



# Global Lakes Sentinel Services

Grant number 313256

## GLaSS Training material, Lesson #3

### Eutrophic lakes

What is the spatial distribution of water quality parameters over Lake Peipsi?

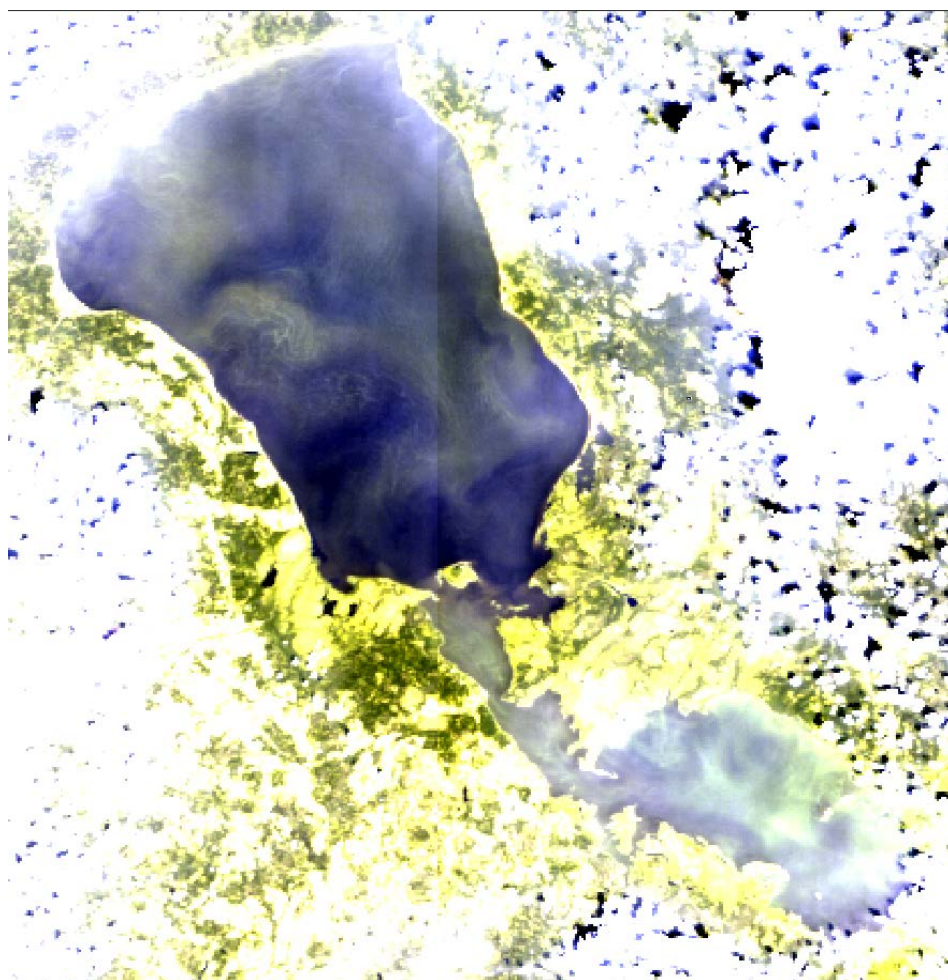
Evelin Kangro (TO), Kersti Kangro (TO), Elar Asuküll (TO), Annelies Hommersom (WI)



## Lesson summary

Problems with eutrophication and algal blooms around the world have generated the need for cost-effective ways of monitoring the ecological status of water bodies and its changes. Earth Observation methods have proved to give far better coverage both in spatial and temporal scale for evaluation of in-water constituents in the water bodies.

In this lesson we will learn how to analyse the spatial variability in algal concentrations in Lake Peipsi, Estonia, using MERIS satellite data. This includes some basic handling of the image, atmospheric correction, application of a concentration-retrieval algorithm and finally validation of the results with in situ measurements



## GLaSS training material outline

This lesson is part of the GLaSS training material. The complete training material outline is listed on [http://data.waterinsight.nl/GLaSS/trainingmaterials/GLaSS\\_lesson\\_outline.pdf](http://data.waterinsight.nl/GLaSS/trainingmaterials/GLaSS_lesson_outline.pdf).

Note that the lessons logically follow up on each other, the later lessons might require skills that can be acquired during the earlier lessons.

## Table of contents

Lesson summary .....	2
GLaSS training material outline .....	2
Table of contents .....	3
List of abbreviations .....	3
1 Introduction .....	4
1.1 Eutrophication of lakes.....	4
1.2 Effect of cyanobacteria blooms .....	5
1.3 Lake Peipsi - Estonia .....	6
1.4 Short intro on atmospheric correction.....	8
2 This lesson .....	11
2.1 Research question .....	11
2.2 Training objectives / skills to gain in this lesson.....	11
2.3 Required software and data .....	11
Software and tools.....	11
Downloadable files .....	11
3 Exercise .....	12
Part 1 Basic visual analysis of spatial variability .....	12
Part 1 Extra analysis .....	15
Part 2 Atmospheric correction .....	16
Part 2 Extra analysis .....	19
Part 3 In water component retrieval .....	19
Part 3 Extra analysis .....	23
4 More information and further reading.....	25
References.....	26
Colophon.....	30

## List of abbreviations

Abbreviation	Description
Chl-a	Chlorophyll a
CY	Cyanobacteria
EO	Earth observation
FLH	Fluorescence line height
L <sub>toa</sub>	Top-of-the atmosphere radiance
MERIS	Medium Resolution Imaging Spectrometer
PC	Phycocyanin (pigment in cyanobacteria)

## 1 Introduction

### 1.1 Eutrophication of lakes

Problems with eutrophication and algal blooms all around the world (Hallegraef, 2003; Glibert et al., 2005; Steffensen, 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.

Problems that occur in many shallow eutrophic lakes (GlaSS Deliverable 5.2, 2015) are:

- 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 cyanobacteria (CY) blooms, which reduce the value of a lake

Many eutrophic lakes are located in highly populated areas. Discharge of nutrient sewer and runoff of water from land that is use for intensive farming are factors that contribute to the eutrophication. On the other hand, especially in highly populated areas, 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 bio-available 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. A 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 knowledge 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 diffuse pollution is much harder. For example in case of Lake 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).

## 1.2 Effect of cyanobacteria 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<sub>2</sub> 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 parts of the 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 bloom-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) (Hudnell & 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 three 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 by the time of writing this lesson, for the current lesson we will work with MERIS. MERIS serves as a proxy for S3 OLCI: in principle, S3 OLCI data can be used in the same way as MERIS data, using the same algorithms and assumptions.

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<sup>3</sup>), 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.

Except by monitoring PC to trace CY blooms, it is also possible to monitor Chlorophyll-a (Chl-a). Chlorophyll-a is not specific to CY: all autotrophic phytoplankton contains Chl-a, like diatoms and green algae, which are also abundant in lakes. However, it is known that toxin concentrations of toxin producing cells increase with cell density. Therefore, according to WHO (2003) 'For practical purposes, the present state of knowledge implies that health authorities should regard any mass development of cyanobacteria as a potential health hazard'. High concentrations Chl-a indicate a phytoplankton bloom, which is potentially a toxin producing CY bloom, but could also be a harmless green algae bloom. Because of the validation issues for PC, this exercise will focus on Chl-a.

### 1.3 Lake Peipsi - Estonia

Lake Peipsi is located in Eastern Estonia on the border of Russia and Estonia, being the largest trans boundary water body in Europe. It consists of three parts: the largest and deepest mesotrophic Lake Peipsi s.s., the middle strait-like eutrophic Lake Lämmijärv and hypertrophic Lake Pihkva, which belongs entirely to Russia. Lake Peipsi has a surface area of 3555 km<sup>2</sup>, a maximum depth of 15.3 m, a mean depth of 7.1 m, a water volume of 25 km<sup>3</sup>, and a catchment area of 47800 km<sup>2</sup>. Its surface elevation is 30 m. The majority of nutrients are carried into the lake by the rivers Velikaja and Emajõgi: from the total drainage basin of Lake Peipsi the catchment areas of those two rivers cover up to 80% of the area (Loigu et al., 2008). The largest 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 Lake 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 Lake Peipsi the 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 Lake Peipsi shows an increasing trend of CY biomass based on in situ data, which is most pronounced in the southern parts of the lake (Laugaste et al., 2007).

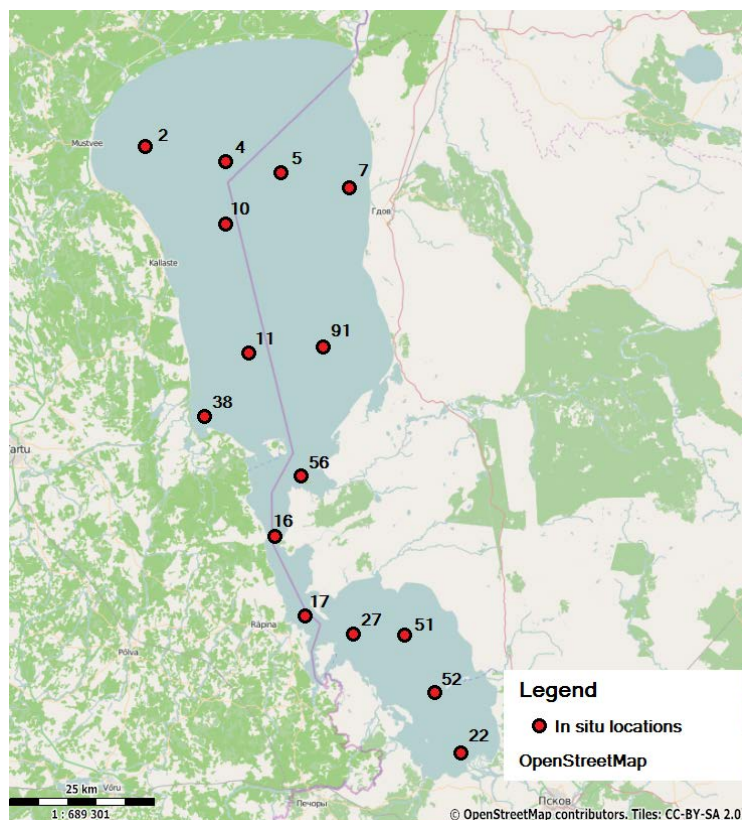


Figure 1. Map of Lake Peipsi with national monitoring points. Points 2,4,11,38,16,17 are visited once a month from May to September, rest of the points once a year during August.

From ecosystem services perspective, besides recreational activities like boating, swimming, skating and recreational fishing, Lake Peipsi provides 80-88% of freshwater fish catches in Estonia, whereas 3-10 % is caught from Lake 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.

*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 Lake 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). Lake 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).

#### 1.4 Short intro on atmospheric correction

It is important to realise that most of the signal, minimal 90%, that is received by the satellite is caused by reflection of sunlight on the atmosphere (National Research Council, 2011).



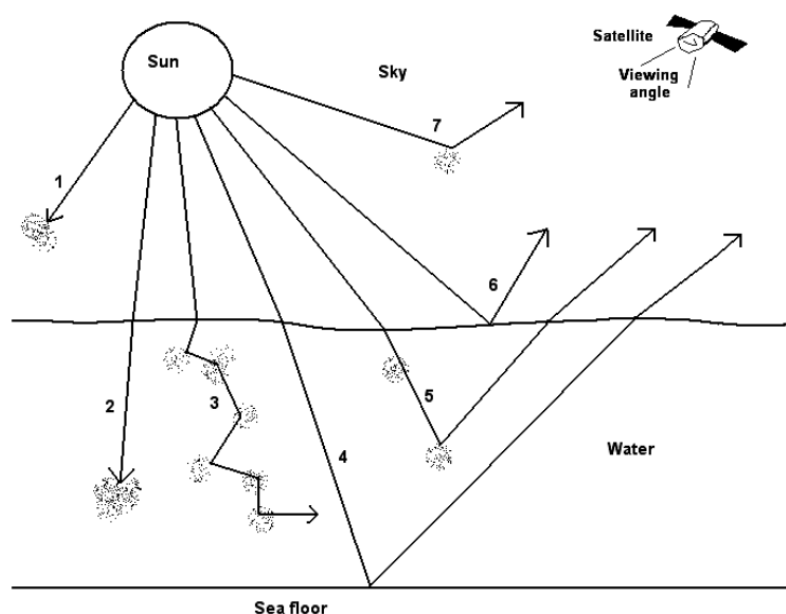


Figure 2. This figure above shows the most common routes of sunlight on its way to a satellite above the sea. Ray 1 is absorbed by the atmosphere and never reaches the water surface and the sensor. Rays 2 and 3 are respectively absorbed and scattered by the water or its contents and so never reach the sensor. Rays 4, 5, 6 and 7 reach the sensor. However, only ray 5 is interesting for water quality monitoring. This ray is partly absorbed by water or its contents, but enough is scattered over an angle  $> 90^\circ$  (backscattered) to reach the sensor. Rays 4, 6, and 7 are, respectively, reflected by the sea floor, by the water surface and scattered by the atmosphere. Combinations of these routes can also occur. (Figure and text taken from Hommersom, 2010, with permission).

Atmospheric correction methods try to remove the atmospheric effects from the signal as it is received by the satellite, on top of the atmosphere (TOA). On its way to the satellite, the light penetrates the atmosphere twice: from sun into the water and back to the sensor. Processes such as adjacent scattering from land into the light path can also be considered as part of atmospheric correction, or correction for water surface impacts to retrieve the pure reflectance of the water bulk. As a minimum, bidirectional effects of scattering and absorption in atmosphere under varying aerosol optical depth are usually accounted for. Some atmospheric correction methods apply constant aerosol optical properties over the scene, while others reflect the atmospheric heterogeneity and retrieve an actual aerosol properties per pixel. While the first approach is often subject to large uncertainties and is applicable only for small areal extend, the second method is required for processing of large data quantities or large areas in an operational environment. However, this requires a certain spectral resolution and radiometric quality of the sensor.

Within the project GLaSS, existing atmospheric correction methods were investigated. The selected methods covered both commercial (MIP, ATCOR) and open source available algorithms, which are implemented e.g. in BEAM like FUB or C2R. Moreover, some of the methods (e.g., C2R and MIP) were specifically developed to correct the atmospheric effect for water body, while others are general purpose atmospheric correction methods (e.g., ATCOR and SCAPE-M) for EO data over Earth surfaces. The first class of methods usually estimate the water leaving radiance reflectance or remote sensing reflectance or similar quaintest which are properly defined for water body only. Moreover, these methods are usually coupled with retrieval of water constituents. Instead, the not water oriented atmospheric processor methods provide a dimensionless surface reflectance value whose

transformation into water leaving radiance reflectance (or remote sensing reflectance) require further computation such as the air/water interface correction, the assumption of the light field shape (e.g. Q factor) or further corrections for the specularly reflected sun and sky radiance. GLaSS compared the methods based on access and licences, implementation, configuration options, processing efforts, applicability to different satellite sensors and performance on inland waters. In general, the development of atmospheric corrections for inland waters is a very dynamic field and a lot of investigations and developments are ongoing. There was no 'generally better' algorithm, instead, depending on the lake type and the situation (specific atmospheric properties are known or not, funding for licences available or not etc) the report (GLaSS Deliverable 3.2, 2014) will help to select the most suitable method for a specific case.

In this lesson we will use the CoastColour atmospheric correction method. It was the one performing the best for Lake Peipsi and no commercial software is required for running it.

## 2 This lesson

### 2.1 Research question

What is the spatial distribution of Chl-a over Lake Peipsi?

### 2.2 Training objectives / skills to gain in this lesson

Learn how to use satellite data to retrieve chlorophyll concentrations, as a proxy for eutrophication.

1. Open an optical satellite image and perform some visual analysis on spatial variability
2. Apply an atmospheric correction method
3. Validate the results with in situ data (spectral + concentrations)

### 2.3 Required software and data

#### Software and tools

To complete this lesson tasks, the following tools and software are required or suggested:

- BEAM (required, see Lesson #1).  
SNAP2.0 cannot be used, but later versions that include the CoastColour processing can be used. As it is expected that SNAP will mostly be used in future, most screenshots in this lesson (except those including the CoastColour processing) are based on SNAP.

#### Downloadable files

- GLaSS\_Training\_Lesson3.pdf  
The main document of the lesson including exercises and questions.
- GLaSS\_Training\_Lesson3\_Answers.pdf  
A document containing answers to all questions proposed in the exercises.
- GLaSS\_Training\_Lesson3\_DataAndTools.zip  
Supplied data and tools, described below.

The zip-file with supplied data and tools contain:

- A folder 'Original satellite data', containing two original MERIS images (e.g. MER\_FRS\_1PPBCM20110708\_090036\_000001013104\_00194\_48915\_0277.N1)
- A folder called 'In situ data', containing two (Excel) spreadsheets with in situ data:
  - 'In\_situ\_reflectances.xlsx'
  - 'In\_situ\_chlorophyll.xlsx'
- A folder called 'Additional data', containing:
  - A file with the in situ locations, in BEAM/SNAP format: In\_situ\_locations.placemark
  - Two files with a colour scale to use in BEAM/SNAP: e.g. Chlorophyll\_colour\_scale.cpd
- A 'Answer data' folder containing the same imagery as provided in the Original satellite imagery and In situ data folders, after performing the steps that are explained in the lesson

### 3 Exercise

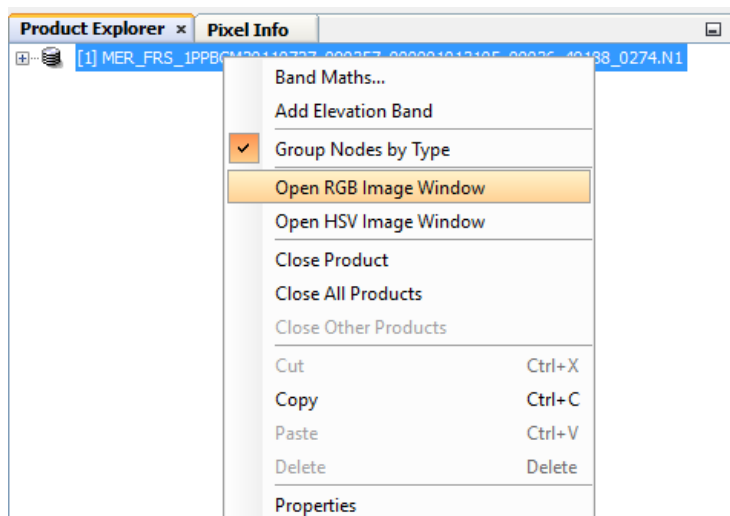
#### Part 1 Basic visual analysis of spatial variability

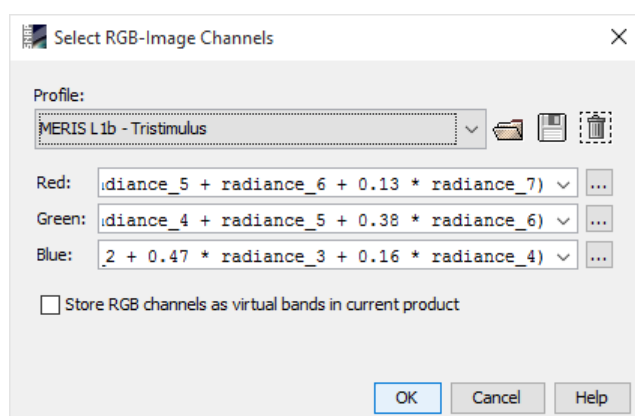
- Start SNAP
- Open the MERIS image of 27th July 2011 (File > Open Product > select the image MER\_FRS\_1PPBCM20110727\_090357\_000001013105\_00036\_49188\_0274.N1).
  - “FRS” stands for the full resolution, which means the ~300\*300 m pixel size. MERIS imagery is also available at reduced resolution of ~1\*1 km.
  - “1P” stands for L1P processing level. L1 is on top of the atmosphere, e.g. what the satellite records, including the atmospheric effects. P is the standard pre-processing applied.
  - “20110727” is the date when the image was taken (27th of July 2011).
  - “090357” is the time when image was taken in UTC (09:03:57)
  - “N1” is the file type of original MERIS images.

After opening, in the "Product Explorer" window (left side of your screen) you can click the +- signs to open the folders for the Metadata, Flag codings, Tie-point grids and Bands.

To easily get an idea of what the image looks like:

- Right-click the image in the Product Explorer > Open RGB Image Window >> it automatically selects MERIS L1P Tristimulus

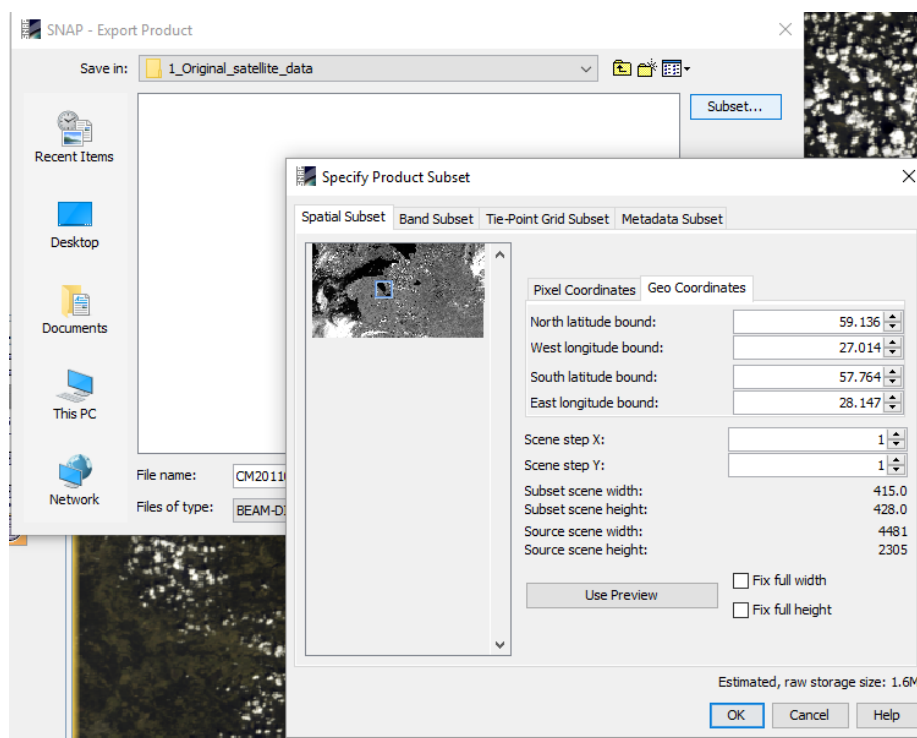




You now get to see the Gulf of Finland and surrounding land. Zoom in and out with the mouse and click-move around to see if you can find Lake Peipsi.

It is easier and it will save a lot of memory on your computer if you cut out the part of the image that you are interested in, in this case Lake Peipsi. To apply such a bounding box and save that part of the image:


- File > Export > BEAM-DIMAP
- Subset > Geo Coordinates >> fill out the coordinates: 59.1360 North, 27.0140 West ; 57.7640 South, 28.1470 East (note that for locations of the Southern hemisphere you need to use the minus sign)
- Make sure you select a folder where you can find the exported image > Export Product

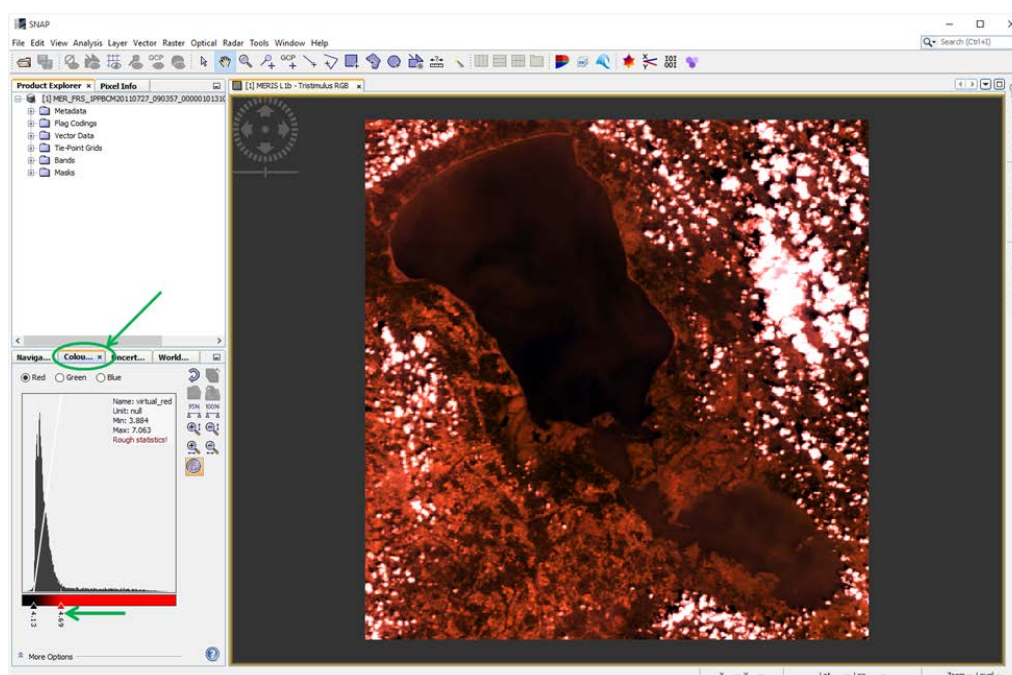


To further work with the small file:

- File > Close Product
- File > Open Product >> select the just exported file

For a more detailed look:

- Open again a RGB image view (Right-click the image in the Product Explorer > Open RGB Image Window > MERIS L1P Tristimulus)
- Select the Colour Manipulator tab (  ) (or next to navigation)
- Adjust the colours by selecting the “Red” slider and moving it to the left, where the higher values of the histogram are found. Then select “Green” in the Colour Manipulator window to adjust green in the same way, and finally also “Blue”.



After some playing around with this, you should be able to see the spatial variability in the lake.

On a first glance, already some basics can be seen:

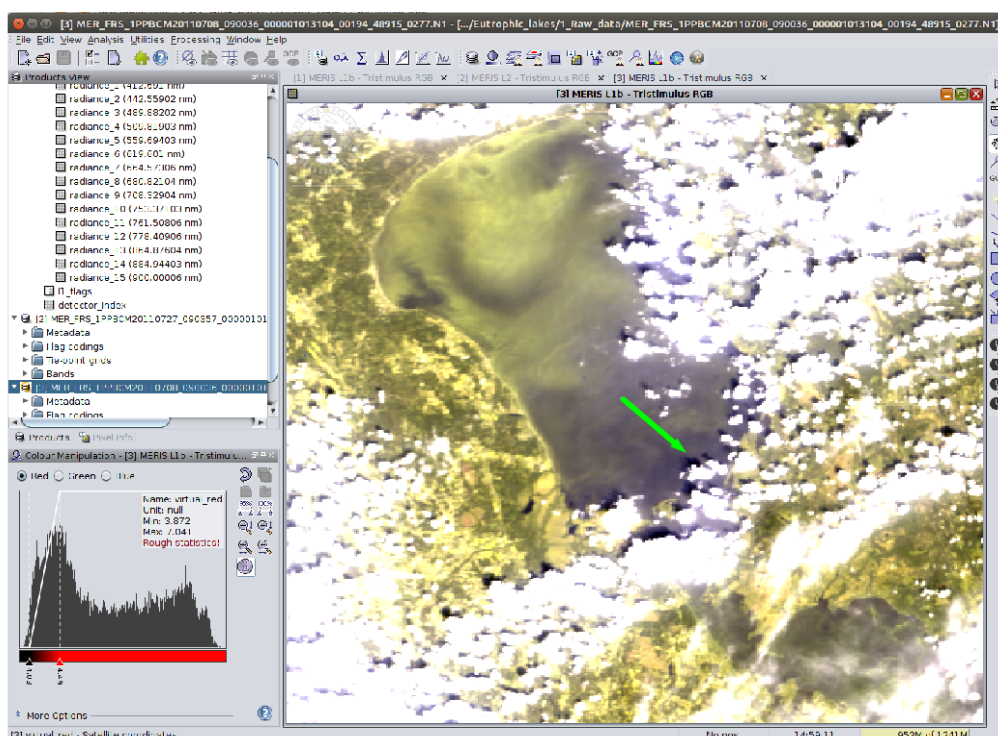
- The white dots on land are clouds, those are the most bright
- Land is relatively bright, water is the darkest
- The northern part of Lake Peipsi (Peipsi s.s (sensu stricto) is darker than the southern part (Lake Pihkva). Lake Pihkva contains more suspended sediments (TSM), which reflect the light and therefore causing the water to have a higher reflection than the northern part of the lake.
- In Lake Pihkva and also to a lesser extent in Lake Peipsi s.s., some spatial features of a mixture of Chl and TSM can be seen.

If you adjust the colours even more, also features in the northern part become more pronounced. Also a vertical line will become visible. This shows that the image is composed of two cameras of the MERIS instruments that are slightly different.

You can leave the image open for the next part of the exercise.

## Part 1 Extra analysis

- Open the other MERIS .N1 file  
(MER\_FRS\_1PPBCM20110708\_090036\_000001013104\_00194\_48915\_0277.N1)
- Select it in the Product Explorer by clicking it
- Analyse it. You can make a subset, open RGB image view, zoom in and out.
  - *What can be seen just next to the clouds?*



Close all the products you opened in this extra section by selecting them in the product view  
> File > Close Product (this needs to be done per image).

## Part 2 Atmospheric correction

First make sure you only have the image subset you created from the image of 27<sup>th</sup> July 2011 open (called e.g.

MER\_FRS\_1PPBCM20110727\_090357\_00001013105\_00036\_49188\_0274.dim).

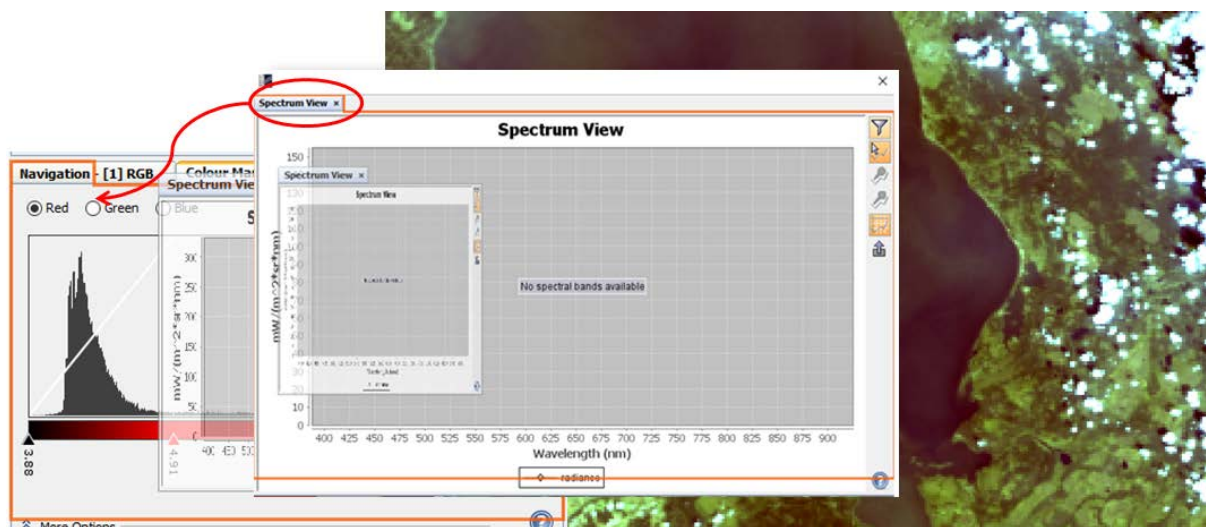
As mentioned before, the image you are looking at is L1, data as recorded by the satellite (TOA), so without correcting for the atmospheric effects.

First we will check the in situ (ground truth) reflectance data:

- Open the file In\_situ\_reflectance\_data.xlsx in a spreadsheet program such as Excel. Check the reflectance spectra.
  - *What are the units?*
  - *In what order of magnitude is the maximum light intensity?*
  - *In which colour is the maximum intensity recorded?*

Now we will compare this with the L1 satellite data:

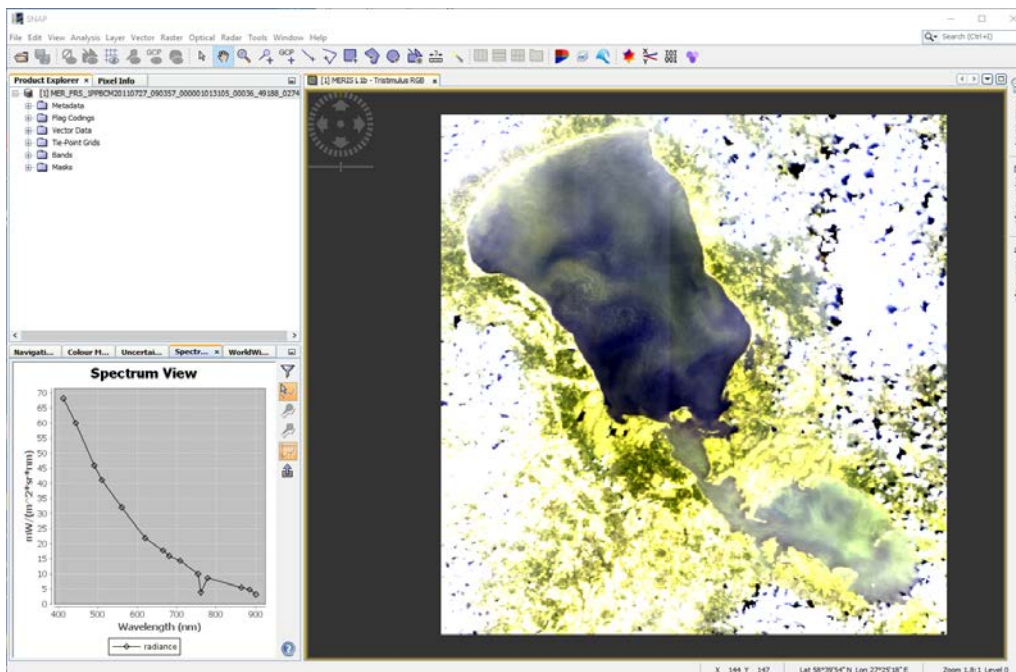
- Optical > Spectrum View (icon with a graph)
- Standard the window is shown as a pop-up. To simplify using it you can select it by click-hold the left top "spectrum view" tab and drag it to the place where also the Colour Manipulator is.



- Now navigate over the image, reading the reflectance spectrum in the Spectrum View window.
- Check out the differences over clouds, land, water and the different parts of Lake Peipsi:
  - *What are the units?*
  - *In what order of magnitude is the maximum light intensity over the water surface?*
  - *In which colour is the maximum intensity recorded over the water surface?*



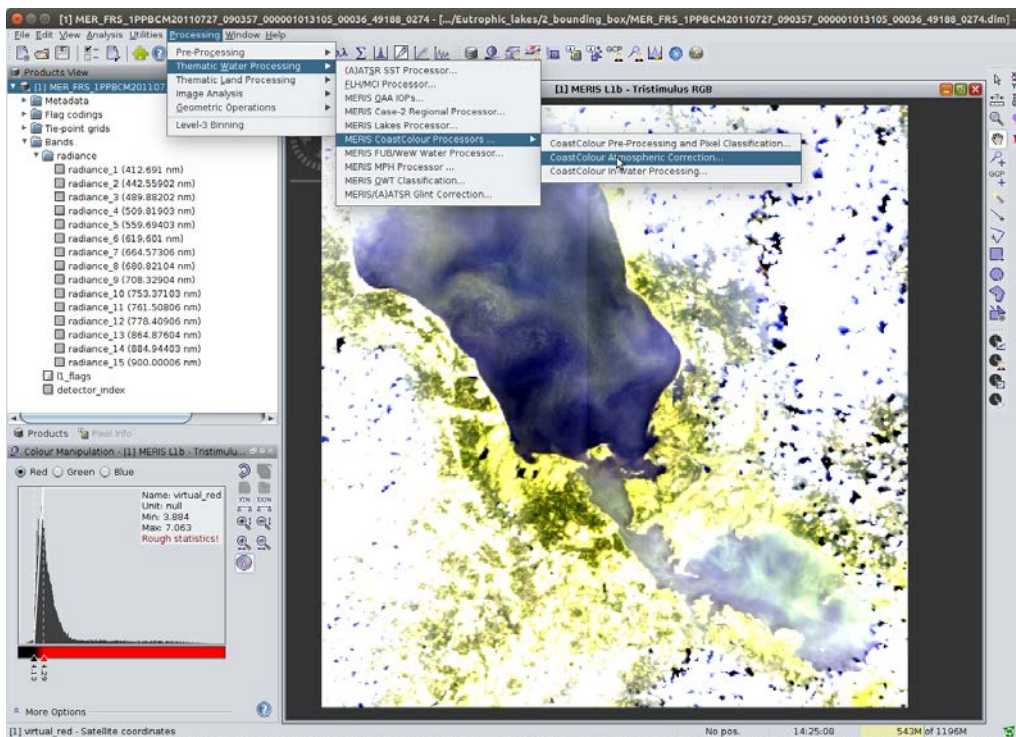
- Why is this colour different than that recorded in the in situ data?



After correction for the atmospheric effects, the reflectances derived from the satellite should be similar as the in situ data.

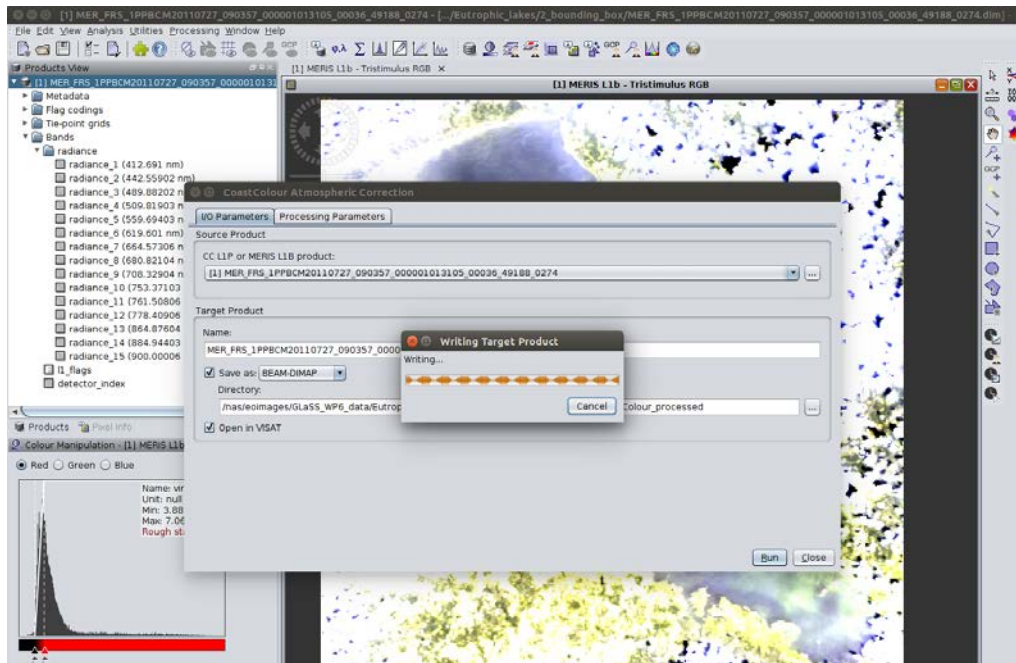
We will now apply the CoastColour atmospheric correction schema to retrieve L2 (atmospherically corrected) data:

- Optical > Thematic Water Processing > MERIS CoastColour Processors > CoastColour Atmospheric Correction



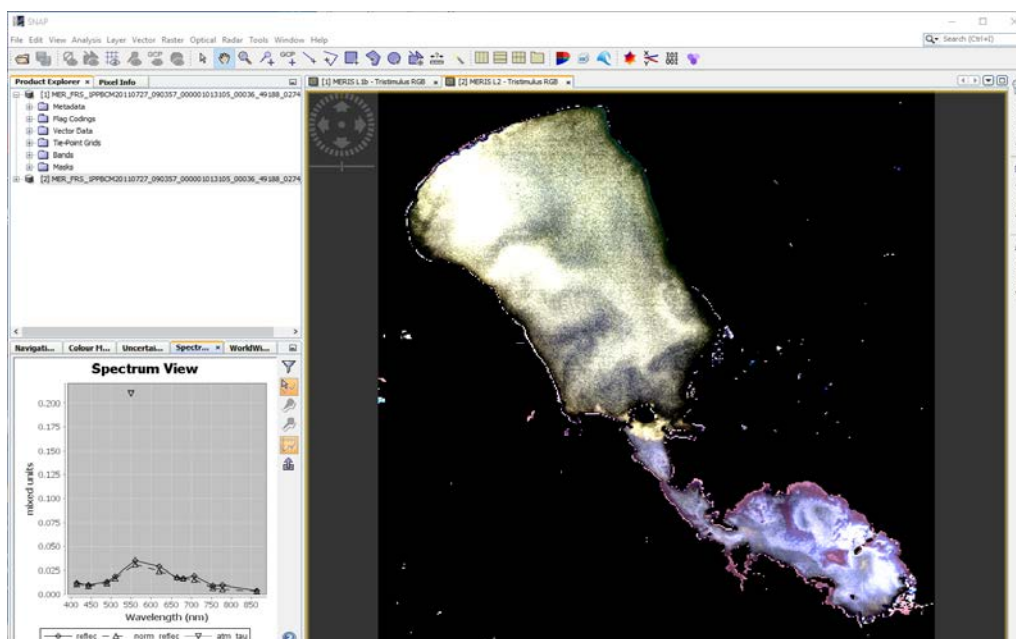
(BEAM screenshot)

- Keep all parameters according to their standard settings, just check on the tab “processing parameters” what is set for “Write all reflectance as” (this should be RADIANCE\_REFLECTANCES)
- Make sure you select the correct folder to store the image >> Run



(BEAM screenshot)

- After the CoastColour atmospheric correction, click OK and Close
- Scroll down in your “Products Explorer” window, select the new image by clicking it
- Open again a RGB image view (Window > Open RGB image view > MERIS L2 Tristimulus)
- *What happened with the land? And the clouds?*







Now we will compare the L2 satellite reflectance with the in situ reflectance data:

- Open the Spectrum View window (icon with a graph)
- Right-click the Spectrum View window > Auto Range > Range axis
- Now navigate over the image, reading the reflectance spectrum in the Spectrum View window.
- Check out the differences over different parts of Lake Peipsi.
- Compare the “reflec” values with the reflectances of the in situ data:
  - *In what order of magnitude is the maximum light intensity over the water surface?*
  - *In which colour is the maximum intensity recorded over the water surface?*
  - *Is there still a difference between the satellite data and the in situ data?*

If you are done you can close the Spectral View window. Keep the L2 image open.

## Part 2 Extra analysis

We can also validate the atmospheric correction results by extracting the reflectance data for the pixels at the in situ stations and comparing the reflectance spectra per station in the spread sheet.

- Open the Pin Manager (  ) and click-hold-drag the window to a convenient location. If the Pin Manager icon is not in your standard view, you can find it via View > Tool Windows > Pin Manager
- Import (  ) the in situ station locations (File: In\_situ\_locations.placemark (in the folder Additional data)) > open
- Select the funnel icon (  ) >> select all “reflec” bands (scroll down) > OK
- Export the data (  ) to a text file and call it Exported\_reflectance\_data.txt)
- Open the Exported\_reflectance\_data.txt in your spreadsheet program, which will lead you through an import function. >> select “separated by tab”.
- Now plot the L2 MERIS reflectance spectra into the plots that came with the in situ data spreadsheet.
  - *How did the atmospheric correction perform?* It is important to check the intensity, but also the spectral shape (which is key to retrieving concentrations)

## Part 3 In water component retrieval

Chlorophyll-a is the main pigment of algae, and therefore a good proxy for the algal biomass. Chlorophyll strongly absorbs around 672 nm, which means that less light is reflected in these wavelengths. If you check out the in situ reflectance measurements (In\_situ\_reflectance\_data.xls) you will notice a strong dip in the intensity at this wavelength, which is caused by chlorophyll-a absorption.

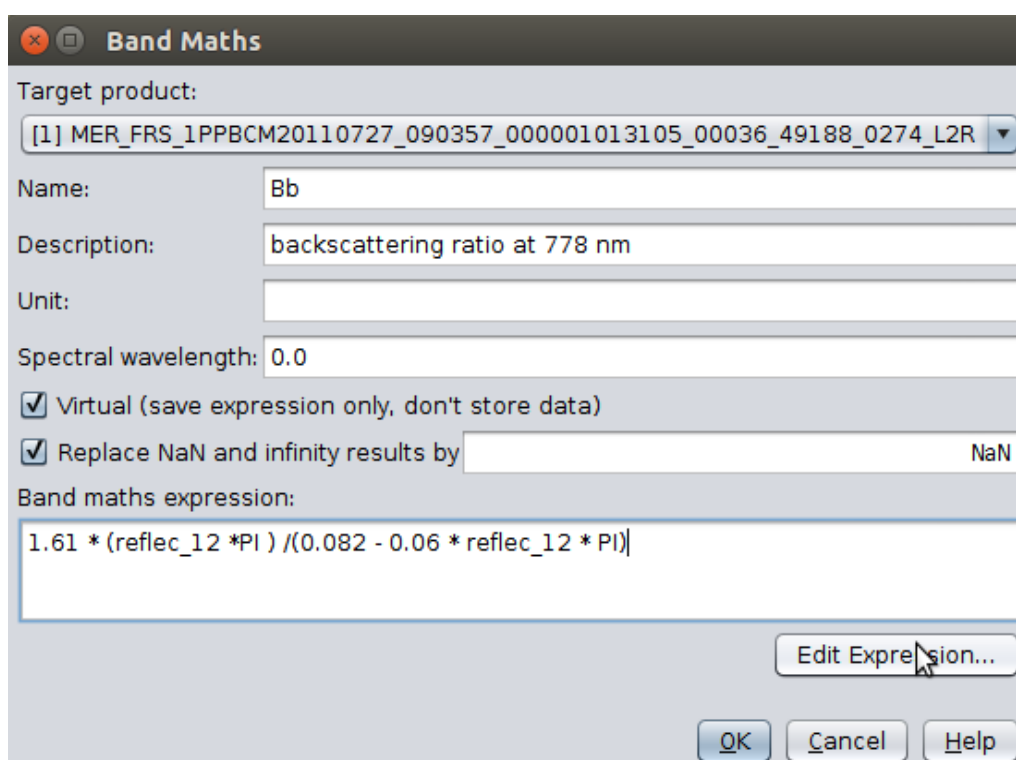
We will now apply an algorithm to retrieve the chlorophyll concentration. The algorithm is developed by Gons (2005), with a small adjustment to accommodate radiance reflectance instead of irradiance reflectance as input (to do this, we multiply by  $\pi$ ).

The equations based on Gons (2005) can be entered in:

- Raster > Band maths (or, if you use BEAM: Utilities > Create Band from Math Expression)

First create a band for the backscattering ratio:

- Name: Bb
- Band math expression:  $1.61 * (\text{reflec\_12} * \pi) / (0.082 - 0.06 * \text{reflec\_12} * \pi)$
- You can also use the Edit Expression button



**Band Maths**

Target product:  
 [1] MER\_FRS\_1PPBCM20110727\_090357\_000001013105\_00036\_49188\_0274\_L2R

Name: Bb

Description: backscattering ratio at 778 nm

Unit:

Spectral wavelength: 0.0

Virtual (save expression only, don't store data)

Replace NaN and infinity results by NaN

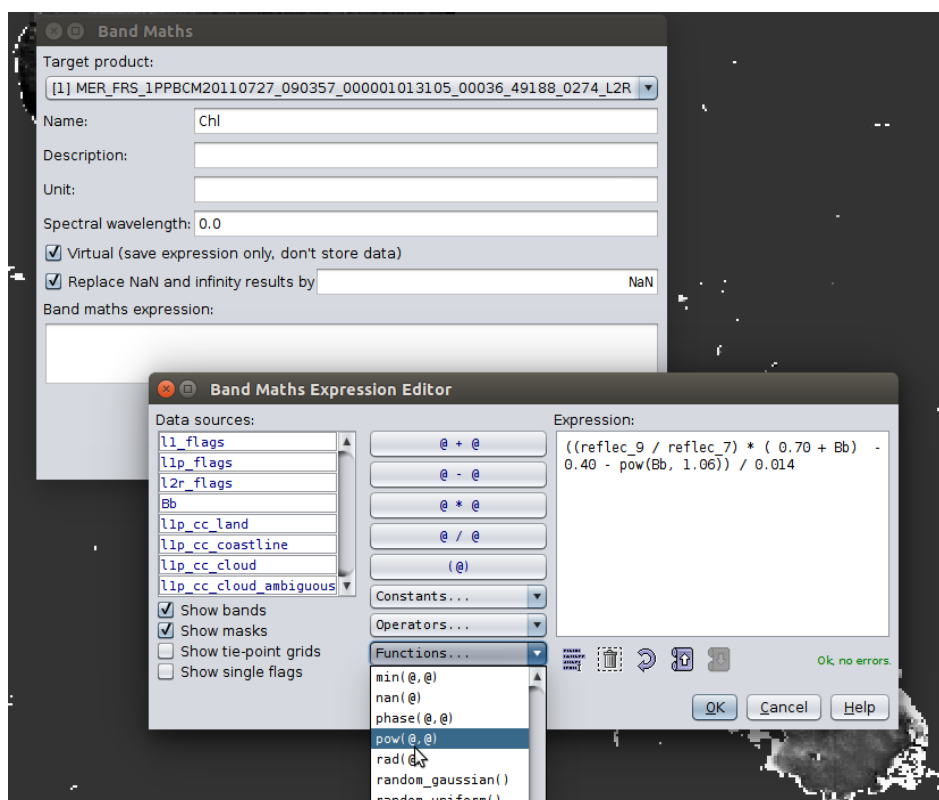
Band maths expression:  
 $1.61 * (\text{reflec\_12} * \pi) / (0.082 - 0.06 * \text{reflec\_12} * \pi)$

Edit Expression...

OK Cancel Help

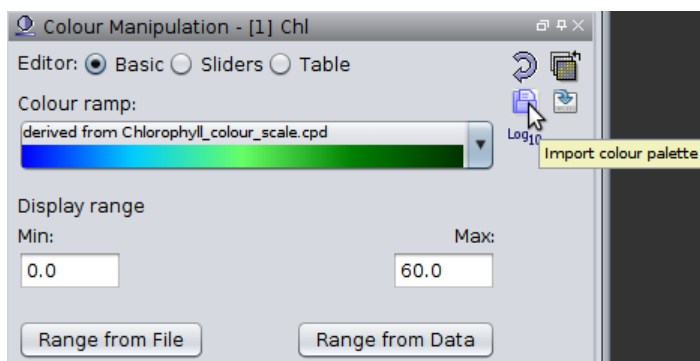
Next, create also a band for chlorophyll:

- Name: Chl
- Band math expression:  
 $((\text{reflec\_9} / \text{reflec\_7}) * (0.70 + \text{Bb}) - 0.40 - \text{pow}(\text{Bb}, 1.06)) / 0.014$



Now use a nicer colour scale:





- Colour Manipulator > Import colour palette from file (the icon with the printer) >> navigate to the additional data folder > Chlorophyll\_colour\_scale > automatically distribute points: no

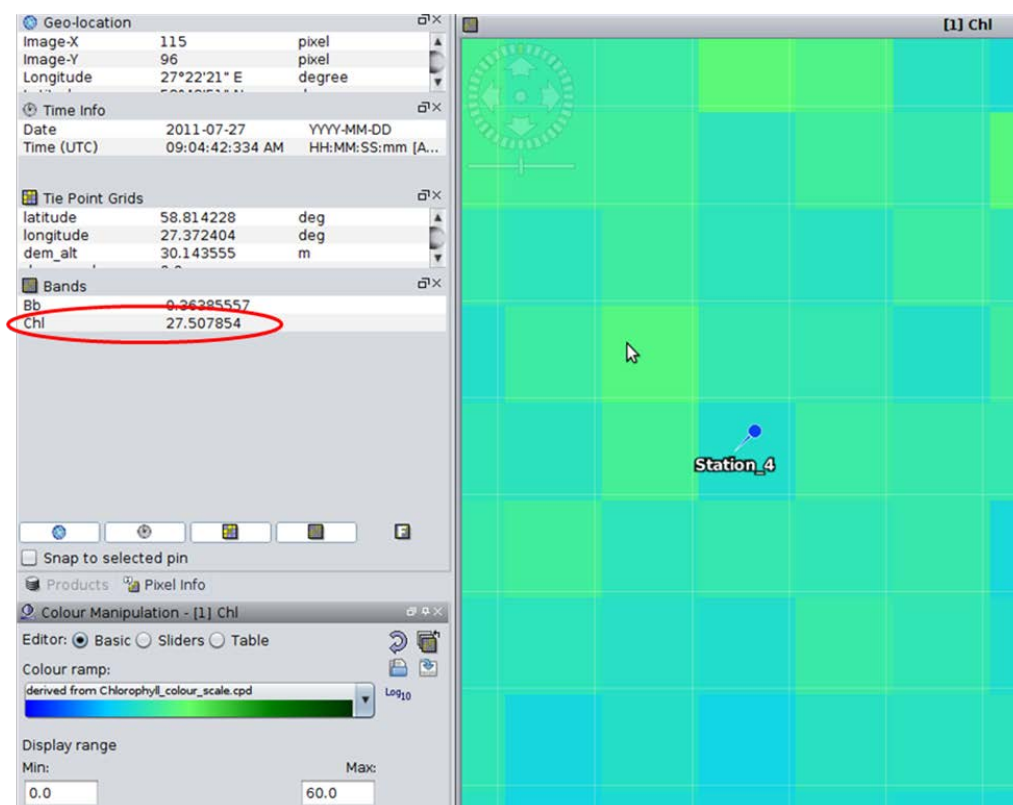


Check out the concentrations:

- Pixel info (that is the tab next to Product Explorer)
- Move around over the image to read the concentrations:
  - Can you still see the spatial patterns that were visible in the L1 RGB view?
  - What is the general difference between the northern part of the lake (Peipsi s.s.) and the southern part (Pihkva)?
  - Are the concentrations at the north-western coastal area of the northern part of the lake (Peipsi s.s.) higher or lower than in other parts of the lake? Does this make sense?

We can also validate the retrieved Chlorophyll-a concentrations by extracting the concentration data for the pixels at the in situ stations and comparing them with the Chlorophyll concentrations that were measured in situ (sampling+laboratory).

- Open the Pin Manager (  ) and click-hold-drag the window to a convenient location
- Import (  ) the in situ station locations (File: In\_situ\_locations.placemark) > open
- Select the funnel icon (  ) >> select the Chl band (scroll down) > OK
- Export the data (  ) to a text file and call it Exported\_concentration\_data.txt)
- Open the file In\_situ\_concentration\_data.xls in year spreadsheet program.
- Open the Exported\_reflectance\_data.txt in your spreadsheet program, which will lead you through an import function. >> select “separated by tab” .
- Now create a scatterplot with the L2 MERIS Chl data versus the in situ chlorophyll data.
- *How did the concentration retrieval perform?*
- *If you zoom in on the calculated chlorophyll band and check the ‘Pixel info’ tab, can you explain the results?*



- Close all products you have open before continuing with the extra analysis (File > Close All Products)

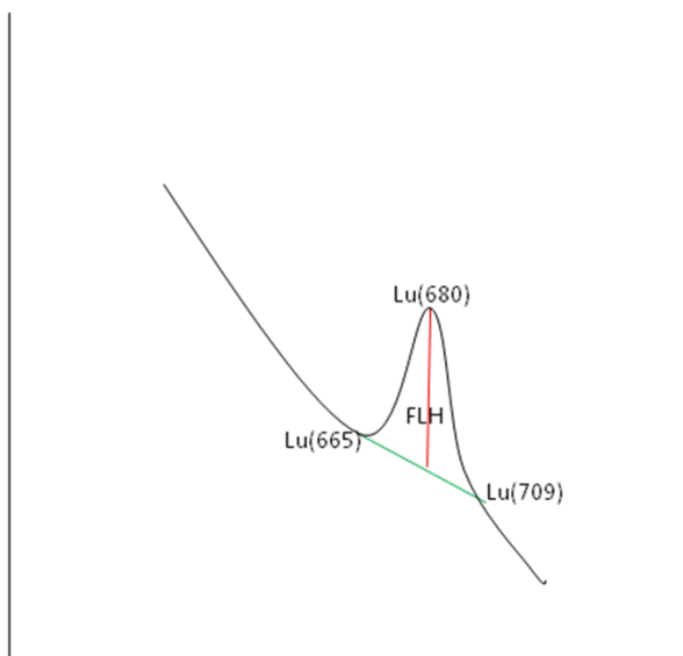
### Part 3 Extra analysis

Another method to information on phytoplankton blooms and check for the presence of cyanobacteria is the Fluorescence Line Height (FLH) method. This algorithm can be used on TOA reflectance data, so there is no need for a functional atmospheric correction. It does not deliver concentrations, but an 'index' value.

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

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. Therefore, the Chl-a signal must be strong enough. According to Palmer et al. (2015), it is especially suitable to those lakes where Chl-a concentration is  $>10 \text{ mg/m}^3$ . 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 (Palmer et al. 2015).



#### Calculation of FLH

- Because this algorithm uses TOA data, first to open a L1 image of 27 July 2011. This can either be the original .N1 image or the subset you created in the first steps of the exercise.

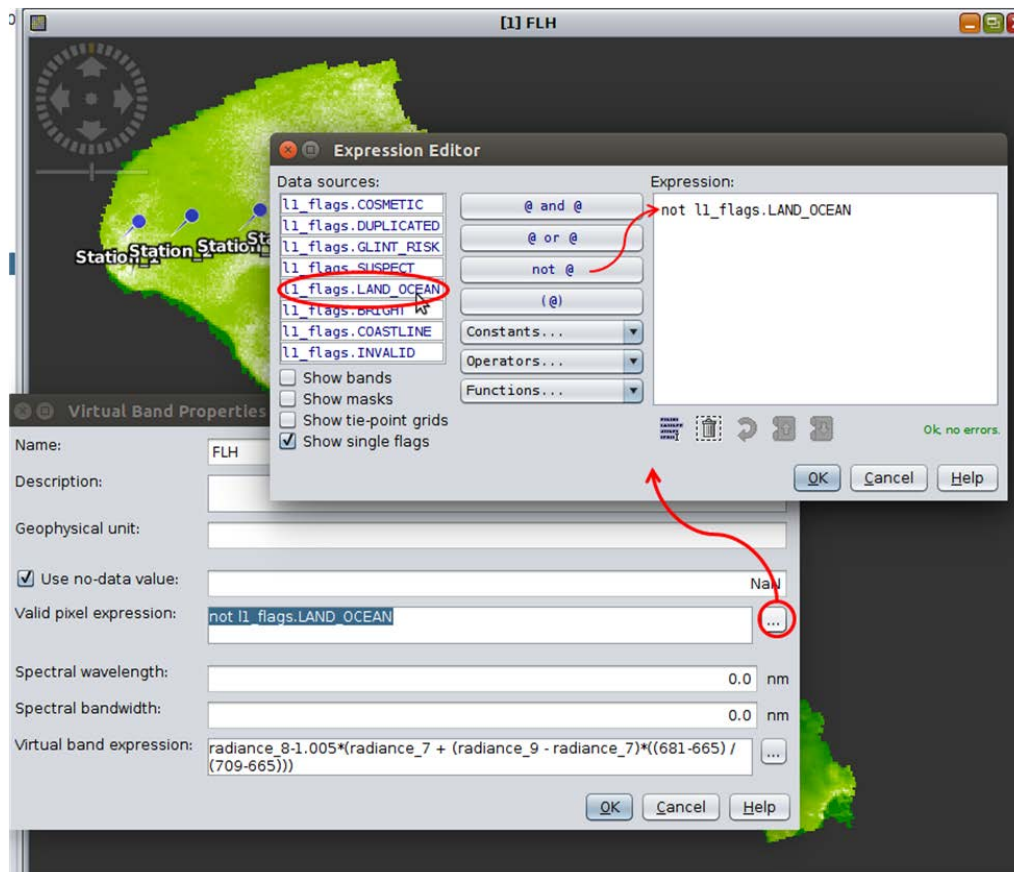
Next, process an image with FLH and analyse the results:

- Raster > Band maths (or, if you use BEAM: Utilities > Create Band from Math Expression)
- Name: FLH
- Band math expression:  $\text{radiance\_8} - 1.005 * (\text{radiance\_7} + (\text{radiance\_9} - \text{radiance\_7}) * ((681 - 665) / (709 - 665)))$  and click OK to calculate
- If it does not open automatically, open de FLHG band by double clicking it in the 'Product Manager'.

- Apply the FLH colour scale (Colour Manipulator > 'file' symbol to import colour scale from file, select the FLH scale from the folder 'additional data')

You will see that also for the land FLH values are calculated. To remove the land:

- Right-click the FLH band in the 'Product Manager' > Properties > fill out the valid pixel expression by clicking on the button with three dots (see image below): `not l1_flags.LAND_OCEAN`



- Compare the patterns in the FLH band you just calculated with the Chl band calculated via the Gons method

You can also extract the FLH values with the Chl in situ data (using the Pin Manager, methods see earlier in this exercise).



## 4 More information and further reading

This lesson is based on the following report:

- GLaSS Deliverable 5.2, 2015. Global Lakes Sentinel Services, D5.2: Shallow lakes with high eutrophication and potentially toxic algae. TO, SYKE, WI, CNR, BC, VU/VUmc. Available via: [www.glass-project.eu/downloads](http://www.glass-project.eu/downloads)

The report is suggested for further reading. It contains processed data for several years for Lake Peipsi (time series), but also for these shallow eutrophic lakes:

- Tuusulanjärvi (Finland)
- Ülemiste (Estonia)
- IJsselmeer, Paterswoldsemeer and Westeinderplassen (Netherlands)
- Müggelsee (Germany)
- Trasimeno (Italy)

For more information on GLaSS, and to download all public reports: [www.glass-project.eu](http://www.glass-project.eu).

## References

- Backer, L.C., Manassaram-Baptiste, D., LePrell, R. & B. Bolton. 2015. Cyanobacteria and Algae Blooms: Review of Health and Environmental Data from the Harmful Algal Bloom-Related Illness Surveillance System (HABISS) 2007–2011. *Toxins* 7: 1048-1064. doi:10.3390/toxins7041048
- Buhvestova, O., K. Kangur, M. Haldna & T. Möls. 2011. Nitrogen and phosphorus in Estonian rivers discharging into Lake Peipsi: estimation of loads and seasonal and spatial distribution of concentrations. *Estonian Journal of Ecology* 60: 18-38.
- Charmicael, W.W. 2001. Health-effects of toxin producing cyanobacteria: “The CyanoHABs”. *Human and Ecological Risk Assessment International Journal*, 7: 1393-1407.
- Codd, G., S. Azevedo, S. Bagchi, M. Burch, W. Carmichael, W. Harding, K. Kaya & H. Utkilen. 2005a. *CYANONET: A Global Network for Cyanobacterial Bloom and Toxin Risk Management. Initial Situation Assessment and Recommendations*. International Hydrological Programme (IHP) of the United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris: 1–5.
- Codd, G. A., J.Lindsay, F. M. Young, L. F. Morrison & J. S. Metcalf. 2005b. Harmful cyanobacterial. From mass mortalities to management measures. In (Eds. J. Huisman, H. C.P. Matthijs, P.M. Visser) *Harmful Cyanobacteria*. Springer.1-25
- Cooke, G.D., E. B. Welch, S. A. Peterson, S. A. Nichols. 2005. *Restoration and Management of Lakes and Reservoirs*. 3<sup>rd</sup> edition. Taylor & Francis. 616 pg.
- Eleveld, M. A. 2012. Wind-induced resuspension in a shallow lake from Medium Resolution Imaging Spectrometer (MERIS) full-resolution reflectances. *Water Resources Research*, 48, W04508, doi: 10.1029/2011WR011121.
- Elser, J. J., M. E. Bracken, E. E. Cleland, D. S. Gruner, W. S. Harpole, H. Hillebrand, J. T. Ngai, E. W. Seabloom, J. B. Shurin & J. E. Smith. 2007. Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. *Ecology Letters* 10: 1135–1142.
- Glibert, P. M., S. Seitzinger, C. A. Heil, J. M. Burkholder, M. W. Parrow & L. A. Codispoti. 2005. The role of eutrophication in the global proliferation of harmful algal blooms. New perspectives and approaches. *Oceanography* 18: 198-209.
- GLaSS Deliverable 3.2, 2014. Global Lakes Sentinel Services, D3.2 Harmonized atmospheric correction method. EOMAP, WI, BC, CNR, SYKE, TO, VU/VUmc. Available via: [www.glass-project.eu/downloads](http://www.glass-project.eu/downloads)
- GLaSS Deliverable 5.2, 2015. Global Lakes Sentinel Services, D5.2: Shallow lakes with high eutrophication and potentially toxic algae. TO, SYKE, WI, CNR, BC, VU/VUmc. Available via: [www.glass-project.eu/downloads](http://www.glass-project.eu/downloads)
- Gons, H.J., Rijkeboer, M., & Ruddick, K.G. “Effect of a waveband shift on chlorophyll retrieval from MERIS imagery of inland and coastal waters”. *J. Phytopl. Res.* 27, 125-127 (2005).
- Hallegraef, G. M. 2003. Harmful algal blooms. A global review. In G. M. Hallegraef, D. M. Anderson, & A. D. Cembella, eds. *Manual on harmful microalgae*. UNESCO, pp. 1-22.
- Havens, K. E. 2007. Cyanobacteria blooms: effects on aquatic ecosystems. In H. Kenneth Hudnell (ed.): *Proceedings of the Interagency, International Symposium on Cyanobacterial Harmful Algal Blooms. Advances in Experimental Medicine & Biology*, 745-759.
- Hogfors, H., N.H. Motwani, S. Hajdu, R. El-Shehawy, T. Holmborn, A. Vehmaa, J. Engström-Öst, A. Brutemark & E. Gorokhova. 2014. Bloom-forming cyanobacteria

- support copepod reproduction and development in the Baltic Sea. *PLoS One*, e112692.
- Hommersom, 2010. "Dense Water" and "Fluid Sand". Optical properties and methods for remote sensing of the extremely turbid Wadden Sea. Thesis, 170 pp. Available via <http://dare.uvu.vu.nl/handle/1871/15939>
  - Horwath, H., A.W. Kovacs, C. Riddick & M. Presing. 2013. Extraction methods for phycocyanin determination in freshwater filamentous cyanobacteria and their application in shallow lake. *European Journal of Phycology* 48: 278-286.
  - Hudnell, H. K., Q. Dortch & H. Zenick. 2008. Theoretical framework for Cyanobacterial Harmful Algal Blooms. (Ed. Hudnell, H.K.) Cyanobacterial Harmful Algal Blooms: State of the Science and Research Needs. *Advances in Experimental Medicine and Biology* 619: 4-16.
  - Hudnell, H. K. & Q. Dortch. 2008. A synopsis of research needs identified at the Interagency, International Symposium on Cyanobacterial Harmful Algal Blooms. Ecosystem sustainability. (Ed. Hudnell, H.K.) Cyanobacterial Harmful Algal Blooms: State of the Science and Research Needs. *Advances in Experimental Medicine and Biology* 619: 31-32.
  - Jaani, A. 2001. The location, size and general characterisation of Lake Peipsi and its catchment area. In: Lake Peipsi: Meteorology, Hydrology, and Hydrochemistry. (Ed. T. Nõges), pp. 10-17. Sulemees Publishers, Tartu.
  - Kangur, K., A. Kangur, P. Kangur & R. Laugaste. 2005. Fish kill in Lake Peipsi in summer 2002 as a synergistic effect of a cyanobacterial bloom, high temperature, and low water level. *Proc. Estonian Acad. Sci. Biol. Ecol.* 54: 67–80.
  - Kangur, K., Y.-S. Park, A. Kangur, P. Kangur & S. Lek. 2007. Patterning long-term changes of fish community in large shallow Lake Peipsi. *Ecological Modelling* 203: 34–44.
  - Kangur, K., P. Kangur, K. Ginter, K. Orru, M. Haldna, T. Möls & A. Kangur. 2013. Long-term effects of extreme weather events and eutrophication on the fish community of shallow Lake Peipsi (Estonia/Russia). *Journal of Limnology* 72: 376 - 387.
  - Kangur, K. & T. Möls. 2008. Changes in spatial distribution of phosphorus and nitrogen in the large north-temperate lowland Lake Peipsi (Estonia/Russia). *Hydrobiologia* 599: 31-39.
  - Karlson, A.M.L., Duberg, J., Motwani, N.H., Hogfors, H., Klawonn, I., Ploug, H., Svedén, J.B., Garbaras, A., Sundelin, B., Hajdu, S., Larsson, U., Elmgren, R., Gorokhova, E., 2015. Nitrogen fixation by cyanobacteria stimulates production in Baltic food webs. *Ambio*. 44(Suppl 3): 413–426. doi: 10.1007/s13280-015-0660-x
  - Kudela, R. M., S. L. Palacios, D. C. Austerberry, E. K. Accorsi, L. S. Guild & J. Torres-Perez. 2015. Application of hyperspectral remote sensing to cyanobacterial blooms in inland waters. *Remote Sensing of Environment*, <http://dx.doi.org/10.1016/j.rse.2015.01.025>
  - Kullus, L. 1964. Peipsi-Pihkva järve uurimisest ajavahemikul 1850-1917. Rmt. *Eesti Geograafia Seltsi Aastaraamat* 1963, Tallinn, 148-158. (In Estonian)
  - Kutser, T. 2009. Passive optical remote sensing of cyanobacteria and other intense phytoplankton blooms in coastal and inland waters. *International Journal of Remote Sensing* 30: 4401 - 4425.
  - Laugaste, R., J. Haberman, T. Krause & J. Salujõe. 2007. Significant changes in phyto- and zooplankton in Lake Peipsi in recent years: what is the underlying reason? *Proc. Est. Acad. Sci., Biol., Ecol.* 56: 106 - 123.
  - Likens, G. E. 1972. Nutrient limitation. *Limnology and Oceanography*, Special Volume 2.

- Loigu, E., Ü. Leisk, A. Iital & K. Pachel. 2008. Pollution load and water quality of the L: Peipsi basin. In: *Peipsi*. (Eds. J.Haberman, T. Timm & A. Raukas), pp. 179-199. Eesti Loodusfoto, Tartu.
- Luigujõe, L., A. Kuresoo, M. Van Eerden & V. Borissov. 2008. Peipsi linnustik (Birds of Lake Peipsi). *Peipsi*. Toim. K. Hein. Eesti Loodusfoto, 341-364. In Estonian.
- Macario, I. P. E., B. B. Castro, M. I. S. Nunes, S.C. Anutnes, C. Pizarro, C. Coelho, F. Gonçalves & de D. R. Figueiredo. 2015. New insights towards the establishment of phycocyanin concentration thresholds considering species-specific variability of bloom-forming cyanobacteria. *Hydrobiologia*, DOI 10.1007/s10750-015-2248-7.
- Mazur, H. & M. Plinski. 2003. *Nodularia spumigena* blooms and the occurrence of hepatotoxin in the Gulf of Gdansk. *Oceanologia* 45: 305-316.
- Merel, S., D. Walker, R. Chicana, S. Snyder, E. Baure`s & O. Thomas. 2013. State of knowledge and concerns on cyanobacterial blooms and cyanotoxins. *Environment International* 59: 303–327.
- Mishra, S. and Mishra, D.R. (2014). A novel remote sensing algorithm to quantify phycocyanin in cyanobacterial algalblooms, *Environmental Research Letters*, 9 (11), DOI:10.1088/1748-9326/9/11/114003
- Moss, B. 2012. Cogs in the endless machine: lakes, climate change and nutrient cycles: a review. *Science of the Total Environment* 434: 130-132.
- Müller, S. & S. M. Mitrovic. 2015. Phytoplankton co-limitation by nitrogen and phosphorus in a shallow reservoir: progressing from the phosphorus limitation paradigm. *Hydrobiologia*, 744: 255-269.
- National Research Council, 2011. Assessing the Requirements for Sustained Ocean Color Research and Operations. By: Committee on Assessing Requirements for Sustained Ocean Color Research and Operations, Ocean Studies Board, Space Studies Board, Division on Earth and Life Studies, Division on Engineering and Physical Sciences. National Academies Press, USA. ISBN 0309210445
- Oliver, R. L. & G. G. Ganf. 2002. Freshwater blooms. In: *The ecology of Cyanobacteria-Their diversity in time and space* (Eds. B.A. Whitton & M. Potts) 149-194. Kluwer Academic Publishers. New York, Boston, Dordrecht, London, Moscow.
- Orru, K., K. Kangur, P. Kangur, K. Ginter, K. & A. Kangur. 2014. Recreational ice fishing on the large Lake Peipsi: socioeconomic importance, variability of ice-cover period, and possible implications for fish stocks. *Estonian Journal of Ecology* 63: 282 - 298.
- Paerl, H. W. 2002. Marine plankton. In: *The ecology of Cyanobacteria. Their diversity in time and space* (Eds. B.A. Whitton & M. Potts) 149-194. Kluwer Academic Publishers. New York, Boston, Dordrecht, London, Moscow.
- Pearl, H. W. & J. Huisman. 2008. Blooms Like It Hot. *Science* 320: 57-58.
- Paerl, H. W. 2009. Controlling eutrophication along the freshwater–marine continuum: dual nutrient (N and P) reductions are essential. *Estuar. Coast. Shelf Sci.* 32: 593–601.
- Paerl, H. W. & J. Huisman 2009. Climate change: a catalyst for global expansion of harmful cyanobacterial blooms. *Environ. Microbiol. Rep.* 1: 27–37.
- Paerl, H.W., H. Xu, M. J. McCarthy, G. Zhu, B. Qin, Y. Li & W. S. Gardner. 2011. Controlling harmful cyanobacterial blooms in a hyper-eutrophic lake (Lake Taihu, China): The need for a dual nutrient (N & P) management strategy. *Water Research*, 45: 1973–1983.
- Paerl, H. W. & T. G. Otten. 2013. Harmful cyanobacterial blooms: causes, consequences, and controls. *Microb. Ecol.* 65, 995–1010.
- Schindler, D. W., R. E. Hecky, D. L. Findlay, M. P. Stainton, B. R. Parker, M. J.

- Paterson, K. G. Beaty, M. Lyng & S. E. M. Kasian. 2008. Eutrophication of lakes cannot be controlled by reducing nitrogen input: results of a 37-year whole-ecosystem experiment. *Proceedings of the National Academy of Sciences of the United States of America* 105: 11254–11258.
- Smith, V. A. & D. W. Schindler. 2009. Eutrophication science: where do we go from here? *Trends in Ecology and Evolution* 24: 201-207.
  - Steffen, M. M., B. S. Belisle, S. B. Watson, G. L., Boyer & S. W. Wilhelm. 2014. Status, causes and controls of cyanobacterial blooms in Lake Erie. *Journal of Great Lakes Research* 40: 215–225.
  - Steffensen, D. A. 2008. Economic cost of cyanobacterial blooms. In: Cyanobacterial Harmful Algal Blooms: State of the Science and Research Needs. *Advances in Experimental Medicine and Biology* 619: 855-865.
  - Sterner, R. W. 2008. On the phosphorus limitation paradigm for lakes. *International Review of Hydrobiology* 93: 433–445.
  - Stumpf, R. P., T. T. Wynne, D. B. Baker & G. L. Fahnenstiel. 2012. Interannual variability of cyanobacterial blooms in Lake Erie. *PLoS ONE* 7, e42444.
  - Waples, J. T., B. Eadie, J. V. Klump, M. Squires, J. Cotner & G. Mckinley. 2008. The Laurentian Great Lakes, p. 110. In: B. Hales, Cai, W., Mitchell, G., Sabine, C.L., Schofield, O. [ed.], *North American Continental Margins: A Synthesis and Planning Workshop. U.S. Carbon Cycle Science Program*
  - WHO, 2003. Chapter 8, Algae and cyanobacteria in fresh water. In: Guidelines for safe recreational water environments. Volume 1: Coastal and fresh waters. Authors: World Health Organization. 253pp. Available via: [www.who.int/water\\_sanitation\\_health/bathing/srwe1/en](http://www.who.int/water_sanitation_health/bathing/srwe1/en)
  - Xu, S., B. Huang, Z. B. Wei, J. Luo, A. J. Miao & L.-Y. Yang. 2013. Seasonal variation of phytoplankton nutrient limitation in Lake Taihu, China: a monthly study from year 2011 to 2012. *Ecotoxicology and Environmental Safety* 94: 190–196.
  - Zhang, F., J. Lee, S. Liang & C. K. Shum. 2015. Cyanobacteria blooms and non-alcoholic liver disease: evidence from a county level ecological study in the United States. *Environmental Health* 14: 41, doi: 10.1186/s12940-015-0026-7.
  - Zhu, W., Q. Yu, Y. Q. Tian, B. L. Becker, T. Zheng & H. J. Carric. 2014. An assessment of remote sensing algorithms for colored dissolved organic matter in complex freshwater environments. *Remote Sensing of Environment* 140: 766-778.
  - Znachor, P., T. Jurczak, J. Komarková, J. Jezberová, J. Mankiewicz, K. Kaštovská & E. Zapomělová. 2006. Summer changes in cyanobacterial bloom composition and microcystin concentration in eutrophic Czech reservoirs. *Environmental Toxicology* 21: 236-243.

## Colophon

### Global Lakes Sentinel Services

GLaSS is funded by the European Commission (FP7)

Grant number 313256

## GLaSS Training material, Lesson #3

### Eutrophic lakes

What is the spatial distribution of water quality parameters over Lake Peipsi?

Evelin Kangro (TO), Kersti Kangro (TO), Elar Asuküll (TO), Annelies Hommersom (WI)

2016

#### GLaSS Consortium

No	Name	Short Name
1	WATER INSIGHT BV	WI
2	SUOMEN YMPARISTOKESKUS	SYKE
3	EOMAP GmbH & Co.KG	EOMAP
4	STICHTING VU-VUMC	VU/VUmc
5	BROCKMANN CONSULT GMBH	BC
6	CONSIGLIO NAZIONALE DELLE RICERCHE	CNR
7	TARTU OBSERVATORY	TO
8	BROCKMANN GEOMATICS SWEDEN AB	BG