STUDY OF THE WATER QUALITY OF ALQUEVA ARTIFICIAL LAKE IN THE SOUTH OF PORTUGAL USING MERIS DATA

M. Potes[(1)], M. J. Costa[(1, 2)] , J. C. B. da Silva[(3)]

[(1)] Évora Geophysics Centre (CGE), University of Évora, Rua Romão Ramalho 59, 7000-671 Évora, Portugal, Email: mpotes@uevora.pt
[(2)]Dept. Physics, University of Évora, Rua Romão Ramalho 59, 7000-671 Évora, Portugal, Email: mjcosta@uevora.pt
[(3)]Institute of Oceanography & Dept. Physics, Campo Grande 1749-016 Lisbon, Portugal, Email: jdasilva@fc.ul.pt

ABSTRACT

The successful launch of ENVISAT in March 2002 has given a great opportunity to understand the changes of water colour with high spatial resolution. In this study, the potential of MERIS sensor to describe variations of optically active substances of Alqueva artificial lake is investigated. Regular *in situ* measurements, from May 2004 to July 2005, are used in combination with MERIS acquisitions. The surface reflectance is derived from Level 1b MERIS data, using radiative transfer calculations to account for the atmospheric effects. The parameterizations obtained are used to map the concentrations of chlorophyll-a, cyanobacteria and suspended sediments. The results obtained are also compared with independent *in situ* measurements.

1. INTRODUCTION

The control and monitoring of the water quality in artificial lakes is crucial, since these constitute essential renewable water resources for domestic, agricultural, and industrial purposes, amongst many others [1], [2], [3]. Alqueva is the largest artificial lake in Europe in terms of surface area (250 km^2). It is located in the south of Portugal - Alentejo, a region that seriously faces the problem of droughts, and therefore is a good example of the importance of water quality control in artificial lakes [4]. The parameters analysed in this study were chlorophyll-a, cyanobacteria and total suspended solids (TSS). The chlorophyll is an important photosynthetic pigment, since its concentration allows to estimate the phytoplankton concentration (microscopic algae) and, indirectly, to estimate the biological activity; it presents a greenish coloration. The cyanobacteria, also known by blue algae, are microscopic and unicellular organisms of fresh waters. They can form colonies becoming perceptible to the unaided eye; presenting a bluish coloration. They can develop massively provoking the fluorescence's, more known as "blooms". The most serious effect resultant of a cyanobacteria bloom is the production of toxins, which represents a serious risk for the public health. The TSS are present in all lakes and lagoons, and its composition can greatly vary, including minerals, plankton and debris of several origins.

The study of surface water properties from satellite remote sensing techniques requires the correction for the effects of the atmosphere. The present study is only concerned with clear sky days, therefore all cloudy situations are discarded. Major gas absorption bands are avoided as well, therefore, the atmospheric correction depends essentially on the type and amount of aerosols present in the atmosphere. 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). Due to the short distance between Évora site and Alqueva area (about 40km), a significant variation is not expected, especially in relation to aerosol type. Therefore the atmospheric correction over Alqueva is accomplished using the aerosol characterization obtained in Évora. The atmospheric correction is done using the Second Simulation of the Satellite Signal in the Solar Spectrum (6S) radiative transfer code [5], obtaining hence the lake surface spectral reflectance. These results are then combined with *in situ* measurements [6] to relate the atmospherically corrected satellite data and the corresponding *in situ* measurements. The parameterizations obtained are then used to estimate the chlorophyll-a, cyanobacteria and TSS over the whole Alqueva surface area, for several case studies. A preliminary validation is addressed comparing the results obtained with *in situ* measurements that were not used to derive the parameterizations.

2. METHOD

The date and time of the MERIS images used are summarized in Tab. 1, together with the aerosol optical thickness (AOT) at the reference wavelength of 550 nm, and the availability of limnological data on the Alqueva lake. The selection of the dates (eight days in total, see Tab. 1) is the result of the fulfilment of three conditions: clear sky, lack of aerosol events (normally desert dust

Proc. 'Envisat Symposium 2007', Montreux, Switzerland
23–27 April 2007 (ESA SP-636, July 2007)

and forest fire smoke) and minimum time lag between MERIS and limnology dates. In the case of aerosols events, it is difficult to know if type and optical thickness of aerosols over Évora are similar over the lake. Since the aerosol concentrations involved in these cases are much higher, also the errors associated with such correction would be elevated, therefore situations of aerosol events are discarded. If the dates of MERIS images and limnology differ by more than six days, the corresponding case is also not considered, due to possible alterations of the water surface parameters.

Table 1. MERIS, Sun-sky photometer and limnological data availability in the period May 2004 - July 2005.

	Date	MERIS acquisition time (UTC)	AOT acquisition time UTC	AOT 550 nm	Limnology dates
2004	08/05	10:36	10:34	0.060	05/05
	11/09	11:16	11:29	0.069	07/09
	13/10	11:11	11:18	0.061	12/10
	14/11	11:05	11:01	0.028	09/11
	04/12	10:36	10:37	0.056	06/12
2005	04/01	11:02	11:06	0.124	04/01
	08/05	11:05	-	-	09/05
	08/07	10:48	10:52	0.135	11/07

2.1. The atmospheric correction

The MERIS spectral reflectance measured at the top of the atmosphere must be corrected with respect to the atmospheric effects [7], to obtain the surface spectral reflectance, which can in turn be related with the in situ measurements of limnology.
For this purpose, the 6S radiative transfer code is used. The inputs provided to the code are: the solar and satellite geometry; the aerosol characterization in terms of concentration, size distribution and chemical composition, and the water vapour (H_2O) vertical column concentration, being the latter two obtained from the AERONET site located in the CGE observatory in Évora; the ozone (O_3) column concentration is obtained from MERIS level 1b. The radiative transfer calculations allow for obtaining the corrected surface spectral radiance and reflectance, which are essential to study the water properties. Fig. 1 exemplifies MERIS radiance measured at the top of the atmosphere (black line) and corrected with 6S to represent the surface (grey line), for 8 May 2004 (clear sky day with no aerosol events). It can be noted from the graph the great dominance of the atmospheric path, especially in the lower wavelengths, with respect to the surface signal.

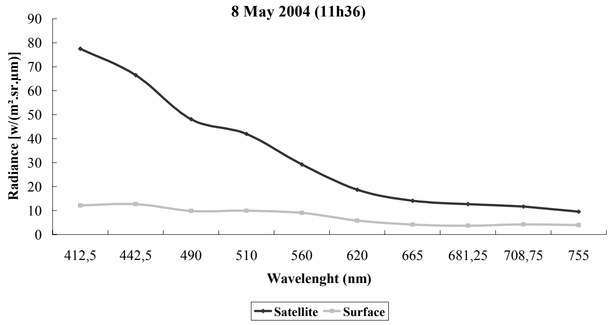

Figure 1. MERIS radiance at the top of the atmosphere (Satellite measurement) and at the surface (after atmospheric correction, on 8 May 2004, 11:36 UTC.

2.2. Parameterizations

The ratio of MERIS surface reflectance in bands 5 and 2 (560nm and 442.5nm), is correlated to *in situ* measurements of chlorophyll-a concentration. Band 2 represent a maximum and band 5 a minimum of chlorophyll-a absorption. The best fit obtained is of exponential growth type, with a correlation coefficient of 0.73, and is given by Eq. 1. Fig. 2 shows the scatter plot of chlorophyll-a concentrations against the ratio of MERIS bands 5 and 2.

$$Chl-a\left[\mu g L^{-1}\right] = 1.35 + 0.02 * e^{\left(4.12*\frac{B_5}{B_2}\right)} \qquad (1)$$

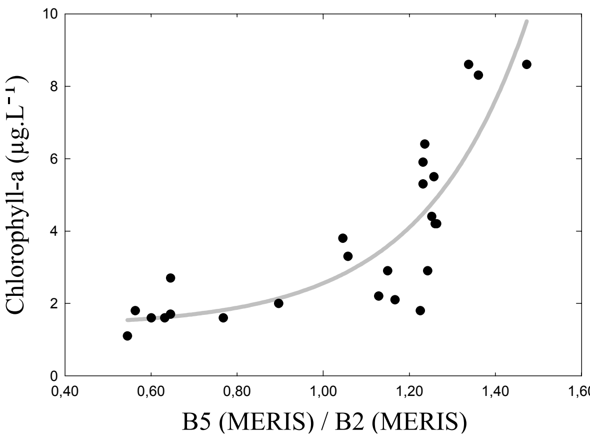

Figure 2. Regression model for chlorophyll-a retrieval from the ratio of MERIS bands 5 and 2.

The regression based on MERIS reflectance ratio in the bands 5 and 10 (560nm and 753.75nm) given by Eq. 2

was found to have the highest correlation coefficient of 0.60 with the cyanobacteria values (Fig. 3). MERIS band 5 represents a maximum of absorption for the phycocyanin pigment (present in the cyanobacteria) and band 10 represents a minimum.

$$Cya[\%] = -19.29 + \left(\frac{152.22 * \frac{B_5}{B_{10}}}{1.05 + \frac{B_5}{B_{10}}} \right) \quad (2)$$

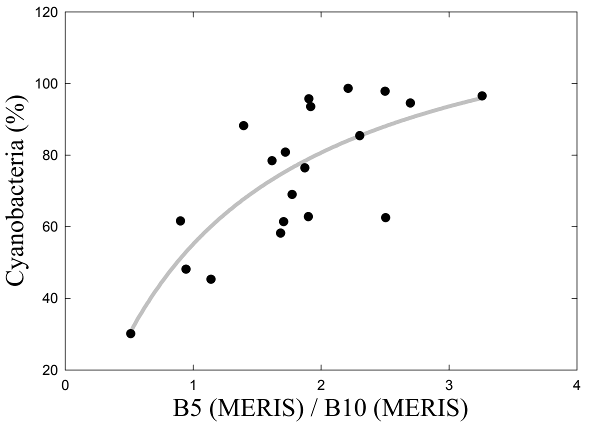

Figure 3. Regression model for cyanobacteria retrieval from the ratio of MERIS bands 5 and 10.

The regression based on MERIS reflectance ratio in bands 1 and 4 (412.5nm and 510nm) given by Eq. 3, was found to have the highest correlation coefficient of 0.52 with the TSS values (Fig. 4). Both bands used have potential for the detection of suspended matter and on the other hand, these bands are out of the absorption bands of the other pigments studied here (chlorophyll-a and cyanobacteria).

$$TSS[mgL^{-1}] = 5.23 + 3.53 * \left(\frac{B_1}{B_4} \right)^{2.98} \quad (3)$$

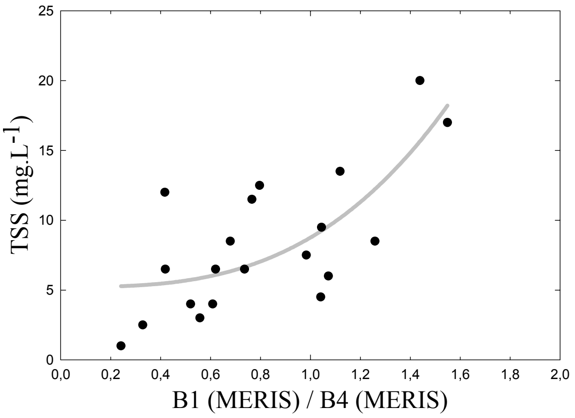

Figure 4. Regression model for TSS retrieval from the ratio of MERIS bands 1 and 4.

3. RESULTS

3.1. Surface reflectance

The surface reflectance is strongly connected to the properties and composition of the water surface. Fig. 5 shows the surface spectral reflectance for three sites of the lake (Alcarrache, Montante and Mourão) on 4 January 2005, obtained after the atmospheric correction scheme was applied to MERIS data. The spectral reflectance in Mourão presents higher values than the other two sites. This fact is probably due to the higher TSS concentration (3 $mg.L^{-1}$) measured in this site, whereas the others two sites present 1 $mg.L^{-1}$ for Alcarrache and 1.5 $mg.L^{-1}$ for Montante. According to [8], a small concentration of suspended minerals (0.1 $mg.L^{-1}$) is enough to increase the value of the reflectance in a column of water where the concentrations of chlorophyll-a and dissolved organic carbon are maintained zero. The reflectance in Montante site presents a maximum at 510 nm (whereas for the other two places the maximum is at 560 nm). This fact can be due to the lower concentration of chlorophyll-a (0.7 $\mu g.L^{-1}$) that this site presents in relation to the other two sites (2.9 $\mu g.L^{-1}$ for Mourão and 4.4 $\mu g.L^{-1}$ for Alcarrache). Once more, according to [8], for a column of water with suspended mineral concentrations of 0.1 $mg.L^{-1}$ and concentration of dissolved organic carbon maintained zero, an increase of chlorophyll-a concentration results in an increase of the spectral reflectance for wavelengths higher than approximately 528 nm and a reduction for lower wavelengths.

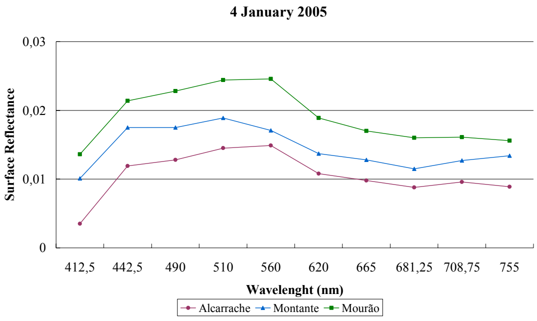

Figure 5. MERIS derived surface spectral reflectance for 4 January 2005 11:02 UTC, for three places of the Alqueva lake (Alcarrache, Montante and Mourão).

3.2. Preliminary validation of the parameterizations

The parameterizations presented in the Section 2.2 were applied to a box of four pixels centred in the sites where the *in situ* measurements were taken, and the results obtained are compared with the corresponding *in situ* analyses. The mean value was used for comparison with the *in situ* measurement and the standard deviation of the four values was used as error bar. The solid lines represent the superior and inferior limits of the established error in each case: ±2 µg.L^{-1} for chlorophyll-a; ±20 % for cyanobacteria and ±2 mg.L^{-1} for the TSS. For the chlorophyll-a case shown in Fig. 6, ten point values are inside the limits of the established error of ±2 µg.L^{-1}; from the remaining eight points. One value was overestimated and seven underestimated (see Fig. 6). MERIS spectral measurements demonstrates to have high potential to estimate concentrations of chlorophyll-a lower than 5 µg.L^{-1} (only one value out of the error limit established). As for chlorophyll-a values higher than 5 µg.L^{-1}, results show in general a slight underestimation. In this case further investigation has to be carried out.

Fig. 7 shows the scatter plot of the *in situ* measurements and MERIS derived cyanobacteria percentages. Regarding this parameter, eleven values are inside the error limit of ±20 %. As for the remaining seven points, five were overestimated and two values were underestimated. The values overestimated correspond to cyanobacteria percentages inferior to 25% and the values underestimated correspond to percentages above 95 %. The methodology is limited with respect to low percentages of cyanobacteria. Nevertheless, the greater impact that cyanobacteria may have in public health, is connected with the occurrence of blooms due to the mass-production of toxins. Results demonstrate the great capability of MERIS to detect cyanobacteria blooms (Fig.7).

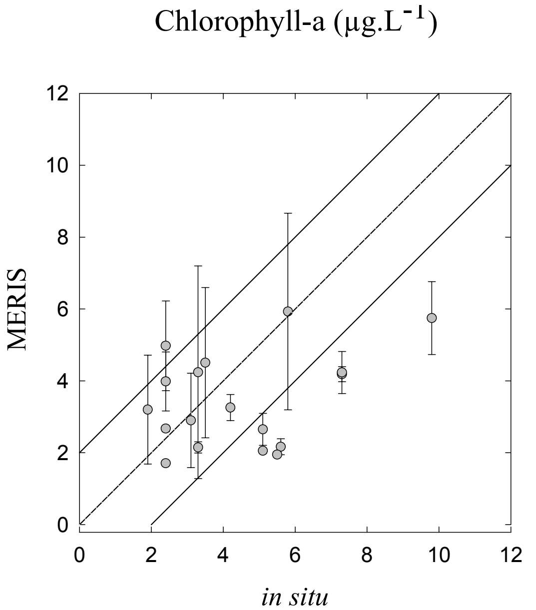

Figure 6. Scatter plot of measured and estimated concentrations of chlorophyll-a.

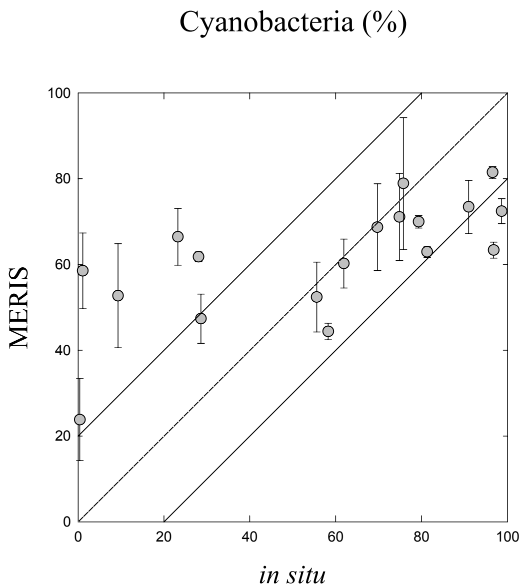

Figure 7. Scatter plot of measured and estimated percentage of cyanobacteria.

As for the TSS shown in Fig. 8, only six MERIS values were inside the limit of error of ±2 mg.L^{-1}; one value was underestimated and the remaining ten values were overestimated by the MERIS based methodology (see Fig. 8). The fact that only six values have been estimated inside the error of ±2 mg.L^{-1} may be due to the great heterogeneity that composes the TSS (it includes organic and inorganic matter of different origins). In summer, TSS are mainly constituted by unicellular seaweeds that compose the phytoplankton (organic matter) and can reach very high densities, superior to 2000 cells/mL. In these situations the water presents a very characteristic green colour. In the autumn / winter period, TSS originates from materials (from the basin of drainage) that are dragged by the waters after haste events. In these situations the TSS are principally constituted by inorganic particles, and the water presents a brownish colour. Therefore, along the year, TSS present different composition (organic versus inorganic) and particles of different dimensions and coloration. Consequently, it is more difficult for MERIS to estimate annual concentrations of TSS. For future studies, it is planned to separate the study in dry and moist seasons, in order to improve correlations.

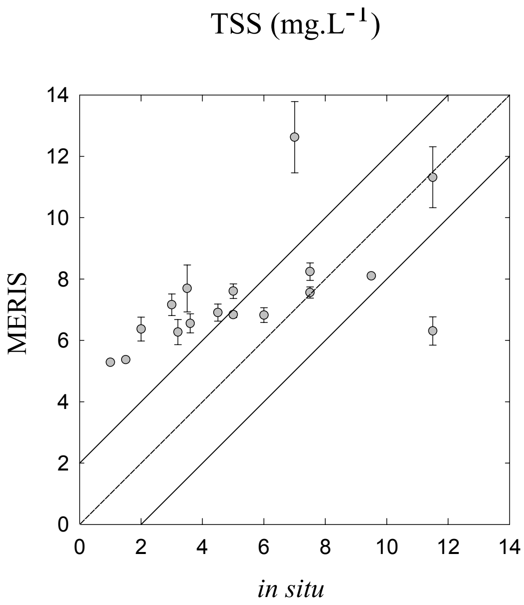

Figure 8. Scatter plot of measured and estimated concentrations of TSS.

3.3. Spatial distribution of water quality parameters

In this section, the maps obtained from applying the parameterizations to the whole Alqueva lake area are presented for 8 July 2005 at 10:48 UTC. Fig. 9 represents the map of chlorophyll-a concentration. It can be observed that higher concentrations are found in tributaries zones since these zones present higher biological activity.

Fig. 10 represents the cyanobacteria percentage, where higher percentages (bloom case) are detected in the central zones of the lake, where still waters are found.

Fig. 11 represents TSS concentration. Note that higher concentrations are observed in the central zone of the lake, as well. As for the TSS, it was also found that in some cases (not shown here), higher values were concentrated on one side of the lake. This has been interpreted in accordance with the wind patterns for the same day.

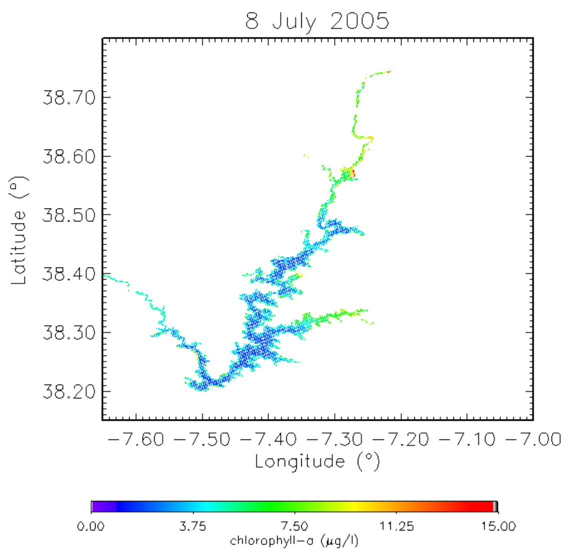

Figure 9. Chlorophyll-a concentration map.

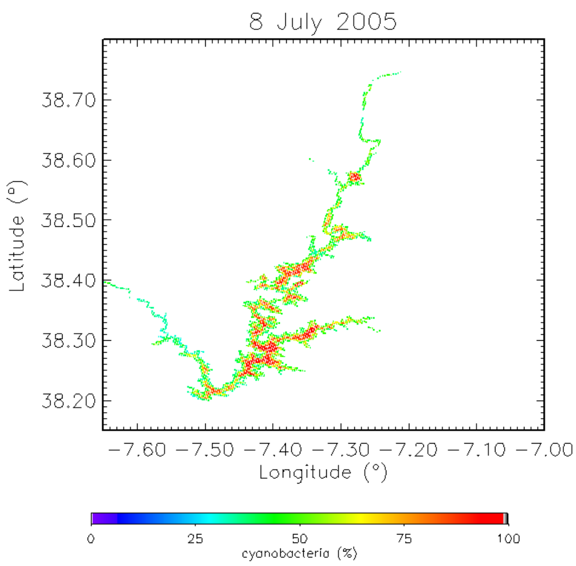

Figure 10. Cyanobacteria percentage map.

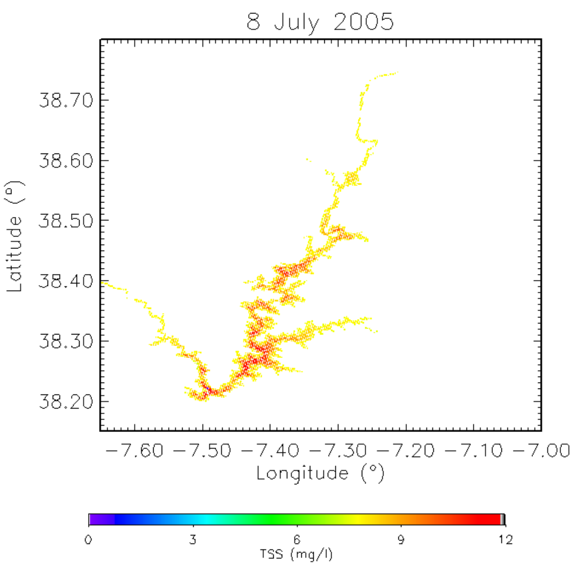

Figure 11. TSS concentration map.

4. CONCLUSION

This study shows the great capabilities of MERIS sensor to monitor the quality of inland waters. Parameterizations have been derived for the retrieval of chlorophyll-a, cyanobacteria and TSS from the ratio of MERIS bands. Although results are preliminary, the good correlations found are encouraging.

A critical issue for the water quality parameter retrieval is the existence of measurements that allow for an accurate atmospheric correction.

5. ACKNOWLEDGEMENTS

The work was funded by the Portuguese FCT through projects **PDCTE / CTA / 49826 / 2003, PDCTE / CTA / 49953 / 2003 and POCI / CTE-ATM / 59773 / 2004.**
Image data has been provided by ESA in the frame of ENVISAT projects **AOPT-2423** and **AOPT-2357**.
We thank Prof. Ana Maria Silva for her effort in establishing and maintaining Évora AERONET site. We also thank Prof. Maria Manuela Morais and the Water Laboratory of the University of Évora, EDIA and INAG for providing the water quality *in situ* measurements used in this work.

6. REFERENCES

1. Floricioiu, D., Rott, H., Rott, E., Dokulil, M. & Defrancesco, C., (2004). Retrieval of limnological parameters of perialpine lakes by means of MERIS data, *Proc. of 2004 Envisat & ERS Symposium*, Salzburg, Austria, 2004.

2. Peña-Martínez, R., Domínguez-Gómez, J.A., Hoyos, C. & Ruiz-Verdú, A., Mapping of photosynthetic pigments in Spanish reservoirs, *Proc. of MERIS User Workshop*, ESA-ESRIN, Frascati, Italy, 10-13 November 2003.

3. Reinart, A., Pierson, D., Water Quality Monitoring of Large European Lakes using MERIS Full Resolution Data, *Proc. of the 2004 Envisat & ERS Symposium*, Salzburg, Austria, 2004.

4. Potes, M. (2006). Estudo da qualidade da água da barragem do Alqueva utilizando medidas de satélite ENVISAT – MERIS. BSc. Thesis. Faculty of Sciences, Univ. Lisbon. Lisbon, Portugal. 56 pp, *in Portuguese*.

5. Vermote, E., Tanré, D., Deuzé, J.L., Herman, M. & Morcrette, J.J. (1997). Second simulation of the signal in the solar spectrum (6S): User guide version 2, 218pp.

6. Serafim, A., Morais, M., Guilherme, P., Sarmento, P., Ruivo, M. & Magriço, A. (2006). Spatial and temporal heterogeneity in the Alqueva reservoir, Guadiana river, Portugal. *Limnetica*. 25(3): 771-786.

7. Costa, M. J. (2004). Aerosol and cloud satellite remote sensing: monitoring and modelling using passive radiometers, Ph.D thesis, Department of Physics of the University of Évora, 233pp.

8. Bukata, R. P., Jerome, J. H., Kondratyev, K. Ya., & Pozdnyakov, D. V. (1995). *Optical Properties and Remote Sensing of Inland and Coastal Waters*, CRS Press.