In situ measurements and satellite remote sensing of case 2 waters: first results from the Curonian Lagoon*

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Abstract

In this study we present calibration/validation activities associated with satellite MERIS image processing and aimed at estimating chl *a* and CDOM in the Curonian Lagoon. Field data were used to validate the performances of two atmospheric correction algorithms, to build a band-ratio algorithm for chl *a* and to validate MERIS-derived maps. The neural network-based Case 2 Regional processor was

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found suitable for mapping CDOM; for chl *a* the band-ratio algorithm applied to image data corrected with the 6S code was found more appropriate. Maps were in agreement with in situ measurements. This study confirmed the importance of atmospheric correction to estimate water quality and demonstrated the usefulness of MERIS in investigating eutrophic aquatic ecosystems.

1. Introduction

The Curonian Lagoon is located in the eastern part of the Baltic Sea, from which it is separated by a narrow sand spit (0.5–4.0 km); the northern part belongs to Lithuania, the southern part to the Russian Federation. With a total area of 1584 km^2 and a mean depth of 3.7 m, the Curonian Lagoon is the largest lagoon in Europe (Ložys 2004). The Klaipeda Strait connects the lagoon with the sea, allowing the intrusion of low salinity water into the northern part. Entering the lagoon in the central area, the River Nemunas supplies 98% of the total freshwater to this water body. The marine intrusion and riverine freshwater not only result in variable salinity patterns but also influence the concentration and distribution of nutrients and biochemical elements, thus giving rise to a complex ecosystem. Moreover, the Curonian Lagoon is one of the most highly eutrophicated coastal lagoons in the Baltic Sea (Krevs et al. 2007); nutrient concentration dynamics are typical of temperate and boreal transitional waters with strong riverine inputs. The highest concentrations of nutrients occur in early spring (Zemlys et al. 2008). The lagoon provides a vital habitat and spawning site for ecologically and economically important species such as those quoted by Breber et al. (2008): European eel (*Anguilla anguilla* L.), gilthead seabream (*Sparus aurata* L.) and grey mullet (e.g. *Mugil cephalus* L., *Liza aurata* Risso). The urgent need for water quality monitoring in the Curonian Lagoon have been highlighted by the presence of cyanobacterial toxic metabolites, recently documented by Paldavičienė et al. (2009): cyanobacterial blooms are the main concern in this region as regards water quality issues and potential risks to human health. Apart from cyanobacteria, the elevated nutrient load, resulting in spring concentrations of N-NO_3 > 100 μM (March 2009), sustains high primary production by phytoplankton communities. Chl *a* concentrations > 50 mg m^{-3}, typical of eutrophic-dystrophic brackish environments, are frequent. The surface sediments exhibit areas with muddy sand or a fluffy organic bottom, receiving labile particles fuelling elevated microbial respiration rates. This results in high nutrient recycling, also favoured by strong winds and shallowness, and high O_2 consumption. Nocturnal hypoxia or anoxia has been reported (Zemlys et al. 2008).

Nevertheless, effective approaches that can fulfil the needs for spatial and temporal water quality monitoring are critical in this large area. In particular, the collection of in situ data with traditional techniques may not be sufficient to acquire an understanding of the characteristics of such an extensive target area, where the water quality conditions can change rapidly as a consequence of blooms or meteorological conditions. Moreover, an important coordination effort would be necessary to sample stations distributed around this entire ecosystem, since the Curonian Lagoon is administratively divided into two by the Lithuanian-Russian border.

Remote sensing may therefore offer a satisfactory response to the challenge presented by the situation described above, given the spatial/temporal frequency of observation by satellite sensors, which capture image data above national borders. In particular, the MEdium Resolution Imaging Spectrometer (MERIS), on board Envisat-1, which combines moderately high spatial resolution (300×300 m for Full Resolution (FR) data) with appropriate spectral resolution in the visible and near infra-red, is useful for the frequent monitoring of optically active parameters.

The main aim of this research is to explore reliable remote sensing methods for full spatial cover and continuous monitoring of key biological and environmental parameters affecting water quality in the Curonian Lagoon. In particular, the study focuses on chlorophyll *a* (chl *a*) as an indicator of the trophic level. Coloured dissolved organic matter (CDOM) is also investigated because of its role in protecting aquatic biota from ultraviolet solar radiation and its influence on overall microbial activity in the water column, determining the shift from net autotrophy to net heterotrophy (Kutser et al. 2005). Mapping chl *a* and CDOM concentrations from different satellite sensors has been demonstrated for the Baltic Sea by several studies (e.g. Kutser et al. 2006, Reinart & Kutser 2006, Kahru et al. 2007, Kratzer et al. 2008). In order to investigate water quality in the adjacent Curonian Lagoon we tested a neural network-based algorithm, recently developed for assessing water quality in case 2 waters (Doerffer & Schiller 2008), as well as band-ratio algorithms (Gitelson et al. 2007). The algorithms were applied to two MERIS FR images and evaluated by comparing the outputs to in situ data collected synchronously with satellite overpasses in March and July 2009. The application of the best performing algorithms to image data enabled us to assess the ecological status of the Curonian Lagoon waters in two different seasons.

2. Material and methods

2.1. In situ data

Two field campaigns were conducted, on 23/26 March 2009 and on 21/22 July 2009 (Figure 1), at a total of 25 stations in the Lithuanian part of the Curonian Lagoon.

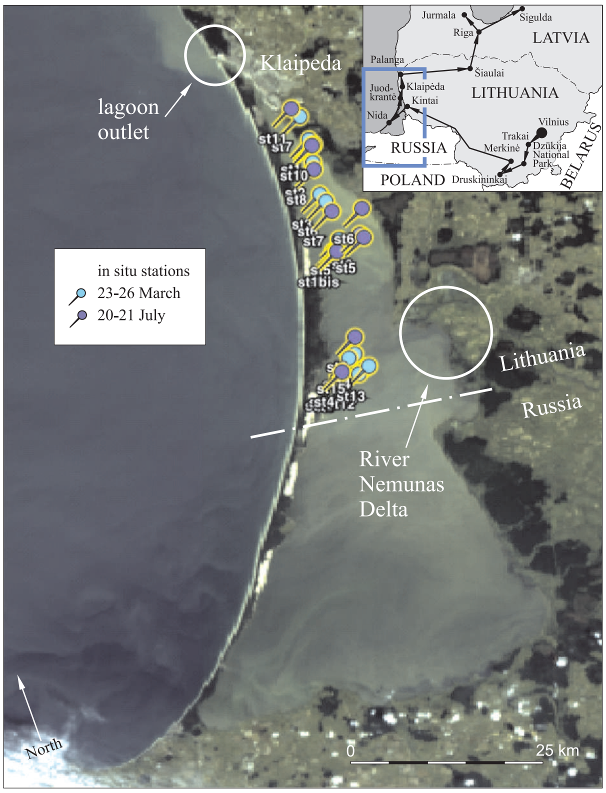

Figure 1. MERIS data acquired on 22 July 2009 with locations of in situ stations. The border between Lithuania and Russia is shown. The image covers an area of about 100 km × 150 km. The pseudo true colour MERIS image clearly shows the different optical behaviour of the Curonian Lagoon and Baltic Sea waters

At each station, water samples were collected just below the surface for subsequent laboratory analysis: chl *a* concentrations were determined by spectrophotometry according to Lorenzen (1967); CDOM concentrations were determined as the absorption coefficients of filtered water at 440 nm as described by Strömbeck & Pierson (2001). The phytoplankton composition was determined in situ along vertical profiles at each station by means of a fluoroprobe. The fluoroprobe (FluoroProbeII) permits 'spectral groups' of microalgae (cyanobacteria, green algae, cryptophytes, diatoms and dinoflagellates) to be differentiated according to the distinctive accessory pigments of the groups (Beutler et al. 2002). Finally, the upwelling radiance below the water surface and the downwelling irradiance above the surface were measured at each station. The measurements were acquired by affixing different lenses (6° for the underwater upwelling radiance; a remote cosine receptor for the downwelling irradiance above water) to a hand-held spectroradiometer (ASD Inc. FieldSpec FR Pro). The underwater upwelling radiance was corrected by the emersion factor according to Dall'Olmo & Gitelson (2005) and Pierson & Strömbeck (2001), then normalised to the downwelling irradiance above water to derive the remote sensing reflectance (R_{rs}) for comparison with atmospherically corrected MERIS data.

Widely different water component conditions were encountered in the study area: chl *a* concentrations varied between 10.2 and 63.7 mg m^{-3} and CDOM concentrations between 0.71 and 2 m^{-1}. Overall, chl *a* concentrations were higher in July than in March, whereas the opposite situation applied to CDOM. Chl *a* and CDOM concentrations were not related ($r^2 = 0.371$, Figure 2), confirming that the Curonian Lagoon is a typical case 2 water body (Morel & Prieur 1977). The phytoplankton composition measured with the fluoroprobe revealed that in March diatom and dinoflagellate species (58%) prevailed, whereas in July cyanobacteria species were predominant (63%).

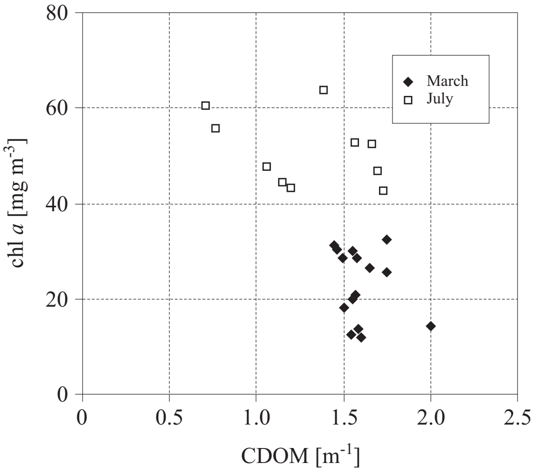

Figure 2. Chllorophyll *a* concentrations versus CDOM concentrations; the poor correlation ($r^2 = 0.37$) is typical of case 2 waters

2.2. MERIS data

Two MERIS FR level 1 images, acquired on 26 March and 22 July 2009 during fieldwork activities, were used in this investigation. The MERIS lake algorithms (Doerffer & Schiller 2008) implemented in the Basic ERS & Envisat (A)ATSR and MERIS (BEAM) toolbox (Fomferra & Brockmann 2005) were used first to assess the retrieval of both R_{rs} data and subsequently the water quality parameters, based on specific ranges of chl *a*, CDOM and total suspended matter. In particular, the Case 2 Regional (C2R) water processor presents a bio-optical model adapted to the variation in a wide range of inherent optical properties; in contrast, the eutrophic lake and boreal lake processors share the same architecture, but the bio-optical models were optimised for extreme concentrations of chl *a* and CDOM respectively (Ruiz-Verdù et al. 2008). The R_{rs} values estimated using the BEAM toolbox were compared to in situ R_{rs} data (Figure 3). The optical closure was good in the blue-green region of the electromagnetic spectrum, whereas a deviation was observed beyond the red wavelengths, both in March and July. In particular, the C2R processor was unable to capture the typical peak of R_{rs} around 700 nm, due to a combination of high backscattering, exponentially increasing absorption by water molecules and low absorption by CDOM and phytoplankton at these wavelengths (Kutser 2009). Therefore, an alternative method to convert the sensor radiance into water reflectance was used. The radiative transfer code 'Second Simulation of the Satellite Signal in the Solar Spectrum (6S)' (Vermote et al. 1997, Kotchenova et al. 2006) was parameterised with the maritime model for an aerosol whose concentration at 500 nm was estimated from in situ measurements of downwelling diffused and total solar irradiance (Baker & Smith 1990). The comparison between 6S-derived R_{rs} values and in situ data (Figure 3) shows up certain problems that 6S has in providing a good closure in this eutrophic environment. In particular, at the shorter wavelengths, the retrieved spectra were overestimated with respect to in situ data with a behaviour that was also observed by Floricioiu & Rott (2005) when they applied the 6S code to MERIS imagery of subalpine lakes.

Based on the comparison between in situ and MERIS-derived R_{rs} data, two different approaches were chosen to provide accurate mapping of CDOM and chl *a* in the study area. Since at shorter wavelengths R_{rs} values are very sensitive to CDOM variations (Giardino et al. 2007) we expected the inversion of R_{rs} data provided by the C2R processor to be good enough to retrieve accurate values of CDOM. In contrast to the chl *a* assessment, we expected the 6S-derived R_{rs} values to be more appropriate, being able to capture the R_{rs} peak around 700 nm, clearly observed for in situ spectra, too.

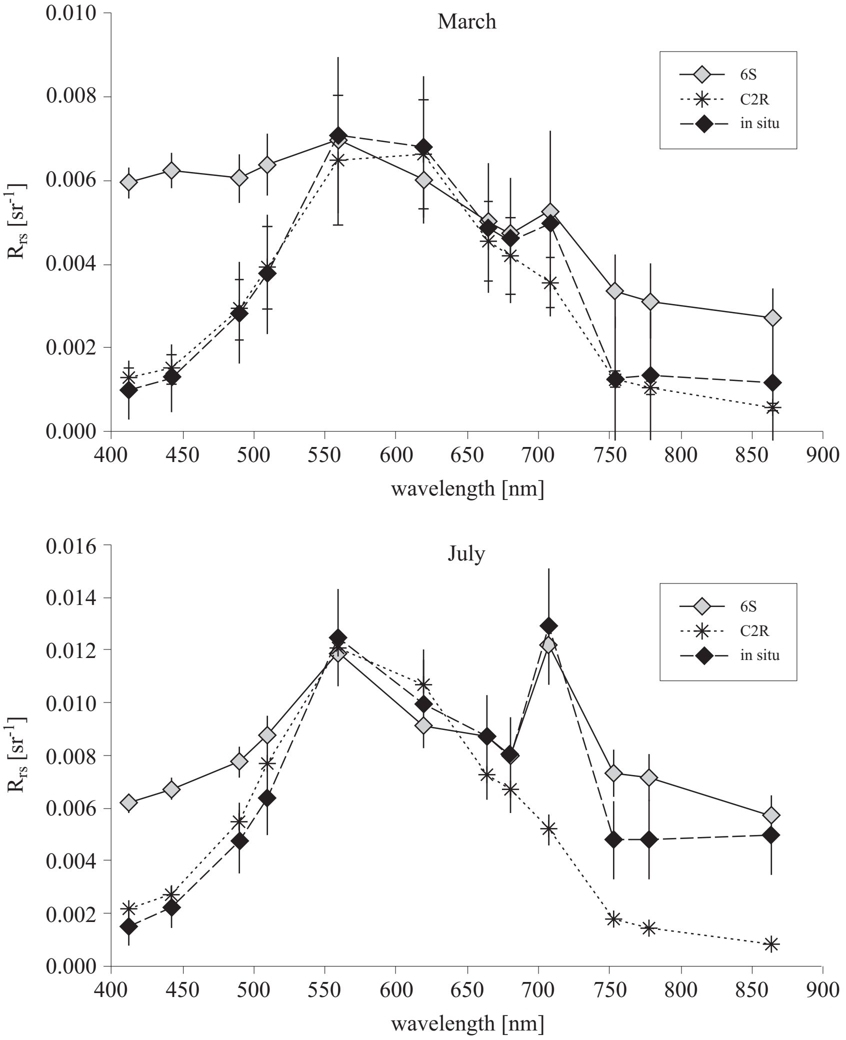

Figure 3. Comparison of MERIS-derived R_{rs} values for image data acquired on 26 March and 22 July 2009 and in situ data. MERIS R_{rs} values were derived using both the C2R processor and the 6S code. In situ R_{rs} data were resampled according to MERIS bands. The plotted spectra are the average values (plus/minus the standard deviation) of 15 (March) and 10 (July) stations

2.3. Band-ratio algorithm for chl *a*

In situ R_{rs} spectra were used to parameterise a semi-empirical algorithm for retrieving chl *a* concentrations. To quantify chl *a* concentrations in eutrophic waters, a variety of algorithms have been developed; all are based on the properties of reflectance values near 700 nm (e.g. Schalles 2006).

These include the ratio of the reflectance peak to the reflectance at about 670 nm (e.g. Dekker 1993). Alternatively, good correlations have been found between chl *a* and the position of the reflectance peak near 700 nm (Gitelson 1992), the first derivative of reflectance at 676 (Han et al. 1997) and the three-band algorithm proposed by Dall'Olmo et al. (2003) and Gitelson et al. (2007). In this investigation we proposed using the band-ratio algorithm involving the two wavelengths in which the matching between 6S-derived R_{rs} values and in situ data was higher, i.e. 708 and 664 nm, which correspond to MERIS bands 6 and 9 respectively (see Figure 3). However, the algorithm was built using in situ data solely in order to develop an image-independent model. Figure 4 depicts the linear correlation between the concentrations of chl *a* and the $R_{rs}(708)/R_{rs}(664)$ ratios, both derived from in situ data.

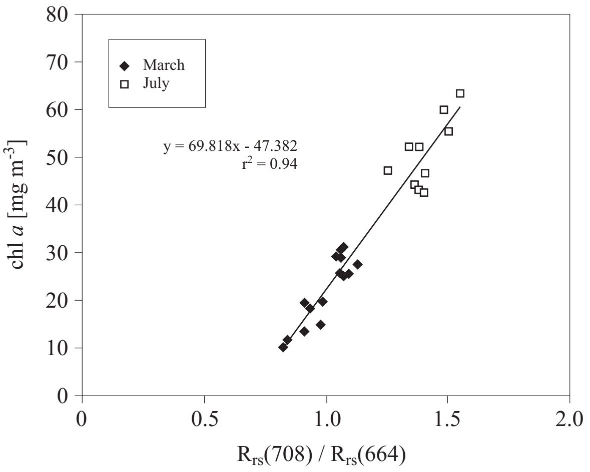

Figure 4. Band-ratio algorithm derived from in situ R_{rs} data versus laboratory measurements of chl *a* concentrations

3. Results and discussion

Figure 5 presents the two CDOM and chl *a* maps retrieved from MERIS imagery acquired on 26 March and 22 July 2009. The CDOM map was derived by using the C2R processor, which simultaneously corrects image data for atmospheric effects and provides concentrations of water quality parameters. The chl *a* map was produced by applying the band-ratio algorithm (see Figure 4) to the 6S-derived R_{rs} values in bands 9 and 7. In March the spatial distribution of CDOM proved to be more heterogeneous than in July, with the highest values being recorded in the Lithuanian

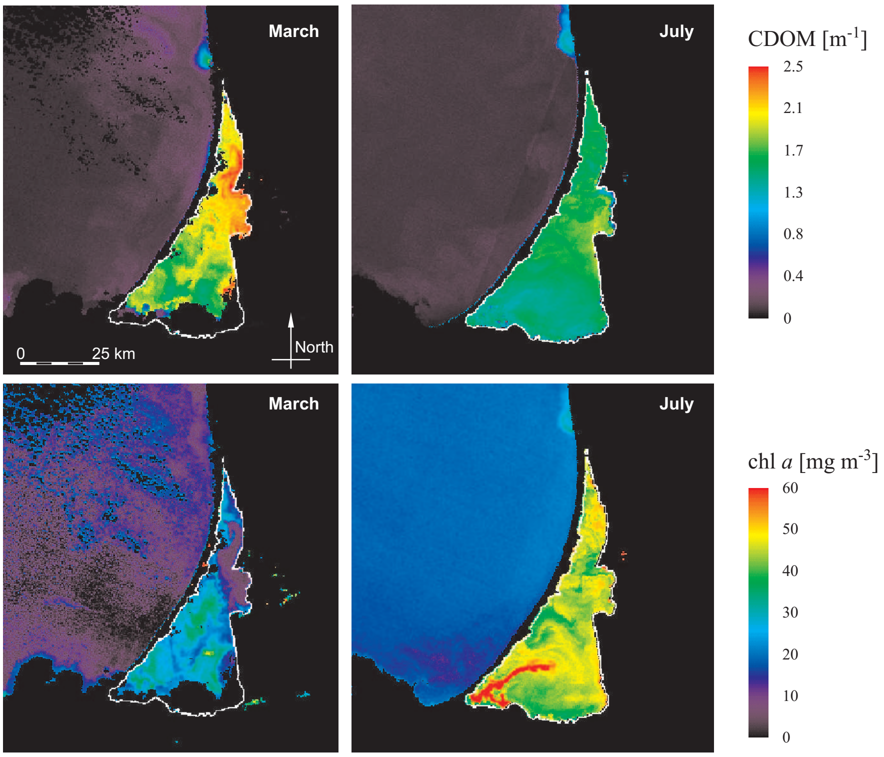

Figure 5. CDOM and chl *a* concentration maps of the Curonian Lagoon and of the nearby Baltic Sea derived from MERIS data

part of the lagoon. In both seasons Curonian Lagoon waters were richer in CDOM than the nearby Baltic Sea, whose CDOM concentrations were higher only at the lagoon outlet. The chl *a* concentration maps show the opposite behaviour, although the patchy distribution of phytoplankton is common to both seasons. In March 2009, the higher CDOM values close to the north-eastern shore were a probable consequence of riverine input and decomposition of macrophytic vegetation (reedbeds) bordering the lagoon.

In March chl *a* was lower in the vicinity of the Nemunas delta, probably because of enhanced solid transport and low transparency. The opposite was found in July, with increasing concentrations over the entire lagoon system. Chl *a* peaks close to the town of Klaipeda (200 000 AE) were probably sustained by point discharges of nutrients from a sewage plant. Hydrochemical analyses revealed a very low nutrient content in the water coupled with the spring phytoplankton bloom when all N and P were in particulate form. The chl *a* peak recorded in the southern part of the lagoon deserves more detailed investigation; it could have been due to a combination of water circulation patterns and point discharges of nutrients in the Russian part of the lagoon.

Table 1 compares in situ data and water quality parameters derived from MERIS imagery at the field stations sampled during the two satellite overpasses. For completeness, the comparison of image-derived products for chl *a* also includes the output of the C2R processor. The C2R-derived CDOM concentrations were comparable to in situ data in both seasons, demonstrating the ability of this processor to describe CDOM variations on both dates. In contrast, the same processor strongly underestimated the chl *a* concentrations, particularly in July, when a cyanobacterial bloom was observed. The most likely cause of such underestimation may have been the uncorrected C2R-derived R_{rs} data at red/near-infrared wavelengths (see Figure 3), which strongly influence chl *a* retrieval from bio-optical modelling. Instead, the band-ratio algorithm, developed by using in situ data and subsequently applied to 6S-corrected MERIS data, gave a more reliable estimate of chl *a* values in both March and July.

Table 1. Comparison of MERIS-derived products and in situ data. For chl *a* the MERIS products were derived with the C2R processor and the semi-empirical model applied to 6S-derived R_{rs} data, while for CDOM the products were generated by using the C2R processor only. The statistics, both for in situ and image data, were computed for the 15 and 10 stations measured in March and July respectively

	chl *a* [mg m^{-3}]						CDOM [m^{-1}]			
	26 March 2009			22 July 2009			26 March 2009		22 July 2009	
	C2R	6S and band-ratio	in situ	C2R	6S and band-ratio	in situ	C2R	in situ	C2R	in situ
Min	10.28	20.39	11.67	7.60	45.36	43.68	0.57	1.45	1.19	0.71
Max	14.26	33.65	32.37	9.27	54.25	74.48	1.85	2.00	1.45	1.73
Mean	**10.91**	**27.00**	**22.96**	**8.36**	**50.52**	**56.49**	**1.59**	**1.60**	**1.33**	**1.29**
Std-Dev	0.89	4.08	7.76	0.52	3.13	11.12	0.46	0.14	0.07	0.38

4. Conclusions

This work presents a procedure to map CDOM and chl *a* concentrations in the Curonian Lagoon from MERIS satellite data based on two different approaches, whose accuracy was validated by comparison with in situ data collected in two different seasons of 2009. For CDOM mapping, the C2R processor available in the BEAM toolbox was considered appropriate, being able to describe R_{rs} behaviour at the shorter wavelengths, hence providing CDOM ranges comparable to in situ measurements. For the chl *a* map, the procedure based on R_{rs} band-ratio in the red/near-infrared wavelengths, developed using in situ data and then applied to 6S-corrected satellite data, provided better results than C2R, confirming the sensitivity of water quality algorithms to the accuracy of the atmospheric correction (Keller 2001).

The results also indicate the patchy distribution of water quality parameters in the Curonian Lagoon and suggest that further MERIS data need to be processed for a thorough investigation of the spatial and temporal dynamics of this very extensive ecosystem. Since promising results were obtained for two different seasons, the procedure presented here appears to be transferable to other images, providing the opportunity to occasionally compare the MERIS-derived estimates to in situ measurements.

Results from this combined in situ and calibration work confirm the hypertrophic/dystrophic conditions of the Curonian Lagoon. The impressive chl *a* values, increasing from March to July, must be considered in the context of the large volume of water in the system. The present status is surely the result of elevated nutrient inputs from diffuse and point sources (the River Nemunas and the town of Klaipeda), slow water renewal and elevated internal loads. We believe that the forcing factors in this shallow system, such as wind, play a key role in determining water quality and optically active parameters; they also sustain primary production via nutrient recycling. We believe that the procedures presented will allow accurate, reliable and frequent screening of phytoplankton and cyanobacterial bloom in this very large area. This information, together with water circulation maps, meteorological parameters (wind speed and direction) or point nutrient inputs, and a map of sediment features will enable us to explore the complex dynamics and the short-term evolution of microalgal blooms. Nevertheless, further calibration/validation exercises will be necessary before more general conclusions can be drawn and algorithms applicable to other time-series images provided.

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