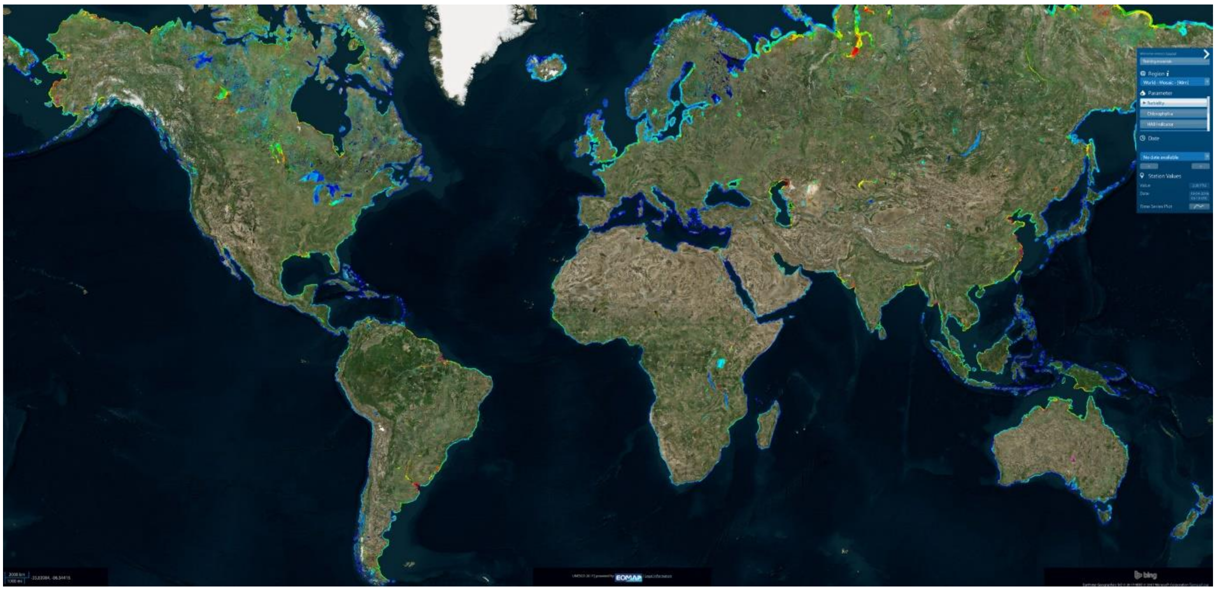

The UNESCO-IHP IIWQ World Water Quality Portal

- Whitepaper -

International Initiative on Water Quality (IIWQ)

This document is accessible through the UNESCO-IHP IIWQ World Water Quality Portal.

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In partnership with: EOMAP GmbH & Co.KG, Seefeld / Germany.

Errors and technical modification subject to change.

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In partnership with

Contents

Abbreviations

EO	EarthObservation
eoHAB	Harmful Algae Bloom Indicator
EWS	EOMAP Workflow System
FEM	Finite Element Model
HPLC	High-performanceLiquid Chromatography
IHP	InternationalHydrological Programme
IIWQ	InternationalInitiativeonWaterQuality
MIP	Modular Inversion andProcessing System
RTD	Radiative Transfer Database
SIOPs	Specific Inherent OpticalProperties

Executive Summary

Access to country-wide or transboundary status information and trends of water quality in inland and coastal waters is essential for high-level water-resource-management of governmental bodies. Such information can support efficient planning on localized comprehensive measurements and serve as a continuous monitoring instrument. Consistent and independent water quality information can be derived extremely cost-efficient and with a minimum of logistical effort for millions of inland and coastal waterbodies, using measurements from satellite-based earth observation (EO) sensors. State-of-the-art, globally harmonized information products in conjunction with a very user-friendly web access support this demand efficiently.

UNESCO, through its International Initiative on Water Quality (IIW) under the International Hydrological Programme (IHP), supports member states in responding to water quality challenges by promoting scientific research, mobilizing and disseminating knowledge, facilitating the sharing and exchange of technological and policy approaches, fostering capacity building, and raising awareness on water quality[1]. It now publishes the first comprehensive global water quality atlas for freshwater systems like lakes and rivers as well as coastal regions retrieved from satellite-based earth observation data. The information is made freely accessible through the IIWQ World Water Portal at:

www.worldwaterquality.org

Water quality products such as turbidity, Chlorophyll content or indicators for toxic Cyanobacteria blooms can now be mapped worldwide with weekly or even daily sampling frequencies under cloud-free conditions. In this first version, a merged global set of parameters is provided at 90m resolution. Time series products are provided at 30m resolution for selected regions of each continent, covering the year 2016. Nowadays, this can be continued for every country and, for historical views, even up to 30 years back in time. With this technology, various temporal and spatial resolutions with accuracies down to a few meters are supported by utilizing a number of different satellite sensors with physics-based analysis technologies.

UNESCO provides direct access to spatial and time series information through its IIWQ portal, a web application accessible from desktop computers as well as mobile devices. It includes functionalities to view water quality measures online and export reports for user defined water bodies and parameters. Environmental managers, politicians and scientists can ingest the service directly into their geospatial information systems for analysis and assessments. Training materials, supporting users to utilize the new information sources, are provided as well within the IIWQ portal.

[1]International Initiative on Water Quality, UNESCO 2015: http://unesdoc.unesco.org/images/0024/002436/243651e.pdf

1. The Unesco-IHP IIWQ World Water Quality Portal

The access to detailed global water quality information is provided online at the IIWQ portal at www.worldwaterquality.org. Here, users can find data for all continents. The web application enables users to interactively browse and access satellite based water quality measurements. Additionally, simple reports, including statistical measures over a full year, can directly be exported for any user-defined station and parameter within the respective time series regions. The digital maps show the turbidity, Chlorophyll, absorption parameters or harmful algae bloom indicators for selected time periods.

A short User Guide for the web application is accessible through the respective button in the main menu (seeFigure 1, top right), describing the satellite-based water quality methodology for a broader audience. Furthermore, a training and capacity building document (this document) about how to utilize satellite-derived information products is included there.

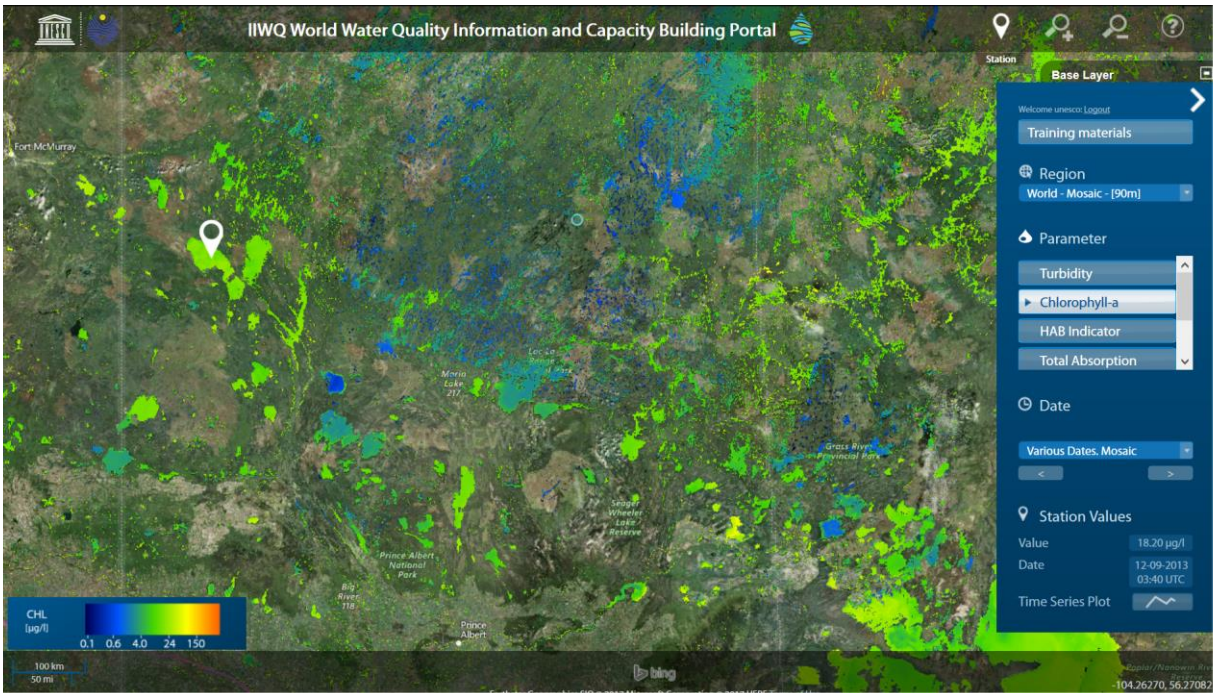

Figure 1: Screenshot of the web application with Chlorophyll data for parts of Saskatchewan and Manitoba, Canada.

In the top bar, the user will find the basic tools for interacting with the map, such as panning, zooming or placing a virtual measuring station. Control panels on the right-hand side allow for the selection of the region of interest and various water quality parameters, but also gather and display values and time series information. When a virtual station has been set, a respective button at the bottom right of the main panel provides access to a graph showing all underlying values for different time steps and therefore gives a visual indication about temporal changes over time (see Figure 2). Below these time series plots, users find a button for reporting, which generates and exports a report in pdf format (see Figure 3), including statistical measures such as mean, minimum and maximum value for the selected coordinate and parameter.

Supported spatial and temporal resolutions

The World Water Quality Portal supports easy access to various spatial and temporal resolutions, which can be provided based on different satellite sensors. The related requirements on the inter-comparability of sensors as well as long-term continuity are fulfilled through the usage of fully physics-based analysis and data processing, providing harmonized, physically calibrated water quality properties. Further details are described in the chapter Technical background.

The merged global dataset of this first version of the portal is provided at 90m resolution, while the time series of 2016 for selected regions is available at 30m. This dataset is based on three different satellite sensors: Landsat 7, Landsat 8 and Sentinel-2a.

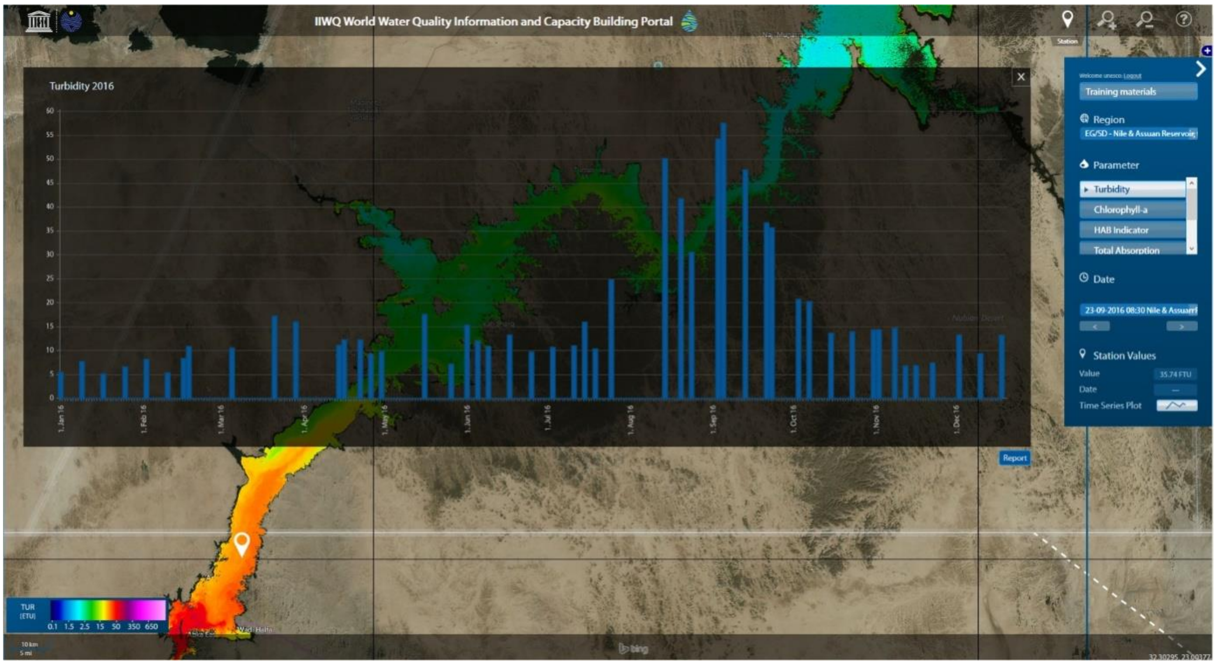

Figure 2: Screenshot of a time series at a virtual station in Lake Nubia, Sudan, as part of the Aswan reservoir, showing the seasonal turbidity trend over the year 2016.

The high temporal and spatial resolution allows for the generation of water quality reports for individually defined virtual stations (Figure 2 and Figure 3). In terms of temporal frequency, currently an 8-day revisit cycle for the 30m products is available by using both Landsat 7 and Landsat 8 satellites from USGS/NASA. This is further enhanced with the European Copernicus Sentinel-2a and -2b satellites run by ESA, which have a 5-day revisiting period and provide a spatial resolution of 10m and 20m. Jointly, this results in up to 10 records per month under cloud-free conditions, or 20-50 records per year, always depending on the regional cloud cover statistics and other environmental impacts. A daily coverage for larger lakes is feasible using 300-500m resolution satellites such as MODISAqua and Terra or Sentinel-3, also operated by NASA and ESA. For some applications, even higher spatial and temporal resolutions may be required. Using physics-based and sensor-independent technologies such as the ones applied here, satellite-based water quality products are also available at resolutions of up to 1-5 m by using various commercial satellite sensors with up to several records per day. Historical satellite systems such as Landsat 5 make it possible to reach back in time and extend monitoring periods for more than 30 years.

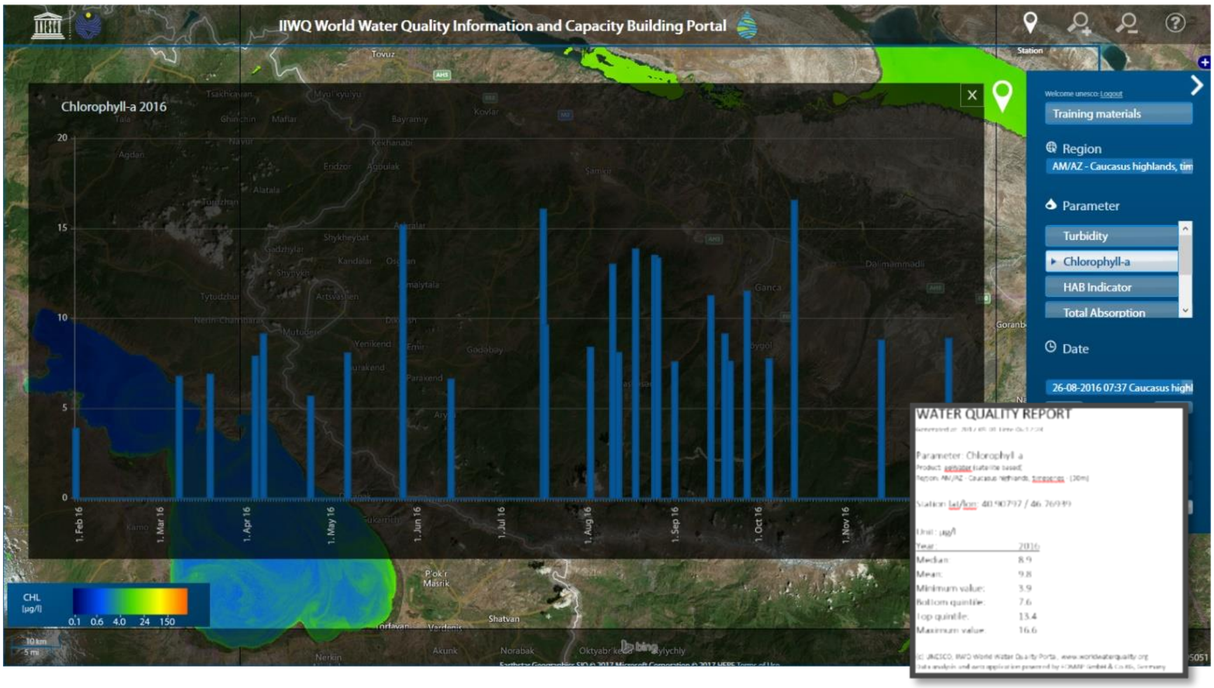

Figure 3: Screenshot of a water quality report, showing the exported statistical analysis of Chlorophyll in the year 2016 over a virtual station in Mingachevir Reservoir, Azerbaijan.

2. Product information

The IIWQ portal hosts water quality information from the eoWater product series of EOMAP. eoWater products are consistently generated over different satellite sensors using globally applicable, physics-based algorithms of the Modular Inversion and Processing System(MIP; see chapte rTechnical background). These EO-based measures and their physical units directly relate to absorption and scattering properties of the water body and thus are harmonized and globally comparable. For example, turbidity is linearly related to the physical process of backscattering of light, while Chlorophyll and organic components relate likewise to its absorption.

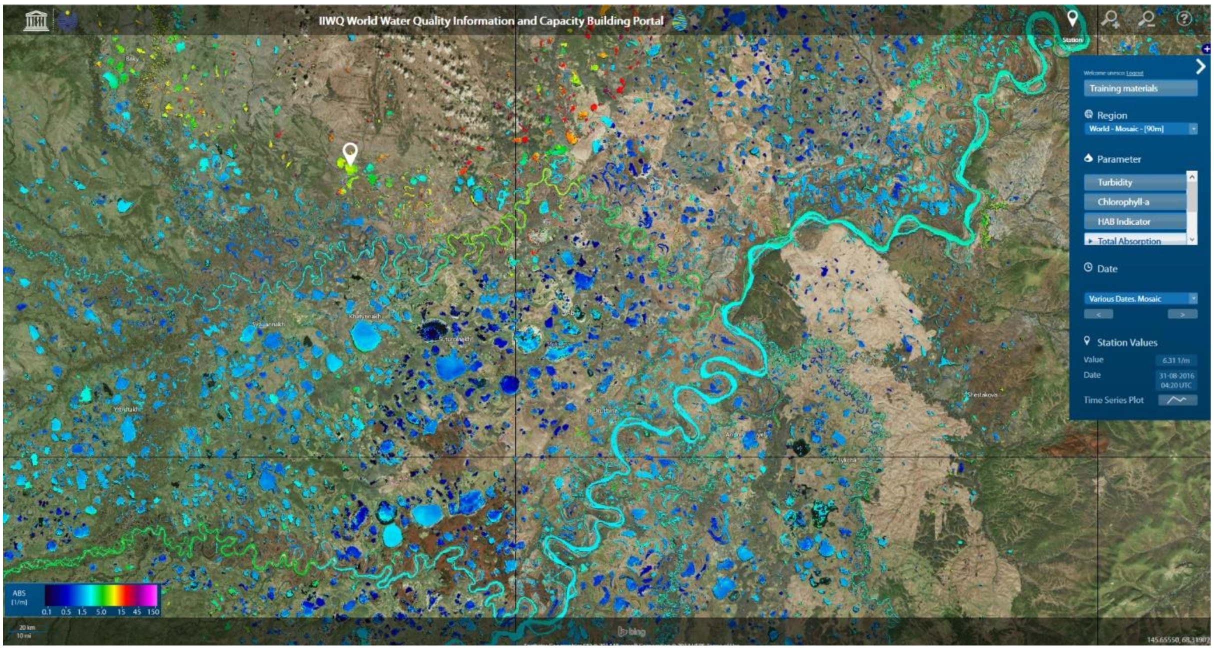

Figure 4: Screenshot of the total (organic and inorganic) absorption of water constituents in the Sakha Republic, Russia, showing the river system of ProtokaUlarovskaja, Selennjach and RekaUyandinawith adjacent inland waters.

- Turbidity (TUR) is a key parameter of water quality and is linearly related to the backward scattering of light by organic and inorganic particles in the water. It is also linearly related to Total Suspended Matter (TSM) for low to moderate turbidity values[2]. The measurement unit is Formazine Turbidity Unit [FTU], which is similar to the Nephelometric Turbidity Unit [NTU]. 1FTU corresponds to 0,0118/m backscattering at 550nm. Turbidity from satellite measurements is determined by measuring the backward scattering of light between 450 and 800nm. The geometrical properties and wavelengths used by in-situ measurement devices may differ in comparison to the satellite product. For example, the standard FTU determination is based on the measurement of light scattered within a 90° angle from a beam directed at the water sample (meaning "sidewards"), while satellite measurements use a scattering angle of approx. 180°(meaning "upwards"). Note: As the shape, size and spectral characteristics of particles vary, the exact relationship between scattering and turbidity may also vary across both location and time (e.g. when the phytoplankton species composition changes).
- Total absorption (ABS) is retrieved from the absorption of light by particulate and dissolved organic and inorganic matter. The relative contribution of inorganic absorptions varies for changing specific inherent optical properties (SIOPs), which are monitored within the retrieval algorithms. The Unit is absorption at 440nmin [1/m]. The total absorption product includes the absorption of organic and inorganic components, which are not shown separately at this portal.
- Chlorophyll-a (CHL) is a pigment included in phytoplankton cells and serves as a proxy for algae in natural waters. Chlorophyll, measured in [µg/l], is provided as a measure that is linearly related to the pigment-specific absorption at 440nm, with 1µg/l Chlorophyll corresponding to 0.035/m pigment absorption. Pheophytin and further pigments cannot be discriminated methodologically with the spectral resolution provided by Landsat 8 and similar

[2] Turbidity in unit FTU or NTU is related to the suspended matter concentration in [mg/l] roughly in a 1:1 ratio. Depending on the particle size distribution and particle agglomeration, the ratio may increase by factor 10 or higher e.g. to 1:10. Therefore, local calibration or as minimum verification is required if the turbidity shall be used as proxy for suspended matter.

sensors and is therefore included in this product. The pigment-related absorption is always smaller than the absorption of organic components.

- The Harmful Algae Bloom Indicator (eoHAB)is sensitive to the appearance of Phycocyanin and Phycoerythrin, which are pigments typically found within the most common Cyanobacteria species. The product does not provide a quantitative measure, but identifies reflectance and absorption discrepancies between the 550nm and 650nm wavelength bands, which indicate the appearance of the Cyanobacteria-related pigments.

The reliability of remote sensing products is influenced by a number of factors, which, under specific conditions, can degrade the quality of certain parameters. Water properties such as turbidity and total absorption have the highest validity over the widest range of water types. The most sensitive product, Chlorophyll, is expected to show validity limitations in turbid rivers containing specific increased inorganic components, in iron- and calcareous-dominated waters as well as in very dark waters with high amounts of humic acids (see chapterLimitations).

3. Technical background

Water has specific reflectance characteristics (measured at different wavelengths of light, so called spectra), based on the scattering and absorbing properties of their optically active constituents. These are directly related to relevant water quality parameters such as turbidity and suspended matter, phytoplankton and its main pigment Chlorophyll, detritus and dissolved colored organic matter. With the knowledge of their optical characteristics it is possible to retrieve quantitative values of the concentrations for these water constituents, solely based on the reflectance of light measured by satellite sensors.

The water quality products at the IIWQ portal are generated within a fully physics-based retrieval approach, using the Modular Inversion and Processing System MIP[3][4][5][6]. Such approaches are capable to provide harmonized, globally comparable basic products[7]due to their relation to the absorption and scattering properties of water constituents. This concept ensures the long-term continuity of the IIWQ data: Products related to physical units are in principle not restricted, neither to specific algorithms nor to dedicated production software.

The initial version of MIP was developed at the German Aerospace Center (DLR) and the Technical University of Munich(TUM) from 1996 on and has been continued since 2006 within the company of EOMAP. MIP has been subject to extensive validations within international research projects and commercial applications for a wide range of lakes, reservoirs and rivers worldwide (see chapterValidity).

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[3]Heege, T., Fischer, J. (2004): Mapping of water constituents in Lake Constance using multispectral airborne scanner data and a physically based processing scheme. Can. J. Remote Sensing, Vol. 30 (1), pp. 77-86

[4]Heege T, Kiselev V., Odermatt D., 2008: How can I map water constituent concentrations? In: Fitoka, E.&Keramitsoglou, I.(editors) (2008): Inventory, assessment and monitoring of Mediterranean Wetlands: Mapping wetlands using Earth Observation techniques. EKBY & NOA. MedWet publication. (scientific editor Riddiford, N.J.)

[5]Heege, T., Kiselev, V., Wettle, M., Hung N.N. (2014): Operational multi-sensor monitoring of turbidity for the entire Mekong Delta. Int. J. Remote Sensing, Special Issues Remote Sensing of the Mekong, Vol. 35 (8), pp. 2910-2926

[6]Dörnhöfer, K., Klinger, P., Heege, T., Oppelt, N. (2017): Multi-sensor satellite and in situ monitoring of phytoplankton development in a eutrophic-mesotrophic lake. Science of the Total Environment 612C (2018), pp. 1200-1214, http://dx.doi.org/10.1016/j.scitotenv.2017.08.219

[7]Bumberger J., Heege T., Klinger P., Röttgers R., Utschig C., Krawczyk H., Gerasch B., Gege P., Grossart H-P., Jechow A., Stelzer K., Werther M., Frassl M., Lausch, A., Rinke K., Borg E., Oppelt N. (2018): Towards a Harmonized Validation Procedure for Inland Water Optical Remote Sensing Data using Inherent Optical Properties, Internal Report of the German Environmental Research Centre UFZ.

Within MIP, all physical relationships, e.g. those between in-water absorption and backscattering and at-sensor radiances, are calculated by a highly accurate reference radiative transfer model and stored in a large Radiative Transfer Database(RTD) for usage by retrieval algorithms. The radiative transfer model is based on a Finite Element Model (FEM)[8], calculating the light transfer in a multi-layer system, including atmosphere, water surface[9][10], water body and seafloor. All bidirectional dependencies of scattering and absorption properties in the atmosphere and the water body as well as bidirectional reflectance and transmission of the water surface are accounted for within this FEM, as well as the full range of possible geometrical conditions between sensor, sun and target (the individual water pixels). The accounted dependencies include variable water level and observer altitudes, variable atmospheric aerosol properties and other parameters. Light polarization is not accounted for,possible fluorescence is set to zero (since it is extremely rare in surface waters) and the ozone correction algorithm[11] uses a standard value for ozone content in this survey. Semi-analytical formulas[12] for the description of the underwater light field and decoupling of atmospheric and in-water calculations as practiced in former MIP versions before 2015 are no longer used in the fully physics-based and fully coupled software version used here, to improve the accuracy in global applications.

The retrieval algorithms applied here account and correct for each individual point measurements and a number of environmental impacts: the adjacency impact of reflected by the land surface and interfering with light reflected by the waterbody is accounted for by following the procedure of Kiselev[13]. It calculates and corrects the impact of lateral scattering from adjacent land targets in terms of contributing adjacency radiance. The altitude of the water level is reflected as variable within the Radiative Transfer Base and thus accounted and corrected for each individual pixel through usage of a global elevation data set. Reflection of sunlight at the water surface[14] is accounted for in different elements: (i) in form of the physical implementation of the bidirectional water surface in FEM and the RTD; (ii) the spatial variations of sun glint are still partially compensated through the retrieved aerosol content (independent sun glint correction is accounted with the 2018 MIP version); (iii) high levels of sun glint are flagged depending on the calculated sun glint appearance[15]. The central algorithm for water quality retrievals uses the radiative transfer database to simultaneously retrieve the atmospheric aerosol content and in-water absorption and backscattering properties.

Due to the consistent physical implementation, MIP is applicable for any water type and any remote sensing sensor delivering calibrated radiance input spectra. The retrieval algorithm is controlled by a least square minimization of the modelled versus the measured sensor radiances. It includes a full error propagation model to calculate internal used uncertainties. For SIOPs, an established configuration for inland waters has been used, where the wavelength dependency of scattering is

[8]Kiselev, V.B., Roberti, L. and Perona, G. (1995): Finite-element algorithm for radiative transfer in vertically inhomogeneous media: numerical scheme and applications. Appl. Opt., 34, 8460-8471
[9]Kiselev, V.; Bulgarelli, B. (2004): Reflection of light from a rough water surface in numerical methods for solving the radiative transfer equation. Journal of Quantitative Spectroscopy and Radiative Transfer 85, 419-435.
[10]Bulgarelli, B., Kiselev, V., Roberti, L. (1999): Radiative Transfer in the Atmosphere Ocean System: The Finite-Element Method. Appl. Opt. 38, pp. 1530-1542
[11]Richter, R., Heege, T., Kiselev, V., Schläpfer, D. (2014): Correction of ozone influence on TOA radiance. Int. J. of Remote Sensing. Vol. 35(23), pp. 8044-8056,http://dx.doi.org/10.1080/01431161.2014.978041
[12]Albert, A., Mobley, C. D. (2003): An analytical model for subsurface irradiance and remote sensing reflectance in deep and shallow case-2 waters. Optics Express, 11(22), 2873 -2890
[13]Kiselev, V., Bulgarelli, B., Heege, T. (2014): Sensor independent adjacency correction algorithm for coastal and inland water systems. Remote Sensing of Environment, ISSN 0034-4257, http://dx.doi.org/10.1016/j.rse.2014.07.025
[14]Heege, T., Fischer, J. (2000): Sun glitter correction in remote sensing imaging spectrometry. SPIE Ocean Optics XV Conference, Monaco, 16.-20. Oct. 2000
[15]GLASS EU FP7-Projekt (2014): WP3 D3.2 Atmospheric correction report. http://www.glass-project.eu/assets/Deliverables/GLaSS-D3.2.pdf

described in Heege&Fischer[16], and the absorption of water constituents is described as a mixture between a Gaussian absorber model[17] and a phytoplankton-specific absorption spectrum as used by Heege[18]. Further adaptations of the specific optical properties to the characteristics of specific waters such as highly humic or highly sediment-loaded waters can improve the accuracy of the retrievals and are so far performed for regional applications, but not yet for this version provided here. For global applications, an automated adaptation to these specific characteristics is planned to be operational from summer 2018.

Various satellite data sources were used to generate the water quality products. To comply with the requested spatial resolution of 30m and 90m, data of the satellites Landsat 5,7,8 and Sentinel 2 data were used. The data processing is orchestrated by the EOMAP Workflow System (EWS) for automated job scheduling, using server infrastructures of EOMAP and of external commercial cloud computing providers. The data products and the IIWQ web application are stored and hosted on a Geoserver within a cloud computing facility.

4. Validity

Comparisons of satellite-derived products with in-situ measurements are used to prove the validity of the range of the water quality outputs. Both, the validation and automated processor-internal retrieval controls, shall help to evaluate the quality and to understand the harmonized nature of the products.

Validation exercises of water quality parameters are complex because of the highly dynamic nature of inland and coastal waters - concentration ranges over 4-5 magnitudes are common. The range within each waterbody typically varies by factor 10-100 over time and space. Reliable validation therefore requires time- and location-coincident measures, but this is rarely achievable. In-situ measures are seldom fully inter-comparable due to differences in the methodology applied, the sampling depth and the uncertainties in the sampling location or the applied in-situ analysis.

To prove the validity of EOMAP's processes, the system was therefore tested on temporal, seasonal and spatial quantitative consistency over a large range of waterbodies around the globe, and compared to data with in-situ measurements over a wide range of inland water bodies within several European and international projects[19]. The results are summarized and accessible online at:

http://www.eomap.com/exchange/pdf/EOMAP_Validation_Examples_Water_Quality.pdf

[16] Heege, T., Fischer, J. (2004): Mapping of water constituents in Lake Constance using multispectral airborne scanner data and a physically based processing scheme. Can. J. Remote Sensing, Vol. 30 (1), pp. 77-86

[17] Gege, P., (2000): Gaussian model for yellow substance absorption spectra.Proc. Ocean Optics XV, Monaco 16.-20. Oct. 2000

[18] Heege T (2000): Flugzeuggestützte Fernerkundung von Wasserinhaltsstoffen im Bodensee (Ph.D. thesis, Freie Universität Berlin), publishedas Research Repoert Vol. 2000-40 by Deutsches Zentrum für Luft- und Raumfahrt, Köln (Germany), ISSN 1434-8454

[19] FRESHMON. 12/2010 - 11/2013. Development of satellite based freshwater monitoring services. Funded by EU FP7. Consortium coordinator: EOMAP. www.freshmon.eu

WISDOM. 10/2010 - 9/2013. Bilateral German-Vietnamese project consortium, developing an Information System for the Mekong delta. Fundet by BMBF/Germany. EOMAP: Water Quality Remote Sensing project. http://www.wisdom.caf.dlr.de/

GLASS 3/2013 - 2/2016. Global Lakes Sentinel Services. Funded by EU FP7.

INFORM 1/2014 - 12/2017 Research on Remote Sensing Services for Inland Waters. EU FP7 fund

WOODSIDE ENERGY 2007 - 2010. Operational daily dredging impact monitoring for regulatory requirements, Mermaid Sound Australia. http://earth.eo.esa.int/workshops/gasoil2010/Hausknecht.pdf

BAW 2014. River Elbe Suspended Matter Monitoring Project for BAW National Water Construction Agency. Operational generation of SM maps from Landsat 7 & 8

Validation exercises

The MIP processing system is proven and validated for a wide range of inland waters, lakes and rivers around the globe. Validations were performed within projects financed by the European Commission and are publicly available within the respective reports of the EU-GLASS[20] and EU-FRESHMON[21] projects. Especially in the most recent projects such as the EU-GLASS or the current EU-SPACE-O, validations for the universal EOMAP processors mainly focus on independently retrieved water quality information in the standard processing mode. The same applies to recent validation studies of the University of Kiel[22] and the German Environmental Research Center (UFZ)[23].

For the Mekong delta, validation results are available in publications resulting from the WISDOM[24] project. Further validations were undertaken by a number of clients in Australia, USA or Germany, including Water Agencies (e.g. Environmental State Authority Baden-Württemberg (LuBW), Federal Waterways Engineering and Research Institute (BAW), Environmental Authority Italy (ISPRA), by large industrial companies such as AmecFosterWheeler, RioTinto or Woodside Energy as well as water industry and environmental consultancy companies. The EOMAP processors are also used as the official ground segment processor for the upcoming hyperspectral satellite EnMAP to provide atmospherically corrected data of water areas[25]. A large number of validation exercises is summarized and publicly available at the EOMAP homepage[26].

In the light of the huge variety of waterbody types around the globe and the sparse availability of in-situ data in comparison to the actual satellite sampling rates, further major efforts should be spent on extended validation exercises, and the consideration of the various uncertainty sources causing differences: Instrinsic, epimistic and ontologicaluncertainties.

Comparability of in-situ and satellite data

When comparing EOMAP water quality products with in-situ data, the methodological differences between the various in-situ approaches and remote sensing need to be accounted for. For example, in-situ turbidity measurements are typically based on the scattering of light at a 90° angle between light source and detector, while remotely sensed turbidity products are physically related to a scattering angle of approx. 180° (backscattering; see also Product information). Chlorophyll from in-situ measurements is typically based on one of three different methods, which include photometric, fluorescence and High-performance liquid chromatography (HPLC) approaches and their subcategories. In the physics-based method applied at EOMAP, remotely sensed Chlorophyll is related to a linear relation of both pigment-specific absorption and scattering. The pigments contributing to

[20]EU FP7-Projekt GLASS: WP4 Validation report (29. Feb.2016): www.glass-project.eu/assets/Deliverables/GLaSS-D4.2.pdf

[21]EU FP7-Projekt FRESHMON: WP54 Final Calibration and Validation Report (Update 31. Oct. 2013): www.freshmon.eu/static/media/uploads/fm_ph3_wp54_d543_update_pr.pdf, and EU FP7-Projekt FRESHMON: Project summary and final project report (29. Jan. 2014): http://cordis.europa.eu/result/rcn/141731_en.html ; http://cordis.europa.eu/docs/results/263287/final1-fm-wp11-final-report.pdf

[22]Dörnhöfer, K., Klinger, P., Heege, T., Oppelt, N. (2017): Multi-sensor satellite and in situ monitoring of phytoplankton development in a eutrophic-mesotrophic lake. Science of the Total Environment 612C (2018), pp. 1200-1214,http://dx.doi.org/10.1016/j.scitotenv.2017.08.219

[23]Bumberger J., Heege T., Klinger P., et al: (2018): Towards a Harmonized Validation Procedure for Inland Water Optical Remote Sensing Data using Inherent Optical Properties, Paper in preparation, to be submitted 2018

[24]Heege, T., Kiselev, V., Wettle, M., Hung N.N. (2014): Operational multi-sensor monitoring of turbidity for the entire Mekong Delta. Int. J. Remote Sensing, Special Issues Remote Sensing of the Mekong, Vol. 35 (8), pp. 2910-2926

[25]de Miguel, A.; Bachmann, M.; Makasy, C.; Müller, A.; Müller, R.; Neumann, A.; Palubinskas, G; Richter, R.; Schneider, M; Storch, T.; Walzel, T.; Wang, X.; Heege, T.; Kiselev, V. (2010): Processing and Calibration Activities of the Future Hyperspectral Satellite Mission EnMAP. Proceedings of the Hyperspectral Workshop 2010 (Frascati, Italy, 17.-19. Feb. 2010)

[26]EOMAP Validation Report (2017): www.eomap.com/services/water-quality/ and www.eomap.com/exchange/pdf/EOMAP_Validation_Examples_Water_Quality.pdf

this quantifiable absorption, which is measured by the spectral satellite sensors, not only include various Chlorophyll pigments, but also other pigments such as Pheophytin (see chapterProduct information). Of course, different environmental impacts and the algorithmic capabilities to correct them influence the intrinsic accuracy of the remote sensing method and need to be evaluated on their own.

Finally and of significant relevance, the sampling differences between in-situ data and remote sensing products need to be accounted for within any validation exercise. Typical differences include the sampling location, the sampling depth interval, the sampling time, etc. For each of them, water quality parameters might vary naturally by typically 20-100%, even for measurements taken close to each other (e.g. for a time difference of 1 day, or location differences of 1km horizontal, or 3m vertical), and many times higher for larger sampling distances or time differences.

Considering all these impacts, a match between the physics-based, satellite-derived water quality parameters and the various in-situ measures might hardly be closer than 30-100% for large scale validations.

Results and applicability range

The results from the various stated comparisons are in accordance with the achievable expectations: Typically, differences of at least 30% and up to factor 2 can be observed for most water types, and the uncertainty range is approx. 50% higher of that of single in-situ measurements[27].Nonetheless, the method delivers independent results, and the uncertainty is still equivalent to the methodological differences to and between distinct in-situ approaches. The relevant temporal and seasonal changes can be reproduced very well for the majority of investigated cases. This proves evidence that the physics-based approach for satellite data is intrinsically consistent and applicable as an independent method under most conditions. It deems to be an acceptable and valuable contribution, especially for large scale observations, as the natural variability of concentrations varies by more than 4 magnitudes, e.g. from approx. 0.1 to 1000µg/l Chlorophyll, or, in extreme cases, even one magnitude for turbidity in case different scattering angles are observed.

However, caution and particular attention is still required for specific conditions and rather sensitive parameters, as also the intrinsic physics-based water quality accuracy can degrade:

- In general, the standard processor (which is also applied for this study) is only applicable for optically deep surface waters (which means that the bottom of the waterbody is not visible) with a minimum depth between 50cm and 25m, depending on water turbidity and absorption. For optically shallow waters, increased errors will occur due to interferences of, e.g., proportions of seafloor in the water signal.
- In general, the sensitivity of products is degraded also in very dark natural waters, e.g. with very high concentrations of dissolved organic matter.
- The applicability range for Chlorophyll products and the eoHAB indicator is limited for water with exceptional optical properties, e.g. for extremely humic, calcareous or ferruginous waters.

[27] We expect that the most relevant intrinsic error source of the 2017 version used for the UNESCO IIWQ portal is the limited flexibility of the specific inherent optical properties (SIOP's). For a quarter of natural water bodies where we expect a notable mismatch to the actual optical properties, The resulting methodological retrieval error may result in 50% differences, and in 10% of cases even a multiple of that. From summer 2018 we expect that this intrinsic error source can be minimized through the fully automatic adaptation of SIOP's.

- Chlorophyll is expected to be critical and not yet adequately validated in waters with very high ratios between scattering and absorption or with high inorganic absorption components, such as rivers.
- The sensitivity to differentiate turbidity and especially Chlorophyll levels is decreased for older, less sensitive satellite sensors going back 30 years in time, such as Landsat 5 and 7.
- The turbidity and total absorption products have the highest validity for the widest range of water types. Here, the intrinsic accuracy of parameters only relies on the capability of the specific algorithms and corrections to match the specific optical conditions in water and atmosphere.

The liability of products is sensitive to the specifications of the underlying satellite sensors and their specific characteristics, such as radiometric or spectral sensitivity. Still, with physics-based analysis methods, the products are comparable, as long as the common reference properties, absorption and scattering spectra, are maintained as comparison standard. The overall accuracy then results from the capability of the physical method to account for, correct or quantify the various environmental and sensor-cased uncertainties.

Exemplary validation results

The following graphs show EOMAP's satellite-derived concentrations compared to in-situ measurements derived from various data sources. The satellite data has been typically collected in a 3x3 pixel matrix around the coordinate of the in-situ measurement, in other terms: a point measurement is compared to an area measurement. The collection dates for both methodologies are often not on the same day, therefore temporal variations as well as different sampling depths need to be considered in the interpretation.

Lake Tohopekaliga in Florida is an example of a eutrophic lake, with Chlorophyll concentrations up to 100µg/l. Almost 15 years of satellite records were processed and compared. Satellite data from the sensors Landsat 7 and 8 with 30m resolution have been used in this comparison.

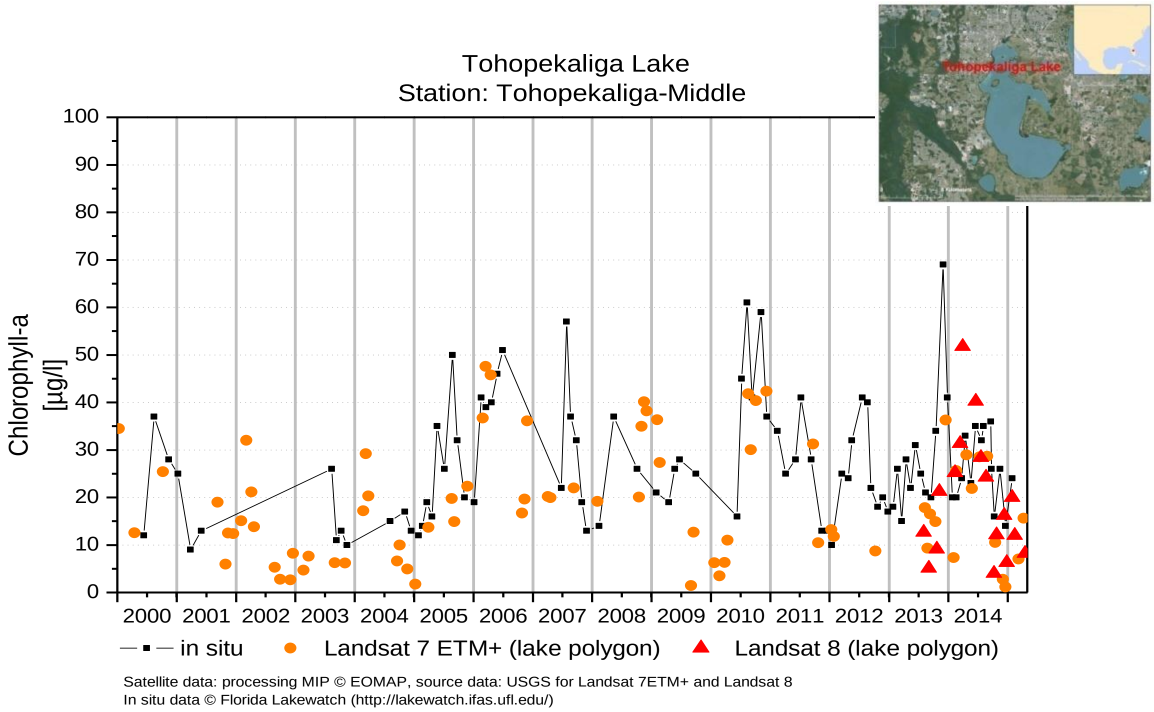

Figure 5: Chlorophyll-a time series validation of Lake Tohopekaliga, Florida, from 2000-2014, using Landsat 7 and 8.

Lake Zurich in Switzerland is an example of a mesotrophic lake, with Chlorophyll concentrations between 2 and 25µg/l. A slightly increasing trend is visible for the years of investigation, both from the in-situ and the satellite-retrieved data. Satellite data from the sensor MERIS in 300m resolution and from Landsat 7 in 30m resolution were used here.

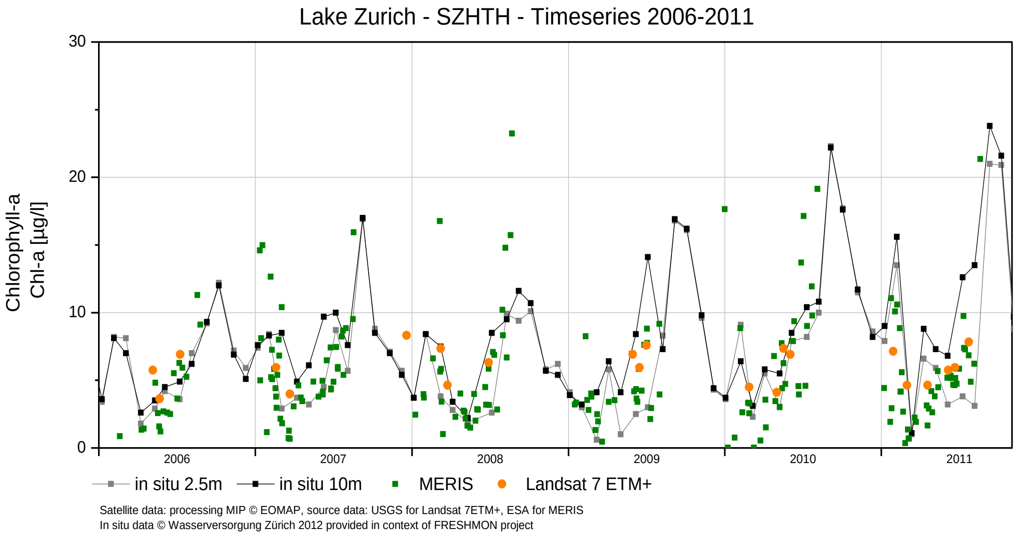

Figure 6: Chlorophyll-a time series validation of Lake Zurich, Switzerland, from 2006-2011, using Landsat 7 and MERIS.

Lake Constance between Germany and Switzerland is an example of an almost oligotrophic lake, with Chlorophyll concentrations between 0.5 and 8µg/l. Satellite data from the sensor MERIS in 300m resolution as well as from Landsat 7 and Landsat 8 in 30m resolution have been used.

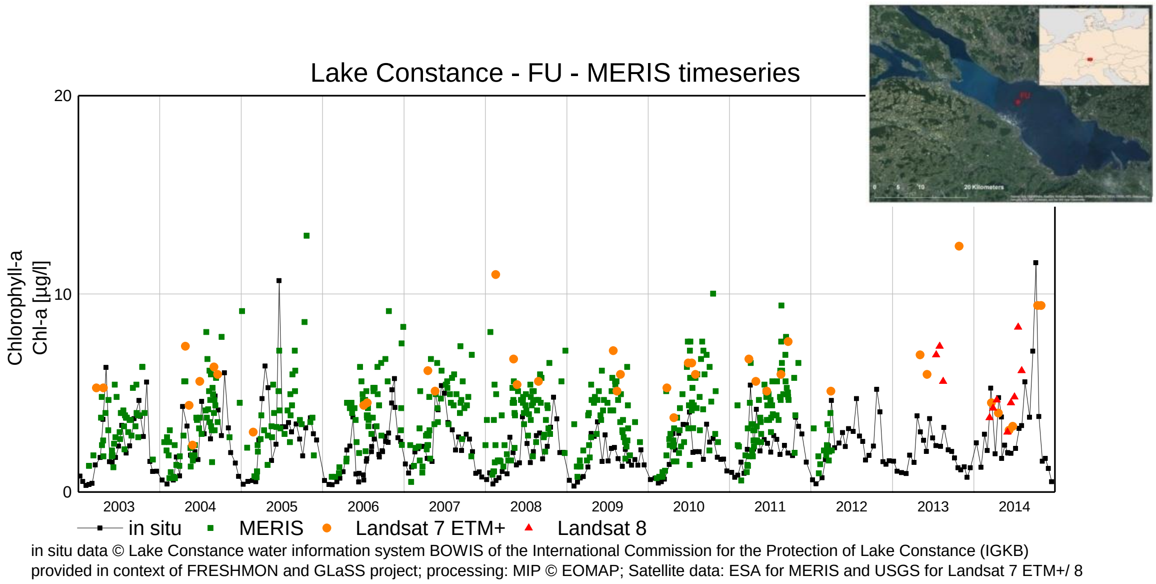

Figure 7: Chlorophyll-a time series validation for Lake Constance, Germany, from 2003-2014, using Landsat 7,8 and MERIS.

For the center of Lake Constance, the suspended matter concentrations range between 0.2 and 5mg/l or 0.2 and 5NTU turbidity.

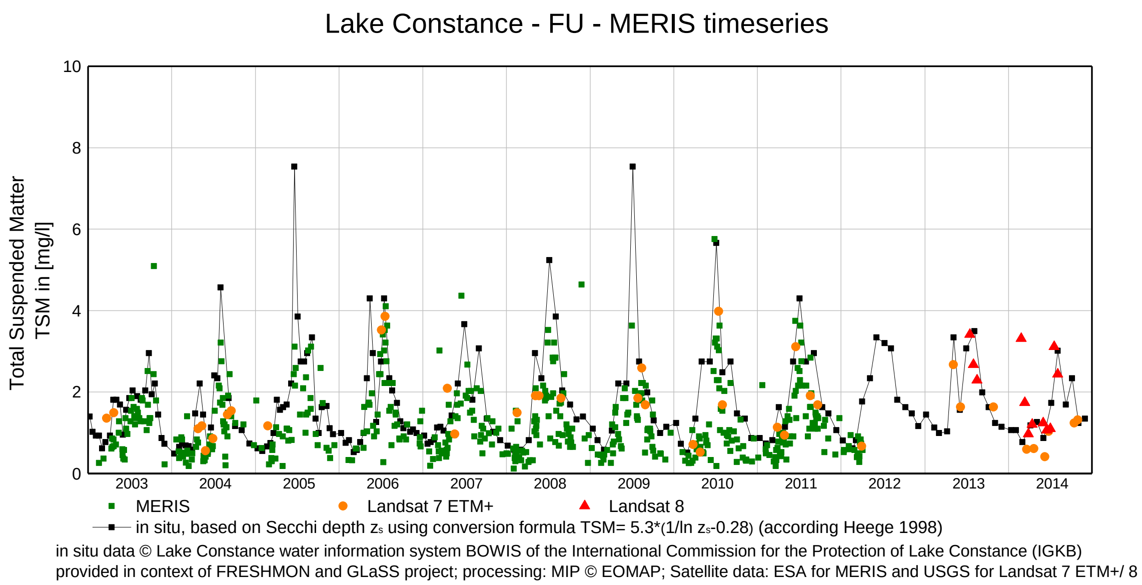

Figure 8: Total Suspended Matter time series validation for Lake Constance, Germany, from 2003-2014, using Landsat 7, 8 and MERIS.

For the river Elbe in Northern Germany, Landsat 5 and 7 were used within a validation exercise for data in 2010 at station Pagensand close to Hamburg. The error bar reflects the range of the temporal and spatial dynamics within 15 minutes and 200m around the sampling time and point.

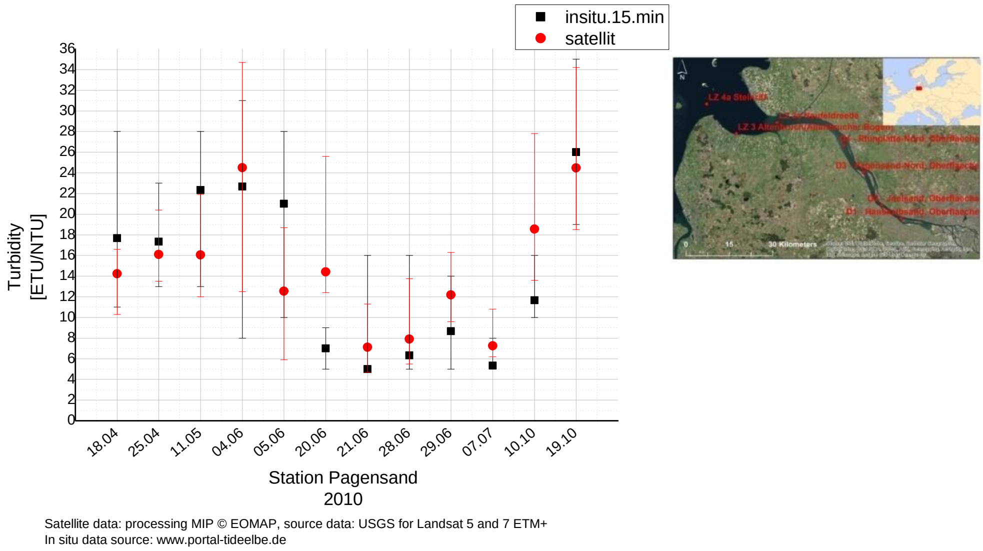

Figure 9: Turbidity time series validation for river Elbe, Germany, for 2010, using Landsat 5 and 7.

For the Basacriver in Vietnam, the limitations of the validity have been analysed for cases when the spatial resolution of a sensor comes close to the width of the river itself. In this case, 250/500m data from the sensors MODIS Aqua and Terra were validated with in-situ data at a location where the river width is up to 1.5km. Furthermore, exemplary records from satellites Landsat 7 with 30m and RapidEye with 5m spatial resolution were compared (from: Heege et al. 2014[28]).

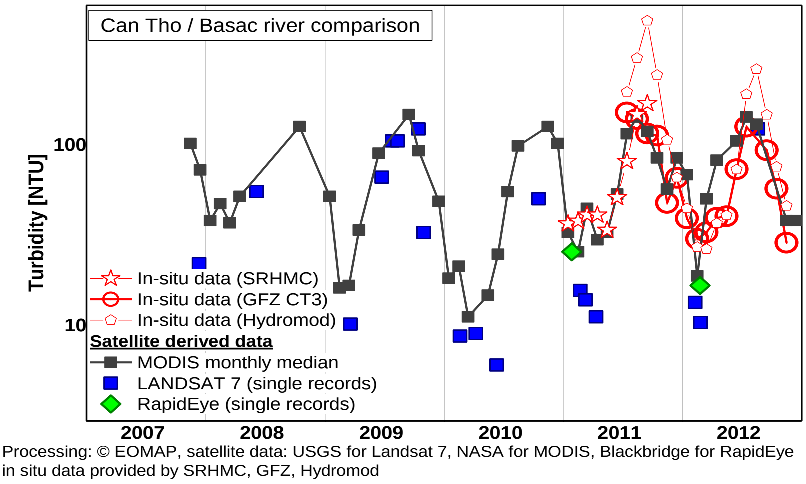

Figure 10: Turbidity time series validation of the Basacriver, Vietnam, 2007-2012, using Landsat 7, MERIS and RapidEye.

At the Po river mouth in the Adriatic Sea, Italy, a virtual station has been selected to check the consistency of productsderived with the sensors MODIS Aqua and Terra, Landsat 7 and 8. Interestingly, all sensors show a significant increase in the turbidity values for the years 2012-2014, while the Chlorophyll values do not show such a strong increase.

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[28]Heege, T., Kiselev, V., Wettle, M., Hung N.N. (2014): Operational multi-sensor monitoring of turbidity for the entire Mekong Delta. Int. J. Remote Sensing, Special Issues Remote Sensing of the Mekong, Vol. 35 (8), pp. 2910-2926

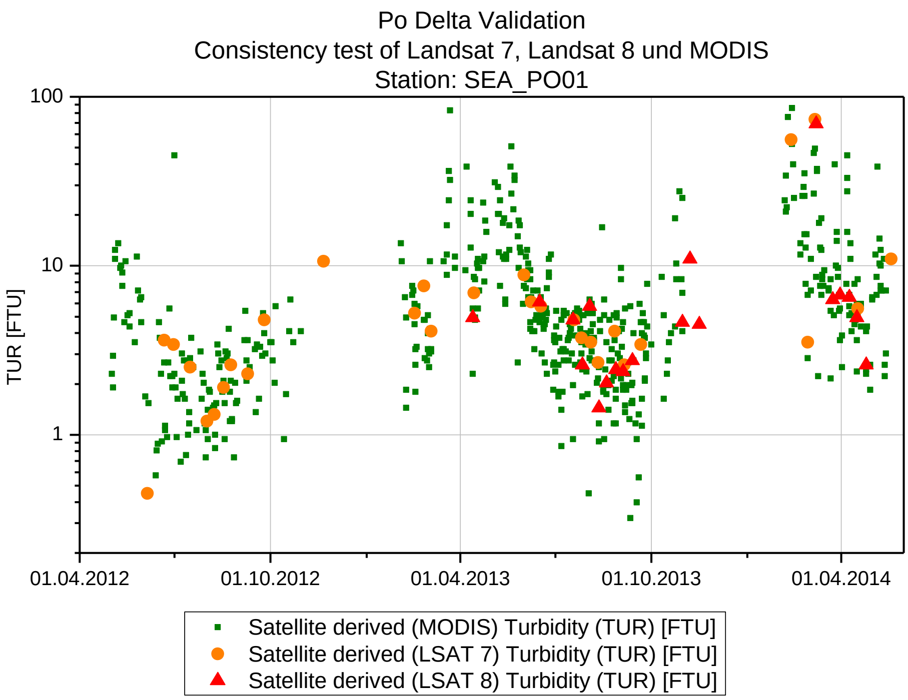

Figure 11: Turbidity time series validation for the Po river delta, Italy, for 2012-2014, using Landsat 7, 8 and MODIS.

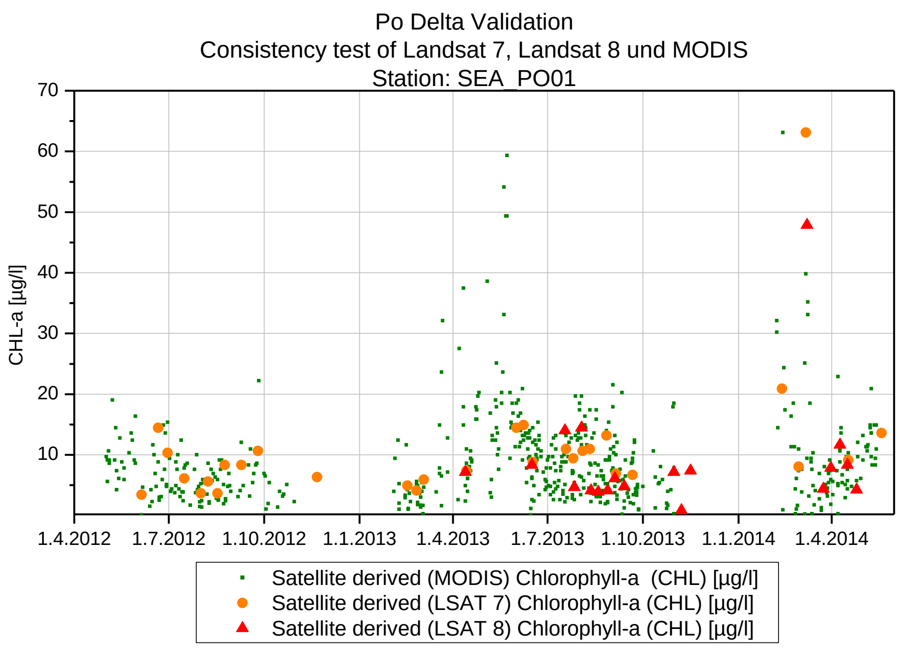

Figure 12: Chlorophyll-a time series validation for the Po river delta, Italy, for 2012-2014, using Landsat 7, 8 and MODIS.

Overall, the satellite-derived eoWater products deliver consistent values in long-term tests for the relevant parameters such as turbidity and Chlorophyll content. The sensitivity for spatial variations is about 10% of the actual concentration value for satellite sensors such as Landsat 8, while the temporal product consistency varies by typically 20-40%. Typical quantitative differences when comparing the eoWater products with different in-situ data are approx. 25-100% and therefore relatively low in comparison to the huge range of the natural concentration of up to factor 100.

Further validation results can be found in publications and validation reports, e.g. from the EU-FRESHMON project:

- D54.3 D54.3 Report on FRESHMON data quality and data comparability
- D54.3_2 Update Report on FRESHMON data quality and data comparability

5. Limitations

Remote sensing based water quality information products are subject to a number of limitations, which should be considered when using the data. In general, all optical impacts on the signal which are not reflected in the retrieval algorithms can increase uncertainties or result in retrieval failures. Thus, the range and accuracy of the used physical model is most relevant when applying global monitoring.

Below, an incomplete list of impacts is summarized, which can increase product uncertainties to the current stage:

- Optically shallow waters: Errors and overestimation of water constituents can occur for optical conditions, where the signal reflected at the seafloor still noticeably contributes to the total signal. Such areas at not flagged in this global survey. The standard water quality products are therefore only applicable for optically deep surface waters with a minimum depth, typically between 1m and 15m, depending on water turbidity.
- Light availability: In general, the passive remote sensing approach to determine water quality depends on the analysis of light reflected back to the sensor. For dark targets such as extreme humic waters, or geometric recording conditions under low sun elevation angles, an increase of uncertainties up to retrieval failures can apply. Products related to absorption such as Chlorophyll are most impacted by this effect.
- Product sensitivity: The liability of sensitive products such as Chlorophyll varies, depending on the underlying satellite sensors and their specific characteristics, such as radiometric or spectral sensitivity. For example, the sensitivity to differentiate turbidity and especially Chlorophyll levels decreases for old satellite sensors going back 30 years in time (e.g. Landsat 5). Harmful algae bloom detection is currently only evaluated for present high-quality satellite sensors such as Landsat 8 or Sentinel-2 and -3.
- Adaptation of specific optical properties: As outlined in the previous chapter, water quality products are influenced by the level of adaptation of the local specific optical properties. In this version, an adaptation of the specific absorption coefficient is applied to cover the range of oligotrophic to hypereutrophic waterbodies within the seasonal time series areas. Future versions will provide automated adaptations.
- Spatial resolution: Ambiguity measures resulting from mixed land-water pixels should be expected if the smallest extent (shortest diagonal across) of a waterbody is lower than 5 times the spatial resolution of a product. For example, the minimum extent of optically deep waterbodies for the 30m products should be 120m. Spatial and/or temporal aggregation of single pixel measures per waterbody can improve the temporal sampling rate.

- Exceptional optical features: The applicability range for Chlorophyll products and the eoHAB indicator is limited for water with exceptional optical properties, e.g. for extremely humic, calcareous or ferruginous waters. Furthermore, these products are not yet proven in river bodies with high suspended sediment loads. The validity in such water environments should be doubted.
- Temporal sampling rate and quality flagging: Typically, the actual temporal sampling rate is reduced by a factor between 0.8 and 0.2 compared to the theoretical satellite record rate, depending on regional and seasonal characteristics. Pixels are flagged due to clouds and cloud shadows, haze, disturbances by floating materials or mixed land-water pixels, and sun glitter for dedicated sun-observation geometries. EOMAP applies automated flagging and quality estimate calculations for each pixel on all derived products. Furthermore, a basic manual quality control process to mask remaining artefacts is implemented for all products with a spatial resolution of 30m or better. A detailed quality control can be implemented on request to clean remaining artefacts.

For further details on the Unesco-IHP IIWQ World Water Quality Portal, please contact:

Dr. Sarantuyaa Zandaryaa, Programme Specialist, Division of Water Sciences, International Hydrological Programme, Natural Sciences Sector, Unesco.

6. Support and additional information

Information on the International Initiative on Water Quality under the UNESCO IHP Programme are available here:

https://en.unesco.org/waterquality-IIWQ

Further information about satellite-based water quality monitoring services, technical information and please use link below:

http://www.eomap.com/services/water-quality/

For further information about EOMAP's contribution to the portal, please refer to:

http://www.eomap.com/world-water-quality/

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