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Assessment of suspended solids in the Guadalquivir estuary using new DEIMOS-1 medium spatial resolution imagery

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ABSTRACT

Measurements of Total Suspended concentrations (*TSS*) are critical for monitoring geomorphological processes as well as ensuring the "good status" of transitional and coastal waters. Here, we explore the potential of the new DEIMOS-1, multi-spectral, medium-resolution satellite sensor for quantifying *TSS* dynamics within the large, turbid Guadalquivir estuary (SW Iberian Peninsula). Eight scenes were atmospherically corrected using various image-based procedures (apparent reflectance; Dark Object Subtraction, DOS; and solar zenith angle approximation, COSTZ). In-situ measurements (100 to 1400 mg L^{-1}) from three campaigns coinciding (±15 min) with satellite overpasses were used to assess the semi-analytical algorithm from Nechad et al. (2010) relating water-leaving reflectance (ρ_w) to *TSS*. All bands were very sensitive to *TSS*, however saturation of the visible wavelengths was observed at the highest sediment loads. The best correlation was obtained for the NIR band (755–906 nm) using the simple band-reflectance model at the top of atmosphere reflectance ($\rho_{w(TOA)}$), TSS (mg L^{-1}) $= 21428.77\ \rho_{w(TOA)} / (1 - \rho_{w(TOA)} / 0.21) - 346.17$ ($r^2 = 0.864$, $p < 0.001$, $\varepsilon_r = 25.411\%$, $n = 53$), which was used to generate maps. This approach revealed detailed spatio-temporal variability in sediment concentrations within the river plume, near to shore and far up the river channel. We demonstrate that DEIMOS-1 has a high capability as a valuable tool for the frequent, synoptic monitoring of water-quality parameters needed for the optimum management of coastal and transitional waters.

1. Introduction

Estuaries are one of the most sensitive, complex and biologically productive aquatic environments in the world. They are vital to commerce, transportation, and fisheries, and recently, have acquired increasing social significance for recreation activities, providing economic benefits via tourism (Prandle, 2009; Wolanski & McLusky, 2011). They correspond to buffer protecting zones which are important for coastal geomorphology, whose dynamics are dependent on a subtle balance between sediment inflow from inland waters or the sea and sediment outflow (Volpe, Silvestri, & Marani, 2011). Transport of terrestrial material through estuaries typically follows the seasonality of the local climate and may show marked interannual variability (Chen, Hu, & Muller-Karger, 2007; Doxaran, Froidefond, Lavenderb, & Castainga, 2002), producing plumes over the continental shelf and particularly in inner shelf areas.

The concentration of Total Suspended Solids (*TSS*), also called Total Suspended Matter or Suspended Particulate Matter (*TSM* and *SPM*, respectively) within the water column is an important parameter that when combined with volumetric flow rates, allows the estimation of river-borne sediment transport through transitional waters (i.e., estuaries) into the coastal zone (Nezlin, DiGiacomo, Stein, & Ackerman, 2005; Warrick, Mertes, Washburn, & Siegel, 2004). *TSS* can also give an indication of the extent of nutrient (Mayer et al., 1998) and pollutant loading (Martin & Windom, 1991), as well as directly determine the underwater light climate, and thus indirectly affect primary production (May, Koseff, Lucas, Cloern, & Schoellhamer, 2003). Regular observations of *TSS* in inland, transitional and coastal waters are thus critical for monitoring coastal geomorphological processes as well as ensuring the "good status" of these waters (European Union Water Framework Directive, EU-WFD).

Conventional sampling methods (i.e., filtering water samples) can be costly and time-consuming, making them difficult to apply over large areas at a high temporal resolution. Long-term deployment of instruments, such as optical backscatter devices, allow continuous turbidity measurements (Navarro, Gutiérrez, Díez-Minguito, Losada, & Ruiz, 2011; Navarro et al., 2012), however these can be tricky to calibrate and maintain, again pushing up costs. Remote sensing (RS) offers the possibility of high-spatial resolution measurements of surface water *TSS*, as well as other important parameters (e.g., photosynthetic pigment concentrations, chromatic dissolved organic matter and temperature) at a reasonable cost and high temporal resolution (days to weeks) (Baban, 1993, 1997; Hu et al., 2004; Saldías, Sobarzo, Largier, Moffat, & Letelier, 2012; Tassan, 1994). Hence, the complementary use of RS has been suggested for a number of critical problems in coastal management (Alparslan, Aydöner, Tufekci, & Tüfekci, 2007; Ritchie, Cooper, & Schiebe, 1990; Ritchie, Zimba, & Everitt, 2003).

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Satellite-borne sensors have been effectively used to assess the relationship between *TSS* and the water-leaving radiance (L_w) or water-leaving reflectance (ρ_w) of surface waters allowing detailed synoptic views of sediment dynamics in rivers and lakes (Carpenter & Carpenter, 1983; Ritchie & Cooper, 1988), wetlands (Bustamante, Pacios, Díaz-Delgado, & Aragonés, 2009), estuaries (Baban, 1995; Caballero, Morris, & Navarro, 2012; Chen et al., 2007; Doxaran et al., 2002; Hu et al., 2004), harbors (Hellweger, Schlosser, Lall, & Weissel, 2004) and coastal zones (Miller & McKee, 2004; Teodoro, Veloso-Gomes, & Gonsalves, 2008). *TSS* retrieval in Case II waters (Gordon & Morel, 1983; Mobley, 2004; Morel & Prieur, 1977) is particularly difficult due to the presence of a variety of suspended and dissolved materials; such as colored dissolved organic matter (CDOM or yellow substances), phytoplankton and terrestrial debris (Volpe et al., 2011). Moreover, the historical focus of bio-optical oceanography on Case I waters has led to a lack of reliable algorithms for estimating water-column parameters in these complex Case II regions (Morel & Prieur, 1977). Land vicinity as well as the relatively small size and shallow waters of estuaries are other challenging factors that also contribute to the difficulty of RS in coastal regions.

Because the mix of materials found in Case II waters significantly changes the backscattering characteristics of surface waters (Jerlov, 1976; Kirk, 1983), models relating *TSS* to L_w or ρ_w tend to be empirical (Doxaran et al., 2002), accounting for the particular situation of the considered area (Bricaud & Morel, 1987), rather than based on inherent optical properties (IOPs) (Ritchie et al., 2003). A notable exception was provided by Doxaran, Cherukuru, and Lavender (2006), who established empirical quantification relationships from several field data and a reflectance model integrating the mean values of the water constituents' inherent optical properties. Furthermore, semi-analytical approaches and neural network models based on physical knowledge of the relationship between reflectance and *TSS* concentrations have been established in coastal waters (e.g., Nechad, Ruddick, & Park, 2010; Stumpf & Pennock, 1989; Zhang, Pulliainen, Koponen, & Hallikainen, 2002). Suspended sediments increase reflectance throughout the visible and near-infrared (NIR) proportion of the electromagnetic spectrum (Ritchie, Schiebe, & McHenry, 1976). However, in part because of the minimal interference from other constituents, changes in ρ_w (NIR) due to changes in *TSS*, at high turbidity, are often more easily detected (Doxaran et al., 2006). Thus, a number of site-specific algorithms based on the ratio of NIR to visible remote sensing reflectance (R_{rs}) have been developed with some success (Hu et al., 2004; Miller & McKee, 2004). Several studies have demonstrated that these bands have sufficient sensitivity to detect a wide range of *TSS* in coastal and estuarine waters.

The aim of this paper is to estimate total suspended sediment concentrations in the Guadalquivir estuary (SW Iberian Peninsula, Fig. 1) using the DEIMOS-1 satellite sensor. This relatively new satellite can provide multispectral (green, red and NIR) images of medium spatial resolution (22 m) with a large extent (600 km), and offers the opportunity to collect images on demand (repeat time of 1 day). Hence, DEIMOS-1 can potentially be used to regularly map *TSS* and examine the detailed dynamics of river plumes, providing useful information for the optimal management of coastal regions. Here we focus on two key issues to be resolved before DEIMOS-1 data can be routinely applied to examine *TSS* in coastal studies: 1) Atmospheric correction of the data (see Supplementary data for details), and 2) Calibration of a semi-analytical algorithm for the retrieval of *TSS* from water-leaving reflectance. We then go on to demonstrate the potential of these approaches for the retrieval of detailed information about *TSS* dynamics within a large estuary.

2. Material and methods

2.1. Guadalquivir estuary

The Guadalquivir river is located in the southwest of the Iberian Peninsula (Fig. 1a) and flows into the Gulf of Cádiz (Atlantic Ocean). It is one

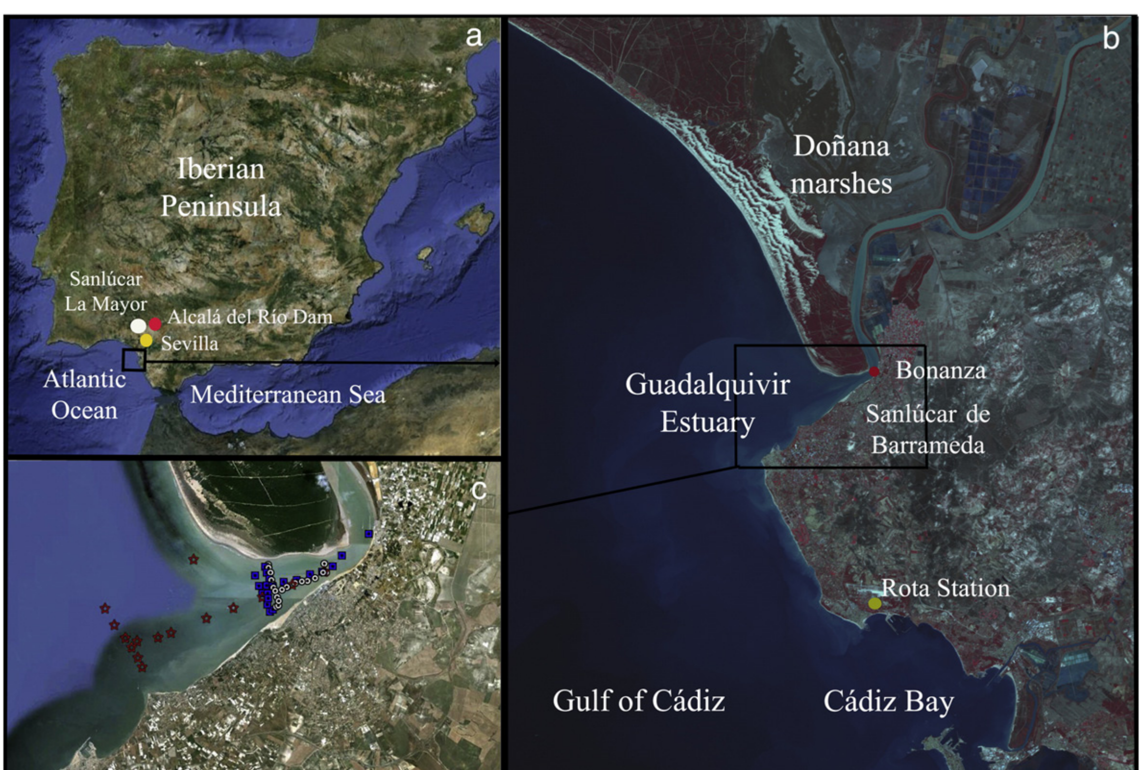

Fig. 1. a) Localization of the study area (SW Iberian Peninsula). b) Map showing the Gulf of Cádiz and the Guadalquivir estuary. c) Dots, squares and stars represent the position of samples collected during 3 campaigns in 16 December 2010, 14 January 2011 and 3 March 2011, respectively (Google Earth).