MONITORING WATER QUALITY OF THE PERALPINE ITALIAN LAKE GARDA THROUGH MULTI-TEMPORAL MERIS DATA

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ABSTRACT

This study represents a preliminary test to build up an operational tool for the evaluation of water quality of Italian perialpine lakes from space using Full Resolution MERIS data. To the aim, 9 Level-1P (L1P) and 7 Level-2P (L2P) image data acquired close to in situ measurements of chlorophyll-a (chl-a) concentration in Lake Garda were analysed. L2P data already comprises the chl-a concentration map, while the top of atmosphere radiances of L1P were converted to remote sensing reflectances Rrs(\(\lambda\)). The Rrs(\(\lambda\)) values were obtained with an algorithm based on the 6S radiative transfer model. When no in situ measurements were available the aerosol properties were estimated from MERIS data with the Dark Dense Vegetation approach. To estimate concentrations of chl-a from Rrs(\(\lambda\)) values a bio-optical model, parameterised with the specific inherent optical properties of the lake, was inverted using fast inversion procedures, such as band-ratios or optimisation techniques. All the image products were then compared to in situ data measured close to the image acquisitions. The optimisation technique (bands 5 to 9) and the band-ratio (B5/B7) applied to 6S-corrected L1P data provided chl-a values in agreement with in situ data (RMSE=0.87 mgm\(^{-3}\) for optimisation, RMSE=1.20 mgm\(^{-3}\) for band-ratio). Also the Algal2 products gave promising results (RMSE=1.60 mgm\(^{-3}\)) even the presence of several invalid pixels. Nevertheless, more tests with additional field data and MERIS L1P and L2P imagery are required to validate and improve the method we shown.

1 INTRODUCTION

Lake water is an essential renewable resource and its sustainable use requires the combination of surface waters assessment and monitoring programs, coupled with decision making and management tools. The Water Framework Directive (WFD) [1] is the major reference to guide efforts for attaining a sustainable aquatic environment in the years to come. The WFD includes guidelines which define the categories of quality and the corresponding components and parameters. Because some of these parameters can be determined by Remote Sensing (RS) with a reasonable accuracy, RS-related technologies may be integrated in the monitoring programs defined by the WFD. To this aim the MERIS sensor, onboard of Envisat, offers an excellent choice in terms of costs, revisiting time, spectral and radiometric resolutions.

Most of the largest European lakes are located in the Nordic countries and in the Alpine regions [2]. The most important Italian lake district is located in the northern part of Italy and represents more than 80% of the total Italian lacustrine volume [3]. With respect to the lakes of the district, Lake Garda was chosen because the RS-related activity has a pretty long tradition at this lake and hence optical properties are studied [4, 5, 6, 7, 8]. The lake dimension is also in agreement with the pixel size of FR MERIS data, at least for the southern part. The lake is therefore also used as a benchmark to implement RS in the monitoring programs of the whole southern perialpine lake district, when appropriate Earth Observation (EO) systems will be available. The Full Resolution (FR) acquisition mode of MERIS seems in fact still too coarse for the smallest and narrowest lakes of the region.

2 MATERIAL AND METHODS

2.1 Water quality data

With an area of 368 km\(^2\), Lake Garda is the largest Italian lake and one of the most important lake of the European region. The lake needs accurate care not only for its natural relevance, but also for its economical importance due to tourist-related activities. The lake is oligomitic and oligo-mesotrophic in accordance with the Organisation for Economic Cooperation and Development (OECD) classification [9].

The water quality parameters that were considered relevant for the bio-optical model used in this study were the concentration of chlorophyll-a (chl-a), the concentration of suspended particulate matter (SPM) and the absorption of coloured dissolved organic matter (CDOM) at 440 nm. The most likely concentrations of these parameters in the lake is described by Probability Density Functions (PDFs). The PDF of each water quality parameter was built from a quasi-
homogenous database which includes in situ measurements acquired since 1997. The statistical analysis performed has retrieved the log-normal distribution to be the most suitable probability distribution for each parameter (Fig. 1).

Fig. 1. The PDFs of the investigated water quality parameters of Lake Garda. For each panel: left y-axis is frequency, the right y-axis is the probability and the x-axis is the parameter concentration.

2.2 The bio-optical model

An important parameter in the interpretation of water quality from remote sensing is the remote sensing reflectance \( R_{rs}(\lambda) \). \( R_{rs}(\lambda) \), in fact, can be related to the water quality parameters by means of a function of the spectral absorption and backscattering coefficients.

The spectral absorption coefficient \( a(\lambda) \) is often divided into four components which account for the contribution of pure water (w), phytoplankton (F), nonalgal particles (NAP) and CDOM [10]:

\[
a(\lambda) = a_w(\lambda) + a_F^*(\lambda, \text{chl-a}) \cdot \text{chl-a} + a_{NAP}^*(\lambda, \text{SPM}) \cdot \text{SPM} + a_{\text{CDOM}}^*(\lambda, a_{\text{CDOM}}(440)) \cdot a_{\text{CDOM}}(440). \tag{1}
\]

While for the pure water absorption was chosen [11], the absorption coefficients of the other three components were modelled using simple models able to describe different water conditions. These models were parameterized using absorption spectra measured in laboratory. In particular, \( a_F^*(\lambda, \text{chl-a}) \) was calculated according to [12], \( a_{NAP}^*(\lambda, \text{SPM}) \) and \( a_{\text{CDOM}}^*(\lambda, a_{\text{CDOM}}(440)) \) terms were calculated according to [10]. Similar to [13], the analysed NAP data shown a relationship between \( S_{\text{NAP}} \) and \( S_{\text{CDOM}} \) and an average \( S_{\text{NAP}} \) value equal to 0.0079. For CDOM absorption an inverse relationship was found between \( S_{\text{CDOM}} \) and \( a_{\text{CDOM}}(440) \), with an average \( S_{\text{CDOM}} \) value close to 0.14.

The spectral backscattering \( b_\nu(\lambda) \) is expressed as the sum of three absorption coefficient for water, phytoplankton and Suspended Inorganic Particulate Matter (SPIM):

\[
b_\nu(\lambda) = b_w(\lambda) + 0.091 \cdot \lambda^{-0.515} \cdot \text{chl-a} + 0.040 \cdot \lambda^{-0.138} \cdot \text{SPM} . \tag{2}
\]

In this case the backscattering value of pure water was taken from [14]. Backscattering coefficients of phytoplankton and SPIM were modelled using measurements achieved with HydroScat-6 during several field campaigns and they were considered to be constant. For the purposes of the model also a relationship between SPM and SPIM was found using 114 discrete measurements of both parameters.

Defining

\[
u(\lambda) = \frac{b_\nu(\lambda)}{a(\lambda) + b_\nu(\lambda)} . \tag{3}
\]

\( R_{rs}(\lambda) \) can be expressed as

\[
R_{rs}(\lambda) = g \cdot u(\lambda) , \tag{4}
\]

where \( g \) itself is a function of \( u \) [15]:

\[
g = g_0 + g_1 \cdot u(\lambda)^{12} . \tag{5}
\]
To define $g_0$, $g_1$, and $g_2$, Hydrolight 4.2 was employed to generate $R_{rs}(\lambda)$ values. These Hydrolight-simulated values were compared with values given by approximations from (4) and (5) varying the set of $g$. The $g_0$, $g_1$, and $g_2$ coefficients were determined by minimizing the following quantity as in [15]

$$\delta = \text{average} \left\{ \frac{R_{rs}^B(\lambda)}{R_{rs}^H(\lambda)} \right\},$$

(6)

where $R_{rs}^B(\lambda)$ is a bio-optical model simulated value and $R_{rs}^H(\lambda)$ is an Hydrolight-generated value. The resulting best-fit set of $g$ values gave us $g_0 \approx 0.045$, $g_1 \approx 0.088$ and $g_2 \approx 1.192$, and hence the final bio-optical model parameterization was:

$$R_{rs}(\lambda) = \left\{ 0.045 + 0.088 \cdot u(\lambda)^{1.192} \right\} u(\lambda).$$

(7)

### 2.2 MERIS data

In this study 9 Full Resolution (FR) Level-1P data were analysed and, for all the dates except two, also Level-2P data were available (Tab. 1). The MERIS imagery was selected according to data already acquired within AO533 and AO164 ESA PI projects and to available in situ chl-a data, routinely measured by local agencies (Tab. 1).

In order to obtain the spectral reflectance from the L1P MERIS data a correction based on the 6S radiative transfer model [16] was applied. The atmospheric profiles of air temperature, pressure and absolute humidity were derived from radiosonde data at Milano acquired at 12:00 UTC on the days with MERIS overflights. The average Aerosol Optical Thickness value at 550 nm ($\text{AOT}_{550}$) and the Ångström $\alpha$ coefficient were derived from sun photometric measurements carried out on the shore of Lake Garda or by means of the Dense Dark Vegetation (DDV) approach [17] applied to the area around the lake. The Junge size distribution was chosen with a parameter, $\nu$, related to $\alpha$ by $\nu=\alpha+3$. A detailed description of the atmospheric correction procedure can be found in [18].

A reflectance spectrum derived from the MERIS spectral radiance over an area in the south basin of Lake Garda on the day with field measurements is shown in Fig. 2. The agreement between MERIS and SpectraScan PR-650 spectra is generally good. Some differences appear in the blue/green bands, possibly due to path radiance, which is large in this spectral region. The maximum at-surface reflectance values $\rho$ of Lake Garda are around 4% in all processed MERIS scenes, which reveals a weak signal coming from the lake.

### Tab. 1. List of MERIS data investigated in this study and in situ chl-a data close to satellite overpasses (only on 22-Jul-03 there is coincidence between in situ and MERIS data)

<table>
<thead>
<tr>
<th>In situ chl-a data</th>
<th>09-Jun-03</th>
<th>17-Jun-03</th>
<th>09-Jul-03</th>
<th>22-Jul-03</th>
<th>23-Jul-03</th>
<th>14-May-04</th>
<th>14-Jul-04</th>
<th>03-Aug-04</th>
<th>09-Aug-04</th>
</tr>
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<tbody>
<tr>
<td>Level-1P</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Level-2P</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<td>✓</td>
</tr>
</tbody>
</table>

To directly compare imagery data to the forward bio-optical modeling the atmospherically corrected $\rho$ data were converted into $R_{rs}$ (since now the $\lambda$-dependency of $R_{rs}$ is omitted for simplicity). This conversion was simply performed dividing L1P-derived $\rho$ data by $\pi$. The assumption implies that $R_{rs}$ of our MERIS data may include components due to specular reflection effects occurring at the surface.

A geo-located region of interest (ROI) of 195 pixels, defining a common lake area for all the images, was defined for the data analysis. All the lake-water pixels of the Lake Garda ROI (LG-ROI) were located in the southern part of the basin, were image data are less affected by residuals of adjacency effects and were Algal2 products all shown valid pixels.
The average Rs spectra extracted from the LG-ROI for each date were then plotted together with the average values of bio-optical derived Rs spectra (Fig. 3). For the generation of these simulated spectra, the bio-optical model was run 200 times using random combinations of chl-a, SPM and CDOM distributed according to their PDFs (as in Fig. 1). In this way, the 200 simulated spectra of Rs could be considered to be realistic for Lake Garda. The order of magnitude of 6S-corrected L1P data was generally in agreement with the average value of the 200 forward runs of the bio-optical model. At longer wavelengths, 6S-corrected L1P data appeared in less agreement with modelled spectra showing Rs values larger than simulated ones. Also at shorter wavelengths, 6S-coderived Rs were generally larger than simulated spectra.

Fig. 3. Comparison between MERIS-derived and forward bio-optical modelled Rs values. MERIS spectra are the average values extracted from the geo-located LG-ROI, modelled Rs spectra are plotted as average values (of 200 spectra) ± 1.96 the standard deviation.

3 RESULTS

There are several approaches to derive water quality parameters from image-derived Rs data (or other quantities such as the subsurface irradiance reflectance), when an analytical bio-optical model is available for a certain lake. In this study an optimisation technique and a band-ratio method, the second already tested on Lake Garda [7], were considered.
In the optimisation technique \((opt)\) the quantity in equation (6) was minimised. With respect to equation (6) the denominator was now the MERIS-derived \(Rrs\). In order to avoid uncertainties related to the atmospheric correction, the inversion was applied to MERIS spectra from band 5 (560 nm) to 9 (708 nm). For the generation of the band-ratio algorithm \((br)\), the 200 \(Rrs\) values simulated using the bio-optical model and the PDFs were used. The \(Rrs\) value of each band was divided by each other and regressed against each of the chl-a concentration. In this way, the regression function based on the \(br\) with highest correlation with chl-a was derived. The B5/B7 \((r=-0.7)\) was selected to describe the chl-a variability even if the chl-a changes were better described by band-ratios located in the red-NIR wavelengths. Nevertheless, these bands were not considered to avoid wavelengths where the atmospherically corrected MERIS data shown some anomalies (see Fig. 3).

Fig. 4 shows the comparison between \textit{in situ} data, measured close to image acquisitions, and the MERIS-derived chl-a concentrations, estimated according to the \textit{opt} and \textit{br} techniques: on 22-Jul-03, when \textit{in situ} data were collected the same day of MERIS acquisition, all the MERIS-derived chl-a agree to \textit{in situ} observations; for all dates except for 19-Jun-03 and 13-Aug-04, the chl-a derived with \textit{opt} technique falls within average ± the standard deviation of \textit{in situ} observations (even if on 07-Aug-03 the \textit{opt} technique value is slightly larger than \textit{in situ} data, ± its standard deviation). Erroneous estimation on 13-Aug-04 may be due to the location of \textit{in situ} stations (all in the northern part and no matching any pixel of the LG-ROI); on 19-Jun-03 all the MERIS-derived chl-a concentrations are larger that \textit{in situ} data (this behaviour seems in agreement with a surface \textit{Anabaena} bloom observed \textit{in situ} on 20-Jun-03 that may be not revealed by laboratory analysis of the 1-integrated meter of subsurface sampled water).

Excluding data acquired on 19-Jun-03 and on 13-Aug-04 (due to problems mentioned above) the Root Mean Square Error (RMSE) computed using \textit{in situ} data was 0.87 mgm\(^{-3}\) for the \textit{opt} technique and 1.20 mgm\(^{-3}\) for the \textit{br} algorithm. Still excluding the 19-Jun-03 and the 13-Aug-04 dataset, the RMSE computed using 5 Algal2 products was 1.60 mgm\(^{-3}\).

4 CONCLUSIONS

Preliminary results obtained from atmospherically corrected L1P FR MERIS data are promising to implement a scene-independent method to assess chl-a concentration in Lake Garda. Up to now the estimation using the \textit{opt} technique applied to the 6S-corrected \(Rrs\) MERIS data performed better than the \textit{br} algorithm. Algal2 products also provided encouraging results, even if the spatial information seems minor due to the presence of several invalid pixels (more in the 2003 than in the 2004 dataset). More images, as close as possible to field data, are necessary to verify the method concerning the inversion of \(Rrs\) spectra using \textit{br} algorithms and \textit{opt} techniques (as well as other inversion methods).

Moreover, the responsibility of IOPs on chl-a assessment had to be better understood and new data on optical properties of Lake Garda waters are going to be collected.
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REFERENCES


