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Optical remote sensing of lakes: an overview on Lake Maggiore

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ABSTRACT

*Optical satellite remote sensing represents an opportunity to integrate traditional methods for assessing water quality of lakes: strengths of remote sensing methods are the good spatial and temporal coverage, the possibility to monitor many lakes simultaneously and the reduced costs. In this work we present an overview of optical remote sensing techniques applied to lake water monitoring. Then, examples of applications focused on Lake Maggiore, the second largest lake in Italy are discussed by presenting the temporal trend of chlorophyll-a (chl-a), suspended particulate matter (SPM), coloured dissolved organic matter (CDOM) and the z90 signal depth (the latter indicating the water depth from which 90% of the reflected light comes from) as estimated from the images acquired by the Medium Resolution Imaging Spectrometer (MERIS) in the pelagic area of the lake from 2003 to 2011. Concerning the chl-a trend, the results are in agreement with the concentration values measured during field surveys, confirming the good status of Lake Maggiore, although occasional events of water deterioration were observed (*e.g.*, an average increase of chl-a concentration, with a decrease of transparency, as a consequence of an anomalous phytoplankton occurred in summer 2011). A series of MERIS-derived maps (summer period 2011) of the z90 signal are also analysed in order to show the spatial variability of lake waters, which on average were clearer in the central pelagic zones. We expect that the recently launched (*e.g.*, *Landsat-8) and the future satellite missions (*e.g.*, *Sentinel-3) carrying sensors with improved spectral and spatial resolution are going to lead to a larger use of remote sensing for the assessment and monitoring of water quality parameters, by also allowing further applications (*e.g.*, *classification of phytoplankton functional types) to be developed.*

Key words: Earth observation, MERIS, lakes, water quality, surface temperature.

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INTRODUCTION

In 1978, UNESCO estimated the area of the world's lakes to be 2,058,700 km^2, or about 1.4% of the Earth's total land area (Durand *et al*., 1999). In Europe, lakes cover an area of over 200,000 km^2 and about 500.000 lakes are larger than 0.01 km^2 and 106 lakes exceed an extent of 100 km^2. In some countries (*e.g*., Finland, The Netherlands) over 9% of the total land area is covered by lakes. Lakes and reservoirs contain over 98% of the European fresh water volume. In Italy there are more than 2000 lakes, of which 389 are freshwater (natural, enlarged natural and reservoirs) and 104 are coastal with brackish water, excluding lagoons. The most important Italian lacustrine region is located in Northern Italy and includes the deep subalpine lakes and some small-medium lakes; these lakes represent more than 80% of the total Italian lacustrine volume (Salmaso and Mosello, 2010).

Lake water is an essential renewable resource for mankind and the environment; it plays a key role in the European and world wide economy since it is exploited for civil (drinking water supply, irrigation, transportation), industrial (processing and cooling, energy production, fishery) and recreational purposes. Lakes constitute an environment for ecosystem (flora and fauna), tourism, bathing, intake of drinking water, and aquaculture. Due to the increasing demand for fresh water, the effect of climate change (global warming) and the anthropogenic pressure on natural resources, water quality of lakes is worldwide in danger (Brönmark and Hansson, 2002). Moreover, the nutrient loads coming from the basin are responsible for eutrophication in inland water systems, which already affects a significant number of lakes and reservoirs across the whole of Europe. Eutrophication can make these water bodies unsuitable for human use, thus causing serious problems for public water supply (Schindler, 2006). For this reason, the European Commission (EC) has adopted the Water Framework Directive (WFD) (European Commission, 2000), which defines water quality categories as well as the parameters that should be monitored for an appropriate assignment of each water body to its correct quality category. The WFD applies to all countries of the European Union and its main goals are i) to achieve sustainable management, ii) to maintain ecosystem functioning (including dependent wetlands and terrestrial ecosystems) and iii) to reach good ecological status of inland waters. Monitoring is an essential part of the implementation of the WFD, which forces the member states to monitor natural and artificial lakes with a surface area greater than 0.5 km^2 and requires lakes to be managed at catchment scale, rather than according to geographical or political boundaries (Premazzi *et al*., 2003).

Traditionally lake water quality has been monitored by *in situ* data collection and laboratory analyses, which can be very expensive (Harrington and Schiebe, 1992) and time consuming when large areas have to be monitored frequently during the season. For this reason, remote sensing is a strategic tool for assessing and monitoring the quality of lakes waters since it allows frequent surveys over large areas; thus providing data in a cost-effective way for a variety of studies which need multi -scale -temporal analyses (Coppin *et al.*, 2004; Chen *et al.*, 2007). In particular, the strength of remote sensing methods for lake monitoring is the good spatial and temporal coverage and the possibility to monitor several lakes simultaneously as also stated by Salmaso and Mosello (2010) who, in their review article, draw the conclusion that in limnological applications/studies synoptic analyses at a macro-regional scale are mandatory.

The term *remote sensing* refers to the numerous techniques which allow monitoring from distance (non-contact) and it includes data acquired by satellite and airborne active and passive sensors. Compared to airborne sensors, satellite sensors certainly offer a systematic acquisition of data which are routinely processed and archived thus making data available to the researchers in a very cost-effective way. The archives can be accessed easily and an increasing number of space agencies are changing their policies to make data available at no cost. Moreover, technological development led in the recent decades to building satellite sensors with improved geometrical and radiometric characteristics which provide data with very high spatial and spectral resolution. Airborne sensors, although they offer very high spatial resolution and ad-hoc acquisitions at the optimal time for monitoring (*e.g*., during the occurrence of the event of interest) can be very expensive and they often represent a one-time acquisition. Passive sensors measure the radiation as reflectance from the Earth surface in the visible/near infrared/thermal domain of the electromagnetic spectrum. In contrast, radar systems are active instruments that transmit a coherent signal into the target and measure the backscatter signal (Zhang *et al.*, 2003). A radar signal does not penetrate significantly into the water hence the information that can be derived from these measurements can be limited to water surface characteristics (waves and ripples, material on the surface, permittivity). However, radar systems can be used as complementary information to data acquired by optical (*i.e*., passive) sensors, an innovative possibility to improve the understanding of algal bloom development (Adamo *et al*., 2013).

In this work we present optical remote sensing techniques applied to lake water monitoring by describing the physical basis for using remote sensing, the most common optical sensors used for this type of application and some examples of applications focused on Lake Maggiore, the second largest lake in Italy.

OPTICAL REMOTE SENSING

The major factors which can influence the quality of inland water bodies (excluding the aquatic macro-fauna) are: suspended sediments (turbidity), phytoplankton and cyanobacteria (*i.e*., chlorophylls, carotenoids), dissolved organic matter (DOM), organic and inorganic nutrients, pesticides, metals, thermal releases, macrophytic algae, pathogens, and oils. With the exception of chemicals and pathogens, the above mentioned factors affect the optical and/or thermal properties of waters thus directly changing the signal acquired by optical sensors over water bodies. For this reason they are also called optically active parameters. On the contrary, chemicals and pathogens can only be inferred indirectly from measurements of other water quality parameters affected by their presence.

The parameters which can be directly quantified using remote sensing techniques are the following:

- *suspended particulate matter (SPM),* which is placed in suspension by wind-wave stirring of shallow waters and can be a tracer for inflowing pollutants (Eleveld, 2012);
- *phytoplankton and cyanobacteria pigments mainly as chlorophyll-a (chl-a) or phycocyanin (PC*), that can be used to indicate the trophic level, to evaluate the presence of potentially toxic algal blooms and as a proxy of phytoplankton biomass (Randolf *et al*., 2008; Ruiz-Verdù *et al*., 2008);
- *coloured DOM (CDOM),* commonly called yellow substances, whose might indicate the presence of either fulvic or humic acids; CDOM is also investigated because of its role in protecting aquatic biota from ultraviolet solar radiation and its influence on specifically heterotrophic bacterial productivity in the water column, indicative of the shift from net autotrophy to net heterotrophy (Kutser *et al.,* 2005);
- *the spectral attenuation coefficient (Kd),* which is theoretically inversely related to the depth of the photic zone (Kratzer *et al.*, 2003; Pierson *et al*., 2008).

Usually, the assessment of the water optically active parameters relies on the knowledge of the behaviour of light in waters as affected by these light-attenuating constituents. The molecular scattering of pure water follows an approximately parabolic trend with higher values at short (ultraviolet) wavelengths, while the absorption is highest in the red-infrared (Morel, 1974). The absorption of CDOM decreases exponentially with increasing wavelengths while it has negligible backscattering (Kirk,

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1994). The particulate constituents that attenuate incoming light include suspended sediments (both organic and inorganic) and phytoplankton (Morel and Prieur, 1977; Dall'Olmo and Gitelson, 2006), quantified by the main photosynthetic pigment, chl-a but also by accessory pigments as PC (Simis *et al*., 2007). Light scattering by suspended sediments strongly depends on the particles size, shape, and composition while absorption by mineral particulates is usually low (Woźniak and Stramski, 2004). The organic fraction of suspended sediments (Suspend particulate organic matter, SPOM) and phytoplankton both absorb and scatter light appreciably. The spectral absorption of SPOM is similar to that of CDOM and contrasts with absorption by phytoplankton, which has two distinct peaks at approximately 440 nm and 675 nm (Bukata *et al.*, 1995; Babin *et al*., 2003). The inorganic fraction of suspended sediments (Suspend particulate inorganic matter, SPIM) scatters light significantly while its absorption is usually negligible (Strömbeck and Pierson, 2001). Overall, the absorption and back-scattering of light by the above mentioned components of water influence the shape and the magnitude of the water leaving reflectance (Albert and Mobley, 2003), which is the information that can be retrieved by remote sensing sensors.

Fig. 1 shows the water reflectance whose shape and magnitude reflects the optical properties of the medium

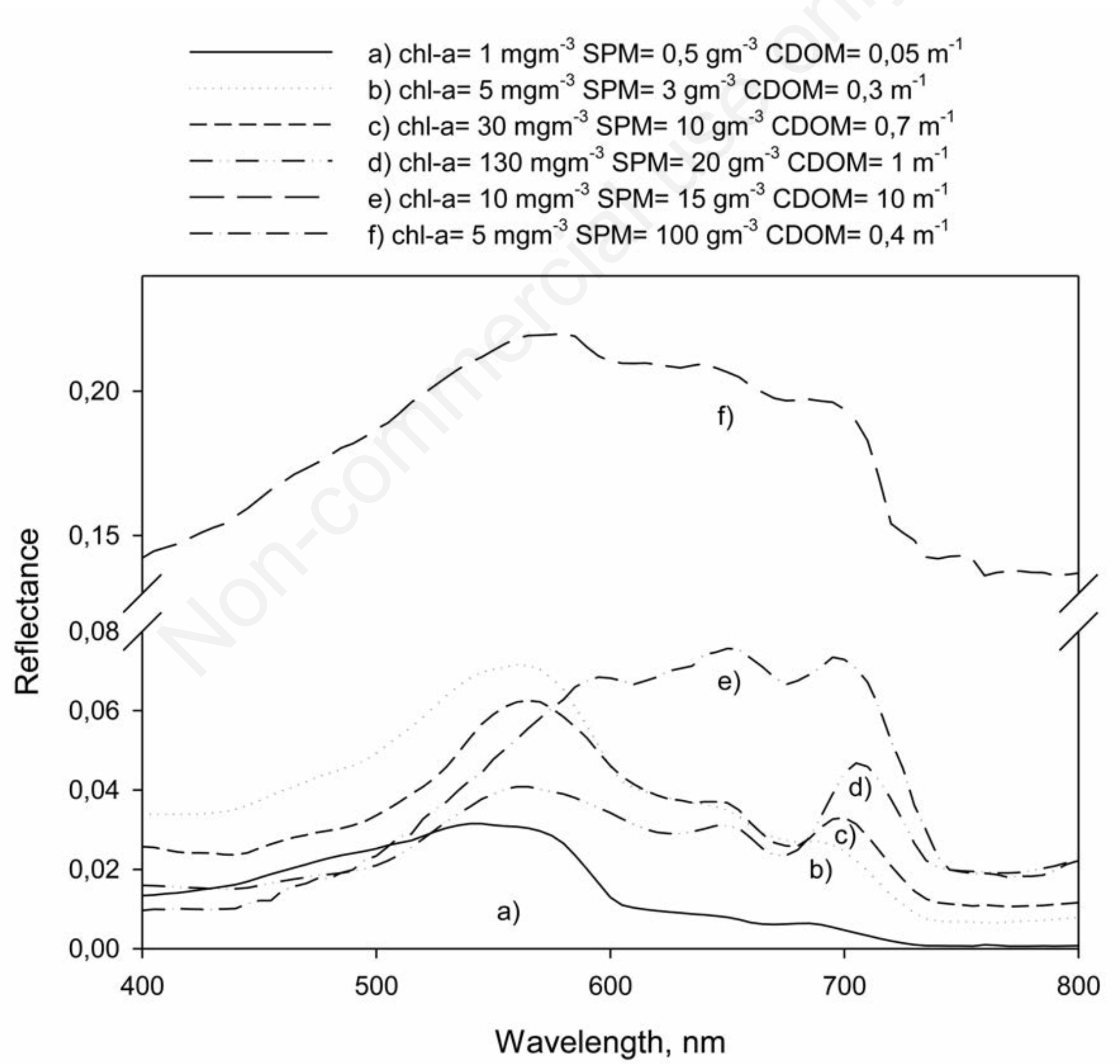

Fig. 1. Water reflectance spectra (dimensionless) for various concentrations of water quality parameters measured in different lakes: a) Lake Garda, b) Lake Iseo, c) Lake Trasimeno, d) Lakes of Mantua (those located in Italy), e) Lake Vänern (Sweden), f) Lake Neusiedl (Austria, Hungary). These data have been collected during several campaigns distributed over several years and typically carried out in summertime.

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with respect to absorption and/or backscattering of downwelling light. The spectra have been derived from *in situ* measurements we performed in different lakes: Lake Garda (Italy), characterised by clear, low backscattering waters, hence generating low water reflectance (Fig. 1a). The spectra measured in Iseo (Fig. 1b), Trasimeno (Fig.1c) Mantua Lakes (Fig. 1d) – those in Italy – are characterise by a peak around 700 nm, whose magnitude increases with increasing chl-a concentrations because an enhanced particulate scattering visible outside the pigment absorption areas (around 680 nm) (Gitelson *et al*. 2008). The spectrum taken near the tributary of Lake Vänern (Sweden) (Fig. 1e) is typical of those taken in CDOM-rich waters where CDOM absorption lowers reflectance at short wavelengths (Kutser *et al*., 2005; Koponen *et al*., 2007), Finally, Lake Neusiedl (Austria, Hungary) (Fig. 1f), characterised by very turbid waters (SPM=100 gm^{-3}), hence producing an high backscattering of downwelling light, hence generating high water reflectance (Bukata *et al*., 1995).

Besides being useful for assessing the concentration of constituents suspended/dissolved in water, remote sensing has been proved to be able to map oils (Adamo *et al*., 2009), cyanobacteria scum (Matthews *et al.*, 2012), floating vegetation (Hunter *et al.*, 2010), hence whatever is floating on the water surface which can be consequence of unusual events (*e.g*., oil-spill, massive blooms of cyanobacteria). These events have relevant impacts on the landscape (*e.g.,* dead algae washed onto the beaches must be physically removed in a prompt fashion, and represents an economic burden to local management) hence monitoring tools are needed for frequent monitoring during and after the event. In case of optically shallow waters, those where the bottom is visible from the water surface and measurably influences the water leaving radiance, remote sensing provides essential information in the form of maps of bathymetry and bottom properties (*e.g*., submersed macrophytes, sand, macroalgae and coral reefs), as needed for science and resource management (Green *et al.,* 2000; Dekker *et al.,* 2011). Finally, remote sensing provides information on water temperature, which is one of the most important parameters determining ecological conditions in lakes, because it influences water chemistry as well as biological processes inside a lake (Horne and Glodman, 1994; Arnell *et al.*, 1996). Thermal infrared measurements of water surfaces have a long heritage (~30 years). They are derived from radiometric observations at wavelengths of ~3.7 μm and/or near 10 μm. Though the 3.7 μm channel is more sensitive to SST, it is primarily used only for night-time measurements because of relatively strong reflection of solar irradiation in this wavelength region, which contaminates the retrieved radiation. Thermal infrared remote sensing applied to freshwater ecosystems has aimed to map surface temperatures (Oesch *et al.*, 2008; Reinart and Reinhold, 2008; Crosman and Horel, 2009), bulk temperatures (Thiemann and Schiller, 2003), circulation surface (Schladow *et al.*, 2004) and to characterize upwelling events (Steissberg *et al.*, 2005).

OPTICAL REMOTE SENSING SENSORS

Matthews (2011) and Kutser (2009) have recently provided a detailed review of remote sensing instruments which can be used to assess water quality in inland and near-coastal waters. Overall, we can group the sensors based on their spatial resolution, which basically influences their exploitation depending on the lake size.

- High spatial resolution multi-spectral sensor such as IKONOS and Quickbird provide image data at about 4 m resolution with four bands ranging from blue to near-infrared wavelengths. These sensors have a revisiting time of about 3/5 days but, being commercial platforms, image acquisition is available only on-demand and costly. Their swath is about 15 km and they are able to collect strips for more than 100 km. They are typically designed for terrestrial applications and the radiometric performance (*e.g*., low signal to noise ratio) usually does not allow quantitative investigations of the water optical properties necessary to retrieve water quality parameters. Nevertheless, these sensors allow us to successfully carry out qualitative estimations of water quality (*e.g.,* more turbid *versus* more clear waters) and of the bottom substrates (*e.g.,* mapping of macrophytes) (Wolter *et al.*, 2005). This group of sensors has been recently enriched with WorldView-2 with improved spatial resolution (2 m) and an increased number of bands (8 bands) that could also increase the number of applications in this field.
- Medium spatial resolution multi-spectral sensor such as Advanced Land Imager (ALI) (30 m), Advanced Land Observation Satellite (ALOS) (10 m), SPOT-5 (10 m) and Landsat provide images in the visible and near-infrared wavelengths; compared to the higher spatial resolution sensors, these sensors are characterised by a higher radiometric performance which contributes to a more accurate assessment of the concentrations of quality parameters over water. Examples of use of medium spatial resolution sensors are: ALOS to map SPM concentrations in Himalayan lakes (Giardino *et al.*, 2010b), ALI to assess CDOM in boreal lakes (Kutser *et al.*, 2009), and SPOT to map total suspended sediments in the Southern Frisian lakes in the Netherlands (Dekker *et al.*, 2002). The Landsat data deserves to be described more in details due to the relevance of the Landsat mission, which represents the world's longest continuous collection of data at medium spatial resolution and with revisiting time of 16 days. The Landsat Thematic Mapper (TM) and Enhanced TM plus (ETM+) archive contains imagery since 1984 and although it was not designed for aquatic applications, researchers have at-

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tempted to test its capabilities since the archive is a valuable source of data for retrospective change analysis (Sass *et al.*, 2007). In the literature, we find numerous examples of applications of Landsat images for estimating and/or monitoring lake water and in particular water transparency (Stadelmann *et al.*, 2001; Olmanson *et al.*, 2008), phytoplankton concentration (Tyler *et al.*, 2006), SPM (Zhou *et al.*, 2006), CDOM (Brezonik *et al.*, 2005), blooms of cyanobacteria (Vincent *et al.*, 2004) and macrophyte (Albright and Ode, 2011). On May 30, 2013, data from the Landsat-8 satellite (launched on 11 February, 2013) became available allowing the continuance of studies on water quality of lakes (until now mainly accomplished with Landsat-5 and Landsat-7). Moreover, the Landsat spectral band available in the thermal infrared region (TIR) allowed the estimation of water surface temperature (Giardino *et al.*, 2001; Wloczyk *et al.*, 2006; Oesch *et al.*, 2008). Finally, the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor with a spatial resolution of 15 m in the visible and near-infrared bands and 90 m in the thermal infrared could be suitable for assessing water quality in lakes (Becker and Daw, 2005). Medium spatial resolution sensors also include the category of hyperspectral satellite sensors, which, compared to the multi-spectral sensors, are characterized by an increased number of bands with narrower bandwidths. The Compact High Resolution Imaging Spectrometer (CHRIS) sensor has 19 bands which are perfectly positioned for water-related applications, a spatial resolution of 18 m (swath width is about 14 km) and an image acquisition frequency of about 7 days. Data acquired by these sensors have, for example, been used by Domínguez-Gómez *et al.* (2011) for estimating chl-a in Spain. Hyperion has 220 bands between 0.4 and 2.5 μm, a spatial resolution of 30 m and an overpass time equivalent to the Landsat; these data have been exploited by Giardino *et al.* (2007b) to estimate chl-a and SPM over Lake Garda. The recently launched experimental Hyperspectral Imager for the Coastal Ocean (HICO) on board the International Space Station is designed specifically for monitoring the littoral coastal environment and has been acquiring imagery since 25 September 2009. HICO has a high signal-to-noise ratio and a ground resolution of 90 m, making it suitable for lakes (Corson *et al.,* 2008). Similar sensors are likely to be used increasingly in the future (*e.g.*, the Enmap Hyperspectral Imager scheduled for launch in 2017, *PRecursore IperSpettrale della Missione Applicativa* (PRISMA) by the Italian Space Agency, scheduled for launch in 2017).

- Coarse spatial resolution ocean-color sensors more suited to real-time operational and detailed parameter retrieval, such as Moderate Resolution Imaging Spectroradiometer (MODIS), Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Ocean Colour Monitor (OCM) and MEdium Resolution Imaging Spectrometer (MERIS), have high acquisition frequencies (every 1-2 days) and bands ideally centered at wavelengths which are suitable for the detection of water constituents. The spatial resolution of those satellites is, however, very coarse (usually only about 1 km) thus making these sensors suboptimal to map the spatial variability of lakes' water at local scale. MERIS with its spatial resolution of about 300 m therefore offers possibilities for improved lake and coastal remote sensing (Gons *et al.*, 2008; Odermatt *et al.*, 2010; Matthews *et al.*, 2010; Tarrant *et al.*, 2010; Giardino *et al.*, 2010a; Song *et al.*, 2013;). On the other hand MODIS allow us to map water surface temperature (Reinart and Reinhold, 2008) and, even if for few pixels, the temporal trend of surface temperature to be monitored (Giardino *et al.*, 2010a; Bresciani *et al.*, 2011b).

Airborne remote sensing is another technology which has been intensively used in water-related studies. The high performance of airborne imaging spectrometry (*e.g.*, AISA, CASI, MIVIS, HyMap, APEX) in terms of pixel size and number of channels (they are typically hyperspectral systems) make these sensors useful for a variety of user-oriented applications. For instance, airborne data have been used in algorithm development (Sterckx *et al.*, 2011; Keith *et al.*, 2012), for mapping of water quality in a single lake (Sugumaran *et al.*, 2007; Bresciani *et al.*, 2009) or a small group of lakes (Kallio *et al.*, 2001; Moses *et al.*, 2012) and for mapping macrophytes beds in the littoral zones (Giardino *et al.*, 2007a; Hunter *et al.*, 2010). Airborne campaigns can be timed to coincide with events such as blooms, tides, floods and other episodic events providing more flexibility than satellite sensors. Finally, the upcoming European Space Agency (ESA) satellite constellations Sentinel-2 and Sentinel-3 will provide unprecedented monitoring capabilities for inland waters thanks to the high overpass frequency of Sentinel-3 and the high spatial resolution of Sentinel-2. Sentinel-2 will deliver high-resolution optical images globally, providing enhanced continuity of Satellite Pour l'Observation de la Terre (SPOT) and Landsat-type data. It will carry an optical payload with visible, near infrared and shortwave infrared sensors comprising 13 spectral bands: 4 bands at 10 m, 6 bands at 20 m and 3 bands at 60 m spatial resolution, with a swath width of 290 km. The mission orbits at a mean altitude of approximately 800 km and, with the pair of satellites in operation, has a revisit time of five days at the equator (under cloud-free conditions) and 2-3 days at mid-latitudes.

The first satellite is planned to launch in 2014. The Sentinel-3 mission's main objective is to measure sea-surface topography, sea- and land-surface temperature and ocean- and land-surface colour. In particular, Sentinel-3 will carry the SLSTR (Sea and Land Surface Temperature Radiometer) with thermal bands at 1 km of resolution and the Ocean and Land Colour Instrument (OLCI) which is based on heritage from MERIS having 21 bands, compared to the 15 on MERIS and a resolution of 300 m over all surfaces.

THE LAKE MAGGIORE CASE STUDY

Lake Maggiore, the second largest Italian lake by surface and volume (212.5 km^2 and 37.5 km^3 respectively), underwent, as most lakes in Europe, an eutrophication process since the 1960s. Maximum total phosphorus (TP) was recorded at the end of the 70s, with a peak value close to 40 µg L^{-1} at winter mixing. Chlorophyll-a increased as well up to 6 µg L^{-1} as annual average in 1978. Detrimental effects on water quality were recorded earlier, such as phytoplankton blooms, some mentioned by Vittorio Tonolli in an unpublished letter in 1964 and others described by Ravera and Vollenweider a few years later (1968), as well as the increase of areal phytoplankton productivity, measured after mid-60s.

A reversal trend of phosphorus in-lake concentration started since the early 80s, as a result of activation of wastewater treatment plants; an action also supported by the Italian legislative efforts that in the same period have reduced the content in phosphates in detergents. A time-lag in response of plankton communities became thereafter evident, with a temporary un-coupling between phosphorus concentration and phytoplankton biomass. Response of plankton communities to oligotrophication after lake restoration included a gradual increase in the number of phytoplankton taxonomic units and in cell density along with a decrease of average cell size (Ruggiu *et al.*, 1998) as well as rearrangements in the functional structures of planktonic assemblages and changes of the trophic relationships (Manca and Ruggiu, 1998). During lake oligotrophication the role of climatic constraints became increasingly important: over a general increasing mean water temperature trend (Ambrosetti and Barbanti, 1999), the most recent studies pointed out the response of planktonic organisms to water temperature changes (Visconti *et al.*, 2008; Salmaso *et al.*, 2012), as well as modifications of the phytoplankton assemblage, including the recent unexpected cyanobacterial blooms driven by extreme climatic events (Bertoni *et al.*, 2007; Morabito *et al.*, 2012).

In the present oligotrophic condition of the lake, climatic drivers strongly control the biological dynamics: air temperature and wind during winter influence the extent of mixing and, therefore, the nutrient supply to productive layers (Salmaso and Mosello, 2010). Heavy rains can affect, through the increased runoff from the watershed, the in-lake nutrient concentration and the N:P ratio (Morabito *et al.*, 2012). The patterns and the time scales of ecosystem response to these meteo-climatic forcings are often difficult to analyze and predict through the usual limnological monitoring. High frequency observations, covering the whole surface of the lake, such as those allowed through remote sensing, would greatly improve our knowledge about the dynamics of physical, chemical and biological events related to meteorological and climatic forcing. Fig. 2 shows the Lake Maggiore case study as imaged by Landsat-8 sensor, which captured this almost-cloud free image on 13 May 2013, acquired only 2 months later the successful launch of the satellite. On the right we show also the related map obtained in the thermal infrared region which describe the spatial patter of surface lake temperature (not corrected for atmospheric effects). A gradient of temperature is noticeable across the lake, with warmest waters in the southern part.

In order to exploit remote sensing technologies intensive fieldwork activities were run in the whole lake. More than 12 days over 10 years of *in situ* measurements were performed to achieve a comprehensive dataset of concentrations of water quality parameters, inherent optical properties, both inherent and apparent, leading to the parameterisation of both semi-empirical and semi-analytical models ensuring the estimation of water quality parameters from remote sensing data (Gitelson *et al.*, 2008). Moreover, *in situ* data collected synchronously to image acquisitions can also used to perform the validation of remote-sensing inferred products (*e.g.*, water reflectance and concentration maps) as well as to calibrate radiometric measurements acquired by Earth Observation systems (*i.e.*, vicarious calibration). In particular, *in situ* water reflectance (R) measures have been gathered with the objective of characterizing the spatial and temporal variability of the optical properties of lake waters throughout all seasons. The measurements, which have been collected with a FieldSpec Analytical Spectral Device (ASD) Full Range Pro and Water Insight Spectrometer spectroradiometers (WISP-3) (Hommersom *et al.*, 2012), are shown in Fig. 3. The plots show the more than 60 water reflectance spectra collected in Lake Maggiore; the spectra are those typical of lakes with transparent water (the average Secchi disk depth range is 8-15 m) and low nutrient concentration (TP at mixing around 11 µg L^{-1}). Overall, the low reflectance suggest the presence of a small amount of SPM, the gentle slopes in the wavelength range 400-500 nm suggest low concentrations of both CDOM and chl-a. With respect to chl-a, the weak peak of reflectance in the 680-700 nm region it is also a consequence of small quantity of phytoplankton. Indeed, the latter region of the spectrum is used as a reference for quantifying chl-a concentration in meso-trophic lakes (Gitelson *et al.*, 2007). In Fig. 3, the bold line highlights the average spectrum derived from all the *in situ* radiometric

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measurements (grey lines); in the panels above are shown the spectra as obtained by resampling the *in situ* spectra over the bandwidth (central wavelength and band width) of the most common sensors which can be exploited for monitoring surface waters of Lake Maggiore. The resampled *in situ* spectra of Fig. 3 clearly show that the availability of satellite sensors with narrow bandwidth (*e.g.*, MERIS, HICO, and in the future Sentinel-3) is a key issue for representing properly the Lake Maggiore water reflectance. Then, about 250 images acquired by the MERIS sensor over the period 2003 to 2011 were acquired. These images, according to the method proposed by Odermatt *et al.* (2010) have been processed with the BEAM-VISAT software (Basic ERS & Envisat (A)ATSR and MERIS Toolboox VISualisation and Analysis; Fomferra and Brockmann, 2006). This tool implements routines for correcting radiometric noise (SMILE correction), adjacency effects (tool Improved Contrast between Ocean and Land by Santer and Schmechtig, 2000) and, with the Case-2 Regional (C2R) neural network processor (Doerffer and Schiller, 2008a, 2008b), for converting R values into values of optically active parameters (chl-a, SPM, CDOM) and transparency (z90 signal depth, which indicates the water depth from which 90% of the reflected light comes from). C2R applies a dedicated neural network based atmospheric correction and bio-optical modeling dedicated to water bodies characterized by high transparency and low trophic level.

Fig. 4 shows the temporal trend of the four optically active parameters as estimated from MERIS images in

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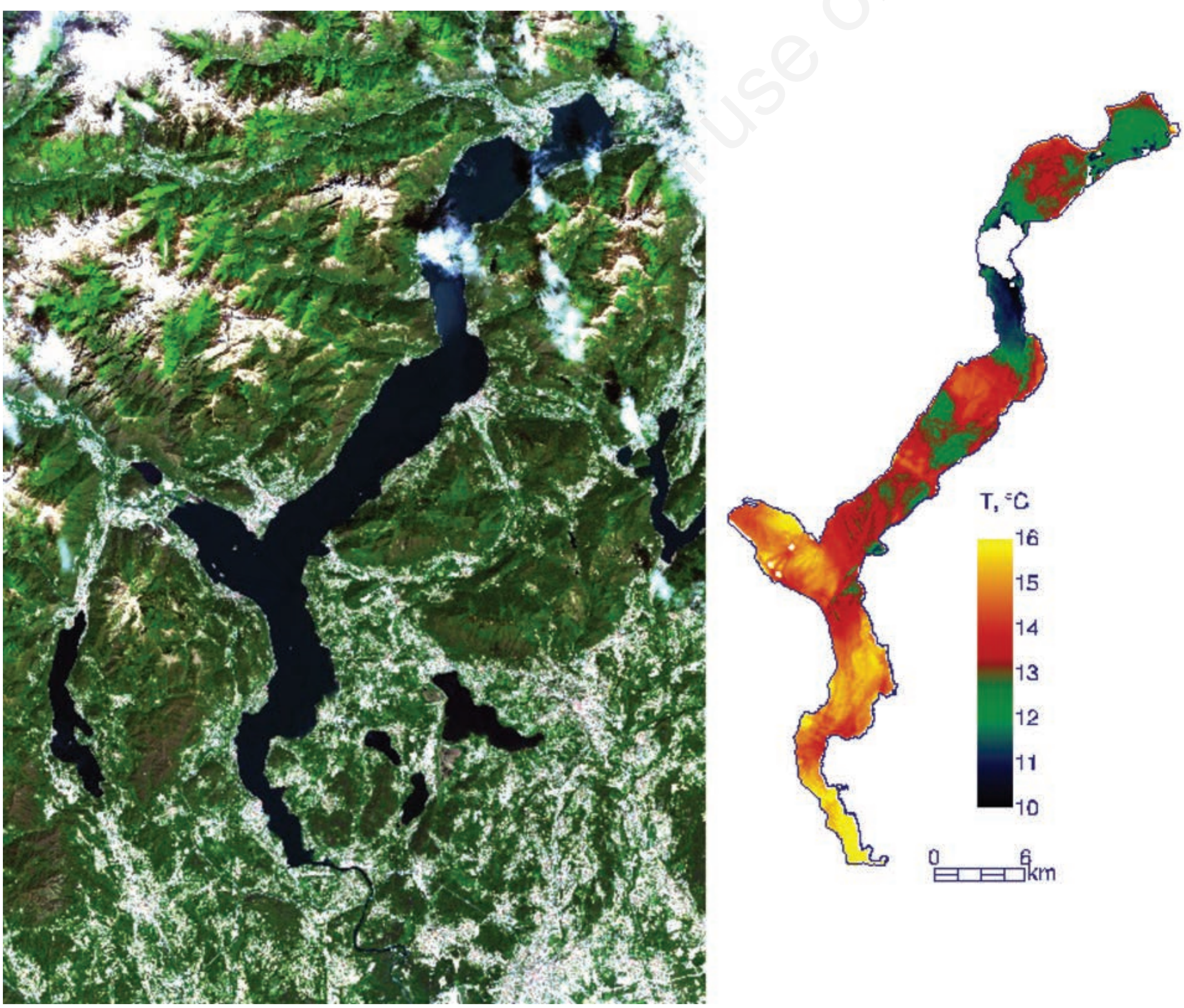

Fig. 2. Lake Maggiore, the case study used to show some of the capabilities of optical remote sensing techniques for lake water quality monitoring. On the left, a Landsat-8 scene of Lake Maggiore, acquired on 13 May 2013 just after the successful launch on 11 February 2013 of Landsat-8. On the right, lake surface temperatures (not corrected for the atmospheric effects).

correspondence with a point located in the pelagic area of the lake. In the same figures are also shown the annual average values as computed by applying the procedure suggested in the Italian official protocol for sampling phytoplankton in lakes, according to WFD (Buraschi *et al.*, 2008) which foresees sampling at six different times of the year. Yet the number of sampling during the year can be increased with the use of remote sensing acquisitions as suggested by Bresciani *et al.* (2011c), who could derive the six annual values by averaging more frequent measurements in order to better describe the variability of the characteristics of the lake water.

Concerning the chl-a trend, the results are in good agreements with the concentrations measured during the field surveys (Giardino *et al*., 2009). Apart the variability in the average values, dependent on the six samples chosen for its calculation, the seasonal fluctuations recorded by remote sensing mirror those measured in lake: some differences in the absolute values can be reasonably expected, due to the different methods used. The z90 values obtained from satellite data get along with in lake observations (Morabito *et al*., 2013) as concerns the seasonal fluctuations of phytoplankton. Both the average increase of chl-a concentration and the decrease of transparency in 2011 clearly reflect the effect of a massive *Mougetia* bloom which occurred during the summer months. With respect to CDOM, the multi-temporal data show an average value of 0.04 m^{-1}, denoting the low inflow and runoff of organic matter from the lake catchments. The SPM concentration trend is again quite low (average of 0.6 gm^{-3}) as a consequence of the reduce load of suspended sediments preset in these waters. As observed for z90 and chl-a, also CDOM and SPM in 2011 show an increase compared to previous years. Besides the multi-temporal analysis described above, images acquired by the MERIS sensor also allowed the description of the spatial variability of the same parameters to be achieved. As an example of this type of spatial analysis, we show in Fig. 5 a map of the water transparency derived at different times/dates during the summer period of the year 2011 (from June to the end of August). These maps clearly show the high spatial variability of the lake water properties thus confirming that a single/punctual measurement poorly represents the whole lake conditions.

The satellite observation allowed to reconstruct in detail the temporal evolution of the chlorophyte bloom that develops in June, reaches its peak around the middle of July, and affects the entire Lake Maggiore. Starting from the month of August there was a general increase in transparency, with the exception of some portions of the lake where transparency remained low (-3.5 m).

CONCLUSIONS AND PERSPECTIVES

We have presented an overview of the retrieval of water quality parameters in lake waters from earth observation data. The principle at the basis of remote sensing is to derive information on the optical properties and the concentration of substances from variations observed in water colour, hence in water reflectance.

Investigation of the use of satellite remote sensing for lake water monitoring, mainly employing passive instru-

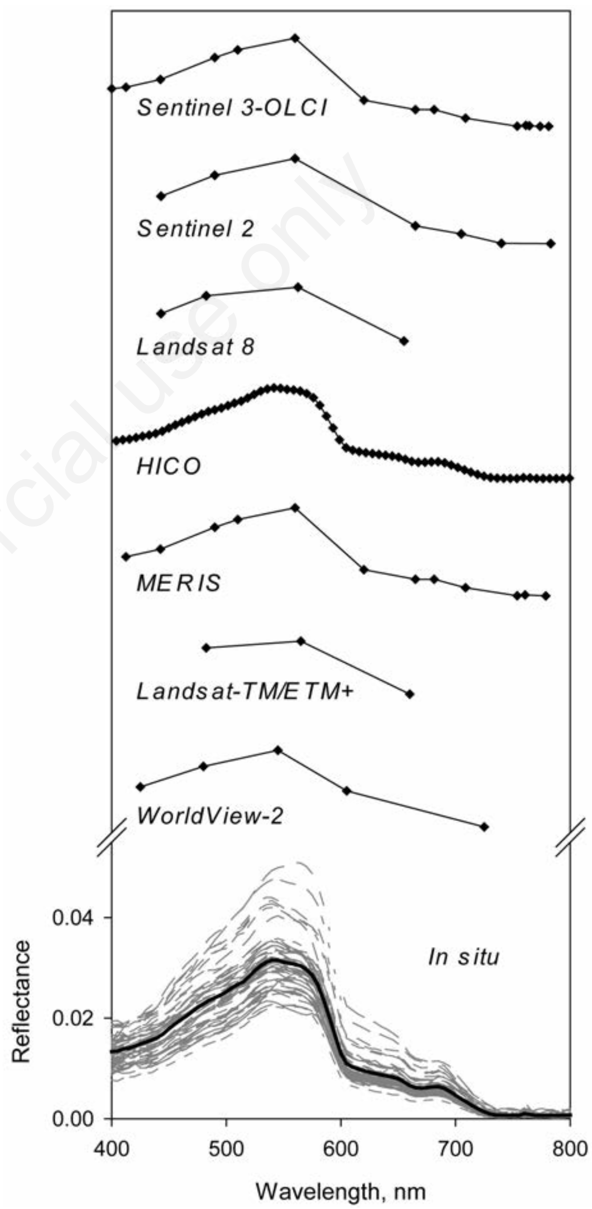

Fig. 3. Water reflectance spectra measured in Lake Maggiore in the last ten years (in bold, the mean value) from 400 to 800 nm. At the bottom, the spectra are plotted at the spectral resolution of the instruments (*i.e.*, ASD and WISP-3) used to collect them. The mean spectrum of the *in situ* observations is shown above, resampled to the spectral resolution of the most common sensors used to assess water quality of lakes from space.

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ments, was under way already in the 1980s, after the launch of the TM sensor onboard the Landsat satellites. In the 2000s, the use of satellite imagery for water quality monitoring has witnessed a significant step forward with the launch of several satellite instruments specifically designed for water applications such as MODIS and MERIS. The latter until 2012, when the Envisat mission ended following the unexpected loss of contact with the satellite, has provided images with an almost daily frequency and has several narrow channels optimised for assessing water quality. Yet their coarse spatial resolution (250 to 1000 m) limits their use only to large and medium-sized lakes. Over smaller lakes, satellite remote sensing has been possible with Landsat-type instruments (*e.g*., SPOT, ALOS and ALI), which typically have a 30 m spatial resolution. Higher resolution instruments, such as IKONOS, typically have a spatial resolution of 1-4 m and are more appropriate for mapping aquatic macrophytes since water quality can be assessed only qualitatively. Hyperspectral satellite instruments such as CHRIS PROBA, Hyperion and HICO, usually combining good spectral and spatial resolutions, have commonly been available only for research use. Airborne remote sensing can provide hyperspectral data with a high spatial resolution and it is suitable from small areas and few acquisitions since data become very expensive to perform continuous monitoring large areas. Future satellite missions, such as the ESA Sentinel-2 and Sentinel-3, will provide more functional data for assessing water quality in lakes than are currently available.

The case study of Lake Maggiore has shown how satellite data, in particular data gathered from MERIS, can be used to map the spatial and temporal variability of parameters describing the lake water status (*i.e*., chl-a, SPM, CDOM and z-90). Although MERIS data do not allow us

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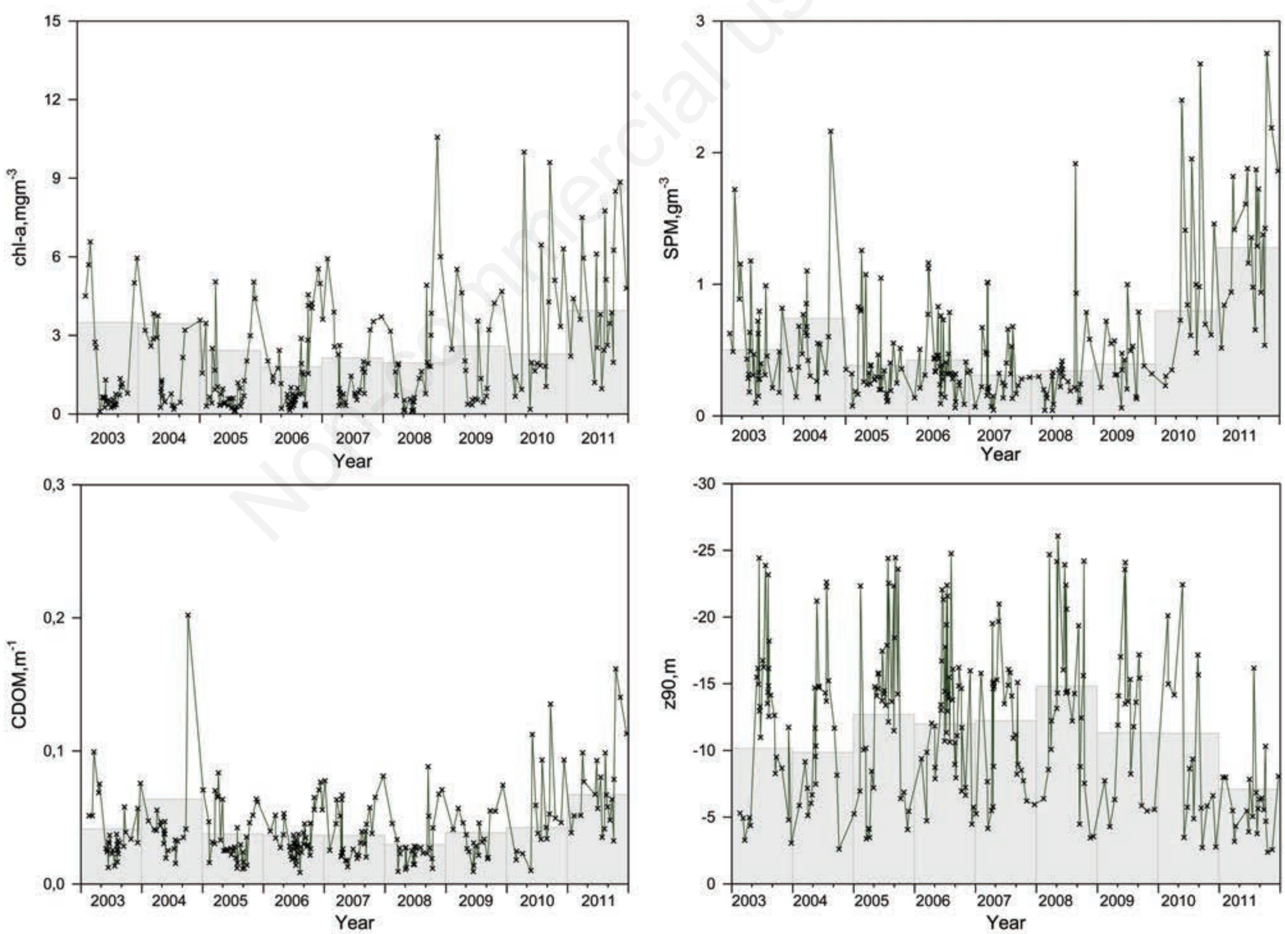

Fig. 4. Estimates of CDOM, chl-a, SPM and transparency (z90) derived from MERIS images for a point located in the pelagic area of Lake Maggiore (star markers) which describe the temporal trend of the parameters. CDOM, chl-a and SPM values are estimated in water depth from which 90% of the reflected light comes from (*i.e.*, z90). The bars represent the annual average obtained from the measurements that fall in the six periods identified by the WFD for monitoring lake water quality.

to characterize the entire water column, they provided 521,170 observations [with 521,170=250 (number of MERIS images) x 2100 (number of pixels of each image of Lake Maggiore)] which were exploited to estimate the quality parameters. The reliability of the results derived from satellite data depends on the effort put on the assessment of the accuracy of the quantitative measures derived (validation). Validation largely relies on fieldwork activities, which are required to collect data necessary to build procedures and models for turning satellite imagery into a quantitative and dynamic research instrument. The agreement between parameters estimated from remotely sensed data and those measured during the field campaigns suggests that satellite information, although excluding a large volume of the water column, can provide a valuable description of the biological activity taking place in the euphotic zone.

We conclude that in the recent years the application

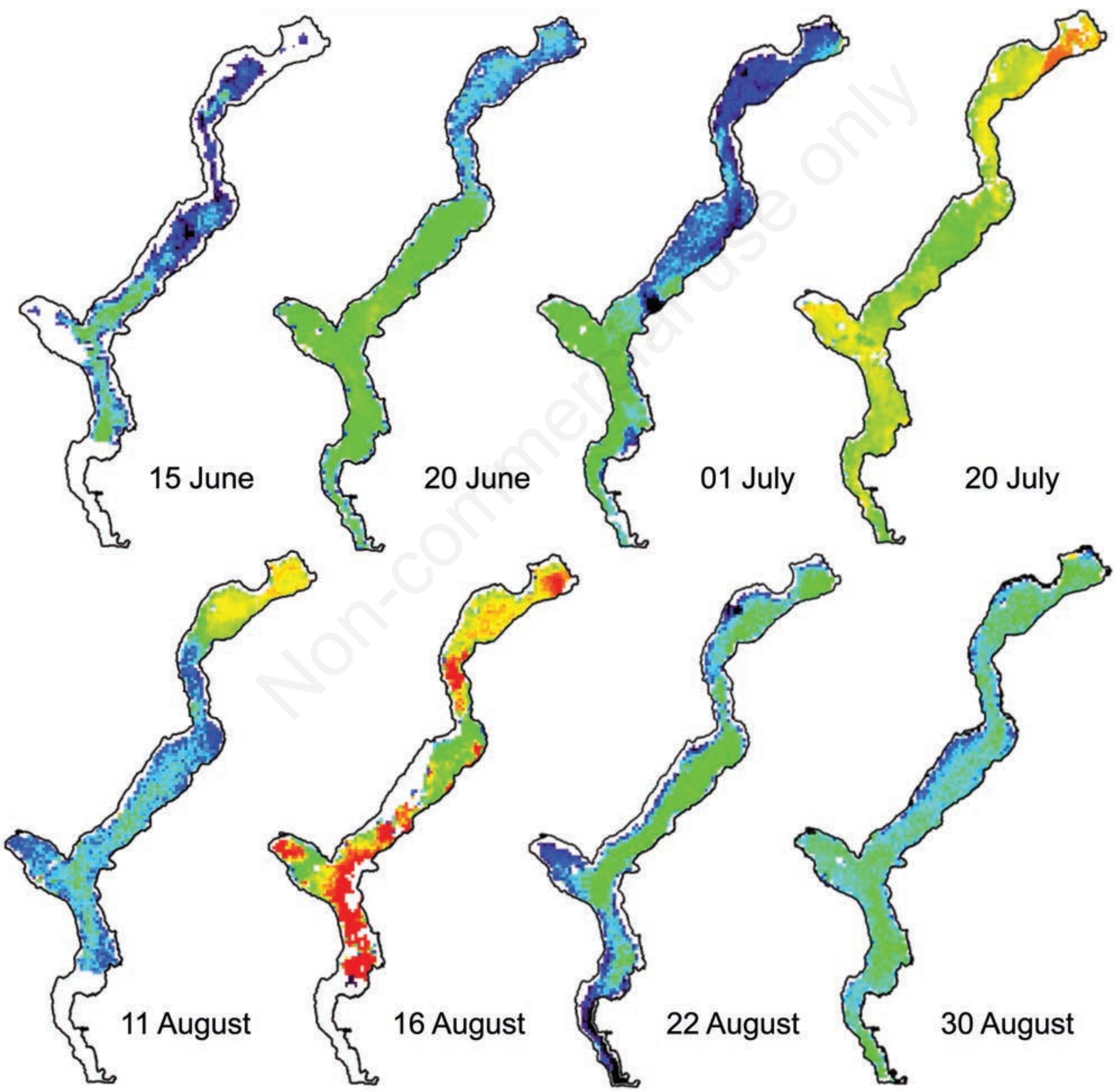

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Fig. 5. Maps of water transparency (z90) obtained from MERIS images acquired in different dates of the summer period of 2011. Maximum water transparency (darker pixels) is -10 m. Data are unavailable in case the algorithm fails due to different source of noise (*e.g.*, clouds, cloud shadows, adjacency effects).

studies focused on water quality monitoring have mainly been driven by the availability of MODIS and MERIS images and their specific capacity (mainly MERIS with its spatial resolution of 300 m therefore offers possibilities for improved lake remote sensing) in resolving issues related to turbid coastal waters. The water quality products obtained at a finer scale are instead feasible by using medium resolution sensors (*e.g*., Landsat and more recently WorldView-2) or airborne imaging spectrometry. We expect that the advent of Ocean Land Colour Instrument onboard ESA Sentinel-3 and of satellite hyperspectral mission (DLR-EnMap, ASI-PRISMA) will stimulate further EO-based programs for inland waters monitoring. Moreover, EO data could contribute to applications related to aquaculture, eutrophication monitoring according to relevant water quality classes (Koponen *et al.*, 2004) and for detecting starting/ending phase of cyanobacterial bloom (Hunter *et al.*, 2009; Bresciani *et al.*, 2011a; Hu *et al*., 2010), light penetration depth (*e.g*., for scuba diving) and to the develop products such as primary production (Bracher *et al.*, 2009) and partial pressure of CO_2 (Sobek *et al.*, 2003).

The possibility to provide large scale and high frequency data makes remote sensing a technique suitable for tracking phenomena at a temporal scale suitable to the development of the event. This is true, for example, for algal blooms, since the traditional limnological surveys are inadequate and expensive. Moreover, satellite data are key information for monitoring the effect of climate change. The indirect effects of meteorological conditions on algal productivity (*via* control of nutrient inputs) are probably of greater importance than the direct influence of temperature, usually taken as the most immediate proxy for climate change (Anderson, 2000). Climate-related factors, such as the amount and intensity of rainfall, affecting the basin runoff, can have major effects on the availability of nutrients for algae in lakes. Because the frequency and the severity of extreme events, such as heavy rainfalls, are expected to increase (Dokulil and Teubner, 2011) as a consequence of climate warming, climate-related eutrophication (Dokulil *et al.* 2009) could be expected to occur in many lakes, due to larger runoff, floods, increased soil erosion and wash out of nutrients. Limnology can benefit from techniques that allow the collection, in near real time, of large scale data, thus accomplishing a better understanding of the response of lacustrine ecosystem to peculiar meteorological events related to climate change.

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