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Remote sensing retrieval of suspended sediment concentration in shallow waters

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ABSTRACT

The dynamics of coastal lagoons and estuarine areas is characterized by a delicate balance between biological and physical processes and the comprehension and monitoring of such processes require observations over a wide range of temporal and spatial scales. Remote sensing techniques in this context are very advantageous and potentially allow overcoming the spatial limitations of traditional in situ point observations, providing new opportunities for a better understanding of the relevant bio-geomorphological processes and for the calibration and validation of spatially-distributed hydrodynamic and transport models. Remote sensing of suspended particulate matter (SPM) concentration in shallow waters must, however, overcome the difficulties associated with i) the influence of bottom reflection, which may interfere with an accurate retrieval; ii) the necessity of accurately knowing the optical properties of the suspended matter, and iii) the importance of providing an assessment of the uncertainty associated with the estimates produced. This work presents a method to estimate SPM concentration in lagoon/estuarine waters by use of a simplified radiative transfer model. We use a calibration/validation method based on cross-validation and bootstrap techniques to provide a statistically sound determination of model parameters and an evaluation of the uncertainty induced by their inaccurate determination as well as by the uncertain knowledge of the bottom sediment reflectance. The method is applied to the Venice lagoon, using observations from a network of turbidity sensors and from several multispectral satellite sensors (LANDSAT, ASTER and ALOS AVNIR). The bootstrap and cross-validation procedures employed show that consistent estimates of SPM concentration can indeed be retrieved from satellite remote sensing, provided that sufficient in situ ancillary information for appropriate calibration is available. The quantification of the estimation uncertainty shows that retrievals obtained from remote sensing are accurate, robust and repeatable. The SPM concentration maps produced show a general coherence with known features in the Venice lagoon and, together with suitable biological information, point to the role played by benthic vegetation in the stabilization of the bottom sediment.

1. Introduction

The geomorphic dynamics of shallow coastal areas, such as lagoons and estuaries, is crucially dependent on a subtle balance between sediment inflow from inland waters or the sea and sediment outflow originated by wind-wave erosion and tidal currents. From a broader perspective the entire bio-physical evolution of a tidal environment is largely controlled by the transport of sediment, organic matter and other suspended or dissolved substances (Fagherazzi et al., 2004, 2007; Marani et al., 2007; Perillo et al., 2009).

Suspended particulate matter (SPM) dynamics, in particular, plays a major role in erosion/deposition processes, biomass primary production, the transport of nutrients, micropollutants, and heavy metals. It is thus of great importance to acquire reliable and space-distributed observations of SPM concentration in order to advance our understanding of the biogeomorphic dynamics of estuarine and lagoon systems and to develop effective and quantitative monitoring schemes. Ideally, observations of SPM would be required with a high spatial and temporal resolution (order of tens of meters and of tens of minutes respectively). In practice, while turbidity observations can be acquired at a high temporal resolution (e.g. hourly) observation networks are typically sparse (spacings of several kilometers) as compared to the intrinsic scale of variability of SPM, which is induced by morphological features having a typical size ranging from a few meters to kilometers.

Remote sensing can be used to obtain information about several water quality parameters, including SPM concentration, and it has indeed been applied to several test sites. SPM retrievals in lagoon and estuarine waters (Case II waters, (Mobley, 2004)) are particularly difficult due to the presence of a variety of suspended and dissolved materials and to the potentially large contribution of the bottom sediment to the detected remote sensing signal, which becloud the identification and accurate measurement of the contribution coming from sediments in the water column. Additionally, the literature on

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the estimation of SPM concentration from remote sensing is quite developed but it mostly concerns oceanic or relatively deep marine coastal waters (Ferrari & Tassan, 1991; Babin et al., 2003a,b; Binding et al., 2005; Giardino et al., 2007) and, often, low-resolution sensors unsuitable for applications in estuaries and lagoons (e.g. Chen et al., 2007). Finally, much of the existing literature concerns empirical approaches, which attempt to link, through an assumed algebraic relation, observed turbidity to the observed remote sensing signal (Östlund et al., 2001; Zhang et al., 2002; Ekercin, 2007; Chen et al., 2007). These approaches, which have the merit of demonstrating the existence of a clear and detectable relation between water composition and remote sensing observations and are certainly useful for specific study sites, are not suitable for general applications to estuarine/lagoon studies because they fundamentally depend on the specific data and conditions under which they are calibrated. This means that any application to a new site or any change of sensor or resolution requires a new calibration, leaving little room for generalization. A more general approach should be based on theoretical models of radiative transfer in turbid waters, which, with varying degrees of approximation, provide a representation which is consistent with the governing physical processes, possibly allowing insights in the processes themselves and applications to a wider range of conditions than afforded by empirical approaches (e.g. Dekker et al., 2001; Mobley, 2004; Giardino et al., 2007; Brando et al., 2009). Here we follow a theoretically- and physically-based approach using a simple radiative transfer model (Lee et al., 1998, 1999) to relate at-satellite radiance measurements and in situ turbidity observations with application to the Venice lagoon (Italy).

Previous contributions to the literature usually lack an assessment of the uncertainties involved in the estimation of suspended sediment concentration (or, more generally, of the water quality parameters of interest). This information, on the contrary, is extremely important when estimates are to be compared with in situ observations or with results from numerical models. The main sources of uncertainty in an algorithm for the retrieval of SPM concentration from remote sensing (but generalizations to other water parameters are quite straightforward) can be identified as i) uncertainties in the measurement of at-sensor radiances (the 'input' of the retrieval algorithm), ii) uncertainties in the model structure (e.g. due to simplifying assumptions and/or neglected processes), and iii) uncertainties in the determination of the parameters appearing in the model. Interestingly, even though statistical methods allowing a formal quantification of uncertainty are widely used in other disciplines (e.g. Montanari, 2007), they are seldom applied to remote sensing retrieval methods.

We focus in the following on the quantitative assessment of the total estimation uncertainty (sum of i) through iii)) through cross-validation techniques, and of the error induced in SPM concentration retrievals by the uncertain determination of model parameters (source iii)), often the dominant contribution to the overall uncertainty. This latter quantification is obtained by estimating the probability distribution of model parameters and of the associated uncertainty in SPM concentration retrievals using bootstrap procedures. The Matlab codes implementing the model introduced are made available as supplementary online material.

2. Methods

2.1. The radiative transfer model

The remote sensing reflectance of a 'water pixel' is a function of the water depth, of the properties of the matter suspended in it, and of the optical properties of the bottom. In order to obtain a physically-based estimation of SPM concentration we invert a simple radiative transfer model (Lee et al., 1998, 1999), which links the directional remote sensing reflectance in the nadir direction (at a fixed wavelength of interest, λ, which is omitted here to simplify the notation) to the controlling physical factors in a direct and controllable manner. The below-surface remote sensing reflectance r_{rs} (sr^{-1}) is defined as the ratio between upwelling (directional) radiance and downwelling irradiance (Table 1). In this framework, it is modeled as:

$$r_{rs} = r_{rs}^{dp}\left[1-e^{-\left(K_d + K_u^C\right)H}\right] + \frac{\rho_b}{\pi}e^{-\left(K_d + K_u^B\right)H} \tag{1}$$

where:

- H = water depth (m);
- ρ_b = bottom albedo (assuming bottom as a Lambertian reflector);
- r_{rs}^{dp} = subsurface remote sensing reflectance for an infinitely deep water column $(1/sr) = (0,084 + 0,17u)u$ (Lee et al., 1999);
- $u = b_b/(a+b_b)$, with b_b backscattering coefficient ($1/m$) and a absorption coefficient ($1/m$);
- $K_d = D_d\alpha$ = downwelling diffusive attenuation coefficient;
- $K_u^C = D_u^C\alpha$ = upwelling diffusive attenuation coefficient due to the water column;
- $K_u^B = D_u^B\alpha$ = upwelling diffusive attenuation due to the bottom reflectance;
- $\alpha = a + b_b$;
- $D_d = 1/\cos\Theta_w$, Θ_w = subsurface solar zenith angle (rad);
- $D_u^C = 1{,}03(1+2{,}4u)^{0,5}$ (Lee et al., 1999);
- $D_u^B = 1{,}04(1+5{,}4u)^{0,5}$ (Lee et al., 1999).

A complete list of symbols is provided in Table 1. The above-surface remote sensing reflectance R_{rs} (sr^{-1}), defined as the ratio between water-leaving radiance and downwelling irradiance, may be expressed, for the nadir direction, by the following approximate relationship (Lee et al., 1999):

$$R_{rs} = \frac{0.5r_{rs}}{1-1.5r_{rs}}. \tag{2}$$

Eqs. (1) and (2) together constitute a model relating the surface directional remote sensing reflectance R_{rs}, which can be obtained from remote sensing observations upon proper atmospheric correction, with the quantity and type of matter suspended in the water column. In fact, the absorption and backscattering coefficients are influenced by suspended sediments (organic or inorganic), dissolved solids and

Table 1
List of symbols.

Symbol	Description	Unit
r_{rs}	Subsurface remote sensing reflectance	sr^{-1}
R_{rs}	Above-surface remote sensing reflectance	sr^{-1}
ρ	Surface reflectance	–
ρ_b	Bottom albedo	–
r_{rs}^{dp}	r_{rs} value for optically deep waters	sr^{-1}
K_d	Vertically averaged diffuse attenuation coefficient for downwelling irradiance	–
K_u^C	Vertically averaged diffuse attenuation coefficient for upwelling radiance from water-column scattering	–
K_u^B	Vertically averaged diffuse attenuation coefficient for upwelling radiance from bottom reflectance	–
θ_w	Subsurface solar zenith angle	rad
a_w	Absorption coefficient of pure water	m^{-1}
a_{NAP}	Absorption coefficient of non algal particles	m^{-1}
a_{ph}	Absorption coefficient of phytoplankton pigments	m^{-1}
a_{CDOM}	Absorption coefficient of yellow substances	m^{-1}
a	Absorption coefficient of the total: $a = a_w + a_{NAP} + a_{ph} + a_{CDOM}$	m^{-1}
b_b	Backscattering coefficient	m^{-1}
b_w	Scattering coefficient of pure water	m^{-1}
b_{ph}	Scattering coefficient of phytoplankton pigments	m^{-1}
b_{NAP}	Scattering coefficient of suspended particles	m^{-1}
b	Scattering coefficient of the total: $b = b_w + b_{ph} + b_{NAP}$	m^{-1}