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Tracking the turbidity maximum zone in the Loire Estuary (France) based on a long-term, high-resolution and high-frequency monitoring network

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Abstract

A unique dataset of turbidity from 7 years of continuous monitoring at six stations, distributed evenly along a 62-km long transect, is presented to discuss, for the first time, the present-day dynamics of the turbidity maximum zone (TMZ) in the Loire Estuary. This system is considered one of the largest macrotidal, hyper-turbid estuaries of the European coast, mainly as the result of intense engineering works in the last two centuries. Besides accurate TMZ tracking, from tidal to multi-annual time scales, the high temporal and spatial resolution of measurements allows us to address TMZ aspects scarcely reported in the literature on estuarine sedimentary dynamics. In the Loire Estuary, TMZ moves upstream during periods of low discharge and its upstream boundary may reach up to 62 km from the mouth. The TMZ displacement is faster during its downstream flushing by river floods than during its upstream migration by tidal pumping (respectively 1.6 km day^{-1} and 0.9 km day^{-1} during 2011). However, the expulsion of the TMZ from the upper reaches requires higher discharge levels than its installation (respective discharge thresholds of 497-1034 m^3 s^{-1} and 300-360 m^3 s^{-1}). This is due to the presence of mobile mud remaining after the TMZ presence, as confirmed by clockwise turbidity-discharge hysteresis patterns. While the installation threshold barely varies over years, the expulsion threshold is higher during years with a more concentrated and persistent TMZ. The interannual variability of the TMZ concentration and persistence is explained by the water volume transported during the previous high discharge period and the duration of the low discharge period, respectively, as recently shown for the Gironde Estuary, leading to a better understanding of TMZ features in macrotidal estuaries. The summer-averaged river flow is introduced as a hydrological indicator of the upstream boundary of the TMZ. In the context of global change, these three discharge-based indicators of TMZ behavior provide powerful tools to assess future scenarios.

Keywords: turbidity maximum; Loire estuary; monitoring; high-frequency; long-term variability; suspended sediment dynamics

1. Introduction

Regions of high suspended sediment (SS) concentrations, named turbidity maximum zones (TMZ), are key features of tidal estuaries (Allen et al., 1980). The spatial and temporal evolution of the TMZ govern the transport and deposition of fine sediments (Uncles et al., 2006b) and hence may cause significant morphological changes, such as the siltation in channels and ports (Ponte et al., 2004). The TMZ also influences biochemical processes, such as particulate transport of nutrients and pollutants (Turner and Millward, 2002; Etcheber et al., 2007) and alter light and oxygen conditions (Talke et al., 2009; Lanoux et al., 2013). While the TMZ formation is governed by universal basic mechanisms (Dyer, 1988), its concentration and persistence vary from one estuary to another under the control of local tidal and river regimes, morphology, and type and availability of sediments (Grabemann et al., 1996; Uncles et al., 2006a; Garel, 2009; Mitchell, 2012).

Observational studies of the TMZ have usually been carried out for short periods of time or for specific regions of an estuary (Guézennec et al., 1999; Grabemann and Krause, 2001; Mitchell et al., 2003; Uncles et al., 2006a; French et al., 2008). The long-term tracking of the TMZ in an entire estuarine system is not very common, despite it provides worthwhile information to advance our understanding of sediment processes (Mitchell et al., 2012). More specifically, the tracking of the TMZ becomes essential for two reasons: i) the temporal evolution of the TMZ is a factor that can help to explain long-term morphodynamic trends in estuaries, typically shifts in sedimentation zones, changes in SS concentration or general infilling; ii) a good knowledge of TMZ geometry from field data is necessary to validate numerical models, which are increasingly widespread and used to simulate estuarine processes that couple sediment transport, morphodynamics and water quality at annual time scales.

Currently, two main techniques are used to track the TMZ: typically remote sensing and *in situ* long-term monitoring. Remote sensing is an efficient tool to characterize the spatial distribution of turbidity in surface waters along estuaries (Doxoran et al., 2009; Cai et al., 2015). However, despite recent improvements in algorithms and sensors (Gernez et al., 2015), temporal resolution remains limited. In addition, *in situ* measurements of SS concentrations are necessary for calibration of the satellite signal, and the quality of the image is highly dependent on atmospheric conditions. The use of *in situ* long-term and-high frequency monitoring has demonstrated its efficiency to address TMZ dynamics from semi-diurnal to multi-year time-scales (Jalón-Rojas et al., 2015). The spatial representativeness can be limited, depending on the number of monitoring stations. At present only few estuaries throughout the world utilize this technique, mainly due to the financial and practical constraints (Buchanan and Ruhl, 2000; Etcheber et al., 2011; Contreras and Polo, 2012).

Situated on the French Atlantic coast (Fig. 1), the Loire Estuary, extending 100 km from the mouth, is one of the three largest French estuaries. This macrotidal and highly turbid system plays the double role of an ecologically important wetland and an axis of economic development. During the last two centuries, continuous interventions of channeling and deepening have heavily modified the morphology of the Loire Estuary (Sogreah, 2006). These engineering works have favored tide amplification and flood-dominant conditions, upon which fine sediments are pumped more upstream, reducing the effective hydraulic drag (Winterwerp and Wang, 2013; Winterwerp et al., 2013). As a consequence, the estuary has evolved into a self-maintaining hyperturbid state, characterized by a highly-concentrated TMZ. Gallenne (1974) defined this TMZ as the region of the Loire where SS concentration exceeds 0.5 g L^{-1}, and explained its basic mechanisms of formation due to gravitational residual circulation, even if tidal processes are also important and probably dominant, as shown later by a 1-D numerical model (Le Hir and Thouvenin, 1994). However, since Gallenne's thesis to the present-day, there has barely been any study about SS dynamics based on field observations. Based on ^{7}Be budgets, Ciffroy et al. (2003) estimated the residence time of TMZ suspended sediments to be 6-10 months in summer, and about 0.7 month during flood periods. A sediment transport model based on the TELEMAC-3D system has been implemented for the Loire Estuary, but until now the applications (Cheviet et al., 2002; Walther et al., 2012) were focused on improving the simulation of basic physical processes, such as salinity gradients and bottom friction in the presence of mud. More recently, the SS distribution in the entire estuary has been estimated for a two day period through satellite data (Gernez et al. 2015). However, TMZ dynamics in the Loire Estuary are still not detailed despite the TMZ’s environmental impact.

This study aims to describe and understand, for the first time, TMZ dynamics in the Loire Estuary over all the relevant time scales. This work is based on 7-year (2007-2013) records of turbidity from an automatic, high-frequency monitoring network called SYVEL (SYstème de Veille dans l’Estuaire de la Loire, Watch system in the Loire Estuary). Firstly, we present in detail the turbidity dataset and describe trends. Secondly, we discuss TMZ dynamics in terms of the TMZ’s position, persistence, concentration, rhythms of upstream migration and downstream flushing, and inter-annual variability.

2. Material and Methods

The Loire Estuary relies on the six monitoring stations of the SYVEL network distributed from the mouth to 62 km upstream, near the limit of salinity influence (Fig. 1), in order to assess water quality (http://www.loire-estuaire.org). The stations were implemented in 2007, except for the station of Donges that was added in December 2010. Operation of the Cordemais station was stopped in December 2011. Each station measures four parameters at 1 m below the surface: dissolved oxygen, salinity, temperature and turbidity. Turbidity is also measured at 4 m below the surface in Donges, since December 2010, and in Le Pellerin, intermittently during 2007, from February to April and from late November to early December. Except for the station of Bellevue, the sites are equipped with real-time autonomous monitoring systems (see Etcheber et al., 2011, for details of the automated systems). The turbidity sensors (Endress and Hauser, CUS31-W2A) measure values between 0 and 9999 NTU every 10 minutes (60 minutes for Cordemais). The saturation value (9999 NTU) corresponds to about 5.5 g L^{-1} (GIP, 2014). Since the station of Bellevue is in the most upstream position, and hence has lower turbidity, it was instrumented with a SMATCH multiparameter sensor (0 – 2000 NTU; NKE) in order to save the high costs and the particular needs (e.g. electricity socket) of the automated stations. The SMATCH and CUS31-W2A turbidity sensors have the same response in the 0-2000 NTU range that is expected in the upper estuary.

There are three levels of data validation. First, an automatic control based on the range of values that assigns a quality code to each data: (0) unqualified; (1) good; (2) out of statistics; (3) doubtful; (4) false; (9) missing data. Secondly, data is visually inspected by an expert. Thirdly, the sensors are calibrated and validated every 3 months. The validated dataset of turbidity records from the SYVEL network has1.034.173 values between 2007 and 2013. The mean rate of correct operation of all the stations is about 85.4% (excluding bottom measurements at Le Pellerin).

As tide and river discharge are the main factors explaining the TMZ variability in estuaries, water level and river flow records are used to discuss its dynamics. The hydrometric station of Montjean-sur-Loire, managed by the DREAL Pays de la Loire, provides validated data of river flow on the national French web site: http://www.hydro.eaufrance.fr/. A total of 7 tide gauges, managed by the Port of Nantes Saint-Nazaire, are distributed along the estuary (Fig. 1), recording water level every 5 minutes. Turbidity data at each SYVEL station are compared with tide data from the nearest gauge. In the absence of data of current velocity to identify the mechanisms of sediment transport associated with tidal cycles, water level is used as a surrogate for tidal currents. For example, an increase of turbidity around mid-tide level, roughly when current velocities are close to their maximum, point to resuspension at the recording station; turbidity minima at low and high tide, when current velocities are almost negligible, indicate deposition; an increase of turbidity after the mid-tide level, when current velocities decrease, or at low tide or high tide, indicates mainly advection by horizontal currents.

To track the TMZ, we used two criteria based on tidally-averaged values of SS concentrations. The first uses a threshold of 0.5 g L^{-1} (300 NTU), historically used in the Loire Estuary to define the TMZ (Gallenne, 1974). The second one corresponds to the threshold of 1 g L^{-1} (600 NTU), used in the other main Atlantic French estuaries that exhibit a similar order of magnitude in turbidity: the Gironde (Allen et al., 1977; Jalón-Rojas et al., 2015) and the Seine (Némery and Garnier, 2007) Estuaries. Here, we define the presence of two categories of TMZ following the range of tidally-averaged turbidity (next noted turbidity*). A moderately-concentrated TMZ (TMZ^{low}) is when turbidity* is between 300 and 600 NTU at a given station, and lower both landward and seaward. A highly-concentrated TMZ (TMZ^{high}) is when turbidity is > 600 NTU at a station and lower both landward and seaward. We use the terms “TMZ installation” and “TMZ expulsion” to denote the transitional periods when turbidity oscillates around 300 NTU at a given station, during the TMZ upstream and downstream migrations (see Fig. 2).

3. Results

3.1. Hydrological conditions between 2007 and 2014

The Loire estuary drains the longest river in France (1012 km), with a drainage basin of 118 000 km^2, covering about one fifth of the French territory (Benyoucef et al., 2013). The Loire hydrological regime is pluvial with a high seasonal variability of discharge. The mean daily river flow over the study period (2007-2013, Fig. 2.A) was 775 m^3 s^{-1}, with considerable variation ranging from 103 to 3980 m^3 s^{-1}. The annual-average discharge ranges from 425 m^3 s^{-1} (year 2011) to 1128 m^3 s^{-1} (year 2013), with a mean of 860 m^3 s^{-1} (Table 1). For the same period, the mean discharge was 1389 m^3 s^{-1} in winter (22 December - 21 March) and 341 m^3 s^{-1} in summer (22 June - 21 September).

The semi-diurnal (12 hours and 24 minutes) tide becomes increasingly asymmetrical (flood shorter than ebb) as it propagates upstream (Fig. 3). At the mouth (Saint-Nazaire, Fig. 2.B), the minimal, mean and maximal tidal ranges during the study period were 1.5, 3.7 and 6.4 m respectively. Tidal range increases towards upstream reaching maximum values at Cordemais (mean tidal range of 4.1 m), and significantly decreases at Bellevue (mean tidal range of 3 m) (Fig. 3). Spring and neap tides were defined here as the tidal cycles for which tidal range is, respectively, above the percentile 75 (p75) and below the percentile 25 (p25). At Saint-Nazaire, these values were about 2.9 m (p25) and 4.6 m (p75).

3.2. Intratidal variation of turbidity

We first present three examples of high-frequency records in each SYVEL station to illustrate the range of variability of turbidity at the intratidal time scale for different hydrological conditions (Figure 3). These examples also show the mechanisms of transport of fine sediments causing the TMZ, as described in section 2. When a station temporarily holds bed deposits of sediments, turbidity records show the typical resuspension-advection-deposition cycles (Grabemann and Krause, 1989), and turbidity varies over a large range of values. The more downstream stations (Donges and Paimboeuf, Fig. 3.I and 3.II) show such turbidity cycles whatever the hydrological conditions, which result in turbidity variations from several tens of NTU (during deposition phases) up to more than 9900 NTU (during advection or resuspension peaks). When the river discharge decreases, the resuspension-advection-deposition cycles, and hence the temporary deposition of sediments, are present more upstream. During low river discharge, resuspension peaks may reach values up to about 9600, 7600 and 1050 NTU at Le Pellerin, Trentemoult and Belleveue, respectively (Figs. 3.IV-VI).

To check the presence of turbid waters at depth, Figure 4 compares turbidity recorded at 1 and 4 meters below the surface in Donges (down estuary) and Le Pellerin (upper estuary) for two hydrological conditions. At Donges, turbidity peaks show higher values at the bottom whatever the river flow: up to 8 and 4.5 times higher for the examples of high (Fig. 4.A) and medium (Fig 4.B) river discharges respectively. However, for high discharges (Fig. 4.A), bottom-surface turbidity differences are weaker during high tidal range (12-14 March) due to stronger vertical mixing. At Le Pellerin, turbidity is very low and does not show differences between bottom and surface during high river discharge (Fig. 4.C). For medium river discharges, turbidity peaks are higher at the bottom, especially during higher tidal ranges (up to 7.5 higher in the example of Figure 4.D).

3.3. Subtidal variation of turbidity

Turbidity* time series illustrate variability over longer time scales, highlighting significant oscillations in the response of SS to tidal range and freshwater flow (Fig. 2). Considering tidal range only, turbidity* varies with the spring-neap cycle, as described in Fig 2.D, which details the period from July to November 2011. This oscillation is linked to the differences in erosion flux and vertical mixing, which is maximum during spring tides and minimum during neap tides. River discharge controls the redistribution of fine sediments in the estuary, which varies seasonally. The annual increase of turbidity* in the upper stations (Fig. 2.D, E and F) shows the upstream transport of sediment during periods of decreased river discharge.

To summarize subtidal variations and turbidity* trends, Figure 5 presents the percentile values of turbidity* in each SYVEL station for three ranges of tidal range and three contrasting hydrological conditions. First, turbidity* is systematically modulated by tidal range only in stations that exhibit high levels of turbidity. For example, the effect of tidal range is negligible at the upstream stations during floods (Fig. 5.A) where median turbidity* is around 65 NTU whatever the tidal range. For this same hydrological situation, median turbidity* at Paimboeuf varies between 91 NTU and 682 NTU for low and high tidal ranges respectively. Figure 5 also shows the spatial evolution of turbidity for different hydrological situations. During river floods (Fig. 5.A) the maximum values of turbidity are situated between Donges and Paimboeuf (median turbidity* for medium tidal range of 150 and 310 respectively). For medium river discharge (Fig. 5.B), Paimboeuf and Cordemais present the highest turbidity* with median values for medium tidal range of 390 and 380 NTU respectively. During low river discharge (Fig. 5.C) a longer region of the estuary exhibits high levels of turbidity*. The maximum values correspond to Cordemais, Le Pellerin and Trentemoult, where medium turbidity* is respectively 876, 1026 and 446 NTU for a medium tidal range.

Turbidity also varies at the interannual time scale. Figure 2 illustrates marked differences in the levels of turbidity* for the different years, especially at Cordemais, Le Pellerin and Trentemoult. To detail this variability, Table 1 collects the annual maximum of turbidity* ($Turbidity^{*}_{max}$) in all the SYVEL stations. While the highest values of $Turbidity^{*}_{max}$ occurred in 2011 at most of the stations (2009 for the two uppermost stations), the year exhibiting the lowest values varies between stations. Nevertheless, 2007 and 2013 showed lower values in the upper estuary. The ratio between the highest and the lowest maxima of turbidity* is lower in the down estuary (1.4 for Paimboeuf) than in the central region (2 for Le Pellerin), which is in turn lower than in the upper estuary (9.6 at Bellevue). This interannual variability will be discussed in more detail in section 4.2.

4. Discussion

4.1. Upstream migration and downstream flushing of the TMZ

The dependence of the position of the TMZ on river discharge is well known in macrotidal estuaries (e.g. Allen et al., 1980; Uncles et al., 1998). However, only good-quality data collected for a number of years ensures the establishment of a reliable local relationship of turbidity against the whole range of possible discharges in a given estuary (Mitchell et al., 2012). The present turbidity dataset in the Loire estuary allows an accurate tracking of the TMZ and its variability. Figures 2.D to 2.F show the periods of the annual occurrence of the TMZ in the upstream stations during low discharges. However, the TMZ is present throughout the year in the down estuarine reaches (Fig. 2.C). Besides the downstream shift of the TMZ during high river discharges, the section between Donges and Paimboeuf is located downstream of wide tidal flats (Cheviet et al., 2002) and therefore receives large amounts of SS downstream transported by advection (Fig. 3.I-II).

Figure 5 details the position of the TMZ along the Loire's axis. Shaded regions delimit the thresholds of $\mathrm{TMZ}^{\mathrm{low}}$ and $\mathrm{TMZ}^{\mathrm{high}}$. It is noticeable from the three situations that the TMZ becomes more turbid and elongated when moving toward the upper reaches for decreasing river discharges (Fig. 5.A to 5.C). On average, the TMZ migrates over a distance of approximately 40 km. Mitchell (2013) compared the average distance of TMZ migration with the typical high flow in four European estuaries (Weser, Seine, Scheldt, and Humber). We have included the Loire estuary in such a comparison and the result indicates that the TMZ is shifted over a greater distance than in the Weser, Seine and Humber estuaries. As suggested for the Scheldt, dredging and channel management operations could increase the SS transport, but also a high ratio of high to low fresh water flow may contribute to explain this observation. We will further discuss the variability of TMZ migration in Section 4.2.

Based on a similar 9-yr continuous monitoring in the nearby fluvial Gironde Estuary, it was demonstrated that turbidity in the upper reaches is lower during the period of upstream TMZ migration than during the period of downstream TMZ flushing (Jalón-Rojas et al., 2015). This is because mobile mud remains on the bed after the presence of the TMZ in the upstream estuarine sections. Following this finding, for each annual TMZ event in the upper reaches, turbidity* was represented as a function of river flow during periods of decreasing discharge (TMZ installation) and increasing discharge (TMZ expulsion). This was achieved for the upper stations of Le Pellerin and Trentemoult. Figure 6 illustrates this relationship for a dry (2011) and a wet (2013) year at Le Pellerin. As observed in the Gironde estuary, the discharge turbidity curve follows a clockwise hysteresis pattern over the transitional periods of TMZ installation and expulsion. This suggests the existence of mobile mud on the bottom, accumulated during the presence of the TMZ, that needs large river flow to be expelled (Jalón-Rojas et al., 2015).

The plot of turbidity* against river flow enables us to delimit the discharge thresholds of the TMZ installation and expulsion at a given station (Fig. 6). River flows associated with the installation of the $\mathrm{TMZ}^{\mathrm{low}}$ are very similar for the period 2007-2014, ranging between 300 $m^3 s^{-1}$ in 2013 and 360 $m^3 s^{-1}$

in 2011 at Le Pellerin (160 $m^3 s^{-1}$ in 2012 and 250 $m^3 s^{-1}$ in 2011 for TMZ^{high}), and between 200 $m^3 s^{-1}$ and 220 $m^3 s^{-1}$ at Trentemoult. On the contrary, river flows associated with TMZ^{low} expulsion vary by a factor of 2: between 497 $m^3 s^{-1}$ in 2013 and 1034 $m^3 s^{-1}$ in 2011. While conditions of the TMZ installation do not vary significantly between wet and dry years, the required river flow to expel the TMZ is higher during dry years. Therefore, these results show the need of larger volume of water, for the downstream TMZ shift during dry years, such as 2011 (Fig. 6). This is explained by a more persistent and concentrated TMZ (Fig. 3.E; Table 1) that promotes greater deposition of bottom mobile mud. Relationships between TMZ characteristics and hydrology will be analyzed in detail in Section 4.2. The discharge thresholds of TMZ^{high} installation at Le Pellerin (38 km from the mouth over 100 km of total estuarine length) are very similar to that of the upper stations of the nearby Gironde estuary (Jalón-Rojas et al., 2015): between 200 and 300 $m^3 s^{-1}$ at Bordeaux (100 km over 170 km) and around 160 $m^3 s^{-1}$ at Portets (140 km over 170 km). In the Gironde estuary, the TMZ moves more upstream, but the required river flow to expel it from its usual averaged position during low discharge periods is approximately the same for both estuaries.

Displacement velocities of the TMZ core along the estuarine axis are difficult to quantify through *in situ* measurements, and therefore, to our knowledge, there are no studies that address this aspect. The visualization and quantification of TMZ shifts require continuous monitoring over long time periods, a high-density network covering the whole estuary, and a low rate of missing data. The data used here meet the two first criteria, but the later start of the Donges station, in 2010, and the early stop of the Cordemais station in December 2011 preclude such analysis except for the period 2010-2011. Figure 7 shows the interpolated time series of turbidity over the six SYVEL stations from October 2010, at the end of the period of low discharge, to May 2011, at the beginning of the following low discharge period. To track the TMZ shifts, only values above the TMZ^{low} threshold (300 NTU, light blue) are plotted and the TMZ^{high} threshold is highlighted (600 NTU, bright blue). During low river discharges (October 2010), the uppermost extensions of the TMZ^{high} varied between pk 43, for neap tides, and pk 62 for spring tides (pk 49 and pk 58 for the TMZ^{low}, pk denotes the kilometer distance from the mouth). During the first discharge increase (river flow peaks of 624 and 886 $m^3 s^{-1}$) in November 2010, the TMZ was flushed downstream. Considering the time interval of this change, this implies a TMZ^{high} displacement velocity of about 1.6 km d^{-1} from the pk 58 to pk 38. Then, TMZ^{high} reached pk 25 at about 5.2 km d^{-1} during a flood peak of 1205 $m^3 s^{-1}$. During the period of large floods (December 2010-February 2011), turbidity remains higher than 600 NTU from the mouth up to pk 26 (Cordemais) during spring tides. Mid-January 2011, after the highest flood of the period (river flow peaks of 2190 $m^3 s^{-1}$), the whole estuary exhibits turbidity below 300 NTU, even during spring tides. In February 2011, as river flow decreases, the TMZ moves slowly up-estuary. The upstream migration of TMZ^{high} from pk 34 to pk 56 begins barely below 450 m^3 s^{-1} at about 0.9 km d^{-1}. Thus, the TMZ downstream flushing is faster than its upstream migration. We explain this observation by the smooth decrease of river flow, compared to the sudden and rapid changes during floods. This was suggested by Mitchell et al. (2012) for the Thames estuary. As no study had calculated the real displacement velocities of the TMZ, we have no comparative values for a further discussion of our results.

4.2 Control of TMZ concentration, persistence and upstream reaching

One of the main reasons for recording turbidity in estuaries over long time periods is to analyze factors affecting the long-term (multiannual) variability of TMZ features such as concentration, position and persistence. For an initial analysis of the interannual variability of TMZ characteristics, Figure 8 compares river flow, seasonal turbidity and the percentage of TMZ occurrence for a dry (2010-2011) and a wet (2012-2013) period. The large floods during winter and spring 2012-2013 (Fig. 8.A) resulted in turbidity* below the threshold of TMZ installation for the entire estuary (Fig. 8.B.2). By contrast, in 2010-2011, the TMZ was present at Paimboeuf during winter and migrated to the upper estuary during spring, reaching its maximum concentration at Le Pellerin. During summer, the TMZ migrated to the upper estuary but was more concentrated during the driest year. In addition the TMZ extended more upstream during 2010-2011. The averaged upstream boundary of the TMZ ($boundary^{up}$), defined as the maximum distance from the mouth where the median turbidity* exceeds 300 NTU, reached the pk 55 during summer 2011 (Fig 8.B.1), and the pk 41 during summer 2013 (Fig 8.B.2). The percentage of time during which the TMZ was present in each station also varied between both periods, especially in the upper estuary. During 2010-2011 (Fig. 8.C.1), the TMZ^{low} occurred for 41%, 21% and 5% of the time at Le Pellerin, Trentemoult and Bellevue, respectively. Meanwhile during 2012-13 (Fig. 8.C.2), it only occurred for 16% and 3% of the time at Le Pellerin and Trentemoult, respectively, and never at Bellevue. Therefore, the concentration, the persistence, and the upstream extent of the TMZ varied strongly inter-annually, depending on hydrological conditions.

Previous studies have already analyzed the relationship between the TMZ position and river flow on seasonal time scales in macrotidal estuaries. For example, Uncles et al. (1998; 2006a) established multiple regressions between the TMZ location and the monthly-averaged river flow in the Humber estuary. This suggests that the interannual variability of TMZ position should be related to river flow. However, no study has carried out such an interannual approach, mainly due to the lack of an appropriate dataset. As shown in Section 4.1, the Loire's TMZ reaches a given section of the upper estuary when river flow decreases below a threshold. This discharge threshold decreases upstream, 300-360 m^3 s^{-1} and 200-220 m^3 s^{-1} for Le Pellerin (pk 38.5) and Trentemoult (pk 52), and is rather constant for the period 2007-2013. This suggests that the TMZ reaches the upper estuarine sections during the dry periods characterized by lower discharges, independently of previous river flow. There is indeed a good correlation between the boundary^{up} and the corresponding summer-averaged river flows (Fig. 9). For most of the monitored years, summer river flow (Table1, from July to September) decreases down to 250-350 m^3 s^{-1} and boundary^{up} is around pk 40-45. However, boundary^{up} was quite different during the driest (pk 56, year 2011) and the wettest (pk 32, year 2007) summers, with a difference of 24 km between both years, i.e., a quarter of the estuary length. The year 2012 shows that hydrological conditions prior to summer also exert a small influence. After a dry winter, important floods during late spring 2012 (Fig. 2.A) delayed the upstream TMZ shift and, then, influenced its uppermost intrusion. For this same reason, river flow threshold of TMZ^{high} installation at Le Pellerin was also quite low during 2012 (Section 4.1). The variability range of boundary^{up} for the Loire Estuary (~25 km) is higher than the variability of the TMZ migration distance for the Humber, Seine and Weser estuaries (~5-15 km; Mitchell (2013). Therefore, the comparison of different estuaries should consider the interannual variability of the TMZ, especially to draw general conclusions about the TMZ's nature.

The annual turbidity* maximum ($Turbidity^*_{max}$) is a good indicator of the concentration of the TMZ at each station. It is remarkable that the most concentrated TMZ occurred during the driest years (Table 1). The less concentrated TMZs in the mid-upper estuary were observed during 2013, the wettest year, and during 2007, characterized by a moderate river flow but a very wet summer (Fig. 2.A, Table 1). Based on 9-years 10min-pass turbidity records in the fluvial Gironde estuary, Jalón-Rojas et al., (2015) demonstrated a good correlation between:

- $Turbidity^*_{max}$ and the water volume transported mainly before the TMZ installation, during periods of high discharge (HD) but also during the TMZ presence (Volume$_{HD+TMZ}$);
- Duration of the TMZ (Duration$_{TMZ}$) and duration of the period of low river discharge (Duration$_{LD}$), which is calculated as the number of days per year river flow is below the installation threshold.

We have reproduced the same relationships for the upper Loire Estuary and compared them to stations of the Gironde Estuary showing similar TMZ dynamics (Fig. 10 and 11). As both estuaries have different ranges of turbidity and water volume, $Turbidity^*_{max}$ and Volume$_{HD+TMZ}$ were normalized by their respective medians. There is a good correlation between Duration$_{TMZ}$ and Duration$_{LD}$ also in the Loire Estuary (R^2=0.87, Fig. 10), and it is noticeable that both estuaries follow the same tendency. $Turbidity^{*}_{max}$ and Volume$_{\mathrm{HD+TMZ}}$ exhibit a good correlation in the Loire Estuary (R^2=0.66, Fig. 11) and a similar tendency when considering both estuaries. The confirmation of summer discharge, Duration$_{\mathrm{LD}}$ and Volume$_{\mathrm{HD+TMZ}}$ as hydrological indicators of TMZ features provides a powerful tool to evaluate future scenarios. The prediction of a decrease of averaged discharges in French river basins, particularly during summer and fall (Boé et al., 2009) would lead to more upstream, more persistent and more concentrated TMZs. Other factors, such as sea level rise or morphodynamic adjustment of the estuarine sections (Chernetsky et al., 2010; De-Jonge et al., 2014), can modulate or even re-inforce the trend forced by river flow. However, because the latter is the main driver, river-discharge-based indicators of TMZ behavior should play an important role in the future management of estuaries.

5. Conclusions

Turbidity was measured over a 7 year period (2007-2013) in the Loire Estuary using a continuous monitoring network (SYVEL) formed of six stations distributed between the mouth and 62 km upstream. The analysis of turbidity data series together with water level and river flow records detailed the behavior of the TMZ. River discharge controls the position changes of the TMZ. During low river discharges, the TMZ migrates upstream over an average distance of 40 km, and its upstream boundary may reach up to 62 km from the mouth. The sudden and rapid increase of river flow after periods of low river discharge causes a faster downstream TMZ flushing compared to its upstream migration by tidal pumping. During 2011, the TMZ shifted downstream with a velocity of 1.6 km day^{-1} during the first, moderate floods, which changed to 5.2 km day^{-1} with the following higher flood, whilst the speed during the upward shift was 0.9 km day^{-1}.

The maximum and minimum river flow thresholds promoting the installation and expulsion of the TMZ at upstream stations have been delimited. For example, at Le Pellerin, and for a moderately-concentrated TMZ, the critical values were 300-360 m^3 s^{-1} and 497-1034 m^3 s^{-1}, respectively. This means that the expulsion of the TMZ from this region requires higher river discharge levels than its installation, which is explained by the presence of remaining mobile mud during and after the presence of the TMZ. The presence of mobile mud is confirmed through turbidity-discharge hysteresis patterns over the transitional periods of installation and expulsion of the TMZ, as already reported by Jalón-Rojas et al. (2015) in the Gironde estuary. In addition, in contrast to the installation threshold, river flow promoting the TMZ expulsion varies considerably between years. Our explanation is that the more turbid and persistent TMZs during dry years need more volume of water to be shifted downstream.

The use of the duration of low discharge periods and the water volume passing before and during the presence of the TMZ as indicators of the TMZ persistence and concentration, respectively, has been tested for the Loire Estuary. The agreement of such indicators to those of the nearby Gironde Estuary makes them a reliable and effective tool to better understand TMZ dynamics in tidal estuaries. Thanks to the high-density SYVEL network, a new hydrological indicator of TMZ behavior has been defined: the summer-averaged river flow as indicator of the upstream extent of the TMZ. In the context of global change, the mean river discharge of European rivers is projected to decrease (Alfieri et al., 2015) resulting in changes of the TMZs. The three indicators could thus be very useful for the future management plans of estuaries, by estimation the TMZ intensification, in terms of persistence, concentration and location in upper reaches, resulting from long-term river flow changes.

The use of continuous monitoring over time periods of several years allows a detailed description of turbidity from tidal to multi-annual time scales. However, only a high-density monitoring network covering most of the estuarine axis, such as in the Loire, enables the permanent tracking of the TMZ, including the estimation of seasonal displacement velocities. In addition, for an accurate calculation of TMZ features, such as the turbidity level, persistence, upstream boundary and, especially, migration velocities, it is essential to minimize missing data by ensuring a high percentage of good operation at the measurement stations.

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Tables

		2007	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
Annual-averaged river flow (m^3 s^{-1})		842	947	567	762	425	738	**1128**
Summer-averaged river flow (m^3 s^{-1})		**537**	359	199	267	151	234	347
$Turbidity^{*}_{max}$ **(NTU)**	**Donges**	-	-	-	-	3055	2292	**1949**
	Paimboeuf	3232	2791	**2734**	3183	3734	3343	2966
	Cordemais	7490	**4076**	4648	6515	8775	-	-
	Le Pellerin	1409	2056	-	1892	2856	2142	**1206**
	Trentemoult	**192**	532	1524	716	1410	566	537
	Bellevue	**47**	244	491	136	450	188	120

Table 1. Annual and summer averaged river flow (m^3 s^{-1}) and annual turbidity* maximum ($\boldsymbol{Turbidity^{*}_{max}}$, NTU) in each SYVEL station. The lowest river flow and $\boldsymbol{Turbidity^{*}_{max}}$ per station are in bold; the highest are underlined.

Figures

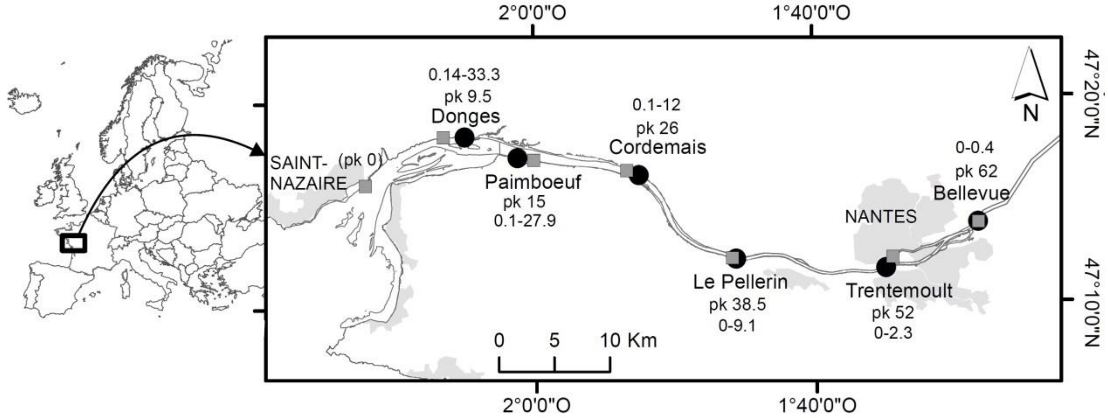

Figure 1. Location map of the Loire Estuary showing the six stations of the SYVEL network (black circles). Grey squares locate tide gauges (enumerated from the mouth): Saint-Nazaire, Donges, Paimboeuf, Cordemais, Le Pellerin, Nantes and Sainte-Luce. Grey areas represent urban agglomerations. pk = kilometer distance from the mouth. The range of salinity is shown for each station.

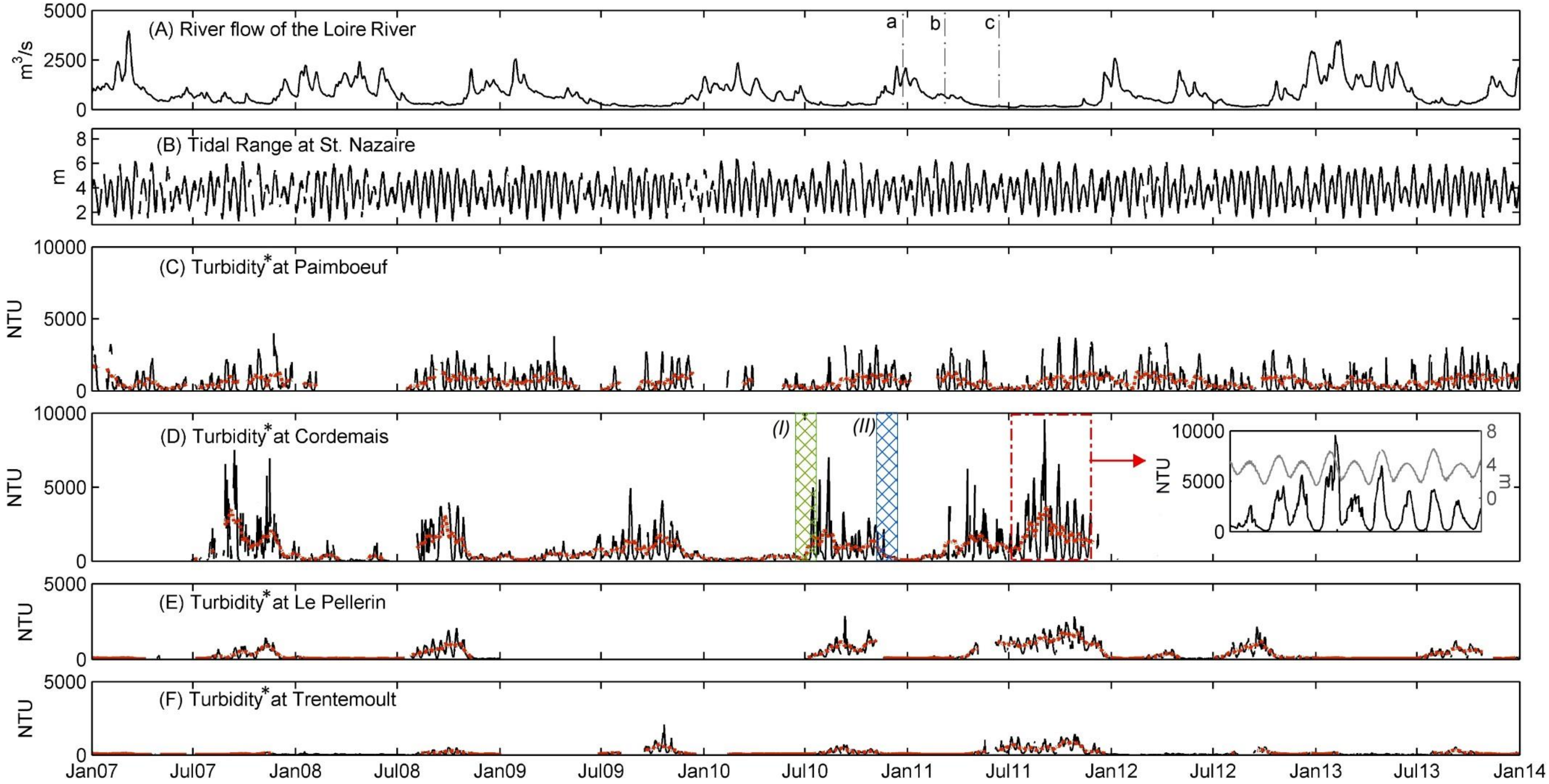

Figure 2. (A) Daily-averaged river flow of the Loire River at Montjean-sur-Loire; (B) tidal range (difference between high and low waters) at St Nazaire; and turbidity* at (C) Paimboeuf, (D) Cordemais, (E) Le Pellerin and (F) Trentemoult. Red dashed lines represent turbidity* trends using a low-pass filtered data (40-tides running averages). An example of periods of TMZ installation (I) and expulsion (II) is highlighted in panel (D). The insert in Fig. 2 D details turbidity* at Cordemais and tidal range at Saint-Nazaire between July and November 2011. Letters “a”, “b” and “c” in panel (A) refer the tidal cycles represented in Fig. 3.

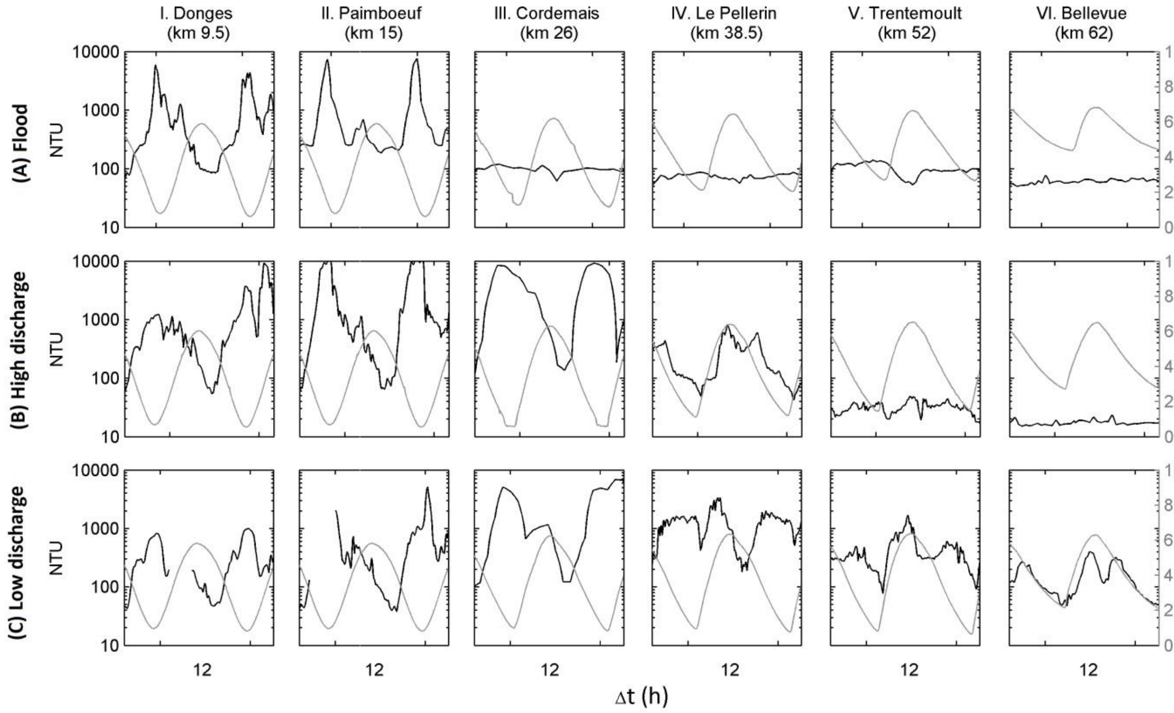

Figure 3. Temporal and spatial changes in turbidity (NTU, black, log-scale) and water height (meters, grey) during a tidal cycle for three contrasting hydrological conditions: (A) flood (1600 $m^3\ s^{-1}$); (B) high river flow (730 $m^3\ s^{-1}$); (C) low river flow (160 $m^3\ s^{-1}$).

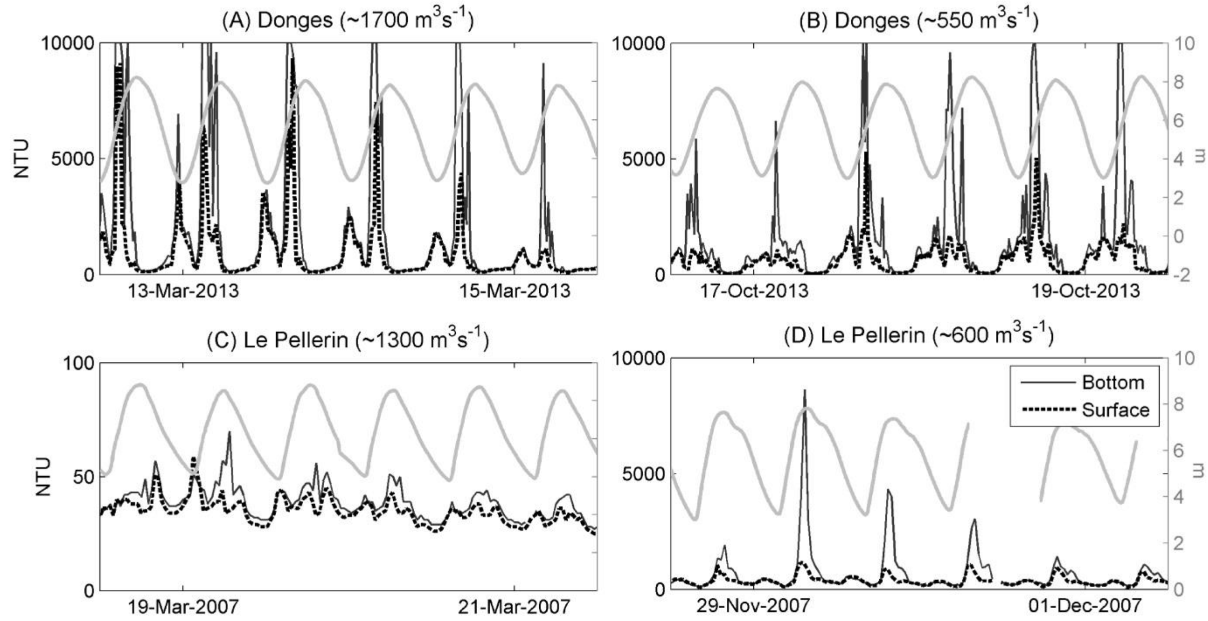

Figure 4. Time series (72-hours) of turbidity recorded simultaneously at the surface (dotted black line) and the bottom (solid black line) for two contrasting hydrological conditions at Donges (in the down-estuary, A and B) and at Le Pellerin (in the up-estuary, C and D). Grey lines correspond to water level.

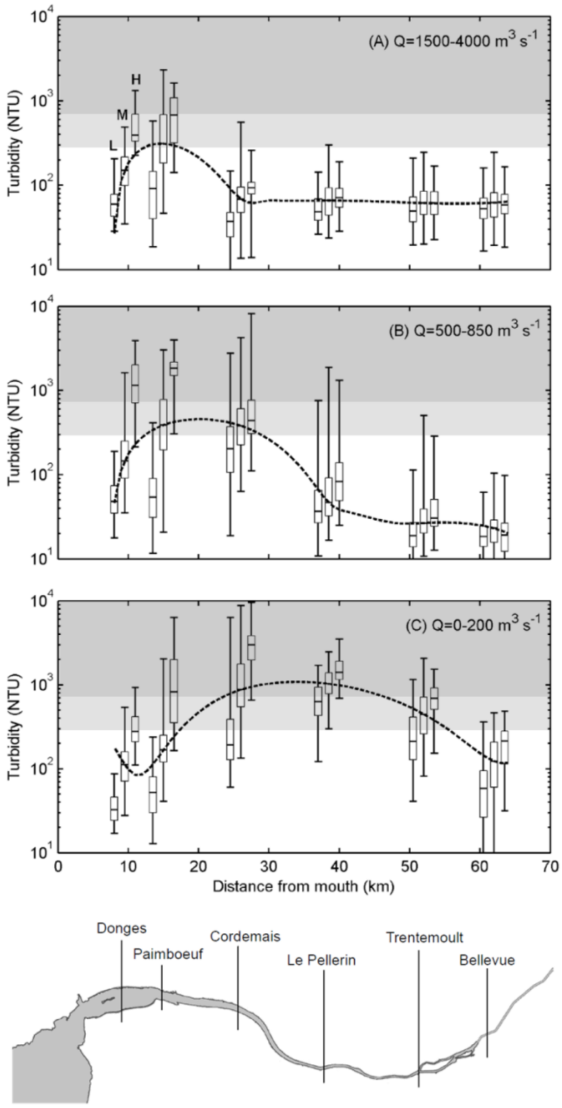

Figure 5. Percentiles (0, 25, 50, 75 and 100) of turbidity* by ranges of river flow (A-C panels) and tidal range (L, M and H represent low, medium and high tidal range, which are always represented in the same order) in each SYVEL stations. Grey areas represent the turbidity thresholds of the moderately (300 NTU) and highly (600 NTU) concentrated TMZ.

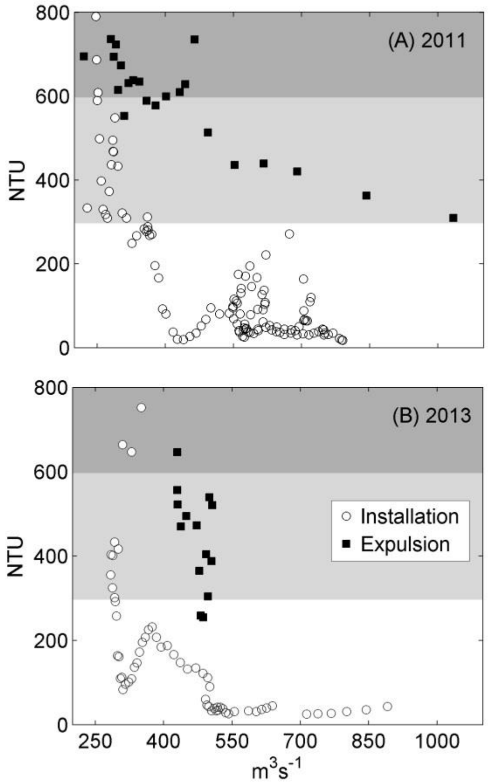

Figure 6. Turbidity* as a function of daily river flow during the installation (white circles) and the expulsion (black squares) of the TMZ in Le Pellerin for the years 2011 (A) and 2013 (B). Grey areas represent the turbidity thresholds of the moderately (300 NTU) and highly (600 NTU) concentrated TMZ.

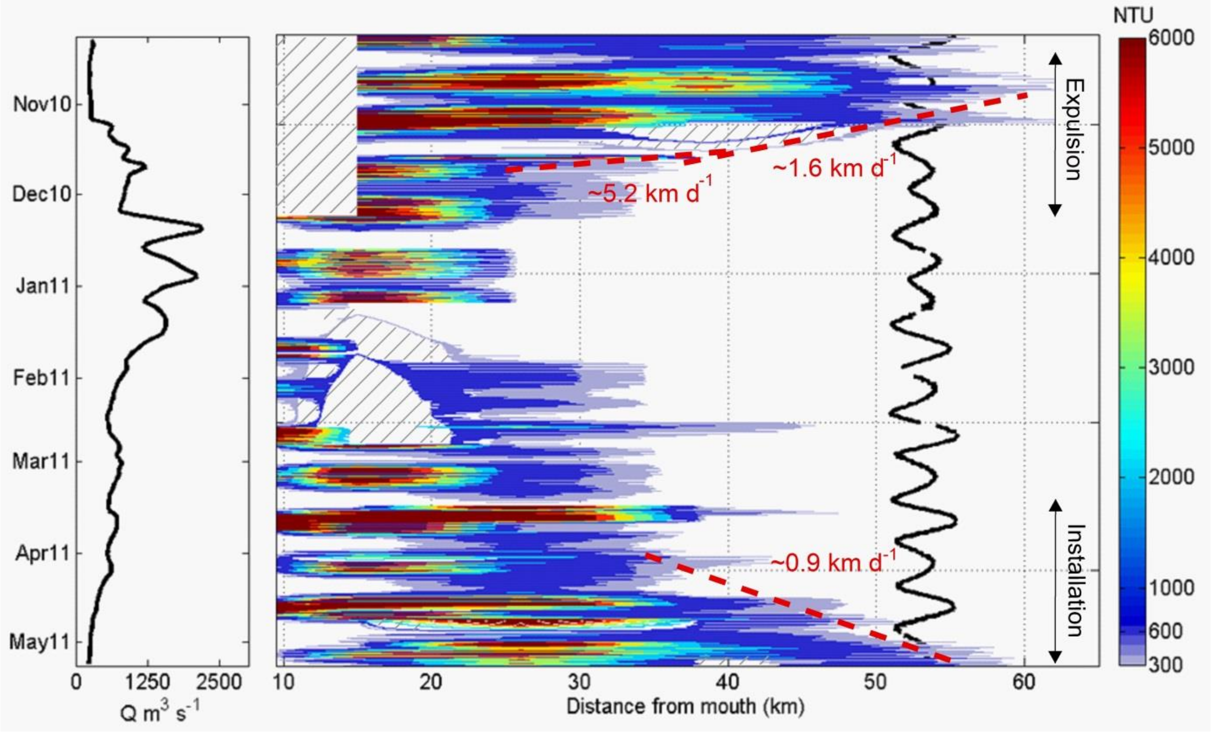

Figure 7. Temporal and spatial distribution of turbidity (above 300 NTU, color scale) from October 2010 to May 2011. Left panel shows river flow for this period. Black line in right panel represents the tidal range modulations. Hatched surfaces denote missing data. The dashed lines indicate the turbidity intervals used for determining displacement velocities.

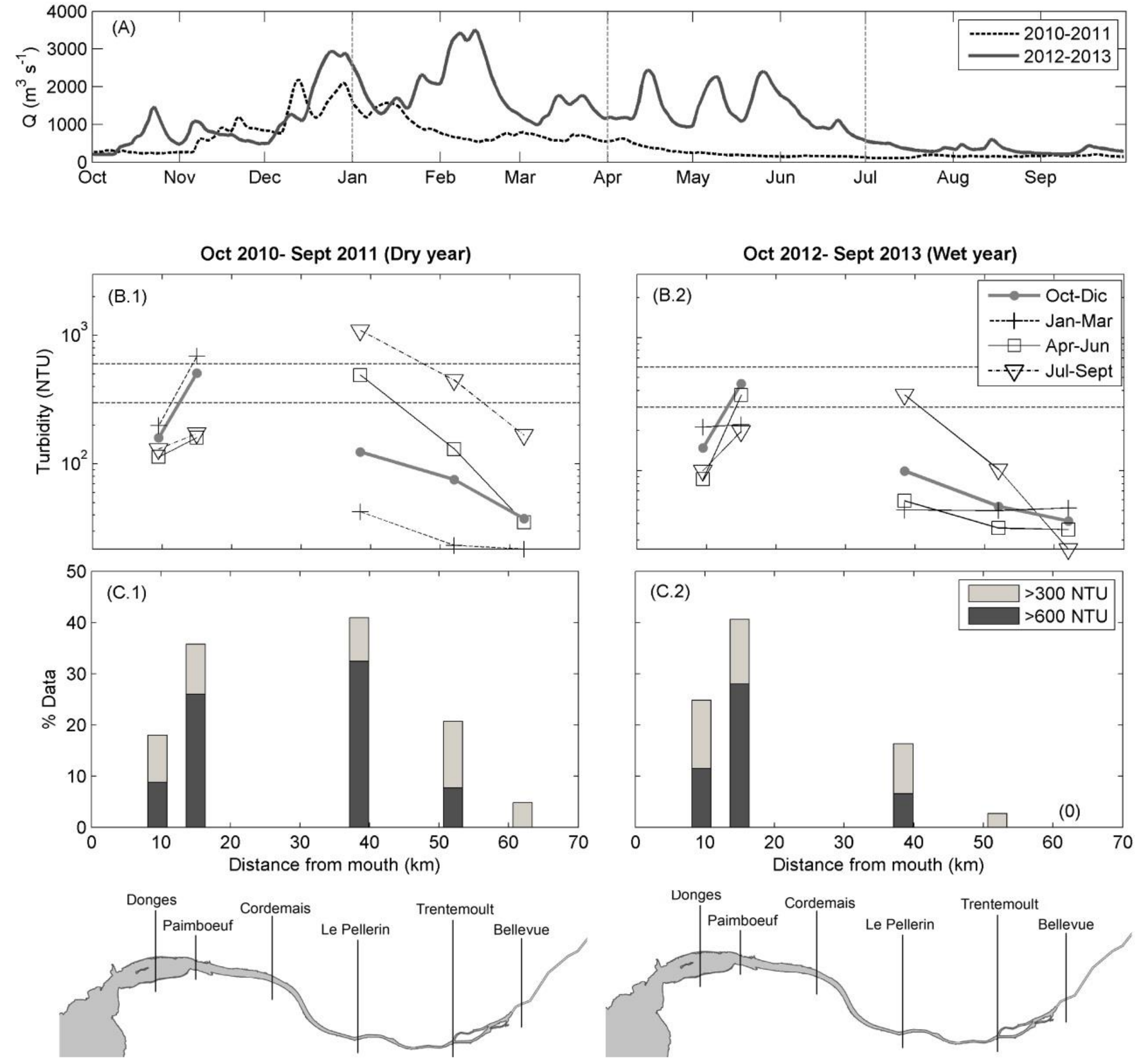

Figure 8. Comparison of two hydrologically-contrasted periods, 2010-2011 (dry period) and 2012-2013 (wet period): (A) daily-averaged river flow; (B) median turbidity* in each SYVEL station according to the season; (C) percentage of values turbidity* above 300 and 600 NTU in each SYVEL station (percentage of TMZ presence). Cordemais is not considered as there are no data during the years 2012 and 2013. (0) denotes 0% of values, i.e. the TMZ was not observed for the corresponding period.

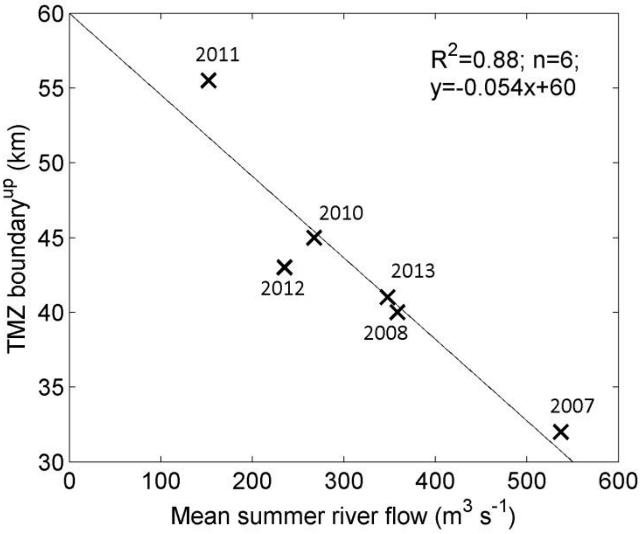

Figure 9. Upstream boundaries of the TMZ (boundary^{up}) during summer as a function of the summer-averaged river flow per year. Boundary^{up} during 2009 was not possible to estimate due to the number of missing data (Fig. 2).

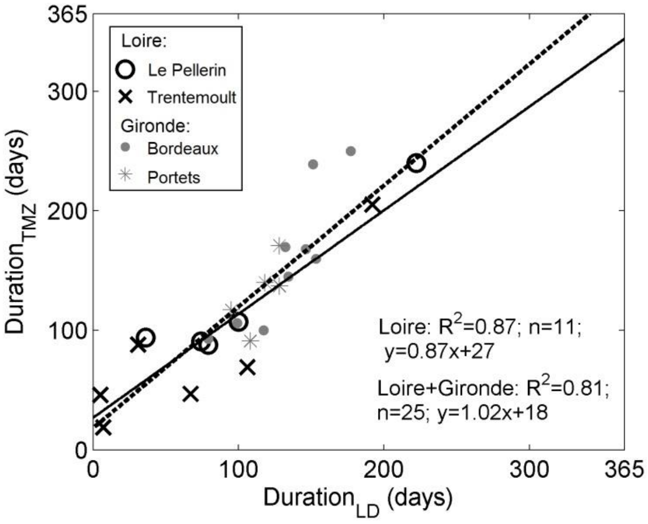

Figure 10. Duration of the TMZ presence as a function of the duration of the low discharge period in the upper Loire estuary (Le Pellerin and Trentemoult). Data from the Gironde estuary (Bordeaux and Portets) are plotted for comparison (Jalon-Rojas et al., 2015).

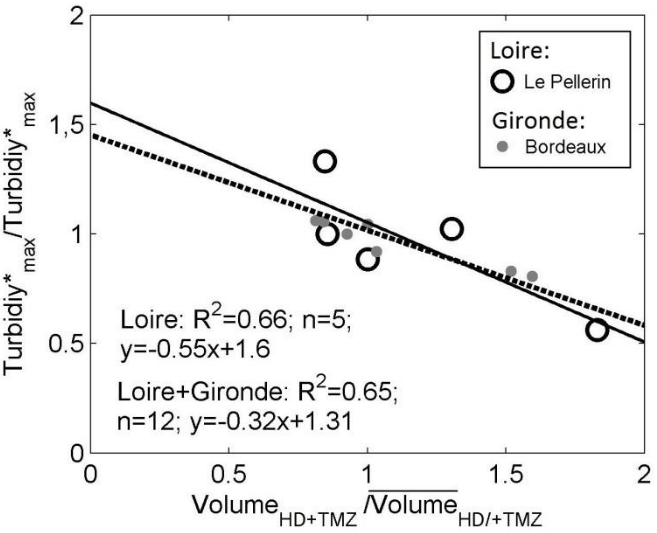

Figure 11. Normalized TMZ turbidity maxima as a function of the normalized water volume passed the previous wet period + during the presence of the TMZ at Le Pellerin, in the upper Loire Estuary, and Bordeaux, in the upper Gironde estuary. $\boldsymbol{Turbidity}^{*}_{\boldsymbol{max}}$ and volume values are normalized to their respective medians ($\overline{\boldsymbol{Turbidity}}^{*}_{\boldsymbol{max}}$, $\overline{\mathbf{Volume}}_{\mathbf{HD+LD}}$). Data of the Gironde Estuary were derived from Jalon-Rojas et al. (2015).