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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.

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 (Pontee 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., 1997; Uncles et al., 2006a; Garel et al., 2009; Mitchell et al., 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

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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 (Doxaran 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

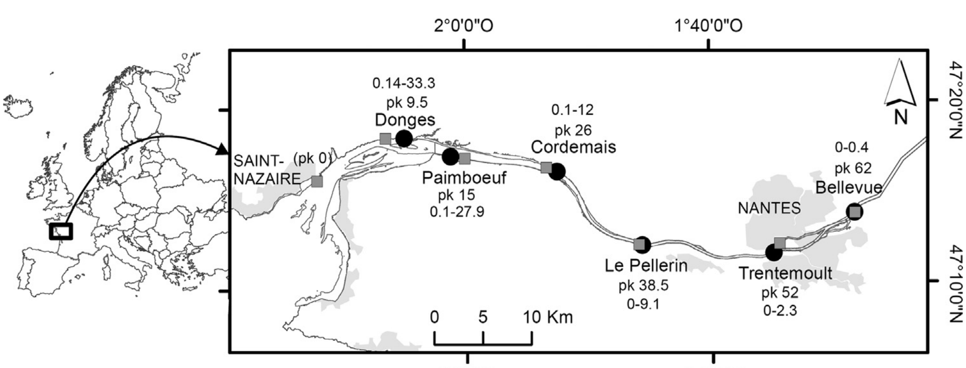

Fig. 1. Location map of the Loire Estuary showing the six stations of the SYVEL network (black circles). Gray squares locate tide gauges (enumerated from the mouth): Saint-Nazaire, Donges, Paimboeuf, Cordemais, Le Pellerin, Nantes and Sainte-Luce. Gray areas represent urban agglomerations. pk=kilometer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