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Application of Remote Sensing in Water Resource Management: The Case Study of Lake Trasimeno, Italy

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Abstract Satellite multi-sensor data were used to investigate the evolution in time and space of Lake Trasimeno, a shallow and turbid lake in central Italy. Large-swath MERIS and MODIS sensors were proposed for regular broad scale monitoring of water quality, having compared the retrieved chlorophyll-*a* (Chl-*a*) concentration, Secchi disk (SD) depth and surface water temperature with the 2005–2008 time-series of the in situ data. Although, in a shorter time span, also the MERIS-derived total suspended matter (TSM) matched the in situ data. MERIS-derived water quality products confirmed the meso-eutrophic conditions of Lake Trasimeno (average Chl-*a* = 8.5 mg/m^3) and the low levels of transparency (average SD = 1 m). A negative correlation found between water levels and Chl-*a* suggest the importance of maintaining water levels as close as possible to the hydrometric zero. A spatial analysis of TSM also reveals how small tributaries may affect the load of suspended solids in the southern part of the lake. Higher spatial resolution satellite images were exploited both to describe land use/cover transformation from 1978 to 2008 and to assess the recent changes in macrophyte colonisation patterns. Land cover change detection analysis results showed a decrease in cultivated areas starting from the early Nineties and the subsequent increase in unproductive terrain (bare land and pastures) and natural woods as well as the changing fragmentation of agricultural areas through time. A reduction in macrophyte beds from 2003 to 2008 was also observed. We expect the results of this study to support local water authorities in redrawing the management plan of Lake Trasimeno.

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1 Introduction

Lentic ecosystems are an inestimable renewable natural resource for biodiversity, which can be altered by human activities and climate change. Their ecological state vitally affects their value as drinking water reservoirs, for irrigation, fisheries or recreation and any effort is justified to improve the capabilities for monitoring and for preserving or improving these resources in the years to come. For this reason, the European Commission (EC) has adopted the Water Framework Directive (WFD; Directive 2000/60/EC 2000), which defines water quality categories as well as monitoring parameters for the appropriate assignment of these categories. The Directive applies to all countries of the European Union and main goals are to achieve sustainable management; to maintain the ecosystem's functioning (including dependent wetlands and terrestrial ecosystems); to reach good ecological status. Monitoring is an essential part of the implementation of the WFD; the WFD forces the Member states to monitor natural and artificial lakes with 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). The WFD also includes guidelines which define the categories of surface water quality and the required components and parameters. As some of these parameters can be determined by remote sensing with reasonable accuracy, satellite-related technologies may be integrated in the monitoring programs defined by the WFD. Satellite remote sensing is, in fact, an important source of information: it allows us to viewing larger water areas with greater temporal coverage than we can with point measurements and it is also very cost-effective. The strength of remote sensing techniques lies in their ability to provide both spatial and temporal views of surface water quality parameters that is typically not possible from in situ measurements. Remote sensing makes it possible to monitor the landscape effectively and efficiently, identifying water bodies with significant water quality problems, so that it can support developing lake management strategies (Baban 1999; Sharma and Anjaneyulu 1993).

When deterioration of lake water quality is caused by optically active substances, the effect of these changes can be observed with optical remote sensing instruments. In general, the parameters that have been identified in literature as detectable by modern satellites are: (1) green algae pigments mainly as chlorophyll-*a* (Chl-*a*; Lindell et al. 1999 and the reference herein); (2) total suspended matter (TSM; Dekker et al. 2001); (3) coloured dissolved organic matter, commonly called yellow substance (YS; Kutser et al. 2005); diffused attenuation as a measure for water transparency and Secchi disk depth (SD; Lee et al. 2005); the cyanobacterial pigment phycocyanin (Simis et al. 2005) and water surface temperature (ST; Oesch et al. 2005). Recent improvements in sensor design and advances in data analysis have made the prospect of the remote sensing of lake-water quality an emerging technology. In particular, the new developments in water quality algorithms have mainly been driven by the advent of moderate resolution imaging spectroradiometer (MODIS; Pozdnyakov et al. 2005; Wu et al. 2009) and of medium resolution imaging spectrometer (MERIS; Gons et al. 2008).

Besides water quality parameters, remote sensing enables us to investigate land cover dynamics and evolution; depending on the extent of target areas, a wide variety of satellite instruments, mostly coming from spatial medium resolution sensors (e.g. Landsat) are available for describing land cover at catchment scales. Remote sensing has successfully extracted and provided relevant information on catchment characteristics, e.g., assessing the change of land cover through time and mapping the extension and change in agricultural lands (Yu and Ng 2006) or assessing the crop-water demand (Casa et al. 2009).

Finally, remote sensing is a suitable technology for monitoring the extension of aquatic vegetation (Brando et al. 2009; Giardino et al. 2007), which often grows in shallow shore areas of lakes. Macrophytes are an important component of aquatic ecosystems and are used widely within the WFD to establish ecological quality. Monitoring their distribution with standard limnological approaches requires considerable time and costly field campaigns, usually performed on small areas, and for this reason such approaches are not representative of larger scale processes. Remote sensing is suitable for filling these gaps, due to its repeatability and synoptic spatial coverage.

The aim of this paper is to help improve environmental knowledge of and the reference conditions for Lake Trasimeno, a shallow and turbid lake in central Italy. On behalf of the Environmental Protection Agency of Umbria Region (ARPA Umbria), which is in charge of monitoring, the Italian Ministry of the Environment and Tevere River Basin Authority set up the Trasimeno Observatory in order to support the realisation of the environmental measures. Within its activities ARPA Umbria adopted a technical proposal concerning an integrated approach for Lake Trasimeno, a new ecological assessment derived from WFD, based also on remote sensing. Multi-sensor remote sensing images were used to investigate the evolution in time and space of water quality and land cover. Water quality parameters from 2005 to 2008 are derived from MERIS according to the most recent findings on algorithm development for lakes (Doerffer and Schiller 2008a, b) and from MODIS land-surface temperature products. The ability of these instruments to describe Lake Trasimeno water quality are evaluated by comparing satellite-derived water quality products (Chl-*a*, SD, TSM and ST) with in situ measurements. This study is complemented with mapping recent changes in land use/cover types in Lake Trasimeno basin from Landsat, ASTER and ALOS imagery. The higher spatial resolution of ASTER and ALOS allowed us to extend the classification to the macrophytes.

2 Materials and Methods

2.1 Study Area

Lake Trasimeno, a post-tectonic lake located in central Italy (43°06′ N; 12°07′ E), is the fourth largest Italian lake (124 km^2) belonging to the Tevere River Basin. The lake is almost round with a diameter of about 11 km, with three small islands and, in the south-eastern area, an open bay colonised by aquatic vegetation (Fig. 1). It is a close lake, with un-stratified and very shallow waters (average bottom depth 4.5 m; maximum depth 6 m). The lacustrine ecosystem is an area of exceptional value for

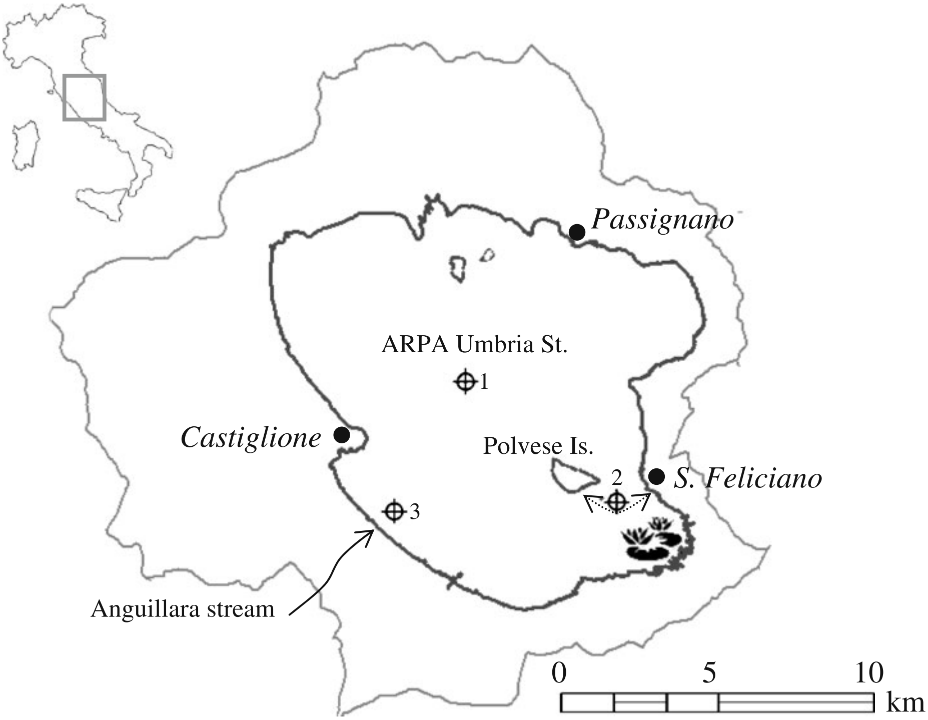

Fig. 1 The figure shows Lake Trasimeno location (central Italy) with its small catchment basin. The positions of the pelagic station sampled by ARPA Umbria (nr. 1) is indicated together with other two stations (i.e., nr. 2 and 3) used in this study to investigate water quality trends. The substrates in the southern-eastern bottom of the lake are colonised by wide extensions of macrophytes (indicated by an *icon*). The lake has no tributary but is fed by small streams (the one with the highest flows is Anguillara). The *dotted line with two arrows* indicate the ferry route from S. Feliciano to Polvese Island

its wealth of flora and fauna and its diversity of species and in 2000 it was declared a protected area (Directive 1979/409/CEE 1979).

Tourism, agriculture and livestock breeding are the most important activities in the Trasimeno area: cultivated lands cover about 70% of the catchment area of the lake, even if intensive agriculture with irrigational needs is only present in 28% of the area. The annual load of organic carbon (500t), nitrogen (550t) and phosphorus (30t), even if not consistent, negatively affects water quality (Cingolani et al. 2005a).

The lake shows from mesotrophic to eutrophic conditions if the classic evaluation is adopted (Vollenweider and Kerekes 1982), where principal critical parameters are phosphorous and chlorophyll-*a*, despite biological evidence of euthrophic–hypertrophic conditions. Ecological constraints are algal blooms of cyanobacteria, reduced conditions of sediments, modification of and decrease in fish community and plankton and recession of common reeds (Cingolani et al. 2007; Cecchetti and Lazzerini 2007; Natali 1993). In recent years, the lake has experienced serious difficulties to recover the ecological equilibrium as recommended by the WFD. Without natural outlets, only small water courses and runoffs have fed the lake. The regime is very variable depending on meteorological conditions but the current climatic evolution shows a significant reduction in water availability. In the early 1990s Trasimeno water levels started to diminish, reaching −180 cm with respect to the zero hydrometric in September 2008.

ARPA Umbria is the water authority in charge of monitoring Lake Trasimeno water quality. Relevant for this study are in situ measurements of Chl-*a* concentration (ISO 10260-E 1992), SD and bulk ST, sampled monthly or bi-weekly since 2002. The average values recorded by ARPA Umbria (at the station nr. 1 in Fig. 1) between 2002 and 2008 are the following: Chl-*a* = 8.5 mg/m^3, SD = 1.1 m and ST = 18°C. Moreover, in coincidence with our remote sensing activities, ARPA Umbria began to collect water samples for TSM; the average value, determined with the gravimetric method (Strömbeck and Pierson 2001) was 10.4 g/m^3.

2.2 Image Processing

To analyze the variety of elements of Lake Trasimeno (i.e., water quality, coastal vegetation, land use/land cover) different satellite sensors have been used (Table 1). The images were processed according to the object of investigation as described in the following paragraphs.

2.2.1 Surface Temperature from MODIS

MODIS surface temperature data (MOD11A), with 1-km nominal resolution, were obtained from the National Aeronautics and Space Administration Land Processes Distributed Active Archive Center. All available clear-sky MODIS Terra imagery between 2005 and 2008 were used, resulting in a total of 497 cloud-free images for subsequent analysis. The MOD11A swath files, subset and regridded to a 1-km equirectangular grid, and re-projected to the Gauss Boaga (Monte Mario) national plane coordinate system are directly used to evaluate the ST of Lake Trasimeno.

2.2.2 Water Quality Parameters from MERIS

MERIS FR top-of-atmosphere radiance level-1, 300-m nominal FR data were obtained from the ESA-Eolisa catalogue (v. 6.0.1). A selection of 118 clear-sky MERIS

Table 1 Summary of satellite data used in this study with their nominal spatial resolution. The number of images processed and time of acquisition are also indicated together with the purpose for which they have been investigated

Sensor (platform, space agency)	Spatial resolution	Temporal window	Number of images	Object of investigation
MERIS (Envisat-1, ESA)	300 m	2005–2008	118	Water quality (Chl-*a*, TSM, SD)
MODIS (Terra, NASA)	1.1 km	2005–2008	497	Water quality (ST)
TM (Landsat-5, NASA)	30 m	07/08/1988 18/07/1998	2	Land use/cover
MSS (Landsat-4, NASA)	80 m	22/05/1979	1	Land use/cover
AVNIR-2 (ALOS, ESA-JAXA)	10 m	08/07/2007 23/06/2008	2	Land use/cover, aquatic vegetation
ASTER (Terra, NASA)	15 m[a]	22/06/2003	1	Land use/cover, aquatic vegetation

[a]For the bands used in this study

images between 2005 and 2008 were used. Each year included about 20 scenes, save for the 2008, where the number of images (55) is almost twice the previous years because greater attention of our project activities was paid in 2008. The images were processed with the ESA Basic Envisat/ERS ATSR and MERIS (BEAM v. 3.6.1) toolbox (Brockmann Consult, Geesthacht, Germany). Level-1 data were corrected for adjacency effects using the Improved Contrast between Land and Ocean (ICOL) plug-in and then converted into water quality products. For such a purpose, three plug-in algorithms based on the MERIS Case-2 Core Module are available: Case-2 Regional (C2R), Boreal Lakes and Eutrophic Lakes (Doerffer and Schiller 2008a), all implementing a dedicated atmospheric correction (Doerffer and Schiller 2008b). For the purposes of this study the C2R processor was used because it is more suitable for describing the optical properties of Lake Trasimeno (Giardino et al. 2008). C2R's water constituent retrieval provides different products including Chl-*a*, TSM and YS, but also the minimum irradiance attenuation coefficient and the signal depth z_{90}, that was assumed to be comparable to SD depths. Image-derived products were then geo-located to the Gauss Boaga national plane coordinate system.

2.2.3 Land Use/Cover and Macrophytes

In order to study the recent changes in land use/cover types of the Lake Trasimeno basin, we used Landsat MultiSpectral Scanner (MSS)/Thematic Mapper (TM), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2) imagery, acquired between 1979 and 2008 (cf. Table 1). Remotely sensed multispectral images were acquired in summer seasons of 1979 (Landsat MSS), 1988 (Landsat TM), 1998 (Landsat TM), 2003 (Terra ASTER) and 2008 (ALOS AVNIR-2). Satellite data were preprocessed using radiometric normalization based on the selection of pseudo-invariant features and the transformation of linear regression. Only homologous spectral bands across the whole dataset were considered for further analysis, thus comprising the 3 bands of visible green wavelengths (0.52–0.60 μm), visible red wavelengths (0.63–0.69 μm) and near infrared wavelengths (0.76–0.89 μm).

Normalized data were subsequently corrected for atmospheric effects by subtracting dark pixels (Chavez 1988) and finally georeferenced and co-registered in the Gauss Boaga national plane coordinate system. From the multitemporal dataset a collection of samples covering seven land cover classes were extracted, each one for every date available. The seven cover classes were: water, woods on hills, woods in the plain, barren land (bare rock and pastures), bare soil (dark), bare soil (bright) and vegetated fields. The design of the decision tree classifier (Fig. 2) was based on spectral characteristics and normalized difference vegetation index (NDVI; Rouse et al. 1973) measures derived from satellite images in correspondence of those locations whose land cover was known. Further elements of the decision tree classifier were the ground elevation from SRTM-v2 DTM and the definition of the thresholds for binary discrimination within tree branches (Coppin et al. 2004). Using the CORINE Land Cover Maps of 1990 and 2000 as ancillary data from which to extract built up areas, the classified land cover maps for the five dates (from 1979 to 2008) were extracted, showing now a legend of eight classes (water, woods on hills, woods in the plain, barren land, bare soil [dark], bare soil [bright], vegetated fields, and urban).

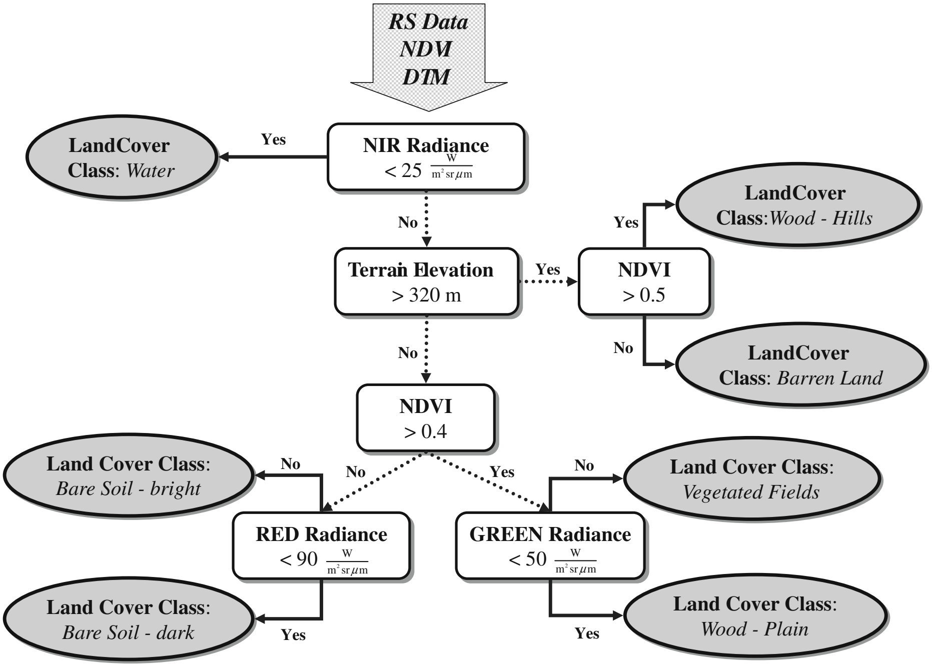

Fig. 2 Decision Tree binary classification schema adopted for multitemporal land cover mapping over the Trasimeno catchment basin

The next processing step focused on agricultural areas, in order to investigate the consequences of changes in the water quality of the lake. Only the agricultural features in the dataset were segmented according to Shapiro and Haralick (1985) in order to extract the agricultural parcels. Agricultural land fragmentation analysis was made by calculating the number of cultivated land parcels over each 1 × 1 km cell grid, for every scene in the dataset: 1979, 1988, 1998, 2003 and 2008.

The two images with the highest spatial resolution (i.e., AVNIR-2 and ASTER) were furthermore used to investigate recent changes in macrophyte patterns, comprising both helophyte (common reeds) and pleustophyte (floating and rooted vegetation). The normalised and georeferenced images were classified using the Maximum Likelihood classification algorithm, which was trained by an expert who selected the two aquatic vegetation classes by means of both photo interpretation and based on the vegetation map from Sinnassamy and Mauchamp (2001).

3 Results and Discussion

3.1 Monitoring Water Quality

For the long time validation of C2R Chl-*a* and SD products and of MODIS-derived surface temperatures, the in situ monitoring data collected in the lake centre (station nr. 1 in Fig. 1) by ARPA Umbria were used. Overall, a good agreement between in situ data and satellite-derived products is observed by considering that satellite data are produced independently by those in situ data and therefore two absolutely independent datasets (Fig. 3). We observed that MERIS-derived products agreed with in situ trends of Chl-*a*, despite a tendency of MERIS to underestimate the highest values of Chl-*a* both in summer 2005 and in summer 2008 (Fig. 3a). In order to explain this mismatch, it is necessary to add that both events were characterized by cyanobacterial blooms (Cingolani et al. 2007). The difficulty in evaluating MERIS with respect to in situ data when the observed phenomenon is characterized by a high degree of change and patchy structure, equally occurring in case of cyanobacterial blooms, had in fact already been discussed by Kutser (2004) on the occasion of cyanobacterial bloom in the Baltic Sea. The temporal mismatch between in situ and satellite measurements (usually hours versus seconds) as well as the scale differences (samples from point-like station versus measurements relative to an area 300 m × 300 m), both hinder the comparison between remote sensing and in situ measurements. Similarly to Chl-*a*, MERIS's ability to describe SD is very promising since MERIS can describe the temporal trends of water clarity (Fig. 3b). Although for a shorter time-series, satisfactory results were also found for TSM, since C2R estimates were comparable to in situ data (Fig. 3c). Finally, the agreement between MODIS and in situ ST measurements (Fig. 3d) is almost prefect, both at highest and lowest water temperatures.

Having demonstrated that remote sensing can monitor the Lake Trasimeno water quality parameters, we herewith present an analysis for its management. Chl-*a* values derived from MERIS are plotted against water levels (Fig. 4) and a negative correlation was found between the two quantities so that Chl-*a* increases when water levels decrease and *vice versa*. The statistics of the regression analysis between the two parameters show a value of the Pearson's correlation coefficient r of −0.48. Despite the low correlation the single-tailed Fisher test (p-value < 0.01) indicated

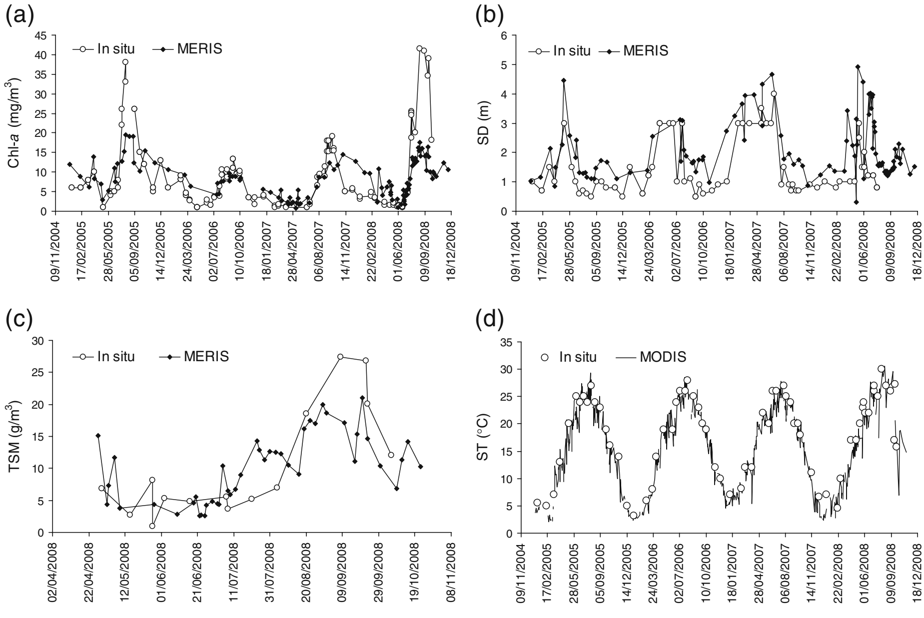

Fig. 3 2005–2008 time-series of in situ measurements and satellite estimate for three water quality parameters: **a** chlorophyll-*a*, **b** Secchi disk depths, **c** total suspended matter (for a shorter time-window) and **d** surface temperature

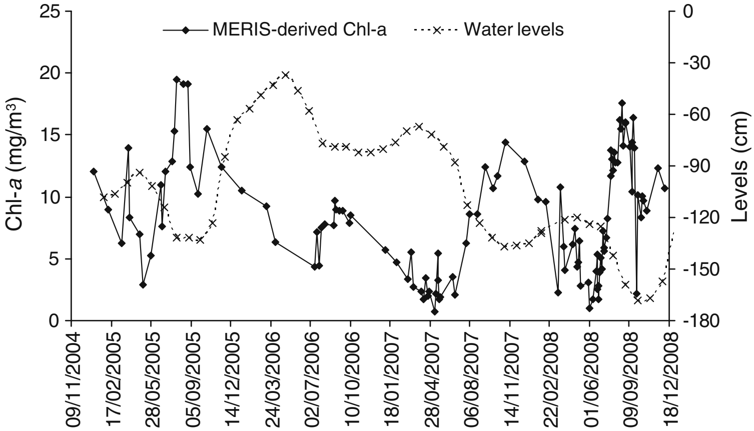

Fig. 4 Negative correlations (Pearson coefficient −0.48) between MERIS Chl-*a* estimates and water levels, which for the whole temporal range investigated in this study were lower than the hydrometric zero

that the relationship among the variables did not occur by chance. A reduction of water levels may therefore contribute to increase the trophic level of the lake. This is making it increasingly difficult to recover the ecological equilibrium and the good ecological status according to WFD.

The spatial variability of TSM was investigated by counting the number of times in which MERIS-derived TSM concentrations were higher than a predefined level in three different locations (Fig. 5), each of them identified with a 3 by 3 pixels window. The selected sites were the pelagic station sampled by ARPA Umbria (nr. 1

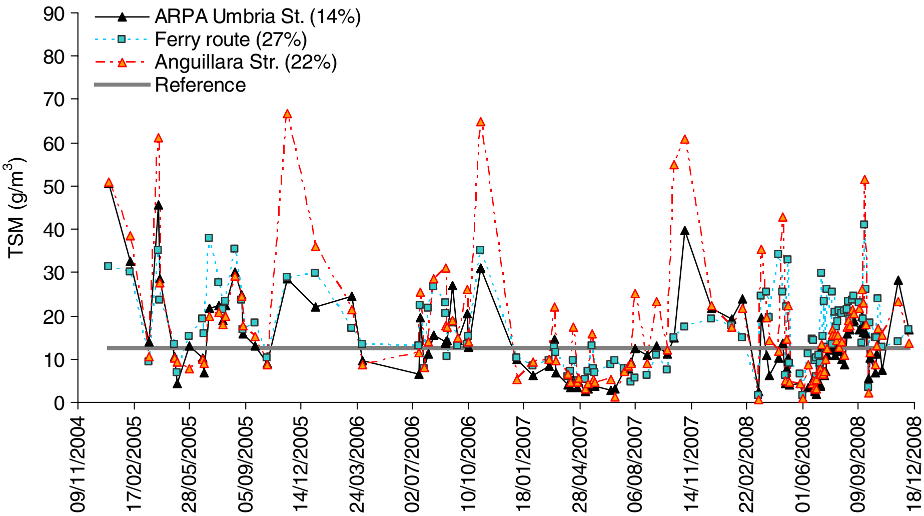

Fig. 5 The time series of the three locations (cf. Fig. 1) against the marked reference threshold of 18.2 g/m^3 (i.e., average plus standard deviation of TSM in ARPA Umbria station, from 2005–2008). The number of times (in percentage) in which the TSM concentrations are higher than the reference is indicated between brackets for each station

in Fig. 1), the ferry route from S. Feliciano to Polvese Island (nr. 2 in Fig. 1) and the area in front of Anguillara (nr. 3 in Fig. 1), where some small tributaries of Lake Trasimeno are located. The level used as a reference to make this analysis was 12.8 g/m^3 (i.e., the average value plus the standard deviation between 2005 and 2008, relative to the ARPA Umbria station). The area crossed by the ferry has the highest number of events (i.e., 27%, cf. Fig. 5) with high TSM concentrations. Below the ferry route the bottom of the lake is periodically dragged to allow the boats to cross; this re-suspends sediments favoured by wind-driven effects and by the absence of macrophytes that colonize the substrates near the channel and are removed by dredging activities. Another area distinct from the ARPA pelagic station is located in front of Anguillara, where small streams may transport significant loads of suspended solids (i.e., 22%, cf. Fig. 5) into the lake (Cingolani et al. 2005b).

3.2 Change Detection

The results derived from land cover classification of satellite data between 1979 and 2008 show the dynamics of landscape and environment changes over the Lake Trasimeno basin during the last 30 years (Table 2). Apart from the slight increase in urban areas, derived from CORINE Land Cover Maps of 1990 and 2000 only, and apart from the little variations in the Trasimeno lake area (due to seasonal variations and heterogeneity of acquisition dates for satellite images), the main point emerging from these data is the apparent decrement in cultivated areas (Agricultural class) starting from the early Nineties and the subsequent increment in unproductive terrain (bare land, pastures and natural woods land cover), composed of Barren Land and Woods (hills and plain) classes.

Agricultural land use, which amounted to 35% of the catchment areas in 1988, dropped to 31% as seen in the 2008 map, whereas unproductive terrain (barren land, pastures, and natural woods) show an increment from 23% in 1988 to 27% in 2008 (Table 2). A simple validation of remotely sensed derived land cover classification is done by comparing with areal data provided by local authorities and showing that cultivated fields in 1999 were estimated at a total of 107 km^2 over the whole basin (Boggia and Pennacchi 1999); by comparison, Agricultural land cover class terrain estimated from 1998 Landsat TM data amounts to 102 km^2, which represents a slight underestimation but nevertheless quite good accordance.

The maps (Fig. 6) resulting from fragmentation analysis show the spatial distribution of agricultural fragmentation over cultivated areas along the catchment area of

Table 2 Land cover/use change results in term of coverage percentage over the whole Trasimeno basin (total area 306 km^2), derived from remote sensing produced maps between 1979 and 2008

Class	MSS 1979	TM 1988	TM 1998	ASTER 2003	ALOS 2008
Urban[a]	2.76	2.76	2.87	2.87	2.87
Water	39.17	39.13	39.16	38.94	39.07
Agricultural[b]	34.66	34.85	33.25	32.78	30.87
Barren Land	7.25	9.05	7.03	7.50	4.91
Forest[c]	16.16	14.21	17.68	17.91	22.27

[a] CORINE 1990 and 2000 data

[b] Fusion of bare soil (dark), bare soil (bright) and vegetated fields classes

[c] Fusion of Woods on hills and Woods in the plain classes

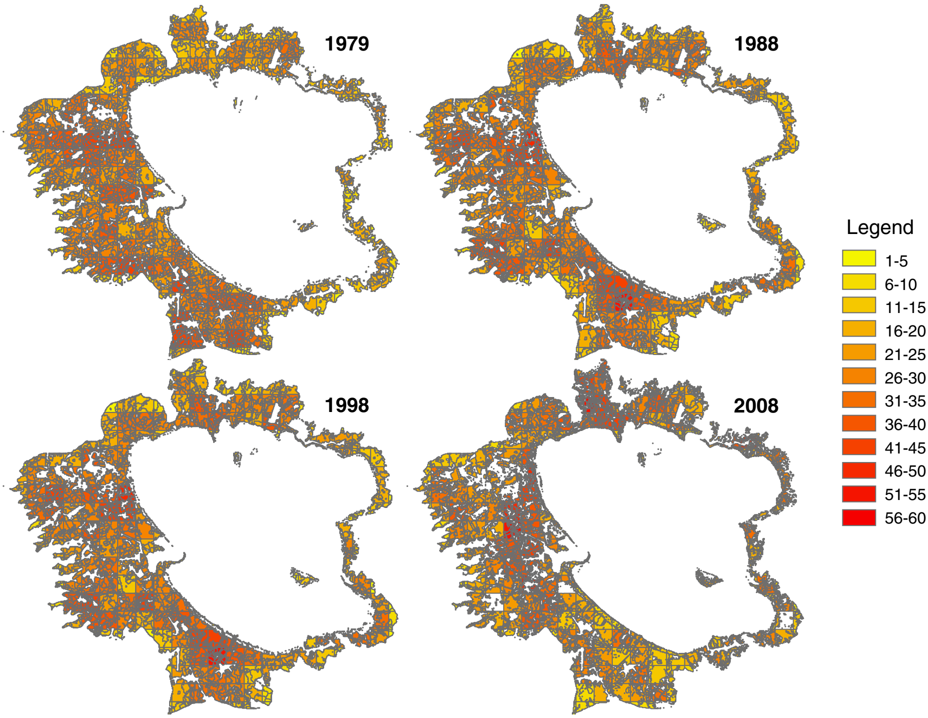

Fig. 6 Spatial distribution maps of agricultural fragmentation over cultivated areas along the catchment area of the lake, calculated as the number of segmented polygons falling into 1 × 1 km cells, covering the time range from 1979 to 2008

the lake. These maps are indicator of the agricultural use of the area and could be used to estimate the agricultural pressure on the Trasimeno lake coastal zone and water quality. Those data depict the local status of agricultural parcel fragmentation, where a high number of polygons included in a 1 km × 1 km cell points to high fragmentation, which indicates small parcels dedicated to homogeneous crops, while a low number of polygons stands for low fragmentation and bigger size of agricultural parcels.

The evolution of fragmentation through time (Table 3) shows the decreasing fragmentation as a symptom of homogenization of cultures and the increasing fragmentation as a symptom of agricultural partitioning and differentiation. Those data show a slight pattern of increasing fragmentation along the south-western shores of the lake, which are also the areas with the highest concentration of agriculture-related activities over the Trasimeno basin.

The results derived from ASTER and ALOS images acquired in 2008 and 2003, respectively showed a slight decrease in common reed areas, which have changed from covering about 3.9 km^2 to 3.7 km^2. These estimations were in agreement with Cecchetti et al. (2005) who estimated at 3.56 km^2 the extension of common reeds in the study area. The recent slight reduction of common reed areas was in agreement with the decrease of their vegetation vigour, derived from remote sensing measurements of NDVI observed over the same targets by Bresciani et al. (2009).

Table 3 Agricultural areas fragmentation status and dynamics over cultivated areas in the Trasimeno basin, expressed as the percentage relative frequency of 1 km × 1 km cells containing an increasing number of segmented polygons

Polygons in 1 km^2	Relative frequency (in %)				
	1979	1988	1998	2003	2008
1–5	14.7	15.0	15.9	15.4	14.1
6–10	15.6	11.9	12.3	7.0	13.2
11–15	13.8	13.2	14.1	14.1	12.3
16–20	11.2	13.7	13.2	11.9	13.7
21–25	11.2	8.8	17.6	9.3	15.0
26–30	14.7	16.3	14.5	16.3	11.9
31–35	8.5	10.6	6.2	14.1	7.9
36–40	6.7	6.6	4.4	7.0	6.6
41–45	3.6	3.1	1.3	2.2	2.6
46–50	0.0	0.4	0.4	1.8	1.8
51–55	0.0	0.4	0.0	0.4	0.9
56–60	0.0	0.0	0.0	0.4	0.0

Unlike common reeds, the temporal comparison between 2003 and 2008 revealed a sharp decrease in areas occupied by the pleustophyte. The substrates colonised by submerged vegetation passed from 20 km^2 to 16.5 km^2, with the most significant loss in the southern area of Polvese Island (cf. Fig. 1), where *Najas* and *Chara* species are dominant (Cecchetti and Lazzerini 2007).

4 Conclusions

The ability of multi-source remote sensing data to assist the management of Lake Trasimeno was demonstrated in this study. Different satellite sensors were considered to support ARPA Umbria in refining the environmental knowledge of Lake Trasimeno.

High revisiting time sensors such as MERIS and MODIS were used for coarse scale regular monitoring of water quality (e.g., Chl-*a*, SD, ST). The image processing methods of MERIS and MODIS are scene-independent and may provide Lake Trasimeno water authorities with an alternative method for water quality monitoring. The great variability of optical properties hampers in situ measurements with the necessary temporal and spatial resolution. MERIS time-series analysis showed that Chl-*a* concentration increases when water levels go down, suggesting the need for political strategies to reach a good quality status according to WFD objectives. The plan to increase water levels by external derived waters to the lake with an irrigation/drainage network or an artificial inlet in the north-western part of the lake seems reasonable, if ecologically planned. The patchy spatial distribution of TSM also reveals the resuspension phenomena of sediments produced by wind actions, an effect which may affect many shallow lakes with sandy bottoms but which in Lake Trasimeno seems partially conditioned by human activities for navigation requirements. Also at the small inlets in the southern part of the basin the TSM loads are higher than in the pelagic areas. Although MODIS measures the surface temperatures only, in the shallow and un-stratified Lake Trasimeno, they are an important source of information due to the influence of water temperatures both on chemical oxygen demand and biological oxygen demand (Gilbridea et al. 2006; Wetzel 1983).

Higher spatial resolution satellites, such as Landsat or ASTER, were used for intermediate/fine scale change detection studies on aquatic vegetation and surrounding lands. A decrement in agricultural land cover in favour of barren lands and natural woods, as frequently observed in mountainous areas of central and southern Italy during the last decades (Galante et al. 2009), was observed. A segmentation analysis showed a light increase in the agricultural parcels located in the south-west part of the basin, a phenomenon to be taken into account when managing the impact of agriculture (fertilizers, water consumption, etc.) on the lake. Although minor, the decrease in areas covered by aquatic vegetations from 2003 to 2008, suggests implementing a management plan in order to prevent the loss of these valuable habitats. It could be carried out on an annual basis as a function of local meteorological and ecological conditions and cannot be excluded by the monitoring of water quality because Bresciani et al. (2009) already observed how in situ measurements of leaf area indexes were lower for common reeds facing the waters than for those not directly in contact with the lake. Similarly, the sharp decrease in substrates colonised by submerged macrophytes indicated the need for concrete actions for their preservation, since they are extremely valuable components of the aquatic ecosystem as they have well recognised ecological functions (Jeppesen et al. 1998). In particular for Lake Trasimeno, submerged macrophytes hinder the suspended sediment re-suspension and are a vital habitat for fish.

The results presented in this study provided feedback with which ARPA Umbria and Regione Umbria are defining a conceptual model for the Lake Trasimeno basin management plan. We also expect remote sensing to be integrated in ARPA Umbria's monitoring plans because financial resources at the state and local level are insufficient to assess water quality in a timely fashion using conventional methods.

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References

Baban SMJ (1999) Use of remote sensing and geographical information systems in developing lake management strategies. Hydrobiol 395/396:211–226

Boggia A, Pennacchi F (1999) Sviluppo agricolo sostenibile del bacino del lago Trasimeno. Dipartimento di Scienze Economiche ed Estimative—UNIPG, ARUSIA. Regione Umbria, Italy

Brando VE, Anstee JM, Wettle M, Dekker AG, Phinn SR, Roelfsema C (2009) A physics based retrieval and quality assessment of bathymetry from suboptimal hyperspectral data. Rem Sens Environ 113:775–770

Bresciani M, Stroppiana D, Montagna M, Fila G, Giardino C (2009) Monitoring reed vegetation in environmentally sensitive areas in Italy. Ital J Rem Sens 41(2):125–137

Casa R, Rossi M, Sappa G, Trotta A (2009) Assessing cropwater demand by remote sensing and GIS for the Pontina Plain, Central Italy. Water Resour Manag 23:1685–1712

Cecchetti A, Lazzerini G (2007) La vegetazione idrofitica del Lago Trasimeno. Campagna di monitoraggio 2007. Parco del Lago Trasimeno, Regione Umbria, Italy, p 82

Cecchetti A, Ficola M, Lazzerini G, Pedini A, Segantini F (2005) Vegetazione, habitat di interesse comunitario, uso del suolo del Parco del Lago Trasimeno. Parco del Lago Trasimeno, Italy, p 227

Chavez PS Jr (1988) An improved dark-object subtraction technique for atmospheric scattering correction of multispectral data. Rem Sens Environ 24:459–479

Cingolani L, Marchetti G, Martinelli A, Rapi G, Cantucci A (2005a) Misure per il contenimento del carico diffuso nel Piano di Tutela delle acque della Regione Umbria. 2nd Int. Conf. LIFE. Libri ARPA Umbria, Italy

Cingolani L, Charavgis F, Neri N, Notargiacomo T (2005b) Monitoraggio qualitativo dei corsi d'acqua superficiali. Piano Stralcio per il Lago Trasimeno. Regione Umbria, Italy

Cingolani L, Padula R, Di Brizio M, Ciccarelli E (2007) Eutrofizzazione del Lago Trasimeno: il problema delle fioriture algali. 14th Conf. Igiene Industriale. Corvara, Italy

Coppin P, Jonckheere I, Nackaerts K, Muys B, Lambin E (2004) Digital change detection in ecosystem monitoring. Int J Rem Sens 25:1565–1596

Dekker AG, Vos RJ, Peters SWM (2001) Comparison of remote sensing data, model results and in situ data for total suspended matter (TSM) in the southern Frisian lakes. Sci Total Environ 268:197–214

Directive 1979/409/CEE (1979) Council directive on the conservation of wild birds, Offic J L 103, 25 April 1979

Directive 2000/60/EC (2000) Water framework directive of the European parliament and of the council of 23 October 2000 establishing a framework for Community action in the field of water policy. Offic J L 327, 22 December 2000

Doerffer R, Schiller H (2008a) MERIS lake water algorithm for BEAM ATBD. GKSS Research Center, Geesthacht, Germany, version 1.0, 10 June 2008

Doerffer R, Schiller H (2008b) MERIS regional, coastal and lake case 2 water project—atmospheric correction ATBD. GKSS Research Center, Geesthacht, Germany, version 1.0, 18 May 2008

Galante G, Mandrone S, Funaro M, Cotroneo R, Panetta S (2009) Spatial and temporal changes in Aniene river basin (Latium, Italy) using landscape metrics and moving window technique. Ital J of Rem Sens 41:157–172

Giardino C, Bartoli M, Candiani G, Bresciani M, Pellegrini L (2007) Recent changes in macrophyte colonisation patterns: an imaging spectrometry-based evaluation of southern Lake Garda (northern Italy). J App Rem Sens 1:011509

Giardino C, Bresciani M, Brando VE, Dekker AG (2008) Observations of the largest Italian lakes from MERIS. 2nd MERIS/(A)ATSR User Workshop, Frascati, Italy, (ESA SP-666, November 2008)

Gilbridea KA, Frigonc D, Cesnika A, Gawata J, Fulthorpe RR (2006) Effect of chemical and physical parameters on a pulp mill biotreatment bacterial community. Water Res 40:775–787

Gons HJ, Auer MT, Effler SW (2008) MERIS satellite chlorophyll mapping of oligotrophic and eutrophic waters in the Laurentian Gt Lakes. Rem Sens Environ 112:4098–4106

International Organization for Standardization (1992) Water quality measurement of biochemical parameters Spectrophotometric determination of chlorophyll-a concentration. Geneva, Switzerland (ISO 10260-E)

Jeppesen E, Søndergaard M, Søndergaard M, Christoffersen K (1998) The structuring role of submerged macrophytes in lakes. Ecological Series, Springer-Verlag 131:423

Kutser T (2004) Quantitative detection of chlorophyll in cyanobacterial blooms by satellite remote sensing. Limnol Oceanol 49:2179–2189

Kutser T, Pierson D, Kallio K, Reinart A, Sobek S (2005) Mapping lake CDOM by satellite remote sensing. Rem Sens Environ 94:535–540

Lee ZP, Darecki M, Carder KL, Davis CO, Stramski D, Rhea WJ (2005) Diffuse attenuation coefficient of downwelling irradiance: an evaluation of remote sensing methods. J Geo Res 110:C02017

Lindell T, Pierson D, Premazzi G, Zilioli E (1999) Manual for monitoring European lakes using remote sensing techniques. Luxembourg, Office for Official Publications of the European Communities, EUR Report n. 18665 EN

Natali M (1993) The fish fauna of the Trasimeno Lake. Provincia di Perugia, Italy

Oesch DC, Jaquet JM, Hauser A, Wunderle S (2005) Lake surface water temperature retrieval using advanced very high resolution radiometer and Moderate Resolution Imaging Spectroradiometer data: validation and feasibility study. J Geo Res 110:C12014

Pozdnyakov D, Shuchman R, Korosov A, Hatt C (2005) Operational algorithm for the retrieval of water quality in the Gt Lakes. Rem Sens Environ 97:352–370

Premazzi G, Dal Miglio A, Cardoso AC, Chiaudani G (2003) Lake management in Italy: the implications of the water framework directive. Lakes Reserv Resour and Manag 8:41–59

Rouse JWR, Haas H, Schell JA, Deering DW (1973) Monitoring vegetation systems in the Great Plains with ERTS. Third ERTS Symposium, NASA SP-351 I:309–317
Shapiro LG, Haralick RM (1985) Image segmentation techniques. Comput Vis Graph Image Process 29:100–132
Sharma SK, Anjaneyulu D (1993) Application of remote sensing and GIS in water resource management. Int J Rem Sens 17:3209–3220
Simis SGH, Peters SWM, Gons HJ (2005) Remote sensing of the cyanobacterial pigment phycocyanin in turbid inland water. Limnol Oceanol 50:237–245
Sinnassamy M, Mauchamp A (2001) Roseliers: gestion fonctionelle et patrimoniale. Atelier Technique des Espaces Naturels, ATEN, Cahiers Techniques 63, Montpellier, France, p 79
Strömbeck N, Pierson D (2001) The effects of variability in the inherent optical properties on estimations of chlorophyll a by remote sensing in Swedish freshwater. Sci Total Environ 268: 123–137
Vollenweider RA, Kerekes JJ (1982) Eutrophication of waters: monitoring assessment and control. Organisation for Economic Co-operation and Development (OECD), Paris, p 150
Wetzel RG (1983) Wetzel, limnology. In: Saunders College Publishing, Philadelphia, p 767
Wu G, de Leeuw J, Liu Y (2009) Understanding seasonal water clarity dynamics of lake dahuchi from in situ and remote sensing data. Water Resour Manag 23:1849–1861
Yu X, Ng C (2006) An integrated evaluation of landscape change using remote sensing and landscape metrics: a case study of Panyu, Guangzhou. Int J Rem Sens 27:1075–1092