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Invited research article

In situ high frequency long term measurements of suspended sediment concentration in turbid estuarine system (Seine Estuary, France): Optical turbidity sensors response to suspended sediment characteristics

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ABSTRACT

The aim of this study is to investigate the complex response of optical turbidity sensors (side- and back-scattering sensors) to Suspended Particle Matter (SPM) characteristics and the consequences when investigating SPM dynamics from long-term high frequency monitoring networks. Our investigation is based on the analysis of a unique dataset of monthly 12 h cycle measurements of SPM characteristics such as turbidity, concentration, floc size distribution, floc density and organic matter content in the macrotidal Seine Estuary (France) between February 2015 and June 2016. Results reveal that despite calibration to a Formazin standard, turbidity sensor response to SPM concentrations (in the range of 7–7000 mg L^{-1}) are strongly variable, from the tidal scale to the annual scale and in different compartments of the Seine Estuary. The variability in the calibration relationships is related to changes in the sensor sensitivity according to *(i)* the sensor intern technology (mainly due to optical geometry) and *(ii)* the variability in inherent optical properties (IOP) of SPM.

Side-scattering optical instruments (measuring scattering at 90°) provide at the annual scale a more stable optical response than backscattering sensor (measuring scattering at angles larger than 100°) for a wide variety of floc size and density in the estuarine environment, while at the tidal scale the backscatter sensors are the most accurate. Sensor sensitivity is strongly affected by floc characteristics, i.e. their median size D_{50}, dry density ρ and the scattering efficiency Qb. Results highlight that the median particle diameter contribute to modify the scattering efficiency Qb as well as the dry density: Qb increases with increasing floc size, and for a given floc size, Qb increases with floc density.

In this study, the results are next applied to turbidity data from the long-term automated monitoring network in order to estimate SPM concentrations and estimate the related uncertainties.

1. Introduction

In recent years, assessment of water quality has become a major issue worldwide and is illustrated in Europe by the implementation of the European Water Framework Directive (WFD; 2000/60/EC, Commission of European Community (CEC), 2000) and the Marine Strategy Framework Directive (MSFD; 2008/56/EC, Commission of European Community (CEC), 2008). These guidelines are intended to establish a water policy to protect, conserve and restore the state of groundwater, inland surface waters, estuarine and coastal waters. The WFD/MSFD constitute a strategic lever in water resources management against anthropogenic pressures (Borja et al., 2006). In this sense, the WFD/MSFD require the monitoring and assessment of biological, hydro-morphological and physico-chemical quality parameters. Among all required parameters, turbidity (quantified in Nephelometric Turbidity Units, NTU) can be considered as one of the most relevant marker for monitoring water quality in coastal or estuarine waters. Turbidity can be defined as an index of water clarity, measured by the degree of light scattered by suspended material such as sand, clay, silt, particulate organic matter, plankton and other microorganisms in a water volume (ASTM International, 2003; Merten et al., 2014; Rymszewicz et al., 2017). Accordingly, turbidity measurements are used as a proxy to

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accurately estimate Suspended Particulate Matter concentrations (SPM; in mg L^{-1}). Variations in turbidity help to understand the SPM dynamics and therefore processes which govern particles dynamics and associated contaminants (Deloffre et al., 2005; Chen et al., 2007). It is also a critical parameter limiting light availability and hence controlling phytosynthesis and primary production.

Water sampling and filtration methods are very accurate to monitor SPM concentrations in estuarine systems but time consuming, low frequency and costly. These methods often fail to characterize turbidity variability because of the limitation in term of temporal and spatial coverage (Petus et al., 2010). Consequently, for the WFD/MSFD to be effective, the deployment of high frequency long-term monitoring networks is a suitable tool to assess turbidity and therefore, to estimate SPM concentrations in estuarine systems. For long term high frequency monitoring, turbidity is generally measured by optical sensors (mainly side and back-scattering optical instruments) (Downing et al., 1981; Sternberg et al., 1986; Beach et al., 1992; Kineke and Sternberg, 1992; Schoellhamer, 2002; ACT, 2006).

However, optical turbidity is a complex analytical parameter that is affected by inherent optical properties (IOP) of particles (Boss et al., 2009a, 2009b). Although optical sensors are primarily affected by SPM concentrations (Kineke and Sternberg, 1992), factors such as individual particle size (Ludwig and Hanes, 1990; Conner and De Visser, 1992; Green and Boon, 1993; Merten et al., 2014), particle shape (Bunt et al., 1999; Downing, 2006), sediment color (Sutherland et al., 2000) and degree of flocculation/disaggregation (Gibbs and Wolanski, 1992) also influence sensor response. However, most studies on optical sensors responses to IOP of particles were mainly investigated from controlled calibration experiments in laboratories with homogeneous SPM. In estuaries and coastal seas, suspended particulate matter consists in a population of flocs (or aggregates) with heterogeneous size, density and shape, highly variable in response to complex flocculation processes. Laboratory experiments may not reliably represent field conditions because of the difficulty of reproducing the chemical, physical and biological processes involved (Manning and Bass, 2006). Few studies are investigated interactions between IOP's and optical turbidity devices (Boss et al., 2009a, 2009b).

This paper investigates the complex response of optical turbidity sensors (side- or backscatter sensors) to the estuarine SPM variability, from the tidal scale to the annual scale and in different compartments of the Seine Estuary. This issue is examined both in terms of sensor calibration and sensor sensitivity to SPM characteristics. It is supported by a comprehensive dataset of monthly 12 h cycle measurements of SPM characteristics such as concentration, floc size distribution, floc density, and organic matter content, between February 2015 and June 2016. The results are next applied to turbidity data from the Seine estuary long-term automated monitoring network to estimate SPM concentrations and associated uncertainties.

2. Study area and field measurements

2.1. Regional settings

The Seine Estuary is one of the largest macrotidal estuarine system located in the English Channel, in the northwestern European continental shelf (Fig. 1). Hydrological conditions in the Seine Estuary are highly variable and controlled by tidal forcing and seasonally by the river discharge (Guezennec et al., 1999). This estuary is characterized by a maximum tidal range at the mouth of the estuary (Le Havre – KP 360) of 8 m (3 m) at spring (neap) tide and up to 2 m at the upper limit of the estuary (Poses dam – KP 202). The tidal wave propagates up to 160 km from the estuary mouth. The mean annual Seine river flow is 450 $m^3 s^{-1}$ with extreme daily values of up to 2200 $m^3 s^{-1}$ (Avoine et al., 1981).

The Seine Estuary is divided in three compartments according to spatial and temporal variations of salinity and SPM concentrations, in response to major hydrodynamic forcing (Fairbridge, 1980; Guezennec et al., 1999). The upper (or fluvial) estuary corresponds to the tide-affected fluvial freshwater zone which is artificially limited upstream by Poses dam (KP 202) and downstream by the salt intrusion limit located near Caudebec en Caux (70 km from the mouth – KP 310). The lower (or marine) estuary is limited to the estuary mouth and corresponds to a low salinity gradient area. Finally, the middle estuary is characterized by strong salinity and SPM concentration gradients and the presence of a distinct estuarine Turbidity Maximum Zone (TMZ). Its maximum mass is estimated to be between 300,000 and 500,000 tons (Avoine et al., 1981) with SPM concentrations between a minimum of 0.05–0.1 g L^{-1} and a maximum of 2–4 g L^{-1} (Lemoine and Verney, 2015).

Sediment transport processes in estuarine environments (i.e. erosion, deposition, flocculation, and advection) control the fate of SPM (Verney et al., 2009). The sediment dynamics in the Seine Estuary is driven by tidal currents coupled with waves at the mouth, the seasonal river discharge and the annual biogeochemical cycle (planktonic bloom development) (Guezennec et al., 1999). In estuaries, SPM primary particles of organic or mineral origin, are mainly aggregated in flocs (or aggregates), of variable shape, size and density, through flocculation/disaggregation processes (Eisma, 1993; Van Leussen, 1994; Manning and Dyer, 1999; Wang et al., 2013). Turbulence and SPM concentrations are the two major parameters controlling flocculation processes, and to a lesser extent, environmental conditions (salinity and organic matter) modulate the flocculation processes intensity (Dyer, 1989). In the Seine Estuary, the primary particles of few microns (inferior to 10–20 μm) are usually organized in microflocs and macroflocs population, reaching sizes of a few tenth microns during strong ebb/flood current periods, to hundredth of microns during slack periods or by the organic content increase (Verney et al., 2009).

2.2. Long-term automated monitoring network

Since 2011, the Seine Estuary is instrumented with an automated monitoring network, called SYNAPSES, to follow estuarine water quality (data accessible on website: http://www.seine-aval.fr/synapses/). The SYNAPSES network includes 5 stations located from the estuarine fluvial compartment to the estuary mouth, including three in the turbidity maximum zone (Fig. 1). The stations are equipped with YSI 6600 V2 multi-parameter probe, recording every 5 min the main physico-chemical parameters (conductivity, temperature, turbidity, dissolved oxygen and fluorescence). The data are collected at sub surface (1 m) and also 1 m above the bed for the two downstream stations, where vertical gradients are very important (i.e. TMZ – Fatouville and Tancarville). The environmental conditions, biofouling, electrical/mechanical/numerical failures and sensor malfunctions could cause missing or erroneous data, requiring a database cleaning. A first quality check is realized by an automated post-processing routine which includes (i) all numerically invalid data (out of bounds data) and (ii) all periods where optical sensor is emerge (using pressure sensor values). Finally, the post-processing step is verified by data user according to scientific experts.

2.3. Measurement protocol at the tidal scale

The field data were collected from 4 SYNAPSES stations during 36 tidal cycles between February 2015 and June 2016. Each campaign was performed during spring tides (tidal range between 6.35 and 7.8 m) and for different hydrological conditions (rivers discharges between 168 and 2100 $m^3 s^{-1}$). Data cover both average (14 campaigns around about 450 $m^3 s^{-1}$), low (16 campaigns around 250 $m^3 s^{-1}$) and high river flow (6 campaign greater than 700 $m^3 s^{-1}$) including an exceptional flooding condition (decennial, reaching 2010 $m^3 s^{-1}$). The field survey was carried out in the TMZ (Fatouville – Tancarville stations) and further upstream in the estuarine fluvial zone (Rouen – Val des Leux stations).