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Abstract

Lake Omodeo is the largest artificial reservoir of Sardinia and its waters are a valuable resource for irrigation, domestic and industrial purposes. Lake Omodeo has serious problems of eutrophication. Since 2007 the local water authority has been undertaken a monitoring program designed to test an integrated methodology based on field measurements and remote sensing. This study illustrates the production of multitemporal spatialised maps of chlorophyll-a concentrations from satellite data acquired from Medium Resolution Imaging Spectrometer (MERIS). The analysis confirmed the eutrophic status of Omodeo, especially between spring and summer (mainly due to cyanobacteria bloom) assessing their dependency on weather conditions and river inputs.
Keywords: Chlorophyll-a, cyanobacteria, MERIS sensor, meteorological factors, trophic status.

Introduction

The world water resources status cannot be correctly estimated without a suitable acquisition program, by means of precise, frequent and long-term samples. Consequently, water conservation and reclamation programs cannot easily achieve the assumed objectives, and specific results obtained from the above-mentioned programs cannot be adequately evaluated [Glasgow et al., 2004]. As the FAO document reports [2006] "Monitoring per se is concerned with the procedures and activities for collecting data and information in the formulation and implementation stages of an action or a series of initiatives. It is particularly aimed at providing regular feedback to guarantee coherence, efficiency and effectiveness against the underlying objectives set at the national and international levels". This will both stimulate support to the initiatives being implemented, and improve the formulation of the subsequent programs, through a "learning circle" informed by the lessons drawn from previous and ongoing activities.

In such a context an efficient approach for monitoring water quality of lakes is the integration of traditional limnological methods and remote sensing (RS) techniques. Limnological methods are fundamental for the understanding of aquatic ecosystems dynamics. Nevertheless, they are characterised by onerous and time consuming fieldwork activities in predefined spatial and temporal locations, thus not allowing, an exhaustive description of the aquatic ecosystems complexity [Allee and Johnson, 1999; Liu et al., 2003; Nausch et al., 2008]. Moreover, the data quality may depend both on procedures for collecting water samples and on laboratory measuring protocols. Other sources of uncertainty are the geo-location and the transcription mistakes of field notes [Pettinger, 1971; Teillet et al., 2002]. For these reasons, in recent years, traditional limnological methods have been increasingly joined by multiparameter probes technology. Being activated even from afar [Salmaso et al., 1997; Bertoni et al., 2008], this technology allows you to acquire remotely data. The acquisition method is commonly continuous and automatic in order to easily detect fast changes and trends of water quality indicators. Despite several advantages, probes have to be accurately and continuously calibrated and their usual use still cannot provide spatialised water condition information. RS, that have been used to assess water quality parameters in several lakes [e.g., Paavel et al., 2007; Odermatt et al., 2008; Bresciani et al., 2011a, 2011b] and reservoirs [e.g. Van Mol and Ruddick 2005; Simis et al., 2007], can fill this gap, being able to provide spatialised and multitemporal information of the top most layers of water bodies in a very cost-effective way. However, RS techniques have their limitations too, since they need adequate calibration and validation in situ data [e.g., Dekker et al., 2001; Pierson et al., 2008], and they can be used only in absence of clouds [e.g. Vis et al., 2003; Reinart and Kutser 2006]. Moreover the retrieval of water quality parameters might be tricky; for instance, Kutser [2009] describes that the densest areas of cyanobacteria blooms in the Baltic Sea are usually undetected by standard satellite products due to atmospheric correction or processing errors.

It appears quite obvious now that an integrated approach based on traditional limnological methods, multiparameter probes technology and RS is the suitable way for implementing a suitable monitoring program of water resources.

In this study we present the experience of using this integrated approach for the monitoring water quality status of the Lake Omodeo, the largest reservoir of Sardinia (Italy). Being used for irrigation and both industrial and domestic purposes, the monitoring of water quality in the reservoir has a strategic importance that goes beyond the preservation of the ecosystem. The Ente Acque Sardegna (ENAS) is a regional entity that after the approval of the Regional Law n. 19/2006, has the mandate to manage of the reservoirs of the region. To control the water quality, ENAS has been using both traditional limnological methods, multiparameter automatic probes mounted on buoy, while the RS technology has been introduced more recently. Therefore, the study firstly evaluates the accuracy of the RS data with respect to in situ limnological measures of chlorophyll-a (chl-a) concentration, that being used as a proxy of phytoplankton biomass, including cyanobacteria, is a good indicator of water quality. Secondly, it integrates the observations coming from the above-mentioned in situ methods to describe water quality condition of the lake.

Study area

Lake Omodeo is situated in central Sardinia (Italy), the second largest island in the Mediterranean Sea. Lake Omodeo is the largest water reservoir of Sardinia (water capacity

of around 800 Mm³) and its waters are strategically used for irrigation and both industrial and domestic purposes. Lake Omodeo belongs to the catchment basin of Tirso river (3375 km²), the most important river of Sardinia (160 km), which feeds the reservoir together with Taloro river. The lake is contained by the Cantoniera dam (also known as Eleonora d'Arborea) build in 1997. Indeed, there is another dam, placed more towards north (S. Chiara), which was built in 1924 but that nowadays is submersed (Fig. 1).
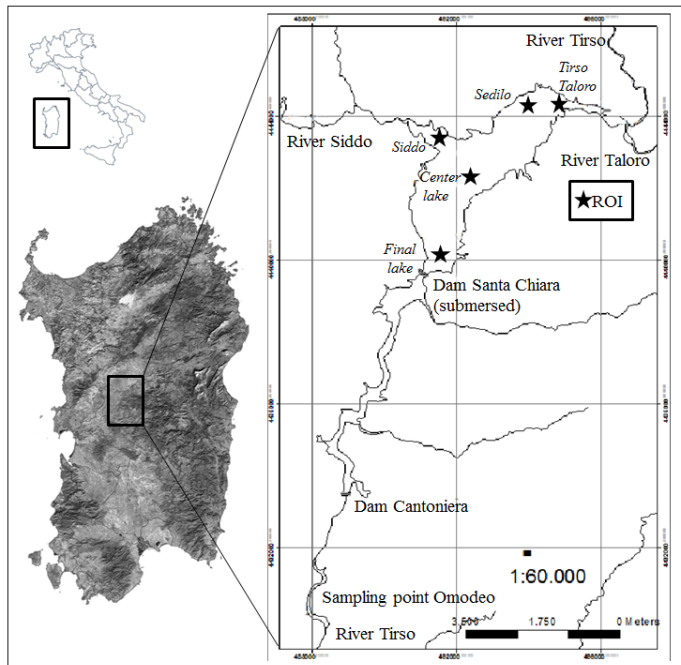

Figure 1 - Study area with representation of Lake Omodeo with the two dams and most important tributaries. The station for limnological sampling and multiparameter probe is indicated as "Sampling point Omodeo". The regions of interest (ROI), used to evaluate the spatial variability from MERIS data have been marked with stars.

The *Piano Tutela delle Acque* (PTA) [2006] of the regional authority of Sardinia (*Regione Sardegna*) provides a synthetic description of physical data of Lake Omodeo. The PTA, which sets the lake inside the *Unità Idrografica Omogenea* of Tirso river, considers sufficient and good the environmental condition of the two lake tributaries Tirso and Taloro, save for oxygen saturation percentage which is critical for both rivers. In Lake Omodeo, near the Cantoniera dam, extremely worrying levels of transparency and chl-a have been found, in addition to critical level of dissolved oxygen. On the whole, the trophic status of Lake Omodeo has been classified as eutrophic, on the base of theoretical natural phosphorus concentration (around 57 µg/l) computed using the MEI index [Vighi and Chiaudani, 1985]. Lake Omodeo is also affected by important algal blooms which are mainly due to cyanobacteria species. In particular, in May 2009 a bloom of *Microcystis* spp., *Planktothrix*

sp., *Anabaena circinalis* with more than 250000 cells 10^3 l^{-1} representing more than 90% of total phytoplankton community was observed. From 1970 to 1980 limnological investigations revealed highly trophic conditions, with the occurrence of cyanobacteria blooms during the summer period [Sechi, 1986].

Materials and methods
Field data
Field data used in this study were sampled at the Omodeo station (i.e. "Sampling point Omodeo" in Fig. 1) about 200 m south of the Cantoniera dam in a narrow stream of the reservoir in proximity of the emissary. They are the following:
- water sampling along vertical profile from which chl-a concentrations and monthly algal count have been extracted. Sampling depths are: 0 m (surface), 1, 2.5, 5, 7.5, 10, 15, 20, 30, 40 and 50 m (bottom). The chl-a concentrations has been extracted in acetone 90% solution, and correspondent concentrations have been estimated through absorbance data following Lorenzen methodology [1969].
- In situ data recorded by an automatic multiparameter probe: pH, O_2, temperature, turbidity, conductivity, salinity and chl-a (via fluorimetric measurements). The probe takes measures in the water column once a day, every meter till a depth of 15 m, and with interval of 5 m from 15 to 50 m. The buoy where the probe is placed is also equipped with a meteorological station, which records wind, temperature, rainfall, evaporation and solar incident radiation data.

Satellite images
24 Medium Resolution Imaging Spectrometer (MERIS) full resolution images, acquired from spring to autumn of 2009, 2010 and 2011, with an additional scene acquired on 3 August 2008 (Tab. 1), have been used to define the water quality status of Lake Omodeo. MERIS is a pushbroom imaging spectrometer on board of the Envisat-1, with a ground sampling distance of about 300 m (full resolution mode). MERIS operates in the visible and near-infrared spectral range (from 400 to 900 nm) with a wavelength configuration sensitivities to the most important optically-active water constituents.

Table 1 - List of MERIS images used in this study.

2008	3-Aug								
2009	7-May	13-May	23-May	8-Jun	14-Jun	13-Jul	29-Jul	23-Aug	17-Sep
2010	19-Apr	24-May	18-Jun	7-Jul	14-Jul	8-Aug	24-Aug	29-Oct	25-Nov
2011	10-Apr	23-Jun	26-Jun	6-Jul	6-Aug	28-Aug			

Based on previous studies [Odermatt et al., 2010; Giardino et al., 2010a], image processing was based on different BEAM (Basic ERS & Envisat (A)ATSR and MERIS) [Fomferra and Brockmann, 2006] routines. In a first step, the BEAM's smile correction has been applied to the original level 1B data. It applies an irradiance correction to all bands, which accounts for the difference between actual and nominal wavelengths of the solar irradiance in each channel. The smile corrected level 1B data were then processed with the ICOL (Improved

Contrast between Ocean and Land) [Santer and Schmechtig, 2000]. ICOL calculates top of atmosphere reflectance and applies a correction for adjacency effects that might strongly influence the determination of water reflectance in those pixels nearby the coastline [Candiani et al., 2005]. Finally, the adjacency effect corrected data are simultaneously converted into water reflectance and chl-a concentrations with the Eutrophic Lake (EL) tool [Doerffer and Schiller, 2008a; Doerffer and Schiller, 2008b]. This tool applies a dedicated neural network based atmospheric correction and bio-optical modeling for the waters whose optical properties depend on high value of phytoplankton.

In addition to the neural network BEAM EL tool, MERIS images have been atmospherically corrected with the 6S [Vermote et al., 1997; Kotchenova et al., 2006] by knowing the inadequacy of BEAM EL in estimating water reflectance and hence chl-a concentration in occasion of algal bloom [Giardino et al., 2010b]. The images corrected with the 6S have been analysed to evaluate the occurrence and patterns of algal bloom. To this aim, a three-band algorithm developed for turbid case-2 waters [Gitelson et al., 2007; 2008] was applied to remote sensing reflectance values (R_{rs}) derived from MERIS bands 8 (681 nm), 9 (708 nm) and 10 (753 nm) according to the relation:

$$3 - \text{band index} = \left[R_{rs}^{-1}(\text{band }8) - R_{rs}^{-1}(\text{band }9)\right]R_{rs}^{-1}(\text{band }10) \quad [1]$$

The index, is a proxy of chl-a concentrations and its value increase for increasing concentrations of chl-a [Gitelson et al., 2007].

Results

Analysis and validation of MERIS-derived products

The validation of MERIS-derived chl-a concentration was tricky because of the availability of one single sampling point located in the terminal narrowest part of the Lake Omodeo. Nevertheless, the comparison (Fig. 2) between in situ data (merging between laboratory and fluorimetric probe data) at the "sampling point Omodeo" and MERIS data (relative to the whole lake surface) shows an acceptable agreement of mean, standard deviation and minimum values. The largest deviation is observed for the maximum sampling values and indeed also for MERIS data in 2011, probably due to the limited number of images acquired in this year and for the more restricted time range.

The dataset offered 8 matches between MERIS and synchronous field data. In correspondence of the "sampling point Omodeo" the correlation between MERIS and in situ chl-a gives r^2=0.74, with a tendency of MERIS in underestimating highest chl-a concentrations. However, even in situ data show some mismatch since on average laboratory measurements and fluorimetric-probe data showed a deviation of 43% (average chl-a of 4.3 mg/m³ with lab-data and of 7.6 mg/m³ with probe), proving that chl-a concentrations are not easily detectable even with in situ observations. In order to investigate the reason of mismatch between MERIS and in situ data in occasion of algal bloom (i.e., high chl-a concentration) the estimates of water reflectance derived from BEAM EL tool have been compared to those computed with 6S (Fig. 3). A good match between water reflectance values estimated with both methods is generally achieved (r^2 of 0.84, ***p<0.001), save for images (r^2<0.2) acquired in occasion of significant algal bloom. In case of high concentration of phytoplankton, water reflectance shows a peak around 700 nm [e.g., Gitelson et al., 2008] which seems better described by 6S rather than BEAM EL.
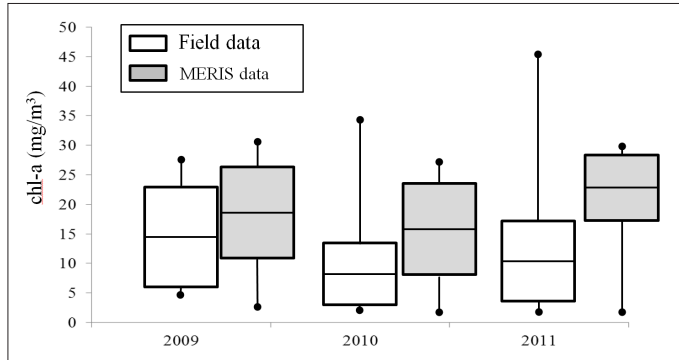
Figure 2 - Mean values of chl-a concentration derived from in situ and MERIS data. The box plot displays the average series value included inside the standard deviation box. The vertical lines shows maximum and minimum values registered in the time range of Table 1.
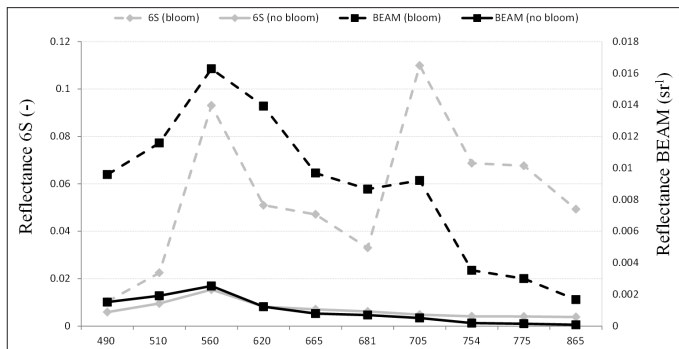

Figure 3 - Comparison (note the different scale) between water reflectance derived from MERIS by applying the BEAM EL tool and the 6S code. Two pairs of spectra are plotted: one for image data acquired in occasion of an algal bloom event (dotted line) and the other in absence of bloom (solid line).

MERIS images have been therefore processed with one of the two methods (i.e. BEAM EL or 6S+Eq.1) depending on the blooming conditions which, in Lake Omodeo, are mainly due to cyanobacteria species. According to Kutser et al. [2006] a threshold of 30 mg m^{-3} of chl-a concentration could be used to define the most suitable method for image processing.

Mapping and ecological considerations

The multitemporal analysis of chl-a concentrations derived from BEAM EL tool from 2008 to 2011 sets the lake in the eutrophic status (mean chl-a concentration higher than 12 mg/m^3). Maximum average values were observed in 2008, with concentrations of 17.67±1.74 mg/m^3, while minimum values appeared in 2011, with concentration of 14.18 ± 0.83 mg/

m³. Figure 4 shows an example of MERIS-derived products for the four scenes acquired in summer of every year.
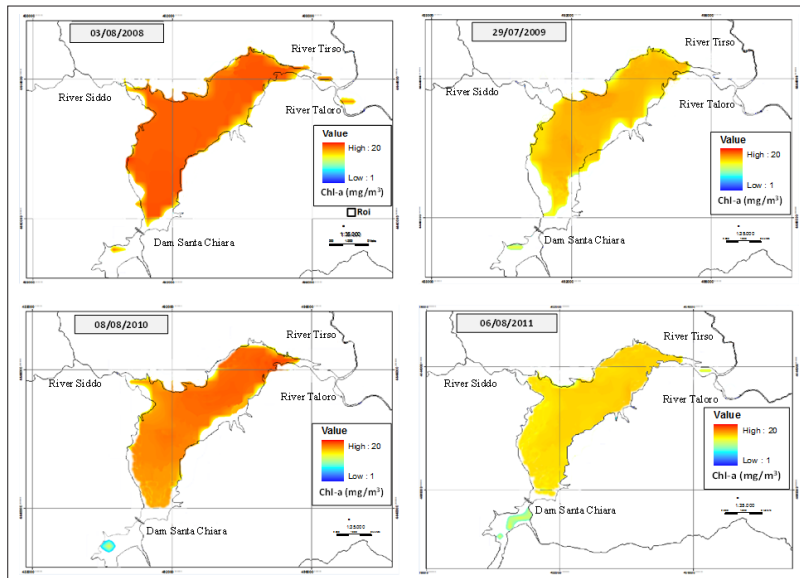

Figure 4 - Chl-a concentration maps derived in summer from MERIS data acquired in the time range 2008-2011.

In order to evaluate the spatial patterns of the chl-a concentrations five Regions of Interest (ROI) in correspondence of both potentially critical points, such as the entrance of tributaries (Fig. 1), and less sensitive areas such as the pelagic zones have been defined. Figure 5 shows a spatially homogeneous pattern, with higher values of chl-a recorded close to the entrance of Tirso and Taloro rivers and lower values in the Final lake place, close to the lake emissary. More in detail, it appears that the spatial pattern is more homogenous when the lake is in the eutrophic status than in the oligotrophic status, when the maximum value of chl-a are registered in the Center lake.

The 6S+Eq1 method was instead used to investigate the dynamic of algal blooms, in case of Lake Omodeo mainly due to cyanobacteria species, occurred in spring-summer 2009. The 3-band index [cf. Eq. 1], which is used as a proxy of chl-a concentrations [Gitelson et al., 2007] shows (Fig. 6) a rapid grow passing from 7 to 13 May, reaching the maximum on 8 June 2009.

The bloom event occurred in May 2009 is strictly correlated with environmental and water quality conditions. Meteorological data registered an increasing incident radiation from 5 kWh/m² at the end of April to 7.5 kWh/m² at the beginning of May together with an increasing of temperature, which passed from 13° C (during the first days of May) to more than 16° C beyond on 7 May. Meteorological data also reveal a lack of rain and weak winds. A so fast change of environmental conditions facilitates the beginning of intense blooms [Ressom et al., 1994] since cells can replicate so quickly to generate a very dense bloom just in few days.
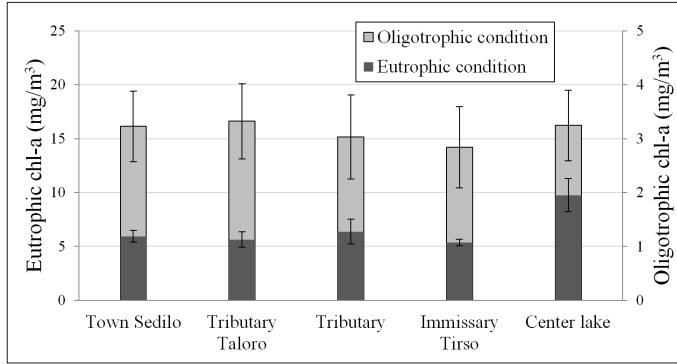
Figure 5 - Spatial variability of mean chl-a concentrations from the complete data set (with standard deviation) in the ROIs displayed in Figure 1. Typical eutrophic conditions are separated (with light grey bars) from characteristic oligotrophic ones (dark gray bars).
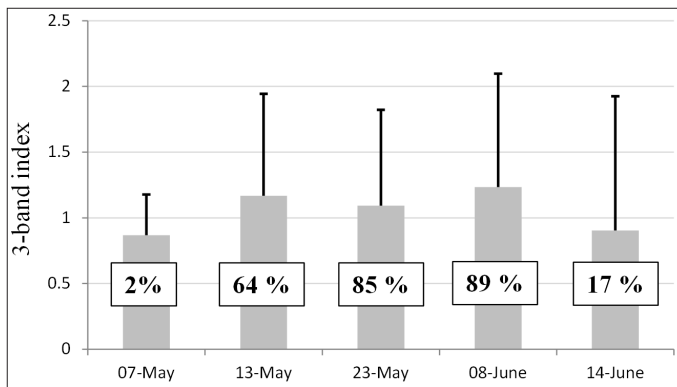

Figure 6 - Temporal of the 3-band index qualitatively depicting the occurrence of the algal bloom in 2009. The mean (grey box) and maximum values (vertical bar) of the 3-band index are displayed. The percentage of pixel of Lake Omodeo with the 3-band index >1 (i.e., chl-a > 30 mg/m³ according to the model developed by Gitelson et al. [2007]) are also given.

In situ water quality data pointed out that during cyanobacteria bloom (pH=10 on 9 of June 2009), pH values have been much higher with respect to the periods without any presence of bloom (i.e. pH=8.8 on 29 of September 2009). The increase of pH is also a typical bloom situation [Stumm and Morgan, 1981], which further favors cyanobacteria proliferation [Shapiro, 1990]. The dissolved oxygen percentage also grew in the same period (from 133% on 9 of June 2009 to 100% on 29 of September 2009) while the nutrients availability assures a good environment for cyanobacteria bloom event. In situ data show that at the beginning of the bloom period the waters were very rich of nitric nitrogen (500 µg/l on 13 of May 2009), while it has lower values in absence of blooming (i.e. 30 µg/l on 29 of

September 2009). According to Tandeau de Marsac and Houmard [1993] the cyanobacteria is concurrent with high concentrations of ammonia nitrogen and this was also observed in Lake Omodeo (11 µg/l on 13 of May 2009 on the surface against 4 µg/l on 29 of September 2009).

Conclusions and further work

This study confirmed the effectiveness of an integrated approach based on RS and in situ measurements for the evaluation of water quality in reservoirs. The integrated approach allows ENAS to take the advantage of each technique: 1) the analytical description of chemical, physical and biological parameters with traditional limonogical methods (but time-consuming and expensive); 2) the continuous automatic collection of data with multiparameter probes (but only for few points and requiring serious calibration and maintenance); and 3) multi-temporal, synoptically RS data, a cost-effective technology that has been demonstrated to be an important source of information to support the definition of the water quality status of Lake Omodeo.

The results demonstrated that during the spring-summer period, Lake Omodeo reaches chl-a concentrations typical of eutrophic conditions, with cyanobacteria blooms in case of particular environmental conditions as observed in May 2009, when surface water temperatures increase with a reduction of water dissolved oxygen. Such events, which may originate algal toxins, damage the water quality and consequently, the water authority needs to solve the problems of multiply water treatments in order to assure the distribution of the Lake Omodeo waters. This work demonstrated that very often tributaries can hold the balance of power, acting as vector of different pollution sources: punctual as well as diffused or organic as well as inorganic. A careful land planning has to be done through the joint operation of local authorities, regional agencies and regional institutions.

Further work will extend the approach presented in this study to other Sardinian water bodies, such as Lake Mulargia, whose preliminary analysis confirm its poor water quality condition during springtime, as well as the possibility to employ MERIS images despite its narrow morphology. Integration between field measures and RS data will proceed with the organization of suitable fieldworks of in-situ radiometric measures during cyanobacteria bloom. This information will be essential to provide a quantitative estimation of algal concentrations during the bloom.

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