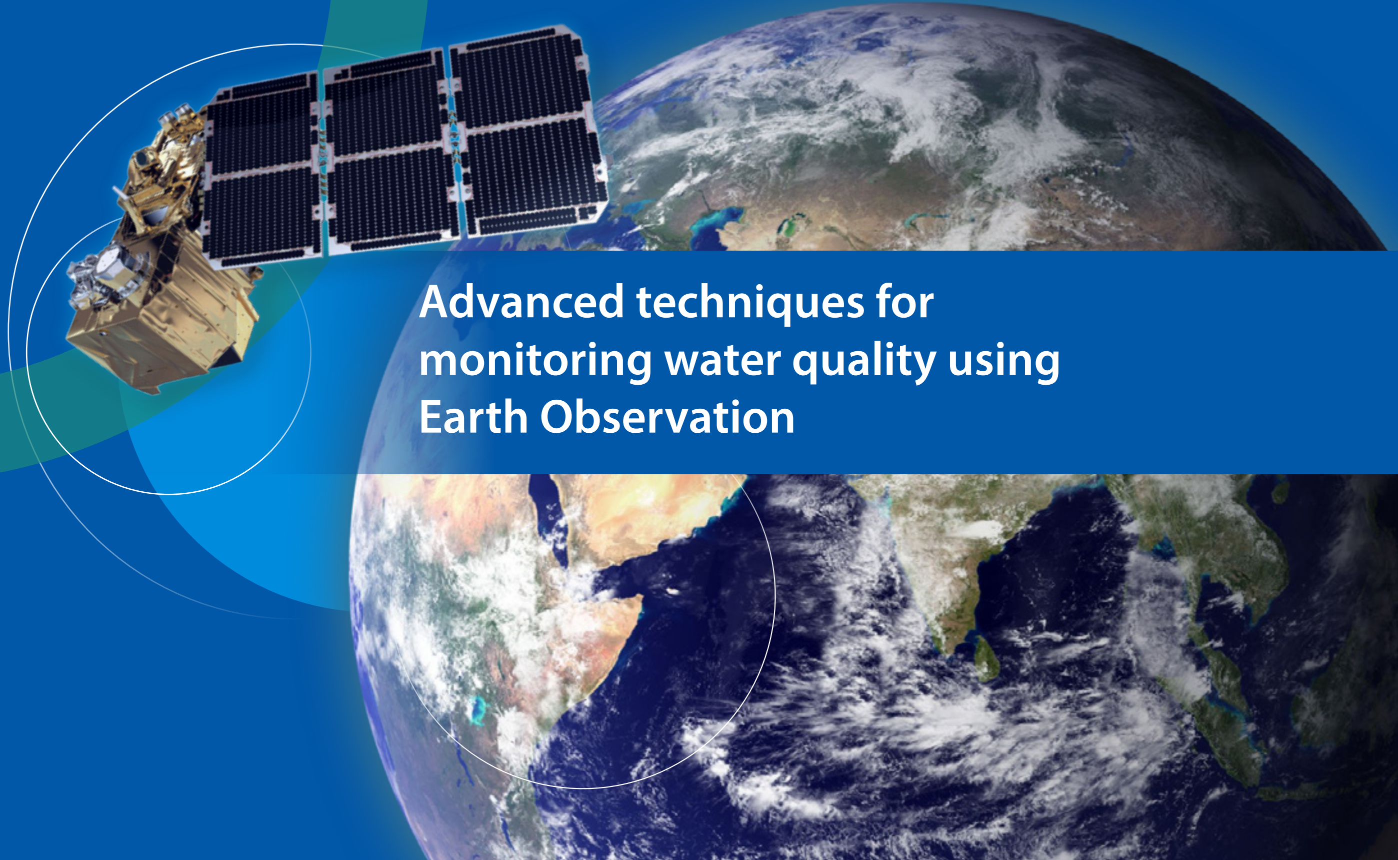
GEO GROUP ON EARTH OBSERVATIONS

AquaWatch

The GEO Water Quality Initiative



Advanced techniques for monitoring water quality using Earth Observation

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The GEO Water Quality Initiative

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Content

Preface

AquaWatch is a water quality community within the Group on Earth Observations (GEO). GEO aims to address global challenges and improve decision making by coordinating and developing Earth Observation efforts among participating governments and organizations. AquaWatch aims to develop international operational water quality information systems based on Earth Observations with a focus on the developing world. Data and information produced by the AquaWatch community are being used to tackle fundamental questions about the changing ecological status of inland and coastal waters to support water governance.

This booklet presents information about water quality issues and monitoring in a variety of habitats and exemplars of water quality monitoring using archived and next generation Earth Observation data using technologies developed and exploited by researchers within the AquaWatch community.

The information and examples in this booklet are set out to inform parties involved in water resource management, policy and sustainable development about water quality issues and the available technologies and methods available for monitoring water quality around the globe.

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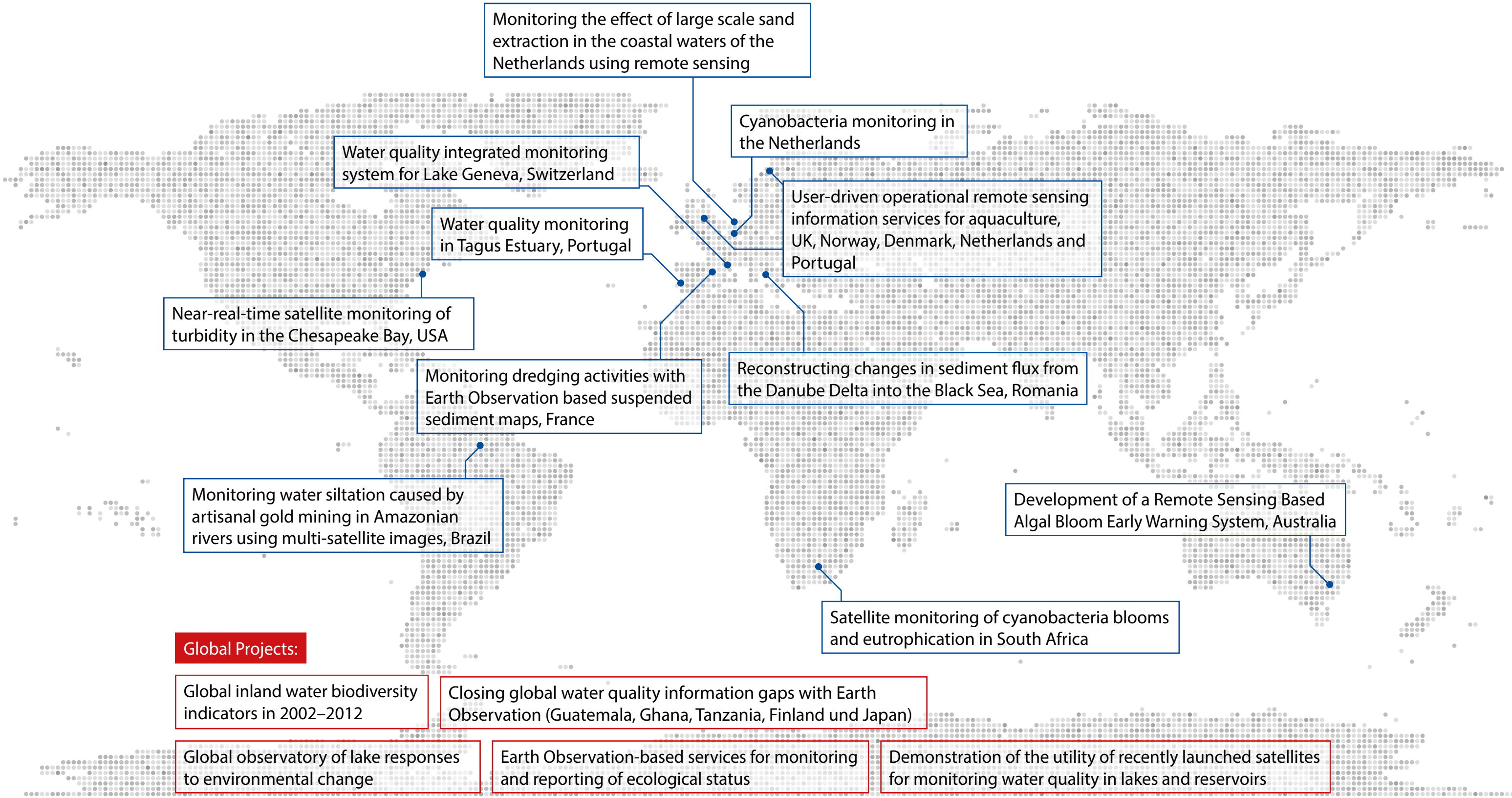

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A primer on water quality monitoring

Why monitor water quality?

Water quality is essential for human, ecosystem and economic health. Degradation of water quality can result in human exposure to disease and harmful chemicals, reduction in productivity and diversity of ecosystems and damage to aquaculture, agriculture and other water-related industries.

The development of the United Nations Sustainable Development Goal to ensure availability and sustainable management of water and sanitation for all (SDG 6) highlights the importance of water quality at the global level and access clean, safe and secure supplies of water is fundamental to attaining sustainable development.

Improvements in water governance can only be achieved through access to data to support effective decision making. To manage and reduce these risks and ensure sustainable development, regular and sustained water quality monitoring and forecasting is required at a local to regional level, whilst global scale monitoring can yield new insights into understanding of how water quality is changing in response to environmental perturbation and climate change.

How is ambient water quality monitored?

Water quality data is generated through the sampling and analysis of the physical, chemical and biological content of water. This is done through various water and laboratory analyses (commonly referred to together as "in situ" analyses) as well as through remote sensing technologies. Taken together, these measurements are commonly referred to as "earth observations".

In situ sampling allows for the analysis of a wide range of parameters at various depths while remote sensing technologies supporting synoptic analysis of regions and countries and the ability to analyze water bodies that are not reachable by in situ techniques or are in regions that lack the capacity for in situ sampling. In situ and remote sensing techniques are complementary and support a wide range of possibilities for water quality monitoring in this growing field including incorporation into regional and local models for the forecasting of water quality.

In situ techniques are used to measure a wide range of aspects of a water body including temperature, pH, dissolved oxygen, optical properties, nutrients, chemical pollutants and the abundance of bacteria and algae. In situ measurements are collected by field measurements and by laboratory analysis of water samples. In recent years, significant technological developments in autonomous in situ instruments have come about. These autonomous systems can run continuously or episodically and provide increased range and rates of data collection.

Remote sensing of water quality makes use of various space-borne, airborne and ground-based platforms and is expanding in technological capacity. The strength of remote

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sensing techniques lies in their ability to provide both spatial and temporal views of surface water quality parameters that is typically not possible from in situ measurements. Additional advantages include spatially synoptic measurements at a point in time, resulting in increasing data availability.

Recent and upcoming advances in satellite sensors and processing techniques are expanding the utility and range of water quality monitoring. Space-borne remote sensing techniques have been around for more than 40 years and are used to measure optical and thermal aspects of a water body, including temperature, suspended sediments and algal pigments. Satellites vary in terms of their resolution, sensors, geographical coverage and spatial revisit frequency.

Some satellite programmes such as Landsat have a legacy of historical imagery, which may be processed for retrospective analysis (e.g. long-term trends). Many satellite imageries are now available for free and are easily accessible.

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Combining satellite coverages, such as the US Landsat 8 and European Sentinel-2 high-resolution satellites will lead to increased frequencies of coverage. A strong science programme supporting satellite remote sensing continues to improve robust algorithms and develop information and operational products for water quality monitoring. Remote sensing can also enable policy makers and environmental managers to analyze land use and development practices that can negatively impact water quality. Land use information derived from satellites can be used to simulate water quality changes due to changing land and climate conditions.

07 Sentinel-2 brings land into focus, © ESA/ATG medialab.

08 October 22, 2016 true colour image of the Earth from the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi National Polar-Orbiting Partnership. Data supplied from VIIRS is generated at a 750 m resolution.

09 October 22, 2016 true colour image of the Earth from the OLCI instrument onboard ESA's Sentinel-3 satellite. Data supplied from Sentinel-3 OLCI is generated at a 300 m resolution.

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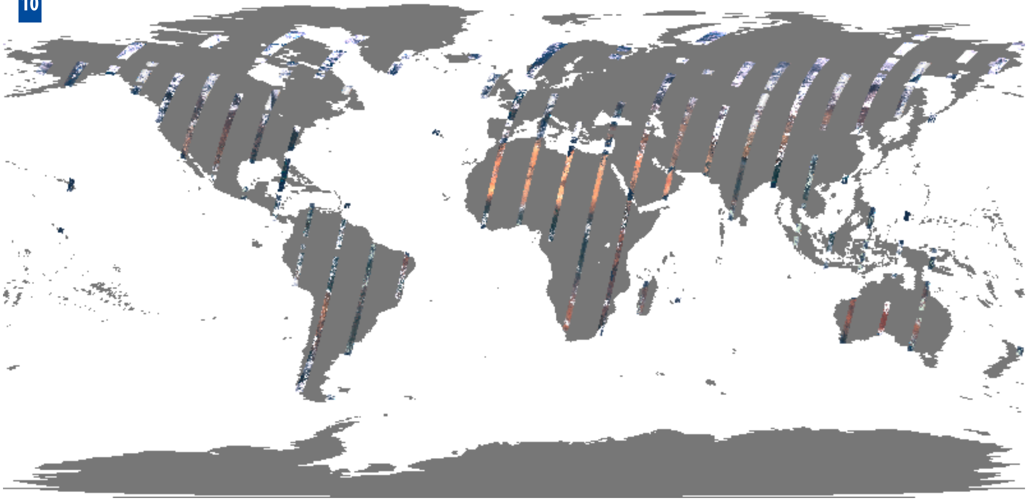

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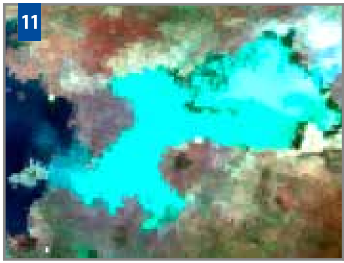

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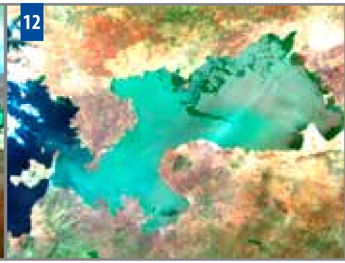

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October 22, 2016 true color image of the Earth from the Landsat 7 and 8 satellites. Spectral data supplied from Land 7 and 8 is generated at a 30 m resolution. 10

Red/green/blue images of Lake Victoria's Winam Gulf at 750 m resolution (S-NPP VIIRS – January 12, 2017). 11

300 m resolution, Sentinel-3 OLCI – January 11, 2017). 12

10–60 m resolution (Sentinel-2 MSI – January 12, 2017). 13

Water quality monitoring in estuaries, deltas and coasts

Background

Water quality issues

Ecosystems in estuaries, deltas, and coasts provide immense recreational and economical benefits to coastal communities. Half the world's population lives within 60 km of the coastline, and three-quarters of all large cities are located on the coast, among which many are important ports and harbours. Coastal water is also the interface between land and ocean, receiving discharge from rivers which collect and transport sediment, carbon, and anthropogenic materials from the catchment areas on land.

The high population density, intense human activities, and the concentration effect that rivers induce, impose huge pressure on coastal ecosystems and water quality. This is further compounded by the pressures of environmental change, including those occurring within the catchment, sea level rise, and CO_2 increase. As a result, coastal waters are subject to many water quality issues such as over-fertilization, acidification, industrial pollution, municipal pollution, oil spills, habitat loss or transformation, invasive species, sediment starvation, and increasing concentrations of refractory plastics. These issues further lead to harmful algal blooms, pathogen proliferation, wildlife kills, aquaculture loss, human health risks, and changes in channel and coastal morphology, all of which impair the recreational and economical functionalities of estuarine, delta and coastal environments.

Water quality monitoring challenges and advances

Traditionally, coastal waters have been measured using in situ water quality monitoring techniques. The advantages of in situ sampling in these regions include the ability to monitor a full suite of chemical, biological, and physical parameters quantifying all issues mentioned above, including trace metals, organic and inorganic micro pollutants, nutrients, algal species, and optical properties. However, the dynamic and vast nature of coastal waters brings challenges to in situ monitoring, such as biofouling of equipment, loss of important events due to weather, hard to collect statistically representative samples, and inconsistency in methodologies and data sharing.

The development of remote-sensing techniques allows for synoptic coverage and the ability to monitor water quality during inclement conditions and in areas lacking in situ sampling regimes. The variety of water quality parameters that can be directly detected from satellite are limited compared with field sampling. The remote sensing of water quality parameters relies on the absorption, scattering, reflection, or fluorescence by the target water after receiving electromagnetic radiation which can be solar or artificial. For example, suspended particles can be detected owing largely to the scattering of visible and near-infrared light; algal pigments can be detected owing to the absorption of visible light; oil spills can be detected owing to the absorption and scattering of the shortwave infrared radiation.

The challenges facing remote-sensing techniques for coastal water monitoring include a lack of near-real time coverage at required resolutions, and capability to resolve parameters with desired accuracy. At the present stage, revisit frequency of typical satellite sensors with 300 – 1000 m resolution is once a day and is further reduced by cloud coverage. Recent and planned launches of new satellite sensors and next-generation geostationary sensors are expected to alleviate this challenge. With higher spatial resolution which is desired for many applications, the revisit frequency is even lower (but will be around 4 to 5 days by combining Landsat-8 and the Sentinel 2A and 2B programmes from mid 2017). With respect to parameter accuracy, there are significant challenges to derive Chlorophyll-a concentration because of terrestrial inputs of pigmenting agent that discolours water in a similar way as algae do, and scattering agent which brightens water and causes an apparent change in water colour.

In the case of the detection of harmful algal blooms, there are additional problems to deal with. Unlike inland waters where the only toxin-producing algal group is cyanobacteria, in coastal waters a variety of diatom, dinoflagellate, haptophycae, raphidophycae, as well as cyanobacteria can produce toxins that cause human sickness and fish kills. The number of candidate harmful species makes it more difficult to model their optical properties and to give early warnings on which kind of poisoning is outbreaking. To make it worse, some species can be harmful even when their cell density is below satellite detection limit.

The retrieval of mass concentration of suspended matter is also challenging. The conversion from optical measurements to mass concentrations is subject to variability in particulate size and optical properties. Unlike inland waters which is relatively enclosed, coastal waters range from semi-enclosed estuaries to open waters. Complex ocean currents can laterally advect particles from elsewhere, potentially introducing more heterogeneity to particle size distribution and optical properties.

The exemplars presented in this section demonstrate a range of recently developed local applications and the methods used to monitor water turbidity and mass concentration of suspended particles in estuaries, deltas and coasts.

Monitoring dredging activities with Earth Observation-based suspended sediment maps

Dredging activities are required to guarantee proper access of vessels to harbours and for the construction of offshore structures. However, during dredging activities sediment is released from the bottom that can affect ecologically valuable ecosystems like coral reefs or mangroves. Many countries developed directives or regulations stipulating maximum allowed values of sediment concentrations in order to protect these vulnerable ecosystems. When these maximum allowed values are exceeded, dredging companies are obliged to stop their dredging activities.

The Belgian research organization VITO provides satellite derived sediment maps to dredging companies in order to support company compliance with maximum allowed sediment concentrations. VITO uses satellite observations to identify the natural background for use as a reference and also provides satellite analysis during dredging activities that can be used in concert with in situ point measurements

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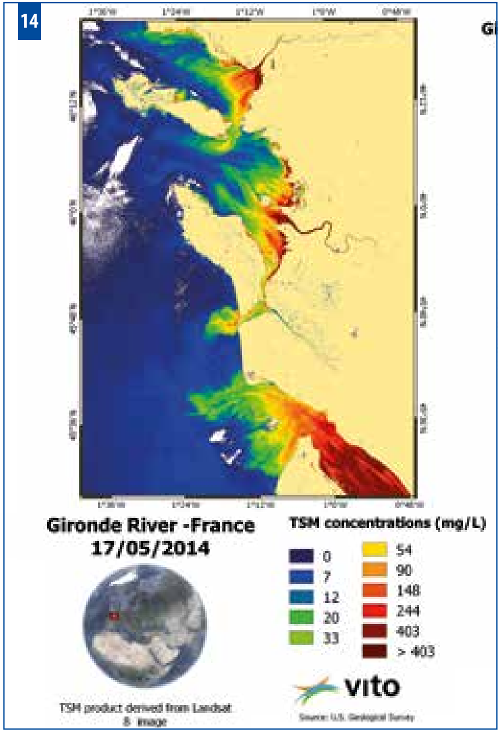

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Satellite sediment distribution product showing total suspended matter in France's Gironde. These satellite based sediment maps help the dredging companies to analyze the cause of exceeding the maximum allowed sediment concentration.

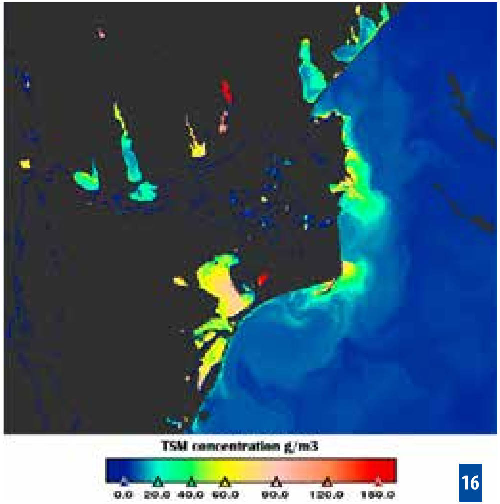
to track dredging impacts. These maps are also useful for the development of sediment transport models and support environmentally responsible dredging activities.

User testimonies

Our online web service enables to take on-site decisions based on different information layers including Earth Observation data with a goal to limit the environmental impact during dredging activities.
Mark Bollen, project engineer at International Marine and Dredging Consultants (IMDC)

15 **Ongoing dredging activities.**

Reconstructing changes in sediment flux from the Danube Delta into the Black Sea



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The Danube-Black Sea interaction area encompasses the Danube Delta and the western Black Sea shelf. The hydrology of this zone is governed by the discharge of fresh-water, sediment, and associated materials from the Danube river. The sediment flux directly affects nutrient dynamics, primary production, and the transport of pollutants into the coastal zone and shelf.

Researchers at the University of Stirling (UK), GeoEcoMar (Romania) and the Marine Sciences Research Institute of the Italian National Research Council are collaborating on a project to model hydrological processes in this region.

This project focuses on understanding the sediment flux from the Danube Delta to the Black Sea, its spatial and temporal patterns and links with bottom water sedimentation. Satellite data are being coupled with a spatially-resolving hydrodynamic model of the Black Sea, in part to validate the sediment transport component of the model and in part to link the surface estimates of suspended matter with transport and deposition occurring at depth. These data are being validated by sediment cores and in situ measurements of bio-optical parameters and in-water

16 **Total suspended matter concentration derived from ESA satellite imagery on 11/05/2016.**

17 **Researchers taking measurements in the Black Sea in front of the Danube Delta.**

constituents. Archived satellite data collected in the last fifteen years will be used to reconstruct the effects of the changes occurring within the complex Danube catchment on the Danube Delta and the Black Sea.

This will be used to better understand the environmental effects of sediment flux variation on decadal and seasonal time scales in river-sea interaction zones.

User testimonies

Phenomena occurring at the interaction zone between the Danube, Europe's second longest river, and Black Sea waters are extremely complex. Humans have strongly interacted with this system during the last centuries, whilst global climate changes also play significant roles in altering the state of the environment in the same areas.

EO is probably the most suitable tool to understand these processes and their evolution, due to the significant increase in quantity and quality of data it provides. This huge volume of information thus becomes the basis for the much more detailed understanding of the phenomena controlling the evolution of the Danube river mouths and the area under the influence of the Black Sea.
Dr Adrian Stanica, Scientific Director of GeoEcoMar (Romania) and Coordinator of the DANUBIUS-RI ESFRI Project

Monitoring the effect of large scale sand extraction in the coastal waters of the Netherlands using remote sensing

In the period 2009 – 2011, the Port of Rotterdam Authority expanded its port facilities with a large land reclamation project, Maasvlakte-2 (MV2). This reclamation required significant sand extraction from 10 – 15 km offshore, with a total volume of about 200 million m^3. The extracted sand contains a silt percentage of about 1.5 – 2.5 %. This silt is released by the sand extraction activities mostly through the dredger overflow systems and hence is dispersed into the water column as Suspended Particulate Matter (SPM). Despite the fact that SPM will tend to settle to the bottom sediments, some of it will be transported into the coastal system and remain suspended in the coastal waters for a prolonged time. This SPM can be observed from space, due to its scattering of the incident sunlight.

Environmental monitoring and assessment of this infrastructure project was required by the coastal authorities. This was conducted using a combination of MERIS remote sensing data and in situ data which were processed, analysed and integrated with a Delft3D SPM transport model, to provide patterns and trends of SPM in the coastal waters during the period of concern. In this strategy, the model serves as an integrator of information, providing high-resolution and quasi-continuous coverage of SPM in space and time. An important aspect

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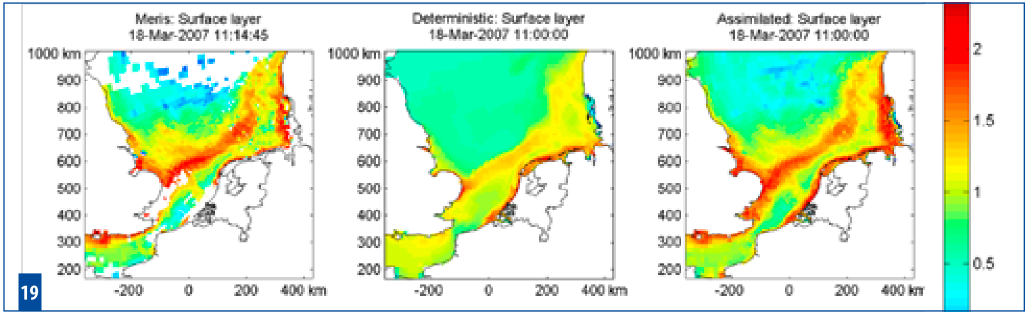
The new Port of Rotterdam facilities (lower left, image courtesy of Port of Rotterdam Authority). Suspended Particulate Matter (SPM), visible in a satellite image of the study area (right; image courtesy of NASA). Localized SPM resulting from sand extraction (top left).



19 Satellite images processed to obtain SPM concentrations (left). SPM from a water quality model based on SPM inputs, background concentrations and actual meteorological conditions (centre). The remote sensing data was assimilated into the model to improve calculated concentrations (right).

of the project was the formal approval of the regulatory authorities to use combined remote sensing and modelling results to assess the environmental conditions and changes.

User testimonies

For Rijkswaterstaat as the Dutch governmental authority responsible for evaluating marine sand extraction it was very important to have a good assessment of the increased amount of suspended matter due to sand extraction for the enlargement of the Rotterdam harbour. The remote sensing data were crucial for the monitoring and modelling of this aspect of the large scale sand extraction in a short time.
Ad Stolk, Rijkswaterstaat

Near-real-time satellite monitoring of turbidity in the Chesapeake Bay, USA

Water turbidity can be reliably and remotely retrieved, thus making satellite sensors ideal for monitoring water turbidity at large and synoptic scales. One issue with the utility of satellite turbidity products is that many potential users of these products are unfamiliar

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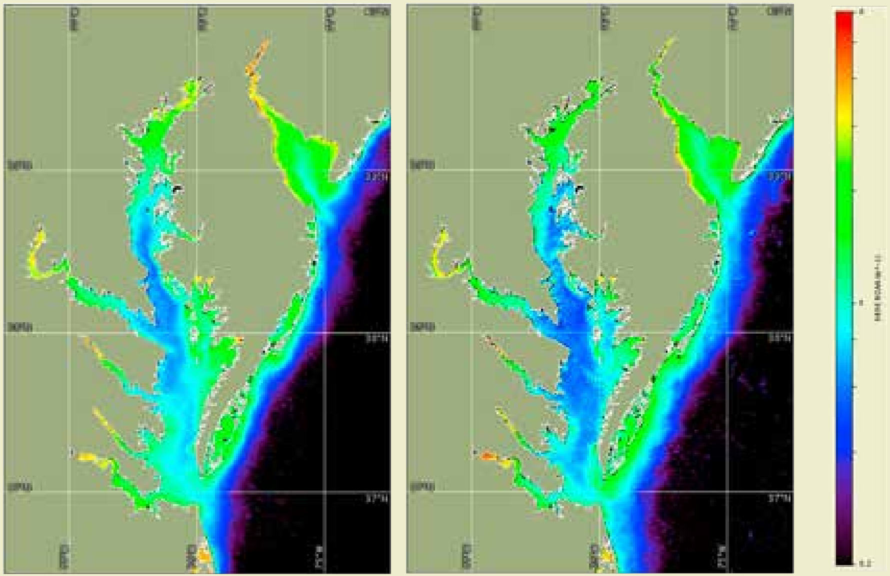

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NOAA CoastWatch October turbidity composite Kd(490) product showing a low turbidity year (2015 – right) compared to the average of previous years (2010 to 2014 – left). Final product of this project will be provided in NTU/FNU values.

with remote-sensing terms. For example, most field turbidity measurements are reported in Nephelometric Turbidity Units (NTUs) or Formazin Nephelometric Units (FNUs) whereas many satellite turbidity products are reported as remote-sensing reflectance at a single wavelength.

To remedy this issue, the U.S. National Oceanic and Atmospheric Administration (NOAA) CoastWatch programme (https://coastwatch.noaa.gov) is conducting a pilot project in the Chesapeake Bay to develop a satellite turbidity product in NTU/FNU values. This product will allow for direct comparisons with NTU/FNU field measurements. Another unique feature of this product is that it will be valid for the full turbidity range in coastal and inland waters. This can be achieved by using the information carried by progressively longer wavebands (from green, to red, and to the near-infrared) for progressively more turbid waters. The new turbidity product will allow users such as the U.S. Environmental Protection Agency, the NOAA National Marine Fisheries Service, and various state and local governments to more effectively evaluate the effectiveness of regulations towards reducing nitrogen, phosphorous and sediment discharge into the bay.

User testimonies

"The Chesapeake Bay Interpretive Buoy System (CBIBS) has a consistent issue with validating our in-situ turbidity observations. More highly resolved satellite images in the Chesapeake Bay would help to delineate between real episodic turbidity events and fouling on the instrument lens. ...I feel certain this topic is of

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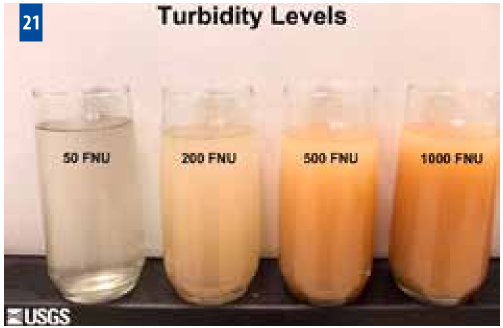


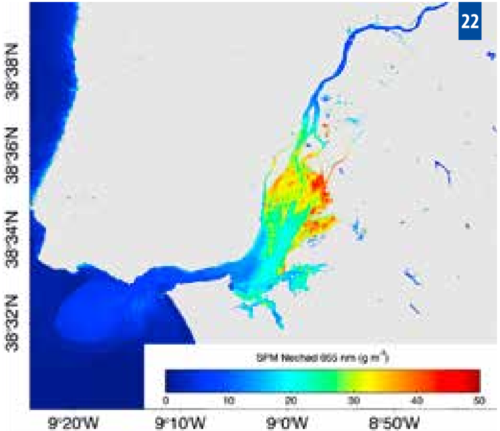
21 Examples of water turbidity levels reported in FNUs.

interest to those interested in benthic habitat and the maintenance of navigation channels."
Byron F. Kilbourne, Oceanographer at NOAA Chesapeake Bay Office

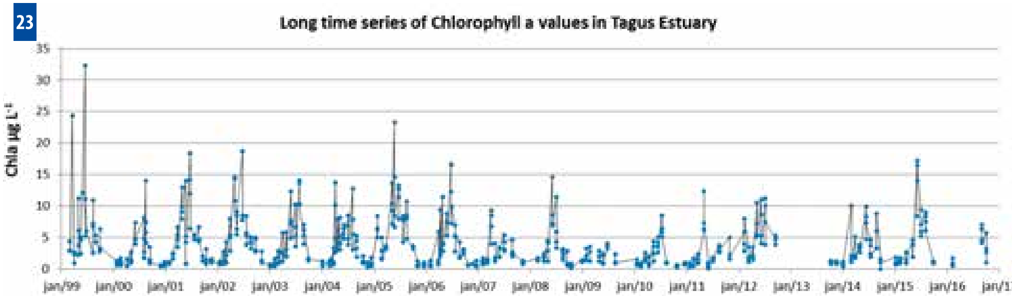
"The Maryland Department of Natural Resources is responsible for tidal water quality monitoring and habitat assessments for aquatic living resources. ... Having both satellite turbidity data in NTU and chlorophyll throughout the Chesapeake and Coastal Bays on a regular basis would allow us to more accurately assess these (water quality) criteria, by identifying the duration and severity of habitat impairments when in situ data are not being collected."
Mark Trice, Program Chief, Water Quality Informatics Resource Assessment Service, Maryland Department of Natural Resources

Water quality monitoring in Tagus Estuary, Portugal

The Tagus estuary (Portugal) is a large estuary on the west coast of Europe, with a broad shallow bay covering an area of about 320 km^2. It is mesotidal with semi-diurnal tides. A monitoring programme with monthly sampling in 4 sites has taken place since January 1999, and is planned until December 2018. This long in situ time series includes Chlorophyll-a and other photosynthetic pigments, total suspended matter, in-water photosynthetically active radiation, Secchi depth, nutrient concentration, and in some years, phytoplankton cell counts.



22 **Distribution of total suspended matter in Tagus Estuary, 18 February 2015.**



23 **Concentration of Chlorophyll-a along the time series, with monthly sampling in 4 stations, showing the seasonal cycle with a late spring maximum and the decrease from 2007–2014, possibly due to the Japanese clam introduction in the estuary.**

The results obtained showed a consistent seasonal pattern with a unimodal biomass peak occurring in spring or early summer, diatoms being the dominant group. Inter-annual variability is strongly related with hydrological conditions. A decrease in phytoplankton biomass from 2007 – 2014 has been linked with the introduction of the Japanese clam Ruditapes philippinarum in 2005 and its exponential growth in abundance in subsequent years.

Compared to other temperate estuaries, the Tagus can be classified as low- to moderately productive, where the principal factor limiting phytoplankton growth is the turbidity-induced low light conditions.

Satellite observation of total suspended matter conducted for the estuary shows a fortnightly variation coincident with the spring-neap tidal cycle evidencing the importance of satellite observation to reveal temporal scales not sampled during the programme.

User testimonies

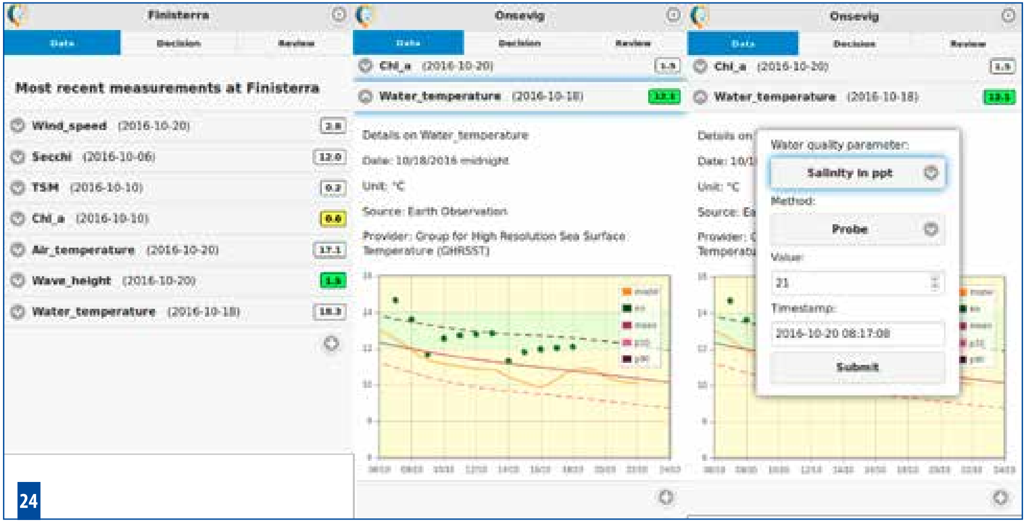
The General-Directorate for Natural Resources, Safety and Maritime Services (DGRM) is a Central Department under direct administration of the State, at the Ministry of the Sea, with a mission related to preservation policies and knowledge of marine natural resources, execution of fishing and aquaculture policies, including the control of those activities, and maritime services. The DGRM is fully committed to develop the use of Satellite Observations (SO) within the public administration. The DGRM has the responsibility of implementing the Marine Strategy Framework Directive, where SO plays an important role, in particular in relation with the Eutrophication Descriptor.
The General-Directorate for Natural Resources, Safety and Maritime Services

The Hydrographic Institute (IH), an agency of the Portuguese Navy recognized as a state laboratory, has the fundamental task of undertaking activities related to marine science and technology, supporting military applications, and contributing to the protection of the marine environment. The IH acknowledges the importance of using Satellite Observations as a tool to monitor water quality, including in estuarine ecosystems, as the Tagus Estuary.

The Hydrographic Institute

User-driven operational remote sensing information services for aquaculture

Water quality is a critical factor when culturing aquatic organisms. The quality of the water in the production system can greatly affect the health and growth of the produced species and the production costs. Earth Observation can provide valuable information for the aquaculture industry, including information on water temperature, turbidity, concentration of chlorophyll and total suspended matter and the presence of harmful algae blooms. On the one hand, long-term historic observations can help to find sites with optimal production and



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The AQUA-USERS app presenting near-real-time data for specific aquaculture sites derived from Earth Observation, modelling and in situ measurements.

25 **AQUA-USERS developed services for the aquaculture industry based on a combination of Earth Observation, optical in situ measurements and models (Sentinel-3 artist's impression © ESA).**

environmental conditions, on the other hand, near-real time information on water quality can help with operational management at the farm site.

To support the growth of efficient and sustainable aquaculture production, AQUA-USERS developed water quality indicators based on Earth Observation data for aquaculture management. Particular focus was put on improving methods for the detection of harmful algae blooms based on dedicated ocean colour satellite sensors.

A web portal and mobile application were developed that bring together the satellite information on water quality and temperature with in situ observations as well as relevant weather prediction and met-ocean data. The applicability of the methods and tools in the aquaculture sector was evaluated together with users from the industry.

User testimonies

Satellite monitoring is a valuable service used by salmon farmers to detect advance warning of harmful blooms. The remote sensing technology developed as part of the AQUA-USERS project expands its capabilities, providing real-time information and predictive tools to help them understand how blooms might develop and spread, as well as the potential

impact for their farms. And with the incorporation of this technology into a smartphone app is a real added bonus, as it means farmers can access information at all times of the day – a real positive for our technology-driven industry.
Jamie Smith, Technical Executive of Scottish Salmon Producers' Organisation (SSPO)

These alerts could be the first indicator of an unseen bloom heading our way, literally a life-saving service.
Dave Cockerill, Head of Fish Health at Marine Harvest Scotland

Water quality monitoring in inland rivers, lakes and reservoirs

Background

Water quality issues

Globally, a total of 84 % of our freshwater resources are derived from surface inland waters that cover 3.7 % of the world's non-glaciated land surface. Inland waters provide us with the most fundamental resource for survival including water for drinking, bathing, irrigation, fishing, aquaculture, recreation and transport. Inland waters are also recognised for their cultural value, contributing to our wellbeing through their aesthetic and spiritual properties and therefore continue to attract visitors and settlements to their shores. Whilst the demands for freshwater are universal, maintaining water quality does not always receive the highest priority, although it is now highlighted as a priority within the UN's sustainable development goals (SDG 6).

Inland waters, and lakes in particular, are sensitive to land use change and integrate the impacts of human activity with their catchment. These waters are therefore vulnerable to a variety of stressors including nutrient and chemical runoff from agricultural intensification, the management of farm waste and human sewage, the introduction of invasive species, the hydrological and hydro-morphic modification of rivers including damming for energy production, industrial development and mining activities. As with coastal environments, these stressors are compounded still further by climate change acting regionally and globally, and together result in a variety of water quality issues that can be damaging to human and ecosystem health. However, global estimates indicate that there are over 100 million lakes and reservoirs. Monitoring the impact of these stressors on each water body remains a challenge with perhaps only a fraction of one percent of lakes being monitored, often using approaches that make assessments and comparisons of their ecological status difficult.

Water Quality Monitoring Challenges and Advances

Surface waters therefore pose significant challenges for conventional monitoring and assessment. Conventional resources available for sampling often limit our ability to adequately capture the dynamics of aquatic systems and our understanding of their status, functioning and response to environmental perturbations. Water quality can be measured by a number of biological, chemical and physical constituents within the water, not all of which can be detected directly through their optical properties. Earth Observation techniques focus on biogeochemical indicators of water quality with optical properties that allow them to be imaged from space using the appropriate sensors, including Chlorophyll-a as an indicator of algal biomass, phycocyanin as an indicator of cyanobacteria biomass, total suspended matter, turbidity and coloured dissolved organic matter. Recent developments in the availability of satellite platforms for Earth Observations (including ESA's Copernicus Programme) offer an unprecedented opportunity to deliver consistent measures of water quality at a global scale at high frequency (daily) and or high spatial resolution (up to 10 m pixel size). These data can yield new insights into the temporal and phenological changes in eutrophication and bloom events, provide early warning of the presence of harmful algal blooms, characterise the flux and impact of sediment within the catchment, and assess the brownification of lakes.

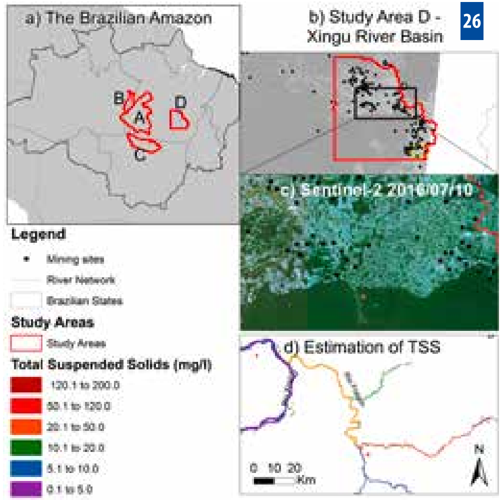
However, the operationalisation of this Earth Observation capability requires careful and robust approaches to correct for atmospheric interferences on optical signals from lakes that are observed from space followed by the application of appropriate algorithms tuned for the types of waters being observed.

The exemplars presented demonstrate a range of applications and the methods used to overcome these operational challenges to successfully deliver reliable data at the local and global scales.

Monitoring water siltation caused by artisanal gold mining in Amazonian rivers using multi-satellite images

Within the Amazon region, artisanal and small-scale gold mining activities have increased dramatically since the 1950s. Despite its contribution to the local economy, artisanal and small-scale gold mining causes several environmental impacts, such as mercury contamination, water siltation and landscape degradation, as well as social conflicts.

Today, given the intense water siltation (discharge of sediment into the water) of the Amazonian rivers combined with the technological capacity of detecting it from satellite images, researchers at Brazil's National Institute for Space Research are working to develop a monitoring system that quantifies water siltation caused by gold mining in the Amazonian rivers using data from multiple satellites. The results of the project's model output are maps of total suspended solids (similar to turbidity) in the local rivers and maps of mining activity.



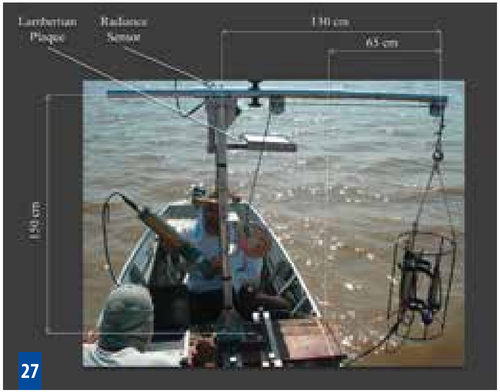
26 a) Map of study areas. b) Example of study Area D located in the Xingu river basin. c) A satellite image used to estimate Total Suspended Solids (TSS). d) Results of TSS classification of the satellite image of an empirical model.

Field campaigns in the Tapajós river basin and Xingu river basin are planned to validate these maps and will include radiometric measurements and water sample filtration based measurements of total suspended solids.

Furthermore, the products will be freely available from the National Institute for Space Research and will be highly beneficial to end-users seeking to monitor and manage mining activities such as the Brazilian Ministry of the Environment.

User testimonies

In managing Protected Land within the Amazon region, we at ICMBio, have a direct interest in the use of water siltation mapping. ASGM activities continue to increase and so to combat this, it is imperative to expand the monitoring process. Water siltation mapping will aid in supporting in loco monitoring by indicating the exact location of ASGM activities. More importantly, it will support the Protected Land Management Plan, the main tool implemented to control these activities.
Vitor Hugo Fernandes de Vasconcelos (ICMBio, Chico Mendes Institute). Itacoatiara, State of Amazonas, Brazil



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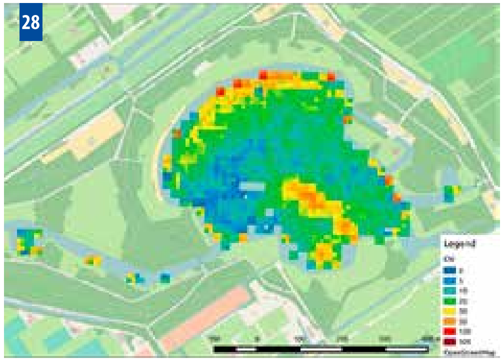
27 Example of radiometric measurement and water sampling for calibration/validation of optical models used to estimate total suspended solids from satellite images.

Cyanobacteria monitoring in the Netherlands

Cyanobacteria can be monitored reliably from space directly if the sensor observes in the Phycocyanin absorption band around 625 nm. Some operational satellites have that capability (MERIS, Sentinel-3, hyperspectral sensors). More indirectly the presence of cyanobacteria can be assessed from measuring the presence of floating layers / scums or from relationships with (high) Chlorophyll-a values. The application of the data (e.g. swimming waters) calls for continuous near-real time information, preferably with also a predictive capability. It is important to set up cyanobacteria monitoring systems based on an integration of satellite data, in-situ continuous spectral observations and eco-hydraulic models.

Remote and close-range optical sensing of ecological water quality parameters implies a paradigm shift from exclusively lab-based monitoring. The objective of the ESA Integrated Applications Program CyMons project has been to identify any obstacles on the way to monitoring water quality and specifically cyanobacteria blooms by proximal sensing and predicting bloom occurrence using models. Services compatible to regular operational data collection systems were prototyped and developed in close collaboration with three local water authorities in the Netherlands, who have since invested in the developed services. The economic feasibility of the CyMons services, accuracy of the monitoring results, requirements and availability of future satellite



28 Map showing an algae bloom along the shores and in the middle of lake Delftse Hout.

images of high resolution, requirements for ground-truthing instruments, the feasibility of reliable forecasting tools for cyanobacteria scum layers (1–5 days ahead), and the potentials to connect data with existing operational data management systems were investigated in this project. The service is currently being set up on an operational basis.

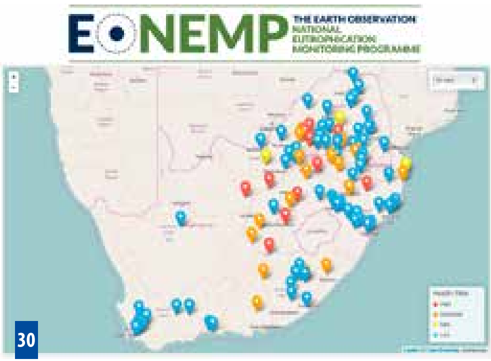
User testimonies

"I would like to have all data in one system: in situ and satellite water quality data, and forecasts of water quality by models, so that I can combine these with hydrological and meteorological data for efficient water management".
Local water manager in the Netherlands

29 **Cyanobacteria scum in the Netherlands.**

Satellite monitoring of cyanobacteria blooms and eutrophication in South Africa

The CyanoLakes Earth Observation National Eutrophication Monitoring Programme (EONEMP) integrates remotely sensed estimates of cyanobacteria blooms and eutrophication (Chlorophyll-a) into the national water management database of the Department of Water and Sanitation of the government of South Africa. The information is being used for near-real time monitoring, and to assess historical changes in cyanobacteria blooms and eutrophication. This has dramatically increased South Africa's ability to both monitor and assess changes in cyanobacteria and eutrophication on a national scale. EONEMP provides a public information service using satellite remote sensing exclusively to provide information about harmful cyanobacteria and algal blooms in South Africa's large water bodies, through a novel web interface (http://eonemp.cyanolakes.com).



30 **A view of the 102 South African water bodies included in the EONEMP public information service showing the health risk posed by cyanobacteria blooms towards recreational water users (http://eonemp.cyanolakes.com).**

Towards this end, EONEMP provides reliable, accurate, historic, timely, and open information in the public interest. The level of risk to human health from cyanobacteria blooms is provided on a lake-by-lake basis (low, mild, moderate, and high). The risk levels are a function of the presence and severity of cyanobacteria blooms detected by satellite remote sensing, and based on World Health Organization guidelines. It provides the general public with recommendations on the safety for partial and full contact recreational activities. On a research basis, EONEMP will

contribute towards the validation and use of the Sentinel-3 OLCI, through the collection of in situ radiometric and biological data, and to the enhancement of algorithms for chlorophyll-a and cyanobacteria detection.

User testimonies

Monitoring on a national scale is very expensive, logistically challenging and labour intensive. The Department of Water and Sanitation is in support of this "eye-in-the-sky" approach to monitoring eutrophication, which will allow monitoring of more water bodies (dams and lakes) which are not considered in the current network. The remote-sensing information will allow us to optimise our monitoring network and streamline our activities. The data generated will lead to a significantly improved ability to manage and mitigate the harmful effects of potentially toxic cyanobacteria blooms and nutrient enrichment (eutrophication), which are widespread in SA dams.

Ditselatsela Elijah Mogakabe, Directorate: Resource Quality Services, Sub-directorate: Resource Quality Monitoring, Freshwater Biological & Chemical Monitoring, Department of Water and Sanitation, Republic of South Africa

31 An autonomous buoy fitted with radiometric sensors for validating remotely sensed data on a small eutrophic water body in South Africa.

Development of a Remote Sensing Based Algal Bloom Early Warning System

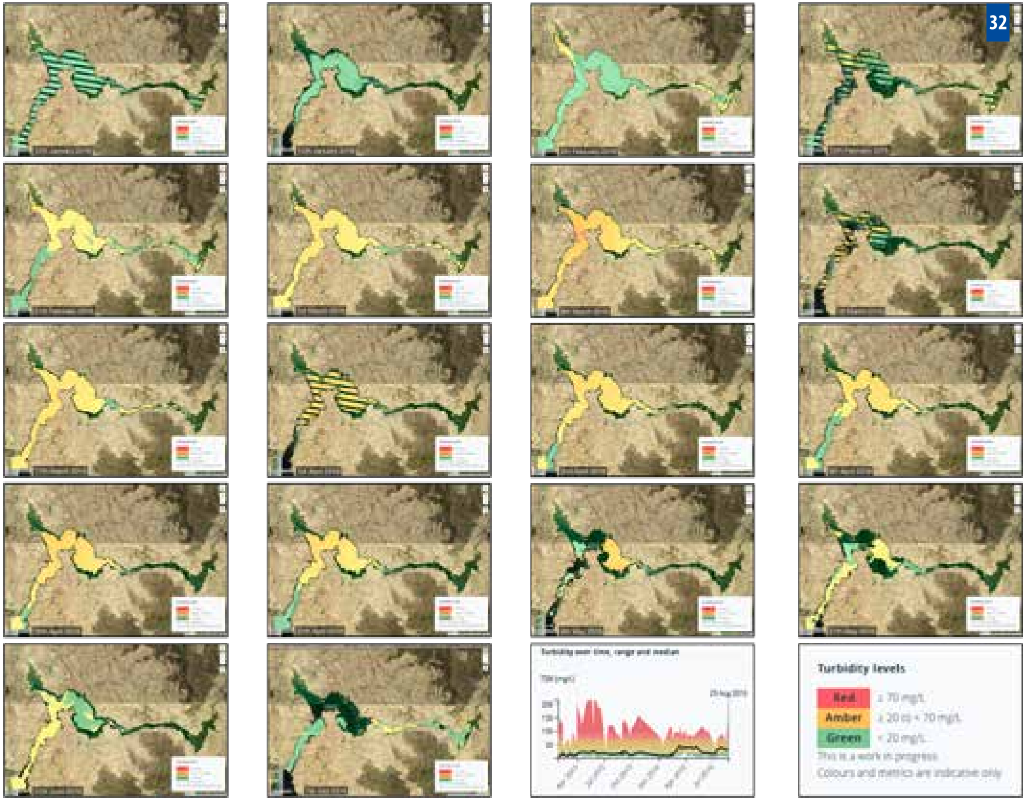
Traditional field monitoring for algal bloom detection involves identification and cell counting which, whilst reliable, imparts a lag time and is limited in spatial extent. Australia's Commonwealth Scientific and Industrial Research Organisation and the New South Wales Department of Primary Industries Office of Water are collaborating on the development of an Algal Early Warning System using remote sensing. The tool is built upon the Australian Geoscience Data Cube, a breakthrough innovation to serve standardised and calibrated satellite image data via Australia's National Computational Infrastructure.

In near-real time, images are processed in the Australian Geoscience Data Cube to inland water quality outputs including turbidity. Data are presented to water managers through a visualisation interface where the turbidity data are translated to relevant bloom alert levels. The interface allows for visualisation at the regional scale to provide a rapid statewide overview of algal alert status, or at the scale of the individual water body, to allow the determination of spatial bloom dynamics.

The generic approach developed here for turbidity will be suitable for all optical water quality products into the future. Project implementation is supported by an in situ optical water quality monitoring programme for algorithm development and validation. Novel above-surface sensors are being trialled to contribute validation data as well as to allow continuous monitoring of bloom status in smaller water bodies. In the future, the project will include forecasting services for bloom condition that will rely on the integration of satellite data with biogeochemical models.

User testimonies

The objective of the project was to develop procedures that use remote sensing technologies to support cyanobacterial monitoring and allow improved timeliness



32 Satellite turbidity images for Lake Hume using the algal bloom visualisation system, covering mid-January to early July 2016. Turbidity levels are coloured on the basis of green, amber and red algal alert status, depicted bottom right.

and a wider spatial coverage of major inland water bodies.

When fully operational, this system has the capability to revolutionise algal management by providing more rapid turnarounds in detection and mitigation. It can help Government agencies to monitor wider areas with the ability to quickly deploy resources at a local scale."

John Brayan, Team Leader - Algal Management, New South Wales Department of Primary Industries - Water

33 **A waterbody colored green by algae in Australia.**

Water quality integrated monitoring system for Lake Geneva, Switzerland

Over the last decades, different research communities have focused on different approaches and information sources for monitoring of inland waters. The challenge is now to improve the coupling of in situ measurements, remote sensing data, and three-dimensional hydrodynamic and biological models, to provide timely, scientifically credible, and policy-relevant environmental information to lake managers.

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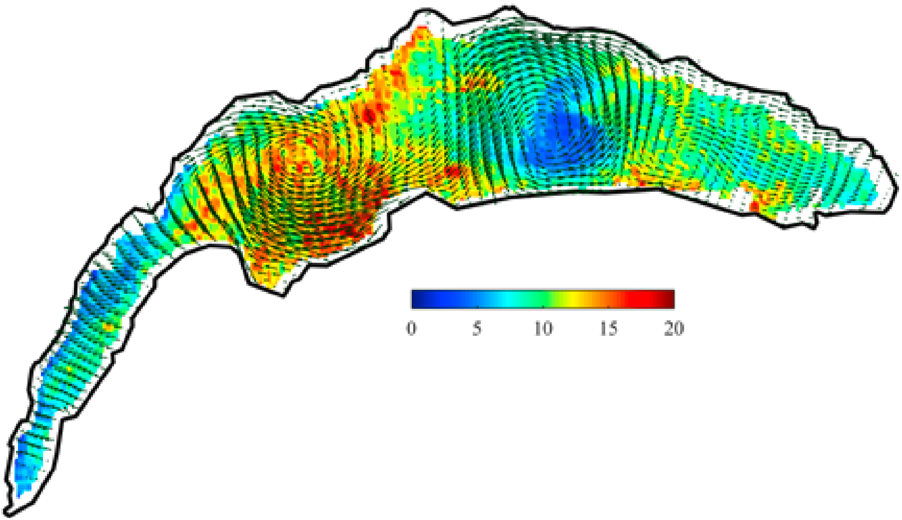

34 **Satellite data of lake Geneva (Oct. 2009) showing the chlorophyll concentration (colour coded, Chl-a mg/m³). The black arrows represent the surface current from a hydrodynamic model.**

35 **Ground validation using hyperspectral sensors.**

Researchers in Europe are currently investigating how mutual feedback mechanisms can be established between all information sources. Model simulations are improved through assimilation of remote sensing products and in situ measurements. Remote sensing methods are improved by ingesting a priori knowledge of optical properties and their vertical stratification from automated in situ measurements and model simulations. Lastly, in situ measurements achieve a better representativeness when carried out along instantaneous gradients known from remotely sensed products and model simulations.

Based on these principles, an integrated water quality observing system is developed for Lake Geneva, a large mesotrophic lake between France and Switzerland, where it enables investigations of the relationship between algae concentration and gyre circulation at unprecedented one-hour time scale. Adaptation of the integrated system for other lakes in Europe is planned to assess its performance against the background of other limnological systems and related questions.

User testimonies

"The coupling strategy including remote sensing, modelling and in-situ data is a promising

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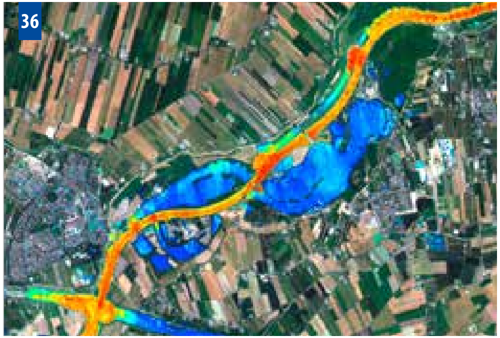

approach for inland water monitoring at high spatial and temporal resolution."
Natacha Pasche, Director of the Limnology Center, Switzerland

Suspended matter in the lower part of the River Rhine and surrounding recreational lakes after a flooding event due to heavy rainfall. 36

Earth Observation-based services for monitoring and reporting of ecological status

Lakes, reservoirs and coastal water bodies constitute essential components of the hydrological and biogeochemical water cycles, and influence many aspects of ecology, economy, and human welfare, providing ecosystem services in multiple and sometimes conflicting ways. Knowledge about the state of these waters is therefore of great importance. This is recognized by the Water Framework Directive (WFD), requiring the EU member states to monitor and improve the status of these water bodies.

The new Sentinel-1 (RADAR), Sentinel-2 (high resolution 10–60 m) and Sentinel-3 (dedicated water quality bands) satellite series allows long term, reliable, operational monitoring of inland and coastal water bodies. Based on these, a consortium of researchers in Europe developed a project (referred to as Earth Observation-based services for Monitoring and Reporting of Ecological Status or EOMORES) that develops information services to support monitoring, management and (WFD) reporting of water quality. This is done in close collaboration with users from several countries.

To tailor the users' needs, EOMORES integrates Earth Observation (Sentinel-1, 2 and 3), continuous in situ monitoring using optical sensors and ecological modeling. The validated data from these components will be further flexibly combined into higher-level products, such as ecological indicators for the WFD. The services are expected to result in lower operational costs, more reliable and more timely water quality data sets for water managers.

User testimonies

"The issue was that monitoring costs were increasing, methods were old fashioned, labour intensive and data not digital. This needed to change, and Earth Observation contributes to that. Also, we want to work in real time, in contrast to e.g. WFD which requires reporting every 6 years only". *National organisation responsible for water quality monitoring*

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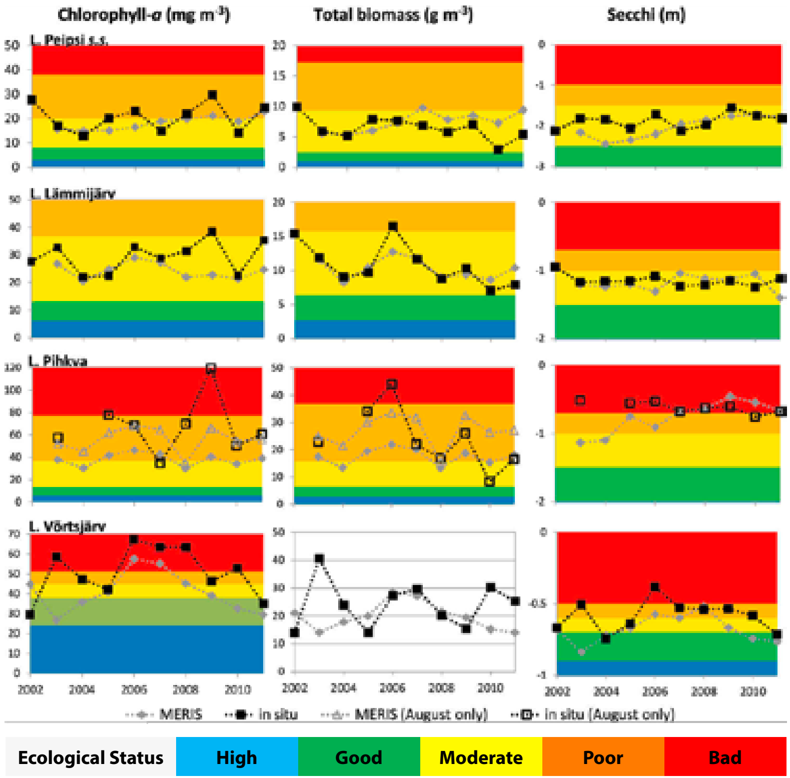

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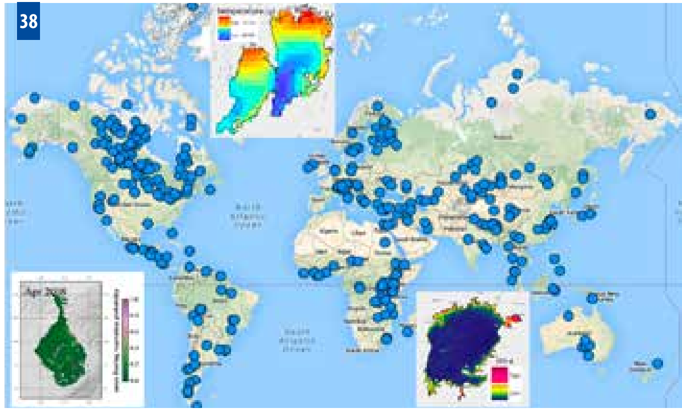
Time series of Chlorophyll-a, total biomass and the Secchi depth plus the resulting ecological status according to the Water Framework Directive as derived from satellite and in situ data, for four Estonian lakes (Alikas et al., 2015, doi : 10.1080/01431161.2015.1083630).

Global inland water biodiversity indicators in 2002–2012

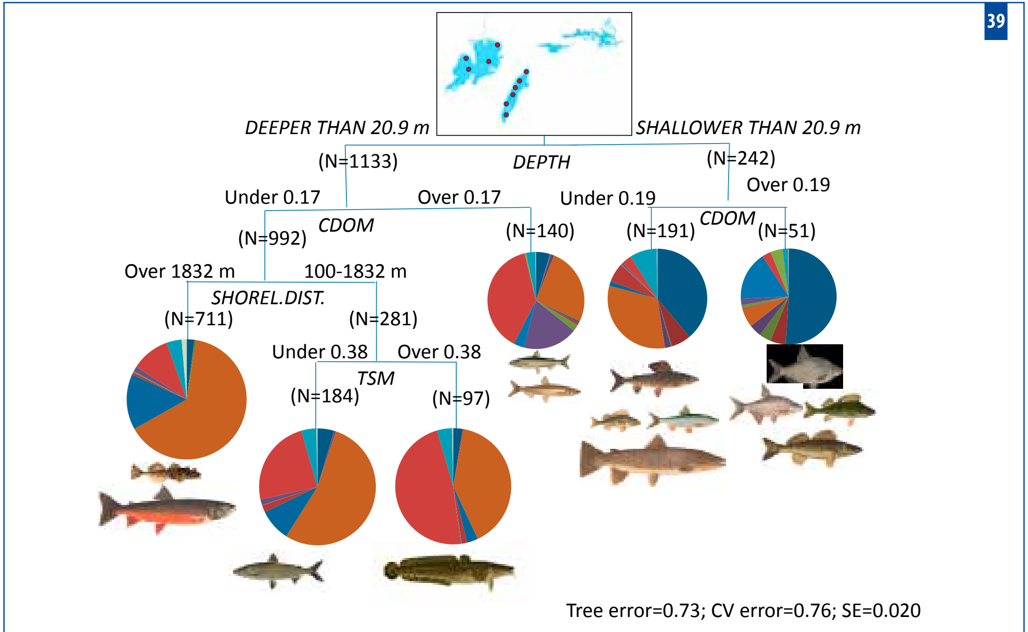


38 DIVERSITY II produced products on water quality, temperature and quantity, enabling the retrieval of biophysical indicators for 300 lakes worldwide. Biodiversity stories highlight the application of the products. All data products and biodiversity stories are available from www.diversity2.info.

Ecosystem functioning is known to be of major importance for the well-being of humans and the conservation of biological diversity is one key element in maintaining ecosystems in good condition and is central to main objectives of the Convention on Biological Diversity. In order to support the information needs for this convention for inland waters, a team from Brockmann Consult GmbH (Germany), Brockmann Geomatics AB (Sweden) and CIBIO (Portugal) has generated and is distributing products on water quality, temperature and quantity. The products enable the retrieval of biophysical indicators for 300 lakes worldwide and have various applications beyond the biodiversity scope.

The dataset provides the first globally representative, multi-year dataset for remotely sensed chlorophyll and suspended matter concentration, cyanobacteria and floating vegetation presence, and turbidity. All data are freely accessible. Water quality indicators are provided as monthly, yearly and nine-year averages for each lake, in a common, geo-referenced grid. Water quantity indicators are available from tabulated water surface level time series for the 100 largest lakes.

The use of the product database was evaluated for several lakes and particular events or environmental issues, such as the spatio-



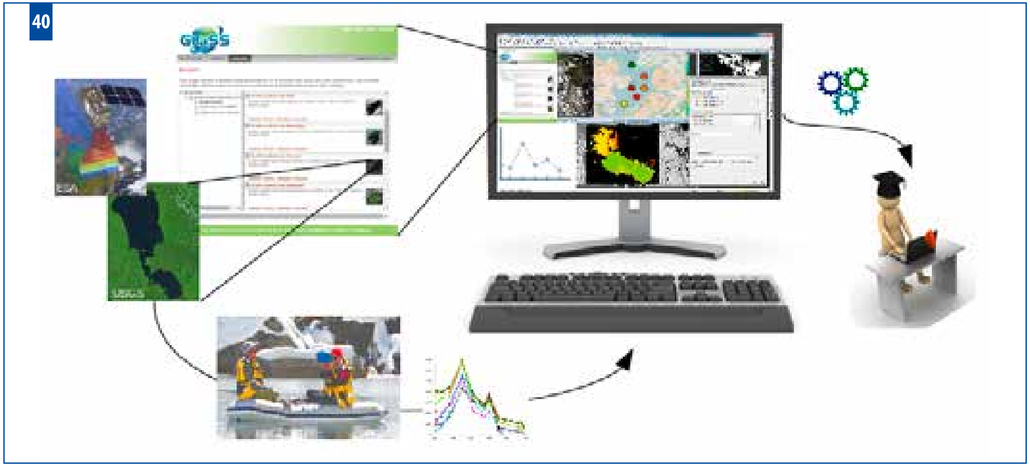
39 **Results of a multivariate tree analysis on inshore fish assemblage composition in L. Vänern, L. Vättern, L. Mälaren and L. Hjälmaren based on catches in multi-mesh gillnets. The figure illustrates the splits of the communities into distinct assemblage groups. The pictures of fish species represent the characteristic species (not necessarily the most common) in each group (Sandström et al., 2016, doi:10.1007/s10750-016-2784-9).**

temporal productivity patterns in Lakes Nicaragua and Winnebago, the cyclonic distribution of floating macrophytes in Lake Maracaibo or their advancement on Lake Victoria, or the linkage between seasonal productivity and vertical mixing in winter for mid-latitude lakes (Lake Biwa, Lake Geneva).

User testimonies

Such products addressing the change in lake water quality are needed especially for lakes outside the Western world, e.g. China or Africa.
Jörg Freyhof, former Executive Director of GEO BON, stated at the second DIVERSITY II User Consultation meeting (2014, Frascati)

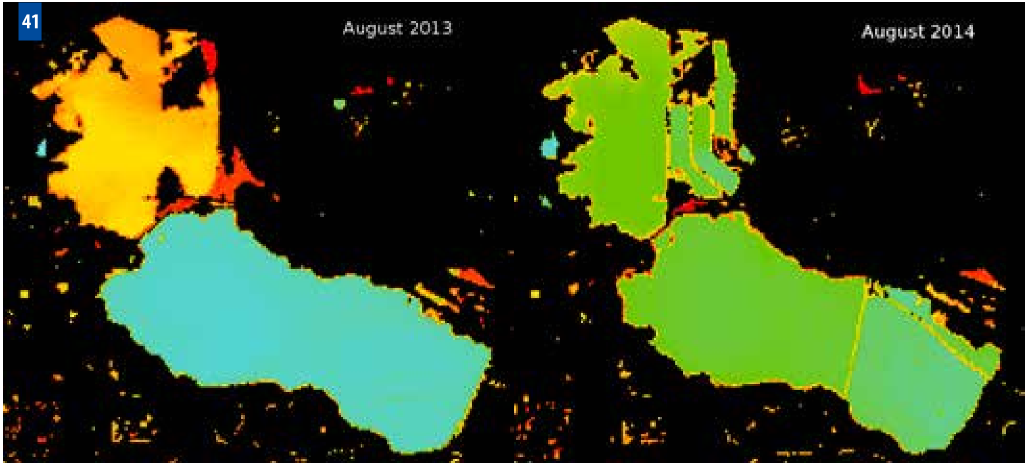
The results of the DIVERSITY II project also support the design of fish monitoring programmes. Since CDOM/Chl a in many cases could be used as the main predictors for fish distribution and assemblage composition, it is possible to use these parameters to assure that all the existing habitats/assemblages are covered in the programmes.
Alfred Sandström (Swedish University of Agricultural Sciences)



40 **GLaSS prepared the systems for access, the algorithms, the first validations, and example use cases for the new Sentinel satellites for water quality monitoring. There is also training material available to learn to work with this data.**

Demonstration of the utility of recently launched satellites for monitoring water quality in lakes and reservoirs

In 2015, the first ESA high resolution (10 – 60 m) optical Sentinel-2 satellite was launched; the second satellite of the series is planned to be launched in spring 2017. The first Sentinel-3 ocean colour satellite was launched early 2016 and also of this type more instruments will follow. The high spatial resolution of Sentinel-2, the high overpass frequency of the Sentinel-3 satellites, and the guaranteed long term operational availability provide unprecedented monitoring capabilities for inland waters. GLaSS developed examples of Sentinel services, to show a larger public what can be done with this new source of EO data.



41 Satellite images of Lake Böyük Şhor. Yellow, orange and red indicate a large(r) chance of oil present on the water surface, green and blue indicate a low change.

A system to ingest and process Sentinel data was created, in-water and atmospheric correction algorithm tests have been performed and several tools were developed to work with the data. Based on a combination of a socio-economic analysis and optical classification, use case lakes were selected globally. The listed lakes were studied in detail with EO and in situ data, using the GLaSS tools and algorithms. Altogether, the use cases demonstrate what can be done with the new Sentinel and other EO data with regard to monitoring, trend analysis and classification such as for the Water Framework Directive.

One of the major outcomes of the project is a collection of training materials that was created, to learn how to work with Earth Observation data on lakes. This GLaSS training material (10 lessons) builds on the global lakes use cases of the project. It allows students (Bsc, Msc, PhD) and professionals in fields such as aquatic ecology, environmental technology, remote sensing and GIS, to learn about the possibilities of optical remote sensing of water quality, by using the Sentinel-2 and Sentinel-3 satellites and Landsat 8. It teaches them how to access the data, choose the right data source, how to run the necessary algorithms and to interpret the results.

The GLaSS materials and reports are available through Researchgate, the "GLaSS training material" is available via several sources, such as ESA LearnEO! and the GEO EO Capacity Building portal.

User testimonies

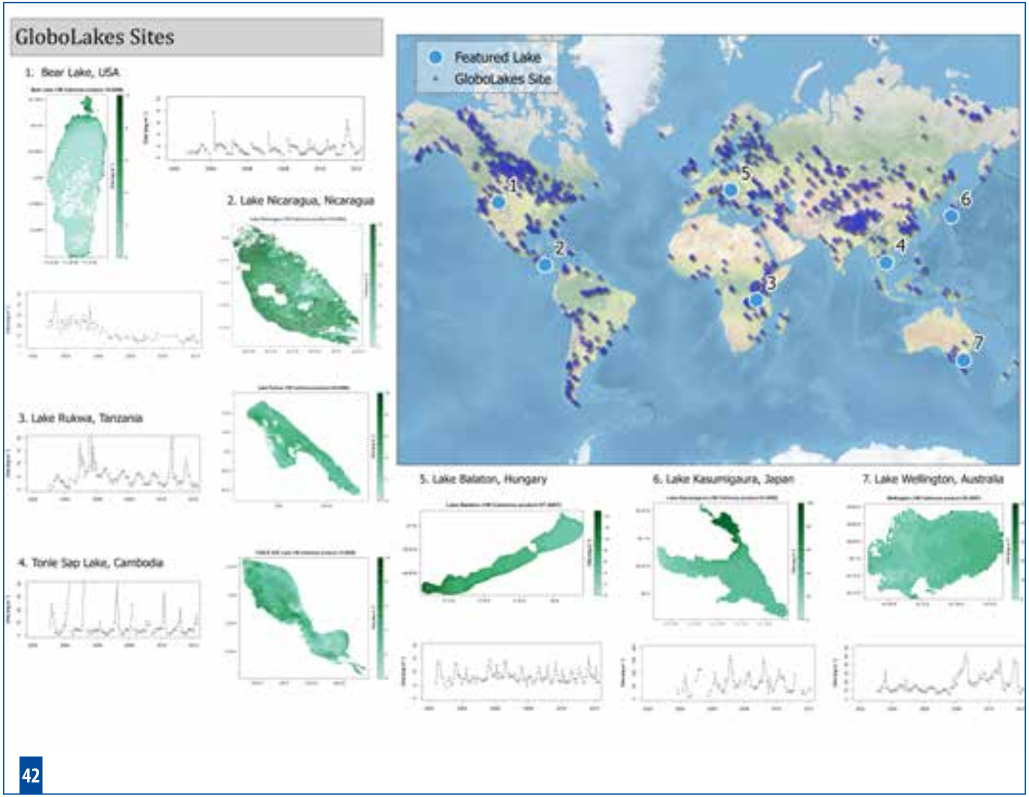
"I like everything about your project, particularly the wealth of resources (the training materials) made available."
Student Hydrology and Water Resources, using the online GLaSS materials

Global observatory of lake responses to environmental change

Recent developments in the availability of satellite platforms for Earth Observations offer an unprecedented opportunity to deliver measures of inland water quality at a global scale. The University of Stirling, Plymouth Marine Laboratory and Brockmann Consult, are collaborating through the UK Natural Environment Research Council funded GloboLakes project to deliver state-of-the-art global Earth Observation data processing and interpretation for inland water bodies. This project has resulted in the development of the processing change "Calimnos" for archived data and near-real-time processing, that adapts to different optical water types allowing mapping of optimised retrieval algorithms that are blended to produce the first consistent global products for Chlorophyll-a (phyto-plankton biomass), phycoyanin (cyanobacte-ria), total suspended matter (turbidity, light climate) and dissolved organic substances (light climate, brownification, lake trophic function), supplemented with additional lake surface water temperature data.

This achievement in characterising the number of optical water types and associated optimiza-tion, development and tuning of algorithms was only possible through the enthusiastic and generous collaborations of over thirty partners from the global water quality and remote sensing community. The data are now available through the community-owned database LIMNADES, an initiative started by GloboLakes, and comprise biochemical data for over 1500 lakes, radiometric data for over 3500 stations on 250 lakes and bio-optical data for 650 stations.

With an archive of over two decades of consistent ecological and physical observa-tions for 1000 lakes globally, GloboLakes is facilitating a paradigm shift in our understan-ding of how lakes respond to environmental changes at different scales and how this impacts on their status and function.



42 **The 1000 lakes in the GloboLakes Observatory. The figures show Chlorophyll-a distribution in selected lakes at selected times and a time series of monthly lake mean Chlorophyll-a concentrations produced by the Calimnos processing chain for featured lakes.**

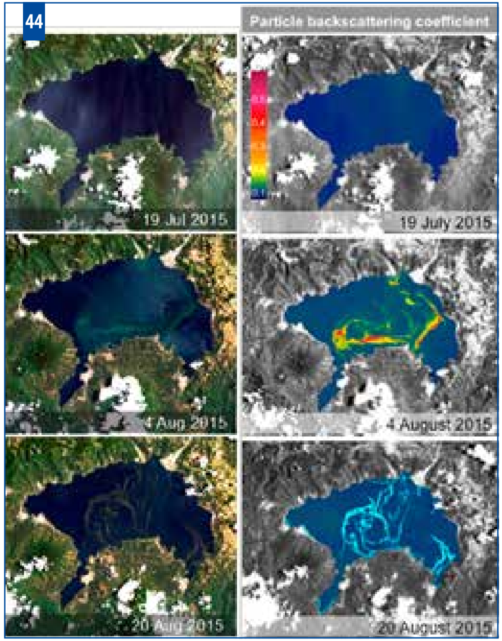
GloboLakes is providing the first insights into how lakes at the global scale are responding to environmental change drivers.
Jan Krokowski, Scottish Environment Protection Agency

User testimonies
Although designed for global scale monitoring, GloboLakes has provided the first steps towards operational monitoring of inland and coastal waters.
Sian Davies, Environment Agency

43 Satellite validation using fast boats and above water radiometers, example Lake Balaton, Hungary.

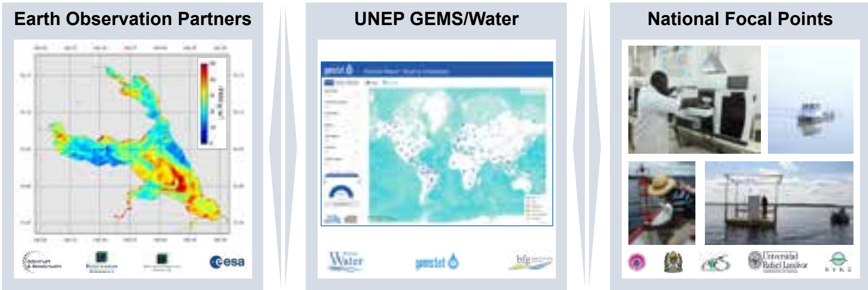
Closing global water quality information gaps with Earth Observation

The UN Environment Global Environment Monitoring System (GEMS) for Water maintains the global water quality database and information system GEMStat building on a monitoring network of National and Collaborating Focal Points. It is managed by the GEMS/Water Data Centre within the International Centre for Water Resources and Global Change on behalf of the German Federal Institute of Hydrology. GEMS/Water supports its partners in developing their capacities to monitor and assess water quality through trainings on monitoring programme design and implementation, data management and analysis and promotes the use of traditional and innovative monitoring techniques. Representativeness and continuity of the data records in GEMStat are affected by administrative, technical and financial capacity constraints.



44 Satellite true-colour images (left) and backscattering coeff-icients (right) of Lake Atitlán (Guatemala) before, during and at the decay stage of an Anabaena bloom (cyano indicates floating matter).

The ESA Innovator III project SPONGE is aimed at the integration of remotely sensed water quality information in GEMStat, by a team including remote sensing service providers, the International Centre for Water Resources and



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Global Change and National Focal Points in five selected countries; Finland, Ghana, Guatemala, Japan and Tanzania. The collaboration is based entirely on open source software and free data, which ensures that results are reproducible and capacities are transferable to potential users.
The close involvement of several National Focal Points allows for thorough validation and an assessment of the service against locally specific environmental issues, such as the encroachment of eutrophication on remote rural areas, the frequency and extent of cyanobacteria blooms, or emissions from aqua farms and artisanal mining.

User testimonies
Improving water quality worldwide is one of the targets of the 2030 Agenda for Sustainable Development and water quality remote sensing can support Member States in tracking their progress.
Philipp Saile (Head of GEMS/Water Data Centre, International Centre for Water Resources and Global Change)
Earth Observation will help in the implementation of a cost-effective national monitoring system by complementing our sparse in situ monitoring network. *Virginia Mosquera Salles (University Rafael Landívar, Guatemala)*

45 UNEP's GEMS/Water programme maintains a global database of in situ water quality measurements in collaboration with National Focal Points. Satellite observations are being used to fill information gaps in this database.

Future directions

Improved and advanced products

Future projects of AquaWatch will involve improved and advanced products in addition to those presented in this booklet. For example, we need to develop more accurate remotely sensed chlorophyll products. Currently there are no universally verified and accepted chlorophyll algorithms for coastal and inland waters, although approaches using an assemble of algorithms that adapt to optical water types is proving very effective.

One of the main challenges is that the apparent water colour, which is essentially what can be measured directly from space, is generated not only by phytoplankton but also by materials independent on phytoplankton, such as yellow substance, and fluvial and resuspended sediments. Secondly, the atmosphere above coastal and inland regions is very complex and variable with respect to aerosol optical properties and vertical distribution. These challenges are being addressed by the AquaWatch community in future research.

We are also aware that water quality managers and decision-makers are ultimately interested in nutrients, toxins, pathogens, and other pollutants. Currently the chlorophyll parameter is used as a typical proxy for nutrients whereas parameters like turbidity/suspended sediment are used to determine the likelihood of the presence of other water quality issues, when interpreted in the context of the catchment characteristics. Currently, these optically inactive constituents influencing water quality are beyond the direct observation capability of EO platforms. However, approaches are being developed to link EO data with modelling techniques to unlock the potential of delivering these advanced products.

Improved resolutions and coverage

More efforts will also be directed into improving the spatial and temporal resolutions of satellite water quality products to characterise the optically complex inland and coastal waters. Geostationary satellites are indispensable to achieving these goals. Although dedicated ocean colour sensors are currently only available from the Korean instrument GOCI (and GOCI-II in the near future), many weather satellites are now equipped with multiple visible and near-infrared bands with greatly improved signal-to-noise ratio and spatial resolutions, e.g., the Japanese Advanced Himawari Imager (AHI) onboard Himawari-8/9 and the US Advanced Baseline Imager (ABI) onboard GOES-R. The use of these data is expected to minimize inevitable data gaps due to cloud coverage, and improve the temporal resolution of satellite imagery at clear view. Along this direction, techniques to merge geostationary satellite data with polar orbiting ones can generate synergistic effects to the advantage of water quality monitoring and thus are highly desired. Coupled hydrodynamic and optical models that can assimilate various satellite radiometric data, reconstruct the past and predict the future of the real world in terms of optical aspects, expected to play a significant role in this effort. To ensure an adequate infrastructure to support these efforts, it is also essential to advise space agencies in the development of satellite platforms with optimal spatial, temporal, spectral, and radiometric requirements.

The AquaWatch community is embracing the first hyperspectral satellite mission with global coverage, the NASA Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission, with a notional launch date in the 2022–2023 timeframe. The significantly improved spectral resolution will help resolve more detailed spectral features in the optical properties of water constituents and may aid in the development of advanced products such as pathogens and pollutants.

Partnering with AquaWatch

If you are interested in funding a project or partnering with AquaWatch, contact the AquaWatch Secretariat:

Dr. Emily Smail, AquaWatch Secretariat, Emily.Smail@noaa.gov

NOAA Center for Weather and Climate Prediction (E/RM3)
5830 University Research Ct., College Park, MD 20740
www.aquawatch.org

Project acknowledgements and contacts

Monitoring dredging activities with satellite based sediment maps
This work was contributed by Ils Reusen (VITO) and funded by the Belgian Science Policy (BELSPO) and the European Union Seventh Framework Programme under Grant Agreement n° 606865 (INFORM) and 606787 (HIGHROC).

Collaborators: Els Knaeps, Liesbeth De Keukelaere and Dries Raymaekers (VITO); Mark Bollen and Boudewijn Decrop (IMDC).
Project contact: Ils Reusen (ils.reusen@vito.be)

Monitoring the effect of large scale sand extraction in the coastal waters of the Netherlands using remote sensing
This work was contributed by Nicki Villars, with support from Ghada El Serafy, Meinte Blaas, Thijs van Kessel and Sandra Gaytan Aguilar (Deltares, the Netherlands) and funded by the Port of Rotterdam Authority.

External Collaborators: Marieke Eleveld, Hans van de Woerd and Nils de Reus (Free University Amsterdam – Institute of Environmental Studies); Wil Borst and Onno van Tongeren (Port of Rotterdam Authority).
Project contact: Nicki Villars (nicki.villars@deltares.nl)

Near-real-time satellite monitoring of turbidity in the Chesapeake Bay
This work was contributed by Guangming Zheng and Ron Vogel (NOAA/NESDIS/STAR) and funded by the NOAA ORS programme and CoastWatch programme.

Project contact: Guangming Zheng (guangming.zheng@noaa.gov)

Water quality monitoring in Tagus Estuary

This work was contributed by Vanda Brotas (Ciências ULisboa) and funded by Valorsul, (Valorisation and Treatment of Solid Waste of the Regions of Lisbon and the West). Acknowledgments are also due to MARE, Marine and Environmental Sciences Centre, Faculdade de Ciências da Universidade de Lisboa.

Project contact: Vanda Brotas (vbrotas@fc.ul.pt)

Reconstructing changes in sediment flux from the Danube into the Black Sea

This work was contributed by Adriana Maria Constantinescu (University of Stirling, GeoEcoMar) and funded by the University of Stirling (UK) and GeoEcoMar (Romania).

Collaborators: Andrew Tyler (University of Stirling); Peter Hunter (University of Stirling), Evangelos Spyrakos (University of Stirling), Adrian Stanica (GeoEcoMar); Georg Umgiesser (CNSR-ISMAR).

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Monitoring water siltation caused by artisanal gold mining in Amazonian rivers using multi-satellite images

This work was contributed by Felipe do Lucia Lobo (National Institute for Space Research, Brazil) and funded by PDJ/CNPq (150835/2015-9).

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Development of a remote sensing based algal bloom early warning system

Development of a Remote Sensing Based Algal Bloom Early Warning System
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Cyanobacteria monitoring in the Netherlands

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Water quality integrated monitoring system for Lake Geneva
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User driven operational remote sensing information services for aquaculture
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Satellite monitoring of cyanobacteria blooms and eutrophication in South Africa
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Closing global water quality information gaps with Earth Observation
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Global observatory of lake responses to environmental change

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Global inland water biodiversity indicators in 2002–2012

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Demonstration of the utility of recently launched satellites for monitoring water quality in lakes and reservoirs

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Earth Observation-based services for monitoring and reporting of ecological status

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Annex

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