Proceedings of the Global Conference on Global Warming 2011
11-14 July, 2011, Lisbon, Portugal

Determination of Water Quality Parameters and their Usefulness on Lake Modelling

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Abstract — The successful launch of ENVISAT in March 2002 has given a great opportunity to understand the optical changes of water surfaces, including inland waters such as lakes and reservoirs, through the use of the Medium Resolution Imaging Spectrometer (MERIS). The potential of this instrument to describe variations of optically active substances has been examined in the Alqueva reservoir, located in the south of Portugal, where satellite spectral radiances are corrected for the atmospheric effects to obtain surface spectral reflectance. In order to validate these spectral reflectances, several field campaigns were carried out, with a portable spectroradiometer, during the satellite overpasses. The retrieved lake surface spectral reflectance was combined with limnological laboratory data to obtain empirical algorithms and with the resulting equations, spatial maps of biological quantities and turbidity were built up.

Keywords — Atmospheric Correction, Remote Sensing, Water Quality

1 INTRODUCTION

The water quality control and monitoring in reservoirs is crucial, since these constitute indispensable renewable water resources for domestic, agricultural, and industrial use, amongst many others. Reservoirs water quality is determined by quite a few aspects; hence, the reservoir management depends on the detection of spatial and temporal modifications that may be an indication of natural and anthropogenic changes in the surrounding environment. Climate seasonality is the most relevant natural temporal change, for the most part rainfall and solar heating, resulting in seasonal variations of water quality [1].

The Alqueva Reservoir, located in southern Portugal along 83 km of the main course of the Guadiana River, constitutes the largest artificial lake of the Iberian Peninsula (Fig. 1). This region faces the serious problem of droughts, and therefore is a good example of the importance of water quality control in artificial lakes. This control belongs to a large monitoring program implemented by Portuguese enterprise responsible for Alqueva reservoir exploration (Empresa de Desenvolvimento e Infra-Estruturas de Alqueva, EDIA). The monitoring program was implemented at the beginning of the filling phase. However, this control is spatially and temporally limited. Monthly water samples are collected, and afterwards analyzed in laboratory, in a few sites inside the reservoir (Fig. 1). Some of the analyzed parameters have a unique spectral absorption signature in the visible part of electromagnetic spectrum giving the possibility to be explored through satellite data. Therefore, the main motivation of the present work is to explore reliable remote sensing methods for full spatial cover and continuous monitoring of key biological parameters which affect the water quality of the reservoir.

In March 2002, ESA (European Space Agency) launched ENVISAT (ENVIronmental SATellite), an advanced polar-orbiting Earth observation satellite which provides measurements of the atmosphere, ocean, land, and ice. ENVISAT data supports earth science research and allows monitoring of the evolution of environmental and climatic changes. Furthermore, the data facilitates the development of operational and commercial applications. ENVISAT flies in a sun-synchronous polar orbit of about 800-km altitude. The repeat cycle of the reference orbit is 35 days, and for most sensors, being wide swath, it provides a complete coverage of the globe within one to three days.

Aboard ENVISAT, MERIS (Medium Resolution Imaging Spectrometer) is a 68.5° field-of-view push-broom imaging spectrometer that measures the solar radiation reflected by the Earth, at a ground spatial resolution of 300 m. The observation is performed simultaneously in 15 programmable spectral bands, ranging from the visible to the near infrared (390 nm to 1040 nm). These spectral bands were carefully chosen to ensure practical applicability of the sensor. In this study the spectral absorption signatures of the pigments chlorophyll *a* and phycocyanin were exploited in order to obtain the chlorophyll *a* concentration and cyanobacteria total density.

The turbidity of the upper layer of water bodies may also be retrieved from spectral reflectances measured with satellite spectrometers [2]. The water turbidity has an effect on the absorption and extinction of light in water and consequently on the

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vertical thermal structure of the lakes, which in turn plays an important role in the energy balance at the water surface.

The study of surface freshwater properties from satellite remote sensing techniques requires the correction for the atmospheric effects. The present study is done only for clear sky days. Major gas absorption bands are avoided, and therefore, the atmospheric correction depends essentially on the type and amount of aerosols present in the atmosphere. The atmospheric correction is done using the 6S (Second Simulation of the Satellite Signal in the Solar Spectrum) radiative transfer code [3], obtaining hence the water surface spectral reflectance, from level 1 MERIS full resolution data. These results are used to estimate the chlorophyll *a* concentration, cyanobacteria density and turbidity over the Alqueva surface area, using empirical algorithms proposed by the authors [4][5]. The study will address the year of 2007, aiming at analyzing the spatial and seasonal variations of water quality parameters over Alqueva reservoir.

2 STUDY AREA

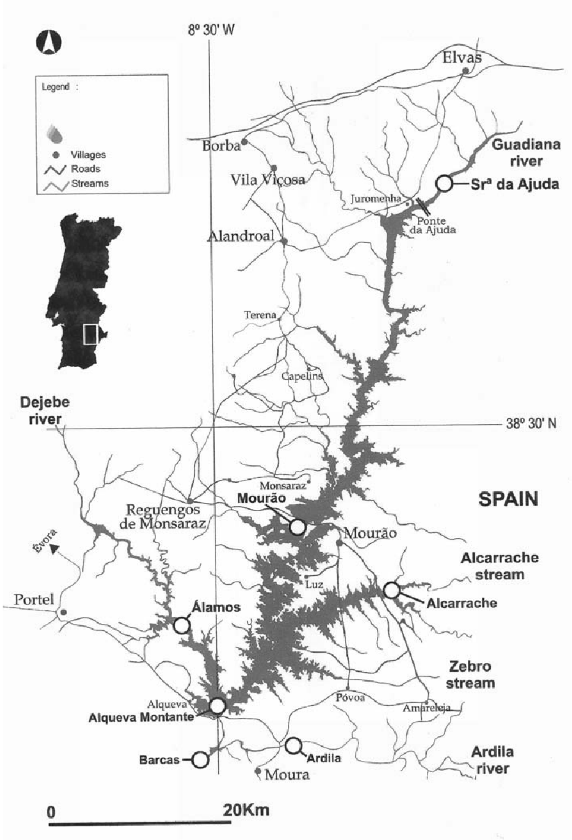

Fig. 1. Alqueva reservoir location and position of the sites where the water samples are collected for laboratory analyses – Map from [6].

Alqueva reservoir is located on the Portuguese section of Guadiana River, as illustrated in Fig. 1. At the full storage level of 152 m, the reservoir has a total capacity of 4.150 km^3 and a surface area of 250 km^2. The filling up of Alqueva reservoir began in February 2002 and lasted about one year to reach a stable storage level of about 135 m.

Two sites were selected for this study (all with lentic characteristics), taking into account not only their geographical positions inside the reservoir, but also the satellite pixel dimension (300 × 300 m^2). Fig.1 illustrates the location of these sites, namely Mourão and Alqueva Montante.

3 DATA

The limnological measurements used in the present work were kindly made available by the Empresa de Desenvolvimento e Infra-estruturas do Alqueva, S.A. (EDIA) and by the Portuguese Water Institute (INAG).

The parameters analyzed in the present work are the chlorophyll *a* concentration, obtained from molecular absorption spectroscopy according to method developed by [7], the cyanobacteria total density, determined using the Utermöhl method with microscopical identification [8] and turbidity obtained with a turbidimeter which uses a tungsten lamp operating between 400 to 600 nm.

MERIS full resolution (FR) level 1 imagery are used, corresponding to spectral top of the atmosphere (TOA) radiances for each of the MERIS spectral channels, with the maximum spatial resolution of 300 × 300 m^2 at the nadir. The selection of the MERIS images was based on three conditions: minimum time lag between MERIS and limnology dates due to possible alterations of the water surface parameters (one day difference), clear sky and lack of aerosol events (normally desert dust and forest fire smoke). Details on the analysis of the satellite images in terms of the last two conditions are given in the next section.

Aerosol measurements (optical thickness, size distribution, and complex refractive index) are continuously obtained at the observatory of the Évora Geophysics Centre (CGE) from the inversion of spectral radiation measurements taken by a Sun-sky photometer connected to the AErosol RObotic NETwork (AERONET) [9]. Due to the short distance between Évora site and Alqueva area (about 50 km), a significant variation of the aerosol type and load is not expected. Therefore, the atmospheric correction over Alqueva is accomplished using the aerosol characterization obtained in Évora. In the case of aerosol events, it is difficult to know if the type and optical thickness of aerosols over Évora are similar to those over the Alqueva reservoir. Since the aerosol concentrations involved in these cases are much higher than usual, the errors associated with such corrections would also be elevated.

Therefore, situations of aerosol events were not considered in the study.

In Tab. 1 MERIS, Sun-sky photometer and limnological data availability is shown for year 2007, which are used to validate the model.

Table 1 - MERIS, Sun-sky photometer and limnological data availability in 2007.

	Day Month	MERIS acquisition time UTC	AOT acquisition time UTC	AOT 550 nm	Limnology Dates
	05.06	10:42	10:45	0.115	05.06
	07.06	11:19	11:16	0.214	06.06
	03.07	11:02	11:06	0.031	03.07
	04.07	10:31	10:36	0.040	04.07
	20.08	10:54	10:51	0.094	20.08
	23.08	10:59	11:05	0.077	22.08
	14.11	10:51	11:01	0.034	14.11
	10.12	10:34	10:30	0.027	11.12

4 ATMOSPHERIC CORRECTION

The study of surface water properties from satellite remote sensing techniques requires the correction for the effects of the atmosphere. Accordingly, MERIS spectral radiance measured at the TOA must be corrected with respect to the atmospheric effects, to obtain the surface spectral reflectance, which can in turn be related with the limnological data. The present study concerns only clear sky days and all cloudy situations have been discarded. Major gas absorption bands were also avoided, therefore, the atmospheric correction depends essentially on the type and amount of aerosols present in the atmosphere. Aerosol measurements are continuously obtained at the observatory of the Évora Geophysics Centre (CGE) from the inversion of spectral radiation measurements taken by a Sun-sky photometer connected to the AErosol RObotic NETwork (AERONET). Due to the small distance between Évora site and Alqueva area (about 40 km), a significant variation is not expected, especially with respect to aerosol type, therefore the atmospheric correction over Alqueva is accomplished using the aerosol characterization obtained in Évora. The Second Simulation of the Satellite Signal in the Solar Spectrum (6S) [3] is the radiative transfer code used to correct the satellite measured signal for the atmospheric contribution. This code can simulate satellite radiation measurements in cloudless atmospheres, between 0.25 and 4.0 μm, for a wide range of atmospheric and surface conditions. The 6S takes into account the atmospheric compounds considering 34 atmospheric levels distributed from the ground up to 100km altitude, which is considered the TOA level. A standard atmospheric profile typical of mid-latitude summer or winter, according to the case under study, the ozone (O_3) column concentration obtained from MERIS level 1b, the water vapour (H_2O) vertical column concentration and the aerosol characterization (concentration, size distribution and chemical composition) were considered. The latter two quantities were obtained from the AERONET site located in the CGE observatory in Évora. Since the atmospheric correction parameters are known, as well as the geometry and the satellite measured spectral radiance, the water spectral reflectance can be determined for the MERIS bands with 6S radiative transfer code.

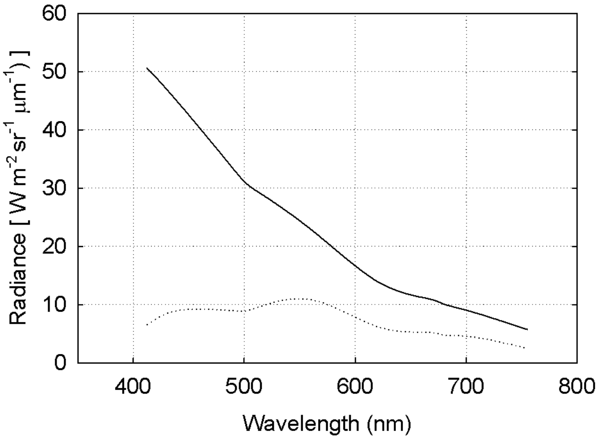

Fig. 2. MERIS spectral radiance at the top of the atmosphere (solid line) and at the surface (dotted line), after atmospheric correction, on 14 November 2007 10:51 UTC.

Fig. 2 shows an example of the difference between the MERIS spectral radiance measured at the top of the atmosphere and the surface spectral radiance obtained after atmospheric correction with 6S radiative transfer code, for 14 November 2007. Note the dominance of the atmospheric path over the surface signal, particularly for lower wavelengths (λ< 510nm), which will be used for the estimation of the bio-optical parameters.

5 EMPIRICAL ALGORITHMS

The reservoir surface spectral reflectance retrieved as described in the previous section is combined with limnological laboratory analyses to relate the atmospherically corrected satellite data and the corresponding limnological data ([4][5]). The algorithms obtained are then used to estimate the chlorophyll *a* concentration, cyanobacteria density and turbidity, over the whole Alqueva surface area and the results compared with laboratory analyses from a different period.

MERIS band 2 (442.5nm) represent a maximum of chlorophyll *a* absorption, whereas band 5 (560nm) represents a minimum. For this reason, the ratio between these two bands is investigated and related to values of chlorophyll *a* concentration. For each sampling site (Mourão and Alqueva Montante; see Fig.1), the mean value of a box with four MERIS pixels centered in the geographical location of the site is considered. Following [10] the best fit is of power type, a correlation coefficient of 0.88 was obtained. The relation is given by Eq. 1, where B2 and B5 represent the atmospherically corrected MERIS reflectance in bands 2 and 5, respectively.

$$Chl-a\left[\mu g.l^{-1}\right]=4.93*\left(\frac{B5}{B2}\right)^{3.90} \qquad (1)$$

A total number of 36 data points is used, corresponding to the two locations considered (Fig.1) and to the period of study, taking into account the conditions imposed for the MERIS image selection (clear sky, lack of aerosol events and minimum time lag between MERIS and limnology dates).

MERIS band 3 (490nm) represents a minimum of absorption for the phycocyanin pigment (present in the cyanobacteria [9]), whereas band 5 (560nm) represents a relative maximum and band 6 (620nm) represents an absolute maximum. The combination of the three bands was investigated and related with the cyanobacteria laboratory analyses. The best grouping found is given by Eq. 2. B3, B5 and B6 represent the atmospherically corrected MERIS reflectance in bands 3, 5 and 6, respectively. Once more, the mean value of a box centered in the geographical location of the site, enclosing four MERIS pixels is considered.

$$Cya\left[10^3 cells.ml^{-1}\right]=4.2x10^5*\left(\frac{B5*B6}{B3}\right)^{2.84} \qquad (2)$$

The fit obtained is again of power type and presents a correlation coefficient of 0.83. The lower number of data points considered (23) in this case, in comparison to the chlorophyll *a* case (36 data points), is due to the fact that INAG analyses do not include out cyanobacteria density.

The ratio between MERIS band 5 (560 nm) and band 1 (412.5 nm) revealed to be the best fit for retrieving the water turbidity. With a correlation coefficient of 0.96 and a linear type has shown in Eq. 3 where B1 and B5 represent the atmospherically corrected MERIS reflectance in bands 1 and 5, respectively.

$$Turb\left[NTU\right]=-6.39+8.93*\left(\frac{B5}{B1}\right) \qquad (3)$$

6 RESULTS AND DISCUSSION

Next we compare results of chlorophyll *a* and cyanobacteria concentrations obtained using the empirical algorithms presented previously, with limnological laboratory analyses that were not used to derive eqs. 1-3. This validation is not applied to turbidity values due to the lack of in situ measurements.

The algorithms presented in Section 5 are applied to a box of four pixels, centered in the geographical coordinates of the sites where the water samples are collected (Alqueva Montante and Mourão - Fig. 1), and the results obtained are compared with the corresponding laboratory analyses. The mean concentration value corresponding to the four selected pixels is computed and used for comparison with the limnological data.

Fig. 3 shows the scatter plot of the MERIS derived chlorophyll *a* concentration versus the corresponding analyses, in a total of 29 data points. The vertical error bars represent the standard deviations corresponding to the four selected pixels. A good correlation coefficient between measurements and retrievals (R = 0.84) was obtained, with MERIS derived values revealing in general a slight overestimation for low values of chlorophyll *a* (lower than roughly 15 μg/l) and a tendency to underestimate for higher values.

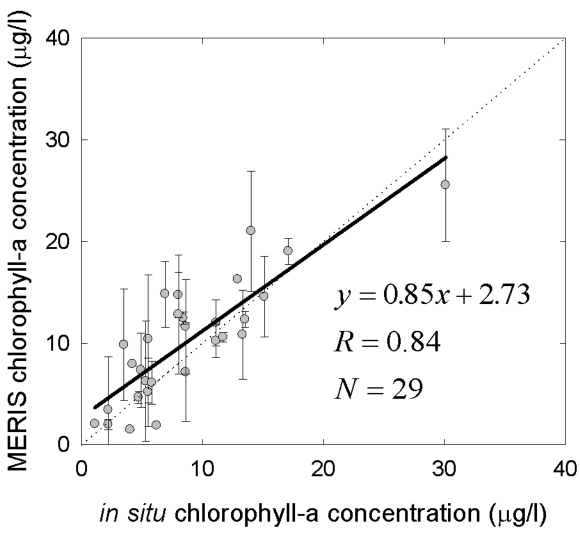

Fig. 3. Scatter plot of estimated *versus* measured chlorophyll *a* concentrations (μg/l).

In Fig. 4 the relationship between MERIS derived cyanobacteria densities and the corresponding analyses, in a total of 29 data points, is illustrated. The vertical error bars represent once again the standard deviations corresponding to the four pixels selected. A correlation coefficient of 0.97 is found for cyanobacteria, which is higher than the correlation for chlorophyll *a*. The methodology shows in general a good agreement over the whole range of cyanobacteria densities, though the satellite derived results present a growing tendency to underestimate the laboratory analyses. This may be connected to the heterogeneity of cyanobacteria colonies at the MERIS pixel spatial scale (300 × 300 m^2 at the nadir). The importance and impact that cyanobacteria may have in public health is primarily connected with the occurrence of blooms (cyanobacteria densities higher than 20000 cells/ml) and the associated production of toxins. The results in Fig. 4 also demonstrate the capability of MERIS to detect cyanobacteria blooms.

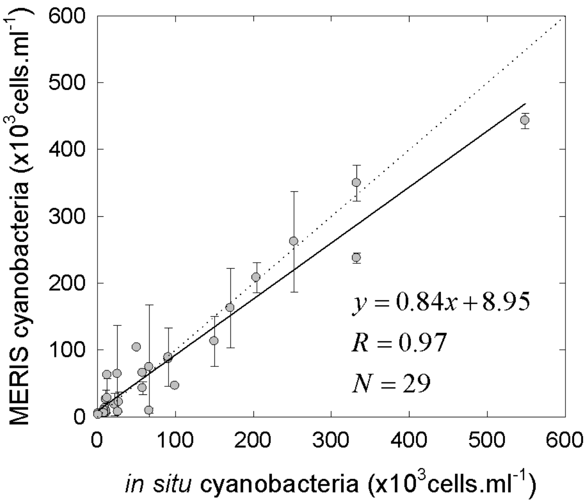

Fig. 4. Scatter plot of estimated versus analyzed cyanobacteria total densities (×10^3 cells/ml).

The results above indicate that both chlorophyll *a* concentration and cyanobacteria density can be estimated reasonably well with the present methodology. It is thus possible to systematically monitor the water quality of Alqueva reservoir in terms of these two phytoplanktonic parameters based on MERIS (FR) image data. Furthermore, our study reveals the potential of MERIS to be used in the implementation of an alert system in case of bloom events.

Figs. 5-6 present maps of cyanobacteria densities and turbidity obtained by applying the algorithms developed and presented in Section 5 to the whole Alqueva reservoir area. We have selected two days in 2007 for these maps, namely 5 June (Figs. 5a, 6a) and 14 November (Figs. 5b, 6b). For June case the reservoir presents low turbidity (Fig. 6a) at the surface allowing deeper light penetration on the reservoir. Together with warm conditions, this leads to a development of algae species namely cyanobacteria (Fig. 6a). This case presents densities higher than 20000 cells/ml, which can be classified as bloom events. In general higher concentrations are found in tributary streams of the reservoir since these zones present higher biological activity.

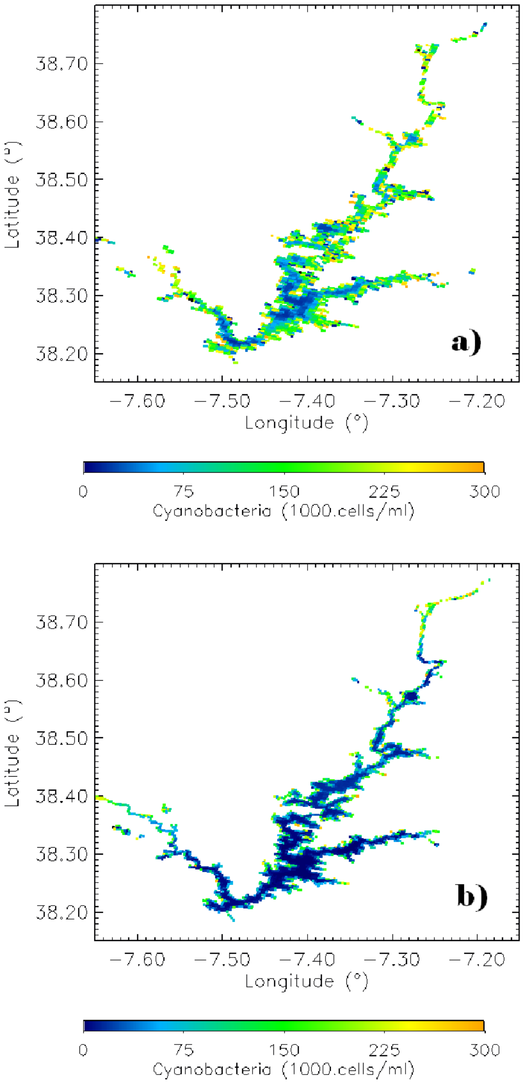

Fig. 5. Cyanobacteria density map over the whole Alqueva reservoir surface for the year 2007: a) 5 June; b) 14 November.

The run-off during the wet season, mainly by the Guadiana River (Fig. 1), usually introduces organic and inorganic matter leading to an increase of turbidity, clearly seen in the map obtained for 14 November 2007 (Fig. 6b). For this case, low cyanobacteria density was obtained in almost all the reservoir.

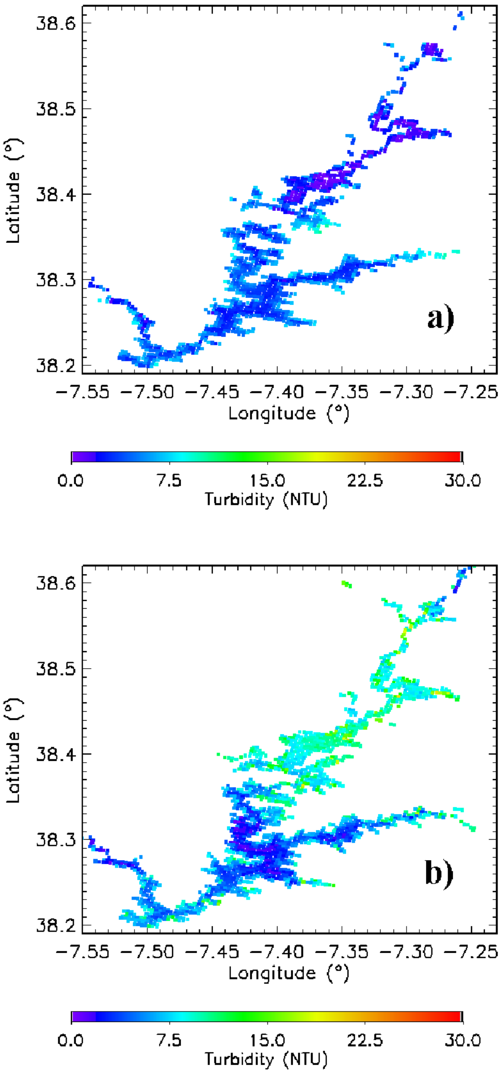

Fig. 6. Turbidity map over the whole Alqueva reservoir surface for the year 2007: a) 5 June; b) 14 November.

8 CONCLUSIONS

A methodology to derive chlorophyll *a* concentration, cyanobacteria density and turbidity, from the combination of satellite (MERIS) spectral reflectance measurements and limnological laboratory analyses is presented. An important aspect of the satellite water quality parameter retrieval is the existence of atmospheric measurements that allow for a good atmospheric correction of the satellite images. This is resolved here by using atmospheric measurements taken on a regular basis at a near distance observatory. The algorithms were derived using four years of data, from 2003 to 2006. A comparison study between the satellite derived quantities and the laboratory analyses was done using data from 2007. The good correlation coefficients found for chlorophyll *a* (R=0.84) and cyanobacteria (R=0.97) demonstrate the great capabilities of MERIS sensor to monitor the quality of inland waters.. Furthermore, the application of the satellite based algorithms to the whole Alqueva reservoir area appear to be consistent with monthly laboratory analyses from two different locations of Alqueva reservoir.

The high correlation coefficient of the linear relation between water turbidity and MERIS reflectance in bands 1 and 5 suggests that it is possible to obtain good estimates of water turbidity from MERIS sensor. This methodology may allow the generation of horizontal fields of water turbidity, which consist of useful information in particular to improve the performance of lake schemes recently inserted in several numerical weather prediction models [5].

The results presented here indicate that the methodology proposed may be used as an instrument in combination with limnological laboratory analyses, allowing for a regular water quality monitoring.

ACKNOWLEDGMENT

The authors wish to thank AERONET investigators for their effort in establishing and maintaining Évora AERONET site, Water Laboratory of the University of Évora, EDIA and INAG for providing the water quality data used in this work. This work was supported by the Portuguese FCT through project PTDC/CTE-ATM/65307/2006 and grant SFRH/BD/45577/2008. Image data has been provided by ESA in the frame of ENVISAT projects AOPT-2423 and AOPT-2357.

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