MULTI-SPECTRAL IR AND VISIBLE IMAGING SPECTROMETER (MIVIS) DATA TO ASSESS OPTICAL PROPERTIES IN SHALLOW WATERS

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ABSTRACT

Extensions of submerged macrophyte and their variation in time along the littoral zone of Sirmione Peninsula, in the southern part of Lake Garda (Northern Italy), were investigated from imaging spectrometry. Two images with a ground resolution of 5 m were acquired by the Multispectral Infrared and Visible Imaging Spectrometer (MIVIS) during summer 1994, 1997, 2000 and 2005. Image data were geo-coded and atmospherically corrected using the 6S radiative transfer code and converted into Remote sensing reflectance R_{rs} values applying an additional correction for skylight reflection at the water surface. The MIVIS-derived R_{rs} values were inverted using a bio-optical model, ad hoc parameterised with inherent optical properties of Lake Garda waters. The inversion was run in the wavelength range from 0.48 to 0.60 μm, where the bio-optical model resulted more sensitive to variation of substrate albedo. The bio-optical model-driven optimisation provided reasonable estimation of bottom depth and of two different bottom albedo substrates: bare sand and submerged vegetation, which include a mixture of valuable freshwater species. Overall, the comparison of the substrate products over 10 years shown a marked disappearance of macrophyte beds, replaced by sandy substrates starting from 2000. In 2005 the situation was comparable to the older imagery, acquired in 1994. It is likely that increasing anthropogenic pressure in the Sirmione Peninsula as well as the increasing of variation range of water levels are responsible for the disappearance of valuable prairies of macrophytes in the study area.

INTRODUCTION

Macrophytes are an essential part of the productive zone in lakes (Hellsten 2001). The vegetation provides food, shelter and breeding habitats for aquatic animals like invertebrates, fish and birds (Lampert & Sommer 1997; Brönmark & Weisner 1992). Macrophytes have an effect on the bottom quality and composition and protect the shore from erosion (Barko *et al*., 1991; Spence 1992). Macrophytes are an important long-term limnological indicator of water and sediment quality but the monitoring of their distribution according to standard limnological approaches requires time and money consuming field campaigns. Measurements are generally performed over relatively small surfaces, by spread point sampling methods (more advanced techniques employs submergible cameras) and resulting vegetation maps may result inaccurate because they do not give the spatial overview that is necessary for a fast global assessment of their distribution. Furthermore, due to the huge sampling effort, such characterisations are not repeated annually.

On the contrary, remote sensing may represent a suitable alternative for the assessment of such information. Recently, remote sensing has been offered as a possible alternative to diver surveys for the large scale inventory of benthic photosynthetic organisms such as macrophytes, seagrasses and corals (Anstee *et al*. 2001; Bajjouk *et al*. 1996; Heege & Fischer 2004; Hochberg *et al*. 2003; Malthus *et al*. 1997, Alberotanza *et al*. 1999).

In this study the extensions of submerged macrophyte and their variation in time along the littoral zone of Sirmione Peninsula, in the southern part of Lake Garda (Northern Italy), were investigated from imaging spectrometry.

Study Area

Lake Garda, along with other large lakes located on the southern edge of the Alp, belongs to a distinct typology of lakes characterised by high depths and large volumes. Lake Garda was formed by glaciers during the last Ice Age, and is Italy's largest lake. It lies in the provinces of Verona, Brescia, and Trento, and is 51 km long and from 3 to 18 km wide (Figure 1). The Sarca river is its chief affluent, and the lake is drained southward by the Mincio, which discharges into the Po River, the Italy's longest river. At the southern end of the lake, a narrow peninsula that extends about 4 km into the lake, is located. It is one of most enchanting places on the lake, and being there the ruins of a Roman villa and a castle of the Scaligers, an Italian family of the 16th century, the Sirmione Peninsula is one of the most visited tourist places in Italy. The presence of hot thermal springs also encourage the increasing of human presences in Sirmione (on average 690000 guests were registered, excluding 1-day visitors).

Coastal zones of the Sirmione Peninsula are characterised by gentle slopes, particularly in the eastern sides. Communities of Phragmites are dislocated in less urbanized areas, while a variety of macrophytes inhabit substrates surrounding the peninsula where *Lagarosiphon*, *Vallisneria*, *Potamogeton*, *Najas* and *Chara* species are recognizable. These plants reach their maximum development in mid September, depending on the meteorological conditions occurred in the preceding winter and spring seasons, on remixing of lake waters as well as on water levels. An exceeding normal growth was observed in the study area in 2000 (Borsani & Contorbia 2000) causing losses in revenue from recreation and tourism-related activities, besides implications linked to navigation and irrigation. More recently scuba divers, fishers and the environmental protection agency of Sirmione instead observed an alarming disappearing of this valuable aquatic vegetation beds (Luca Fila, pers. communication).

MATERIALS AND METHODS

In order to gain additional information on these recent changes in macrophytes colonisation patterns a multi-temporal data set of Multi-spectral IR and Visible Imaging Spectrometer (MIVIS) data has been analysed. MIVIS is a modular Daedalus instrument which consists of 4 spectrometers that simultaneously measure the radiation in 102 channels with an instantaneous field of view of 0.2 mrad. MIVIS imagery of the Sirmione Peninsula were collected on 15th June 1994, 16th September 1997, 13th July 2002 and 27th July 2005, respectively.

Table 1: Main 6S inputs for the atmospheric correction of MIVIS data.

Dates	15/06/94	16/09/97	13/07/00	27/07/05
Flight altitude (m a.s.l.)	4560	2560	4560	2560
Pixel size (m)	9	5	9	5
Sun zenith/azimuth angles	23°/180°	43°/170°	27°/147°	27°/144°
AOT@550 nm	0.23	0.22	0.15	0.57
Visibility ranges*	23	24	50	7
Climatic zone	Mid-latitude summer			
Aerosol model	Continental			

*as computed by 6S from AOT@550 nm inputs.

The atmospheric correction of MIVIS data was accomplished through the 6S code (Vermote *et al.* 1997). Table 1 shows the main 6S inputs for each image: the atmospheric profiles were collected from radiosonde databases; the aerosol type was set as continental, while the aerosol concentration, assessed as atmospheric optical thickness (AOT) at 550 nm, was taken from the internet database of AERONET, in correspondence of the stations nearest to the study area (i.e., Ispra and Venice, about 100 km western and 80 km eastern, respectively).

The 6S retrieved reflectance values *acr6S_R* (for brevity, wavelength dependence may not be explicitly included unless required for clarity) were compared to in situ data measured during the 2005 MIVIS overflight over a car-park surface. A good closure was achieved, in particular within the 470-660 mm range the absolute difference of reflectance values between in situ data and 2005 MIVIS data, was lower than 0.0001. Dimensionless *acr6S_R* values were then converted into remote sensing reflectance R_{rs} (in sr^{-1}) by subtracting the contribution of the diffuse sky radiance reflected from the water surface through the equation:

$$R_{rs} = \frac{1}{\pi}\left(acr6S\_R - \frac{E_{diff}}{E_{tot}} \cdot 0.02 \right) \tag{1}$$

where the diffuse (E_{diff}) to total (E_{tot}) irradiance ratio were computed by 6S and 0.02 is the Fresnel reflectance for low wind speed (Mustard *et al.* 2001).

After correction of MIVIS imagery to R_{rs} values, a normalisation of older acquisitions with respect to 2005 data was accomplished. The empirical-line calibration methods was applied to 1994, 1997 and 2000 data based on spectral invariant surfaces common to each scene. This radiometric post-processing was necessary to take into account some drifts in the radiometric calibration of MIVIS.

Bio-optical model description and inversion

To invert MIVIS R_{rs} data a bio-optical model based on Lee *et al.* 1998, Lee *et al.* 1999 and Albert & Mobley 2003 was defined. The modelled remote sensing reflectance R_{rs}, was expressed as a function of the subsurface irradiance reflectance *R(0-)*, which was approximated as the sum of contributions from the water column $R(0\text{-})^C$, bottom $R(0\text{-})^B$:

$$R_{rs} = \frac{\Pi R(0\text{-})}{(1 - \gamma R(0\text{-}))} \tag{2}$$

$$R(0\text{-}) = R(0\text{-})^C + R(0\text{-})^B = R(0\text{-})^{dp}\left(1 - A_0 e^{\left(-\left(\frac{1}{\cos(\vartheta_w)} + D_u^C\right)kH\right)}\right) + A_1 \rho e^{\left(-\left(\frac{1}{\cos(\vartheta_w)} + D_u^B\right)kH\right)} \tag{3}$$

$$R(0\text{-})^{dp} = \left(g_0 + g_1 \cdot u^{g_2}\right) \cdot \frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)} \tag{4}$$

where $R(0\text{-})_{dp}$ is the subsurface irradiance reflectance for optically deep waters. Π and γ are model parameters which take into account for the viewing angle and the water column properties, H is the water depth, θ_w is the underwater Sun zenith angle, while the definition of model parameters g_0, g_1, g_2, A_0, A_1 and of D_u^C, D_u^B and k (the last three being functions of total absorption and total backscattering coefficients), can be found in Lee et al. 1998. In this study 4860 forward HYDROLIGHT simulation were run to determine the model parameters values.

The bottom albedo in equation 3 was expressed as:

$$\rho(\lambda) = \sum_{i=1}^{2} b_i \cdot \rho_i(\lambda) \text{ , with } \sum_{i=1}^{2} b_i = 1 \tag{5}$$

where b_i represents the relative distribution of the substrate albedo $\rho_i(\lambda)$ characterising the study area. The sand spectra $\rho_1(\lambda)$ was obtained by reducing by 50% a coral sand spectra directly provided by HYDROLIGHT (Mobley & Sundman 2001). The vegetation spectra $\rho_2(\lambda)$ was the average value of measured reflectance spectra of different macrophyte species growing in the study area. Samples of macrophytes species were collected during three surveys carried out in the Sirmione Peninsula from June to September 2005. In occasion of each survey the nadir-viewing reflectance of macrophytes was measured above water using an ASD-FieldSpec radiometer. The reflected radiation field over macrophytes samples was assumed to be Lambertian and $\rho_2(\lambda)$ was finally computed averaging the nadir-viewing reflectance values of the measured species. The coefficient of variation of the entire dataset resulted lower than 0.5 (for each wavelength) so that the average was assumed a good indicator of measured macrophytes albedo.

The total absorption coefficient ($a(\lambda)$ in equation 4) was expressed as the sum of three components which account for the contribution of pure water, total particle (phytoplankton and nonalgal particles), and coloured dissolved organic matter. The pure water absorption coefficient was taken from Pope & Fry (1997) and Smith & Baker (1981). The total particle absorption coefficient $a_p(\lambda)$ was modelled according to Bricaud *et al*. (1995). The absorption coefficient of coloured dissolved organic matter was modelled according to the well known exponential function, where the slope factor was modelled using two scalars which relate the slope to the absorption coefficient of coloured dissolved organic matter at 440 nm (Giardino *et al*., submitted).

The total backscattering coefficient ($b_b(\lambda)$ in equation 4) was expressed as the sum of two components which account for the contribution of pure water and total particle. The backscattering coefficient of pure water was defined according to Dall'Olmo & Gitelson (2006); the specific backscattering coefficient of particle was modelled using a power function relating the concentration of suspended particulate matter to the specific particle backscattering coefficient (Giardino *et al*., submitted).

The optimisation process is then performed through the merit function measuring the spectral distance between modelled and MIVIS derived remote sensing reflectance as shown in Lee *et al*. 1999. Starting from initial values of the unknowns, the predictor-corrector procedure used to invert the bio-optical model change the values of the unknowns computing the distance function until a minimum is reached. Generally, values corresponding to the δ minimum represent the best (optimum) set for the unknown variables: the concentrations of water column parameters (phytoplankton, suspended particulate matter, coloured dissolved organic matter) bottom depth (H) and bottom distribution (b_1 and b_2) of pre-defined albedo classes. Nevertheless, in this study the inversion was run fixing the water column concentrations to Lake Garda long term average values (Giardino *et al*. 2007). The unknowns to be retrieved were hence reduced to bottom depth and to distribution of the two predefined albedo classes (i.e., sand and vegetation). Furthermore, the inversion was run using 7 MIVIS channels in the wavelength range from 480 to 600 nm, which was selected running a sensitivity analysis of the bio-optical model and considering the environmental noise equivalent remote sensing reflectance difference of MIVIS imagery as shown in Hoogenboom *et al*. (1998), Brando & Dekker (2003) and Giardino *et al*. (2007).

RESULTS AND DISCUSSION

Figure 1 shows the MIVIS-derived substrate maps, depicting the fraction of sand (b_1) with respect of macrophyte (b_2) for each date. These achievements allowed evaluating the submerged vegetations extension in 1994, 1997, 2000 and 2005 and their variations within 11-years time range. The total area mapped is about 450 ha. As validation the bottom-retrieved maps were compared to nautical charts: satisfactory results (not shown here) were derived.

The comparison of the substrate products for the four dates had shown an abundance of colonized beds in 1997 and 2000 (extension of un-vegetated areas around 30%). An opposite situation was assessed in 1994 and 2005 (extension of un-vegetated around 50%). The comparison of the substrate products had shown a disappearance of macrophyte beds starting from 2000. At that time many dead macrophytes piled up on beaches causing big problems to recreational activities and navigation (Borsani & Contorbia 2000).

The increased anthropogenic pressure the Sirmione Peninsula seems responsible for the disappearance of valuable prairies of macrophytes in last years (more difficult the interpretation for 1994 since no ancillary information is available). The amplification of range of variations of water levels (related to climatic fluctuations and water need, the latter in terms of increased demands for irrigation and drinking water) can also be an important factor affecting species composition of macrophytes.

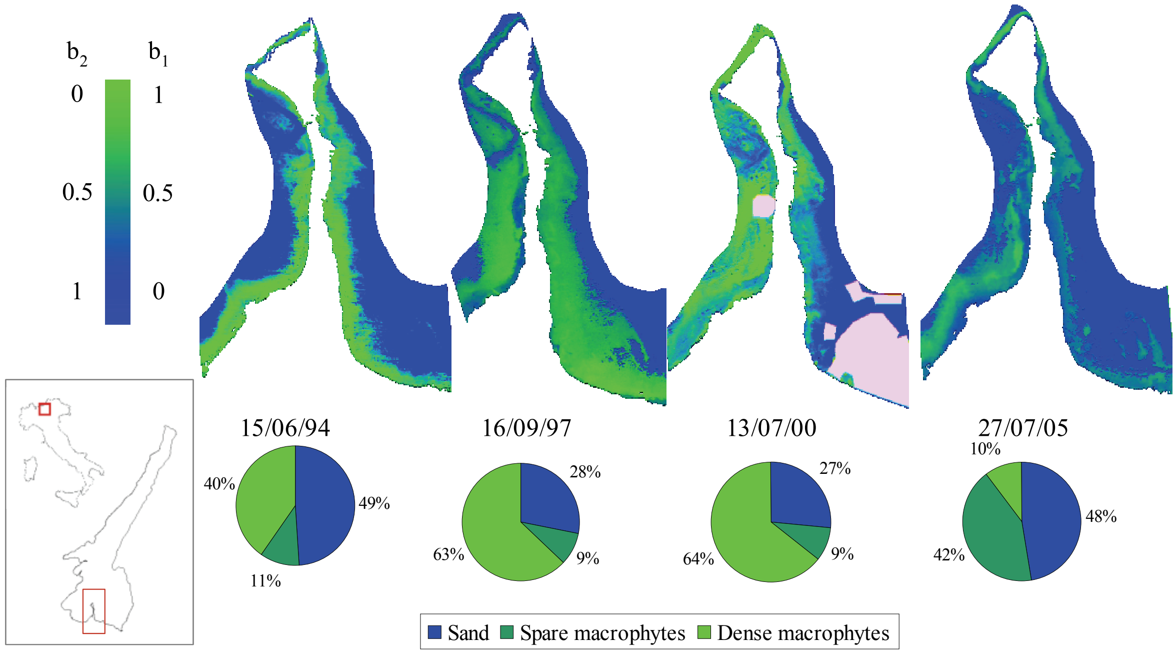

Figure 1: Maps of substrates: colour scale depicts the variation of b1 (representing the relative distribution of sand) versus b2 (the relative distribution of macrophytes); within each pixel macrophytes are classified spare (0<b2≤0.5) or dense (0.5<b2≤1) (on 13/07/00 clouds were masked). Pie-charts resume the distributions of sand and macrophytes for each image. The inset shows the study area location.

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