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Work package 5. Innovation and Application through Use cases

Deliverable 5.2. Shallow lakes with high eutrophication and potentially toxic algae

TO, SYKE, WI, CNR, BC, VU/VUmc

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Task objective (from DoW)

The objective of this task is the application of the S2 and S3 results over shallow and eutrophic lakes (mainly Peipsi and IJsselmeer) in combination with analyses of socio-economic impacts and WFD (reporting) requirements.

This will include the use of validation results from Task3 to select most useful and informative parameters according to user request; comparison of performance of the algorithms in different shallow and eutrophic lakes with each other to estimate the level of generalization and the comparison with other water types.

The performance of the algorithms over the spring-summer-autumn seasons, cases of cyanobacterial bloom, clear water periods, cold periods and flooding will be analysed.
It also includes the production of time series of satellite products and the demonstration of complementarity with field sampling for water quality and trophic status reporting.

Scope of this document

Within this document a short overview is given about special features of shallow, eutrophic lakes, which have potential for cyanobacterial (CY) blooms. The focus is on Chlorophyll-a (Chl-a) amount and the possibilities to analyse its spatial and temporal changes via EO methods. Representative lakes, large enough for using MERIS images (as a substitute to S3) for analyses, are Lake Peipsi and Lake Ülemiste (Estonia), Lake Trasimeno (Italy), Lake Tuusulanjärvi (Finland), Lake IJsselmeer (Netherlands) and Lake Müggelsee (Germany). Additionally, two small lakes from Netherlands were chosen for comparison with Landsat 8 (as a substitute for S2).

A general description of those lakes is given with a focus to the main socio-economic problems. Four algorithms (Maximum peak height, Fluorescence line height, Maximum chlorophyll index, and CoastColour processing) are chosen to describe Chl-a content in the lakes. Diversity-2 processing was used to create L3 images for yearly and monthly analyses of mean Chl-a for those lakes that were analysed with MERIS data. Either the full period (2003-2011) of available MERIS images are used or two contrasting years were chosen for analyses. For the two small lakes, a band ratio was tuned to derive Chl. Several GLaSS tools, such as the core system for data access and ROIStats are used during the analysis. A comparison with in situ measured (mainly spectrophotometrically or via HPLC) Chl-a content was made. Also CY presence was analysed via mean immersed CY products (Diversity-2 processing) and a comparison was made with in situ (microscopically) measured CY biomass or cell count.

The conclusions include the general conclusions from the analysis, and an outlook for the use of Sentinel 2 and 3 to monitor the shallow eutrophic lakes.

Abstract

Eutrophic shallow lakes represent a group of lakes situated in heavily populated areas, where the presence of cyanobacteria (CY) blooms prevent periodically activities in/on a lake, leading to socio-economic problems that authorities have to tackle. Especially drinking water production, irrigation and recreation suffers from an intense algae or CY blooms.

In situ measured Chl-a variation in six European eutrophic shallow CY-rich lakes was compared with four different processing schemes (MCI, MPH, FLH, CoastColour) of MERIS images. Focus was on validation, seasonal differences and year-to-year variation. For chlorophyll concentrations, the MCI, FLH and MPH algorithms gave similar results in all lakes, whereas FLH gave a slightly higher correlation with in situ measured Chl-a than MCI and MPH. Good correlation was found with in situ data in Lake Trasimeno (R^2 around 0.9 for MPH, MCI and FLH) and Lake Peipsi (R^2 around 0.7 for FLH and MCI and 0.5 for MPH), in other studied lakes relatively weak correlation was found (R^2 below 0.4). Detection of CY blooms was studied based mainly via the MPH algorithms in comparison with in situ results of phytoplankton community composition. Seasonal variation of Chl-a was well captured with FLH (Lake Tuusulanjärvi, Lake Ülemiste), MCI (Lake Peipsi) and CoastColour (Lake Müggelsee) algorithms, giving additional information about summer period, but often miss events in September and October especially in northern countries due to presence of cloud-cover.

Year-to-year variation was obtained from Diversity-2 processing, where yearly mean Chl-a values were retrieved via MPH. The Chl-a concentration was always lower in Lake Peipsi in comparison with Lake Lämmijärv and Lake Pihkva, higher concentrations were present there and in Lake Trasimeno during years with lower water level and higher temperatures. The effect of meteorological conditions was visible from daily images of Lake Peipsi: CY blooms diminished in surface layers after storm events. CY presence was analysed via CY index from MPH processing (Diversity-2) for Lake Trasimeno and Lake Müggelsee, for these, very good agreement was found with in situ data.

Two small Dutch lakes were analysed with Landsat 8 images. A band ratio algorithm was applied on L2 data and tuned to the in situ data. The resulting seasonal pattern was as expected for the highly reflecting Lake Paterswoldsemeer. For the clearer, lower reflecting Lake Westeinderplassen no proper trend was found based on Landsat 8. It is expected that for the lakes that were analysed with MERIS, similar results will be obtained with the new Sentinel 3 OLCI instrument, while for the lakes that were analysed with L8, the results are expected to improve with the data from Sentinel 2.

List of abbreviations

Abbreviation	Description
Chl-a	Chlorophyll a
CY	Cyanobacteria
EO	Earth observation
FLH	Fluorescence line height
L.	Lake
L_{toa}	Top-of-the atmosphere radiance
MAE	Mean Absolute Error
MCI	Maximum chlorophyll index
MERIS	Medium Resolution Imaging Spectrometer
MPH	Maximum peak height
OLCI	Ocean Land Colour Instrument
RMSE	Root Mean Square Error
S2	Sentinel-2
S3	Sentinel-3
TBM	Phytoplankton total biomass (g m^3)
TSM	Total suspended matter (g m^3)
WFD	Water Framework Directive

List of related documents

Short	Description	Date
D3.2	Description of atm.correction for CoastColour processing	31.05.2014
D5.7	WFD reporting case study results	October, 2015
D3.5	Automatic ROI and time series generation tool	30.09.2014
D5.1	Analyse large number of lakes based on socio-economic criteria	30.04.2014

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1 Introduction

Problems with eutrophication and algal blooms all around the world (Hallegraef, 2003; Glibert et al., 2005; Staffensen, 2008; Smith & Schindler, 2009, Paerl et al., 2011) have generated the need for cost-effective ways of monitoring the ecological status of water bodies and its changes. Presently the routine field monitoring is both time- and resources-consuming, being able to cover only few field sites with the maximum frequency of once a month or even less for smaller lakes. The applications of the Earth Observation (EO) methods have proved to give far better coverage both in spatial and temporal scale for evaluation of in-water constituents in the water bodies (Kutser, 2009; Eleveld, 2012; Zhu et al., 2014). Since all these lakes are shallow, information about the surface layer, as achieved with EO methods, reflects the entire water column, whereas in case of deeper lakes the surface layer is not representative for the deeper layers.

General problems in all shallow eutrophic lakes that were analysed are:

- Located in highly populated areas
- Shallow, vulnerable to eutrophication and sediment resuspension
- Suffer from overload of nutrients to a lake, which can originate from rivers, runoff of nearby agricultural areas, from air pollution and from sewage systems. These diverse inputs, and the historic load of nutrients in the sediments of the lake that can easily resuspend (self-contamination), make it hard to restore lower nutrient concentrations
- Presence of potentially toxic CY blooms, which reduce the value of a lake

Lakes are expected to provide ecosystem services: drinking water source, shipping, fishing, irrigation, recreation – many of those actions may be halted due to CY blooms.
These lakes are characterized by periodically high Chl-a concentration, mainly due to CY mass development. In the temperate zone the occurrence of CY blooms is most pronounced during summer months, coinciding with the period of higher water demand for irrigation and recreational purposes (Codd et al., 2005a; Merel et al., 2013, Macario et al., 2015).

Historically, phosphorus (P) has been the priority nutrient controlling freshwater productivity, whereas nitrogen (N) limitation has characterized coastal waters (Likens, 1972), and these have remained to be the key nutrients limiting aquatic plant primary production and biomass formation (Paerl, 2009). Usually P is in the focus (Schindler, 1977, Sterner, 2008), but also a co-limitation of N and P might occur (Elser et al., 2007, Müller & Mitrovic, 2015), or different nutrients are limiting at different time period of the year (Xu et al., 2013). Heterocysteous CY will benefit from N limitation due to their ability to fix their own nitrogen and outcompeting other algal groups (e.g. chlorophytes) in that way. Diazotrophic CY make an important contribution to N-limited system: fixed nitrogen is afterwards efficiently assimilated and transferred in food webs directly by grazing on fresh or decaying CY and indirectly through the uptake by other phytoplankton and microbes of bioavailable nitrogen exuded from CY cells (Karlson et al., 2015).

Generally, eutrophication is related to extensive nutrient input from both agricultural and industrial runoff, either from point or diffuse sources. Relatively small water volume makes shallow lakes vulnerable to eutrophication. Small and shallow lakes are the major target of various restoration projects. There is a clear knowlegde that before any lake restoration measures are taken, the first step is nutrient reduction in incoming water. If this is not done, restoration measures have practically no effect (Cooke et al., 2005). It is relatively easy to reduce nutrient income from point sources, and especially P reduction, but tackling with diffuse pollution is much harder. For example in case of L. Erie: despite decades of international efforts to reduce nutrient loading, this lake still receives extensive nutrient input (Waples, 2008) and both the duration and toxicity of CY blooms have increased (Stumpf et al., 2012).

Effect of CY blooms

Many shallow lakes suffer under massive development of CY**,** which affect water quality by biomass accumulation, generating surface scum, producing toxic compounds (Znachor et al., 2006, Paerl & Huisman, 2009), and altering the pH and O_2 regime (Havens, 2007). This leads to altering of the food webs and posing a major threat to drinking and irrigation water supplies, fishing and recreational use of surface waters worldwide (Paerl & Huisman, 2009). Decay of dead organic material leads to lack of oxygen in lower part of water column, and in anoxic conditions P is released from sediments back to the water column, causing secondary nutrient pollution with more algal mass.

An estimated 40 genera of freshwater CY are known to form toxic blooms (Mazur & Plinski, 2003), common blooms-formers are *Dolichospermum* (former *Anabaena*), *Aphanizomenon*, *Microcystis*, *Planktothrix*, *Gloeotrichia*. Presence of CY blooms generally lowers the quality of ecosystem services, which lakes are assumed to provide (recreational value, both commercial and recreational fishing, drinking and irrigation water), whereas blooms are anticipated to increase in frequency and intensity due to climate change (Moss, 2012). Intensity of blooms is related to water temperature ("blooms like it hot", Paerl & Huisman, 2008), increased nutrient amount, inability of grazers due to unpalatability (large colonies, long filaments, mucus, toxin production) (Huddnell & Dortch, 2008). Still, zooplankton that are "used to" live with toxic CY are not inhibited by their toxicity and consumption of toxic CY cells has been seen both *in situ* and in various experiments, whereas an increase in the viable egg production was shown (Hogfors et al., 2014). Bloom-forming species of CY are successful due to their higher temperature optimum, UV-tolerance, ability to fix nitrogen, production of gas-vacuoles, which allow moving to the best position in water-column, and toxin production (Oliver & Ganf, 2002). They prefer a stable and stratified water column: mixing caused by wind or other forces tends to generate unfavorable conditions, affecting negatively both metabolism and growth (Paerl, 2002). Not all bloom-forming CY fix nitrogen, non-heterocysteous species like *Microcystis* prefer conditions with higher nitrogen amount (Hudnell et al., 2008).

There is a historical knowledge about cattle, dog and wildlife poisonings together with human illnesses due to CY blooms in all continents (Codd et al, 2005b, review by Steffen et al., 2014). CY may produce 3 major types of toxins: neurotoxins (anatoxin and saxitoxin), hepatotoxins (microcystin, nodularian, cylindrospermopsin) and various skin and gastrointestinal toxins; often several different toxins are produced simultaneously (Backer et al., 2015). An overview of produced toxins is given by Paerl & Otten (2013). Hepatotoxins are associated with liver cancer (Zhang et al., 2015) and other tumours in humans and wildlife (Charmichael, 2001). Problematic is that presence of CY does not automatically mean that toxins are produced, and thus is impossible to say via EO methods whether the threat is real or only potentially there. Despite of that shortcoming, there is a strong need to monitor and forecast CY blooms, and remote sensing methods provide a cost-efficient opportunity (Kudela et al., 2015).

Although there is a myriad of semi-analytical methods and methods using spectral shape, an issue is the relative unavailability of sensors with both fine spectral and spatial resolution (Kudela et al., 2015). ESA's OLCI on board of Sentinels 2 (S2) and 3 (S3) will hopefully solve that problem. Because these sensors are not yet operational, for the current report we focus on MERIS (as proxy for S3 OLCI) and Landsat 8 (as proxy for S2). Problematic is that CY blooms tend to have extreme spatial variability (Kutser, 2005; Wynne et al., 2010; Lunetta et al., 2015), thus validation with in situ data from a single point in comparison with 300-m pixel might lead to erroneous results.

Identification of CY blooms by optical detection methods is based on algorithms targeting phycocyanin (PC) (overview in Kutser, 2009). Phycocyanin is a pigment-protein complex, specific to CY, with absorption maximum around 620 nm. Mishra & Mishra (2014) review five main types of algorithms that have been developed to estimate phycocyanin concentration from EO data. They also proposed a newest PC algorithm, suitable for MERIS-like sensors (training range of PC 68.13 to 3032.47 mg/m^3), but also admit, that there are still problems with correct detection of PC at low to medium amounts.

Since the in situ measured CY biomass or phycocyanin concentration is often lacking, there is a strong demand for both accurate satellite PC products in lakes as well as for in situ data for model validation. Horwath et al. (2013) showed that PC fluorescence is strongly correlated with extracted PC amount, but according to Macario et al. (2015) the amount of PC in cells is species-specific and fluorescence spectra depend on many factors, e.g. cell density in colony, cell size, light conditions and nutrients. Thus it is problematic to estimate CY abundance via fluorescence only, obtaining additional information about community composition is strongly recommended. Knowledge about phytoplankton community composition demands availability of microscopes, determination books about algal groups and skillful personnel, and also this type of analysis requires lot of time. These are the main reasons why data about community composition is often scarce. For the following analysis, information on the community composition was present for a majority of lakes under study.

Our first goal was to validate algorithms for satellite imagery with in situ chlorophyll and CY data. Subsequently, these algorithms were used for monitoring of CY surface blooms, their seasonal behavior and long term time series. The ultimate goal is to increase monitoring capability for lakes.

2 Description of the lakes

Table 1. Morphometric parameters of investigated lakes.

Parameter	Tuusulan-järvi	Ülemiste	Peipsi	IJssel-meer	Paters-woldse-meer	West-einder-plassen	Müggel-see	Trasi-meno
Surface area (km^2)	6	9.4	3555	1100	2.7	10-20	7.4	128
Max. depth (m)	10	4.2	15.3	22.2	7	4.2	7.9	6
Mean depth (m)	3.2	2.5	7.1	4.4	3	3	4.8	5
Water volume (km^3)	0.19	0.34	25	5.1	*	*	0.036	0.6
Surface elevation (m)	37.8	35.7	30	-0.2	0	0	20	258
Catchment area (km^2)	92	99.24	47800	185000	-	-	7000	383

L. Peipsi is largest, with the biggest catchment area, followed by L. IJsselmeer, which is the deepest lake in this study. Lakes Tuusulanjärvi, Müggelsee and Paterswoldsemeer are small and shallow. What all of these lakes have in common is their low mean depth of less than 10 m. The catchment areas show large variability. The catchment area of L. IJsselmeer is so large because it is mainly fed by water from the River Rhine since the River IJssel is a branch of it (van Eerden et al., 2007). Lakes Paterswoldsemeer and Westeinderplassen have active water inlets that are used to regulate the water level (*), instead of a natural catchment area.

2.1 L. Tuusulanjärvi – Finland

L. Tuusulanjärvi (Figure 1) is a shallow eutrophic-hypertrophic lake located in southern Finland. Its catchment area is 92 km^2, and the share of cultivated area is 30% and that of inhabited area is 20%. As much as 64% of the catchment area is made up of clayish soils and ten inlets carry fine light-weighted clay, which makes the water murky. Leaching of clay gradually increased as agriculture, which still continues today, started in the catchment area. Some humic water also runs into the lake from two bog areas.

As the use of fertilizers around L. Tuusulanjärvi increased (first animal manure, then artificial fertilizers) also the nutrient concentrations in the water increased and eutrophication of the lake started. The first signs were noted already in 1930s when phytoplankton occasionally coloured the water greenish. As the population grew after 1940s also the nutrient loading caused by untreated or insufficiently treated sewage from urban areas increased. This accelerated eutrophication of the lake since the 1950s and especially fast in 1960s and 1970s.

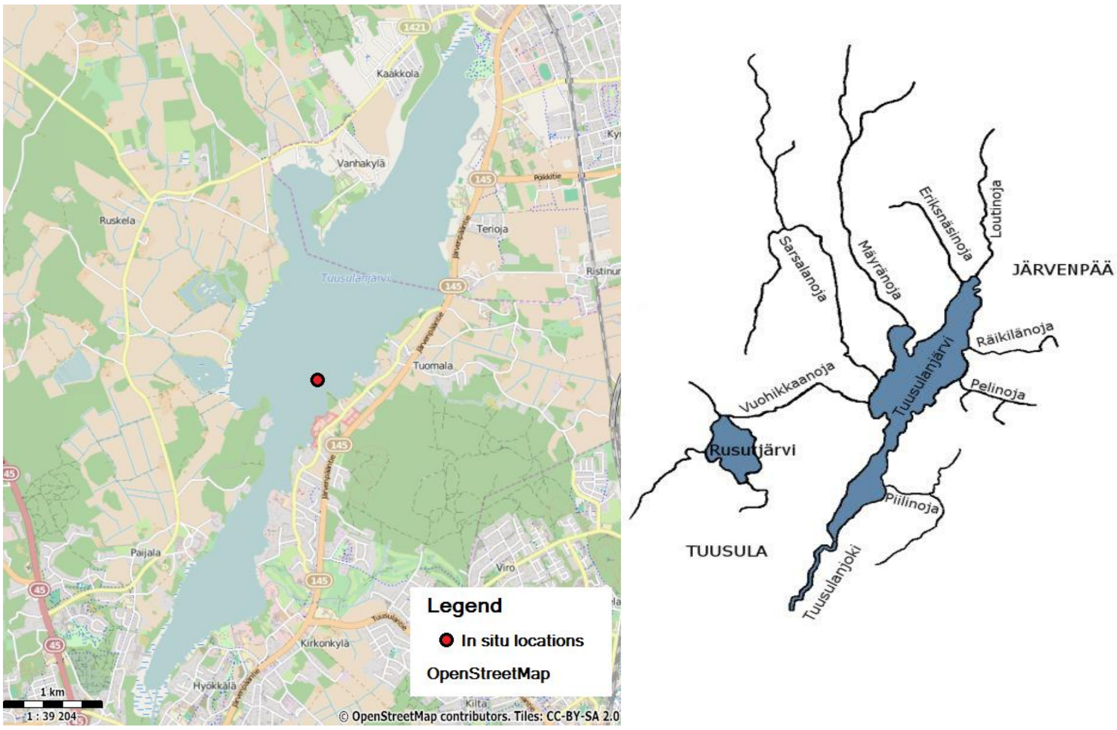


Figure 1. Map of L. Tuusulanjärvi with a monitoring point (left), main inlets and outflow (Tuusulanjoki) (right). The lake is about seven km long.

At the worst in the 1970s the water lacked oxygen already at two meter's depth due to microbial decomposition of organic matter, causing oxygen depletion even in the surface water. The condition was at its worst at late winter when decomposition of organic matter had used up the oxygen of the water and the ice cover prevented supplements from the air. As a result of oxygen depletion phosphorus was released from the sediment and the lake thus fertilized itself. The big step on the lake's path to recovery came in 1979, when the sea sewage pipe that carried wastewaters from the town of Järvenpää to Helsinki to be treated was completed. The largest source of nutrient loading of the lake was thus removed.

Table 2. Water quality values of L. Tuusulanjärvi (mean with min and max in the parenthesis) are in situ monitoring results measured in June-September in 2000-2014.

Theoretical retention time	250 d
Chl-a	29.2 µg/l (3.6-100)
Turbidity	21.4 FNU (9.1-64)
a_{CDOM}(400)	6.3 1/m (3.3-13.1)
Secchi	0.65 m (0.3-1.0)

The intensive restoration measures were started in 1998 and have continued thereafter. The restoration measures include reduction of nutrient loading from catchment area e.g. by building of wetlands. Besides aeration internal loading has been reduced by fish removal (over 100 tons in 1997-2012). The aims of the restoration are to improve water quality and to increase possibilities for recreational activities and to keep the stocks of predatory fish strong. For additional information on L. Tuusulanjärvi, see http://eng.tuusulanjarvi.org/.

2.2 L. Ülemiste - Estonia

It is the third largest natural lake in Estonia and main drinking water source for Estonian capital Tallinn (about 90%), other actions in/on lake are prohibited. Eutrophication problems started during 19 century with CY blooms, which leaded to public complaints over the drinking water quality. From Soviet Union times (after 1990) the need for water declined 4x due to decreasing industry, which caused prolonged hydraulic residence time. Now it is eutrophic to hypertrophic waterbody, “moderate” according to WFD, unstratified and with medium hardness.

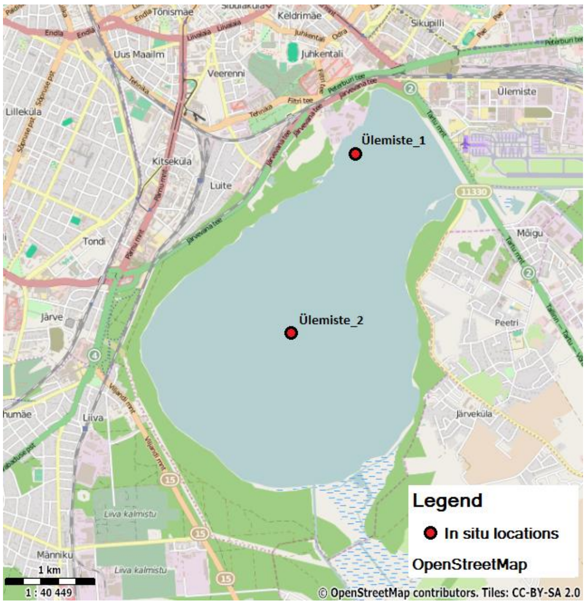


Figure 2. Map of L. Ülemiste together with monitoring points.

At the beginning of 21th century plankton – and benthic feeders dominated among fish community, whereas the share of predatory fishes was less than 5 %. Transparency during summer was about 0.5 m., and algal mass complicated the water purification process leading to bigger expenses. Small share of predatory fishes leaded to suggestion of high potential for biomanipulation activities, since lake is also reasonably small and shallow. Biomanipulation project was conducted jointly with Finnish specialists and scientists from Estonian University of Life Sciences.

The timetable of the project was as follows:

- ✓ 2002: Creation of a small artificial wetland to the entering stream
- ✓ 2001 and 2002: 45 000 predatory fish larvae were added
- ✓ 2003, 2004 and 2005: selective fishing of bream, roach and ruff during wintertime, which leaded to decline in Chl-a and total nutrient (N and P) amounts during 2005-2007 and increase in transparency, which exceeded 1 m during spring clear water period. Visible was also a change in algal community: instead of filamentous cyanobacterium *Limnothrix redekei* colonial CY (including *Microcystis* spp.) began to dominate. Change in algal community did not improve water purification process: *L. redekei* is not known to produce toxins, but *Microcystis* spp. are well-known toxin producers.
- ✓ 2008: extensive fishing together with pike addition
- ✓ 2009: generation of artificial spawning grounds

A conclusion from the project today underlines the difficulties of restoration from eutrophication. The project „Has given ”some” effect, but should be continued“.

2.3 L. Peipsi - Estonia

L. Peipsi is located in Eastern Estonia, on the border of Russia and Estonia (Figure 3), being the largest trans boundary water body in Europe. It consists of three parts: the largest and deepest mesotrophic L. Peipsi s.s., the middle strait-like eutrophic L. Lämmijärv and hypertrophic L. Pihkva, which belongs entirely to Russia. The majority of nutrients are carried into the lake by the rivers Velikaja and Emajõgi: from the total drainage basin of L. Peipsi the catchment areas of those two rivers cover up to 80% of the area (Loigu et al., 2008). The biggest part of the catchment area belongs to Russia (58%), to Estonia (34%) and the rest 8 % belongs to Latvia and Belarus (Jaani, 2001). According to Buhvestova et al. (2011) major Estonian rivers discharged approximately 5600 t of nitrogen (mainly during winter and spring) and 179 t of phosphorus annually to L. Peipsi. There is also a spatial variation in in-lake nutrient content: the northern part has always been significantly poorer than the southern part (Kangur & Möls, 2008). In-lake phosphorus concentrations were not found to be sensitive to year-to-year changes in riverine nutrient loads (Buhvestova et al., 2011), leading to assumption of the importance of self-contamination due to P-rich sediments.
In L. Peipsi dominant algal complex has not changed essentially during the 20th century, and blooms of *Gloeotrichia* were recorded already 100 years ago (Kullus, 1964). Nowadays every part of L. Peipsi shows an increasing trend of CYI biomass based on in situ data, which is most pronounced in the southern parts of the lake (Laugaste et al., 2007).

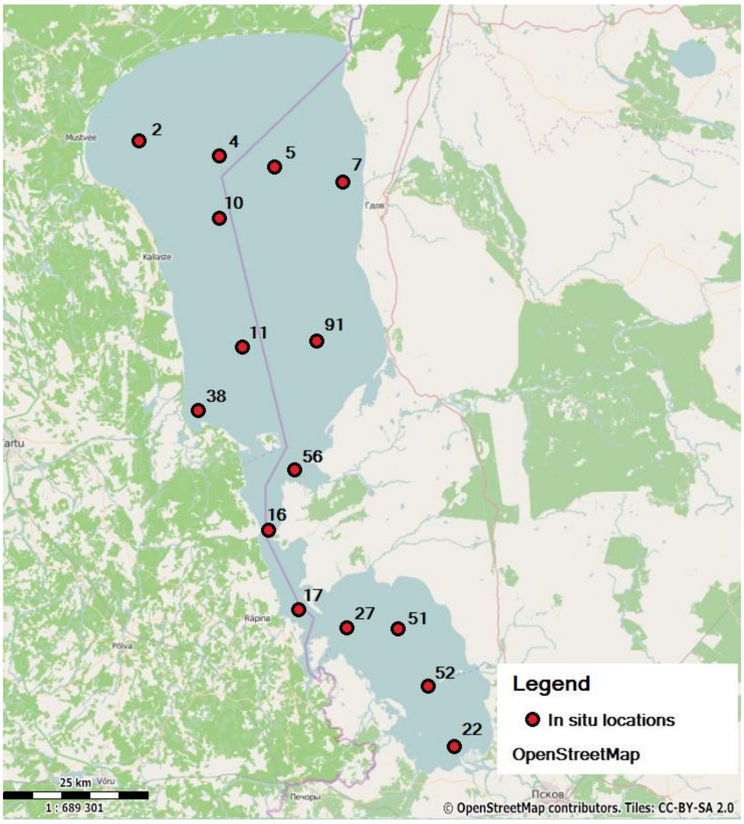


Figure 3. Map of L. Peipsi with national monitoring points. Points 2,4,11,38,16,17 are visited once a month from May to September, rest of the points once a year during August.

From ecosystem services perspective, besides recreational activities like boating, swimming, skating and recreational fishing, L. Peipsi provides 80-88% of freshwater fish catches in Estonia, whereas 3-10 % is caught from L. Võrtsjärv and 1-2 % from the rest of waterbodies. In fish catch dominate mainly warm-water species (bream, pikeperch, perch, pike, roach), whereas cold-water fishes (smelt, whitefish, burbot, vendace) are in decline (Table 3).

Table 3. Fish catch (ton per year): From „Fish catches.., 2014“.

Year	Smelt	Vendace	Whitefish	Burbot	Pike	Bream	Pikeperch	Perch	Roach	Other fish	Total
2005	624	0	6	41	223	1151	1775	628	1041	604	6093
2006	577	0	7	52	238	1160	2104	824	1068	902	6932
2007	0	1	9	75	232	1216	2223	1167	824	641	6388
2008	0	1	2	43	114	1008	1101	1268	673	390	4600
2009	0	1	3	38	128	972	1022	1373	546	339	4422
2010	0	0	3	51	162	1076	938	2015	578	340	5163
2011	1	6	0	55	220	1177	1077	1374	596	299	4805
2012	2	7	3	59	339	1325	1307	2033	681	469	6225
2013	4	10	1	65	303	1274	1218	1791	525	286	5477

The problem with vendace reflects the ecosystem instability of L. Peipsi. Vendace is a cold-water species, which was abundant during 1970/80 (catch 1000-3000 t/year). Vendace population collapsed during 1991-1994 (with no catch), then recovered with 167 t catch during 1998, but during 2001-2011 catch was again zero or close to it. Since 2011 a slow recovery is visible. There is no single reason behind the decline, but rather a combination of environmental factors (Kangur et al., 2005; Kangur et al., 2007, Kangur et al., 2013):

1. Increase in water temperature > 20°C during summer;
2. Effect of CY blooms is also noted as an important factor: changes in oxygen regime, increase in pH and possible effect of toxins;
3. Increase in predator abundance e.g. pikeperch;
4. Eutrophication: siltation of spawning grounds.

Recreational fishing is also popular during wintertime: up to 3000 anglers were observed at weekends on the Estonian side of the ice-covered lake (Orru et al., 2014). L. Peipsi is an internationally important bird area (partly of the Natura 2000 area) with more than 100 different species of water-and swamp-related birds. Altogether is found 266 bird species, including 180 nesting species, 71 passaging species and 15 occasionally present species during last 50 years (Luigujõe et al., 2008).

2.4 L. IJsselmeer - Netherlands

The freshwater L. IJsselmeer was created in 1932 when a 32 km dam, the Afsluitdijk, closed the brackish Zuiderzee. This was part of a major hydraulic engineering project known as the Zuiderzee Works, which years later led to the reclaiming of land from L. IJsselmeer, and branching off of L. Markermeer, thereby diminishing the size of the lake (Van Raaphorst & De Jonge, 2004). After its creation in 1932, the surface area and volume of the IJsselmeer has decreased stepwise due to the construction of three large polders in 1942, 1957 and 1967. In 1975 L. IJsselmeer was further split in two by the completion of the Houtribdijk, this dam runs from Enkhuizen southeast to the city of Lelystad. This former southern part of L. IJsselmeer is now the hydrologically separate L. Markermeer. L. IJsselmeer (Figure 4) functions as a major fresh water reserve, serving as irrigation water source for agriculture and drinking water. It also offers a number of opportunities for recreational activities (water sports: yachting, sailing, ice skating), fishing (eel mainly), and is an important area for waterfowl.

Figure 4. Map of L. IJsselmeer with a monitoring point at Vrouwezand.

L. IJsselmeer exhibits a Secchi disk depth around 0.8 m and Chl-a concentrations up to 200 mg m^{-3} in summer. The vertical light attenuation is mainly due to microalgae and CY. Surface scums of CY occur, but the water column is usually fully mixed. Colonies of *Microcystis* sp. and *Aphanizomenon* sp. filaments represent most of the CY biomass. The distribution of CY and green algae in summer is inhomogeneous, with locations of relatively high CY to green algal biomass and vice versa. From midsummer onward, CY dominate the plankton community (Simis et al., 2005).

2.5 L. Paterswoldsemeer - Netherlands

L. Paterswoldsemeer (Figure 5) is located on the south side of the city of Groningen in the North of the Netherlands. From origin it is a peat lake that developed because the peat was mined. Therefore it is not deep (the maximum depth is around 3 meters) and has shorelines with several small bays and islands. Its surface is 1.7 km^2. Its main use is recreational, basically for surfing and boating. However, there is also a swimming beach. A dike to prevent heavy CY blooms has fenced off the area around the beach.

L. Paterswoldsemeer receives its water via a complex chain of channels and locks. Originally, the water comes from L. IJsselmeer, from which it is lead northwards, to finally discharge in the Wadden Sea. This process includes many manual decisions on closing or opening the locks, to make sure that enough water is saved to cover dry periods, while flooding should also be prevented. Inland commercial shipping (in the channel of water bodies feeding and discharging the lake) needs water levels to be very stable: deep enough for the larger boats, low enough so the boats can still pass under the bridges. Water level and water quality regulation is the responsibility of the local water authority (for L. Paterswoldsemeer this authority is Noorderzijlvest). Farmers and recreants have their own priorities with which the local water authority has to deal.

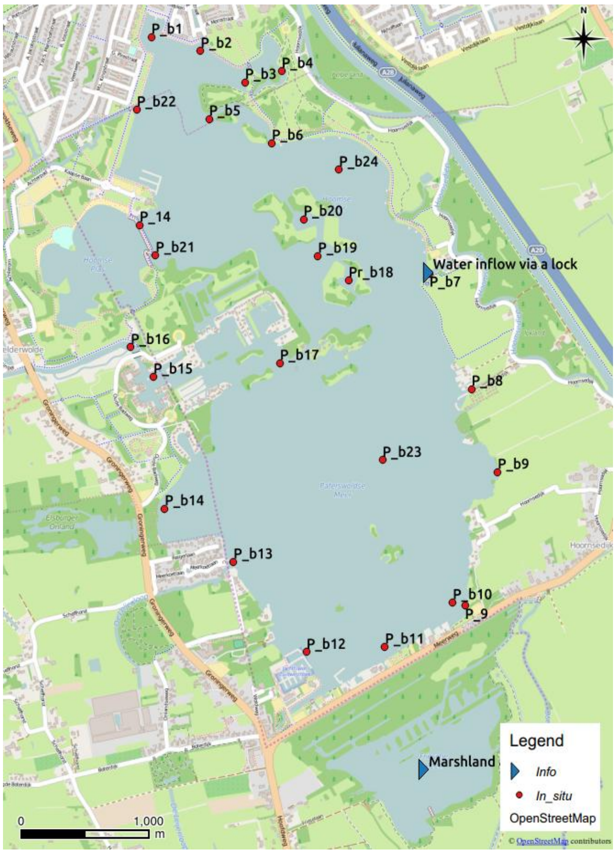


Figure 5. Map of L. Paterswoldsemeer

L. Paterswoldsemeer regularly suffers from intense CY blooms that also form scums. This is an ecological but also socio-economic issue when, because of the scums, the bathing area has to be closed, which causes losses for the local entrepreneurs in the recreational industry. L. Paterswoldsemeer is intensively used for recreation (Figure 6). It is know that sometimes, scums enter the lake via the inlet lock, but in other cases blooms start elsewhere in the lake. Monitoring can increase the knowledge on the appearance of blooms and therefore contribute to water quality management.

Figure 6. Left: CY bloom in lake Paterswoldsemeer; Right: bathing in lake Paterswoldsemeer (Photos: ESA CyMonS project).

2.6 L. Westeinderplassen - Netherlands

L. Westeinderplassen (Figures 7 & 8) has its origin in peat mining, like L. Paterswoldsemeer and is comparably shallow (~3m). L. Westeinderplassen has very many small islands and bays, especially on the North side. By surface (10 km^2) it is much larger than L. Paterswoldsemeer. It is an official swimming area and is used for recreational as well as for commercial shipping. There are about 50 recreational harbours and several recreational areas with swimming beaches.

Figure 7. L. Westeinderplassen. Left: open area. In the middle is an area with a bloom, just visible. Right: bathing area closed because of CY blooms. (Photos: CyMonS project).

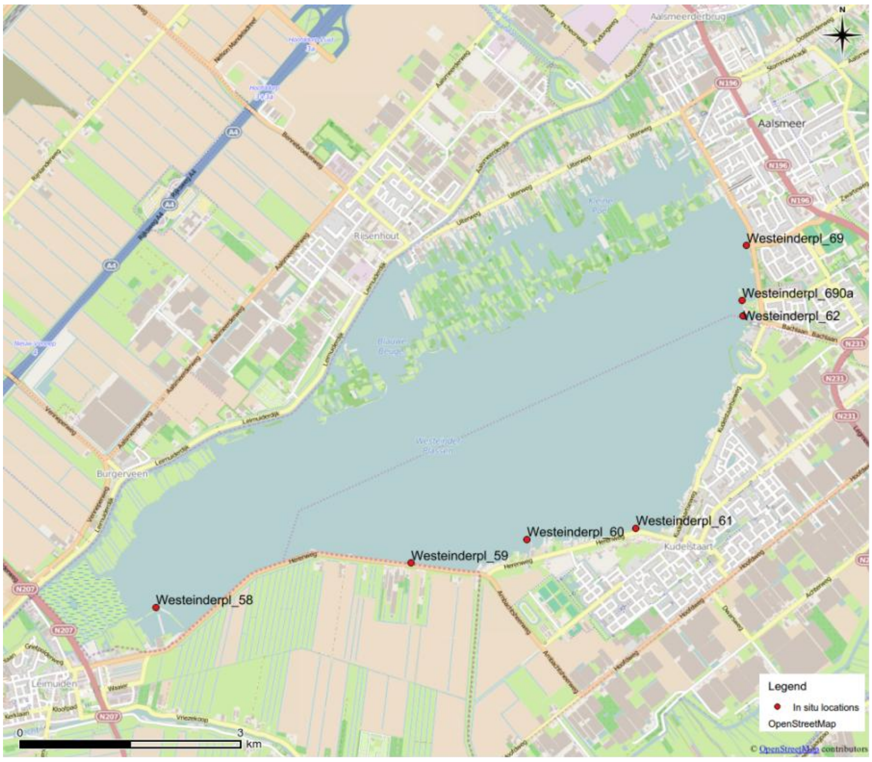


Figure 8. Map of L. Westeinderplassen.

Regional water authority Rijnland has taken several measures during the swimming season to prevent and – if needed – remove scums in Westeinderplassen. In the northeast, behind the islands, a continuous pumping installation prevents the formation of scums. In the same area there is also the option to install shields, to prevent outflow of water from a small channel where scums can easily start. If too many scums accumulated there the water authority removes these. At one location a test with propellers that move the water to prevent scum formation is actually running.

2.7 L. Müggelsee - Germany

The Müggelsee (L. Müggel, Figure 9) is located East of Berlin and has a glacial genesis. Located in a glacial valley, it is surrounded by hilly moraine. With 7.3 km³ it is the largest lake of Berlin. The maximal depth of 8 m is reached only in a small portion of the lake; the mean depth is 4 m. The Spree River discharges in this lake with an average of 60 m³/s.
The lake is used for drinking water (ground water and lake filtrate) that is taken from the northern part of the lake. The water percolates into the ground, filtered by the sand.
The lake is influenced by the River Spree and thus the nutrient concentration in the lake is quite high. The inflow is around 7m³/s with the yearly import of nutrients around 20t phosphorus and 500t nitrate. These volumes were measured in the middle of the 1980s, but they are still too high and algal blooms are frequent in the lake. These vary from year to year and last from spring until autumn. In May/June the algal concentration is usually decreasing (called clear water stadium). Besides the overall concentration also the species composition varies from year to year. Since 1990 a decrease of algal concentration, especially CY is observed. The water quality has improved during the last years, which can also be seen in an increase of underwater vegetation (www.igbberlin.de/grosser_mueggelsee_uebersicht.html).

Figure 9. Map of Müggelsee and the positions of the measurement stations operated by IGB (Leibniz-Institute of Freshwater Ecology and Inland Fisheries Dept. II)

2.8 L. Trasimeno - Italy

The lacustrine ecosystem represents an area of exceptional value due to its flora and fauna richness and species diversity. Moreover, the lake basin has a strong economic impact due to agriculture, tourism and fishery activities. In recent years, the lake showed serious difficulties recovering the ecological equilibrium as recommended by the WFD 2000/60/EC. The shallow L. Trasimeno (Figure 10), belonging to River Tevere basin, is a laminar lake, with an irregular hydrologic regime, susceptible to variations caused by seasonal and long-time cycle. In these last years, meteo-climatic anomalies caused the water level to be too low, growing environmental lake problems and making its waters mainly obtain a poor judgment. Low hydrometric levels, nutrients load from agricultural and zoo technical practices, civil discharges, tourism activities and meteorological events, have been bringing the lake towards eutrophic condition. In general, high concentration of phytoplankton and suspended materials, the second one brought also from the bottom by re-suspension phenomena, makes waters turbid during long period in whole lake.

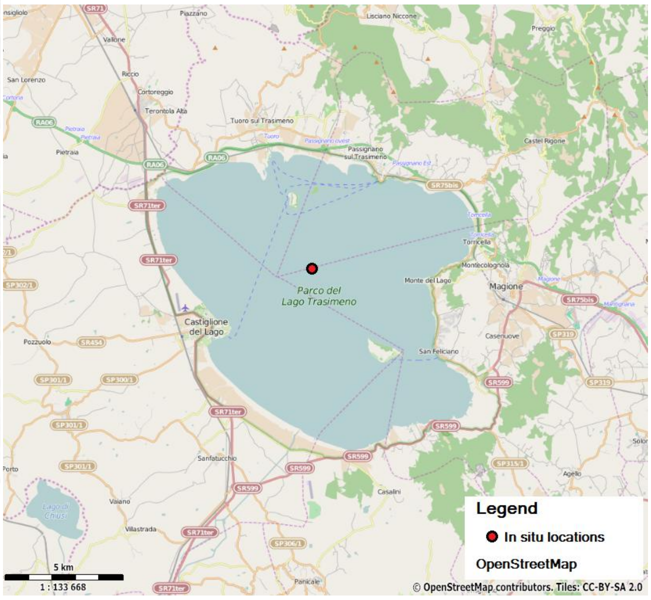


Figure 10. L. Trasimeno, location and map.

In addition the consequent decrease of biodiversity and vegetation complexity, together with the domino effect, brought changes in distribution and variety of submerged vegetation, facilitating CY blooms in summer. In particular, these blooms are a warning of ecological instability and sanitary alarm. Among CY most common species in L. Trasimeno are: *Cylindrospermopsis raciborskii*, *Plankthothrix agardhii*, *Leptolyngbya* sp., *Oscillatoria* sp. Since 1960's, CY community presence has increased from 10% to more than 50% on whole phytoplankton composition and total phytoplankton biomass has triplicated in the last 30 years (Elia et al., 2011).

Water quality worsening in the last decades impacted fishery, which is a leading activity for L. Trasimeno: a lot of non-native and less fine species (e.g. *Carassius auratus*) replaced native species and quality of the catch has decreased (Lorenzoni et al., 2007).

Particular and intense algal blooms occurred in some recent years, characterised by particular meteo-climatic conditions. These were:

- 2006: characterised by high water levels, due to abundant precipitation, and lack of algal bloom, macrophyte vegetation and fish increase;
- 2008: characterised by low precipitation and high temperature, followed by decrease of water levels and intense algal blooms;
- 2010: characterised by meteo-climatic variability and alternating conditions, which caused blooms of several very different algal groups.

3. Material and methods

3.1 Description of used algorithms

3.1.1 Larger lakes: MERIS data

For validation and testing four algorithms were chosen: maximum chlorophyll index (MCI), fluorescence line height (FLH), maximum peak height (MPH) and CoastColour Processing. Processing procedure is illustrated in Figures 11 (MCI, FLH), 13 (MPH) and 14 (CoastColour). All algorithms previously developed for MERIS and validated with *in situ* data are also applicable for data from OLCI on board of satellite Sentinel-3.

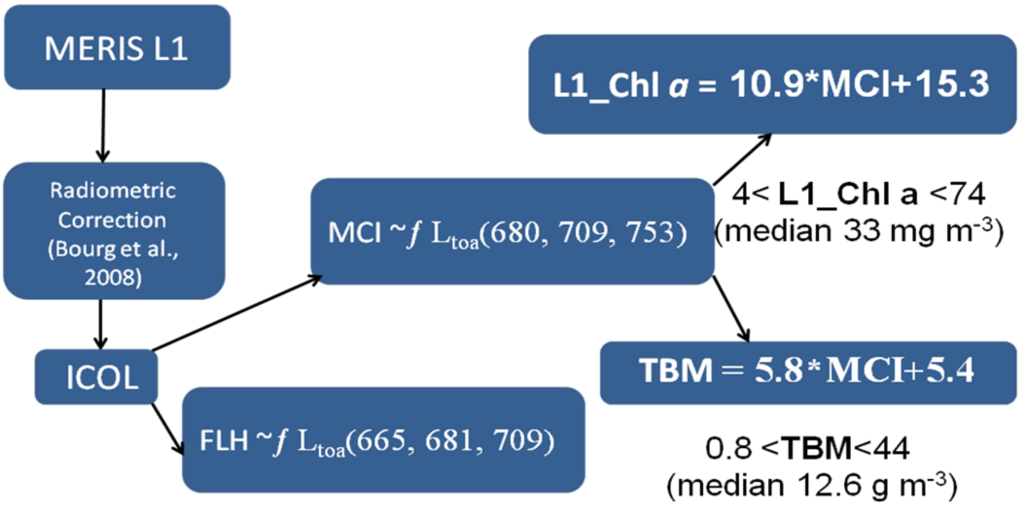


Figure 11. Processing scheme for MERIS data for obtaining MCI and FLH. Chl-a and total biomass (TBM) calculations are an example about calculations in case of L. Peipsi from Alikas et al. (2010).

3.1.1.1 Maximum Chlorophyll Index

Alikas, Kangro and Reinart (2010) demonstrated that the **Maximum Chlorophyll Index (MCI), equation 1**, developed by Gower et al. (2008) for the MERIS processing scheme, is a useful tool for detecting and estimating CY biomass (R^2 = 0.73), phytoplankton total biomass (TBM) (R^2 =0.70) and chlorophyll *a* concentration (R^2 = 0.64), giving also an overview about seasonal dynamics and coverage of CY blooms.

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

where the factor 0.389 is the ratio between the wavelengths determining peak and baseline (709-681)/(753-681) = 28/72 = 0.389 and L indicates radiance in specific MERIS bands. The height of the peak at 709 nm is quantified as the radiance difference between the radiance measured at 709 nm and the baseline radiance at this wavelength (Gower et al., 2008). Binding et al. (2013) showed MCI being a versatile tool in monitoring intense surficial algal blooms with Chl-a concentrations in the 10–300 mg m^{-3} range.

3.1.1.2 Fluorescence Line Height (FLH)

This algorithm (equation 2) can be used for estimations of Chl-a especially in those lakes, where Chl-a concentration is >10 mg/m^3 (Palmer et al., 2015) and is suitable for usage in shallow lakes with elevated Chl-a content.

$$FLH=L_{681}-1.005*[L_{665} + (L_{709}-L_{665})*((681-665) / (709-665))], \qquad (2)$$

where L indicates radiance in specific MERIS bands. Note that the fluorescence only gives a relatively weak signal in a region of the spectrum where water absorption and TSM scattering can be substantial. According to Palmer et al. (2014) negative FLH values indicate the presence of CY bloom and correlate with bloom magnitude, since CY do not produce Chl-a fluorescence signal near 685 nm, but they produce a signal near 665 nm. Positive values indicate lack of CY.

3.1.1.3 Maximum Peak Height (MPH)

This algorithm is also suitable for shallow lakes with Chl-a concentration bigger than 10 mg/m^3 (Matthews & Odermatt, 2015). It was designed to give quantitative Chl-a estimates in optically complex waters, for detecting CY blooms and surface scum together with floating macrophytes (see a detailed description from Matthews & Odermatt, 2015).

The algorithm uses narrow red-edge bands at 681, 709 and 753nm, with 665 and 885nm bands as a baseline (Figure 12) and is proven to be more stable in comparison with MCI and FLH (Matthews & Odermatt, 2015). CY detection is performed using distinctive spectral features in the 620 nm and 681 nm bands, and a separate Chl-a algorithm is used for these CY-dominant waters. Floating matter identification is performed by the detection of a maximum peak position at 753 nm, which is then either classified as floating CY (surface scum) or vegetation (macrophytes), depending on whether the spectral features of CY are present.

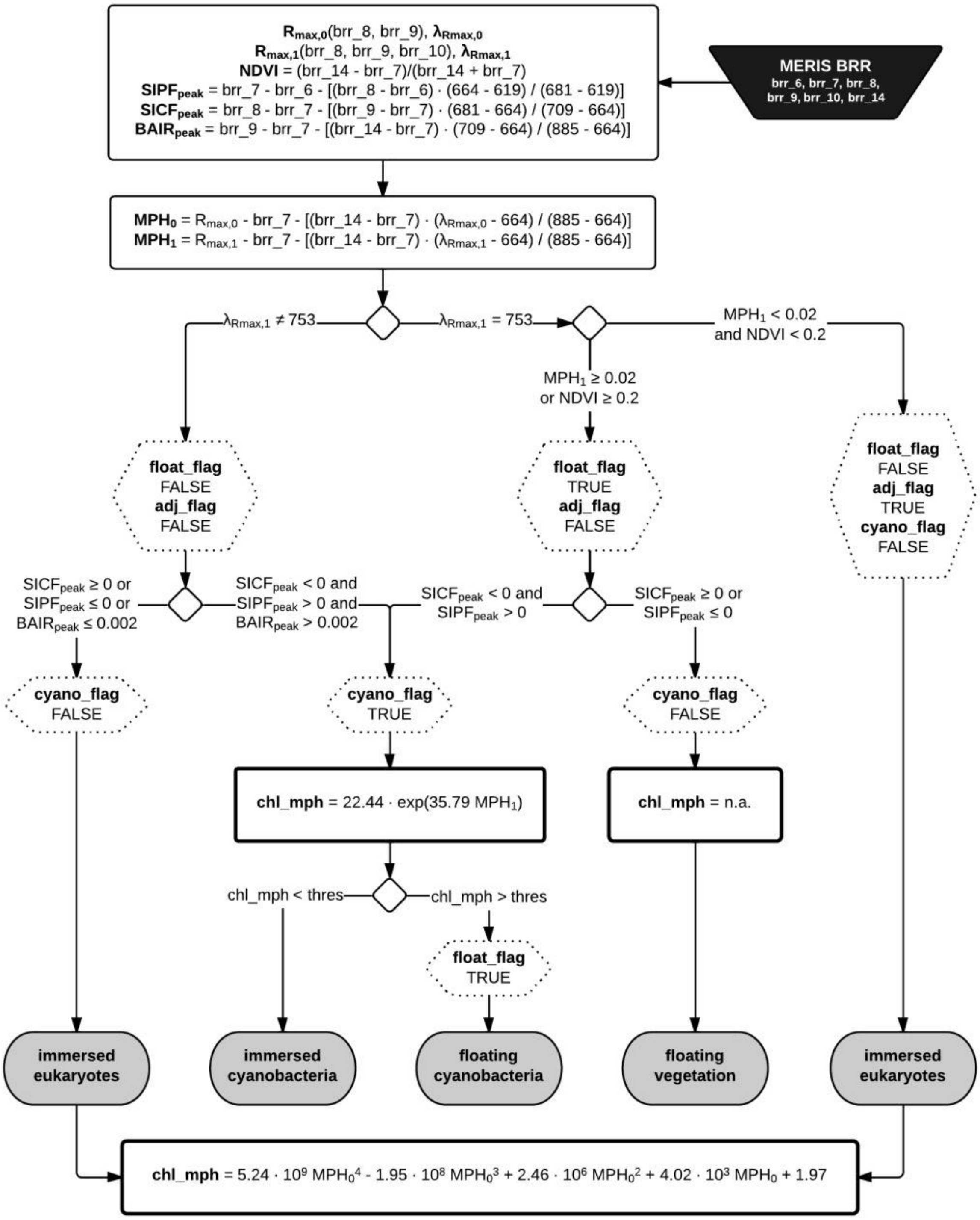


Figure 12. Scheme of MPH calculation by Matthews & Odermatt (2015).

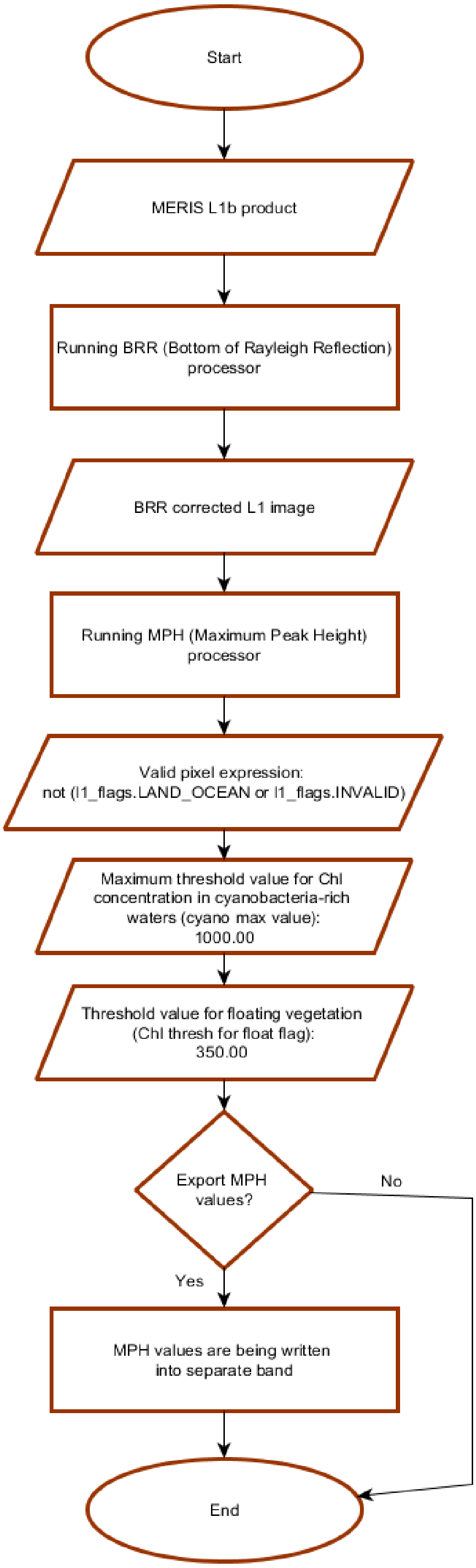


Figure 13. Processing scheme for L. Peipsi, L. Ülemiste and L. Tuusulanjärvi.

As an example of how MPH is applied, Figure 13 shows the processing scheme for MPH in Lake Peipsi, Ülemiste and Tuusulanjärvi. First, MERIS L1b products were pre-processed with special BRR processor available in BEAM and necessary for creating proper input for MPH processor. In order to apply MPH algorithm to BRR corrected L1 images some threshold values for defying maximum chlorophyll concentration in CY-rich waters and floating vegetation were set. Final outcome is MERIS L2 products containing bands of Chl a concentration values and flags for immersed and floating CY. It is also possible to separately export MPH values into a band.

For validation with in situ data for L. Peipsi, Ülemiste and Tuusulanjärvi for all 3 indexes one single pixel corresponding with in situ measurements was taken. Since cloud flagging was not working properly, images had to be screened visually for clouds.

3.1.1.4 CoastColour processing

The **CoastColour** processing is based on a Neural Net (CC NN) algorithm which was developed by Dr. Roland Doerffer in the framework of the CoastColour project focused on coastal complex waters (Brockmann Consult, Product User Guide 2.2, 2014). The algorithm is divided in (1) preprocessing steps (result: L1P products), (2) an atmospheric correction part (result: L2R products) and (3) an inwater part (results: L2W products). The algorithm is included in the BEAM software.

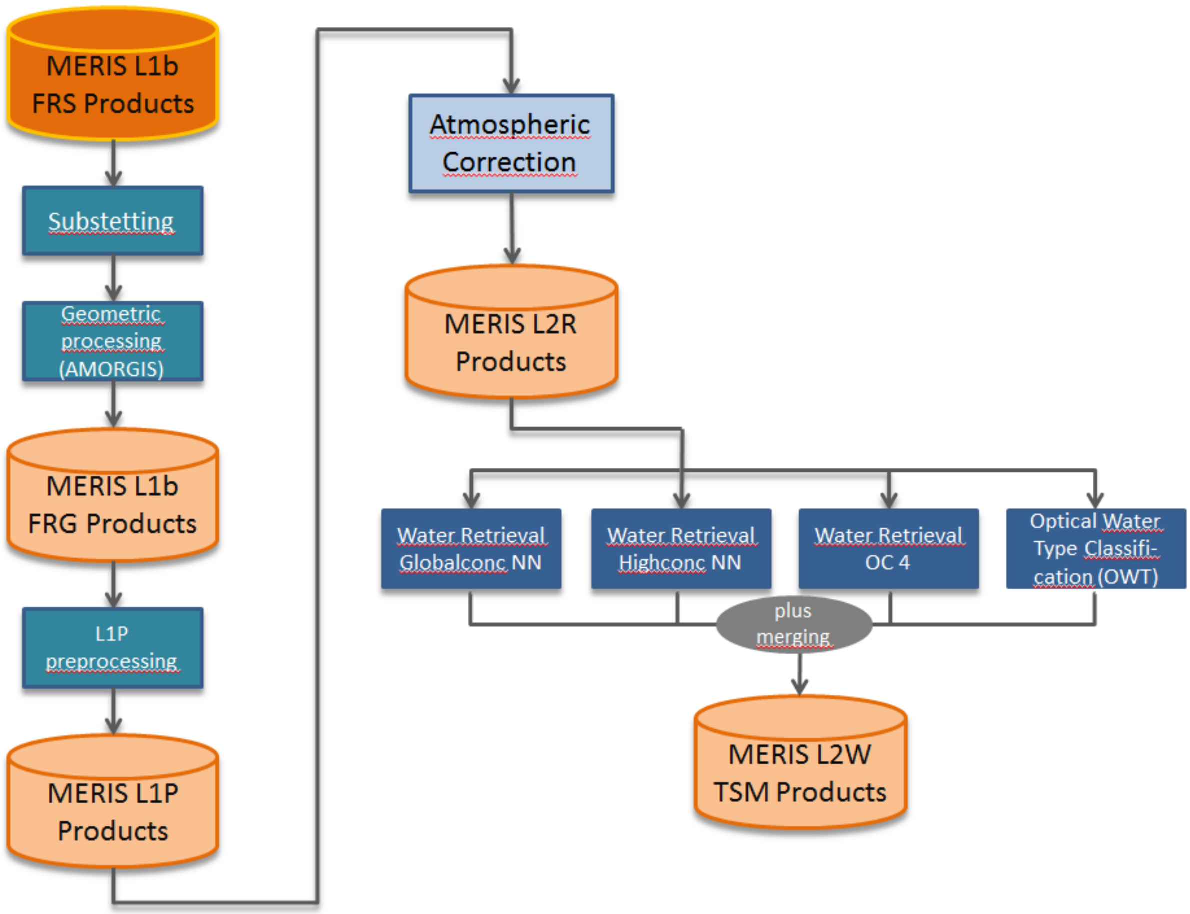


Figure 14. Main steps of the CoastColour processing scheme.

Each of the processing steps is composed of different algorithms. The preprocessing includes improved flagging (clouds, cloud buffer, land, mixed pixel, floating vegetation, glint, cloud shadow) and geometric and radiometric improvements. The AC correction procedure is based on radiative transfer simulations. The simulated radiances are used to train a neural network, which, in turn, is used for the parameterisation of the relationships between TOA radiance reflectance (R_{L_toa}) and the water leaving radiance reflectance (R_{Lw}). Furthermore, it computes the atmospheric path radiances (R_{L_path}), the downwelling irradiance at water level (E_d), the aerosol optical thickness (AOT) at 550 nm and three other wavelengths, and the angstrom exponents of the AOT.

The model atmosphere comprises three parts:
(1) a standard atmosphere, which includes layers with variable concentrations of different aerosols, cirrus cloud particles and a rough, wind dependent sea surface with specular

reflectance, but with a constant air pressure- and ozone profile,
(2) a layer on top of the standard atmosphere, which contains only the difference between the standard and real atmosphere concerning air molecules and ozone, and (3) a module to compute the water leaving radiance reflectance.

Of importance is the correction of the sun glint, which is included in the atmospheric correction. It allows using the full swath of a MERIS scene, even for high glint conditions. The atmospheric correction is based on NN approach procedure is described in detail in GLaSS Deliverable D3.2.

The in-water processing uses a NN approach on the one hand and the OC4 (Ocean Chlorophyll 4) Algorithm on the other hand. The chlorophyll concentrations derived from both algorithms are stored in the L2W product and in addition, a merged chlorophyll concentration is generated which merges the two in dependency of the TSM concentration in the respective pixel. The TSM is derived from the NN approach. The NN works with a 5-component model and provides the absorption from phytoplankton, from detritus and yellow substance. In addition to the water constituents themselves, the optical water type classification provides the information about the water type. It allows pixels to be assigned partial or graded class memberships to different water types with which they share spectral characteristics. This is accomplished by using a fuzzy membership function that expresses the likelihood that a pixel, with its observed radiance vector, belongs to a class with a known reflectance distribution.

For further details about the CoastColour processing please refer to the CoastColour Product User Guide (www.coastcolour.org/publications/Coastcolour-PUG-v2.2.pdf).

3.1.1.5 Diversity processing

The **Diversity processing** (CalLimnos processing) combines different atmospheric and water algorithms. The schematic processing chain is shown in Figure 15. The resulting products are monthly averages of individual lakes containing different chlorophyll concentrations and the dominant OWT class. This classification is an indicator for the user for selecting the suitable chlorophyll algorithm. Furthermore, a CY index is provided by applying the MPH algorithm (Matthews & Odermatt, 2015), see description above.

The diversity processing facilitates binary classification of optical dominance at the level of individual satellite images, but does not indicate species composition or concentrations of CY pigments. The monthly products represent the portion of positive binary identifications in individual observations in the range 0 to 1 for all aggregated images. Accordingly, the precision of this probability depends strongly on the number of observations.

The yearly products are the mean of all valid monthly products, presence of the lake ice leads to zero observations and thus NaN, which has no effect on the averaging. Yearly means are thus only the average of the months with at least one valid observation. However, a melting lake ice may cause artifacts in some products, because it looks very similar to water in MERIS spectra, thus it is generally recommended to handle spring monthly products with extraordinarily high values in all indicators with care. Cloudy pixels - in principle not entire pictures - were excluded from the analysis.

The description of the processing can be found in the Product User Guide of Diversity-2:
http://www.diversity2.info/products/documents/DEL8/DIV2_Products_User_Handbook_Inland waters_v2.0.pdf

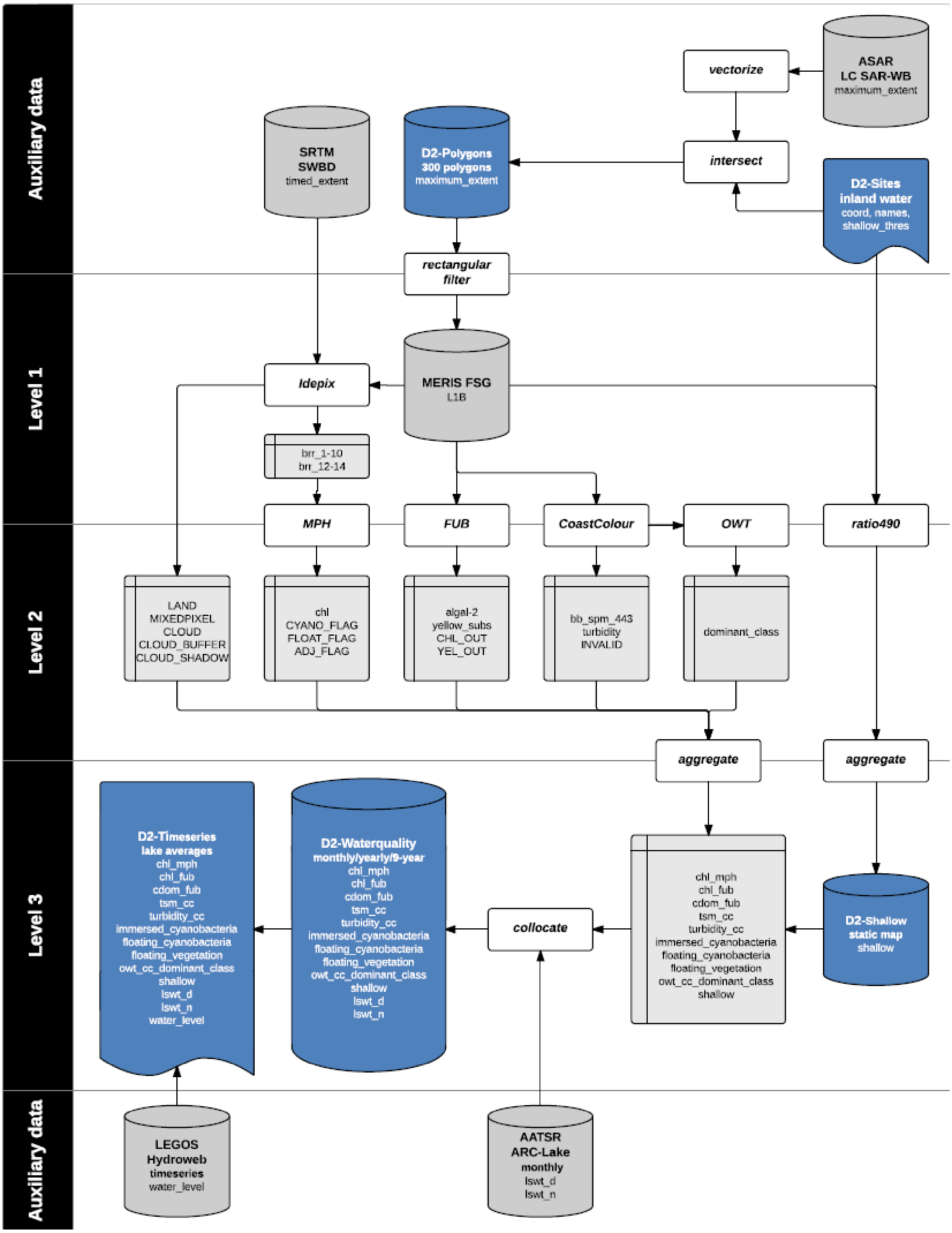


Figure 15. CalLimnos Processing Chain developed within the Diversity-2 project.

3.1.1.6 Trasimeno data and methods

Due to their particular meteo-climatic conditions and thus to their different trophic status, year 2006 and 2008 were chosen for the evaluation of Chl-a concentration time trend for L. Trasimeno, and a particular bloom event in 2010 was analysed.
The work was developed through three steps:

(i) validation of MPH, FLH and MCI products through in situ measurements;
(ii) time series analysis of 78 valid images from 2006 and 112 valid images from 2008 processed through MPH, FLH and MCI;
(iii) CY presence analysis, looking for correlation to meteorological conditions.

The objective of step (i) was achieved exploiting 25 in situ measurements (provided by local agency and IREA field campaigns between 2005 and 2008), to be compared to 6 synchronous products. In particular regarding MPH, Chl-a concentration estimation was extracted as 3x3 ROI mean values in correspondence to in situ measurement points. On the other hand, the validation of MCI and FLH index was conducted using 18 measurements were to estimate the parameters of a linear regression used to retrieve Chl-a concentration.

In the second step, daily values extracted as mean values from selected ROIs (Figure 16) from year 2006 and 2008 were compared looking for different seasonal behavior for all the products. ROIs were selected to be representative of the lake, avoiding coastal area, isles and submersed vegetation and used for the evaluation of possible spatial distribution of algal blooms. Maps of water quality of interesting dates were produced using the products of three algorithms.

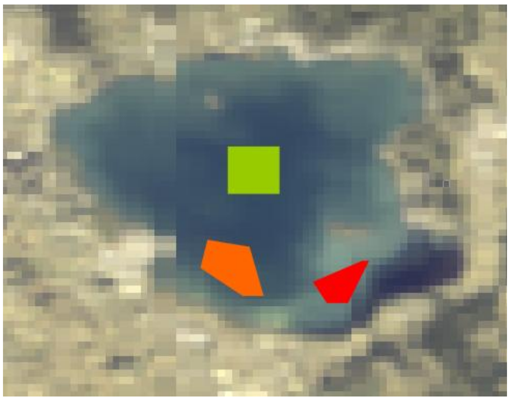


Figure 16. ROIs selected for the extraction of MPH Chl-a mean values. Green colour represents Pelagic, orange South-West and red South-East ROI.

Finally a Boolean value indicating the predominance of CY provided by MPH was extracted by the same ROIs and results from both years were compared. In addition, for this particular objective, also data of a CY bloom in 2010 were exploited, interesting also for the variability of its meteo-climatic conditions.

3.1.2 Processing of Landsat 8 data

For the relatively small Dutch lakes (Paterswoldsemeer and Westeinderplassen), Landsat 8 data was used.

For L. Paterswoldsemeer, the imagery was downloaded from the GLaSS core system (D2.3 System & System implementation report) using the bulk download scripts (D2.4 System Interfaces implementation report). Next, the data was processed to L2 remote sensing reflectance at the water surface, using the C2R-L8 processor in the SNAP toolbox. However,

the standard land-water flag was replaced with:
water = (near_infrared- red) / (near_infrared+ red) < 0.1 and swir_1 < 5 and swir_1 > 0.0.

For L. Westeinderplassen USGS surface reflectance imagery was ordered and downloaded via EarthExplorer (http://earthexplorer.usgs.gov).
The choice of C2R for L. Paterswoldsemeer and surface reflectance from USGS for L. Westeinderplassen was based on validations that will be included in D4.2 (Validation report for nearby lakes).

To derive chlorophyll, the band ratio reflec_3/reflec_4 was applied. The retrieved values were 'tuned' to scale the WISP-3 derived chlorophyll concentrations. These concentrations derived from in situ radiometric measurements using the WISP algorithm were proved to agree well with laboratory results, which were provided to the ESA project CyMonS by the local water authorities Noorderzijlvest and Rijnland (the water managers responsible for these two lakes).

To generate time series, the ROIStats tool (D3.5 Automatic ROI and time series generation tool) was applied to the processed imagery. Therefore, the lakes were split up in logical sections. Paterswoldsemeer was divided in the northern plus mid parts including the island, the bathing area, the more southern open part of the main lake and the marshland area in the south. Westeinderplassen was divided in the northern part with small ditches, the eastern parts with small ditches and the main mid/east southern part. ROIStats was run to calculate statistics over 10-days periods.

3.2 In situ data

- L. Tuusulanjärvi: in situ Chl-a and information about CY (wet weight, CY amount in total phytoplankton biomass) were determined twice a month during 2002-2011 by SYKE. From that period 19 match-ups for validation with MERIS were available. For further comparison two years, 2003 (71 images) and 2006 (157) were selected;
- L. Ülemiste: Chl-a was measured up to 5 times per month (from 2003 July to 2008) by Ltd. Tallinna Vesi from the inlet of the water purification factory, but for comparison with satellite data only in situ data from 2008 was used. Data was acquired from Kristel Panksep's master thesis (Panksep, 2009);

- L. Peipsi: in situ data from 2002-2011 was collected by Centre for Limnology, EULS in the frames of national monitoring program once a month during vegetation period (May-October) from 6 monitoring points. Integrated water samples (from surface to 0.5 m from bottom) were gathered, Chl-a was measured spectrophotometrically and algal composition was determined microscopically;
- L. IJsselmeer: in situ Chl-a and TSM data were collected from measuring point called Vrouwezand that is located in the center of L. IJsselmeer (52.8114 N, 5.3936 W). Data was acquired during the period of MERIS acquisition (20 May 2002 until to 8 April 2012). Co-occurring species counts were available for spring, summer and autumn from 2008 to 2012. These were used to calculate the proportion of CY in total phytoplankton biomass;

- L. Paterswoldsemeer: in situ Chl-a laboratory and in situ CY-chlorophyll measurements (using fluoroprobe) were both provided by local water authority Noorderzijlvest. In situ WISP-3 radiometric measurements were used to derive Chl-a values (using the WISP algorithm by Peters, in preparation) and these were obtained in the ESA CyMoNS project;

- L. Westeinderplassen: in situ Chl-a laboratory and CY-chlorophyll measurements (using fluoroprobe) were both provided by local water authority Rijnland. In situ WISP-3 radiometric measurements were used to derive Chl-a values (using the WISP algorithm by Peters, in preparation) and these were obtained in the ESA CyMoNS project;
- L. Müggelsee: in situ data were provided by Leibniz-Institute of Freshwater Ecology and Inland Fisheries Germany (IGB, Dept. II Prof. Dr. Rita Adrian). These included:
  - weekly measurements in Müggelsee at 5 stations → integrated to one mixed sample and measurement;
  - Chl-a data using HPLC method;
  - proportion of CY using Utermöhl's method;
- L. Trasimeno: 25 in situ Chl-a measurements were provided by local agency and IREA field campaigns from 2005 to 2008;

4. Results and discussion

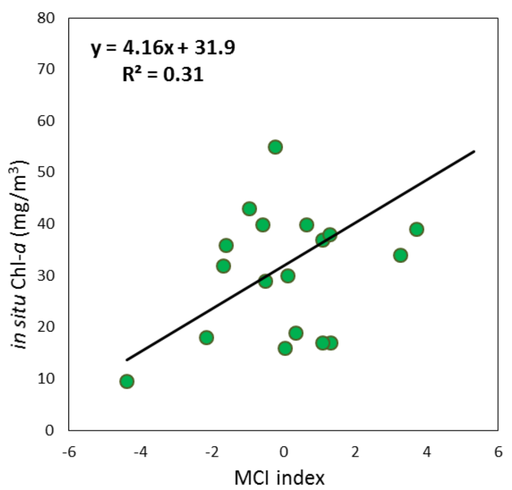
4.1 Algorithm validation

This section presents the results of the algorithm validation, e.g. the results obtained from the various algorithms versus values from in situ measurements (subsections 4.1 a – f). The analysis and comparisons are done in the subsection 4.1 g. There were not enough match-ups for L. Paterswoldsemeer and L. Westeinderplassen and therefore no algorithm validation for these lakes is included in this section. However, some results of spectral validation of these two lakes using Landsat 8 are presented in GlaSS deliverable 4.2.

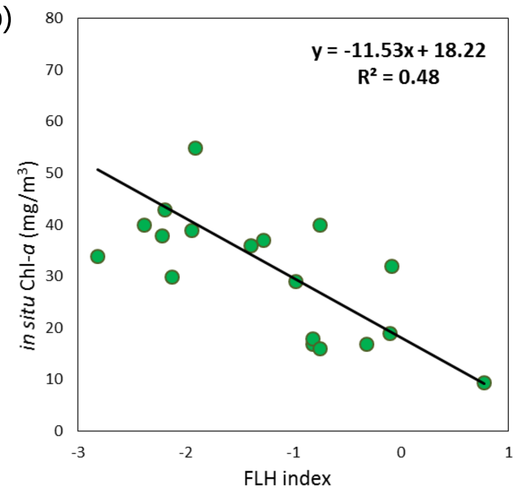
a) L. Tuusulanjärvi

For L. Tuusulanjärvi up to 19 match-ups were available (Figure 17). Strongest concurrency (R^2 = 0.48) with in situ data was obtained from FLH products (Figure 17b) although, RMSE and MAE values were highest (Table 4) compared to other algorithms. Weaker correlation (R^2 = 0.36) was observed between in situ and MPH Chl-a values (Figure 17c) and indexes from products processed with MCI algorithm indicated the worst agreement (R^2 = 0.31) with in situ Chl-a values however, the statistical errors were smallest in this case (Table 4).

a)



b)



c)

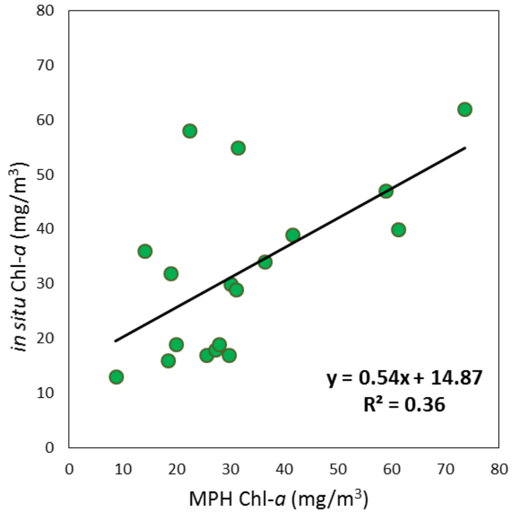


Figure 17. Correlations between in situ Chl-a concentrations and Chl-a estimations from MCI (a), FLH (b) and MPH (c) MERIS products in L. Tuusulanjärvi.

b) L. Ülemiste

For L. Ülemiste up to 18 match-ups from one year (2008) were available (Figure 18). MPH and FLH indicated best correlations (accordingly R^2 = 0.45 and R^2 = 0.43) with in situ Chl-a values (Figure 18, c & b). Bad agreement (R^2 = 0.11) with in situ data was obtained from MCI products (Figure 18a). The highest statistical errors (RMSE, MAE) were received with MPH products (Table 4).

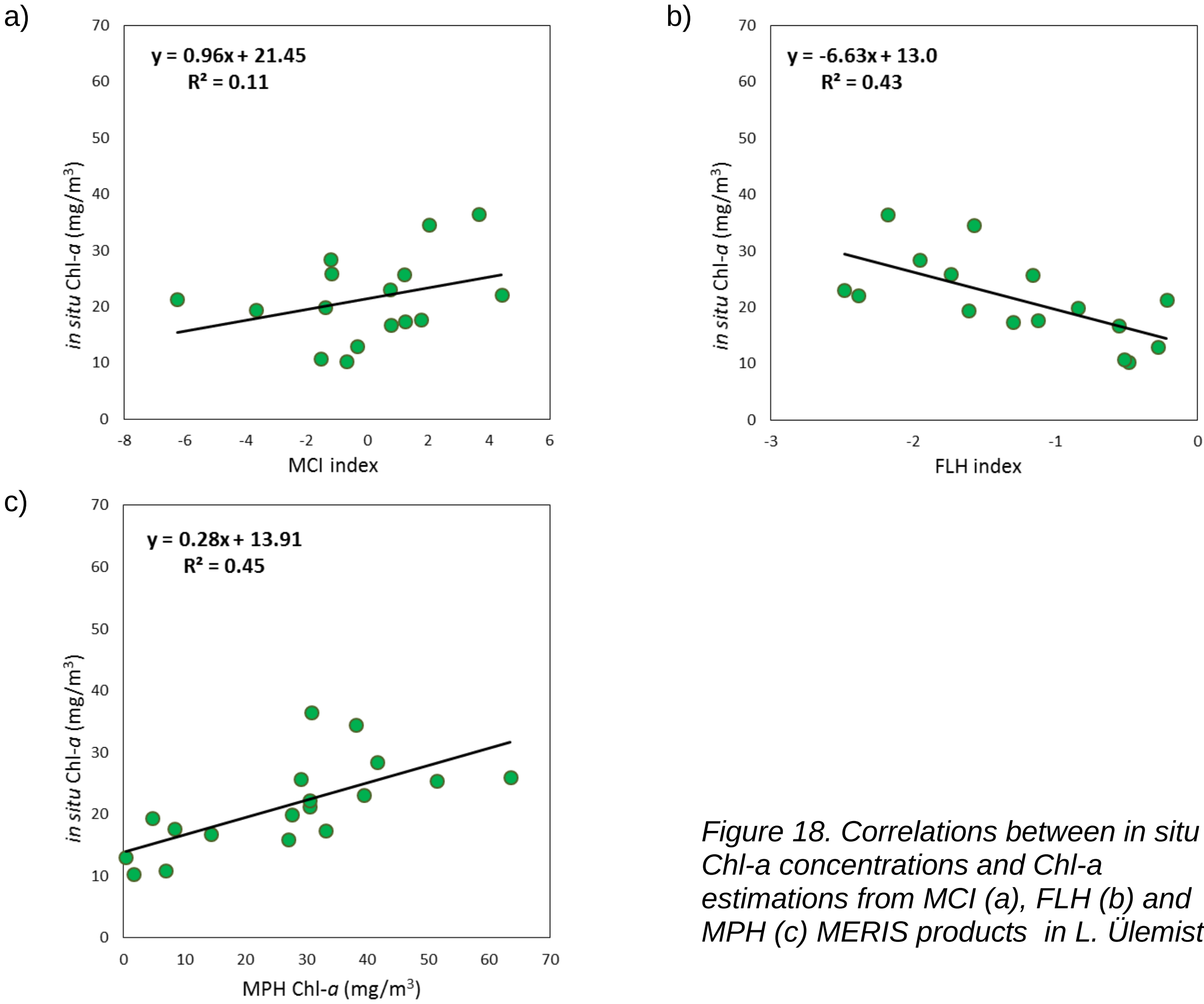
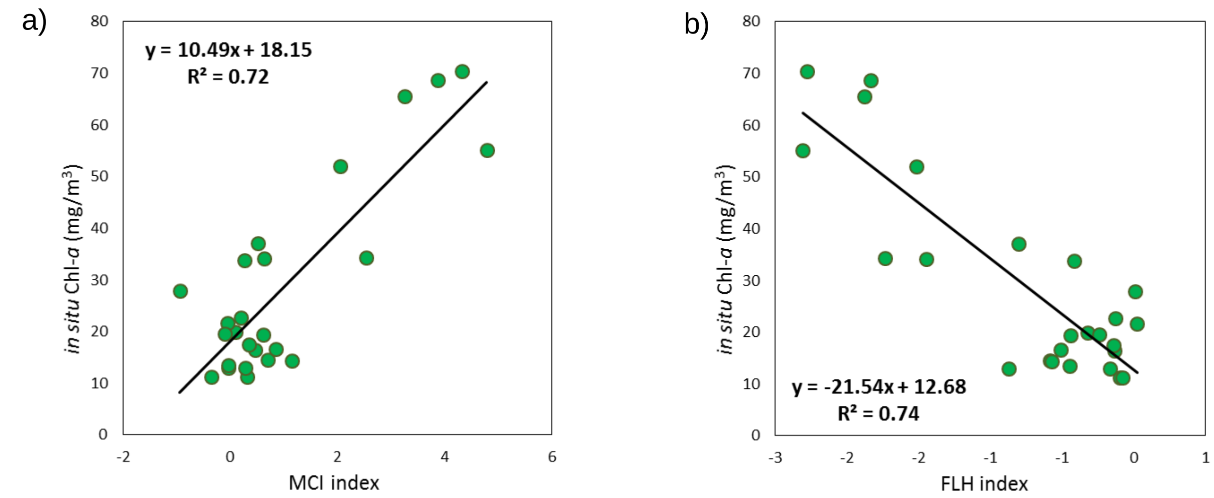


Figure 18. Correlations between in situ Chl-a concentrations and Chl-a estimations from MCI (a), FLH (b) and MPH (c) MERIS products in L. Ülemiste.

c) L. Peipsi

For L. Peipsi up to 25 match-ups were available (Figure 19). FLH and MCI indexes indicated best concurrencies (accordingly R^2 = 0.74 and R^2 = 0.72) with in situ data (Figure 19, b & a). Somewhat weaker correlation (R^2 = 0.53) with Chl-a concentration values were obtained from MPH products (Figure 19c). Also the highest RMSE and MAE values were received with MPH products (Table 4).



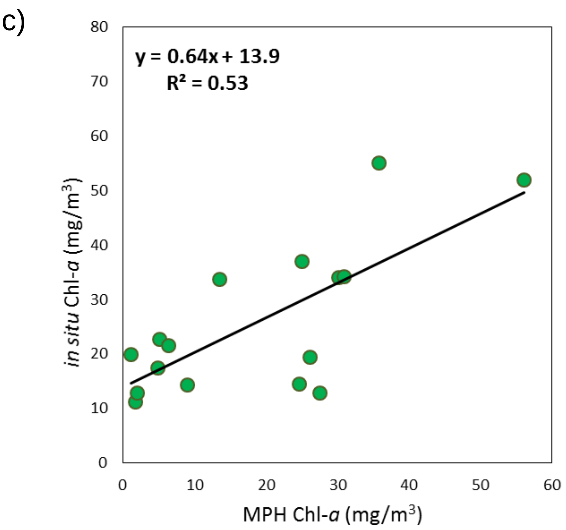
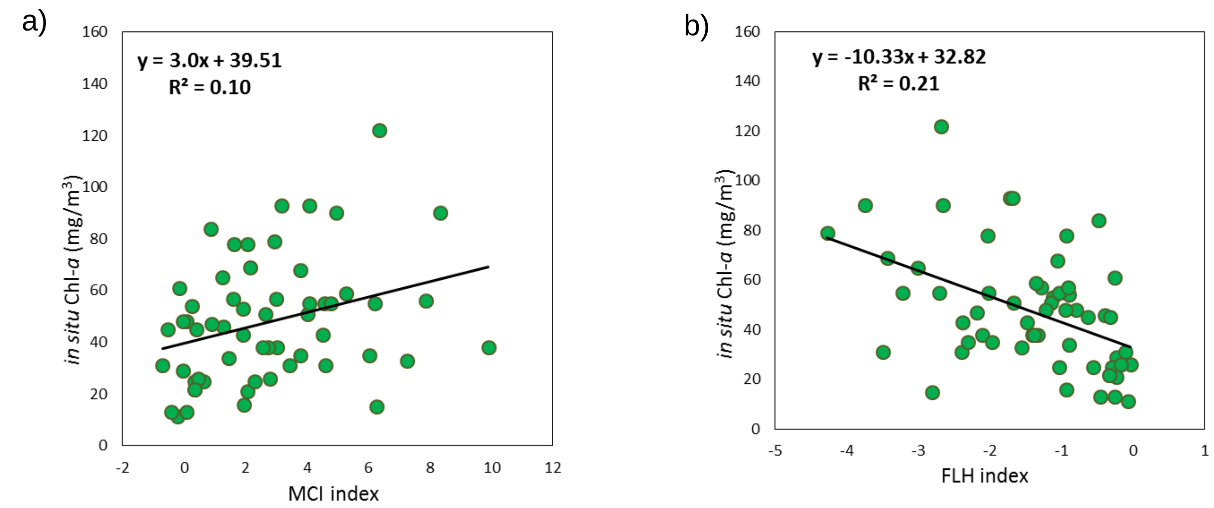


Figure 19. Correlations between in situ Chl-a concentrations and Chl-a estimations from MCI (a), FLH (b) and MPH (c) MERIS products in L. Peipsi.

d) L. IJsselmeer

For L. IJsselmeer up to 155 match-ups were available (Figure 20). All three algorithms indicated weak concurrencies with in situ Chl-a values and high statistical errors (Table 4). These validation results were the worst compared to the results from other lakes. The best correlation with in situ data for L. IJsselmeer was obtained from FLH products (Figure 20b), and also the smallest standard errors were received with FLH products (Table 4). MPH showed occasionally unrealistically high results (up to 1000 mg/m^3) (Figure 20c), but majority of Chl-a values calculated via MPH remained below 150 mg/m^3.



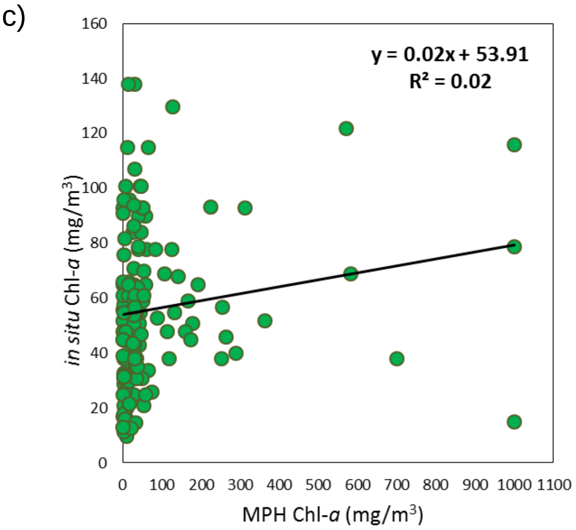
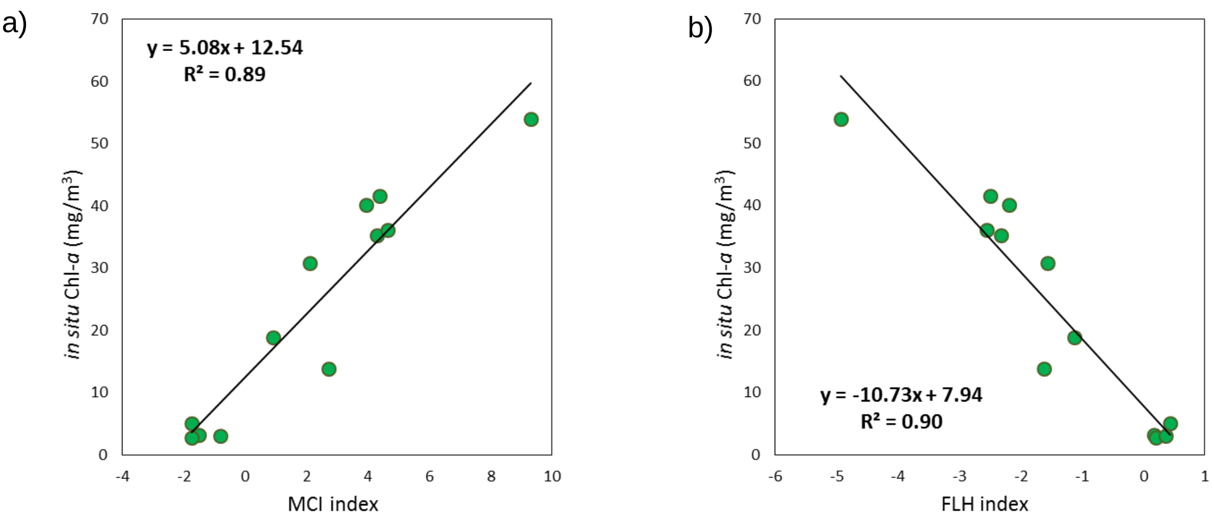


Figure 20. Correlations between in situ Chl-a concentrations and Chl-a estimations from MCI (a), FLH (b) and MPH (c) MERIS products in L. IJsselmeer.

e) L. Trasimeno

For L. Trasimeno up to 19 match-ups were available (Figure 21). All the tested algorithms indicated very high correlation with in situ Chl-a values (Figure 21a, b, c). Also RMSE and MAE were the smallest compared to results from other lakes (Table 4). Again FLH performed slightly better than the other algorithms (Figure 21b, Table 4).



c)

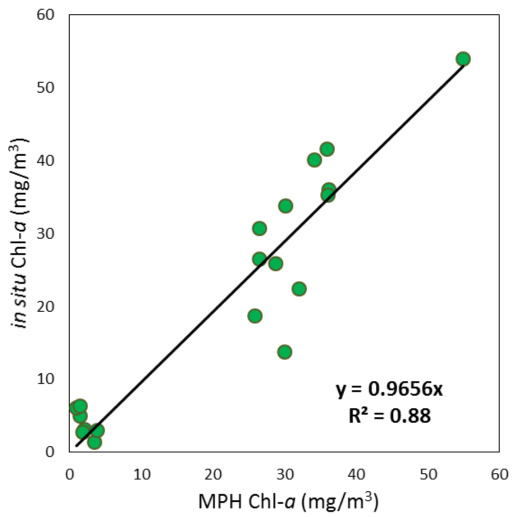


Figure 21. Correlations between in situ Chl-a concentrations and Chl-a estimations from MCI (a), FLH (b) and MPH (c) MERIS products in L. Trasimeno

f) Analysis of validation results

Table 4. Validation results: R^2, RMSE and MAE obtained from the validation of MCI, FLH and MPH products, also number of match-ups and in situ Chl a range is given.

Algorithms	Statistics	Tuusulanjärvi	Ülemiste	Peipsi	Ijsselmeer	Trasimeno
MCI	R^2	0.31	0.11	0.72	0.1	0.89
	n	19	16	25	58	12
	RMSE (mg/m³)	13.27	6.89	9.77	22.33	5.68
	MAE (mg/m³)	10.71	5.96	8.95	18.05	4.33
FLH	R^2	**0.48**	0.43	**0.74**	**0.21**	**0.9**
	n	19	16	25	58	12
	RMSE (mg/m³)	25.72	5.5	9.51	20.84	5.54
	MAE (mg/m³)	22.47	4.69	8.41	16.25	4.43
MPH	R^2	0.36	**0.45**	0.53	0.02	0.88
	n	18	18	16	155	19
	RMSE (mg/m³)	14.23	14.41	12.84	52.47	6.53
	MAE (mg/m³)	10.72	11.65	11.57	39.89	4.74
	In situ range (mg/m³)	9.5-81 (MPH: max 62)	10.2-36.5	11.2- 70.5	10.0-170.0	1.4-54.0

Despite of earlier findings that FLH is not suitable for lakes with CY dominance (Gons et al., 2008; Binding et al., 2011) in case of all studied lakes in general FLH performed the best. Binding et al. (2013) and Zhao et al. (2010) have noted that maximum of the in situ Chl-a absorption peak varies depending on Chl-a concentration, being shifted towards shorter wavelength when concentrations are low. Thus Binding et al. (2013) suggested that FLH will work better than MCI in case of Chl-a being lower than 10 mg/m³. However, the expected level of the fluorescence signal depends on many factors: Chl concentration, the ambient light level, the fluorescence efficiency of the Chl and its distribution with depth. The efficiency is expected to vary with the phytoplankton species composition (majority of CY Chl-a is located in non-fluorescing photosystem (Seppälä et al., 2007), displaying minimal chlorophyll fluorescence) and with its state of growth, whereas high growth rate is associated with lower fluorescence (Gower & King, 2003).

In case of L. Peipsi it must be taken into account that Chl-a is not measured directly from surface water, but from an integrated sample. In case of a surface bloom this method leads to the underestimation of Chl-a content in surface water.

Case II waters are complex in their content: besides phytoplankton also TSM and CDOM have an influence to optical properties of the waterbody. CDOM and TSM content are not constant, but tend to vary, both seasonally and yearly, thus their effect may vary depending on a season. Since a_{CDOM} at L. Tuusulanjärvi may be periodically high (mean about 6.3 1/m (3.3-13.1) at 400 nm) this can be one reason behind poor validation results. The other reason may be the narrow shape of the lake and therefore the adjacency effect which despite of using ICOL still can cause some errors. Also Binding et al. (2011) showed that using ICOL does not always improve water constituent retrieval. However, Binding et al. (2013) claim MCI to be generally insensitive to CDOM and rather be influenced by TSM, especially its mineral part (Binding et al., 2011). Therefore results from L. IJsselmeer might be influenced due to occasionally high TSM values present there (up to 120 g/m^3).

For L. Ülemiste concurrent in situ and satellite measurements were available only for one year. In situ measurements were taken from relatively close to the shore and again, since this area is probably affected by adjascency effect more central pixel from satellite products was used for validation. Although, this lake should be relatively uniform due to its shallowness there is a possibility that *Microcystis* scum, present in surface water from 2007 onwards, generates higher spatial variability. Therefore 2008 is actually not a good year for validation analysis.

4.2 Seasonal changes

This section presents the results of the analysis of seasonal variability per lake (4.2 a-g) based on time-series of in situ, MERIS and Landsat 8 data. In some cases MERIS L3 visualised MPH products that represent monthly mean Chl-a values were provided by Diversity-2 project. A general comparison is made at the end of the section (4.2 h).

a) L. Tuusulanjärvi

In order to investigate the seasonal variability of Chl-a concentrations in L. Tuusulanjärvi two years (2003 & 2006) were chosen for times-series analysis (Figure 22, a & b). In 2003 there were distinct peaks of in situ Chl-a values in April and August (Figure 22a). Unfortunately there is no satellite data in April but the highest value in August is underestimated by the values from differently processed MERIS data. In spring Chl-a values from FLH, MCI and MPH products tend to overestimate real values. Better agreement between in situ and satellite data can be observed during summer months. Generally it can be noticed that values from MERIS products follow the overall tendency of in situ data rather well. In 2006 there were less variability in in situ Chl-a data and FLH and MPH products followed in situ data quite well (Figure 22b). Values from the MPH products on the other hand were more variable and in some cases strongly overestimated in situ values.

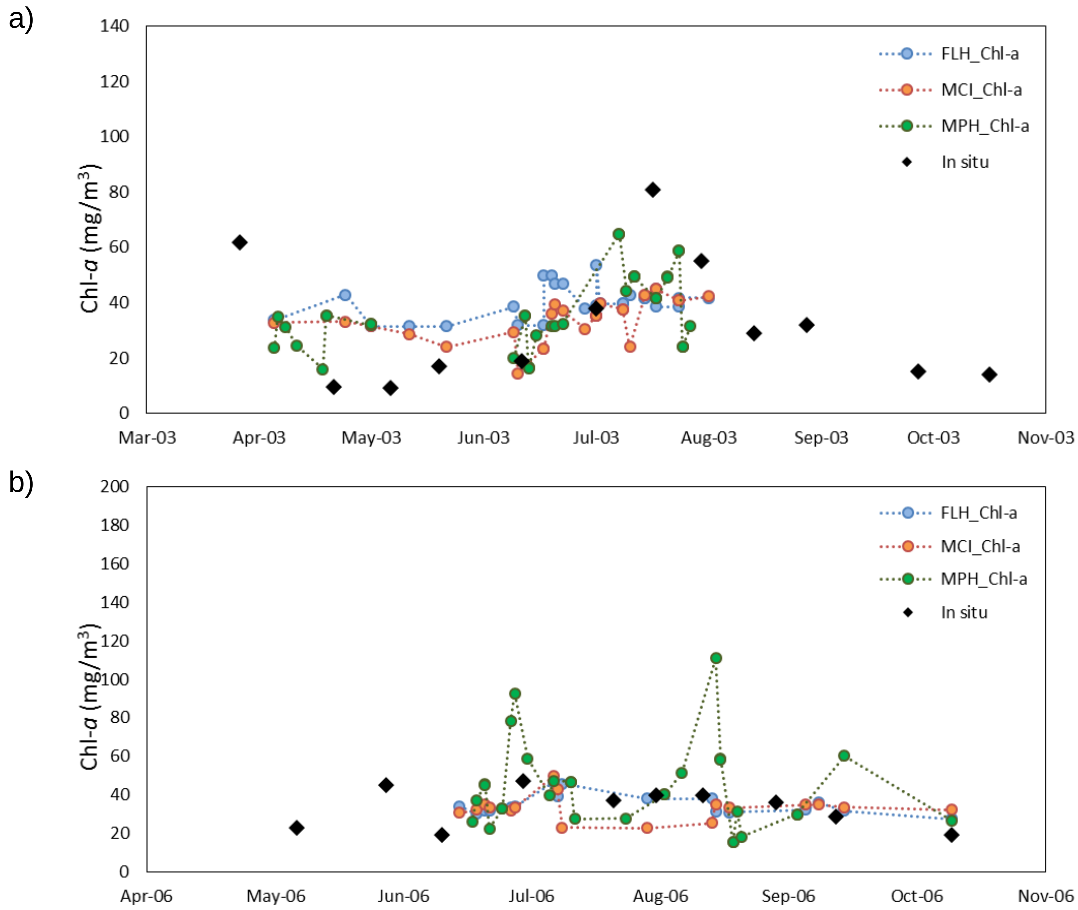


*Figure 22. Time-series of Chl-a estimations from in situ measurements, calculated MCI (MCI_Chl-a=4.16*MCI_index+31.9) calculated FLH (FLH_Chl-a=-11.53*FLH_index+18.22) and MPH products in 2003 (a) and 2006 (b) in L. Tuusulanjärvi.*

In order to analyse seasonal variability of Chl-a values from monthly mean MPH Chl-a products images from 2009 and 2010 were selected (Figure 23) because these contained more informative pixels throughout the vegetation period than years 2003 and 2006. The results indicate that in 2009 the highest values of Chl-a were in May and June. Based on in situ data (not shown) in 2009 the highest Chl-a concentration was also measured in June. The highest Chl-a values in 2010 were received in June and August based on MPH products but according to in situ data very high Chl-a concentrations were measured in August and September. As expected the lowest Chl-a values can be noticed in October, which is also supported by the in situ data, although, it should be also noted that in autumn the frequent cloud cover is preventing the retrieval of adequate results from remote sensing products.

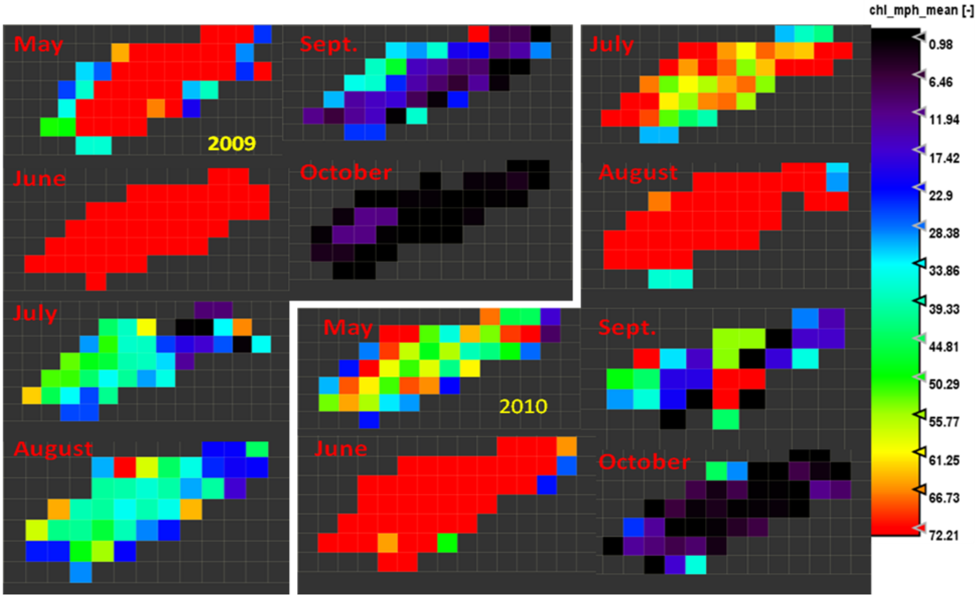


Figure 23. Seasonal variability of monthly mean Chl-a values from MPH products in 2009 and 2010 in L. Tuusulanjärvi.

b) L. Ülemiste

According to in situ Chl-a values from 2003 to 2008 (Figure 24) the amount of Chl-a increases gradually towards August with occasional high values in September. During June and July the Chl-a average values are rather stable and in comparison to August notably smaller.

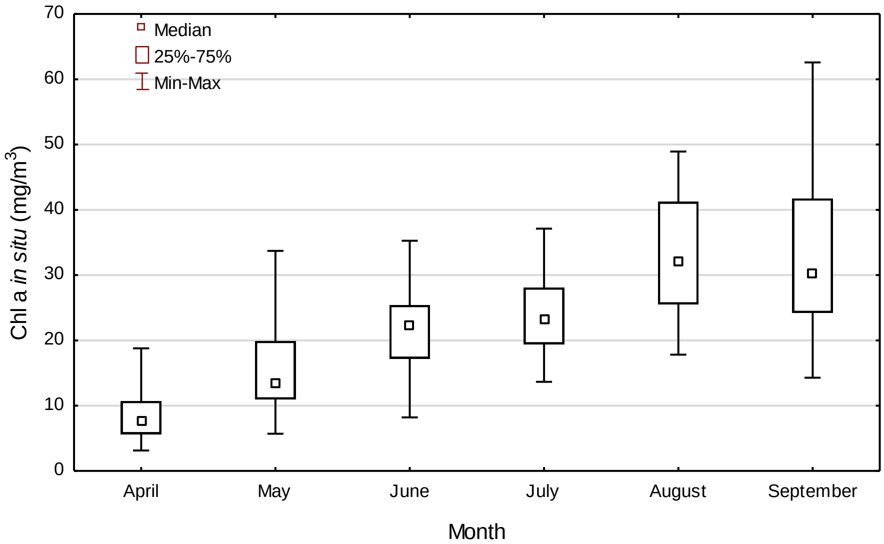


Figure 24. In situ measured Chl-a median values during vegetation period (2003-2008) in L. Ülemiste. Box denotes 25-75 percentiles, whiskers show minimum-maximum values.

For time-series analysis data from 2008, 2009 and 2010 was selected (Figure 25 a, b, c), but in situ data was available only for 2008. It can be noticed in the Figure 25a that values from FLH and MCI products follow the overall variability of in situ data rather well, however, the highest in situ Chl-a values are notably underestimated by satellite data. MPH Chl-a values are more variable and do not indicate good agreement with in situ data, especially during the first half of the vegetation period. In 2009 and 2010 Chl-a estimations from FLH and MCI products show only small-scale variability with higher values during July and August and lower values in spring months (Figure 25, b & c). MPH Chl-a values on the other hand are more variable indicating higher results not only in July and August, but already in May and June (Figure 25, b & c).

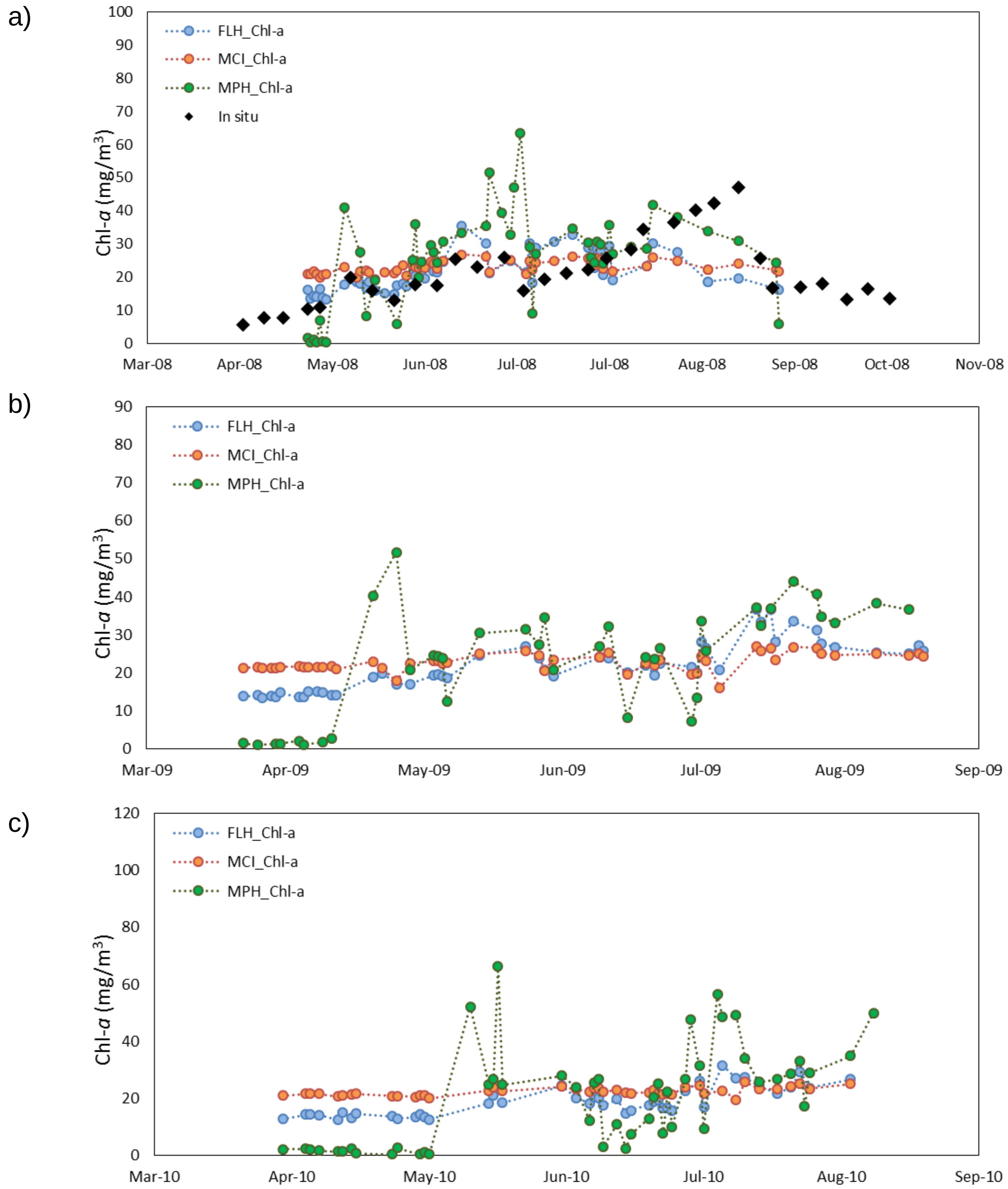


*Figure 25. Time-series of Chl-a estimations from in situ measurements, calculated MCI (MCI_Chl-a=0.96*MCI_index+21.45), calculated FLH (FLH_Chl-a= -6.63*FLH_index+13) and MPH products in 2008 (a), 2009 (b) and 2010 (c) in L. Ülemiste.*

It can be seen that Chl-a values from monthly mean MPH products in L. Ülemiste were rather homogenously distributed (Figure 26). Higher values of Chl-a in 2009 can be observed in May, August and September, whereas in 2010 there were high Chl-a concentrations in June and August, but in May the values were very small compared to rest of the vegetation period.

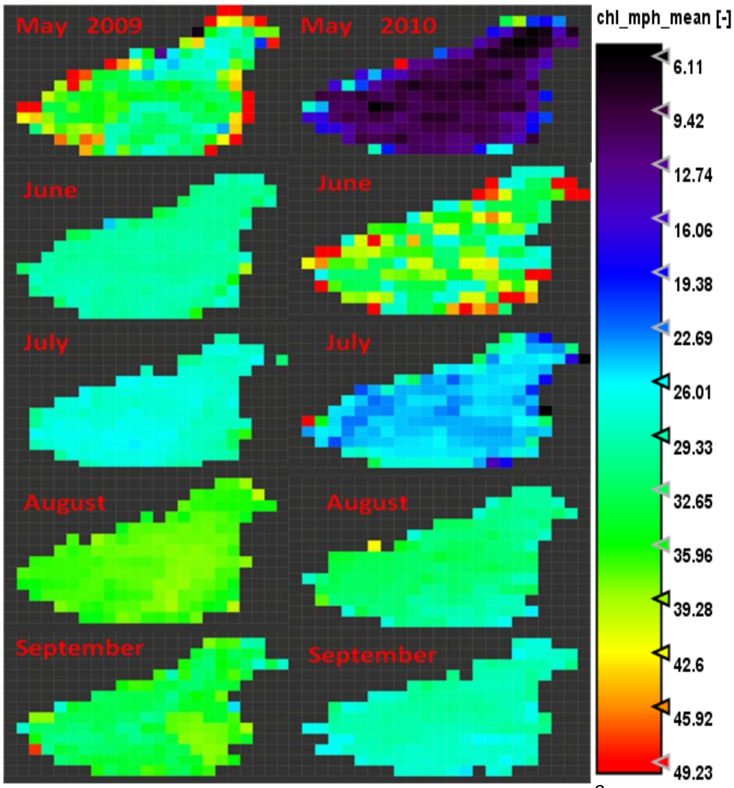
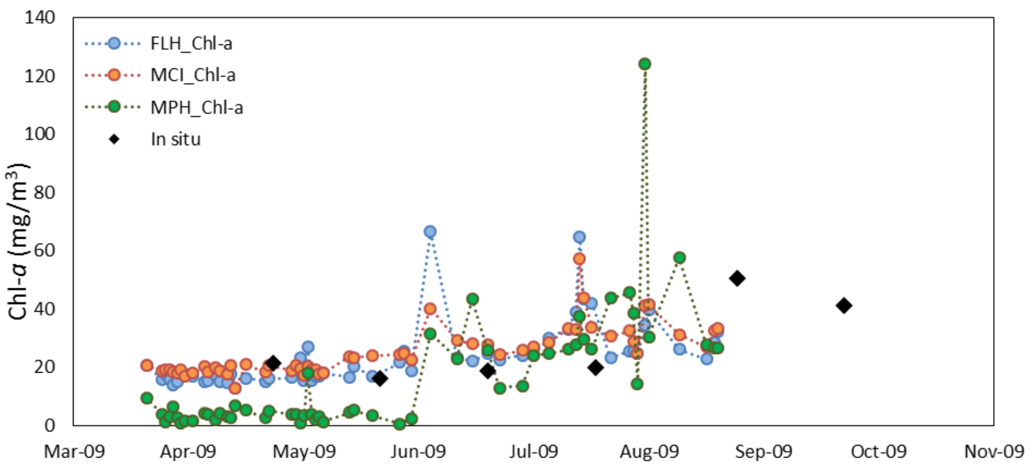


Figure 26. Seasonal variability of monthly mean Chl-a values (mg/m^3) from MPH products in 2009 and 2010 in L. Ülemiste.

c) L. Peipsi

For time-series analysis the data from 2009 and 2010 was selected (Figure 27, a & b). In 2009 the in situ trend is followed better by MCI and FLH products than by MPH Chl-a values, which underestimate the in situ values notably in spring (Figure 27a). Unfortunately there is no satellite data available in autumn which would be important since CY blooms are in L. Peipsi often present during September. Also in 2009 highest in situ values can be noticed in autumn months. In 2010 in situ values were followed slightly better by FLH and MCI products, although in most cases these values overestimated real Chl-a concentrations (Figure 27b). MPH Chl-a values on the other hand underestimated in situ data. There can be also seen from all the products a distinct peak which in situ measurements do not support (Figure 27b).

a)



b)

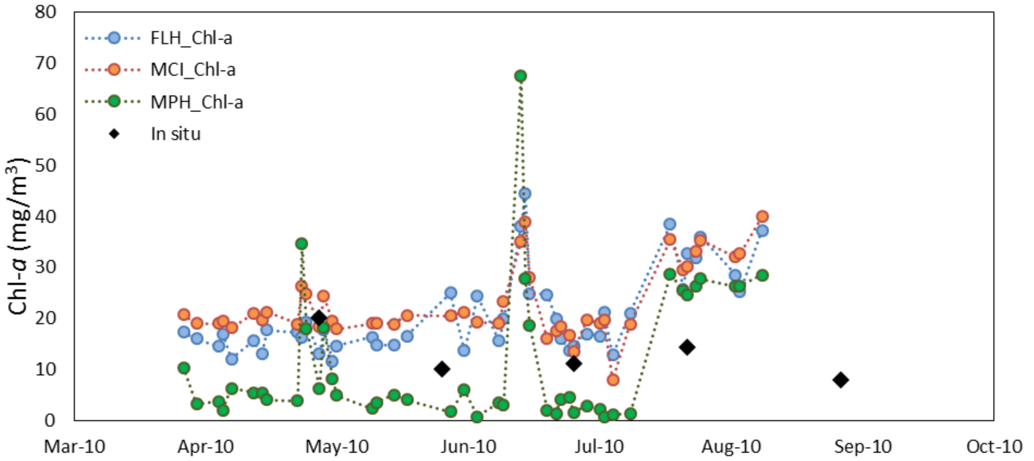


*Figure 27. Time-series of Chl-a estimations from in situ measurements, calculated MCI (MCI_Chl-a=10.49*MCI_index+18.15), calculated FLH (FLH_Chl-a= -21.54*FLH_index +12.68) and MPH products in 2009 (a) and 2010 (b) in L. Peipsi (measuring point no. 4).*

From monthly mean MPH Chl-a products (Figure 28) in 2009 the increase of Chl-a values can be seen, especially in the northern part of the lake. The highest Chl-a values in September were also supported by in situ data. There may be high phytoplankton biomass present also in October because abundant diatoms. In general the higher Chl-a values can be noticed in L. Pihkva and also L. Lämmijärv during vegetation period in both years. In 2010 the values were lower compared to 2009 indicating slightly higher values in August, which can be supported by the in situ values also (Figure 27b).

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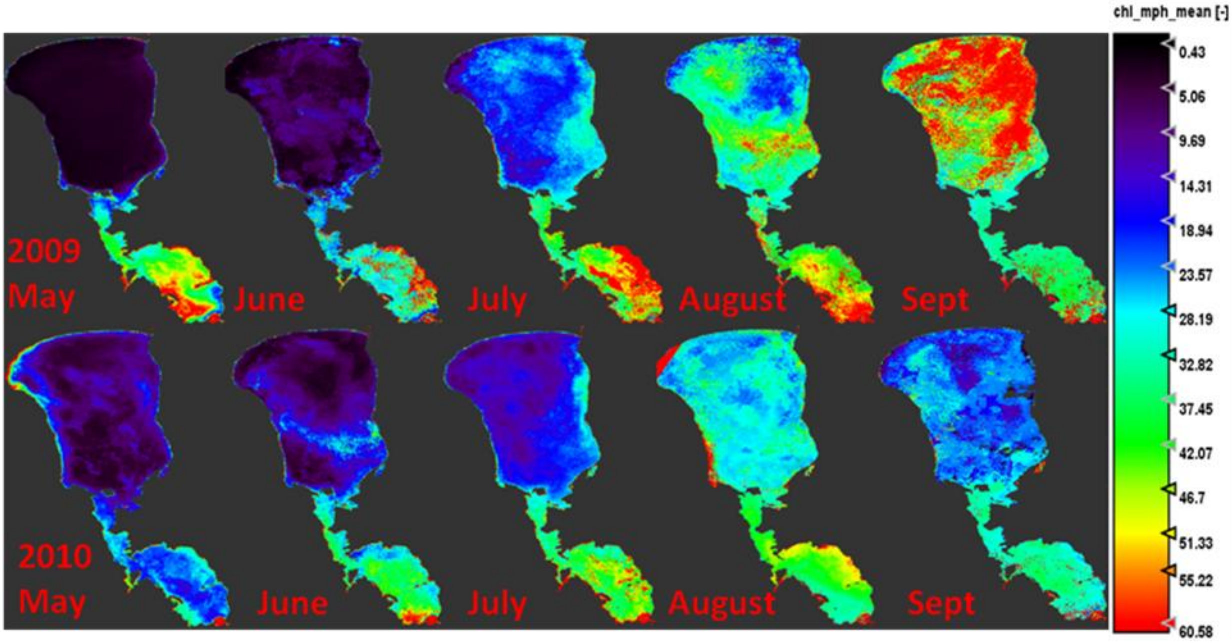
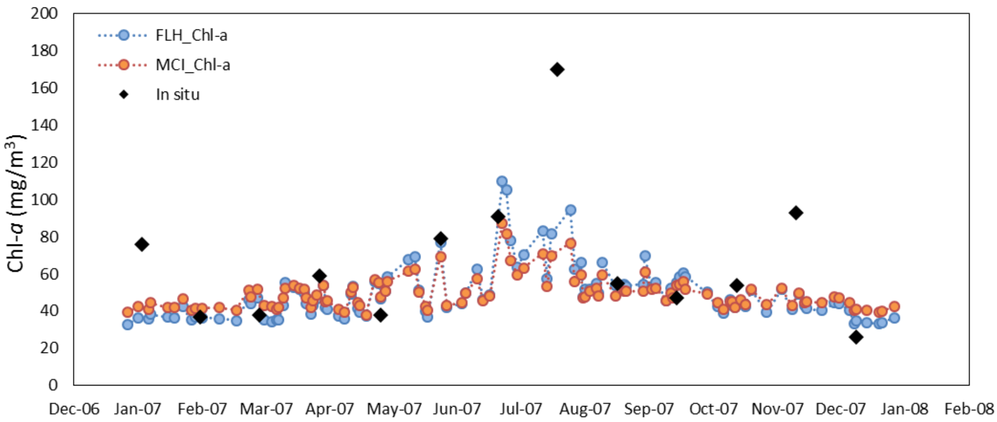


Figure 28. Seasonal variability of monthly mean Chl-a values from MPH products in 2009 and 2010 in L. Peipsi.

d) L. IJsselmeer

For time-series analysis data of 2007 was selected, because there was an extremely high in situ Chl-a value and 2009 due to lower concentration values. It can be seen from Figure 29a that in situ values were rather well followed by Chl-a estimations from MCI and FLH products although the highest peaks in January, August and November were notably underestimated. MPH Chl-a values on the other hand are extremely variable and do not indicate clear trend (Figure 29b).

a)



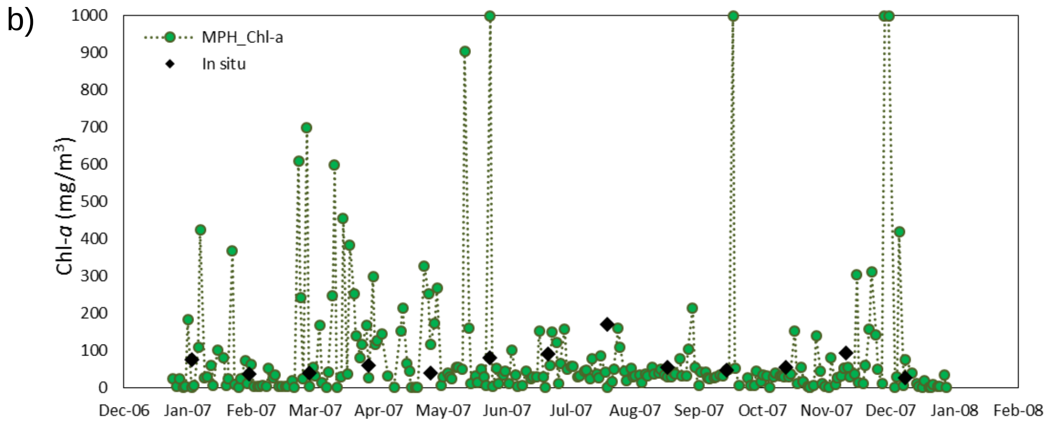


Figure 29. *Time-series of Chl-a estimations from in situ measurements, calculated MCI (MCI_Chl-a=3.0*MCI_index+39.51) (a), calculated FLH (FLH_Chl-a=-10.33*FLH_index +32.82) (a) and MPH (b) products in 2007 in L. IJsselmeer.*

In 2009 there can be noticed greater variability compared to 2007 for MCI and FLH data, which during the vegetation period mainly overestimated real values, but underestimated higher values in spring and autumn (Figure 30a). MPH results were again very variable indicating occasionally extremely high values and not supported the in situ trend (Figure 30b).

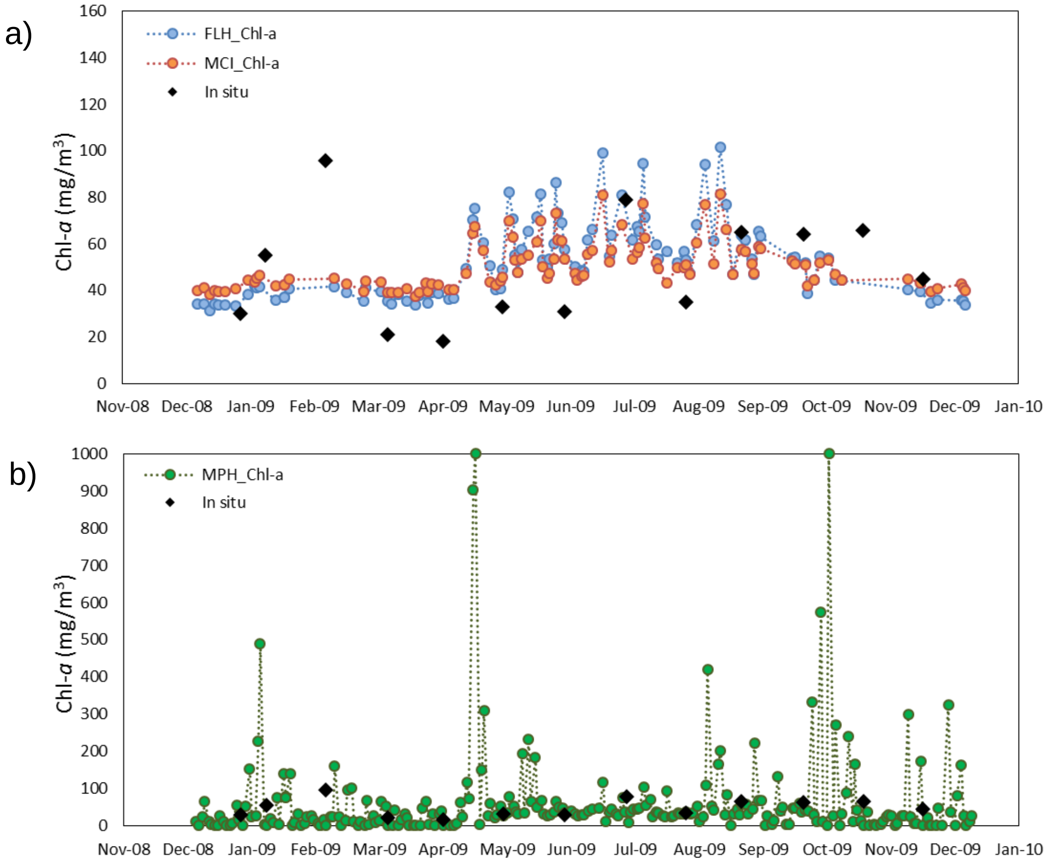


Figure 30. *Time-series of Chl-a estimations from in situ measurements, calculated MCI (MCI_Chl-a=3.0*MCI_index+39.51) (a), calculated FLH (FLH_Chl-a= -10.33*FLH_index+32.82) (a) and MPH (b) products in 2009 in L. IJsselmeer.*

e) L. Paterswoldsemeer

For L. Paterswoldsemeer, tuning the band ratio algorithm to the in situ (WISP-3 derived) data based on the time series showed the best fit when the band ratio was multiplied with a factor of 40 (Figure 31). Three data points were clearly off the scale, but these could partly be explained when the ROIStats results were studied in more detail: for two of these points the standard deviation was much higher than for all other image groups (due to cloud cover).

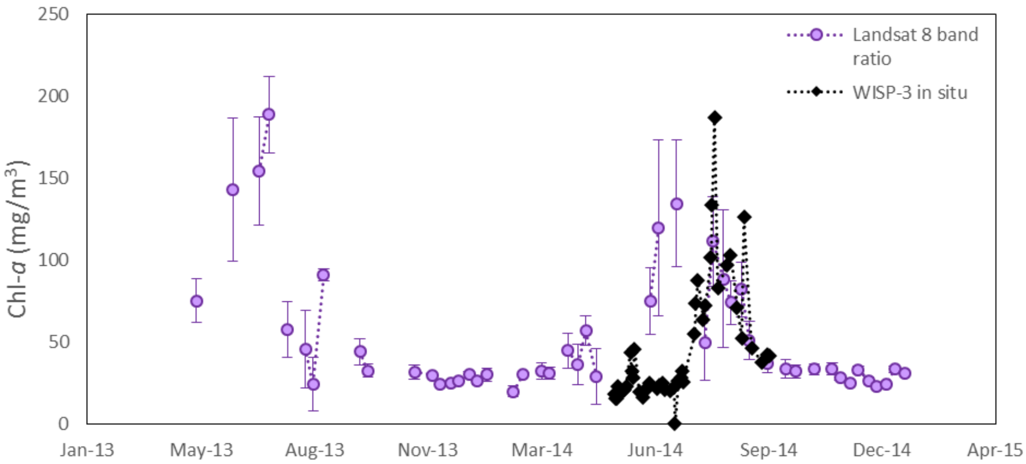


Figure 31. Time-series of Chl-a estimations from WISP-3 derived in situ data (station P_9) and L8 derived Chl-a concentrations (tuned to fit) for the open part of L. Paterswoldsemeer in 2013 and 2014.

f) L. Westeinderplassen

For L. Westeinderplassen, the same 'tuning' (multiplication with 40) as for L. Paterswoldsemeer was applied to the band ratio. Although the resulting time series did slightly show a seasonal pattern, the concentration values were too high compared to the in situ derived data and too high to be realistic for this lake (Figure 32).

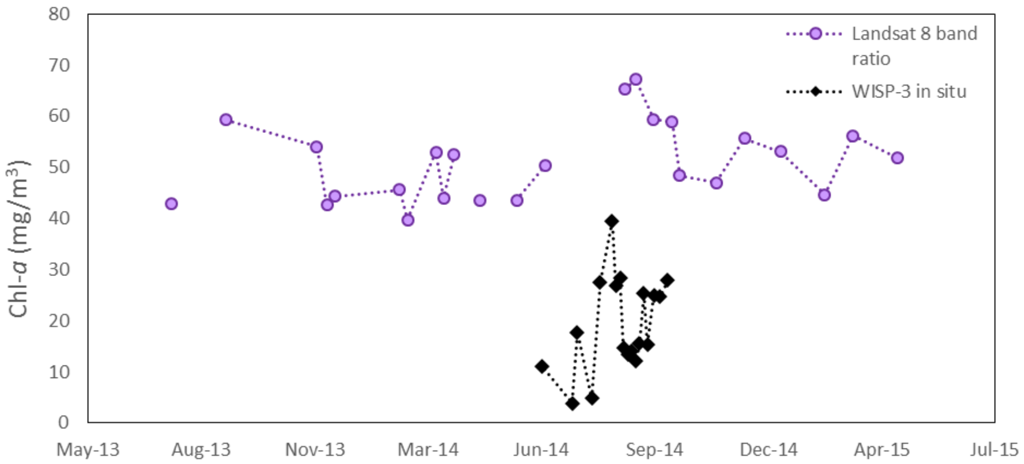


Figure 32. Time-series of Chl-a estimations from WISP-3 derived in situ data (station 60) and L8 derived Chl-a concentrations (times 40) for the open part of L. Westeinderplassen in 2013 and 2014.

g) L. Trasimeno

For time-series analysis data of 2006 and 2008 were selected because they represented opposite results. Low Chl-a values during 2006 caused lack of variety in MCI and FLH indexes (Figure 33a). Much higher variability was present in 2008 where a high peak with values from MCI products together with notably lower indexes from FLH products can be observed (Figure 33b).

a)

b)

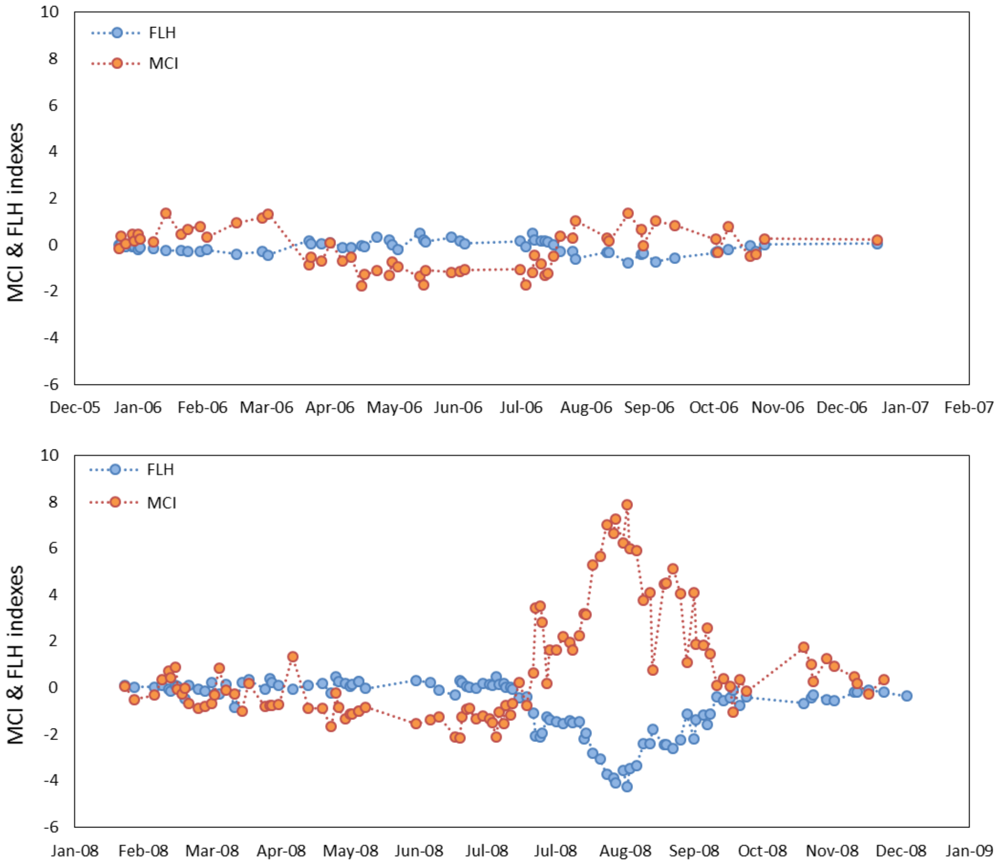


Figure 33. Time-series of daily mean indexes from MCI and FLH products in 2006 (a) and 2008 (b) in L. Trasimeno (Pelagic ROI).

Figures 34a and 34b indicate the time-series of Chl-a values calculated through MCI and FLH indexes and received from MPH products. These figures highlight the differences in terms of Chl-a concentration between investigated years. In both years higher values were recorded between late August and the end of September but the increase was evidently different and actually higher in the 2008. This can be associated with higher temperatures and the lack of precipitation.

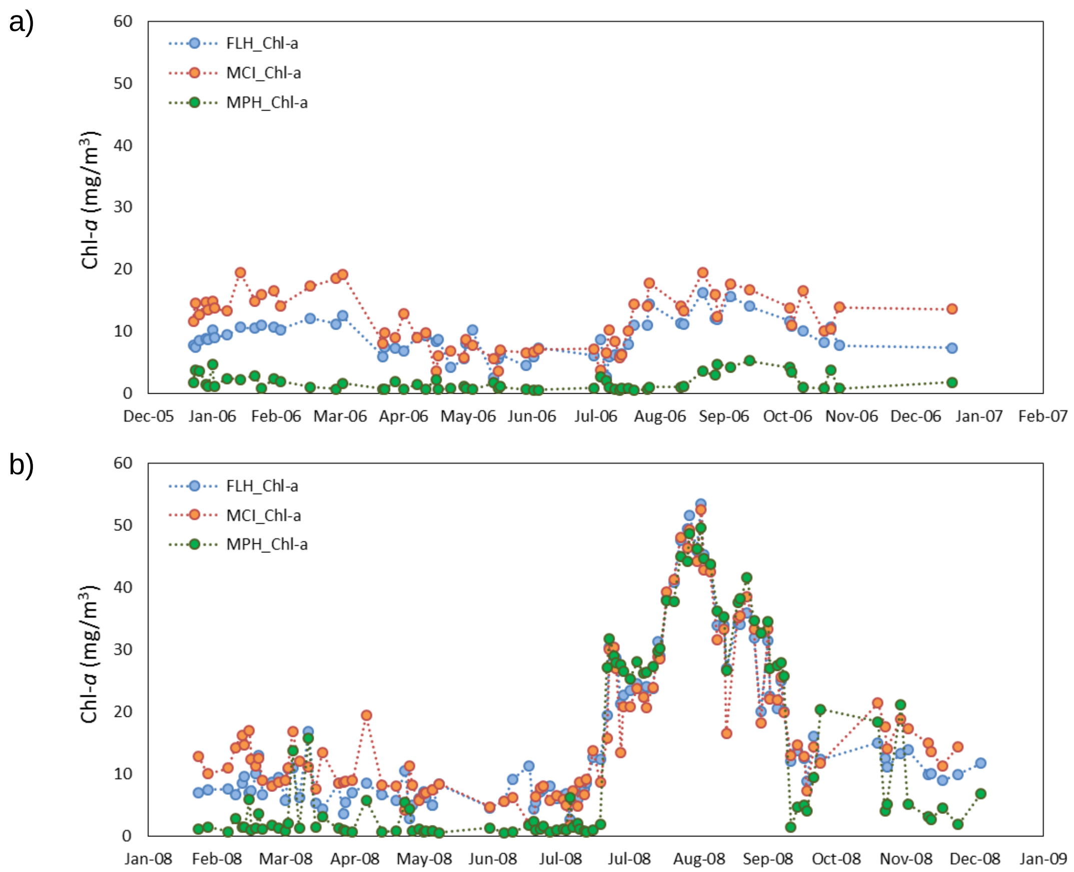
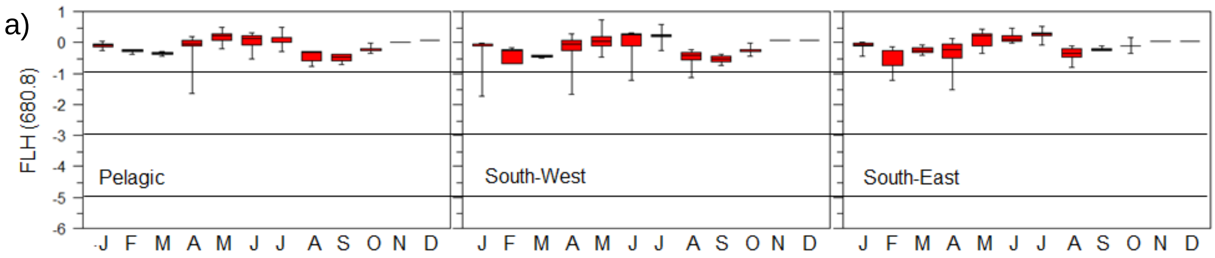


*Figure 34. Time-series of daily mean Chl-a estimations from in situ measurements, calculated MCI (MCI_Chl-a=5.08*MCI_index+12.54), calculated FLH (FLH_Chl-a= -10.73*FLH_index+7.94) and MPH products in 2006 (a) and 2008 (b) in L. Trasimeno (Pelagic ROI).*

In order to evaluate possible differences within the lake and spatial trends monthly mean values were computed for each year for all the ROIs (Figures 35-37). The results confirm seasonal behavior with higher values in summer, but it can be also noted a bit higher values during the first months of 2006, especially from MPH results (Figure 36). Generally trend from MPH values is rather different from variability of MCI and FLH indexes.



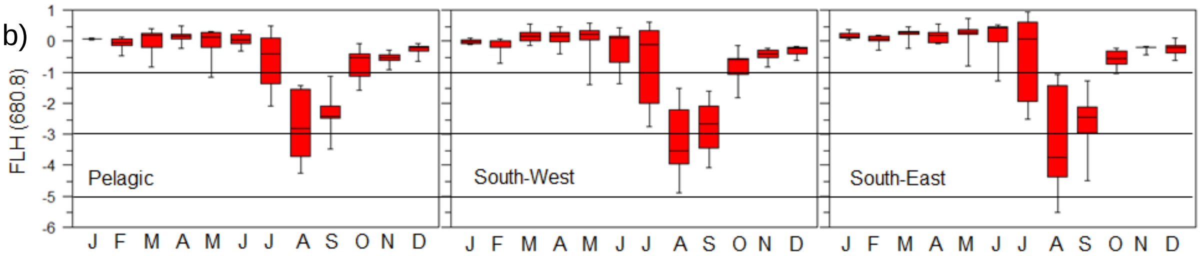


Figure 35. Monthly mean box plots of FLH indexes from all the ROIs in L. Trasimeno in 2006 (a) and 2008 (b).

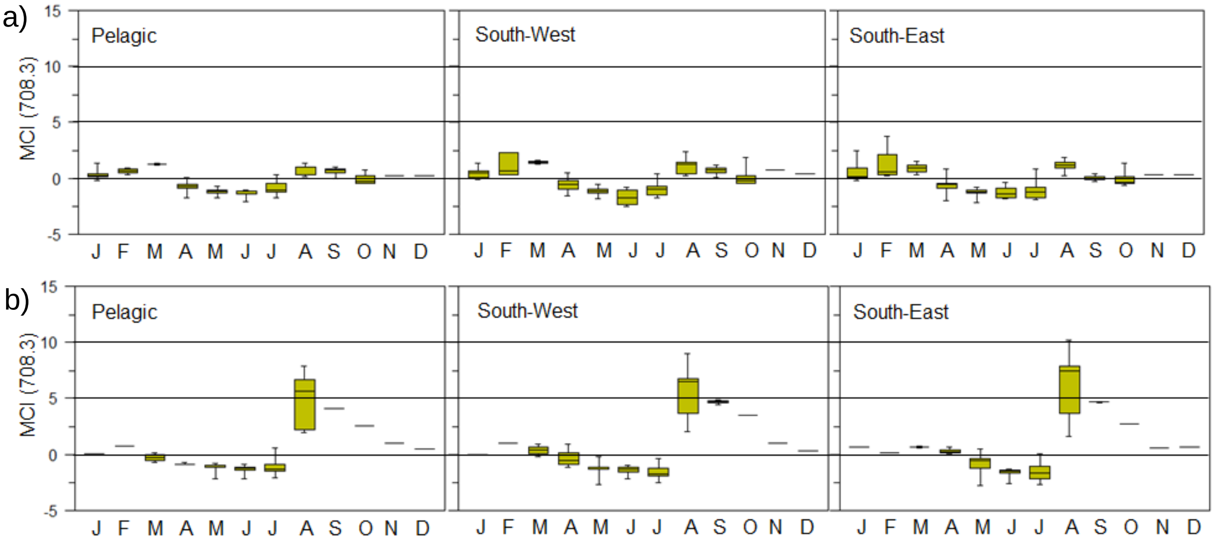


Figure 36. Monthly mean box plots of MCI indexes from all the ROIs in L. Trasimeno in 2006 (a) and 2008 (b).

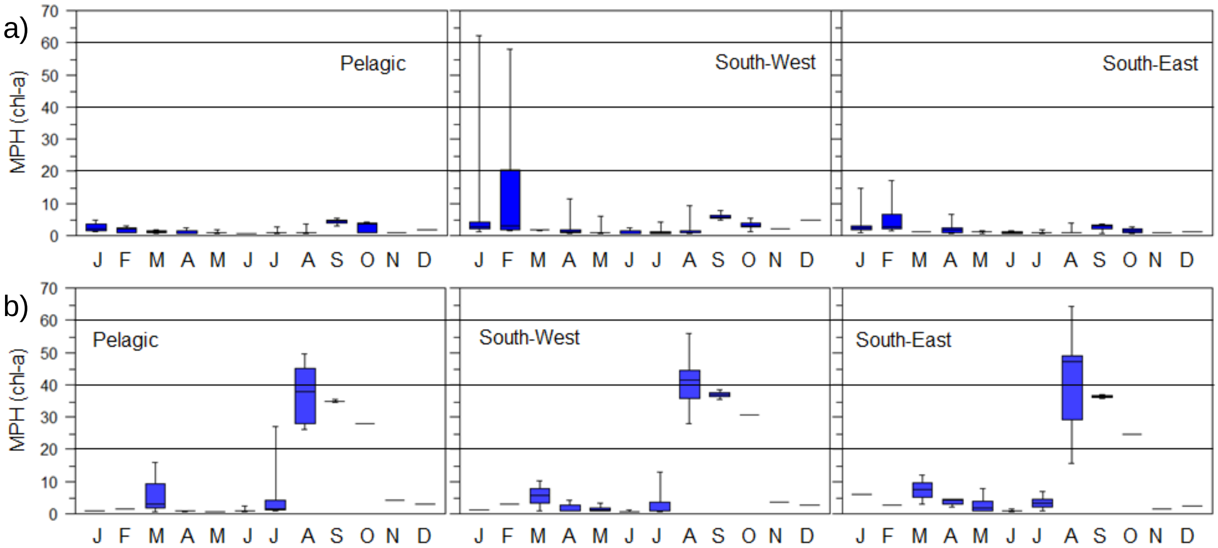


Figure 37. Monthly mean box plots of MPH Chl-a values from all the ROIs in L. Trasimeno in 2006 (a) and 2008 (b).

According to visualised MPH Chl-a products (Figure 38) in 2006 the Chl-a values throughout the year were rather low and uniformly distributed in the entire lake. In 2008 there were higher values in summer and autumn, especially in August and September when there was also a CY bloom present (Figure 48).

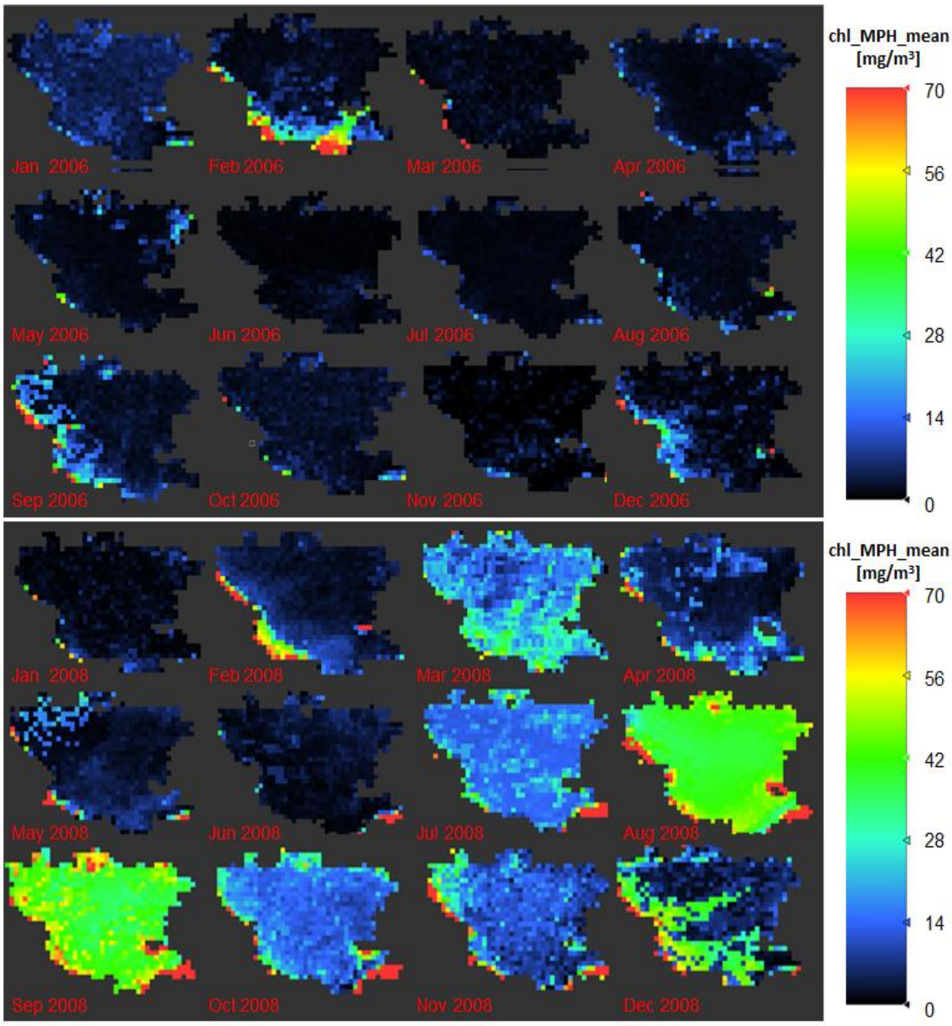


Figure 38. Seasonal variability of monthly mean Chl-a values from MPH products in 2009 and 2010 in L. Trasimeno.

h) Analysis of the seasonal changes

Phytoplankton community varies in all lakes seasonally. In northern lakes there is a Chl-a peak in spring (generally May-June), then a clear-water period (generally June-July) and then an increase in CY biomass towards autumn, whereas in southern lakes peaks and clear water period may be present earlier. The timing and intensity of peaks vary per lake. Generally CY are accompanied with other algal groups but form the majority of biomass (e.g. up to 75% in northern part of L. Peipsi).

From seasonal studies it is evident that estimations of Chl-a from FLH and MCI products are most accurately comparable with in situ measured Chl-a results, whereas values of MPH Chl-a products tend to be more variable indicating occasionally too high values, especially in case of L. IJsselmeer, but also for L. Ülemiste and L. Tuusulanjärvi.

Monthly mean MPH Chl-a visualised products indicated clearly monthly differences and also brought out the variation between investigated years. These products offered good spatial overview as well allowing to have an overview of the entire lake instead of one or few monitoring points. Shallow lakes are supposed to be well-mixed and thus relatively uniform like L. Trasimeno, but for example in case of L. Peipsi differences in lake-parts are clearly visible.

4.3 Long-term studies

This section presents the results of analysis of the long-term time-series per lake (4.3 a-e). For the lakes that were analysed with Landsat 8, no long-term time series were available and these lakes are therefore not included in this section. Also for some lakes yearly averaged MPH Chl-a products were included.

a) L. Tuusulanjärvi

The highest in situ Chl-a values during the MERIS lifetime (100 mg/m^3) were measured in 2010 (Figure 39). CY form up to 83 % of phytoplankton in total biomass. For the period from July to September average proportion of CY was 29 % but it must be noted that CY were practically absent during 2008 and 2009 (Figure 39). Winter period in 2008 was exceptionally warm with high loading of suspended particles to the lake. This resulted in very turbid conditions in the lake during the summer in 2008 and that in turn was unsuitable for CY.

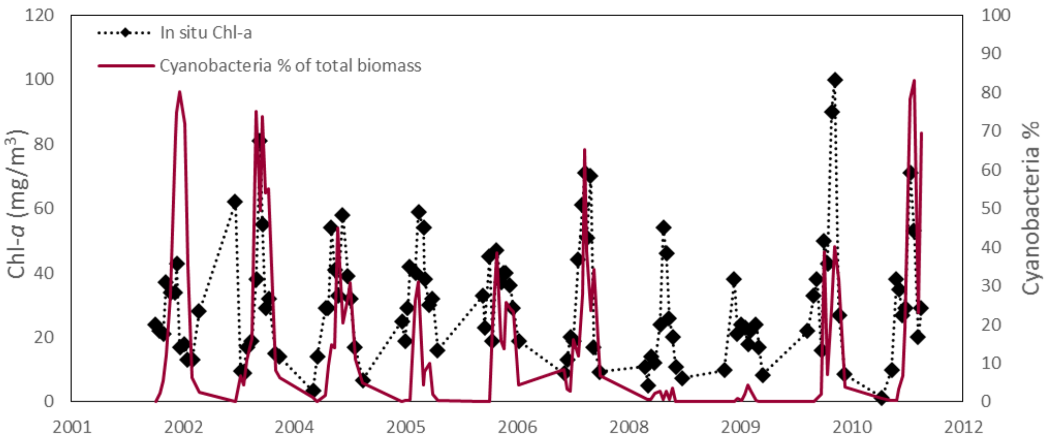


Figure 39. In situ measured Chl-a values and proportion of CY in total phytoplankton biomass in L. Tuusulanjärvi. In situ measurements were taken twice a month.

Unfortunately the highest Chl-a peaks from in situ measurements were not supported by the yearly averaged MPH products (Figure 40). These suggested that the highest Chl-a values were present in 2005, 2007 and 2008 which according to in situ data represented years with moderate or low concentration values (Figure 39).

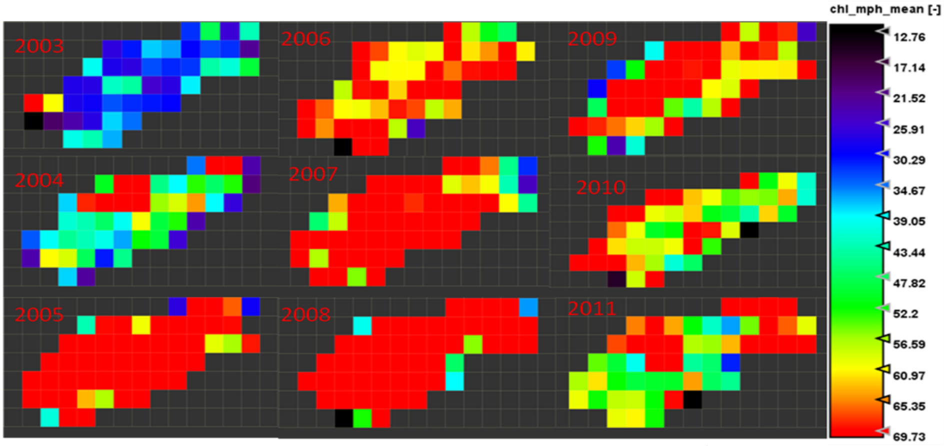


Figure 40. Temporal variability of yearly mean Chl-a values (mg/m^3) from MPH products from 2003 to 2011 in L. Tuusulanjärvi.

b) L. Ülemiste

Yearly averaged MPH Chl-a products indicated the highest concentration values for 2004 and the lowest for 2007 (Figure 41). The effect of biomanipulation can also be seen, as selective fishing (decline of cyprinids) led to decrease in Chl-a concentration and increase in transparency during the period of 2005 to 2007.

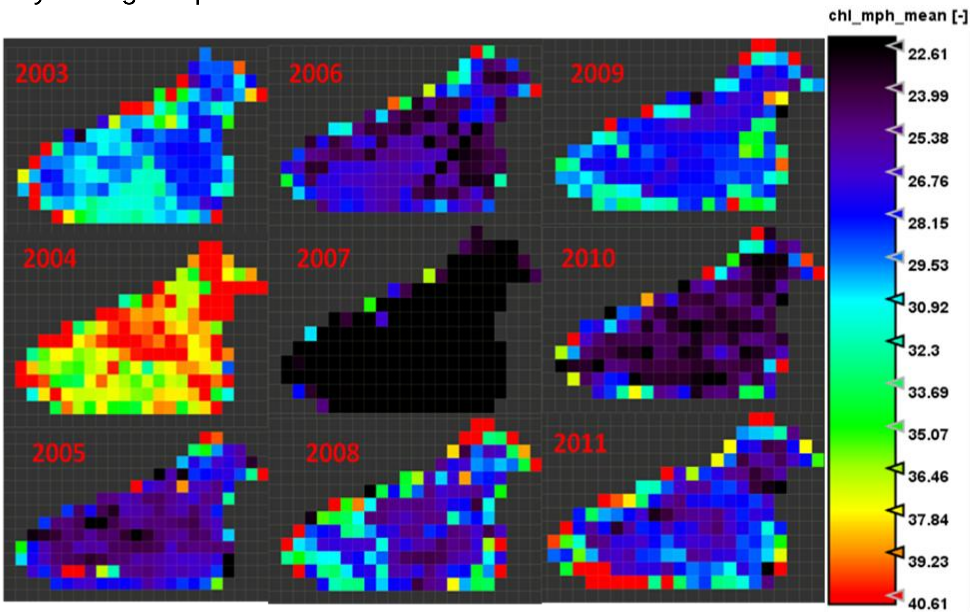


Figure 41. Temporal variability of yearly mean Chl-a values from MPH products from 2003 to 2011 in L. Ülemiste.

c) L. Peipsi

Yearly averaged MPH Chl-a products allow to see variability within years: generally Chl-a concentrations are higher in L. Pihkva and L. Lämmijärv, especially in 2003, 2007 and 2010 (Figure 42). Chl-a concentration in northern part of L. Peipsi was always lower compared to southern parts of the lake. Slightly higher values compared to other years can be noticed in 2007 and this is probably caused by the low water level, warmer water temperatures and dominance of *Aphanizomenon flos-aquae*. The hot summer during 2010 created also conditions for a CY bloom, but that time bloom-formers were from genus *Microcystis* whereas

Aphanizomenon was nearly missing from plankton community (Laugaste, 2011).

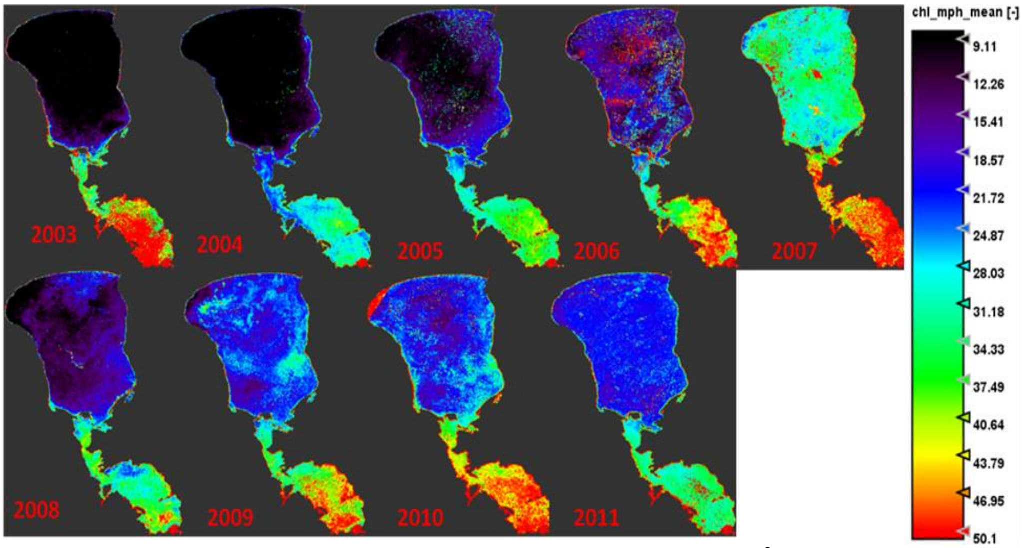


Figure 42. Temporal variability of yearly mean Chl-a values (mg/m^3) from MPH products from 2003 to 2011 in L. Peipsi.

d) L. Müggelsee (L. Müggel)

In order to investigate the long-term time-series in L. Müggelsee the CoastColour algorithm was applied to the full time-series of MERIS data and this was compared with in situ data from a central station of the lake (Figure 43). Time-series from MERIS data has been compiled from 10-days averages and the values were extracted as 3x3 macropixel located in the same central station of the lake. Time-series of in situ and MERIS data show very good agreement in absolute values but also in general variability. There can be seen gaps from data extracted from MERIS products due to light and cloud conditions while in situ Chl-a data provides continuity. Lower concentration values within every season can be caused by a complete mixing of the lake which is probably caused by certain wind conditions (U. Mischke, IGB).

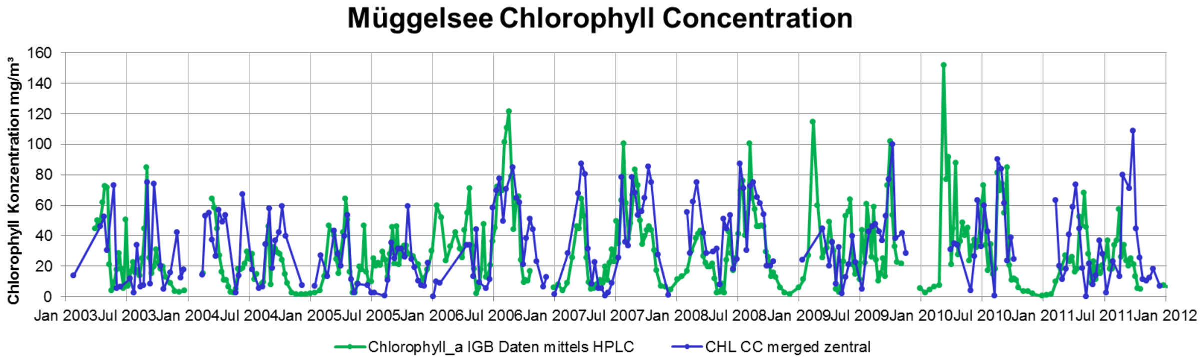


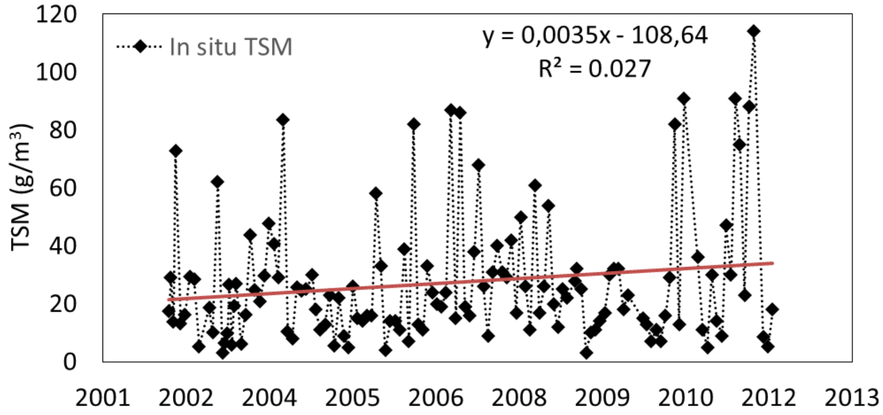
Figure 43. Time-series of Chl-a estimations from in situ measurements (green line) and CoastColour products (10-days averages) from 2003 to 2012 in L. Müggelsee.

e) L. IJsselmeer

Long-term time series based on TSM and Chl-a in situ measurements indicate great variability throughout the years and no significant trends (Figure 44, a & b), although, there is a slight increase of TSM values towards to the end of MERIS lifetime (Figure 44a).

Occasionally very high TSM values are present in lake, which may influence the correct detection of Chl-a amount in the lake from satellite images.

a)



b)

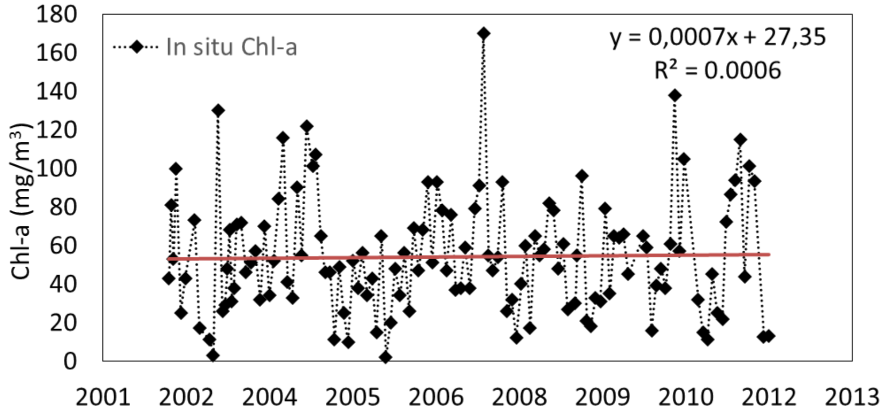
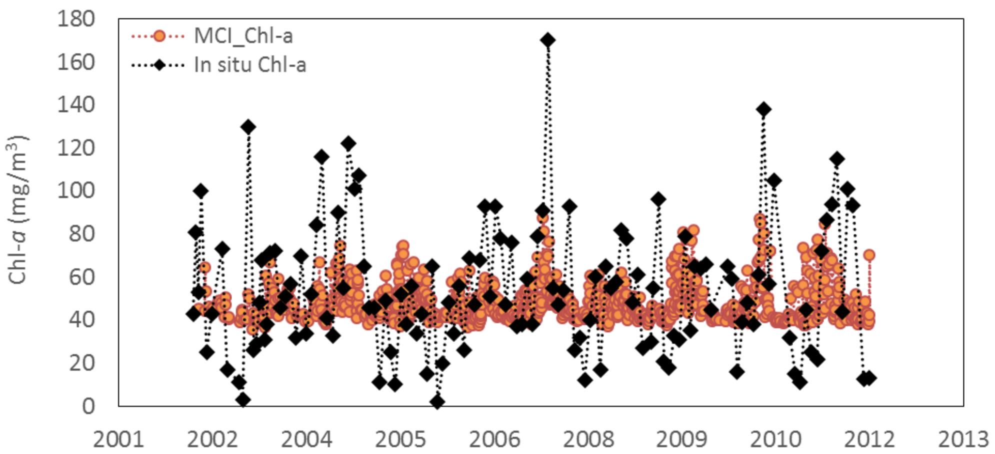


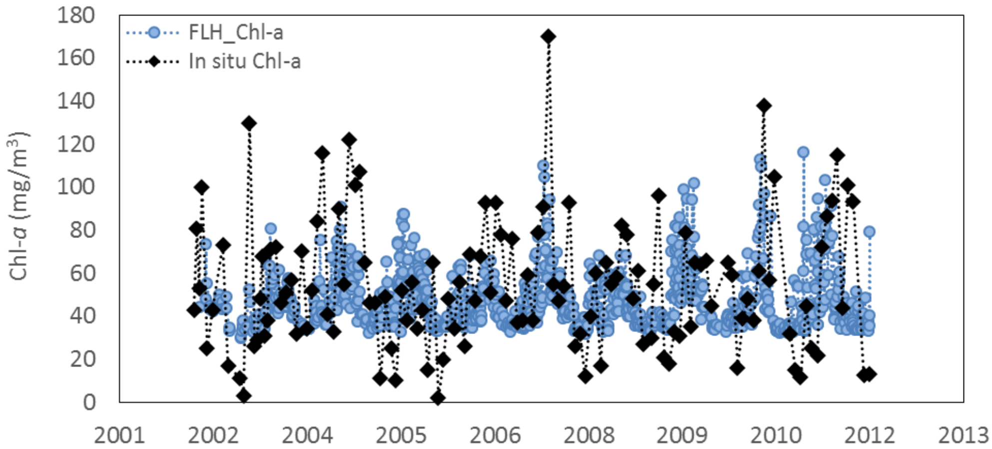
Figure 44. Time-series of in situ measured TSM (a) and Chl-a (b) values from 2002 to 2012 in L. IJsselmeer (at Vrouwezand station).

Time-series constructed from values extracted from calculated MCI and FLH products indicated somewhat similar variability with in situ data, however, the extent of in situ variability was notably larger (Figures 45, a & b). It can also be noticed that values from FLH products are more sensitive to changes in in situ Chl-a values than MCI products. Results from MPH Chl-a products on the other hand do not match with in situ data that well and often strongly overestimate in situ Chl-a values indicating random variability (Figure 45c).

a)



b)



c)

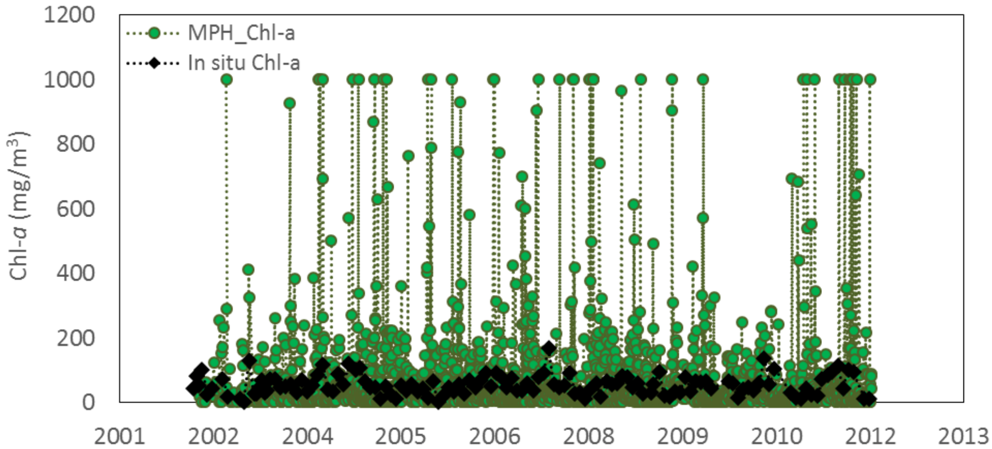


*Figure 45. Time-series of Chl-a estimations from in situ measurements, calculated MCI (MCI_Chl-a=5.08*MCI_index+12.54) (a), calculated FLH (FLH_Chl-a=-10.73*FLH_index +7.94) (b) and MPH (c) products from 2002 to 2012 in L. IJsselmeer (Vrouwezand station).*

f) Analysis of long term studies

One factor shaping yearly differences in Chl-a amount in natural lakes is water level. Low water level allows deeper mixing resulting more suspended material in the water column and lower light availability for the phytoplankton causing Chl-a increase in cells to get sufficient amount of light for growth. At the same time deeper mixing transports more nutrients (especially settled phosphorus) into the water column and that enhances phytoplankton production. This lead to lower status class estimation according to WFD (Alikas et al., 2015). These effects are clearly visible in shallow lake Võrtsjärv, where water level is the most important factor in shaping in-lake processes (Nõges et al., 2003, Nõges & Tuvikene, 2012, Toming et al., 2013) and in less extent in L. Peipsi, where the difference between highest and lowest water level is 2.89 m (Jaani et al., 2008). During high water level period the same amount of cells is diluted in larger amount of water leading to lower Chl-a concentration.

In L. Peipsi the years 2003 and 2007 represented years with low water level. In August 2003 heavy CY bloom was present in L. Peipsi and also fishes died, but for the time of field campaign in August heavy winds had broken down the bloom (Laugaste, 2003), thus in situ data is not reflecting the situation.

The other factor behind Chl-a increase is warm water temperature during summer which enhances CY growth. A combination of shallow water level and high temperature are especially favorable for nitrogen-fixing CY which benefit from phosphorus re-suspended to the water column. Temperature might sometimes be even more important than low water level. For example in L. Peipsi during 2010 water level was high but both spring and summer were extraordinarily hot (Vooremäe & Kangur, 2010), which caused suitable conditions for blooms, changes in timing of phytoplankton maxima and fish kills in July. Also in L. Trasimeno the Chl-a peak in 2008 can be explained with higher water temperature.

CoastColour processing proved to work best in case of Müggelsee, whereas FLH gave more reliable results in case of L. IJsselmeer, when in situ Chl-a values were in range of 30-80 mg/m^3. Lower values were generally overestimated and higher values were underestimated. MPH gave too variable results, possibly due to the invalid cloud flagging, thus rather FLH or MCI should be used.

4.4 CY blooms

This section presents the results of analysis of the presence of CY during vegetation period per lake (4.4 a-e). Since MPH products enable to describe the presence of floating or immersed CY, these were used for bloom detection. Some of these products represent monthly mean values. MCI is not especially sensitive to CY, but shows the elevated Chl-a amount, which requires additional analyse of algal community. However, if such knowledge exists, it can also be used for characterisation of CY bloom development (subsection c). Small Dutch lakes are not included in this analysis.

a) L. Ülemiste

In general CY were not present in May during both investigated years (Figure 46). The potential of CY blooms was higher during summer period of 2009 and in August and September of 2010. CY community changed due to biomanipulation after 2004: earlier dominant filamentous non-toxic cyanobacterium *Limnothrix redekei* was substituted with *Microcystis* spp. *Microcystis* forms scum in surface layers whereas *L. redekei* is not a scum-former and the colonies are usually evenly distributed in the water-column. There is also a difference in timing: if *L. redekei* may be present in the water column during the whole year then *Microcystis* prefers warmer timeperiod.

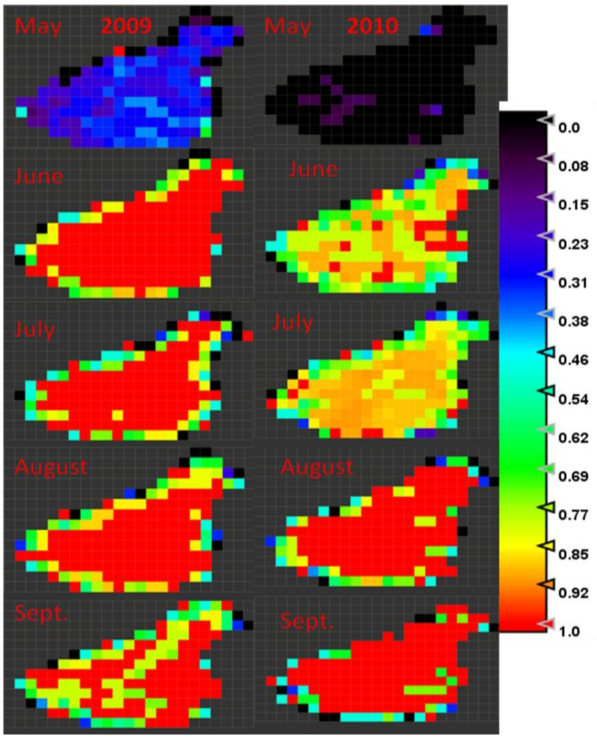


Figure 46. Seasonal variability of monthly mean values of potential CY blooms from MPH products in 2009 and 2010 in L. Ülemiste.

b) L. Peipsi

In Figure 47 the entire phytoplankton composition for L. Peipsi can be seen. CY biomass gradually increases towards autumn forming only a small proportion in May and June when diatoms prevail. Chrysophytes are abundant in spring, proportion of dinophytes and cryptophytes increases towards July.

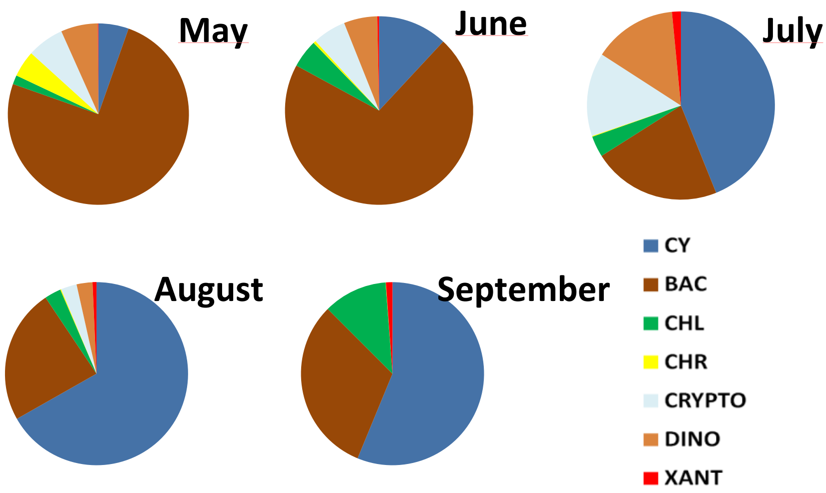


Figure 47. Proportion of different phytoplankton groups during vegetation period (May-September) in 2010 in northern part of L. Peipsi. Entire pie for each month is 100%. Abbreviations: Cy-cyanobacteria, Bac-diatoms, Chl-chlorophytes, Chr-chrysophytes, Crypto-cryptophytes, Dino-dinophytes, Xant-Xanthophyceae.

From the visualised MPH products it can be noticed that immersed CY are more likely present towards the second half of the vegetation period and especially high values are in July, August and September (Figure 48), a tendency, which is supported the in situ data (Figure 47). The potential of CY blooms is also higher in southern part of L. Peipsi (Figure 48).

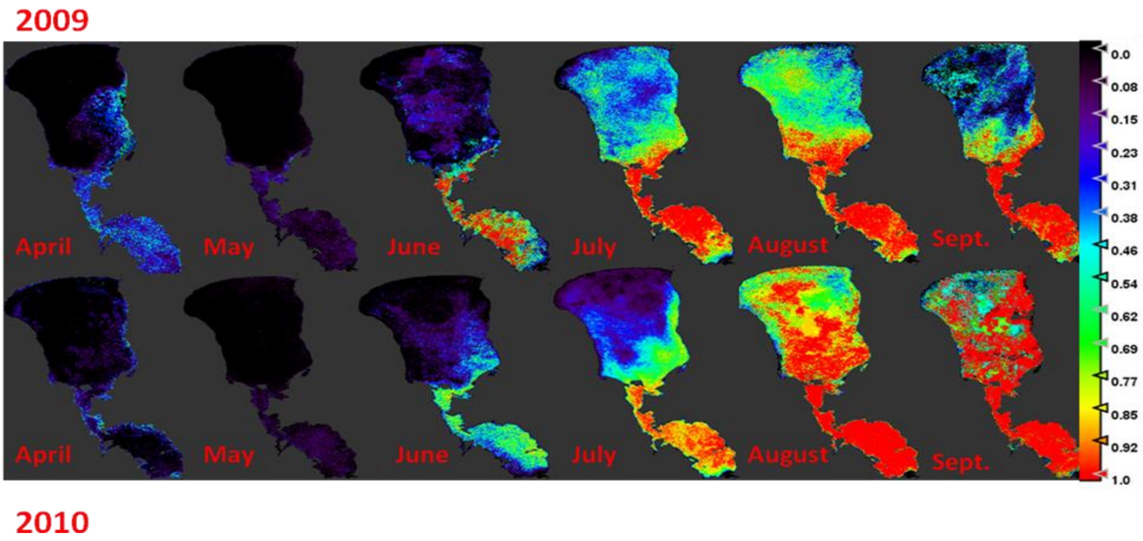


Figure 48. Seasonal variability of monthly mean values of potential CY blooms from MPH products in 2009 and 2010 in L. Peipsi.

Spatial outcome of MCI indexes on daily bases represents a good possibility to detect, for example, the wind effect on the development and movement of CY bloom. The CY bloom in 2010 in L. Peipsi started before 11th July in L. Pihkva (Figure 49). Fluctuation of CY bloom depended on weather conditions – there was a strong wind during 13th and 26th of July which leaded to the decline of bloom in surface layers. Binding et al. (2011) also showed that wind-induced mixing has an impact on surface algal biomass in Lake of the Woods, where *Aphanizomenon flos-aquae* and *Anabaena* spp. are dominating. Wind speed higher than 3 m/s in L. Peipsi caused a notable decline in MCI values, since algal cells were dispersed through the water column and surface bloom returned when higher wind event was over.

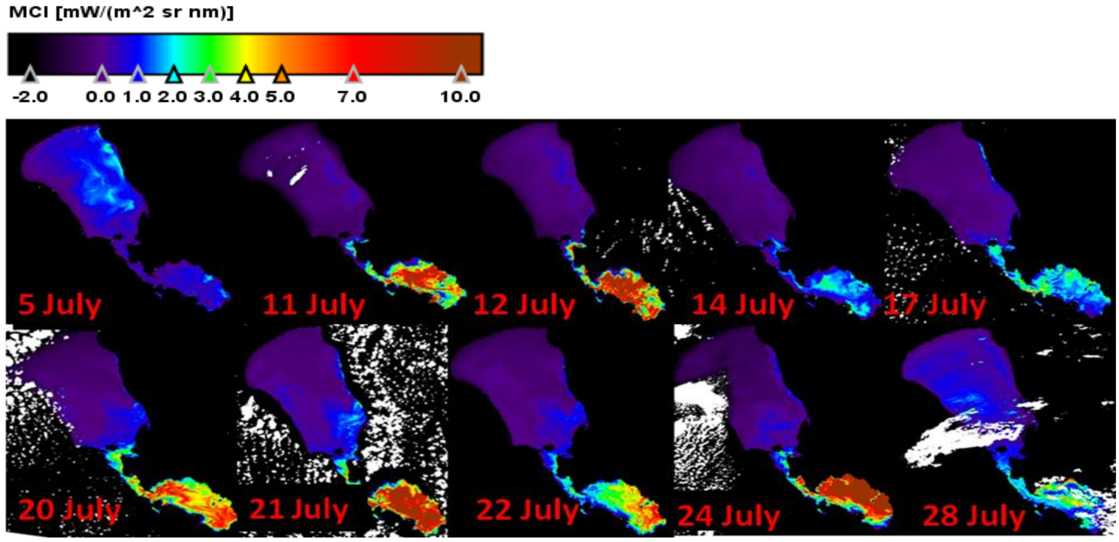


Figure 49. Variability of MCI values during July in 2010 in L. Peipsi.

Microcystin concentrations have been measured in L. Peipsi by K. Panksep (Võrtsjärv Centre for Limnology, EULS). In northern part of L. Peipsi it is generally below 1 µg/L, in L. Lämmijärv >10 µg/L and in L. Pihkva potentially even higher due to higher CY abundance in that part of the lake. It is known that CY tends to aggregate close to coast with potential danger to swimmers and domestic animals (measured level >1000 µg/L). During 2010 and 2011 all analysed samples from L. Peipsi contained microcystins.

c) L. IJsselmeer

For L. IJsselmeer species counts are available from spring, summer and autumn months in 2008 to 2012 (Figure 50). During the dates, when samples were collected, there were always CY present, and as expected, their presence is higher in summer and autumn (Figure 51). Surprisingly, in 2009 it can be seen that CY is also dominating in spring. It can be seen that the proportion of CY in total phytoplankton is high, especially in the second half of the vegetation period (Figure 52).

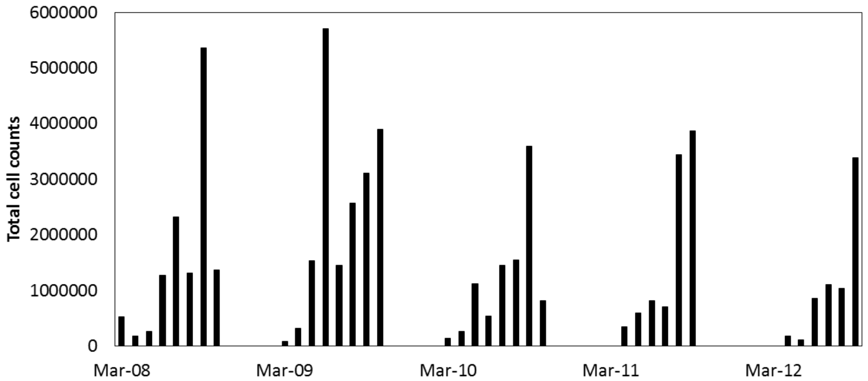


Figure 50. Absolute phytoplankton species counts in L. IJsselmeer (Vrouwezand).

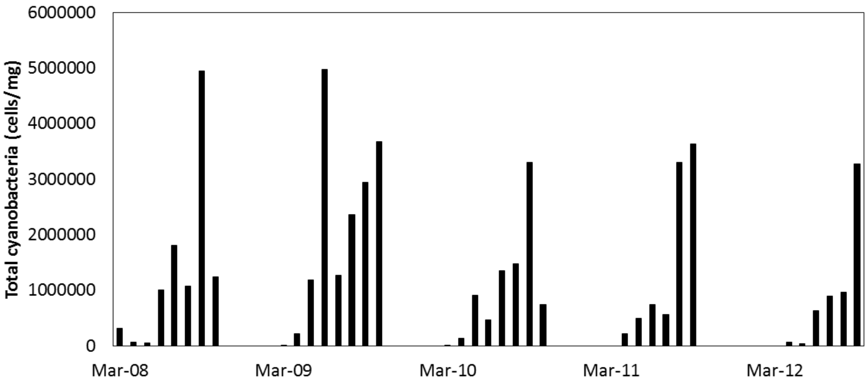


Figure 51. CY species counts in L. IJsselmeer (Vrouwezand).

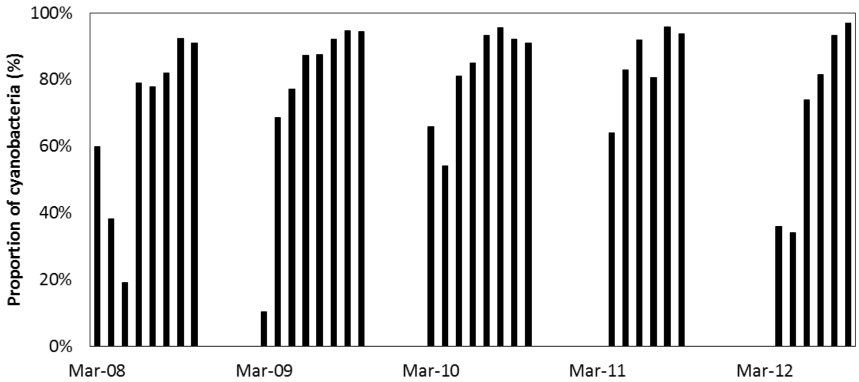


Figure 52. The proportion of CY in total phytoplankton biomass in L. IJsselmeer (Vrouwezand).

Results from MPH products indicate also that more counts were received during summer and in September, although, the absolute counts of immersed CY in March is also high during the investigated years (Figure 53).

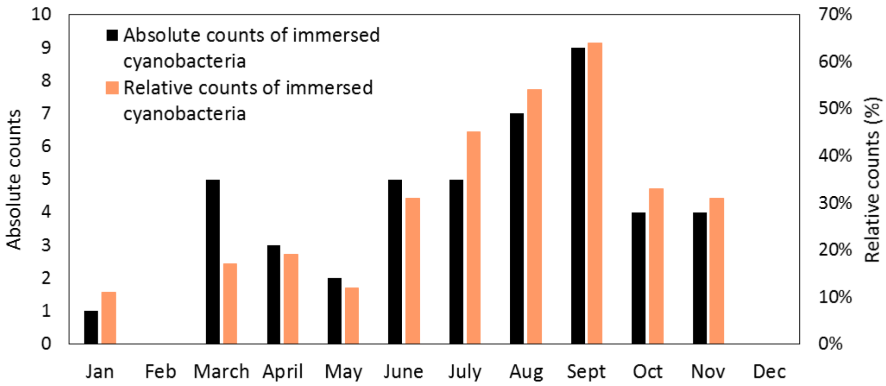
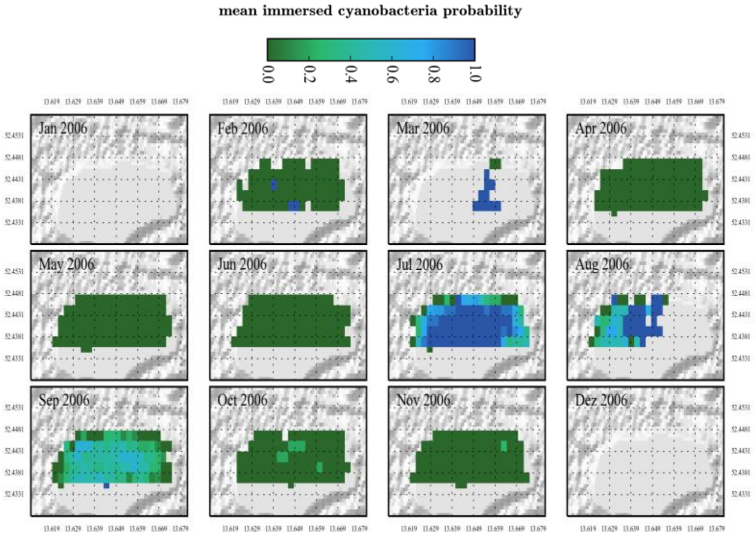


Figure 53. Variability of absolute and relative counts of immersed CY from MPH products from 2002 to 2012 in L. IJsselmeer (Vrouwezand).

d) L. Müggelsee

For L. Müggelsee also the monthly mean products of CY index are available. The results from these products were compared with the in situ CY measurements of IGB. Figure 54 shows the monthly averages of the CY index for each month in 2006 (visualised images) and the corresponding comparison with in situ measurement (table in Figure 54). The CY index derived by the MPH algorithm is in very good agreement with the in situ values. High values in July, August and September (blue pixels) are in agreement with the detection of high CY occurrence in the water samples during that year. This comparison has been performed for years 2006 and 2007 by U. Mischke, IGB, Dept.I.



	IGB	GLASS-cyano.
	result microscopy	MERIS - colour sensor
month	% of cyanobacteria*	
March	1	few grids
April	0	<1
May	0	<1
June	4	<1
July	91	>80
Aug	75	>60
Sept	42	>40
Oct	10	<20
Nov	5	<1
	* all values as monthly means	

Figure 54. Seasonal variability of monthly mean values of potential CY blooms from MPH products in 2006 in L. Peipsi and comparison of proportions of CY index from in situ measurements and MPH products.

e) L. Trasimeno

Based on MPH products the presence of CY from late July until September in L. Trasimeno can be seen (Figure 55). These results are in good agreement with the peak in time-series of MCI, FLH and MPH results (Figure 33b).

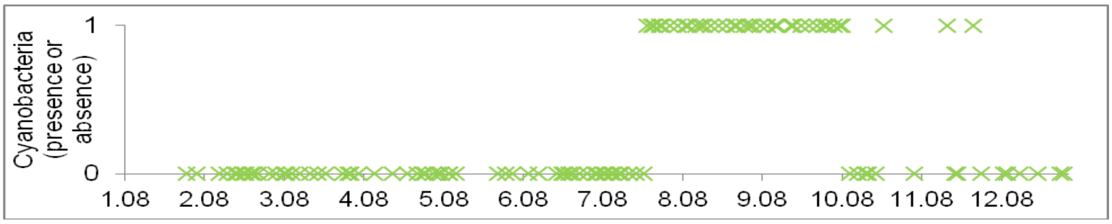


Figure 55. Variability of CY presence and absence from MPH products in 2008 in L. Trasimeno. Value 1 indicates presence, value 0 indicates absence.

In 2006 on the other hand CY were detected only on 31st August, 13rd September and 17th October in the south-west part of the lake. In situ data provided by Environmental Protection Regional Agency ARPA-Umbria (Table 5) in 2010 highlighted the occurrence of an important CY bloom. Extracting Chl-a concentration values and the presence or absence of CY from MPH products it can be noticed that the CY bloom started in the same period that in 2008 although, its magnitude was lower. There is a good agreement between in situ measurements and Chl-a values and CY presence index from MPH products (Figure 56).

Table 5. Cells numbers of Cylindrospermopsis raciborskii measured by Arpa-Umbria.

Cylindrospermopsis raciborskii (cell number 10^7/l)						
	6th July 2010	19th July 2010	2nd Aug. 2010	16th Aug. 2010	6th Sept. 2010	21st Sept. 2010
ARPA-Umbria	0.18	2.88	3.03	10.10	7.00	2.05

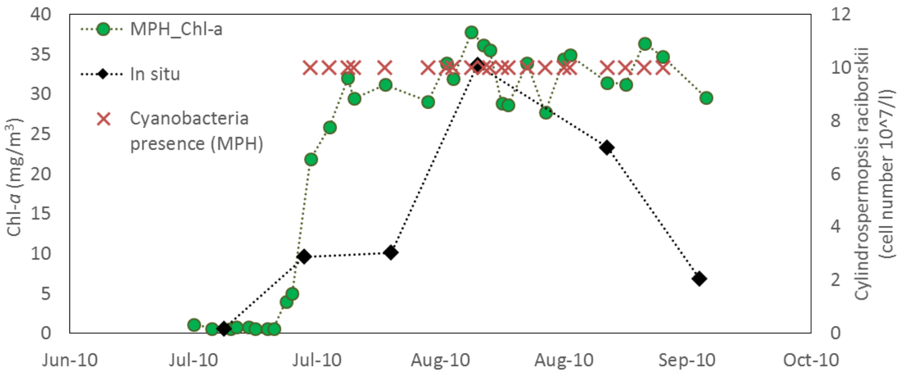


Figure 56. Variability of number of cells of Cylindrospermopsis raciborskii, Chl-a values and CY presence from MPH products in 2010 in L. Trasimeno (Pelagic ROI).

From the visualised MPH Chl-a products it can be also clearly seen, how the bloom reaches its maximum level in August indicating higher values already in July (Figure 57). A slight decrease in Chl-a values can be noticed on 9th September.

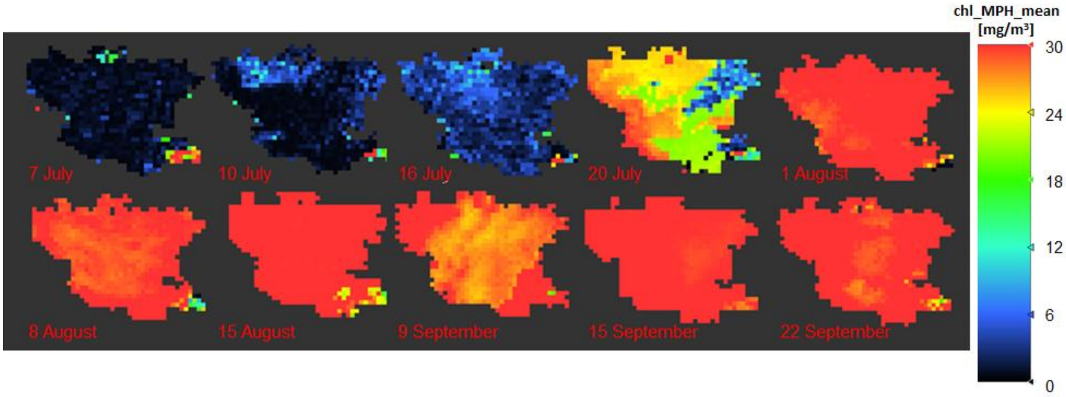


Figure 57. V*ariability of daily mean values of potential CY blooms from MPH products in 2010 in L. Trasimeno.*

Also visualised images representing Chl-a concentrations and presence of CY were investigated in order to show extreme conditions before and during the bloom (Figure 58). The presence of CY in the first image was detected only in some pixel in the coastal area, which is probably caused by adjacency effect. On the second image the presence of CY was detected in the whole lake while Chl-a concentration was also higher compared to the first image and especially in the southern part of the lake. This spatial distribution could be linked to the presence of emergent macrophytes on 01st July, for the 18th August the southern part is probably affected by higher Chl-a concentrations due to the nutrient discharge by the small channel contaminated by zootechnical practices and by the effect of main wind direction during that day.

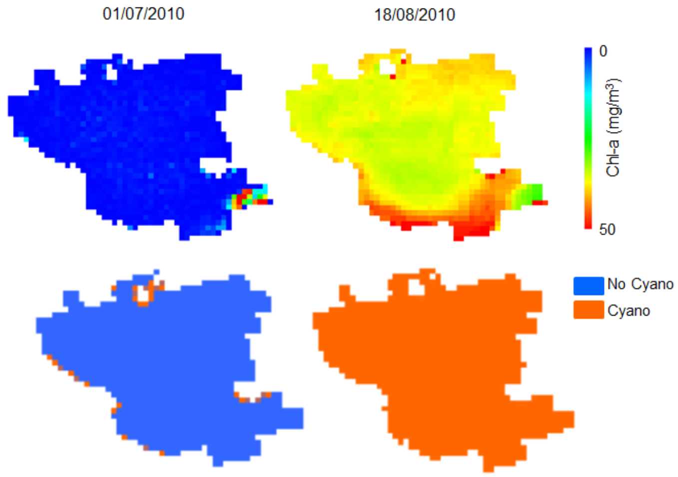


Figure 58. Visualised images of Chl a concentration (mg/m^3) and presence of CY from MPH on 1st July 2010 and 18th August 2010 in L. Trasimeno.

4.5 WFD reporting

Information about WFD reporting in different GLaSS member states, country-specific lake types and ways to give ecological status estimation is described in GLaSS deliverable D5.7 WFD reporting case study results. The application of the directive, monitoring and reporting activities of six member states (Finland, Estonia, Sweden, Germany, The Netherlands and Italy) are described there in detail together with examples of the potential use of EO data for reporting.

In Germany, Netherlands and Estonia EO data are currently not used for reporting, but Chl-a estimations and maps are being produced. From four processing schemes used in this study only MCI is used for mapping Chl-a and total phytoplankton biomass in case of Estonian lakes Peipsi and Võrtsjärv (Figure 59).

In Italy EO data is used to complement in situ monitoring: CNR-IREA has produced several types of maps (Chl-a, surface algal bloom identification and extension, water transparency, TSM concentration) mainly derived from MERIS images during 2003-2011, especially for perialpine lakes (Bresciani et al., 2011), but also Maggiore (Giardino et al., 2014) and Trasimeno (Giardino et al., 2010). EO data has been used in the actual reporting only in a limited manner also in Finland and Sweden. In Finland in the framework of the FRESHMON project (FP7, grant agreement number 263287) Chl-a time-series and histograms (processed from individual MERIS images) of three years were generated for 662 lake waterbodies in southern Finland. In Sweden focus is more on classifying coastal areas.

Our study showed that in case of some lakes (Trasimeno and Peipsi) using all three algorithms give results in accordance with in situ data and results can thus be used for WFD reporting purposes. For L. Tuusulanjärvi and Ülemiste the correlation between in situ and satellite data was weaker, thus for these lakes these three algorithms are not giving the best result. In case of Tuusulanjärvi using MERIS might not be the best selection due to the narrow shape of the lake resulting only some valid pixels in the middle of the lake. In case of Ülemiste more match-ups than from one year for validation should give more realistic picture about suitability of these Chl-a estimation algorithms.

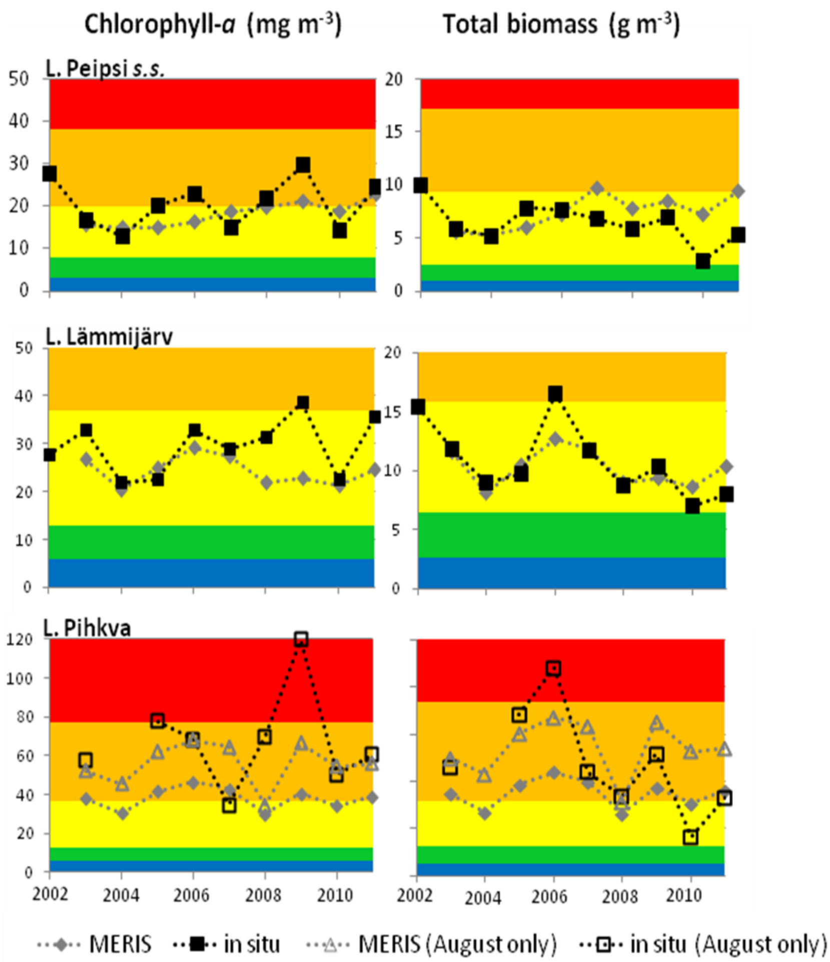


Figure 59. Ecological status class estimations according to Chl-a and total phytoplankton biomass according to MERIS MCI products and in situ data in different parts of L. Peipsi for the period of 2002-2011. Colour coding: blue-high, green-good, yellow-moderate, orange-poor, red-bad. Redrawn from Alikas et al. (2015).

5 Conclusions

Shallow lakes represent a group of lakes that are in public interest since these lakes are situated often in heavily populated areas and often used for recreational purposes and drinking water production. Potentially toxic CY blooms prevent activities on these lakes leading to loss in tourism and generating an extra burden to the local economy. All lakes in this study have problems with heavy algal blooms which periodically affect the usage planned for them. Blooms tend to be heavier during years with low water level and higher temperature.

Chl-a is one of the parameter which give information about the phytoplankton biomass in a lake. It is relatively easy to monitor Chl-a concentrations and it can also be estimated via EO methods. EO methods allow getting more information about Chl-a amount in lakes compared to in situ measurements which are collected with a maximum of once or twice a month only. Also the spatial overview that EO data provides allows analysis of the variation within one lake which generally remains undetected with only one (or few) in situ monitoring point(s). On the other hand, in situ monitoring provides information during early spring and late autumn, when the cloud cover often prevents the use of EO. Cirrus clouds might also influence the EO results by generating erroneously high reflectance values.

For this study four different processing schemes, suitable for Chl-a concentration >10 mg/m^3, were used for the MERIS data. Compared to the in situ reference data the results were best for L. Trasimeno, where R^2 for FLH was 0.9 and equally good for MCI and MPH (0.89 and 0.88). R^2 for L. Peipsi was a bit lower: 0.7 for FLH and MCI and 0.5 for MPH. Not so promising results were observed for L. Tuusulanjärvi, L. Ülemiste (R^2 below 0.4) and L. IJsselmeer (R^2 below 0.2). Tuusulanjärvi is the narrowest of all the studied lakes which leads to higher potential of adjacency effect. In addition, the lake is CDOM-rich which may have an effect on the atmospheric correction and therefore on the detection of Chl-a. In L. IJsselmeer TSM amount may be occasionally high leading to problems with correct Chl-a detection. For those lakes where R^2 was sufficiently high the outcome which is Chl-a concentration may be used for WFD reporting purposes and also information about the presence of CY carries an important value.

Looking into results of seasonal dynamics, MPH showed occasionally too high values in all studied lakes, whereas values from MCI and FLH products were more stable and indicated better agreement with in situ data. Overall tendencies of in situ Chl-a are followed quite well, but high values tend to be underestimated and low values overestimated by satellite-derived products. For L. IJsselmeer, for example, the best concurrency was in range 30-80 mg/m^3. However, MPH processing during springtime might be affected by melting ice, thus high Chl-a amount during April and May in case of Finland and Estonia may be erroneous. However, there is generally a Chl-a peak present in May which is not related to high abundance of CY but rather diatoms, cryptophytes and chrsophytes. The amount of CY starts to increase from June towards September, whereas the peak varies according to the lake: in Müggelsee usually in July, in L. Peipsi and L. Trasimeno in August to September and in IJsselmeer during September.

Long-term studies gave an overview of yearly differences. CoastColour processing proved to work well for L. Müggelsee. Visualised MPH Chl-a products (Diversity-2 processing) showed agreement with in situ results from L. Ülemiste where the effect of biomanipulation was visible being a possible cause for lower Chl-a values during 2005-2007.

The CY index, which is derived by the MPH algorithm, was found to be in very good agreement with the in situ measurements in L. Müggelsee and in L. Trasimeno for detecting the increase of cell numbers of *Cylindrospermopsis raciborskii*. Visualised mages of Chl-a estimations (e.g. MCI indexes) on daily bases represent a good possibility to detect, for example, the wind effect on the development and movement of CY bloom as was presented for L. Peipsi.

Eutrophic lakes generally have a spring and a summer to autumn bloom. The first one is dominated by diatoms and cryptophytes, whereas the second bloom is dominated by CY. Temporal and spatial differences can be large, maximum Chl-a values can reach up to 100 mg/m^3, but may also remain only around 40 mg/m^3 (an example from L. Tuusulanjärvi). Therefore, EO data is a very good tool for monitoring spatial and temporal changes. The MCI and FLH indexes seem to work best for monitoring high intensity of blooms, MPH allows the detection of CY presence. In lakes with high CDOM and TSM values, however, most detection algorithms are not so sensitive.

It is expected that the Sentinel 3 OLCI instrument will provide similar or even better data compare to MERIS results. With regard to the long-term data series the planned lifetime of the Sentinel-3 satellite series is of great importance. Ten years of data from MERIS is good to analyse yearly patters and carry out long-term analysis, however, with regard to ecological changes ten years is not very long. For example, climate change, leading to higher temperature and potentially more CY blooms, and also eutrophication, request longer time-series for proper studies.

For two small Dutch lakes Landsat 8 data was used to derive Chl-a concentrations. The Landsat 8 band ratio algorithm showed expected seasonal trend for L. Paterswoldsemeer, but seemed not sensitive enough for Chl-a retrieval from the clearer L. Westeinderplassen. The Landsat 8 bands, however, are not ideal for Chl-a retrieval. In this study a ratio between band 4 (640-670 nm) and band 3 (530-590 nm) was used. It was assumed that when Chl-a concentrations increase the absorption in band 4 increases, while in band 3 the influence is relatively small. Much better results are expected from Sentinel-2 satellite products, because it has a more dedicated absorption band (band 4 at 665 nm), and a better reference band (705 nm). Also for the smaller lakes especially lakes like L. Paterswoldsemeer that includes many islands and narrow bays the spatial resolution of S2 will be much more suitable.

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