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Airborne hyperspectral data to assess suspended particulate matter and aquatic vegetation in a shallow and turbid lake

Claudia Giardino [a,*], Mariano Bresciani [a], Emiliana Valentini [b], Luca Gasperini [c], Rossano Bolpagni [d], Vittorio E. Brando [a,e]

[a] *Institute for Electromagnetic Sensing of the Environment, CNR-IREA, Milano, Italy*
[b] *Institute for Environmental Protection and Research, ISPRA, Rome, Italy*
[c] *Institute of Marine Sciences, CNR-ISMAR, Bologna, Italy*
[d] *Department of Life Sciences, University of Parma, Parma, Italy*
[e] *Environmental Earth Observation Program, CSIRO Land and Water, Canberra, Australia*

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ABSTRACT

This paper presents an application of a physic-based method that relies on spectral inversion procedures to simultaneously estimate concentrations of water constituents, water column heights (cH) and benthic substrate types in Lake Trasimeno (Italy) from airborne imaging spectrometry. Complex waters of this lake are challenging due to the coexistence of optically-deep turbid waters and of optically-shallow waters, mostly characterised by dense submerged aquatic vegetation (SAV) beds. Airborne data acquired on 12 May 2009 by Multispectral Infrared and Visible Imaging Spectrometer (MIVIS) were converted into remote sensing reflectance $R_{rs}(\lambda)$ with the atmospheric correction code ATCOR. A spectral inversion procedure implementing a bio-optical model (namely BOMBER), parameterised with *in situ* data, was firstly run to retrieve concentrations of suspended particulate matter (SPM), chlorophyll-a (chl-a) and coloured dissolved organic matter (i.e. $a_{CDOM}(440)$) in the optically-deep waters. The areas where the retrieved optimisation error was higher than 10% were instead assumed as optically-shallow. In these areas two maps depicting the linear unmixing of three substrate types (i.e., silty-clay, *Chara* ssp. and other hydrophyte) and the water column heights were produced. The MIVIS-derived products were validated with field data providing a reliable estimation of SPM, chl-a, $a_{CDOM}(440)$ and cH (determination coefficients always $R^2 > 0.7$). SPM concentrations were also similar to a 5.4-km long transect of flow-through turbidity data, and the SAV map was comparable to *in situ* observations. Generally, the colonisation patterns of SAV were reflecting the spatial distribution of SPM concentrations. In particular, the positive role of *Chara* on keeping SPM concentrations low was observed. Future research should extend this application to remote sensing data acquired in other seasons to trace the dynamics of SAV and its effect on spatial water clarity.

1. Introduction

The optical properties of lakes are heavily influenced by catchment physiography and land use (Davies-Colley, Vant, & Smith, 2003). Given that rivers are the dominant inflows to lakes, lake waters might be expected to reflect inflowing materials. Indeed, the sediments originating from land and channel erosion processes are transported through the hydrographic network into lakes and oceans, as the final sinks, modulating their physico-chemical proprieties substantially (Sheng & Lick, 1979; Xu, Xiangdong, Xuhui, & Qian, 2011). Apart from this, the type and abundance of primary producers can greatly influence the characteristics of colonised lakes modulating the interactions among biological, chemical, and physical processes, especially for shallow lakes (Carpenter & Lodge, 1986). However, over the last century a dramatic reduction in representativeness and extent of submerged aquatic vegetation (SAV) has been observed in a major portion of lakes worldwide (Hicks & Frost, 2011; Jeppesen et al., 2010). The main causes are to be found in the shoreline modification and reinforcement, water use and abuse for agricultural, industrial and human purposes, and eutrophication (Dudgeon et al., 2006; O'Hare et al., 2010). Hence, in eutrophic lakes with high concentrations of suspended matter, phytoplankton and dissolved matter, the lake water transparency is very low with a rather poor light field. As a result, a rapid and progressive disappearance of macrophytes is expected.

In shallow lakes, SAV is the principal primary producer representing a key element of the entire aquatic ecosystem (Nõges et al., 2010). SAV actively participates in the cycling of nutrients, regulating the availability of macro-elements, in pollution control mechanisms, in the increasing habitat heterogeneity and in sustaining species diversity (Bolpagni

* Corresponding author at: Institute for Electromagnetic Sensing of the Environment, CNR-IREA, via Bassini 15, 20133 Milano, Italy. Tel.: +39 02 23699298; fax: +39 0223699300.
E-mail address: giardino.c@irea.cnr.it (C. Giardino).

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et al., 2007; Sollie, Coops, & Verhoeven, 2008; Wetzel, 1990). SAV also contributes to limit the resuspension of bottom materials that are expected to be primarily driven by wind-induced currents and wave actions; furthermore, their dominance results in higher concentrations of organically-derived constituents (Barko & James, 1998; Madsen, Chambers, James, Koch, & Westlake, 2001). On the other hand, in bare or poorly-vegetated littorals of wind-exposed shallow lakes frequent resuspension of particulates is expected, resulting in the masking of phytoplankton and increased water turbidity (Van Duin et al., 2001). In general, the sediment resuspension (1) enhances the release of nutrients from sediment, promoting the replacement of aquatic phanerogams by algae and the increase of primary productivity; and (2) increases the concentrations of suspended particulate matter (SPM) that promotes light attenuation. As a general rule, fine layer clays, which attenuate light more intensely than similarly sized spherical particles, might remain suspended almost indefinitely (Kirk, 1994). This is especially true in shallow lakes where an increased impact of water-sediment interface processes upon a lake ecosystem might occur (Scheffer, Hosper, Meijer, Moss, & Jeppesen, 1993).

It is therefore of paramount importance to support the SAV recovery in order to control the regeneration of nutrients from sediments and to limit sediment resuspension. Moreover SAV's allelopathy together with the competition with phytoplankton for nutrients and light may inhibit phytoplankton growth (Blindow, Hargeby, Meyercordt, & Schubert, 2006).

Due to its capability of synoptic spatial coverage, remote sensing helps to understand the interactions between SPM (e.g., Lindell, Pierson, Premazzi, & Zilioli, 1999 and reference therein) and SAV (e.g., Dekker et al., 2011 and reference therein) in inland and coastal waters ecosystems.

Recently, Odermatt, Gitelson, Brando, and Schaepman (2012) provided a review of the algorithms that have been adopted to retrieve water quality parameters (including SPM) from satellite data in optically-deep and optically-complex waters. They distinguished empirical and analytical methods (and in-betweens with the epithet “semi-”) from spectral inversion procedures; the latter build on matching spectral measurements with bio-optical forward models by means of inversion techniques. The development of empirical or semi-empirical models generally needs coincident ground measurements and the algorithms are generally scene- and/or sensor-dependent. Contrary, spectral inversion procedures are more generic and might be applicable independently of ground measurements and sensor characteristics. Nonetheless, they are less used due to the difficulties, or inaccuracies, of obtaining the parameters for model calibration (Ma, Duan, Tang, & Chen, 2010). As SPM is usually quantified outside the optical features of other water constituents (e.g., phytoplankton) (Binding, Jerome, Bukata, & Booty, 2010), the developments of empirical or semi-empirical models is feasible and many studies have applied those methods to satellite of inland waters (Wu, Cui, Duan, Fei, & Liu, 2013 and reference therein). A successful example of spectral inversion procedures for mapping total suspended matter from Landsat data in Dutch lakes can be found in Dekker, Vos, and Peters (2001).

Remote sensing has also been used to make large-scale inventories of benthic substrates (e.g., Dekker, Brando, & Anstee, 2005; Fearns, Klonowski, Babcock, England, & Phillips, 2011; Phinn, Roelfsema, Dekker, Brando, & Anstee, 2008), including lagoons (Alberotanza, Brando, Ravagnan, & Zandonella, 1999; Alberotanza, Cavalli, Pignatti, & Zandonella, 2006; Marani et al., 2006) and lakes (Bresciani, Bolpagni, Braga, Oggioni, & Giardino, 2012; Giardino, Bartoli, Candiani, Bresciani, & Pellegrini, 2007). In particular, airborne imaging spectrometry has been used to make large-scale inventories of macrophytes, sea grasses and corals (Heege, Bogner, & Pinnel, 2004; Hunter, Gilvear, Tyler, Willby, & Kelly, 2010; Kutser, Miller, & Jupp, 2006). Retrieval methods may involve classification techniques that, although precise (e.g., Reguzzoni, Sansò, Venuti, & Brivio, 2003), are effectively limited to application on single scenes. Hence, as for SPM retrieval, spectral inversion procedures have been developed (e.g., Lee, Carder, Chen, & Peacock, 2001; Lee, Carder, Mobley, Steward, & Patch, 1999) and adopted (e.g., Brando et al., 2009) to promote automation of scene-independent approaches from the classification process. Overall, spectral inversion procedures have the advantage of simultaneously measuring information about the concentrations of water quality parameters (including SPM) in the water column and, in the case of optically-shallow waters, of enabling bathymetry and measuring substrate type (including SAV).

In this work, a spectral inversion procedure was adopted for assessing SPM concentrations and SAV colonisation patterns from atmospherically corrected hyperspectral airborne data of a shallow lake (average depth 4.5 m). The lake is characterised by recurring sediment resuspension phenomena (average Secchi disc depth 1.5 m) which makes its water optically-deep, except the areas colonised by thick extensions of SAV in which the bottom is visible (and there is a measurable water-leaving radiance signal from the substrate). As part of this study, SPM concentrations and colonisation patterns of SAV maps were analysed with the aim of describing the role of rooted macrophytes on water clarity.

2. Materials and methods

2.1. Study area

Located in central Italy, Lake Trasimeno is the fourth largest lake for extension in the country (124 km^2). The lake's catchment area covers approximately 30,900 ha and it has not natural emissary (Orsomando & Catorci, 1991). Tourism, agriculture and livestock breeding represent the major pressures in Trasimeno catchment. Cultivated lands cover about 70% of the catchment's area of the lake, with irrigated intensive agriculture occurring in 28% of the area (Mearelli, Lorenzoni, & Mantilacci, 1990). The annual charge of organic carbon (500 t), nitrogen (550 t) and phosphorus (30 t), although not consistent, negatively affects water quality because of the specific seasonal temperature cycle coupled with irregular lake bed properties (Bresciani, Giardino, & Boschetti, 2011; Mearelli et al., 1990). The lake is roughly circular, fluvial in origin and also tectonic, it is a closed lake, with un-stratified and very shallow waters. The actual annual rainfall is about 754 mm; with a main maximum in autumn and a secondary in the spring. The average annual air temperature is 14 °C and the maximum value is recorded in July.

Monthly to biweekly water monitoring programs carried out by the local water authority shows that Lake Trasimeno is a carbonate-rich lake (Charavgis et al., 2011). *In situ* and satellite based observations provide average values of chlorophyll-a (chl-a) and Secchi disc depth of 8.5 mgm^{-3} and 1.1 m, respectively (Giardino, Bresciani, Villa, & Martinelli, 2010). Those conditions make the lake waters turbid, threatened by drought and anoxia. In particular, during the end of almost every summer, the lake is affected by recurrent algal blooms, particularly of filamentous cyanobacteria (*Cylindrospermopsis raciborskii* and *Planktothrix agardhii*), a phenomena that are depending on both water temperature increase and water level decreasing (Bresciani et al., 2011).

The lake sediments generally show a high organic content and grain size classified as clay and silt-clay along the southern coast, and as the sands with varying percentages of clay and silt along the northern coast (Charavgis et al., 2011). Those sediments are often re-suspended into the water column by wind actions; resuspension phenomena that are also locally induced by navigation towards the islands. Overall, for the entire lake, the average value of SPM in the lake is 11.7 gm^{-3} (Giardino et al., 2010).

The southeast part of the lake is densely colonised by emergent species (e.g., *Phragmites australis*, *Typha angustifolia*, *Scirpus* ssp., *Carex* ssp.) and submerged macrophytes (*Potamogeton pectinatus*, *Chara globularis*, *Myriophyllum spicatum*, *Ceratophyllum demersum*, *Potamogeton crispus*). The common reed (*P. australis*) is the widespread species capable of forming dense belts that are among the largest of peninsular Italy. Since 2000, the ecosystem is a protected area (Natura 2000 sites) for

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