



BROCKMANN GEOMATICS  
SWEDEN AB



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## ESA DUE DIVERSITY II

Supporting the Convention on  
Biological Diversity

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## Products User Handbook - Inland Waters

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## Table of Contents

1	Introduction.....	4
2	Input Data and Intermediate Products .....	5
2.1	Auxiliary Data.....	6
2.2	Level 1 Data .....	6
2.3	Level 2 Products.....	7
2.4	Level 3 Products.....	8
3	Product Description.....	8
3.1	Scope of the Inland Water Products .....	8
3.1.1	Spatio-Temporal Coverage .....	8
3.1.2	Lake Perimeter Definition .....	11
3.1.3	Product Aggregation and Number of Observations .....	11
3.2	Product Content .....	13
3.2.1	Eutrophication Indicators .....	13
3.2.2	Physical Disturbance and Contamination Indicators.....	14
3.2.3	Ecosystem Indicators .....	15
3.2.4	Metadata Layers .....	16
3.3	Metadata .....	17
3.3.1	SAR-WB Shapefiles.....	17
3.3.2	Auxiliary Data Table and GLWD Attribute Data.....	17
3.4	Projection.....	18
4	How to use the Diversity II products.....	18
4.1	Obtain Products.....	18
4.1.1	Single file download using a web browser .....	18
4.1.2	Bulk download using an FTP client .....	18
4.1.3	Unzip Products.....	18
4.2	View products.....	19
4.3	Display and Analysis Tools .....	20
4.3.1	Quality Assessment with map_products.py .....	21
4.3.2	Re-binning with the BEAM L3 Binner.....	22
4.3.3	Recalibration with BEAM band arithmetic .....	23
4.3.4	Spatial Averaging using extract_stats.py .....	24
4.3.5	Plotting Time Series with plot_timeseries.py .....	25
5	Indicator Validation and Assessment.....	27
5.1	Indicator Validation .....	27



5.2	Assessment of Indicators as Biodiversity Proxies.....	29
5.2.1	Biodiversity Status Analyses across Lakes .....	29
5.2.2	Biodiversity Trend Analyses, Lake Michigan.....	30
5.2.3	Biodiversity Trend Analyses, Lake Nicaragua .....	32
6	Issues and Limitations .....	34
6.1	Product Properties and Indicator Accuracy.....	34
6.1.1	Melting Spring Ice .....	34
6.1.2	Lake Perimeter Inconsistencies .....	34
6.2	Suitability as Biodiversity Proxies .....	35
6.2.1	Status .....	35
6.2.2	Trend.....	36
7	Biodiversity Stories.....	37
8	Synthesis.....	37
9	References.....	38

# Diversity II Products User Handbook - Inland Waters

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## 1 Introduction

The objective of the Diversity II project is to support the assessment and monitoring of the Aichi 2020 Biodiversity Targets of the CBD for drylands and inland waters, by providing for key parameters to indicate biodiversity statuses and trends. For inland waters these key parameters correspond to the quantity and quality of freshwater. The former is provided in terms of water level variability. The latter includes water constituents such as chlorophyll- $\alpha$  and suspended matter concentration, as well as surface water temperature. The design of all indicators follows requirements expressed during two workshops and summarized in the Diversity II Requirements Baseline document (RB, Wramner et al., 2015).

Spaceborne Earth observation satellite data and in particular ESA's ENVISAT is the primary data source for Diversity II. Optical, thermal and microwave (Radar, SAR) measurements by several different instruments onboard ENVISAT (MERIS, AATSR, RA-2 and ASAR) are used. All data was processed using scientifically sound, globally consistent and reproducible methods. The bulk reprocessed MERIS full resolution (FR) dataset became available in the course of the project, and approximately 300'000 reprocessed MERIS FR images were used to derive the first decade-long global inland water quality archive in the world. Technical and scientific background will be provided in the project's Algorithm Theoretical Basis Document by the end of the project.

Diversity II inland water products are provided for more than 300 large perennial lakes, lagoons and reservoirs and covering the period from 2002 to 2012. Inland water bodies were selected to represent high levels of biodiversity, consist of a wide bio-geographical variety and provide global representativeness. Pilot studies carried out in the scope of Diversity II demonstrate the application of remotely sensed indicators for eutrophication and hypoxia or floating vegetation proliferation, for lake-specific relations to fish abundance and community composition. The analyses are described in the Diversity II Products Quality Report (Brito et al., 2015) and as part of the Biodiversity Stories (see Section 7).

Diversity II was a two-year project funded by the Data User Element component of ESA's Earth Observation Envelope Programme (EOEP). It was carried out by Brockmann Consult GmbH (Germany), Geoville GmbH (Austria), Brockmann Geomatics (Sweden) and CIBIO (Portugal) and completed in 2015.

## 2 Input Data and Intermediate Products

The Diversity II water quality products are output of the CalLimnos processing chain depicted in Figure 1. Coloured elements are briefly explained in Sections 2.1 to 2.4, or in Section 3 as far as final outputs are concerned.

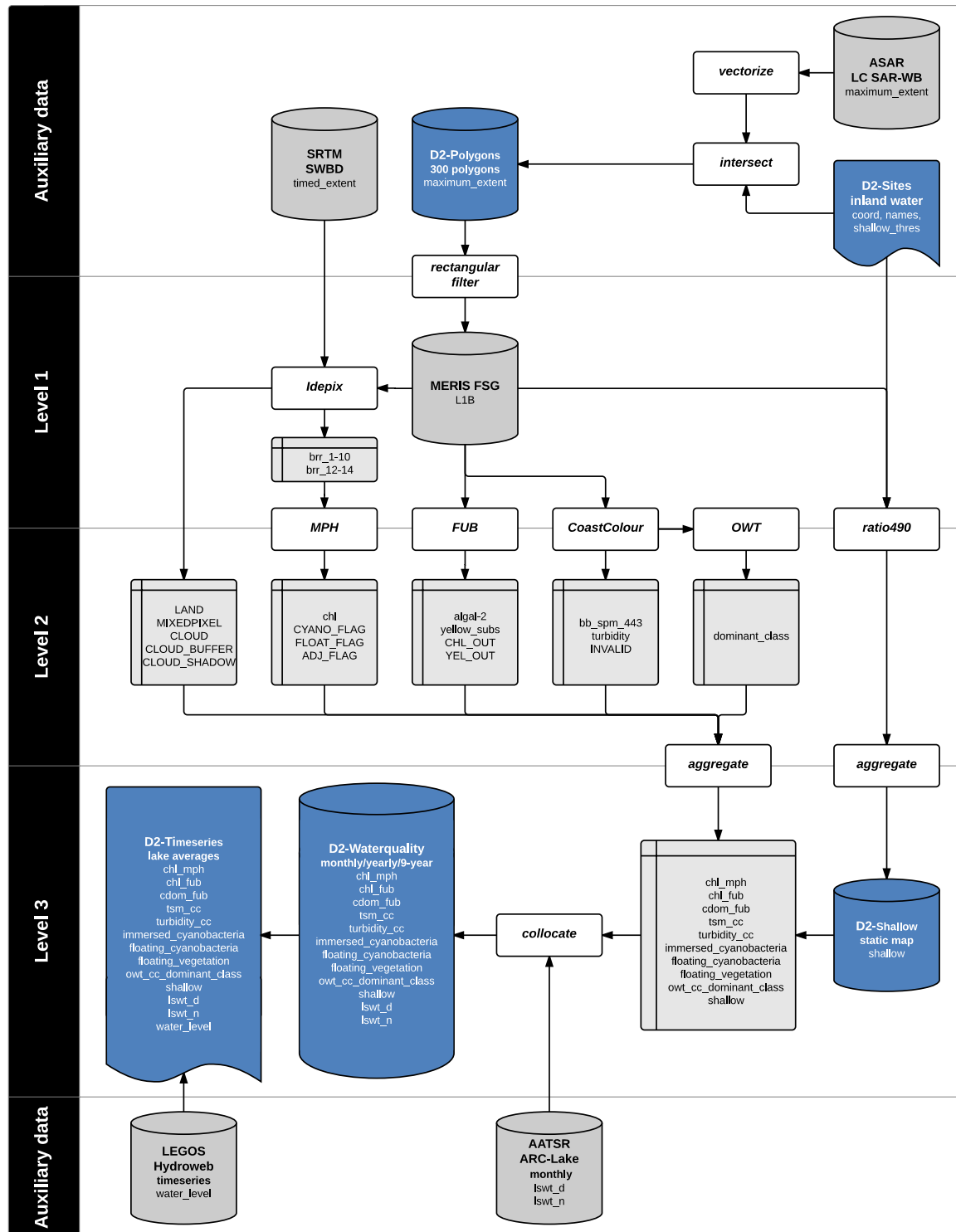


Figure 1: Callimnos inland water processing flow chart as applied for Diversity II. Grey databases indicate input data, light grey indicates intermediate products, white rectangles indicate processing tasks, provided output is in blue.

## 2.1 Auxiliary Data

The SAR Water Bodies (SAR-WB) map is derived from Envisat ASAR Wide Swath Mode (WSM) backscatter time series. A classification of pure water and land pixels is done from the time series' minimum and mean annual variability. Some ambiguity occurs in case of mixed pixels, but e.g. an overall accuracy of 98% in comparison with the CORINE landcover map is achieved (Santoro & Wegmüller, 2012). A manually rectified dataset is available in 300 m resolution and geotiff format. The data represents the maximum extent of water available from ASAR acquisitions between 2002-2012. It is used to define individual lake perimeters.

The SRTM Water Body data set (SWBD) is a high-resolution worldwide coastline and lakes outline dataset in vector format, divided into 12229 files, each covering a tile of 1° x 1°. The data represents the instantaneous water extent during the SRTM acquisition campaign in February 2000. Per definition, lakes greater than 600m minimum length and 183m minimum width are included. The data is available between -56°S and 60° N. Within that range, it is used for improved land/water identification by the Idepix algorithm. Outside that range, the original MERIS L1B flags are used.

AATSR derived lake surface water temperature (LSWT) is adopted from the ESA ARCLake project database. A variety of product types are provided, including different processing techniques, spatial and temporal aggregations. Product description is available in McCallum and Merchant (2011). Algorithm specifications and validation results can be found in McCallum & Merchant (2010; 2007). DINEOF reconstructed, day- and night-time acquired monthly products are used, namely the files ALIDXXXX\_PLREC9D\_TS012SR.nc and ALIDXXXX\_PLREC9N\_TS012SR.nc.

Water level estimates from RA-2 and other satellite altimeter sensors are adopted from the LEGOS Hydroweb database. They are retrieved from individual pulses along the satellite orbit and without spatial resolution. Hydroweb supplies quality controlled products for several hundred lakes in the world, and is currently deploying a near-real time service. Diversity II redistributes all Hydroweb water level products archived for the relevant period between 2002-2012 (ENVISAT operations).

## 2.2 Level 1 Data

Level 1 data refers to top-of-atmosphere radiance MERIS data prior to atmospheric correction. The MERIS full resolution data used in Diversity II is available as FSG (full swath geo-corrected), which means that it comes with enhanced AMORGOS (Accurate MERIS Ortho-Rectified Geolocation Operational Software) geolocation information (latitude, longitude, altitude). For each MERIS detector and each acquisition time AMORGOS-FSG applies precompiled geolocation information to the corresponding MERIS L1B product pixels. It must be noted here that since the MERIS product grid is filled by a nearest neighbour method from the instrument acquisition grid with a slight spatial over-sampling, the same instrument sample can be found several times in the same Level 1B product (it is then identified as a DUPLICATE pixel within the Level 1B product flags). Since the additional geolocation information of the MER\_FSG product is linked to the source Instrument sample, it will be duplicated in the same way as the radiance information.

MERIS standard processing algorithms were continuously revised during ENVISAT operations, including an improving degradation model of the calibration diffuser, which results in modified gain values per detector. The reduced resolution archive was periodically reprocessed (Barker, Lavender, & Ramon, 2011). Bulk reprocessing of the full resolution archive was however only facilitated in 2014, making available the enhanced radiometric calibration in time for the Diversity II inland waters production.

The Idepix tool is used to perform a composition indication for each observed pixel, and raise flags in challenging or ambiguous cases, in particular thin clouds, cloud shadows or mixed pixels. These flags replace and complement the standard flags contained in the MERIS level 1 data. The version at hand for Diversity II was developed for the CoastColour project (Ruescas, Brockmann, Stelzer, Tilstone, & Beltran, 2014).

## 2.3 Level 2 Products

Level 2 products are geophysical maps derived from individual level 1 satellite images. A wide variety of methods exist to retrieve such geophysical information from spectro-radiometric measurements, and only fully automated approaches are eligible for processing large image archives. As far as water quality parameters are concerned, most of these methods imply the removal of atmospheric effects superimposed on the water-leaving signal. The selection of suitable methods depends on the parameters to be retrieved.

The Maximum Peak Height (MPH) algorithm applies a sequence of conditional arithmetic expressions for the retrieval of intermediate to high Chlorophyll-*a* (CHL) concentrations across different optical domains (fluorescence domain, absorption and backscattering domain, floating algae domain). MERIS bands 6-10 and 14 (619, 664, 681, 709, 753, 885 nm) are used. Only a partial atmospheric correction (Bottom-of-Rayleigh, brr) is necessary as relevant peak heights in these bands are insignificantly affected by aerosol scattering. The procedure described in Matthews et al. (2012) was updated to prevent erroneous pixel identification in oligotrophic waters (Matthews & Odermatt, 2015).

The FUB algorithm consists of several individual neural networks (NN) for the retrieval of CHL (referred to as *algal\_2*), coloured dissolved organic matter (CDOM) and other quantities from TOA radiance (Schroeder, 2005; Schroeder, Schaale, & Fischer, 2007). It consists of an explicit atmospheric correction NN that retrieves AOT as well as water-leaving reflectances, however all other NN perform their own, implicit atmospheric correction. This approach is favourable for waters of low turbidity and high absorption levels, where errors introduced by a rigorous atmospheric correction frequently exceed the level of water-leaving signals.

The CoastColour algorithm retrieves atmospheric and aquatic optical properties as well as reflectance for each pixel. Two coupled neural networks account subsequently for atmospheric correction and the retrieval of optical properties from water-leaving reflectance. The algorithms retrieves inherent optical properties such as particle backscattering (*bb\_spm*), which is converted into total suspended matter (TSM) concentration units using empirical relationships. The algorithm is based on a similar architecture as the Case-2-Regional algorithm (Doerffer & Schiller, 2007), but with a significantly enhanced training range to cover high concentration ranges. CoastColour water-

leaving reflectance is further used to classify Optical Water Types (Moore, Dowell, Bradt, & Ruiz Verdu, 2014).

All level 2 products are supplemented with algorithm specific validity flags, which are used together with the Idepix flags to mask inapplicable pixels. Due to their storage space demand, level 2 products are only internally stored in CalLimnos, and removed after aggregation to level 3 products is performed.

## 2.4 Level 3 Products

Level 3 products are temporal aggregates of several collocated level 2 products that were acquired during a specific period. Aggregation is done per pixel and by means of different operators. Arithmetic mean and variance are used for gradient variables; mode is used for class variables (i.e. OWT). Monthly, yearly and decadal aggregates are provided in the Diversity II database.

For custom binning of seasonal or multiannual products, spatial aggregation of user-defined perimeters and other value-adding techniques, a suite of display and analysis tools for use with the Diversity II products is described in Section 4.3.

# 3 Product Description

## 3.1 Scope of the Inland Water Products

### 3.1.1 Spatio-Temporal Coverage

Diversity II aims to provide water quality and quantity parameters for a significant and globally representative number of inland water bodies. In the beginning, 10 sites were selected for experimental development. As a next step, an extensive validation study for water constituents, mainly chlorophyll-*a*, was performed for 50 lakes. Finally, the selected methods were applied to a total of 340 lakes, reservoirs and lagoons (Figure 2). Criteria for selection of the latter were manifold. In a first step, we identified 66 Ramsar Wetlands and LakeNet Biodiversity Priority sites with a minimum of 50 km<sup>2</sup> surface water area. Further criteria included lake size, which generally favours the application of remote sensing and accordingly the availability of water level and surface water temperature products from the Hydroweb and ARCLake database, respectively. 250 out of the 350 largest lakes in the world are included. The largest reservoirs in South America and individual sites in Asia and Australia were included in order to improve the global representativeness. The last 50 lakes were added following user requests during the course of the project.





Figure 2: The global distribution of all 340 inland waters for which geophysical data products are provided in the scope of the Diversity 2 project. The map can be browsed online at [www.goo.gl/9qES0n](http://www.goo.gl/9qES0n).

The Diversity II products are derived from and thus limited to the operational phase of ESA's ENVISAT satellite, which was launched March 1<sup>st</sup>, 2002. The last contact with ENVISAT was on April 8<sup>th</sup>, 2012. During its 10 years of operations, it had an orbit repeat cycle of 35 days until October 2010, when it was maneuvered into a lower orbit of only 30 days repeat cycle. The wide field of views of the AATSR and MERIS radiometers on board of ENVISAT allow for a temporal resolution of 3 days at equator. However, the acquisition of MERIS full-resolution images was also subject to an operational trade-off, which further reduced the acquisition frequency for certain years and geographical areas, in particular Africa in 2002 to 2004, and South America during the entire decade (Figure 3). In combination with local cloud and lake ice coverage, this pattern explains significant differences in the occurrence of product data gaps for different lakes.

The ENVISAT-AATSR-derived LSWT products adapted from ESA's ARCLake project are unaffected by the regionally constrained availability affecting MERIS products, but depend similarly on cloud-free conditions. However, since the dataset chosen for integration in the Diversity II products is a statistically interpolated derivative of individual acquisitions, gaps in the LSWT products occur only during wintertime freezing of lake surfaces. The radar altimetry products from LEGOS' Hydroweb (Crétaux et al., 2011) are derived from several instruments on satellites of different repetition cycles and are unaffected by cloud coverage, but limited predominantly by the availability of suitably located pulses along the satellites' orbit tracks.

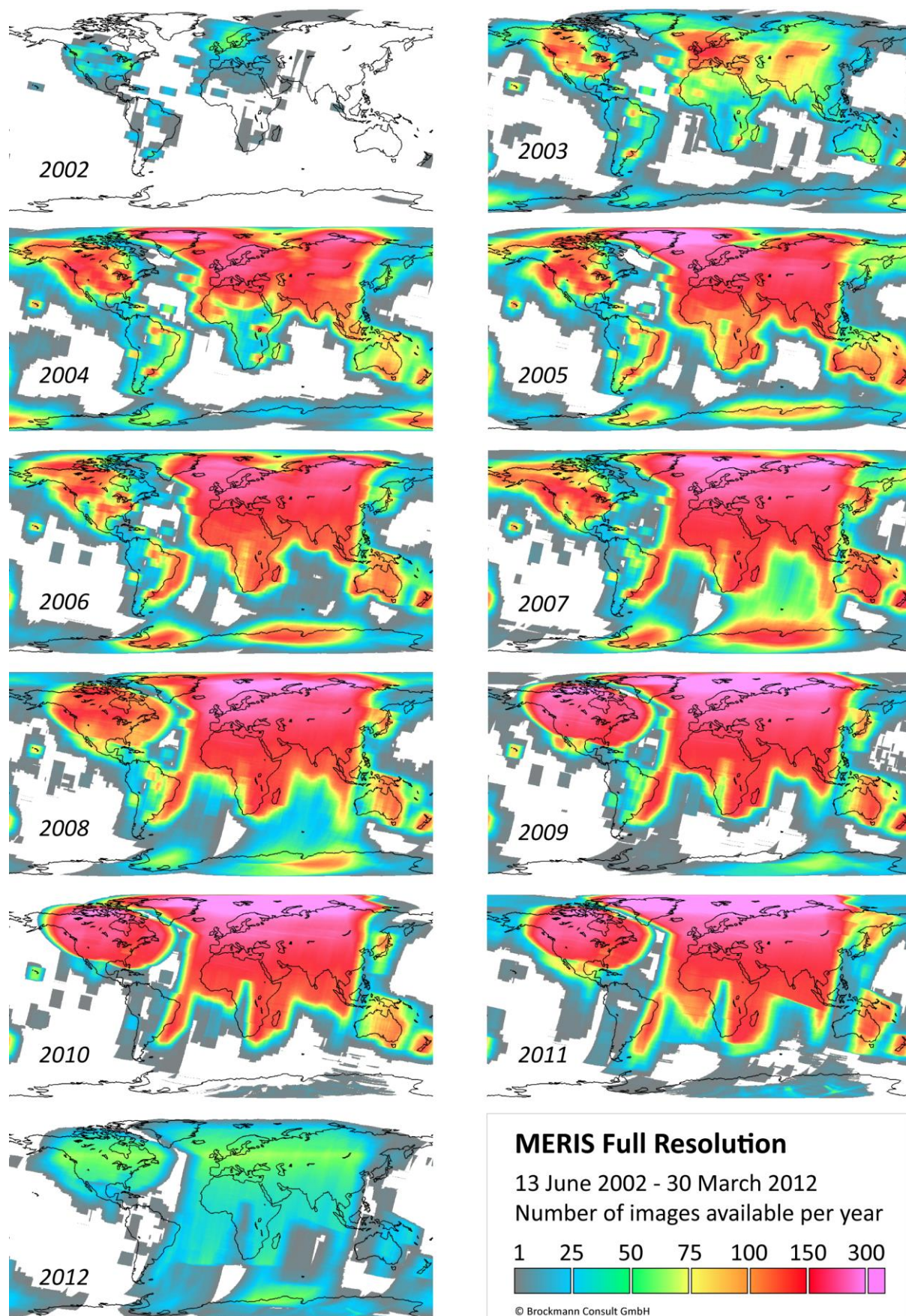


Figure 3: The global annual coverage of ENVISAT-MERIS, indicating the regional availability of all water constituent products available from Diversity II. Cloud coverage is not taken into account.



### 3.1.2 Lake Perimeter Definition

In the scope of the ESA LandCover CCI project, a global dataset of the maximum surface water extent observed during the ENVISAT operations phase was derived (Stephanie C. J. Palmer et al., accepted). The dataset has an original resolution of 300 m. It was vectorized to a shapefile, from which one polygon was extracted for each lake and saved to a lake-specific shapefile (see Section 3.3.1). Thereby, lakes that are elsewhere defined as single entities may have been separated if they comprise of several basins that are connected only by narrow straits. Contrariwise, lakes that are elsewhere considered as separate entities may have been merged where connected by a strait wider than 300 m. For lakes included in the Global Lakes and Wetlands Database (Lehner & Döll, 2004), affected lakes can be identified by comparing the area calculated for the SAR-WB polygons and the GLWD area, both included in the Diversity II metadata list (see Section 3.3.2).

### 3.1.3 Product Aggregation and Number of Observations

The water quality products are provided as monthly, yearly and 9-year aggregates (see Table 1). Shorter aggregation periods would lead to extensive data gaps in most lakes, although 10-day aggregation is feasible for an extraordinarily favourable case like Lake Balaton (S.C.J. Palmer et al., 2015). Larger aggregates are composed from smaller aggregates in order to achieve temporal representativeness, e.g. yearly means are averaged from all available monthly means because the number of valid observations in each month may vary significantly and lead to an overrepresentation of estimates from cloud free months.

When aggregating low numbers of spatially incomplete observations for periods of quickly changing conditions, the spatial patterns in aggregated products may get correspondingly patchy (Figure 4). Such cases do not represent actual spatial gradients and indicate limitations in terms of temporal resolution, but are in principle valid samples.

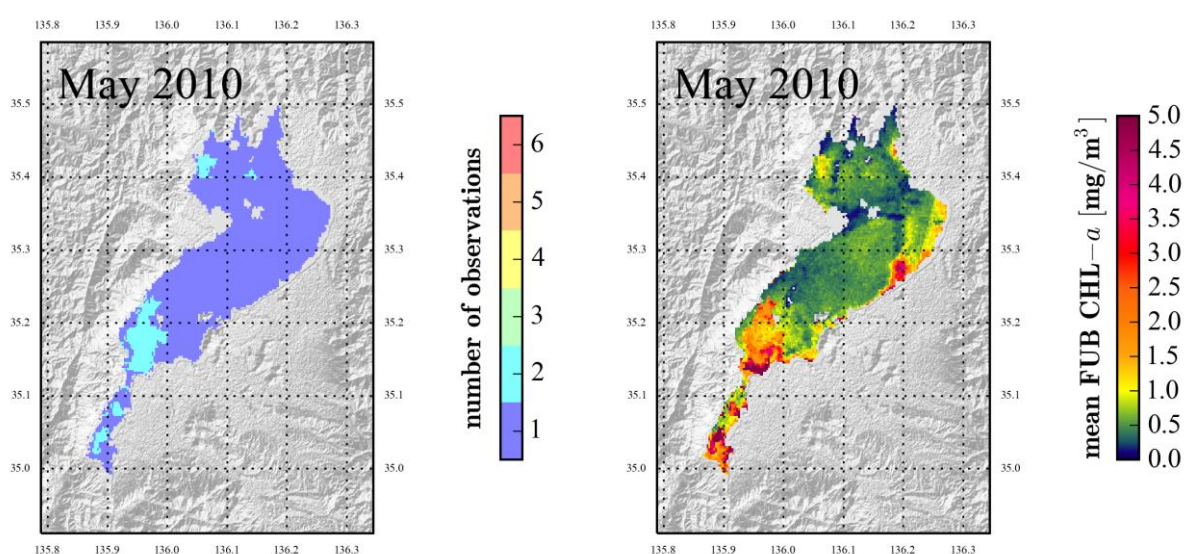


Figure 4: Only 1-2 acquisitions of Lake Biwa are available in May 2010 (left image). One image covers almost the entire lake before the onset of the phytoplankton spring bloom. The other image covers only small portions in the southwest and north of the lake during the bloom, creating a patchy monthly chlorophyll-*a* aggregate map (right image).

**Table 1: Water level, eutrophication, physical disturbance, contamination and ecosystem products available from Diversity II for inland waters, including derivatives which are facilitated using dedicated software tools and user-defined ROI shapefiles to set *region* <r> according to Section 3.1.2.**

Map/Indicator	Source	Description	Resolution	Format
<i>Level 3 temporally aggregated water quality (of parameter &lt;p&gt;)</i>				
<b>monthly &lt;chl, tsm, cdom, turbidity&gt;</b>	MERIS observations	Average and variance	300 m	geotiff
<b>monthly &lt;immersed&gt;, &lt;floating&gt;</b>	MERIS observations	Average	300 m	geotiff
<b>monthly &lt;lswt&gt;</b>	ARCLake <sup>1</sup>		0.05°	geotiff
<b>yearly &lt;p&gt;</b>	monthly <p>	Average and variance of Jan-Dec	As <p> above	geotiff
<b>10y &lt;p&gt;</b>	yearly <p>	Average and variance of 2003-2011	As <p> above	geotiff
<i>Spatially aggregated water quality statistics (of temporal aggregate &lt;t&gt; and region &lt;r&gt;)</i>				
<b>products stats monthly &lt;t&gt;, &lt;r&gt;</b>	monthly <t>, <r>	Avg, var, med, min/max and percentiles of all <p> for selected <t>, <r>	<r>	txt
<b>products stats yearly &lt;t&gt;, &lt;r&gt;</b>	yearly <t>, <r>	Avg, var, med, min/max and percentiles of all <p> for selected <t>, <r>	<r>	txt
<b>products stats 10y &lt;t&gt;, &lt;r&gt;</b>	10y <t>, <r>	Avg, var, med, min/max and percentiles of all <p> for selected <t>, <r>	<r>	txt
<i>Spatially aggregated water quality statistics (of parameter &lt;p&gt; and region &lt;r&gt;)</i>				
<b>parameter stats monthly &lt;p&gt;, &lt;r&gt;</b>	monthly <p>, <r>	Avg, var, med, min/max and percentiles of all <t> for selected <p>, <r>	<r>	txt
<b>parameter stats yearly &lt;p&gt;, &lt;r&gt;</b>	yearly <p>, <r>	Avg, var, med, min/max and percentiles of all <t> for selected <p>, <r>	<r>	txt
<b>parameter stats 10y &lt;p&gt;, &lt;r&gt;</b>	10y <p>, <r>	Avg, var, med, min/max and percentiles of all <t> for selected <p>, <r>	<r>	txt
<i>Time series (of parameter &lt;p&gt; and region &lt;r&gt;)</i>				
<b>timeseries monthly &lt;p&gt;, &lt;r&gt;</b>	product_stats monthly <p>, <r>	Monthly time series plot for <p>, <r> in individual years or 2003-2011	<r>	png
<b>timeseries yearly &lt;p&gt;, &lt;r&gt;</b>	product_stats yearly <p>, <r>	Yearly time series plot for <p>, <r> in 2003-2011	<r>	png
<i>Instantaneous water level observations</i>				
<b>water-level.txt</b>	Hydroweb <sup>2</sup>	Table consisting of individual satellite altimeter observations in 2003-2011	Per lake	txt
<b>water-level.png</b>	water-level.txt	Time series plot for satellite altimeter observations in 2003-2011	Per lake	png

<sup>1</sup> [www.geos.ed.ac.uk/arclake/](http://www.geos.ed.ac.uk/arclake/)

<sup>2</sup> [www.legos.obs-mip.fr/soa/hydrologie/hydroweb/](http://www.legos.obs-mip.fr/soa/hydrologie/hydroweb/)

## 3.2 Product Content

### 3.2.1 Eutrophication Indicators

#### chl\_fub\_mean, chl\_fub\_sigma [mg/m<sup>3</sup>]

CHL- $\alpha$  concentration is provided as a proxy for phytoplankton abundance and algal biomass. FUB CHL- $\alpha$  is retrieved by a neural network algorithm developed at the Free University of Berlin (Schroeder et al., 2007). It is recommended for use with Optical Water Types 1-3 (*owt\_cc\_dominant\_class\_mode*, see Section 3.2.4), i.e. oligo- to mesotrophic waters dominated by eukaryotic plankton. The upper limits of its applicability are constrained by the training range of the bio-optical model, to 50 mg/m<sup>3</sup> CHL- $\alpha$ , 50 g/m<sup>3</sup> TSM and 1 m<sup>-1</sup> CDOM. Conditions exceeding these limits are automatically removed from analyses by a relatively effective internal mechanism.

The algorithm uses most spectral bands available between 412-753 nm, including the wavelengths of maximum water transparency. The depth of the resolved water layer depends strongly on turbidity, but is usually in the range of one to several meters (Odermann et al., 2012).

#### chl\_mph\_mean, chl\_mph\_sigma [mg/m<sup>3</sup>]

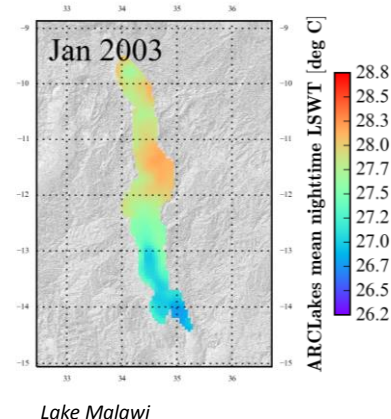
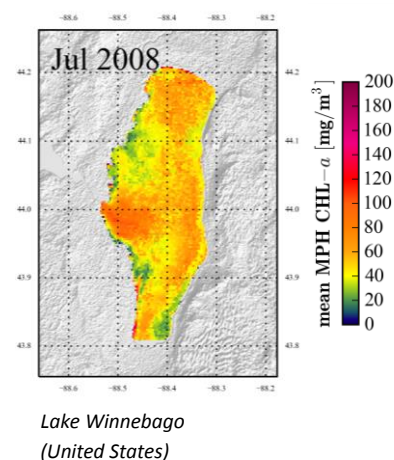
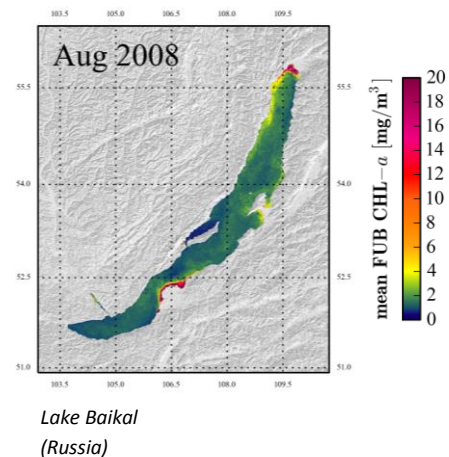
CHL- $\alpha$  concentration is provided as a proxy for phytoplankton abundance and algal biomass. MPH CHL- $\alpha$  is retrieved by the Maximum Peak Height algorithm (Matthews & Odermann, 2015) and meant for Optical Water Types 4-7 (*owt\_cc\_dominant\_class\_mode*, see Section 3.2.4), i.e. eutrophic and turbid waters, including cyanobacteria blooms. The upper CHL- $\alpha$  concentration level retrieved by the algorithm is capped at 1000 mg/m<sup>3</sup>.

The algorithm makes use of optical features at 619-885 nm, where absorption is high, and transparency and reflectance low. The depth of the resolved water layer depends on turbidity and illumination, but is approximately 20-40 cm (Ma, Jiang, Duan, Bracchini, & Loisel, 2011).

#### lswt\_d\_mean, lswt\_n\_mean, lswt\_d\_sigma, lswt\_n\_sigma [°K]

LSWT is a remotely sensed surface temperature, controlled by the thermal emissions from within ~0.01 mm of the air-water interface (Donlon et al., 2002). Both LSWT product layers consist of temperatures in degree Kelvin. Conversion to Centigrade is done only for visualization. The day and night time acquired layers are available, whereas the night time layers are usually more accurate (S. N. MacCallum & Merchant, 2012).

LSWT products are available for 298 lakes but missing for 42, predominantly smaller lakes. They are adapted from the ARC Lake project database and detailed documentation (S. MacCallum & Merchant, 2010, 2011, 2013) is available on the



project webpage [www.geos.ed.ac.uk/arclake](http://www.geos.ed.ac.uk/arclake).

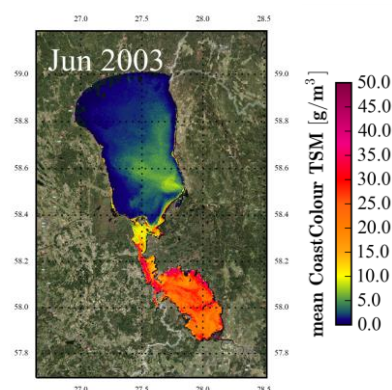
(Malawi, Mozambique, Tanzania)

### 3.2.2 Physical Disturbance and Contamination Indicators

#### **tsm\_cc\_mean, tsm\_cc\_sigma [ $\text{g}/\text{m}^3$ ]**

TSM consists of organic as well as inorganic suspended particles, and is retrieved by a neural network algorithm developed in the scope of the CoastColour project ([www.coastcolour.org](http://www.coastcolour.org)). It is based on the approach described by Doerffer and Schiller (2007), but with extended training ranges in the bio-optical model in particular for backscattering and suspended matter, but also other variables. The upper concentration range limits are at  $100 \text{ mg}/\text{m}^3$  CHL-a,  $2000 \text{ g}/\text{m}^3$  TSM and  $5 \text{ m}^{-1}$  CDOM.

The algorithm uses 12 spectral bands available between 412-865 nm, including the wavelengths of maximum water transparency. The depth of the resolved water layer depends strongly on turbidity, but is usually in the range of one to several meters (Odermatt et al., 2012)

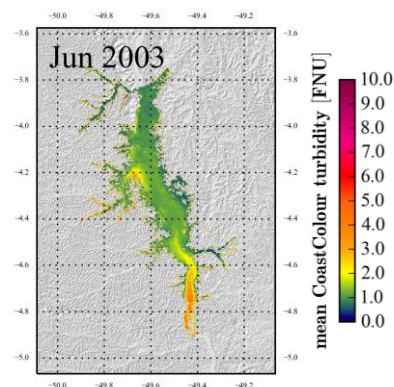


Lake Peipus  
(Estonia, Russia)

#### **turbidity\_cc\_mean, turbidity\_cc\_sigma [FNU]**

Turbidity is retrieved by the same neural network algorithm described for *tsm\_cc\_mean* above (Doerffer & Schiller, 2007). The same applicability constraints apply.

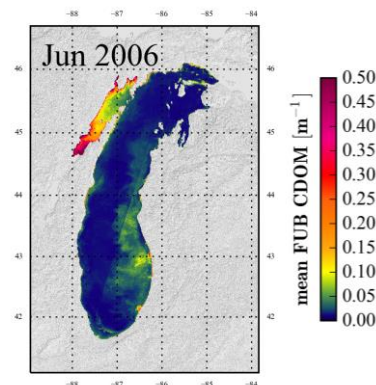
As opposed to the bio-optical model inversion for *tsm\_cc\_mean*, turbidity is calculated directly from the reflected signal at 620 nm using empirical equations. The resolved water layer is accordingly lower as the wavelengths of maximum transparency are not considered.



Tucuruí Reservoir  
(Brazil)

#### **cdom\_fub\_mean, cdom\_fub\_sigma [ $\text{m}^{-1}$ ]**

CDOM is a proxy for dissolved organic carbon and similar organic quantities (Jiang, Ma, Loiselle, & Duan, 2012). It is retrieved by the same neural network algorithm described for *chl\_fub\_mean* above (Schroeder et al., 2007), and corresponds to units of absorption at 443 nm. The same applicability constraints and depth representation apply.



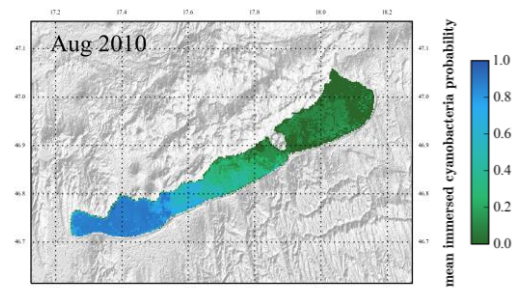
Lake Michigan  
(United States)



### 3.2.3 Ecosystem Indicators

#### immersed\_cyanobacteria\_mean

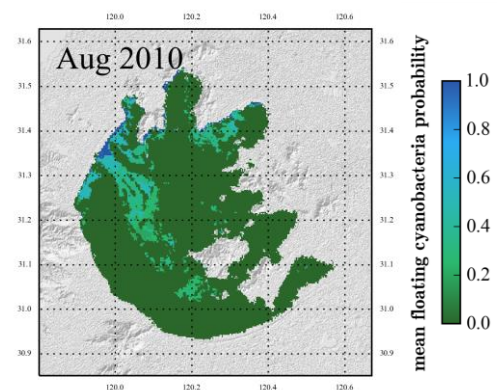
Immersed cyanobacteria are identified by the MPH algorithm (Matthews & Odermatt, 2015). It facilitates binary classification of optical dominance at the level of individual satellite images, but does not indicate species composition or concentrations of cyanobacteria pigments. The monthly products represent 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 (*num\_obs*, see Section 3.2.4).



Lake Balaton  
(Hungary)

#### floating\_cyanobacteria\_mean

Floating cyanobacteria are identified by the MPH algorithm (Matthews & Odermatt, 2015). It is aggregated in the same way as described for *immersed\_cyanobacteria\_mean* above.

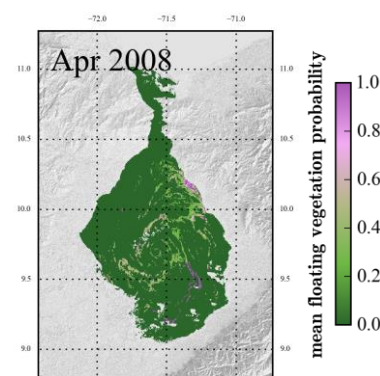


Lake Taihu  
(China)

#### floating\_vegetation\_mean

Floating vegetation is identified by the MPH algorithm (Matthews & Odermatt, 2015). It is aggregated in the same way as described for *immersed\_cyanobacteria\_mean* above.

Very dense floating aquatic vegetation is hardly separable from terrestrial vegetation and therefore not considered. This leads to an underestimation of floating vegetation probability in extreme cases. Moderately dense vegetation floating in cyanobacteria dominated waters leads to a mixed signal that is likely to be interpreted as floating cyanobacteria.



Lake Maracaibo  
(Venezuela)

### 3.2.4 Metadata Layers

#### num\_obs

The number of observations is the count of available observations in each pixel. Its spatial heterogeneity indicates primarily cloud coverage, in large lakes often satellite field-of-view boundaries, and other pixels considered invalid by the processing chain.

Unrealistically sharp gradients within indicator maps are often due to discontinuous acquisitions, which can be verified with the number of observations. For yearly and decadal aggregates, *num\_obs* is the sum of *num\_obs* in all source products, while the indicator products are aggregates of 0-12 monthly or 0-9 yearly source products, respectively (see Section 3.1.3).

#### owt\_cc\_dominant\_class\_mode

Optical Water Types (OWT) are identified according to their fuzzy membership of clustered reflectance measurements (Moore et al., 2014). Types 1-3 represent clear to absorption-dominated waters, class 4-5 represent highly productive waters, and class 6-7 are for high levels of turbidity. The provided products are mode-aggregated, leaving each pixel dominated by the most frequently observed OWT.

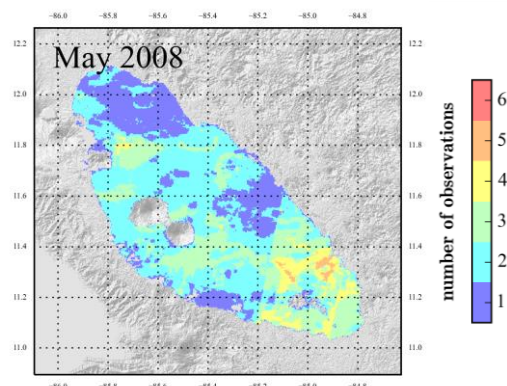
It is recommended to use the decadal OWT to select the more appropriate CHL algorithm: *chl\_fub\_mean* products for classes 1-3, and *chl\_mph\_mean* for classes 4-7. In large lakes, the appropriateness may differ for certain sub basins as for Winam Gulf in the example of Lake Victoria (image on the right).

#### shallow, extent

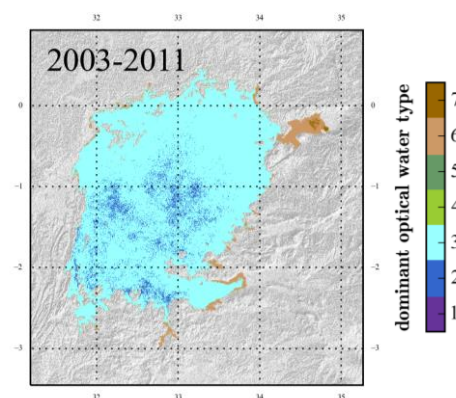
The layers identifying shallow waters and water extent comprise of static maps predefined for each lake.

(Optically) shallow areas are those where a significant portion of water-leaving radiance is reflected by the lake bed. They are mapped by means of a novel approach that identifies a temporally stable optical feature in the spectral domain corresponding to maximum water transparency (Odermatt et al., 2015). An individual threshold for each lake is given in the lake metadata list (see Section 3.3.2). Optically shallow pixels cannot be handled by the applied algorithms and are removed from further analysis.

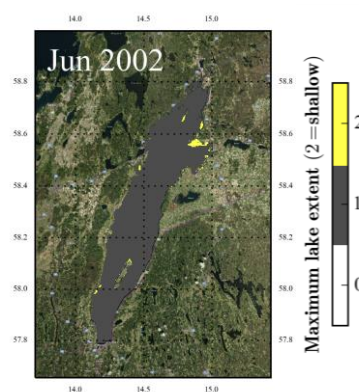
The extent corresponds to the perimeter of the SAR-WB dataset (see Section 3.1.2).



Lake Nicaragua  
(Nicaragua)



Lake Victoria  
(Kenya, Tanzania, Uganda)



Lake Vattern  
(Sweden)



### 3.3 Metadata

#### 3.3.1 SAR-WB Shapefiles

Shapefiles were extracted from the Land Cover CCI SAR-WB dataset as described in Section 3.1.2. They are provided in a separate metadata folder on the Diversity II FTP server, and can be downloaded according to the tutorial in Section 4. Each shapefile corresponds to the maximum extent of a lake (Figure 5), within which valid water pixels are identified and water quality parameters are retrieved. The shapefiles can be applied as default regions of interest when spatial statistics are calculated for the entire lake area as explained in Section 4.3.4.

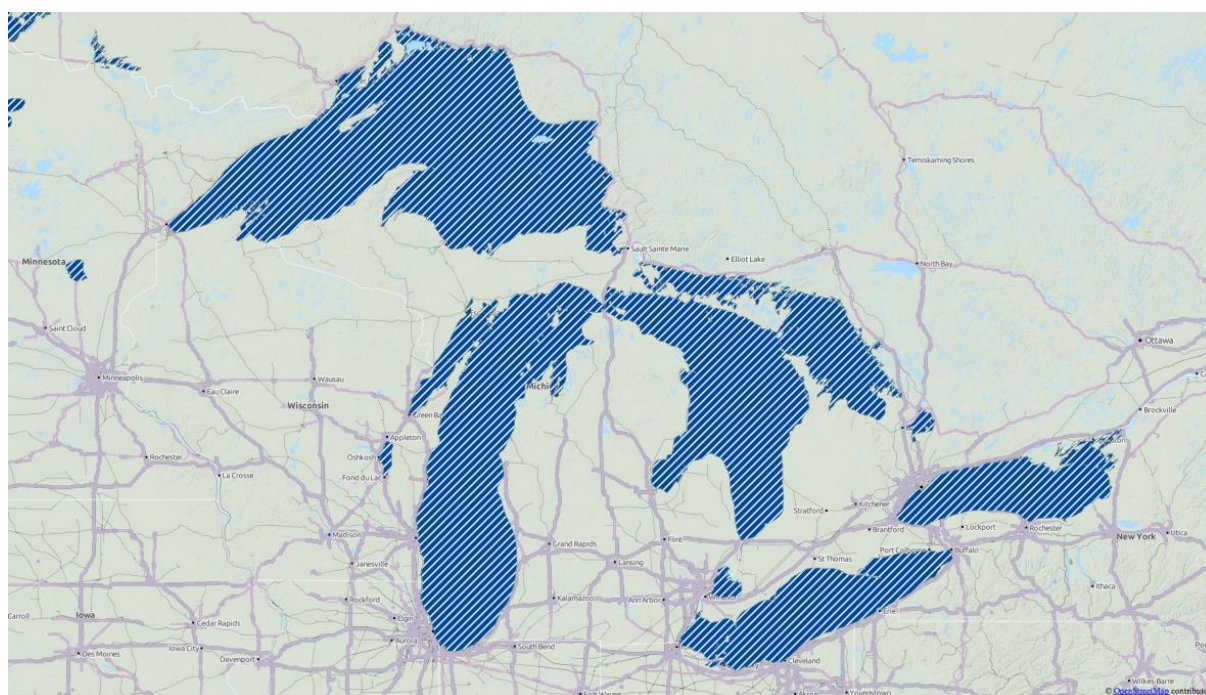


Figure 5: Visualization of the SAR-WB shapefiles used as perimeters for Diversity II products in the North American Great Lakes region. The view was created in open source QGIS with an Open Street Map background.

#### 3.3.2 Auxiliary Data Table and GLWD Attribute Data

A table with auxiliary data is provided with the Diversity II products. It consists of 27 columns, which are summarized as follows:

- **DIV2\_ID:** A lake ID by size, which corresponds to the lake ID in the Global Lake and Wetland Database (Lehner & Döll, 2004) and the ARCLake database (S. MacCallum & Merchant, 2011) unless lake perimeters differ significantly.
- **DIV2\_Name:** The string used for naming Diversity II products is provided along with alternative lake names, translated names or spelling variations as found in the ARCLake database, Hydroweb and Google Maps.
- **ratio490\_threshold:** A lake specific threshold set to identify optically shallow areas in lakes of low turbidity. A description of the applied procedure will be provided in the Diversity II ATBD by the end of the project.
- **Area, Latitude, Longitude:** Values extracted from the SAR-WB polygon (area) or corresponding centroids (latitude, longitude) of each lake.



- **GLWD Attribute Data:** GLWD attribute data were merged with corresponding Diversity II lakes where polygons are sufficiently collocated. Riparian countries, water body type, catchment use, geographic and hydrologic parameters are provided where available.

### 3.4 Projection

All geophysical map products are provided in the WGS84 coordinate reference system.

## 4 How to use the Diversity II products

### 4.1 Obtain Products

Product access information and login credentials are available at: <http://www.diversity2.info/products/access/>. After receiving username and password, the products can be downloaded either individually from the website, or by browsing the FTP archive.

#### 4.1.1 Single file download using a web browser

1. Open a web browser and go to <http://www.diversity2.info/products/>
2. Click "Inland Waters products" in the menu to the left.
3. Click on "Diversity II Products download - Inland Waters (Map view)" or "Diversity II Products download - Inland Waters (Table view)"
4. Navigate to the site you are interested in.
5. In the list of products, click the desired product
6. Enter username and password
7. Download the product

#### 4.1.2 Bulk download using an FTP client

1. Open your favourite FTP client.  
(If you don't have one we recommend FileZilla, <https://filezilla-project.org>)
2. Enter host "<ftp.brockmann-consult.de>" together with your username and password
3. Navigate to the site(s) you are interested in and download the desired product(s).

#### 4.1.3 Unzip Products

In order to prepare a consistent folder structure for use with the display and analysis tools described in Section 4.3, we recommend to create the folders "l3-monthly", "l3-yearly" and "l3-10y" in each lake folder and save the corresponding Geotiffs therein. This is achieved if you download complete lake folders from the FTP or place individually downloaded zip archives in lake specific folders, and run the following OSX/Bash commands therein:

1. `unzip \*monthly*.zip -d l3-monthly && rm \*monthly*.zip`
2. `unzip \*yearly*.zip -d l3-yearly && rm \*yearly*.zip`
3. `unzip \*10y*.zip -d l3-10y && rm \*10y*.zip`

There is no native unzip command in Windows, but several freeware tools may do the job.

## 4.2 View products

The Diversity II products are distributed in the widely applied Geotiff format and can be opened in most EO or GIS programs. In this tutorial we use BEAM, an open-source toolbox and development platform for viewing, analysing and processing remote sensing data. It provides a graphical user interface program, command line tools and Java/Python application programming interfaces and can be downloaded from the BEAM project website: <http://www.brockmann-consult.de/cms/web/beam/releases>.

Please notice that BEAM functionalities will be continued in SNAP, the common software platform for the three Sentinel Toolboxes which are developed by the European Space Agency (ESA) for the scientific exploitation of the Sentinel-1, Sentinel-2 and Sentinel-3 missions.

VISAT is BEAM's visualisation, analysing and processing application. It comes with a clear and intuitive user interface allowing new users to get started quickly. It lets you switch between a "Product browser" providing overview over multiple open products within a tree view and a comprehensive pixel information view to display geophysical values. The main components of VISAT are depicted in Figure 6.

The tool windows of VISAT provide access to tools, as the name says. These windows can be floating, docked or tabbed. This docking concept allows a tidy workspace and you can arrange all tool windows as you like it. All changes you apply to the layout will be saved for the next start of VISAT. A new "Image view" is created by double-clicking on a tie-point grid or spectral/geophysical band. You can open as much images as your computer's memory allows. After you have opened an "Image view" you can inspect the images with the "Navigation window".

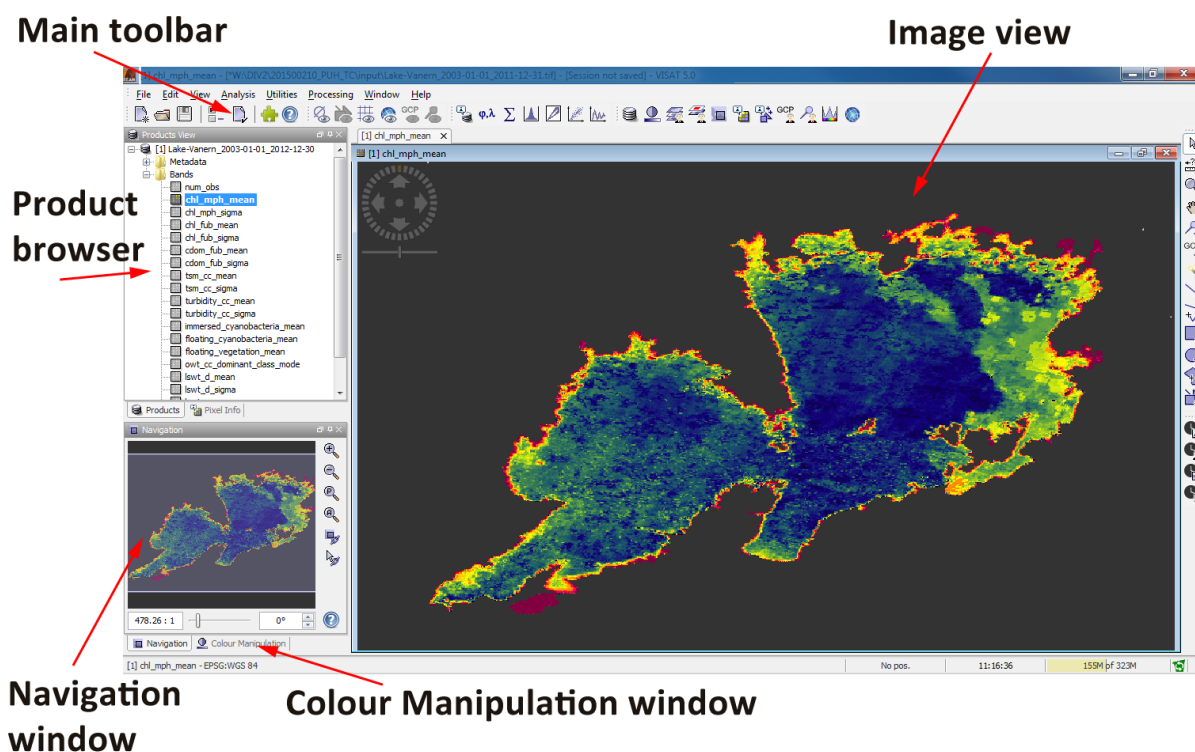


Figure 6: Screenshot of BEAM with some important components highlighted.

After you have opened an Image View you can modify the colours of the image using the "Colour Manipulation window" or overlay an opaque or semi-transparent data mask with the "Mask manager". Both tool windows operate in non-modal mode, which means they float over VISAT's main window and you can place them somewhere on your desktop. More instructions on the main components of VISAT's graphical user interface are available at <http://www.brockmann-consult.de/beam/doc/help/index.html>.

### 4.3 Display and Analysis Tools

According to user requirements, the indicators described in 3.2 are of undisputed relevance for biodiversity. But causes and effects that can be assigned to them differ significantly and require systematic understanding of each individual test site. For example, increasing CHL may be interpreted as increasing productivity and thus improving habitat conditions in some cases, but indicates eutrophication and thus a threat to indigenous niche species in other cases. Therefore, a suite of Python 3 scripts is provided and BEAM functions are described, that shall help users to efficiently explore, customize and extract relevant information from product contents. The workflow in Figure 7 displays an exemplary procedure including all Python scripts and BEAM functions in one sequence. All tasks and tools are described in more detail in the Sections 4.3.1 to 4.3.5.

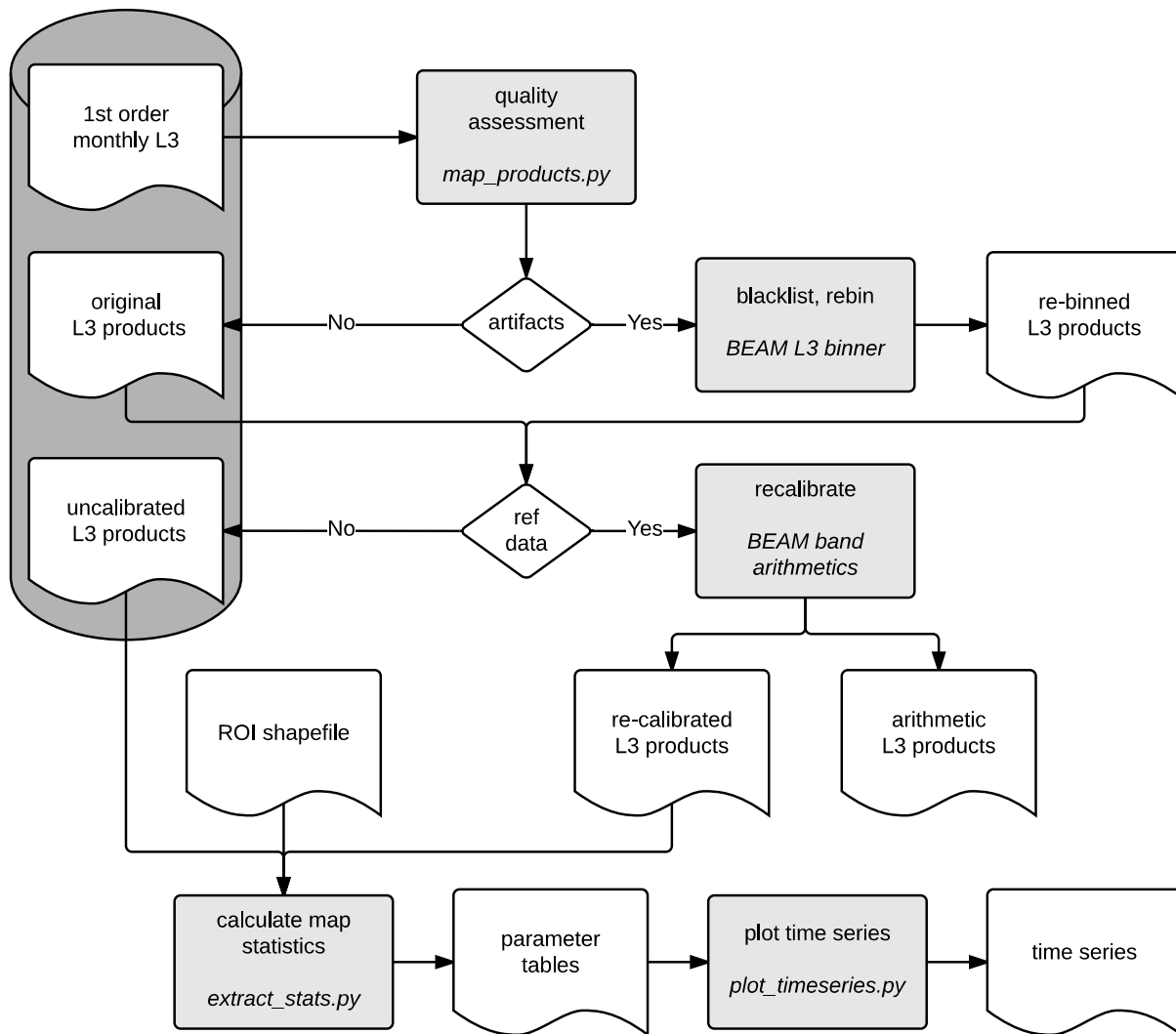


Figure 7: Workflow for plotting and customizing monthly water quality products, and the extraction of statistics and time series plots. The tasks and tools described below are represented in light grey, input, intermediate and output products are white.

### 4.3.1 Quality Assessment with `map_products.py`

`map_products.py` is a Python 3 script that facilitates graphic visualization in image format for quality assessment, presentations and reports. It applies a Mercator projection, a coordinate grid and parameter-specific colour scales. The user can select from different base maps, specify a predefined parameter range and the desired geographic area to be represented by the image.

Running the script requires a Python 3 installation as well as the following Python modules: `numpy`, `math`, `os`, `beampy`, `cartopy` (v0.11), `matplotlib` and `configparser`. `Beampy` is delivered with `BEAM 5`. Installation instructions are provided within the program folder at `beam-5/modules/beam-python-5.0.4/README.md`. Once all dependencies are installed, the script is started in a shell with the command:

```
python3 map_products.py
```



The script is parameterized in the file *map\_products.ini*, which must be located in the same path. It allows setting the following parameters, which are described also in code comments inside the ini file:

- **products\_path**: The path where lake folders are stored (see Section 4.1.3), e.g. `'/Data/Diversity_II'`
- **lake**: A lake name in products\_path, e.g. `'Vanern'` (`C:/Data/Diversity_II/Lake-Vanern`)
- **param\_str**: The name of a single water quality indicator to be plotted, e.g. `'chl_mph_mean'`
- **method**: Options are `'single'`, `'year_by_months'`, `'months_by_year'` (see Figure 8)
- **param\_range**: Optionally define the applicable colour scale range
- **basemap**: Options are `'quadtree_rgb'`, `'srtm_elevation'`, `'srtm_hillshade'`, `'none'`
- **geogr\_area**: Specify coordinate borders to plot subset images
- **add\_margin**: Adds approximately 1/8 of canvas margin, options are `'True'`, `'False'`
- if method is `'single'`, **aggregate\_type** whether `'monthly'`, `'yearly'`, `'10y'` is plotted

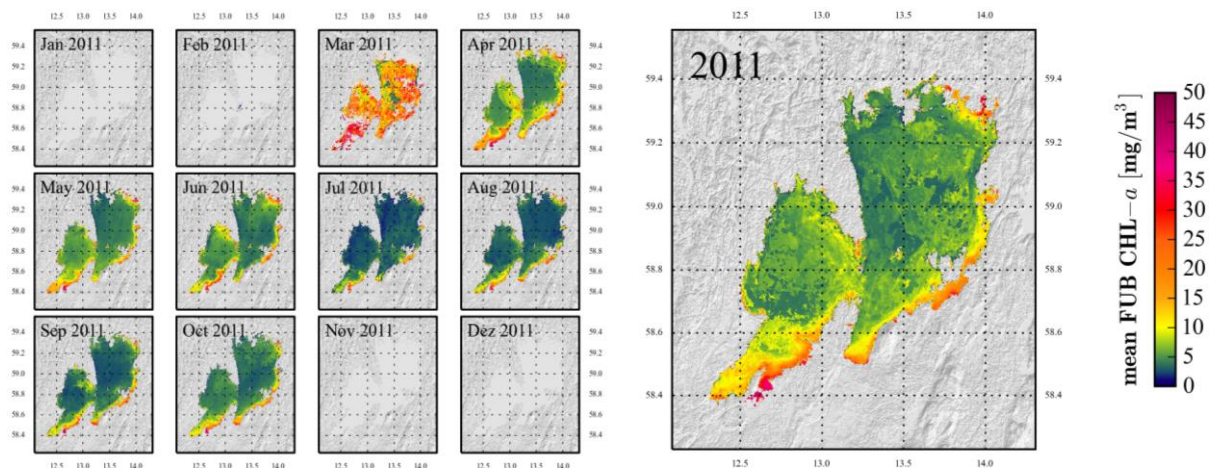


Figure 8: Two example figures from *map\_products.py*, using method `'year_by_month'` (left) and method `'single'` with `aggregate_type 'yearly'` (right). Other parameters for both figures are: `param_str 'chl_fub_mean'`, `param_range '0,50'`, `basemap 'srtm_hillshade'`, `geogr_area 'False'`, `add_margin 'True'`. The March 2011 image is affected by an overlooked lake ice acquisition, which propagates to the yearly product. Mitigation of this issue is explained in Section 4.3.2.

### 4.3.2 Re-binning with the BEAM L3 Binner

Re-binning allows for the creation of user-defined bins, for example seasonal aggregates. Alternatively, it can be applied to remove suspicious products from higher order aggregates, as shown in Figure 8. The BEAM L3 binner is available in VISAT (menu Processing/Level-3 binning), and allows for the selection of arbitrary input products and the configuration of output products (Figure 9). All indicators available in the yearly and 10y products can be reproduced with this procedure, but not the metadata layers *num\_obs* and *owt\_cc\_dominant\_class\_mode*. Output format is dimap, which can easily be converted to geotiff (VISAT menu File/Export Raster Data/GeoTIFF). The re-binned Lake Vanern 2011 aggregate is depicted in Figure 11 (left).

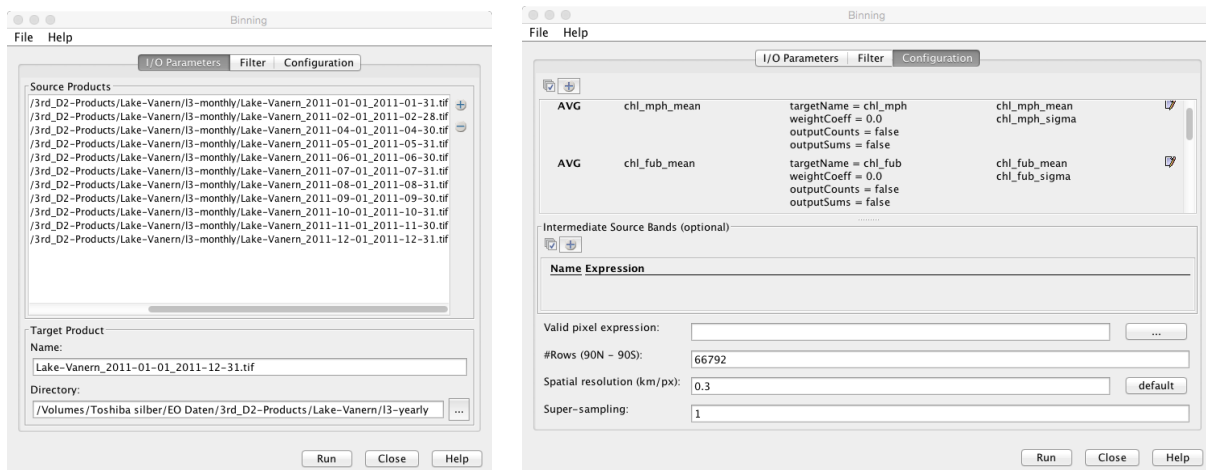


Figure 9: I/O Parameter (left) and Configuration dialogues of the VISAT Level-3 binner. The displayed parameters aim to reproduce the lake ice affected Lake Vanern 2001 yearly product shown in Figure 8. The binning parameters can be stored in an xml file for multiple use or as input for the BEAM gpt command line jobs (menu File/Save Parameters...).

### 4.3.3 Recalibration with BEAM band arithmetic

Satellite Earth observation products are derived from the water constituent's inherent optical properties, absorption and scattering. The approximately linear relationship of absorption and scattering to concentration units is a matter of considerable ambiguity, which affects the absolute accuracy of the products significantly. In a first approximation, linear adjustment using regression coefficients from matchup comparisons of satellite retrieved and in situ measured parameters can help to mitigate this effect. Example regressions for *chl\_mph\_mean* are given in Section 5.1.

In the case of Lake Vanern, matchup regression indicates that *chl\_fub\_mean* strongly overestimates in situ measurements (Figure 10, left). This can be accounted for by using BEAM band arithmetic (VISAT menu Utilities/Create Band from Math Expression...). In order to prevent naming conflicts, the original *chl\_fub\_mean* should be right-clicked and renamed (Properties...) to *chl\_fub\_mean\_old* prior to calculating the new band. A new *chl\_fub\_mean* is then created according to the dialog box depicted in Figure 10 (right). If *chl\_fub\_mean* is used, it should be scaled accordingly.

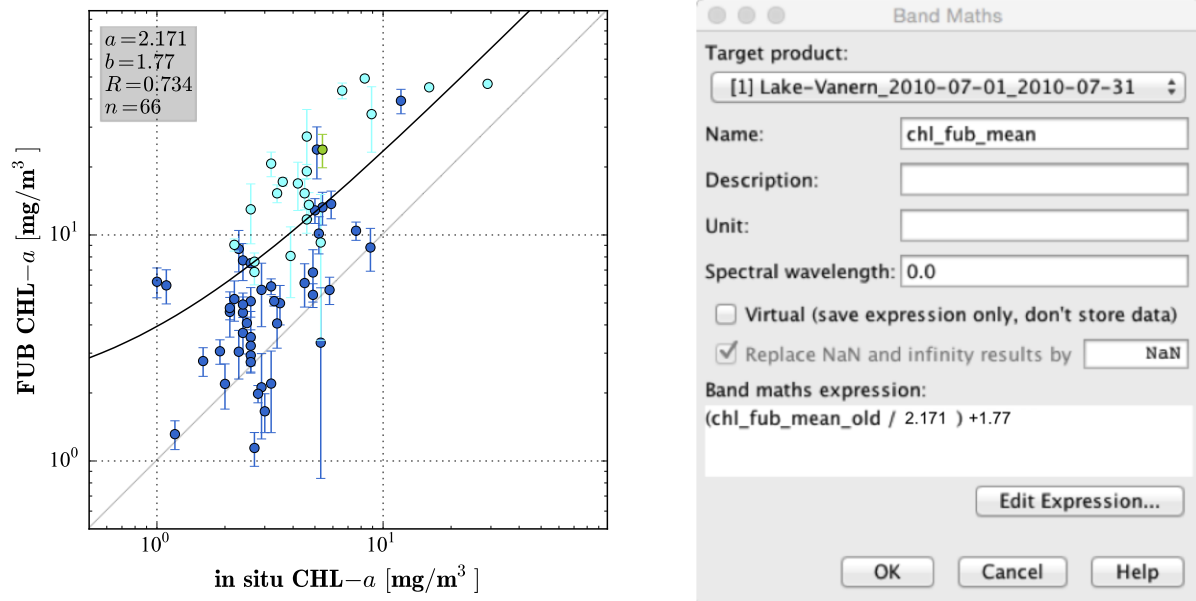


Figure 10: Lake Vanern in situ matchup regression results (left) and adaptation of the linear regression coefficients in the BEAM Band Maths dialogue.

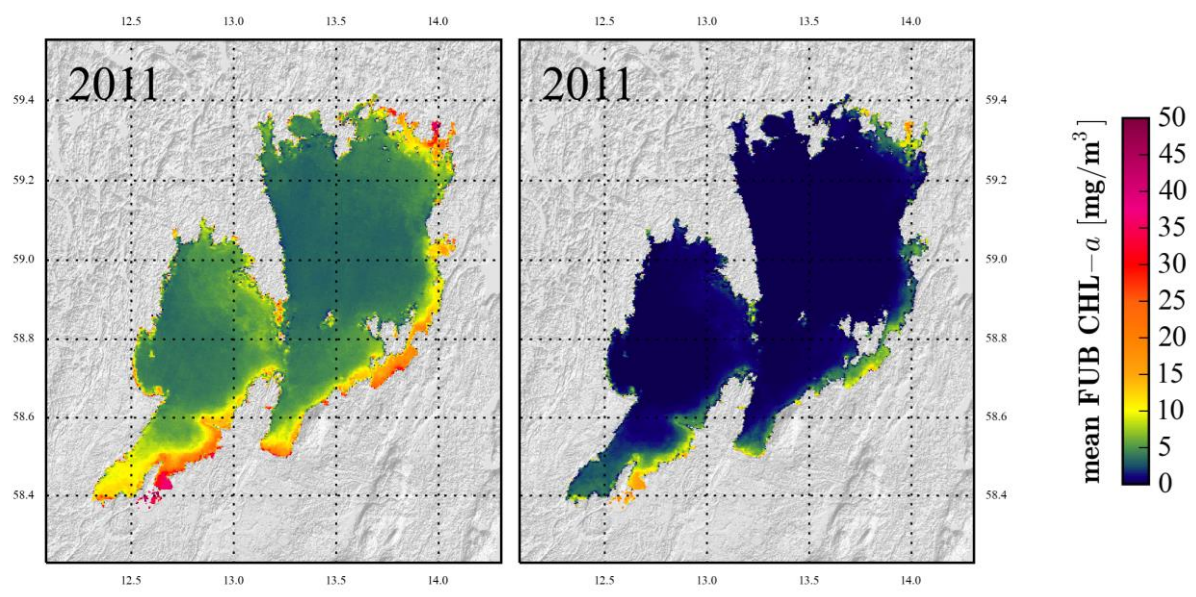


Figure 11: Yearly averaged CHL in Lake Vanern in 2011. The image on the left corresponds to the original concentration range, but after removal of the March product. The image to the right was scaled to match the range of monitoring in situ measurements using matchup regression coefficients, according to Figure 10.

#### 4.3.4 Spatial Averaging using extract\_stats.py

*extract\_stats.py* is a Python 3 script that facilitates the calculation of various statistical parameters for individual indicator maps. It merges these parameters into two different table types, the first one comprising of all indicators for one product (Table 2), the second one comprising of one indicator but all products (Table 3). The user can specify a shapefile that defines his region of interest, or use the maximum lake extent (Section 3.3.1). Other selections include a list of indicator names to be extracted and desired percentile values.

Running the script requires a Python 3 installation as well as the following Python modules: configparser, platform, os, string and pandas. In addition, a BEAM installation is required



because the BEAM StatsOp operator is invoked during execution. Once all dependencies are installed, the script is started in a shell with the command:

```
python3 extract_stats.py
```

The script is parameterized in the file *extract\_stats.ini*, which must be located in the same path. It allows setting the following parameters, which are described also in code comments inside the ini file:

- **beam\_path**: The path to the BEAM program folder, e.g. 'C:/Program Files/beam-5.0'
- **products\_path**: The path where lake folders are stored (see Section 4.1.3), e.g. 'C:/Data/Diversity\_II'
- **lake**: A lake name in products\_path, e.g. 'Vanern' (/Data/Diversity\_II/Lake-Vanern)
- **param\_str**: A comma-separated list of water quality indicators to be extracted, e.g. 'chl\_mph\_mean, tsm\_cc\_mean, lswt\_n\_mean'
- **aggregate\_type**: Specifies whether 'monthly', 'yearly', '10y' products are processed
- **shapefile\_path**: The path of the shapefile defining the area to be extracted, e.g. 'C:/Data/Diversity\_II/Aux/ESACCI-LC-L4-SAR-WB-300m-v2-0\_WOODS.shp'
- **percentiles**: Specifies the percentile value(s) to be calculated, e.g. '10, 90'

**Table 2: Product statistics extracted from the 10y product of Lake Winnebago.**

Band	average	max_error	maximum	median	minimum	sigma	total
lswt_n_mean	283.6879	0	283.7208	283.691	283.6556	0.0185	7334
immersed_cyanobacteria_mean	0.3364	0.0001	0.514	0.3428	0	0.0491	7587
chl_mph_mean	79.2767	0.0125	149.5842	79.3187	24.4007	8.7276	7587
tsm_cc_mean	21.4085	0.008	92.7851	20.4599	12.3434	4.6302	7587

**Table 3: chl\_mph\_mean statistics extracted from yearly products of Lake Winnebago.**

start_date	end_date	average	max_error	maximum	median	minimum	sigma	total
01.01.03	31.12.03	58.3817	0.0227	229.4457	55.9768	2.1542	19.5814	7582
01.01.04	31.12.04	44.8263	0.0146	153.4678	44.2148	7.1533	9.4054	7583
01.01.05	31.12.05	39.6636	0.0163	170.9711	38.9712	7.524	10.2415	7584
01.01.06	31.12.06	58.4701	0.0228	230.8199	57.4622	3.1071	16.7209	7576
01.01.07	31.12.07	58.6078	0.0195	199.1671	57.5363	4.4588	16.0813	7587
01.01.08	31.12.08	55.727	0.0138	149.5578	53.9714	11.0669	10.4695	7586
01.01.09	31.12.09	118.899	0.0262	269.7176	114.5339	7.2283	30.9506	7586
01.01.10	31.12.10	52.9466	0.0196	212.8041	50.367	17.1439	13.1837	7586
01.01.11	31.12.11	225.944	0.0404	457.5571	224.5013	53.7175	32.2115	7585

### 4.3.5 Plotting Time Series with plot\_timeseries.py

*plot\_timeseries.py* is a Python 3 script that plots time series for extracted statistics such as those in Table 3. The user must specify a water quality indicator, a statistical parameter and the parameter range to be displayed. Suspect or outlier values can be blacklisted via the corresponding start date.

Running the script requires a Python 3 installation as well as the following Python modules: numpy, os, datetime, matplotlib and configparser. Once all dependencies are installed, the script is started in a shell with the command:

```
python3 plot_timeseries.py
```

The script is parameterized in the file *plot\_timeseries.ini*, which must be located in the same path. It allows setting the following parameters, which are described also in code comments inside the ini file:

- **products\_path**: The path where lake folders are stored (see Section 4.1.3), e.g. '/Data/Diversity\_II'
- **lake**: A lake name in products\_path, e.g. 'Vanern' (C:/Data/Diversity\_II/Lake-Vanern)
- **param\_str**: The name of a single water quality indicator to be plotted, e.g. 'chl\_mph\_mean'
- **stats\_str**: The name of a statistical parameter previously extracted, e.g. 'average'
- **method**: Options are 'year\_by\_months', 'decade\_by\_months', 'decade\_by\_years' (see Figure 12 to Figure 14)
- **param\_range**: Optionally define the applicable Y axis range
- **date\_blacklist**: A list of start dates of products that shall not be considered in the time series, e.g. '2003-02-01, 2003-11-01'

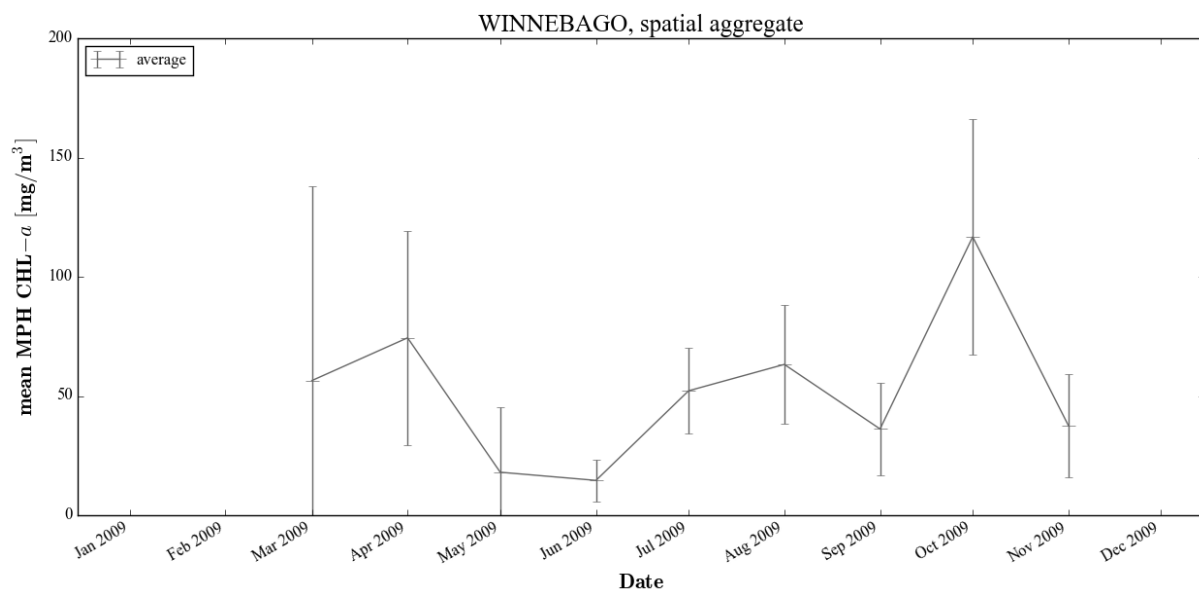


Figure 12: *year\_by\_months* type time series plot showing spatially averaged *mph\_chl\_mean* for Lake Winnebago in 2009.

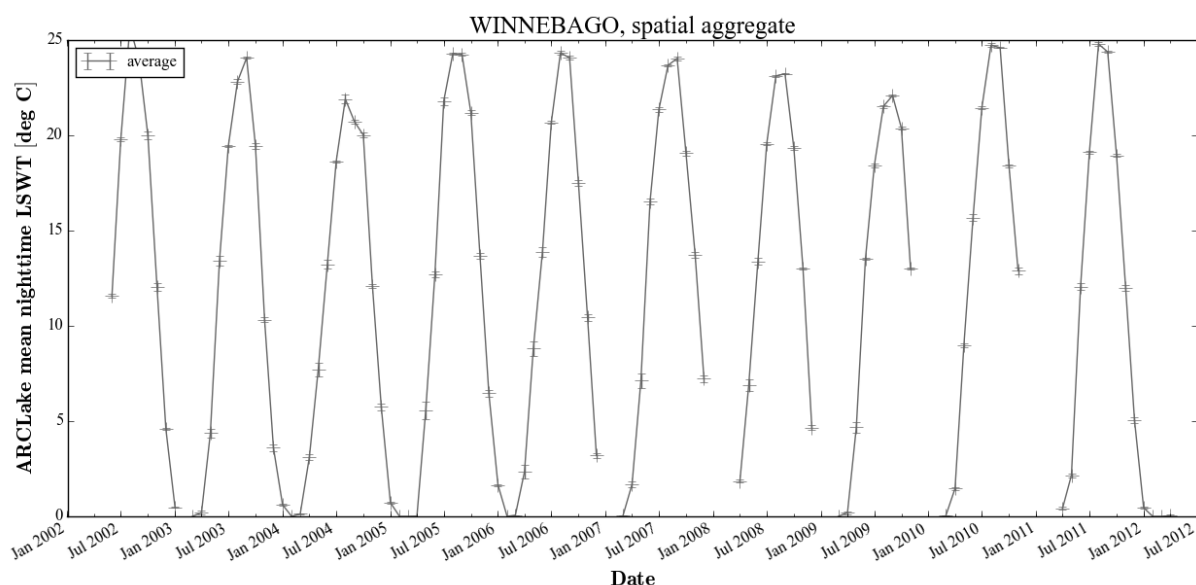


Figure 13 *decade\_by\_months* type time series plot showing spatially averaged *lswt\_n\_mean* for Lake Winnebago in 2002-2012.

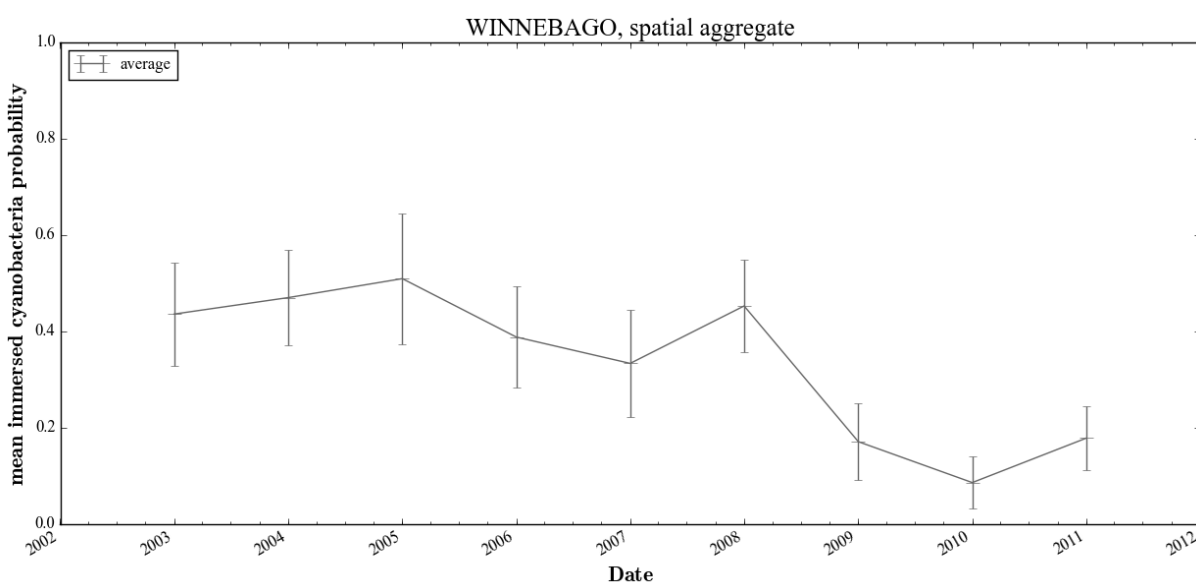


Figure 14 *decade\_by\_years* type time series plot showing spatially averaged *immersed\_cyanobacteria\_mean* for Lake Winnebago in 2002-2012.

## 5 Indicator Validation and Assessment

### 5.1 Indicator Validation

Matchup comparisons with in situ measured CHL, and to a smaller extent TSM, Turbidity and Secchi depth reference data were performed for the CalLimnos processing setup. Exemplary regression results for MPH retrieved CHL are shown in Figure 15. The results provide on one hand a comparison of the EO derived indicators to more established ground measurement techniques, on the other hand they allow for an absolute calibration of the EO indicators according to Section 4.3.3 using slope and intercept of the linear regression. A list of regression parameters is given in Table 4.

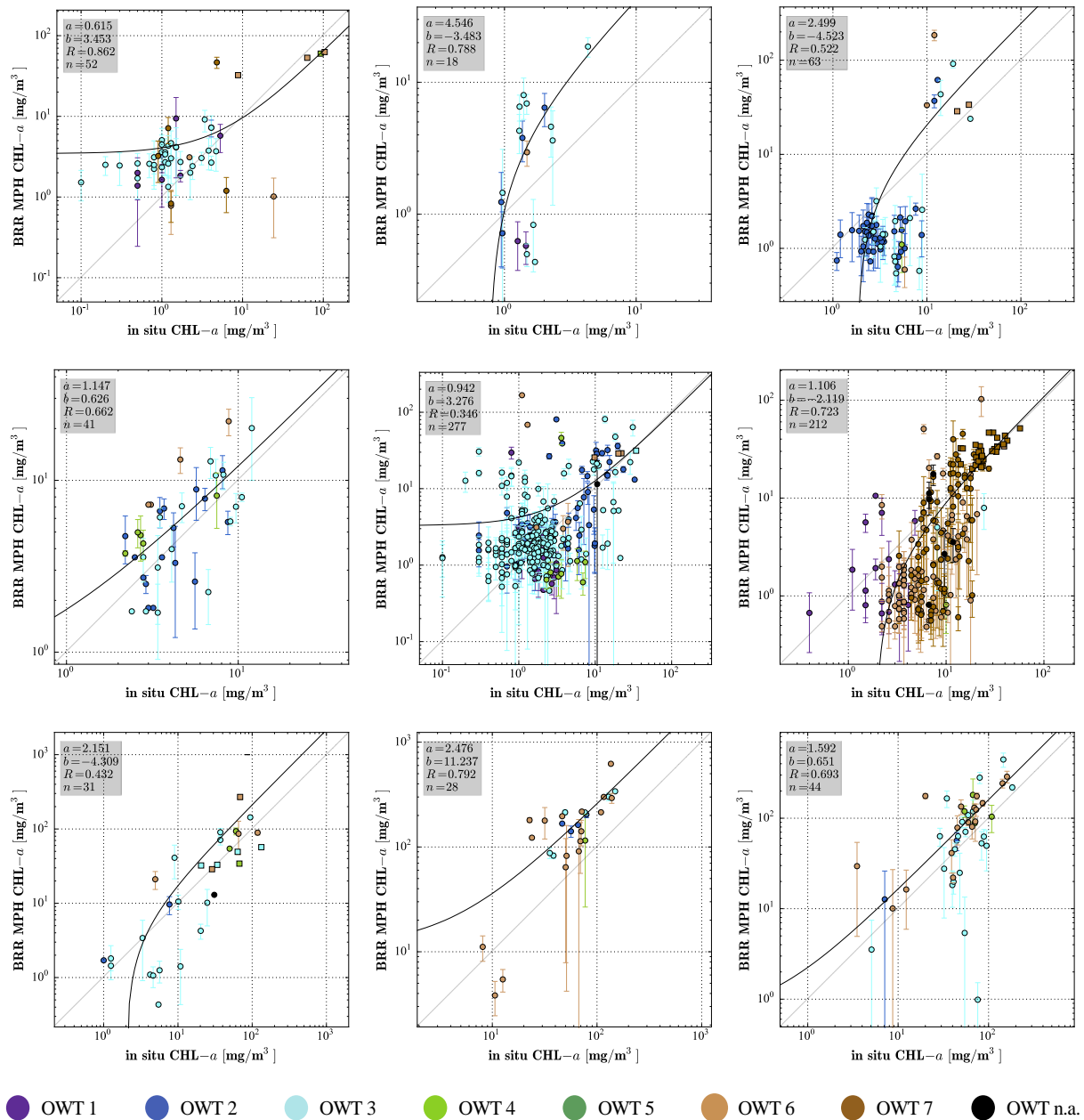


Figure 15: Validation scatter plots for several lakes and datasets. (●) represents  $3 \times 3$  MERIS pixels where no cyanobacteria presence is indicated, (■) includes at least one cyanobacteria flagged pixel. Top to bottom, left to right; Erie (Environment Canada, EC), Zug (Canton of Zug Env. Protection Agency), Vanern (Swedish Agency for Marine and Water Management, SwAM), Paijanne (Finnish Environment Agency, SYKE), Ontario (Environment Canada), Balaton (Central Transdanubian Regional Inspectorate for Environmental Protection, Nature Conservation and Water Management, KdkVI), Lake Hartbeespoort (Republic of South Africa, Department of Water Affairs, DWA), Kasumigaura (Center for Environmental Biology and Ecosystem Studies CEBES, Japanese National Institute for Environmental Studies NIES), Bronkhorstspuit (DWA). The optical water types are also indicated. The Figure corresponds to Figure 7 in Matthews & Odermatt (2015), but was updated with bulk reprocessed MERIS FR data.

**Table 4: Regression results obtained for fub\_chl and mph\_chl in matchup comparisons of the MERIS FR bulk reprocessed database and various chlorophyll-*a* datasets from regional water quality monitoring programs. The dominant OWT is given as mode of all valid matchups. R is the correlation coefficient, a the slope, b the intercept, and n the number of matchups. n may differ due to algorithm specific invalid pixel flagging. Results are only shown for dataset where at least one algorithm retrieved  $R \geq 0.6$  and  $n \geq 10$ .  $R < 0.6$  are in grey letters.**

Lake	Dataset	Dominant OWT	<i>fub_chl</i>				<i>mph_chl</i>			
			R	a	b	n	R	a	b	n
Balaton	KdKVI	✗	0.74	1.14	0.62	187	0.72	1.11	-2.12	212
Kasumigaura	CEBES	✗	0.64	0.09	41.91	4	0.79	2.48	11.24	28
Malaren	SwAM	✗	0.21	0.46	25.45	42	0.71	2.54	-12.9	80
Bronkhorstspuit	DWA	+	0.45	0.24	22.8	12	0.69	1.59	0.65	44
Erie	EC	+	0.46	0.77	1.01	50	0.86	0.62	3.45	52
Geneva	CARRTEL	+	0.72	0.59	-0.84	43	0.07	0.02	1.75	41
Kallavesi	SYKE	+	0.22	0.30	2.73	18	0.63	0.75	4.09	20
Loskop	DWA	+	0.63	5.00	0.92	11	0.39	4.94	16.60	13
Mueritz	IGB	+	0.84	1.78	-2.21	10	0.42	0.11	0.76	10
Neagh	AFBI	+	0.76	0.74	3.79	15	0.51	0.45	12.43	26
Zug	AFJ	+	0.80	3.48	-2.50	18	0.79	4.55	-3.48	18
Haukivesi	SYKE	+	0.60	0.34	0.68	52	0.44	0.44	2.05	36
Of the Woods	EC	+	-0.02	-0.13	17.20	32	0.60	1.0	2.83	23
Paijanne	SYKE	+	0.35	0.40	2.01	124	0.65	1.32	-0.69	106
Vanern	SwAM	+	0.73	2.17	1.77	66	0.49	2.10	-1.31	66
Vattern	SwAM	+	0.88	0.45	0.39	18	0.99	2.97	-1.75	17
Vesijarvi	SYKE	+	0.69	1.50	-0.20	40	0.66	0.58	-2.02	42
Huron	EC	+	0.35	1.57	0.53	14	0.72	3.35	1.12	13

## 5.2 Assessment of Indicators as Biodiversity Proxies

The applicability of the Diversity II indicators as biodiversity proxies is a key to acceptance of the products by the users. This applicability was assessed by contrasting the indicators with the content of multi-scale species databases. This section consists of an extract of the Diversity II PQR (Brito et al., 2015) to give a rough overview of available analyses.

The following data sources were explored: GBIF (Global Biodiversity Facility Information, [www.gbif.org](http://www.gbif.org)), FishBase ([www.fishbase.org](http://www.fishbase.org)) and Distribution Atlases of biodiversity at national or continental level. The advantage of GBIF is that is freely accessible and it comprises worldwide data submitted by Natural History museums and other institutions. However, there are some concerns about accuracy and quality of the geographic, temporal, and taxonomic coverage, suggesting that GBIF records should be used only after careful inspection (Beck, Böller, Erhardt, & Schwanghart, 2014; Costello, Michener, Gahegan, Zhang, & Bourne, 2013; Guralnick, Hill, & Lane, 2007). In this view, the analyses presented here provide a conceptually comprehensive assessment approach.

### 5.2.1 Biodiversity Status Analyses across Lakes

The aim of these analyses was to compare species richness present at test sites with biodiversity indicators in order to estimate consistencies of derived products across diverse environmental backgrounds. Fish species lists for all inland water test sites were generated

based on distribution data extracted from GBIF, and complemented with FishBase data and available bibliography. These extracts were compared to the decadal mean, minimum, maximum and standard deviation aggregates of all Diversity II water quality indicators, and lake altitude and latitude were included in the analysis as co-factors.

An initial total of 47 variables were available. Highly correlated variables were discarded, as well as variables with high levels of missing data or very low variability, resulting in a final set of 19 variables. Identification of the most relevant biodiversity indicators, as well as selected co-factors, affecting biodiversity levels at test sites was assessed through a multiple regression model (GLZ).

We retrieved nine highly significant variables, of which the best two (lowest p-values) are represented in Figure 16. *chl\_fub\_mean* and TSM CC demonstrated to be negatively correlated with species richness, and thus, lakes with higher levels of chlorophyll concentration or total suspended matter were the ones exhibiting lower values of fish species richness, but for both cases species richness is highly variable at low product values, so other confounding effects could be influencing these results.

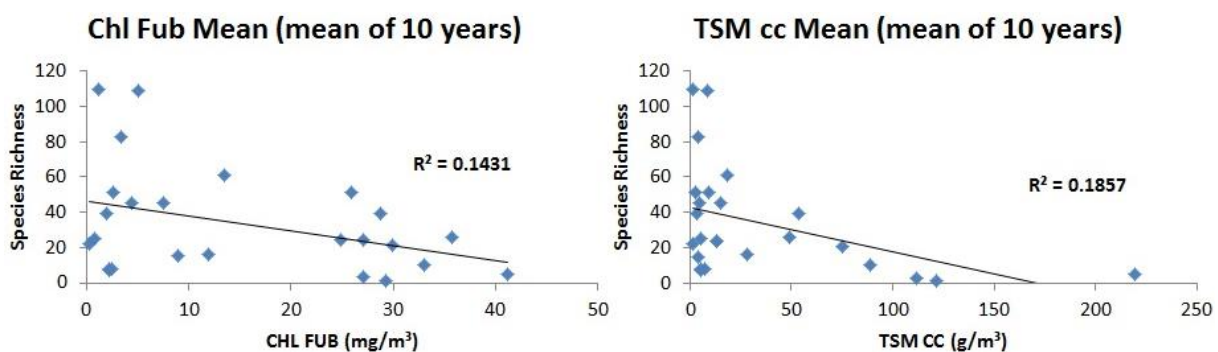


Figure 16: Comparison of the most significantly related Diversity II water quality indicators (x axis) and species counts (y axis). Each marker corresponds to one lake.

## 5.2.2 Biodiversity Trend Analyses, Lake Michigan

Trend data for Lake Michigan was extracted from Bunnell (2011) and consisted of yearly fish catch quantities (from 2002 to 2010) of seven species: Brown trout (*Salmo trutta*), chinook trout (*Oncorhynchus tshawytscha*), coho salmon (*Oncorhynchus kisutch*), lake trout (*Salvelinus namaycush*), rainbow trout (*Oncorhynchus mykiss*), yellow perch (*Perca flavescens*) and sea lamprey (*Petromyzon marinus*). In order to assess if there was any kind of agreement between biodiversity (each species individually, as well as grouped) and indicator measurements (including mean, minimum, maximum and standard deviation) Spearman's rank order correlation analyses (Spearman's  $r$ ) were conducted. Significance of results were tested by their probability values ( $p$ ), considering a confidence level of  $p < 0.05$ .

A greater number of statistically relevant correlations were found for the coho salmon, rainbow trout and lake trout. Figure 17 and Figure 18 display five representative correlations for these species. Overall, the majority of indicators tend to be negatively correlated with biodiversity data, to the exception of TSM CC and immersed cyanobacteria that show positive correlations.



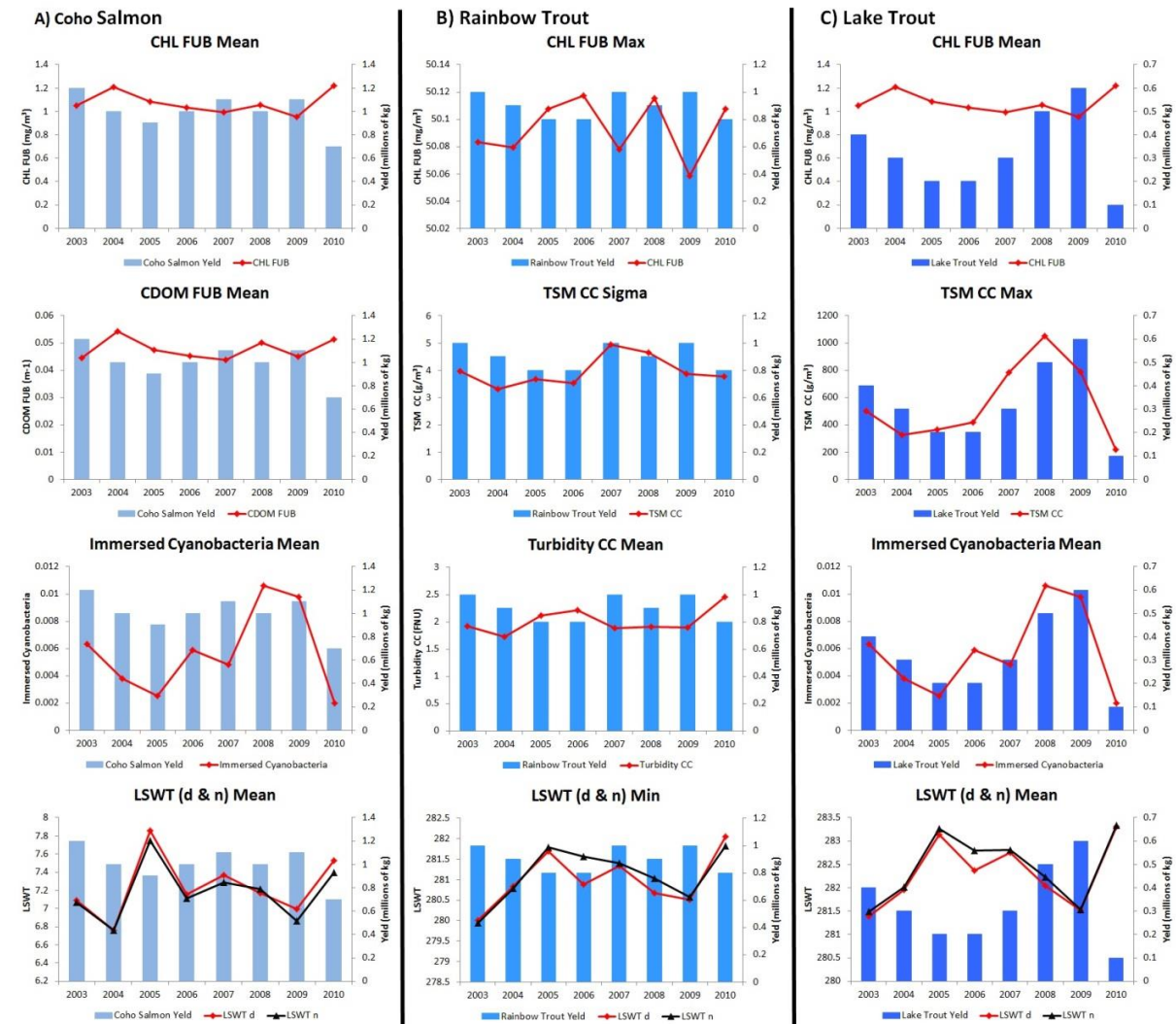


Figure 17: Yearly fish captures of three species and RS indicators for Lake Michigan trend analysis (Bunell, 2011). Charts depict biodiversity measure (right Y axis, blue bars) and RS indicator (left Y axis, red and black lines), from 2003 to 2010 (X axis). A) Coho salmon yearly yield depicted, from top to bottom, with CHL FUB Mean, CDOM FUB Mean, Immersed cyanobacteria Mean and LSWT (d & n) Means; B) Rainbow trout yearly yield depicted, from top to bottom, with CHL FUB Max, TSM CC Sigma, Turbidity CC Mean and LSWT (d & n) Means; C) Lake trout yearly yield depicted, from top to bottom, with CHL FUB Mean, TSM CC Max, Immersed cyanobacteria Mean and LSWT (d & n) Means.

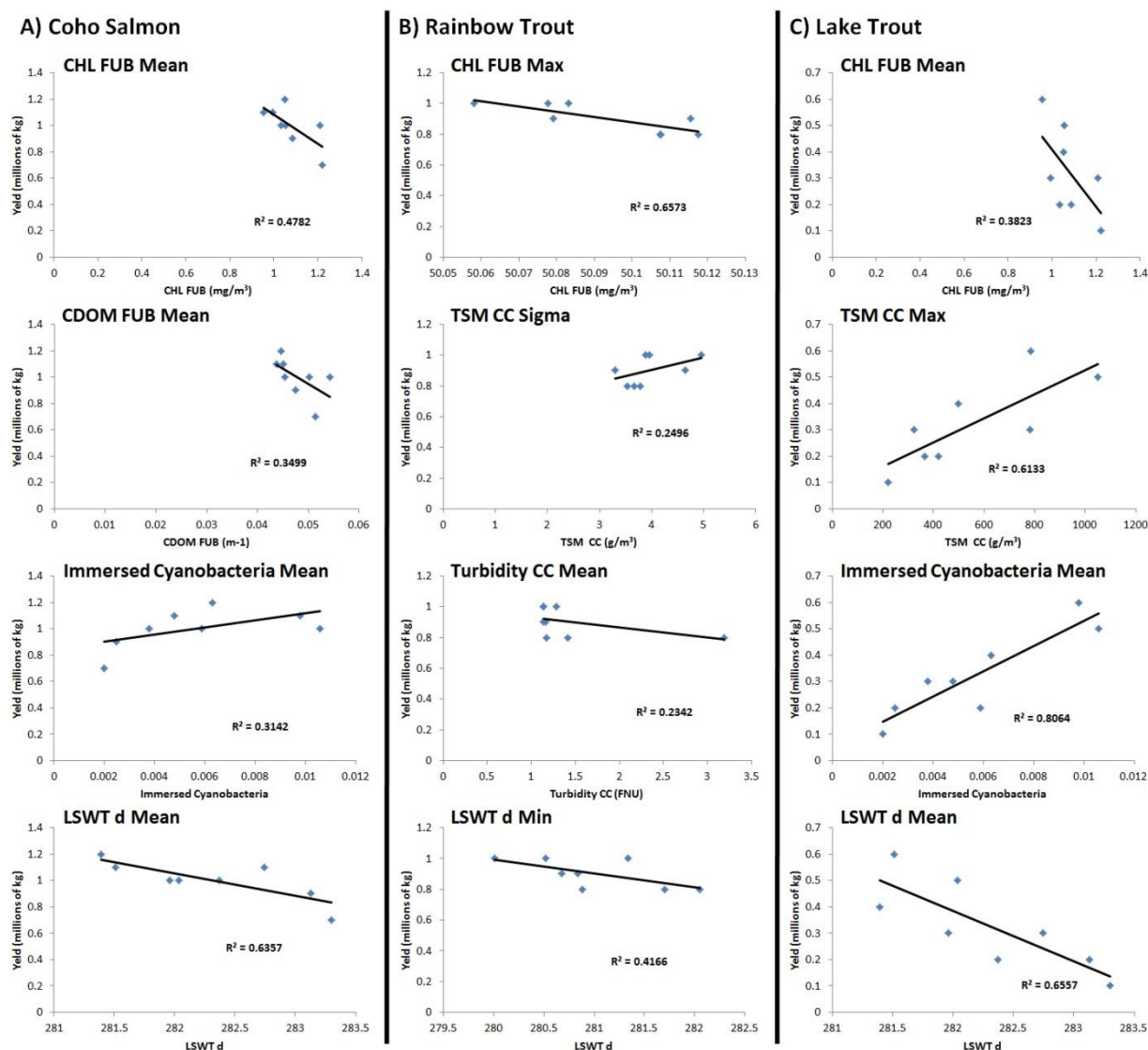


Figure 18: Statistically relevant correlations between indicators and biodiversity data based on Spearman's  $r$ . Scatter plots depict fish capture data (Y axis, yield) and RS indicators (X axis), per year (blue diamond shapes). A) Coho salmon yearly yield depicted, from top to bottom, with CHL FUB Mean, CDOM FUB Mean, Immersed cyanobacteria Mean and LSWT (d & n) Means; B) Rainbow trout yearly yield depicted, from top to bottom, with CHL FUB Max, TSM CC Sigma, Turbidity CC Mean and LSWT (d & n) Means; C) Lake trout yearly yield depicted, from top to bottom, with CHL FUB Mean, TSM CC Max, Immersed cyanobacteria Mean and LSWT (d & n) Means.

### 5.2.3 Biodiversity Trend Analyses, Lake Nicaragua

Trend data for Lake Nicaragua was extracted from Portocarrero (2013) and comprises yearly data on fish catch for six fish taxa, from 2002 to 2010. In order to assess if there was any kind of agreement between biodiversity and indicator measurements we conducted Spearman's rank order correlation analyses between RS indicators – including the mean, minimum, maximum and standard deviation (sigma) - and fish catch data. Significance of results were tested by their probability values ( $p$ ), considering a confidence level of  $p < 0.05$ .

Six statistically relevant correlations were obtained between biodiversity data and RS indicators (Figure 19 and Figure 20). Positive correlations are found for CHL MPH sigma, CHL FUB minimum and turbidity CC sigma, while for CHL FUB maximum, CDOM FUB mean and LSWT n sigma the relationship was negative.



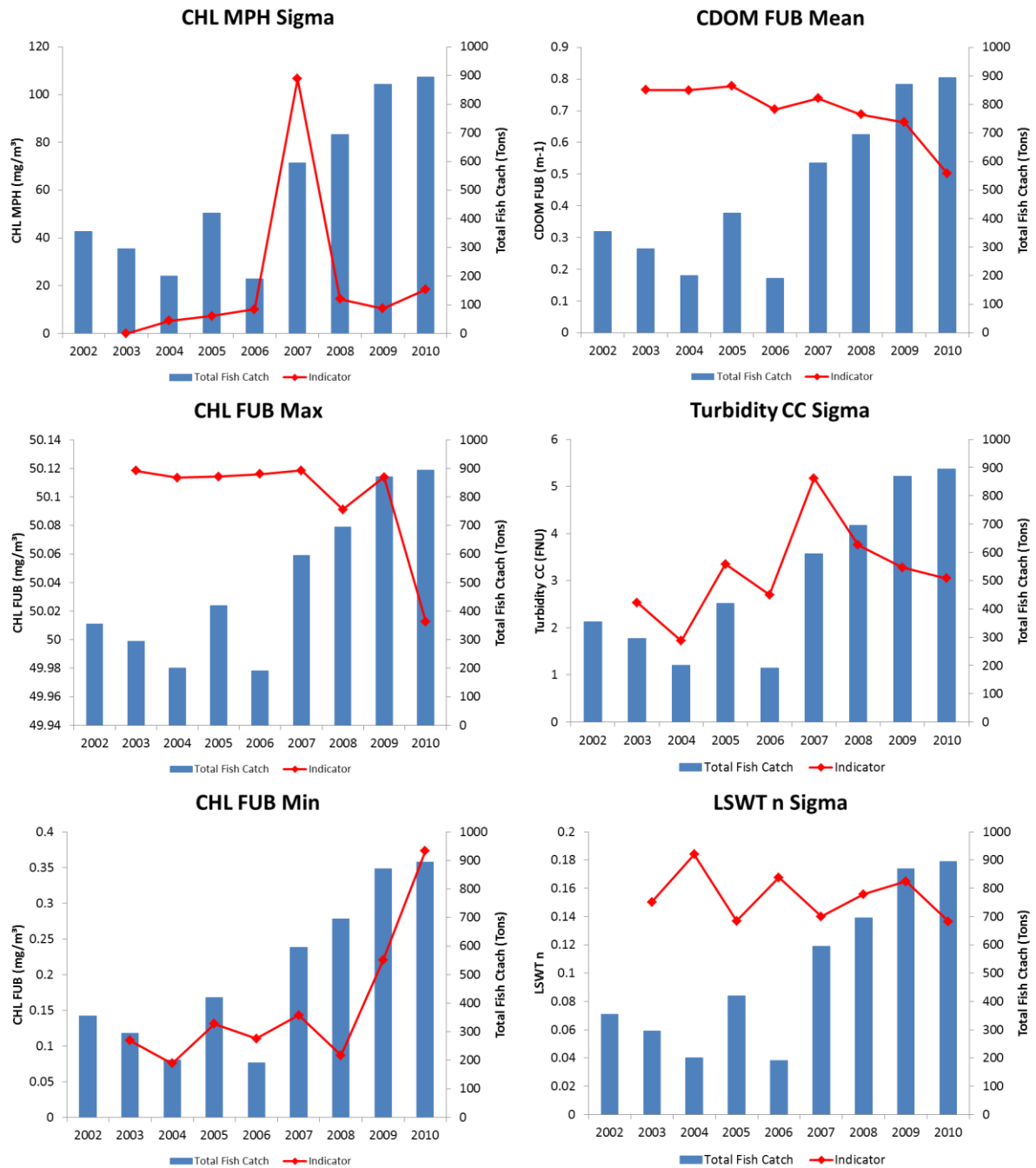


Figure 19: Yearly fish catch and RS indicators for Lake Nicaragua trend analysis (Portocarrero, 2013). Charts depict biodiversity measure (right Y axis, blue bars) and RS indicator (left Y axis, red line), from 2002 to 2010 (X axis).

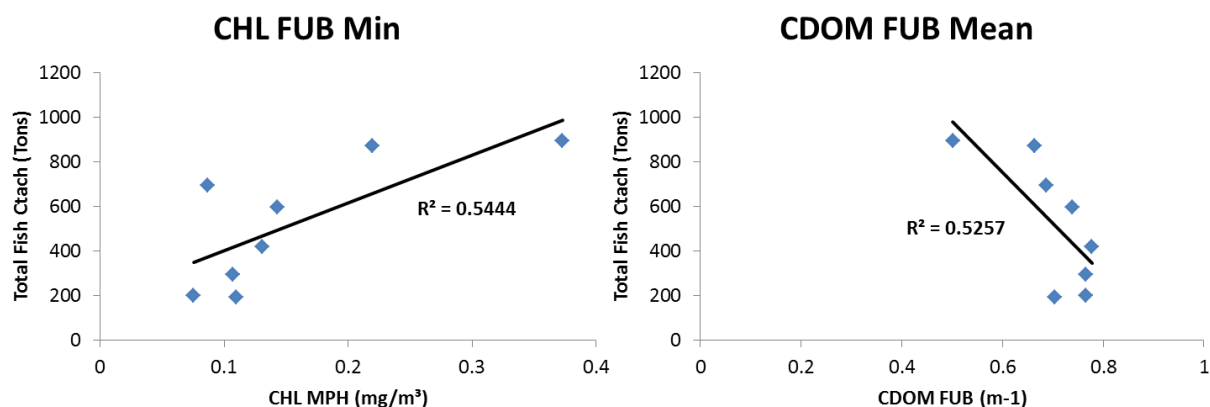


Figure 20: Statistically relevant correlations between indicators and biodiversity data based on Spearman's  $r$ . Scatter plots depict fish capture data (Y axis) and RS indicators (X axis), per year (blue diamond shapes).

## 6 Issues and Limitations

### 6.1 Product Properties and Indicator Accuracy

#### 6.1.1 Melting Spring Ice

Areas of melting lake ice in spring are optically very similar to water. The removal of such pixels by the Idepix algorithm failed in several cases, as illustrated in for Lake Vanern in March 2001 (Figure 8, left). Apart from the seasonal timing, very low values in *lswt\_n\_mean* can be considered as indicators for such cases, however no precise threshold can be specified due to their DINEOF nature. Spatial features provide another evidence for sufficiently large lakes, as sharp linear features frequently indicate lake ice borders. Suitable metadata for the identification of affected cases is provided by the Global Lake and River Ice Phenology Database (<http://nsidc.org/data/g01377>). It is generally recommended to handle spring monthly products with extraordinarily high values in all indicators with care.

#### 6.1.2 Lake Perimeter Inconsistencies

Narrow branches of GLWD polygons are often not included in Diversity II polygons. Comparing the two area estimates (see Section 3.3.2) may help to identify corresponding cases. GLWD lake area is more than twice the Diversity II lake area for the following lakes: Angostura, Ashuanipi, Bienville, Cross, Eskimo, Island, Kaminak, Keban Baraji, Lower Seal, Nueltin, Rainy, Sandy.

Several GLWD lakes are combined in one Diversity II polygon for:

- GLWD\_ID 86 (RUKWA), 260 (NULL)      ≈ ID 243 (RUKWA)
- GLWD\_ID 87 (KREMENSCH.), 361 (NULL)      ≈ ID 156 (KREMENSCH.)
- GLWD\_ID 99 (KYOGA), 325 (KWANIA)      ≈ ID 160 (KYOGA)
- GLWD\_ID 185 (TUZ), 1792 (NULL)      ≈ ID 296 (TUZ)
- GLWD\_ID 377 (NAKNEK), 1630 (NULL)      ≈ ID 196 (NAKNEK)

Single GLWD lakes are split in several Diversity II polygons for:

- GLWD\_ID 175 (NULL)      ≈ ID 163 (LUANG), ID 253 (SONGKHLA)
- GLWD\_ID 89 (IJSELMEER)      ≈ ID 134 (IJSELMEER), ID 183 (MARKERMEER)

## 6.2 Suitability as Biodiversity Proxies

During the validation process of DIVERSITY II products, including data extraction, analyses and interpretation of results, several precautions had to be taken into account in order to draw the maximum input from the derived RS indicators. In this chapter, encountered known issues are reported, recommendations for avoiding them or minimize their impact are presented, and possible solutions for the users are suggested.

### 6.2.1 Status

For the validation process the main source of biodiversity distribution data was the Global Biodiversity Information Facility (GBIF). The advantage of GBIF is that it is freely accessible and it comprises worldwide data submitted by Natural History museums and other institutions. Despite the huge amounts of data available, there are some concerns about accuracy and quality of the geographic, temporal, and taxonomic coverage, suggesting that GBIF records should be used only after a first careful inspection (Guralnick et al 2007, Beck et al. 2013, Costello et al 2013). Depending on the type of analysis, the user should take into account the following topics:

- **Time-period** – species distribution data should be collected in a time-period as similar as possible to the period of DIVERSITY II products (April 2002 to April 2012). Old distribution data may not be well suited for analysis since the landscape may have changed. We recommend the usage of most recently obtained data as possible.
- **Taxonomic revision** – many taxa names (species, sub-species, even genus) are outdated and may skew the number of records for the user's target taxa or group of taxa. We recommend checking certified biodiversity database, such as the IUCN Red List of Species ([www.iucnredlist.org](http://www.iucnredlist.org)), or available literature, for synonyms and taxonomic updates.
- **Geographic range** – many taxa are incorrectly assigned to certain geographic areas, as consequence of local extinction or presently being considered as exotic or invasive species. Depending on the user's intended investigation, we recommend to check for the most recent distribution ranges of the target taxa.

To use the DIVERSITY II products in full, the user should ideally have obtained locally high precision distribution data (coordinates collected in the field with a GPS), which can then be complemented with GBIF records, if needed.

DIVERSITY II products file sizes are considerably large due to their high resolution. When combining biodiversity data (or other environmental variables), the user may end up with very large volumes of data. This can become very difficult to handle, both in terms of practicality and computer power.

In terms of analyses feasibility (but also data extraction and processing), it may become less time consuming if the user has some knowledge on programming languages such as Python (useful with BEAM and ArcGIS), R (statistical analyses for example), Pearl, among others. The use of scripts, macros (for Excel) and batched processes (same task performed for various files) allow users to perform their analyses automatically and less time-consuming.

DIVERSITY II inland water products are provided in three different time frames – nine year averaged, annually averaged and monthly averaged. The user should select the time framed products best suited for their studies.

Users should also be aware of missing data present in the products (mostly related with noisy components, such as ice and cloud cover). If a product is composed by a high percentage of missing data for a certain time frame, then it is probably adequate to exclude the product from subsequent analyses.

### 6.2.2 Trend

An issue that may be encountered during the validation process of trend data is the mismatch between biodiversity data and DIVERSITY II products, whether it was in terms of spatial or temporal coverage (or even both at the same time). When the users' research involves investigating data through time, the following topics should be taken into consideration:

- **Sampling date** – DIVERSITY II inland water trend products can be provided at daily intervals, from April 2002 to April 2012. The exact date of when biodiversity data is obtained in the field should be known in order for the user to maximise the potential of the products.
- **Sampling effort** – Given the high temporal resolution of the DIVERSITY II products, user's biodiversity data should be collected systematically at equal intervals throughout the considered time frame.
- **Temporal frame** – DIVERSITY II products give measures of chlorophyll concentration, turbidity, water temperature, among others. However, biodiversity (especially animals) may react to changes in these parameters with a certain time delay. Also, many species are highly influenced by specific time periods (spring blooms and reproductive seasons for example). All of these factors differ from taxa to taxa. The user should test different product averaging schemes (see the Lake Vanern example given above). Depending on the user's objectives, time frames could go from the exact same date of the sampling effort, to an average during the spring bloom or even annual averages.
- **Geographical extent** - DIVERSITY II products' resolution is 300x300m<sup>2</sup>, but data can be extracted for a larger area, depending on the user's target taxa. While for some species it may be interesting to use pin-point measures of water parameters (low dispersal organisms or highly associated with certain habitats), in other cases it may be better to extract data for a wide area such as an enclosed bay or the entire lake (high dispersal, generalist organisms).
- **Data gaps** – DIVERSITY II products come with data gaps (related for example with cloud or ice cover) throughout the time series, so users should be aware of this when performing their research.

To summarize, for users to take full advantage of the DIVERSITY II products, optimized biodiversity data should have been collected, with spatial and temporal high resolutions.

## 7 Biodiversity Stories

In addition to indicator and map outputs, a number of biodiversity stories have been composed by local experts and project partners. The primary purpose of the stories is to exemplify the value brought by the EO products by providing detailed material about the biology of the sites and how it is manifested in the products. However, their use is also described in view of other purposes, such as further analyses using spatial statistics. Most biodiversity stories include a general presentation of the study site, its biodiversity and a demonstration of the status and/or trend for the lake based on the Diversity products together with an interpretation of them. The completed Inland Waters Biodiversity Stories are listed in Table 5.

Table 5: Overview of the Diversity II biodiversity stories available at <http://www.diversity2.info/products/>.

Site	Theme	Authors
Lake Balaton	Identifying homogenous regions for Chlorophyll in Lake Balaton	O'Donnell, R, Miller, C. and Scott, M. (Univ. of Glasgow)
Lake Biwa	Earth observation indicators for hypoxia in Lake Biwa	Odermatt, D. (Odermatt & Brockmann GmbH)
Lake Geneva	Growth conditions for <i>Mougeotia sp</i> in Lake Geneva	Bouffard, D. (APHYS, EPFL-ENAC), Anneville, O. and Rimet, F. (INRA UMR CARTEL)
Lake Nicaragua	Assessing Earth observation techniques for water quality monitoring in Lake Nicaragua	Greb, S. (Wisconsin Dept. of Natural Resources)
Lake Turkana	Lake Turkana – monitoring the 'Jade Sea' from space	Tebbs, E. (Centre for Ecology and Hydrology), Avery, S. (Kenya Wetlands Biodiversity Research Team & Univ. of Leicester and Odermatt, D. (Odermatt & Brockmann GmbH)
Lake Vanern	EO supported assessment of fish ecology in Lake Vänern	Philipson, P. (Brockmann Geomatics AB) and Sandström, A. (Swedish Univ. of Agricultural Sciences)
Lake Victoria	Traces of Eutrophication in Winam Gulf, Lake Victoria	Ledang, A. B. (NIVA) and Odermatt, D. (Odermatt & Brockmann GmbH)
Lake Winnebago	Toxic Cyanobacterial Blooms in Lake Winnebago	Greb, S. (Wisconsin Dept. of Natural Resources) and Miller, T. (Univ. of Wisconsin-Milwaukee)
Various	Tools from Earth Observation for Lake Management in Emerging Countries	Matthews, M. (CyanoLakes Pty Ltd.) and Odermatt, D. (Odermatt & Brockmann GmbH)

## 8 Synthesis

The water quality and quantity products from Diversity II compose the first globally representative archive that consists of biological and physical indicators for lakes from

remote sensing. On one hand remote sensing allows for spatially more comprehensive, and methodologically more consistent product archives than any other approach. On the other hand, remotely sensed products are limited in view of vertical gradients, and the relationship between the directly retrieved optical parameters and biophysical concentration units are subject to considerable uncertainties. Empirical adjustment is relatively simple where reference measurements are available, but otherwise absolute levels must be used with reasonable care. Trends, distinctive temporal patterns and anomalies, as well as relative dynamics in potentially reciprocal parameter combinations can however be identified at relatively high certainty.

Initial analyses on the biodiversity relevance of the Diversity II inland water products were performed in the scope of the project. They revealed striking evidence of documented environmental processes, although the availability of ground reference biodiversity data for lakes, in particular with regards to the spatial domain, complicate the direct comparability of ecosystem parameters and species abundance. Therefore key challenge in the further use of the product archive will be to develop sound cause and effect concepts that can be generalized for an appropriately constrained selection of lakes.

The Diversity II products were compiled with due attention to state-of-the-art methodology, but it is an inherent asset of remotely sensed product archives that they can and will be recompiled upon the arrival of improved processing methods. Against this background, the handbook at hand shall also enable users to review the products and express their opinion in view of improvements for related activities in the future. We appreciate all feedback submitted to [info@diversity2.info](mailto:info@diversity2.info).

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