

**Detecting cyanobacterial
blooms in large North
European lakes using the
Maximum Chlorophyll
Index***

OCEANOLOGIA, 52 (2), 2010.
pp. 237–257.

© 2010, by Institute of
Oceanology PAS.

KEYWORDS

MERIS

Maximum Chlorophyll Index

Phytoplankton

Cyanobacteria

Chlorophyll *a*

KRISTA ALIKAS^{1,*}

KERSTI KANGRO²

ANU REINART¹

¹ Tartu Observatory,
EE-61602, Tõravere, Tartumaa, Estonia;

e-mail: alikas@ut.ee

*corresponding author

² Centre for Limnology,
Institute of Agricultural and Environmental Sciences,
Estonian University of Life Sciences,
EE-61117 Rannu, Tartumaa, Estonia

Received 8 October 2009, revised 16 April 2010, accepted 17 April 2010.

Abstract

The Maximum Chlorophyll Index (MCI), developed for the MERIS sensor processing scheme, is used to investigate the seasonal dynamics, spatial distribution, and coverage of cyanobacterial blooms over Lake Peipsi (Estonia/Russia) and Lake Võrtsjärv (Estonia). In these optically complex waters, the amounts of suspended matter and dissolved organic matter vary greatly and independently of the phytoplankton biomass. We demonstrate that MCI is a useful, new tool for detecting and estimating cyanobacterial biomass ($R^2 = 0.73$), phytoplankton biomass ($R^2 = 0.70$) and chlorophyll *a* concentration ($R^2 = 0.64$). The MCI-derived results are consistent with known patterns of phytoplankton dynamics in these

* This paper was presented at the Remote Sensing and Water Optics Workshop of the 7th Baltic Sea Science Congress, August 2009, Tallinn, Estonia.

lakes, whose optical properties are in the same range as in many coastal regions of the Baltic Sea.

1. Introduction

In conditions of rapidly changing climate and increasing anthropogenic impact on coastal and inland waters, there is an urgent need to improve the effectiveness of monitoring methods. The need for unified monitoring of waters has resulted in the EU Water Framework Directive 2000/60/EC (WFD) to restore and protect water bodies from further degradation, and therefore various biological quality elements need to be monitored in order to describe the present status of a water body. WFD considers phytoplankton biomass (TBM), cyanobacterial biomass (CY) and chlorophyll *a* concentration (Chl *a*) to be important ecological parameters that give an overview of phytoplankton in lakes and are regarded as essential parameters in conventional monitoring programmes.

The development of satellite sensors and new remote sensing algorithms is an ongoing process; moreover, because of the spatial and temporal variability of cyanobacterial blooms, it is becoming essential to assess whether standard monitoring and mapping methods could be supported with remote sensing techniques. The MERIS (Medium Resolution Imaging Spectrometer) sensor's high spectral and radiometric resolution and processing algorithms make it suitable for monitoring optically complex coastal waters and large lakes (Härma et al. 2001, Koponen et al. 2002, Doerffer & Schiller 2007, Gons et al. 2008). For case 1 waters, where optical properties are determined by phytoplankton and its degradation products, MERIS algorithms tend to give reasonably good estimates (Morel et al. 2007, McClain 2009). In multicomponent case 2 waters the effects of high nutrient and sediment loads make the interpretation of the optical signal more difficult (Sørensen et al. 2004, Alikas & Reinart 2008, Kratzer et al. 2008). In the case of coastal and inland waters the adjacency effect and various types of coastal and absorbing aerosols further increase the complexity of the problem. Therefore, new algorithms have been developed to complement standard case 2 water quality parameters such as the concentration of Chl *a*, total suspended matter (TSM), coloured dissolved organic matter (CDOM) and water transparency (Schroeder & Schaale 2005, Doerffer & Schiller 2008, Koponen et al. 2008). Remote sensing techniques are highly advantageous for monitoring parameters like phytoplankton, which are sensitive to weather conditions (wind, temperature, solar irradiance); these, in turn, may cause rapid changes in concentrations. Moreover, phytoplankton distribution at the water surface can be extremely patchy and could remain unobserved if not for routine

satellite measurements, which can be carried out on a case by case basis or at a global scale.

The seasonal dynamics of phytoplankton can be described by its biomass and Chl *a* concentration. Several studies have used remote sensing data to examine the determination of Chl *a* concentration as a proxy for phytoplankton biomass (Ruddick et al. 2001, Gons et al. 2002). Cyanobacteria often form the main component of the phytoplankton community in lakes and in the Baltic Sea during summer (Smith et al. 1987, Sellner 1997, Jaanus et al. 2009). Attempts have been made to assess the presence of cyanobacteria in a water body by estimating their phycocyanin (PC) pigment content. For example, the nested band ratio approach, developed by Simis et al. (2005), targets the phycocyanin absorption effect in reflectance spectra in the 620 nm region. Quantification of PC through the reflectance at 620 nm was done with a single reflectance band ratio algorithm by Schalles & Yacobi (2000). Kahru et al. (2007) developed algorithms for estimating the frequency of cyanobacterial accumulations using high normalised water-leaving radiances at 670 nm or 555 nm. The time series, starting from 1979, were compiled using data from ocean colour sensors such as CZCS, SeaWiFS and MODIS.

The height of the peak near 709 nm in the radiance spectrum determines the Maximum Chlorophyll Index (MCI) in MERIS data. The spectral features in this region include Chl *a* absorption around 675 nm, Chl *a* fluorescence around 683 nm, and in algae-laden waters the prominent reflectance peak around 690–700 nm caused by algal-cell scattering and a minimum in the combined absorption curves of algae and water (Rundquist et al. 1996). MCI has been used to distinguish phytoplankton blooms from other substances that increase backscattering in the near-infrared spectral region. Gower et al. (2006) provided the first assessment of floating *Sargassum* in the Gulf of Mexico and detected ‘superblooms’ of Antarctic diatoms (Gower & King 2007). MCI has also been implemented to detect plumes carrying high suspended-sediment loads, by means of global time series (Gower et al. 2008a). Global composites by reduced resolution images have shown a significant detection rate by marking one plankton bloom event on any given day, both in remote areas and in the vicinity of more heavily populated areas (Gower et al. 2008b). However, the performance of MCI over lakes has not yet been tested.

In this study we tested MCI over optically complex waters for the following reasons: (i) MCI is a parameter easily available to the water monitoring authorities, as calculations in MERIS processing are carried out with the aid of the user-friendly BEAM software (Brockmann Consult); (ii) it takes into account the band near 709 nm; this is unique to the MERIS

sensor, but it could also be estimated by other existing or new hyperspectral satellite and airborne measurements, and is therefore potentially generally applicable to different remote sensing systems; (iii) the red and near infrared region would be the most useful for the remote sensing of the relatively humic Baltic Sea and boreal lakes, as this region of the spectrum is less affected by CDOM absorption than at shorter wavelengths.

Physically large lakes exhibit several similarities to seas and oceans in their thermal structure and circulation dynamics (Nõges et al. 2008) and also in their phytoplankton composition. In northerly regions, cyanobacterial blooms have become very typical of mid- and late summer in inland waters as well as in the Baltic Sea. Two large north European lakes, Peipsi and Võrtsjärv, have been well studied and regularly monitored since the beginning of the 1960s (Laugaste et al. 1996, Huttula & Nõges (eds.) 1998). Lake Peipsi is the largest trans-border water body in Europe, but regular monitoring of the whole lake is complicated by border restrictions. The benefits of complementing this monitoring with satellite remote sensing have already been recognised. Both lakes are large enough for satellite applications and have specific, unique characteristics relevant to this study.

The main objective of the paper is to determine whether it is feasible to link MCI to the seasonal and spatial distribution of phytoplankton biomass, cyanobacterial biomass and chlorophyll *a* concentration in optically complex waters. The sensitivity of MCI to various species of phytoplankton (cyanobacteria, diatoms) is also demonstrated. The quantitative mapping of the parameters examined here is considered to be just the first step towards the ultimate goal of mapping the movement of blooms and the possibility of calculating the area covered by surface scum or by a higher biomass content, and to characterize the ecological impact of these blooms.

2. Material and methods

2.1. Study area

Lake Peipsi is located in eastern Estonia (Figure 1) on the border with Russia. It consists of three parts: the largest and deepest mesotrophic Lake Peipsi s.s., the middle, strait-like eutrophic Lake Lämmijärv, and the hypertrophic Lake Pihkva, which is entirely in Russia. The phytoplankton in Lake Peipsi is typical of large lowland lakes, with species displaying from oligotrophic to hypertrophic preferences. The characteristics of the phytoplankton (species composition, shape, pigments, seasonal behaviour etc.) in Lake Peipsi tend to resemble those of the central Baltic Sea (dominance of nitrogen fixers) and contain taxa that are similar to those of



Figure 1. Lake Vörtsjärv (left) and Lake Peipsi (right) on a MERIS reduced resolution level 1 image from 26 May 2008

other large north European lakes like Ladoga, Onega, Vänern, Vättern and Mälaren (Laugaste et al. 2008).

In Lake Peipsi, diatoms and blue-green algae are prevalent in the phytoplankton biomass. *Aulacoseira* spp. and smaller centric diatoms (*Cyclotella*, *Stephanodiscus*) are dominant. The dominant phytoplankton species in Lake Peipsi did not change significantly during the 20th century, and blooms of *Gloeotrichia* were recorded already 100 years ago (Kullus 1964). *Gloeotrichia echinulata* prefers a mesotrophic environment; it is numerous in Lake Erken, for example (Karlsson-Elfgren et al. 2005). All parts of Lake Peipsi show an increasing trend as regards cyanobacterial biomass based on in situ data. The trend is most pronounced in the southern parts of the lake (Laugaste et al. 2007). In spring the average phytoplankton biomass does not usually exceed 16 g m^{-3} in Lake Peipsi (Nõges et al. 1996). The blue-greens *Gloeotrichia echinulata* (J.S. Smith) P. Richt., *Aphanizomenon flos-aquae* (L.) Ralfs and *Aphanothece saxicola* Näg. are prevalent in summer, giving rise to cyanobacterial blooms (Nõges et al. 1996). *Planktothrix agardhii* (Gom.) Anagn. & Kom. and species of *Anabaena* and *Microcystis* have occasionally prevailed with growing importance since 2002. The summer cyanobacterial peak occurs every year, even in cold weather (Laugaste et al. 2007). The summer and autumn biomasses (blue-greens and diatoms) are between 3–15 and 7–16 g m^{-3} respectively in Lake Peipsi, and area generally higher in Lake Pihkva (usually < 35 , but with a maximum of $> 125 \text{ g m}^{-3}$) (Nõges et al. 1996, Laugaste et al. 2008).

Lake Võrtsjärv is a shallow eutrophic lake situated in central Estonia (Figure 1). It is a turbid lake (Table 1), where 40–52% of the PAR is attenuated by CDOM, 7–11% by phytoplankton pigments and 19–25% by detritus (Reinart & Nõges 2004). Water transparency depends greatly on water level and wind speed (i.e. on the physical factors controlling the re-suspension of bottom sediments). In Lake Võrtsjärv phytoplankton and nutrient availability is controlled by water level fluctuations. A high water level causes light limitation and phosphorus sedimentation, whereas a lower water level improves light conditions and sediment disturbances enrich water with more phosphorus than nitrogen, giving an advantage to the nitrogen-fixers (Huttula & Nõges (eds.) 1998).

Table 1. Morphometric data and range of concentrations of optically active substances in the three regions of Lake Peipsi (the percentage of the whole surface area of the lake is also shown) as average \pm standard deviation and in Lake Võrtsjärv as minimum–maximum values (Nõges et al. 1996, Reinart & Valdmets 2007)

Parameter	L. Peipsi s. s.	L. Lämmijärv	L. Pihkva	L. Võrtsjärv
area [km ²]	2611 (73%)	236 (7%)	708 (20%)	270
mean depth [m]	8.3	2.5	3.8	2.8
maximum depth [m]	12.9	15.3	5.3	6.0
C_{chl} [mg m ⁻³]	12.8 \pm 8.3	13.9 \pm 9.8	41.4 \pm 33.1	20–102
C_{TSS} [g m ⁻³]	4.5 \pm 2.3	6.6 \pm 4.1	17.3 \pm 9.5	3.9–6.7
$a_{CDOM(443)}$, [m ⁻¹]	2.1 \pm 0.8	2.7 \pm 0.9	3.4 \pm 0.6	2.5–6.7
Secchi depth [m]	2.0 \pm 0.4	1.6 \pm 0.6	0.9 \pm 0.3	0.2–1

Diatoms from the genus *Aulacoseira* in spring and during cooler summers and the blue-greens (*Planktolyngya limnetica* (Lemm.) Kom. & Cronb., *Limnothrix planktonica* (Lemm.), *Limnothrix redekei* Van Goor (Meffert) and *Aphanizomenon gracile* (Lemm.)) are abundant in summer and autumn. These species are dominant during most of the growing season, along with a comparatively small and variable portion of small algae. The phytoplankton biomass reached its maximum in the mid-1970s – up to 110 g m⁻³ as a result of the high nutrient load from agriculture (Huttula & Nõges (eds.) 1998).

2.2. In situ measurements

Phytoplankton samples were taken once per month from 2002 to 2008 during the growing season (April–September), except in Lake Pihkva,

where samples were available from August only. Water was collected with a Ruttner sampler. Integrated water samples for phytoplankton counts, composition and biomass were preserved with Lugol's solution. The counts were carried out under an inverted plankton microscope (400x magnification) according to Utermöhl's method (Utermöhl 1958). The biovolumes of each taxon were estimated by assuming standard geometrical shapes, after which the biomass (wet weight) was calculated. For the estimates of Chl *a* concentration, plankton was filtered using Whatman GF/F filters. Pigments were extracted with 96% ethanol for 24 h at -20°C , then analysed spectrophotometrically (ISO 10260, 1996). The Jeffrey-Humphrey (1975) equation was used for the calculations.

2.3. Satellite data

All available cloud-free MERIS reduced resolution (RR) level 1 images acquired during the April–September period from 2002 to 2008 over the study area were downloaded from the MERCI (MERIS Catalogue and Inventory) database (<http://merci-srv.eo.esa.int/merci>) and processed with BEAM (version 4.6.1) software (<http://www.brockmann-consult.de/cms/web/beam>). Altogether **57** images (same day in situ data and MERIS overpass), consisting of 159 measurement points, were processed: **9 images** (24 sampling points) in 2002; **7**(14) in 2003, **8**(21) in 2004, **11**(25) in 2005, **6**(19) in 2006, **10**(32) in 2007 and **6**(24) in 2008.

2.4. Calculation of the Maximum Chlorophyll Index

The height of the peak at 709 nm is quantified by the MCI, which is the radiance difference between the radiance measured at 709 nm and the baseline radiance at this wavelength. MCI is computed using bands 8, 9 and 10 (681, 709 and 753 nm respectively) of the level 1 MERIS RR images using a linear baseline interpolation between the radiance values at 681 nm and 753 nm (Gower 2008b):

$$\text{MCI} = L_{709} - L_{681} - 0.389(L_{753} - L_{681}), \quad (1)$$

where L_x represents top-of-atmosphere radiances with wavelengths at $x = 709, 753$ and 681 nm. The factor 0.389 represents the wavelength ratio $(709-681)/(753-681)$. MCI was calculated for all valid MERIS pixels covering the study area.

3. Results

3.1. Variation of phytoplankton species composition and biomass

As expected, cyanobacteria and diatoms were dominant in the phytoplankton biomass in the water samples collected from Lake Peipsi during the

Table 2. Biomass minimum (Min), median (Med) and maximum (Max) values (g m^{-3}) of cyanobacteria (CY) by season; diatoms (Bac), total phytoplankton (TBM) and chlorophyll *a* (Chl *a*, mg m^{-3}) for the whole growing season, except in Lake Pihkva, where values from August only were available (*). N – northern part, S – southern part of Lake Peipsi s.s.

Lake	CY (Apr.–May)			CY (June–Sept.)			Bac		
	Min	Med	Max	Min	Med	Max	Min	Med	Max
Peipsi N	0.02	0.2	0.7	0.1	3.5	27.1	0.2	2.1	11.3
Peipsi S	0.1	0.8	5.8	2.9	10.8	38.1	0.8	3.3	14.5
Pihkva*				5.7	19.3	37.9	1.1	4.1	16.3
Võrtsjärv	0.01	3.4	12.9	5.5	18.8	40.0	0.3	3.9	33.5
	TBM			Chl <i>a</i>					
	Min	Med	Max	Min	Med	Max			
Peipsi N	0.8	6.4	23.6	4.1	15.2	73.9			
Peipsi S	3.6	12.6	44.2	5.7	33.2	90.7			
Pihkva*	12.3	25.9	47.7	30.1	64.6	90.6			
Võrtsjärv	0.6	18.6	60.9	0.6	37.3	88.4			

period 2002–2008 (Table 2). Sometimes, particularly in spring, cryptophytes were abundant, but their biomass seldom exceeded 1 g m^{-3} . The dinophyte *Ceratium hirundinella* (O.F. Müller) Schrank dominated the biomass (up to 4 g m^{-3}) during the summer of 2007. The total biomass was higher in the southern part (maximum up to 50 g m^{-3} in 2006, but usually $< 30 \text{ g m}^{-3}$) than in the northern part (maximum up to 30 g m^{-3} , but usually $< 10 \text{ g m}^{-3}$) (Figure 2a). The total biomass was higher in late summer and early autumn.

Cyanobacteria formed up to 91% of the total biomass in the northern part of the lake, being more numerous during July–September. There, the cyanobacterial biomass was generally $< 12 \text{ g m}^{-3}$, except during the *Gloeotrichia echinulata* bloom in 2005, when the biomass was 27.6 g m^{-3} (Figure 2b). In the southern part biomasses can reach higher levels, up to 37 g m^{-3} in 2006. The cyanobacterial biomass was lower in the whole of L. Peipsi s.s. during 2004 and 2008.

Besides *Gloeotrichia echinulata*, the dominant species also included *Microcystis viridis* (A. Braun) Lemm., *M. aeruginosa* Kütz., *M. wesenbergii* Komárek and small-celled chroococcales (*Aphanothece* ssp., *Cyanodicyton* ssp., *Aphanocapsa* ssp.). *Anabaena circinalis* Rabenhorst and *A. spiroides* Klebahn were dominant in the cyanobacterial community during September 2002 and *Aphanizomenon flos-aquae* (L.) Ralfs likewise in late summer from 2006 to 2008. Diatoms were abundant in spring (up

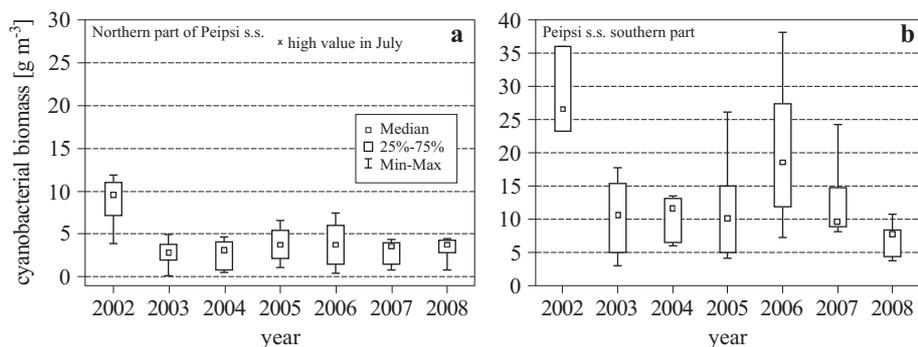


Figure 2. Biomass of cyanobacteria (June–September) in the northern (a) and southern (b) parts of Lake Peipsi s.s.

to 97% of total biomass), the main species being *Aulacoseira islandica* (O. Müller) Sim. and *Stephanodiscus neoastrea* Hak. & Hick. The diatom biomass was the largest in May 2005 (up to 16 g m⁻³) in the northern part of Lake Peipsi, whereas during other years the diatom biomass remained at < 9 g m⁻³. In the southern part *Aulacoseira ambigua* (Grun.) Simonsen and *Cyclotella* ssp. dominated in spring. The biomass reached a maximum in May 2007 (16.2 g m⁻³). The diatom biomass was lower (< 4 g m⁻³) in 2002 and 2004, when diatoms made up < 11% of the total biomass during the spring. The second diatom peak (which did not occur in the northern part) in the southern part took place in September, when *Aulacoseira ambigua* and *A. granulata* were prevalent. In Lake Pihkva, the southernmost part of Lake Peipsi, cyanobacteria were dominant (Table 2, Figure 3), making up 50–92% of the total phytoplankton biomass in August. The prevailing cyanobacteria were *Microcystis viridis* and *M. wesenbergii*, and the dominant diatoms were *A. flos-aquae* and *Aulacoseira ambigua*.

In Lake Võrtsjärv *Limnothrix planktonica* and *L. redekei* were dominant throughout the period investigated; sometimes *Planktolyngya limnetica* was also numerous. Diatoms *Cyclotella* and *Aulacoseira islandica* dominated in spring; the biomass of diatoms was usually > 50% of the total biomass in April and May, and also in June and July 2003. The cyanobacterial biomass increased gradually towards autumn (up to 42 g m⁻³) (Figure 3). The total phytoplankton biomass was generally highest in September (up to 60.9 g m⁻³), except in 2003, when the summer maximum (37.9 g m⁻³) occurred.

In Lake Peipsi the share of cyanobacteria was significantly lower in spring (mainly < 30%) compared to summer (between 60–90%), whereas in Lake Võrtsjärv the proportion of cyanobacteria was only slightly lower during

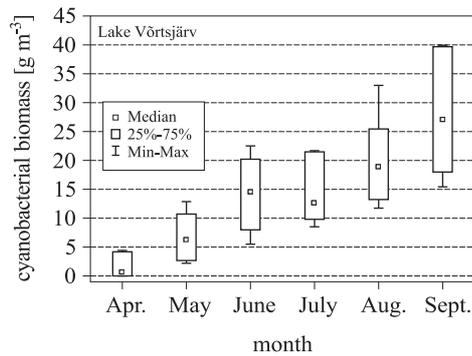


Figure 3. Seasonal dynamics of cyanobacterial biomass in Lake Vörtsjärv from 2002 to 2007

spring (up to 65%) than in summer (60–94%). In the southern part of Lake Peipsi the increase in the percentage of cyanobacteria appears earlier, whereas in the northern part the share of cyanobacteria is also low in June. On the basis of the field measurements from 2002 to 2008, we can infer a pronounced seasonal trend in diatom and cyanobacteria dominance in the total phytoplankton biomass, which is strongly lake-dependent. We had only a few simultaneous measurements of phytoplankton/cyanobacterial biomass and Chl *a* concentration (Figures 4a, 5a, $n = 60$) in Lake Vörtsjärv. The lack of data could have limited the strength of the observed relationships in Figures 4a and 5a. In Lake Peipsi with an ample number of simultaneous measurements ($n = 398$), the phytoplankton biomass and Chl *a* were strongly correlated in summer ($R^2 = 0.65$ in August, Figure 4b), whereas

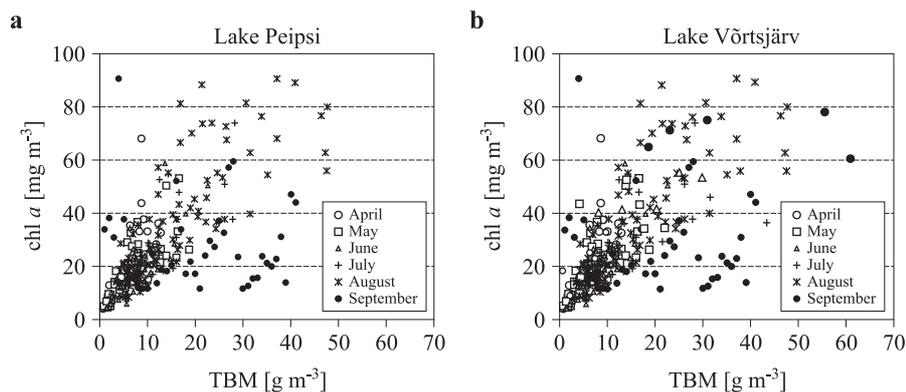


Figure 4. In situ measured Chl *a* and monthly TBM relationship in Lake Vörtsjärv (a) and Lake Peipsi (b)

in September no correlation was found. Cyanobacterial biomass and Chl *a* concentration in Lake Peipsi were strongly correlated only during summer (Figure 5b).

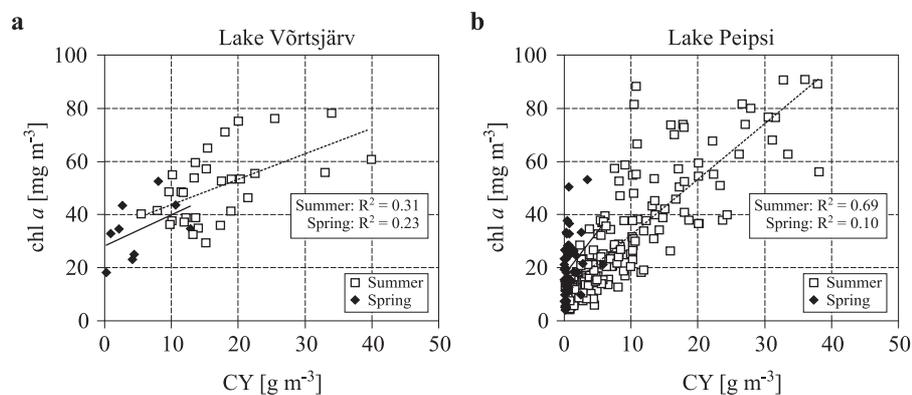


Figure 5. In situ measured Chl *a* and CY relationship in spring (April–May) and summer (June–September) in Lake Vörtsjärv (a) and Lake Peipsi (b)

3.2. Spectral signatures measured by MERIS over cyanobacterial blooms

The variation of radiance spectra according to different MCI values is illustrated by an example of one intense bloom event in the Baltic Sea (MERIS RR image from 31 July 2008) (Figure 6). In the case of strong surface accumulations in the Baltic Sea the index showed values up to 14 units, but such intense blooms have not been detected in lakes, where the MCI reached 9 units. In the case of higher MCI values, there is an increase in radiance values around 560 nm and at wavelengths starting from 709 nm (Figure 6). Typical atmospheric correction algorithms tend to fail in the case of high radiance values in infrared wavelengths as they are outside the standard atmospheric correction range. Standard MERIS level 2 products are then not appropriate for monitoring these events, as pixels are flagged as invalid or not processed at all.

3.3. Seasonal variation in MCI

The relationships between MCI values and three phytoplankton parameters (TBM, CY, Chl *a*) are established in Figure 7 and Table 3 using in situ measurement data and satellite images acquired on the same day or with a difference of up to two days. As mentioned in Section 3.1, the seasonal trend of phytoplankton is different in both Lake Peipsi and Lake Vörtsjärv.

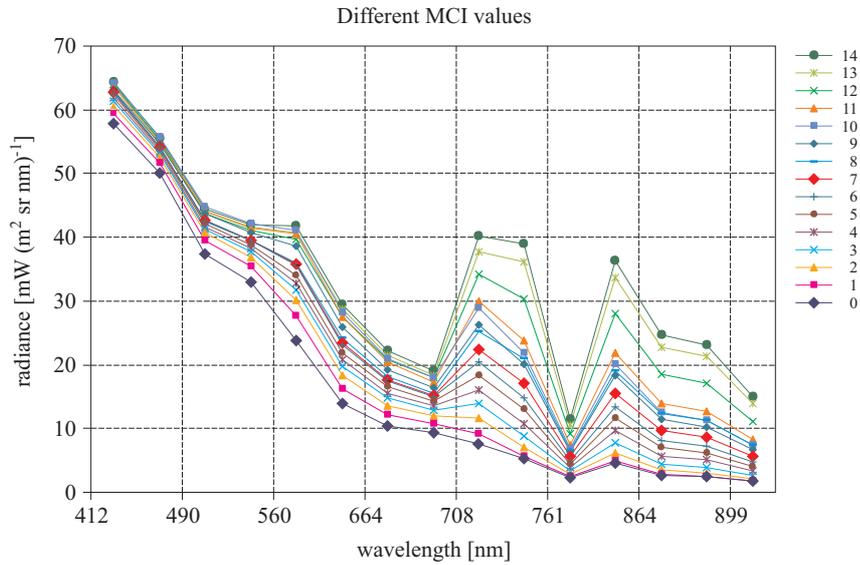


Figure 6. Radiance spectra according to different MCI values from an intensive bloom event in the Baltic Sea (MERIS RR from 31 July 2008)

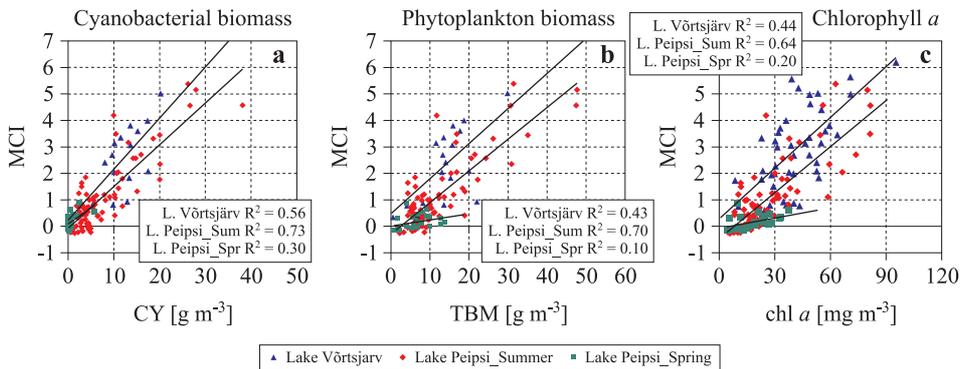


Figure 7. Correlation between MCI and CY (a), TBM (b), Chl *a* (c) in Lake Võrtsjärv and Lake Peipsi (in summer and spring) from 2002–2008

A strong seasonal difference is observed in MCI and the phytoplankton parameters in Lake Peipsi. MCI in spring (April–May) tends to be less sensitive to Chl *a* ($R^2 = 0.20$) (Figure 7c) and TBM ($R^2 = 0.10$) (Figure 7b), resulting in values between 0 and 1, whereas the concentration of Chl *a* can be as high as 40 mg m^{-3} . This may be due to the dominance of diatoms, which tend to be shade tolerant and do not come up to the surface like typical cyanobacteria in the summer. In this season the correlation for every

Table 3. Regression analyses between MCI and 1) chlorophyll *a* concentration (Chl *a*), 2) phytoplankton biomass (TBM) and 3) cyanobacterial biomass (CY). Peipsi (all data) – data from all three parts of the lake are considered; Peipsi (summer) – only data from June–September; Peipsi (N) – northern part of the lake; Peipsi (S) – southern part of the lake

Parameter	Lake	Equation (P < 0.01)	Std. error	R ²	N
1) Chl <i>a</i>	Peipsi & Vörtsjärv	Chl <i>a</i> = (8.8 ± 1.1)MCI + (16.7 ± 2.5)	11.4	0.62	153
	Peipsi (all data)	Chl <i>a</i> = (10.9 ± 1.6)MCI + (15.3 ± 2.4)	10.4	0.62	108
	Peipsi (summer)	Chl <i>a</i> = (11 ± 1.8)MCI + (14.8 ± 3)	11	0.64	82
	Peipsi (N)	Chl <i>a</i> = (11.5 ± 4.9)MCI + (13.6 ± 3)	6.8	0.46	28
	Peipsi (S)	Chl <i>a</i> = (13.6 ± 3.9)MCI	21.2	0.80	13
	Vörtsjärv	Chl <i>a</i> = (6.8 ± 2.4)MCI + (21.5 ± 6.9)	12.8	0.44	45
2) FBM	Peipsi & Vörtsjärv	TBM = (5.6 ± 0.6)MCI + (5.4 ± 1.1)	4.8	0.68	116
	Peipsi (all data)	TBM = (5.8 ± 0.7)MCI + (5.4 ± 1.1)	4.7	0.70	108
	Peipsi (summer)	TBM = (5.8 ± 0.9)MCI + (5.3 ± 1.4)	5.1	0.70	82
	Peipsi (N)	TBM = (5.2 ± 2.2)MCI + (5.9 ± 1.4)	3.1	0.47	28
	Peipsi (S)	TBM = (6.9 ± 1.8)MCI	9.8	0.83	13
	Vörtsjärv	TBM = (6.7 ± 2.2)MCI	7.0	0.83	8
3) CY	Peipsi & Vörtsjärv	CY = (4.4 ± 0.5)MCI + (1.8 ± 0.8)	3.6	0.73	125
	Peipsi (all data)	CY = (4.9 ± 0.5)MCI + (1.5 ± 0.8)	3.5	0.75	108
	Peipsi (summer)	CY = (4.6 ± 0.6)MCI + (2.3 ± 1)	3.8	0.73	82
	Peipsi (N)	CY = (4.0 ± 1.5)MCI + (3.1 ± 0.9)	2.1	0.52	28
	Peipsi (S)	CY = (5.5 ± 1.2)MCI	7.3	0.85	13
	Vörtsjärv	CY = (4.3 ± 0.7)MCI	4.1	0.90	17

parameter is much stronger, especially for CY ($R^2 = 0.73$) (Figure 7a). No such seasonal trends were observed in Lake Võrtsjärv, although overall MCI values were higher than in Lake Peipsi and R^2 was between 0.43 (TBM, Figure 7b) and 0.56 (CY, Figure 7a).

Regression analyses showed that MCI achieves the best fit with cyanobacterial biomass (Table 3, CY), especially in the more turbid water masses in Lake Võrtsjärv ($R^2 = 0.90$, $N = 17$) and in the southern part of Lake Peipsi ($R^2 = 0.85$, $N = 13$). MCI tends to give a lower correlation ($R^2 = 0.46$, Table 3) in the northern part of Lake Peipsi, where the concentrations of optically active substances, including phytoplankton and cyanobacteria biomasses (Table 1), are lower and the water is relatively clear.

3.4. Mapping phytoplankton parameters using MCI

In the next step, a set of phytoplankton parameters (TBM, CY and Chl *a*) was calculated from a MERIS image (Figure 8) using the equations from Table 3 (Peipsi (summer) and Võrtsjärv). The cloud-free MERIS image from 19 August 2005 was selected and compared with the field data (Figure 9) acquired on 18 August 2005 in Lake Võrtsjärv and on 17 August 2005 in Lake Peipsi. There is a strong spatial variation with a north-south gradient in the level 1 image in Lake Peipsi: in the northern part the water seems to be clearer than in the southern part; this is also

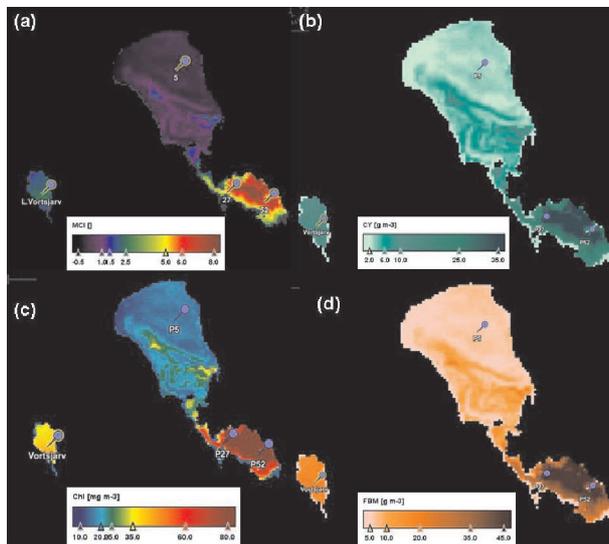


Figure 8. Calculated MCI (a), CY (b), Chl *a* (c), TBM (d) from MERIS L1 reduced resolution data from 19 August 2005

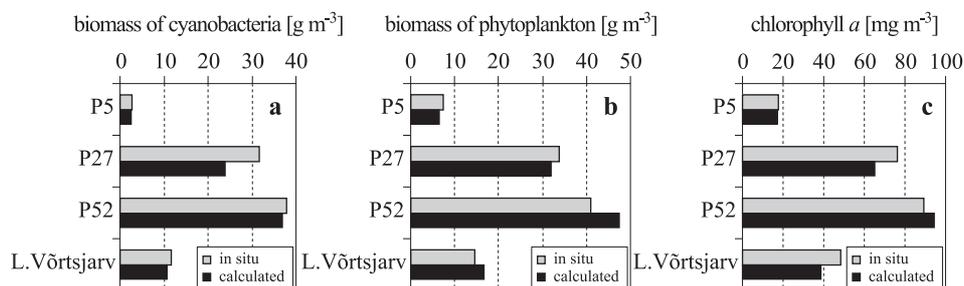


Figure 9. Comparison of in situ measured and calculated biomass of cyanobacteria (a), biomass of phytoplankton (b) and chlorophyll *a* concentration (c)

supported by the field data measurements. Lake Vörtsjärv is homogeneously mixed (Figure 8a). The overall MCI pattern is similar to that of the field measurements.

Three standard monitoring points (P5, P27, and P57 in Figure 8) were used to illustrate different water masses in Lake Peipsi. The water is relatively clear and well mixed at P5. Surface blooms and larger amounts of phytoplankton are present at P27 and P52 (Figure 9). MCI values, as well as in situ measurements, showed only a very small change over the whole of Lake Vörtsjärv, and therefore one point in the middle of the lake was chosen to represent the whole area (Figure 8).

Comparison of the in situ measured TBM, CY and Chl *a* values with the MCI results shows that the variation in concentrations of every parameter is determined quite well (Figure 9). In addition, the spatial distributions are consistent with previous knowledge obtained from in situ data.

4. Discussion

The main goal of this work was to test the usefulness of a new spectral index that could be easily implemented in standard water quality monitoring over large water bodies through remote sensing techniques. It is shown that MCI describes phytoplankton spatial distribution reasonably well, and that the first results for quantitative mapping appear to be promising for water with a relatively high concentration of CDOM and TSM. The best fit with MCI is obtained for cyanobacterial biomass (Peipsi: $R^2 = 0.75$, standard error 3.5; Vörtsjärv $R^2 = 0.90$, standard error 4.1). We have shown that MCI is not sensitive to diatoms, which are dominant in both lakes in spring, possibly because of their relatively small biomass; nevertheless, towards autumn the amount of cyanobacteria in the phytoplankton biomass increases, which results in a more effective detection rate by the index.

Generally, the main bloom-formers in freshwater are cyanobacteria with gas vacuoles, which give them an advantage over settling species even without creating positive buoyancy (Oliver & Ganf 2002). The same functional types of phytoplankters form the surface cyanobacterial blooms in the Baltic Sea (Kahru et al. 2007). Typically these are filamentous nitrogen fixers, which can regulate their vertical position to achieve better growing conditions, as a result of which they can outcompete other algae (Paerl 2002). This is also the case in Lake Peipsi, whereas in Lake Võrtsjärv the share of nitrogen-fixing cyanobacteria is negligible (Frisk et al. 1999), and the dominant phytoplankters are shade tolerant, non-nitrogen fixers that do not form surface scum and are therefore more resistant to ambient conditions (Nixdorf et al. 2003). When conditions are propitious (warm, calm weather), cyanobacteria with gas vacuoles can form dense but extremely patchy surface mats. This results in a larger number of cyanobacteria in the upper water masses, where the strong absorption and backscattering of incident light meets the sensitivity conditions of the spectral index and water sensors such as MERIS, and the light does not penetrate into the deeper water. In addition, we have shown that MCI values tend to be higher in the shallow and homogeneously mixed Lake Võrtsjärv, where vegetation is present in the shallower parts of the lake and macrophytes tend to overgrow the whole open water area in the southern part (Feldmann & Nöges 2007). Gower et al. (2005) have also mentioned that submerged benthic vegetation may be the cause of errors in MCI by producing a peak in water-leaving radiance near 705 nm. Consequently, it is important to have information about the background properties of a water body (dominant phytoplankton species, turbidity etc.) in order to be in a position to interpret the spectral index values correctly.

According to Webster & Hutchinson (1994) a wind speed of $>2-3$ m s⁻¹ is required to cause floating phytoplankton cells to descend from the lake surface into the water column, so during calm conditions intense surface accumulations appear rapidly (Oliver & Ganf 2002). Kutser (2004) showed that collecting representative water samples is a difficult task during extensive cyanobacterial blooms, because the natural distributions of cyanobacteria are destroyed by ships and water samplers. There is thus a need for a higher frequency of spatial and temporal monitoring; satellite airborne/remote sensing monitoring methods are expected to provide more reliable results than the usual sampling methods. It must also be noted that some of the scatter in the relationship between MCI and phytoplankton parameters could be due to the mismatch between the resolution of in situ and MERIS RR data ($\sim 1200 \times 1200$ m pixels). Cyanobacterial blooms can be extremely patchy and variations in biomass may occur at scales

of $\ll 1$ km. Hence, the MERIS RR data is not suitable for describing all the variation and hyperspectral sensors (Hyperion), with a higher spatial resolution, may be more appropriate. At the moment, MCI, as estimated from water colour sensor data, is applicable to ENVISAT/MERIS sensor because of the unique band at 709 nm. In the future, time series with MCI can be continued with the new water sensor on Sentinel-3, which will be launched by ESA to continue the MERIS mission.

Chl *a*, the most commonly and easily measured phytoplankton parameter, has often been used as a proxy for estimating phytoplankton biomass. We have demonstrated that this assumption holds in Lake Peipsi in spring ($R^2 = 0.61$) and in summer ($R^2 = 0.71$). However, in September there was no correlation between Chl *a* and phytoplankton biomass, probably because decay processes in the lake had already begun. There were no seasonal differences, and only a weak correlation throughout the whole year ($R^2 = 0.23 - 0.32$) was found in the case of Lake Vörtsjärv. The amount of Chl *a* in the phytoplankton biomass can be related to light conditions and to the amount of surface-floating cyanobacteria, which was much less in Lake Vörtsjärv than in Lake Peipsi. Changes in phytoplankton composition cause changes in Chl *a* concentration. The chlorophyll content of cells varies between different algal taxa; for example, cyanobacteria and diatoms have more accessory pigments and less Chl *a* per unit biovolume than Chlorophyta (Reynolds 2006). For field measurements, a combination of HPLC and microscopy will be a useful method in the future for monitoring phytoplankton assemblages instead of the time-consuming counting of phytoplankton cells under a microscope. The former method can then be used to implement WFD with respect to phytoplankton (Sarmiento & Descy 2008). To fulfil the criteria of WFD, regular monthly sampling of Chl *a* is recommended (Carvalho et al. 2009), although even in this case the percentage standard error for estimated mean chlorophyll concentrations in shallow lakes is about 14% (Clarke et al. 2006). Therefore, errors are present in field measurements as well as in satellite estimates, which make an accurate validation of phytoplankton parameters difficult.

MCI has its limitations. It may not be specific only to cyanobacteria, but to the higher phytoplankton biomass in general. Gower et al. (2008a) showed high MCI values while detecting different kinds of blooms (cyanobacterial, floating, sediment-dominated). However, background information (knowledge of species composition) or further analysis of spectral signatures (absorption features) was needed to identify the individual cause.

We have demonstrated high top-of-atmosphere radiance values in the case of high MCI at wavelengths starting from 700 nm. In this spectral range, the signal from the water is assumed to be very low or zero as a result

of absorption by water. Hence the processing algorithms from L1 to L2 data may lead to errors in the case of intensive bloom events or heavily sediment-loaded waters, giving high radiance values. Under these conditions standard algorithms may fail, handing the advantage to MCI.

Acknowledgements

This research was financed by Estonian target financed project SF00601 15s08 and Estonian Science Foundation grants EMP1 and 6814. We are grateful to ESA for MERIS images and thank the Centre for Limnology, especially Reet Laugaste and Peeter Nõges, for the phytoplankton monitoring data. We thank Mr. Peter Senn for proof-reading our manuscript.

References

- Alikas K., Reinart A., 2008, *Validation of the MERIS products on large European lakes: Peipsi, Vänern and Vättern*, *Hydrobiologia*, 599 (1), 161–168.
- Carvalho L., Solimini A. G., Phillips G., Pietiläinen O.-P., Moe J., Cardoso A. C., Solheim A. L., Ott I., Søndergaard M., Tartari G., Rekolainen S., 2009, *Site-specific chlorophyll reference conditions for lakes in Northern and Western Europe*, *Hydrobiologia*, 633 (1), 59–66.
- Clarke R., Carvalho L., Maberly S., 2006., *Uncertainty in chlorophyll and total phosphorus classifications*, [in:] *Chlorophyll and phosphorus classifications for UK lakes*, L. Carvalho, G. Phillips, S. Maberly & R. Clarke, Fin. Rep. SNIFFER (Proj. WFD38), Edinburgh, [available at <http://www.sniffer.org.uk/>].
- Doerffer R., Schiller H., 2008, *MERIS lake water algorithm for BEAM, algorithm theoretical basis document*, http://www.brockmann-consult.de/beam-wiki/download/attachments/1900548/ATBD\Lake_water_RD20080610.pdf?version=1
- Doerffer R., Schiller H., 2007, *The MERIS Case 2 water algorithm*, *J. Remote Sens.*, 28 (3–4), 517–535.
- Feldmann T., Nõges P., 2007, *Factors controlling macrophyte distribution in large shallow Lake Võrtsjärv*, *Aquat. Bot.*, 87 (1), 15–21.
- Frisk T., Bilaletdin Ä., Kaipainen H., Malve O., Möls M., 1999, *Modelling phytoplankton dynamics of the eutrophic Lake Võrtsjärv, Estonia*, *Hydrobiologia*, 414 (0), 59–69.
- Gons H. J., Auer M. T., Effler S. W., 2008, *MERIS satellite chlorophyll mapping of oligotrophic and eutrophic waters in the Laurentian Great Lakes*, *Remote Sens. Environ.*, 112 (11), 4098–4106.
- Gons H. J., Rijkeboer M., Ruddick K. G., 2002, *A chlorophyll-retrieval algorithm for satellite imagery (Medium Resolution Imaging Spectrometer) of inland and coastal waters*, *J. Plankton Res.*, 24 (9), 947–951.

- Gower J.F.R., Hu C., Borstad G.A., King S., 2006, *Ocean color satellites show extensive lines of floating Sargassum in the Gulf of Mexico*, IEEE T. Geosci. Remote, 44 (12), 3619–3625.
- Gower J.F.R., King S., 2007, *An Antarctic ice-related ‘superbloom’ observed with the MERIS satellite imager*, Geophys. Res. Lett., 34, L15501, doi:10.1029/2007GL029638.
- Gower J.F.R., King S., Borstad G.A., Brown L., 2005, *Use of the 709 nm band of MERIS to detect intense plankton blooms and other conditions in coastal waters*, Proc. 2004 Envisat & ERS Symp., Salzburg, ESA SP-572.
- Gower J.F.R., King S., Borstad G.A., Brown L., 2008a, *The importance of a band at 709 nm for interpreting water-leaving spectral radiance*, Can. J. Remote Sens., 34 (3), 287–295.
- Gower J.F.R., King S., Goncalves P., 2008b, *Global monitoring of plankton blooms using MERIS MCI*, Int. J. Remote Sens., 29 (21), 6209–6216.
- Huttula T., Nöges T. (eds.), 1998, *Present state and future fate of Lake Vörtsjärv. Results from Finnish-Estonian joint project in 1993–1997*, The Finnish Environment 209, Pirkanmaa Regional Environment Centre, Tampere, 150 pp.
- Härmä P., Vepsäläinen J., Hannonen T., Pyhälähti T., Kämäri J., Kallio K., Eloheimo K., Koponen S., 2001, *Detection of water quality using simulated satellite data and semi-empirical algorithms in Finland*, Sci. Total Environ., 268 (1–3), 107–121.
- ISO 10260, 1996, (E), *Water quality. Measurement of biochemical parameters-Spectrophotometric determination of chlorophyll-a concentration*, ISO, Geneva, 1–6.
- Jaanus A., Toming K., Hällfors S., Kaljurand K., Lips I., 2009, *Potential phytoplankton indicator species for monitoring Baltic coastal waters in the summer period*, Hydrobiologia, 629 (1), 157–168.
- Jeffrey S.W., Humphrey G.F., 1975, *New spectrophotometric equations for determining chlorophylls a, b, c and c2 in higher plants, algae and natural phytoplankton*, Biochem. Physiol. Pfl., 167, 191–194.
- Kahru M., Savchuk O.P., Elmgren R., 2007, *Satellite measurements of cyanobacterial bloom frequency in the Baltic Sea: interannual and spatial variability*, Mar. Ecol.-Prog. Ser., 343, 15–23.
- Karlsson-Elfgren I., Hyenstrand P., Riydin E., 2005, *Pelagic growth and colony division of Gloeotrichia echinulata in Lake Erken*, J. Plankton Res., 27 (2), 145–151.
- Koponen S., Pulliainen J., Kallio K., Hallikainen M., 2002, *Lake water quality classification with airborne hyperspectral spectrometer and simulated MERIS data*, Remote Sens. Environ., 79 (1), 51–59.
- Koponen S., Ruiz-Verdu A., Heege T., Heblinski J., Sorensen K., Kallio K., Pyhälähti T., Doerffer R., Brockmann C., Peters M., 2008, *Development of MERIS lake water algorithms*, Validation Rep., <http://www.brockmann-consult.de/beamwiki/download/attachments/>

- Kratzer S., Brockmann C., Moore G., 2008, *Using MERIS full resolution data to monitor coastal waters – A case study from Himmerfjärden, a fjord-like bay in the northwestern Baltic Sea*, Remote Sens. Environ., 112 (5), 2284–2300.
- Kullus L., 1964, *Peipsi-Pihkva järve uurimisest ajavahemikul 1850–1917*, Eesti Geografia Seltsi Aastaraamat 1963, Tartu, 148–158.
- Kutser T., 2004, *Quantitative detection of chlorophyll in cyanobacterial blooms by satellite remote sensing*, Limnol. Oceanogr., 49 (6), 2179–2189.
- Laugaste R., Haberman J., Krause T., Salujõe J., 2007, *Significant changes in phyto- and zooplankton in Lake Peipsi in recent years: what is the underlying reason?*, Proc. Estonian Acad. Sci. Biol. Ecol., 56 (2), 106–123.
- Laugaste R., Jastremskij V.V., Ott I., 1996, *Phytoplankton of Lake Peipsi-Pihkva: Species composition, biomass and seasonal dynamics*, Hydrobiologia, 338 (1–3), 49–62.
- Laugaste R., Nõges T., Tõnno I., 2008, *Vetikad*, [in:] *Peipsi*, J. Haberman, T. Timm & A. Raukas (eds.), Eesti Loodusfoto, Tartu, 251–270.
- McClain C.R., 2009, *A decade of satellite ocean color observations*, Annu. Rev. Mar. Sci., 1, 19–42.
- Morel A., Huot Y., Gentili B., Werdell P.J., Hooker S.B., Franz B.A., 2007, *Examining the consistency of products derived from various ocean color sensors in open ocean (Case 1) waters in the perspective of a multi-sensor approach*, Remote Sens. Environ., 111 (1), 69–88.
- Nixdorf B., Mischke U., Rucker J., 2003, *Phytoplankton assemblages and steady state in deep and shallow eutrophic lakes – an approach to differentiate the habitat properties of Oscillatoriales*, Hydrobiologia, 502 (1–3), 111–121.
- Nõges T., Haberman J., Jaani A., Laugaste R., Lokk S., Mäemets A., Nõges P., Starast H., Timm T., Virro T., 1996, *General description of Lake Peipsi-Pihkva*, Hydrobiologia, 338 (1–3), 1–9.
- Nõges T., Laugaste R., Nõges P., Tõnno I., 2008, *Critical N:P ratio for cyanobacteria and N₂-fixing species in large shallow temperate lakes Peipsi and Võrtsjärv, North-East Europe*, Hydrobiologia, 599 (1), 77–86.
- Oliver R.L., Ganf G.C., 2002, *Freshwater blooms*, [in:] *The ecology of cyanobacteria. Their diversity in time and in space*, B. A. Whitton & M. Potts (eds.), Kluwer Acad. Publ., New York, Boston, Dordrecht, London, Moscow, 149–194.
- Paerl H.W., 2002, *Marine plankton*, [in:] *The ecology of cyanobacteria. Their diversity in time and in space*, B. A. Whitton & M. Potts (eds.), Kluwer Acad. Publ., New York, Boston, Dordrecht, London, Moscow, 121–148.
- Reinart A., Nõges P., 2004, *Light conditions in Lake Võrtsjärv*, [in:] *Lake Võrtsjärv*, J. Haberman, E. Pihu & A. Raukas (eds.), Estonian Encyclopaedia Publ., 141–149.
- Reinart A., Valdmets K., 2007, *Variability of optical water types in Lake Peipsi*, Proc. Estonian Acad. Sci. Biol. Ecol., 56 (1), 33–46.

- Reynolds C.S., 2006, *Ecology of phytoplankton*, Cambridge Univ. Press, Cambridge, 535 pp.
- Ruddick K. G., Gons H. J., Rijkeboer M., Tilstone G., 2001, *Optical remote sensing of chlorophyll a in case 2 waters by use of an adaptive two-band algorithm with optimal error properties*, Appl. Optics, 40 (21), 3575–3585.
- Rundquist D. C., Han L., Schalles J.F., Peake J.S., 1996, *Remote measurement of algal chlorophyll in surface waters: The case for the first derivative of reflectance near 690 nm*, Photogramm. Eng. Rem. S., 62 (2), 195–200.
- Sarmiento H., Descy J.-P., 2008, *Use of marker pigments and functional groups for assessing the status of phytoplankton assemblages in lakes*, J. Appl. Phycol., 20 (6), 1001–1011.
- Schalles J.F., Yacobi Y.Z., 2000, *Remote detection and seasonal patterns of phycocyanin, carotenoid and chlorophyll pigments in eutrophic waters*, Arch. Hydrobiol., 55 (Spec. Iss.), 153–168.
- Schroeder T., Schaale M., 2005, *MERIS case-2 water properties processor, version 1.0.1*, Inst. Space Sci., Freie Univ., Berlin (FUB), [<http://www.brockmann-consult.de/beam/software/plugins/FUB-WeW-Water-1.0.1.zip>].
- Sellner K.G., 1997, *Physiology, ecology and toxic properties of marine cyanobacteria blooms*, Limnol. Oceanogr., 42 (5 pt. 2), 1089–1104.
- Simis S.G.H., Peters S.W.M., Gons H.J., 2005, *Remote sensing of the cyanobacterial pigment phycocyanin in turbid inland water*, Limnol. Oceanogr., 50 (1), 237–245.
- Smith V. H., Willén E., Karlsson B., 1987, *Predicting the summer peak biomass of four species of blue-green algae (cyanophyta/cyanobacteria) in Swedish lakes*, Water Resour. Bull., 23 (3), 397–402.
- Sørensen K., Aas E., Høkedal J., 2004, *Validation of MERIS water products and bio-optical relationships in the Skagerrak*, Int. J. Remote Sens., 28 (3 & 4), 555–568.
- Utermöhl H., 1958, *Zur Vervollkommnung der quantitativen Phytoplankton-Methodik*, Mitt. Int. Ver. Limnol., 9, 1–38.
- Water Framework Directive, *Directive 2000/60/EC*, Offic. J. Eur. Comm., L327, 1–27.
- Webster I. T., Hutchinson P. A., 1994, *Effect of the wind on the distribution of phytoplankton cells in lakes revisited*, Limnol. Oceanogr., 39 (2), 365–373.