Remote sensing for aquatic habitat quality mapping and EU Water Framework Directive (EU-WFD) reporting

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1. Introduction

The measurement and mapping of a number of parameters important for the water quality, aquatic habitats and biodiversity of lakes have been found to be possible using satellite remote sensing, and particularly the European Space Agency's MEdium Resolution Imaging Spectrometer (MERIS). These include total suspended mater concentration (TSM), the diffuse attenuation coefficient at 490 nm (K_d(490)) and phytoplankton biomass via the proxy chlorophyll-*a* concentration (chl-*a*) (Odermatt et al., 2012; Matthews, 2011). These both affect and reflect environmental conditions of lakes and have been recognized as important to monitor through their inclusion in the Water Framework Directive of the European Union (EU-WFD). The mapping of chl-*a*, TSM and Kd(490) is demonstrated here in application to Lake Balaton, Hungary, and the translation of chl-*a* maps to the classification language of the EU-WFD is carried out, highlighting the improvement to the spatial information of the resulting classes possible through the use of remote sensing.

2. Data and methods

2.1 Study site

Lake Balaton in western Hungary (Fig. 1a) is a large (597 km^2 surface area) and shallow (3.3 m average depth) water body. Characterized by hyper-eutrophication which peaked in the 1980s, water quality has since greatly improved. A strong trophic gradient persists, however, related to the nutrient-rich waters of the Zala River inflowing in the southwesternmost Basin 1 and gradual water circulation northeastward to Basin 4 (Fig. 1b). Two annual phytoplankton blooms typically occur; a small spring bloom and a larger late summer bloom. Moderate to high phytoplankton biomass as well as high concentrations of inorganic suspended matter contribute to the highly turbid nature of Balaton. This restricts the proliferation of both submerged and emergent aquatic vegetation which occurs mainly in the very near shore environment.

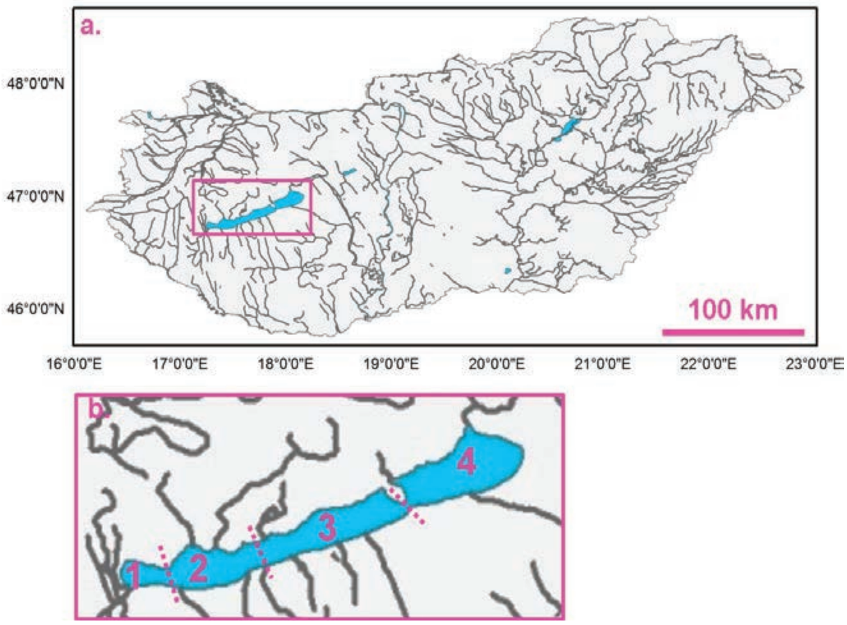

Figure 1. Location of Lake Balaton in western Hungary (a); the division of its four basins (b).

2.2 MERIS satellite water quality mapping

Palmer et al. (2014a) report robust correlation between *in situ* chl-*a* measurements and the Fluorescence Line Height (FLH) algorithm applied to L1b MERIS imagery. The locally calibrated algorithm was then applied to daily MERIS images for chl-*a* mapping, and dekad-binned images were also used by Palmer et al. (2014b) for the extraction, mapping and analysis of phytoplankton phenology metrics. These dekad as well as monthly binned mean chl-*a* maps are translated here for EU-WFD classification. Monthly mean maps of TSM and $K_d(490)$ were produced by and obtained from the ESA funded Diversity-2 project. Both TSM and Kd(490) maps result from the application of neural network-based algorithms (C2R; Doerffer and Schiller, 2007).

2.3 EU-WFD phytoplankton biomass reporting

EU-WFD reporting for Lake Balaton is the responsibility of the Central Transdanucian (Regional) Inspectorate for Environmental Protection and Nature Conservation (Közép-dunántúli Környezetvédelmi, Természetvedelmiés Vízügyi Felügyeloség (hereafter referred to as KdKVI)). Chl-*a* concentrations are measured weekly by the KdKVI between mid-May and mid-September, from samples taken at the centres for the four main basins along the longitudinal axis of the lake (Fig. 1) and are classified in accordance with the commonly referred to trophic status-based water quality classification system of the Organization for Economic Cooperation and Development (OECD; Table 1). The corresponding classification for each sampling date is reported, and made available on the KdKVI website (http://www.kvvm.hu/balaton/lang_en/index.htm), along with the seasonal average. Values reported for August, 2010 are compared here with MERIS image retrieved classes.

Table 1. EU-WFD classification associated with mean annual (mid-May through mid-September) chl-*a* concentrations of Hungarian lakes (personal communication with KdKVI, 2014).

Chl-*a* (mg m^{-3})	OECD classification	EU-WFD classification
< 8	Oligotrophic	Excellent
8 – 25	Mesotrophic	Good
25 – 75	Eutrophic	Average
> 75	Hypertrophic	Poor

3. Results

Maps of chl-*a* concentration, TSM concentration and $K_d(490)$, representing the averages of all retrievals for the month of August 2010, are presented in Figure 2 a-c. The typical trophic gradient described in Section 2.1 is clear in the chl-*a* map, with concentrations as high as 35 mg m^{-3} in Basin 1 and lower than 5 mg m^{-3} in Basin 4. TSM concentrations are found to display a gradient from the north to the south shores of the lake. This is expected to result from the predominant, northerly wind conditions, which favour resuspension along the north shore. TSM concentrations are also lower in Basin 4, which is deeper that the other basins, such that resuspension occurs less readily. $K_d(490)$ reveals a combination of the patterns and features found in chl-*a* and TSM maps, as this parameter is dependent on the light attenuation of these two factors. TSM, however, is clearly the dominant influence.

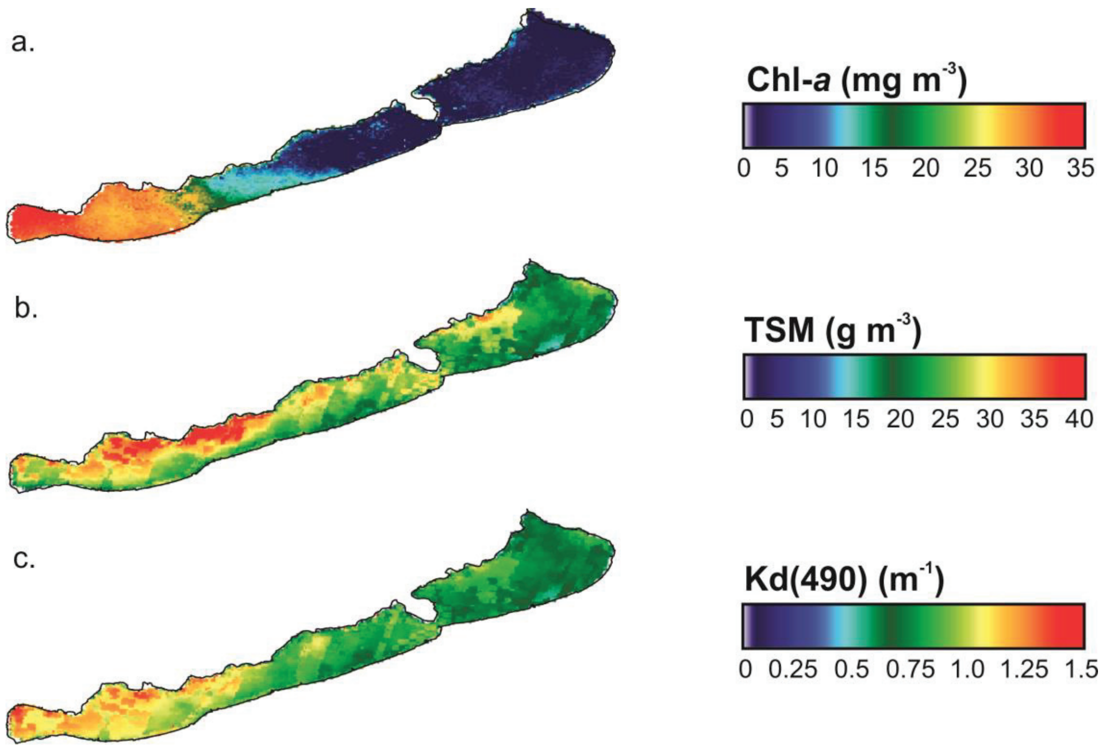

Figure 2. Maps of mean monthly chl-*a* concentration (a), TSM concentration (b), $K_d(490)$, and the probability of cyanobacteria dominance of phytoplankton community composition.

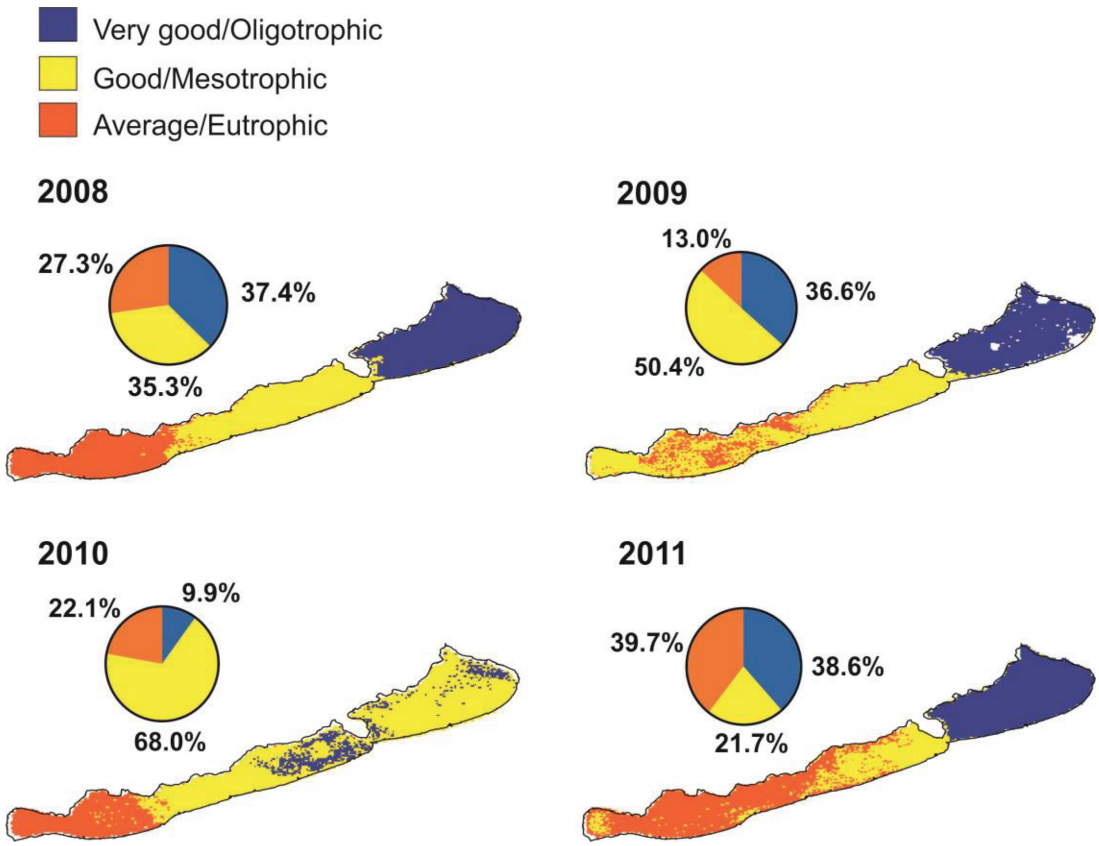

Figure 3. Maps of EU-WFD phytoplankton biomass (chl-*a* concentration) classifications for August 2008, 2009, 2010 and 2011 and % spatial extents of the retrieved classes.

Table 2. Comparison of EU-WFD classifications using *in situ* and using MERIS satellite data from the four main lake basins (Fig. 1) for the same period in August of each year. Of the 16 compared classifications, only 1 (6.25%) is not compatible (highlighted).

Year	Basin	Oligotrophic ("Excellent")		Mesotrophic ("Good")		Eutrophic ("Average")	
		In situ	MERIS	*In situ*	MERIS	*In situ*	MERIS
2008	1					X	X
	2			**X**			**X**
	3			X	X		
	4	X	X				
2009	1			X	X		
	2					X	X
	3			X	X		
	4	X	X				
2010	1					X	X
	2					X	X
	3			X	X		
	4			X	X		
2011	1					X	X
	2					X	X
	3			X	X		
	4	X	X				

Chl-*a* maps from August of 2008, 2009, 2010 and 2011, translated into the classes used for EU-WFD reporting are presented in Figure 3. The spatial extent of each retrieved class for each of the four years was also calculated as a percentage of the total. In addition to revealing the general trophic status of each of the four basins, considerable detail on spatial patterns and trends, and the high variability of these over time was revealed. Classification results obtained using MERIS-retrieved chl-*a* concentrations were found to be similar to the results obtained through the conventional monitoring and reporting currently carried out by the KdKVI. Only one of sixteen comparisons was found to deviate, corresponding to only 6.25 % of comparisons (Table 2).

4. Conclusions & outlook

Maps of three parameters of interest from a water quality and aquatic habitat perspective have been produced for Lake Balaton using archive MERIS data. MERIS is no longer acquiring data, but has similar features to the future Sentinel-3 Ocean and Land Colour Imager (OLCI), which is foreseen to provide continuity to mapping and monitoring activities such as those presented here (ESA, 2013). Validation activities using the MERIS archive are continuing and will be followed by similar exercises using OLCI, as well as Sentinel-2 MultiSpectral Imager data. Such maps will serve as complementary data sources for the EU-WFD, as has been demonstrated here for chl-*a* reporting. In addition to providing results comparable with those using *in situ* point measurements, satellite imagery has been demonstrated to provide quantitative, detailed spatial information. The application and comparison of such EU-WFD compatible mapping to other lakes will be interesting, both within Hungary (Lakes Velence, Tisza and Fertő for example) and internationally. When comparing EU-WFD reports from other countries, it is important to keep in mind that each country follows its own methodology and classification, although the standardization of these is underway.

Acknowledgements

The authors gratefully acknowledge the financial support of this project through GIONET, funded by the European Commission, Marie Curie Programme Initial Training Network, Grant Agreement PITN-GA-2010-264509, as well as data access through the ESA CoastColour and Diversity-II projects. H. Balzter was supported by the Royal Society Wolfson Research Merit Award, 2011/R3 and S.C.J. Palmer by a doctoral scholarship from the Fonds de recherche du Québec – Nature et technologies.

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