide. Such phenomenon was noticed in several studies: the unconsolidated muds are reworked by stronger tidal currents (Uncles and Stephen, 1993, Cook et al., 2007, Sottolichio et al., 2011). Finally, strong trapping of river and sea SSC increases sediment deposition in the upper estuary (Jiufa and Chen, 1998, Woodruff et al., 2001).
Maximum sediment movements occurred between 40 and 100 $m^{-3}.s^{-1}$, channel sediments are rapidly exported, and the intertidal bank stability is threatened: more than 10^4 tons of sediment was transported seaward from ROCH during one tide. Prandle (2004) correlated bathymetric and river flow variations as a relation of cause and effect. As the runoff increased, TM constantly moved seaward, and neap tide is not anymore a stagnation period. Woodruff et al. (2001) explained summer/winter sediment accretion as a shift in landward/seaward accretion. Contrary to their observation, winter floods (>$100m^{-3}.s^{-1}$) exported mobile sediments out of the Charente estuary. Furthermore, strong tidal current on the estuarine mouth does not allow seaward sediment settling in Winter.
Short term effect as wind stress and waves, could also be significant but was not use in this study. Water and air temperature at the river mouth are significantly correlated (Pearson correlation coefficient, r=0.45, n=190).

5. Conclusion and perspectives

The dataset confirmed several general patterns of estuarine circulation in the studied area. The size of the estuary leads to a rapid answer of sediment dynamics for each environmental forcing. The turbidity maximum was concentrated near the freshwater-saltwater interface during neap tide. These fluid muds slowed the water bodies, caused salinity inversion and favored siltation. Spring tides and winter floods spread the TM. These floods rapidly exported the TM and unconsolidated sediments seaward. The river banks are then unstable and bank slope appeared. The river mouth sediment dynamics did not change from Summer to Winter as sediment balance in the area mostly depend upon tide.
Bi-frequency sounding seems to be a good qualitative tool for TM detection. The transition between different sediment concentrations and water characteristics was well detected: such a method is then usable during neap tides.
During next months, surface and cores sediments will be analyzed and summer formation of a new TM will be explored. Special focus will be made on sedimentary exchanges at the interface. In perspective, the global trend described in this paper will be related to model data’s (Toublanc et al., 2013).

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