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Satellite-assisted monitoring of water quality to support the implementation of the Water Framework Directive

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Executive summary and recommendations

The EU Water Framework Directive[1] (WFD) is an ambitious legislation framework to achieve good ecological and chemical status for all surface waters and good quantitative and chemical status for groundwater by 2027. A total of 111,062 surface waterbodies are presently reported on under the Directive, 46% of which are actively monitored for ecological status. Of these waterbodies 80% are rivers, 16% are lakes, and 4% are coastal and transitional waters. In the last assessment, 4% (4,442) of waterbodies still had unknown ecological status, while in 23% monitoring did not include in situ water sampling to support ecological status assessment[2]. For individual (mainly biological) assessment criteria the proportion of waterbodies without observation data is much larger; the full scope of monitoring under the WFD is therefore still far from being realised. At the same time, 60% of surface waters did not achieve 'good' status in the second river basin management plan and waterbodies in Europe are considered to be at high risk of having poor water quality based on combined microbial, physical and physicochemical indicators[3].

Water quality metrics derived from satellite observation can complement conventional water sampling, particularly to achieve much improved spatial and temporal coverage of medium (several square kilometres) and larger waterbodies. Thus, it has the potential to enhance confidence in WFD ecological status classification, firstly by quantifying elements of environmental status that are currently not or under-reported by Member States, such as the frequency, onset, duration and extent of phytoplankton blooms. Second, confidence in ecological status assessment would improve with increased representativeness of the natural diversity of waterbodies that are monitored, their inter-annual variability and water quality trends within larger waterbodies. Moreover, using standardised approaches, it would allow better comparison and standardization of water quality assessment across Member States, facilitating the management of transboundary waters in particular. Finally, by increasing spatial and temporal coverage, satellite observation is expected to enhance the effectiveness of the Programme of Measures (PoM) through early detection of deterioration, improving knowledge of the potential extent of an impact, improving monitoring of the effectiveness of PoMs and providing information to support more strategic in situ sampling.

The European Union and European Space Agency currently boast the most advanced suite of satellite-based instruments designed to observe optical water quality. The Copernicus framework of sensors and services has had significant investment in recent years. Therefore, the vast majority of the cost associated with satellite-based monitoring of surface waters has already been invested.

To promote and support the use of satellite-based water quality metrics in WFD national and statutory monitoring and reporting activities, we make the following recommendations, particularly in light of the ongoing revision of the WFD:

- **Recognition of satellite observation as an assessment method in the context of the revision of the Water Framework Directive.**

  Explicit encouragement to use satellite-based monitoring to complement national and statutory monitoring and reporting, such as already exercised by a limited number of countries (examples in this paper) and available from existing academic, governmental

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[1] Water Framework Directive, 2000/60/EC

[2] European Environment Agency, Report no 7/2018. European waters: assessment of status and pressures 2018

[3] Damania *et al*. 2019. Quality Unknown: The Invisible Water Crisis. Washington, DC: World Bank

and private sector capabilities, will provide a clear signal to Member States that its use is supported. In particular, satellite products that enhance confidence in the classification of phytoplankton biomass (typically measured by chlorophyll-a) by vastly improving spatial and temporal coverage should be considered, since these are already highly mature and can support quality elements that have thus far been considered too costly to include using conventional methods, such as assessing the frequency and intensity of algal blooms in lakes and coastal waters.

- **Create a satellite observation expert group to harmonise metrics across countries and advise member states on best practises.**

  The satellite observation expert group will: ensure harmonisation of the applicable satellite observation methods and their comparability with nationally-approved and intercalibrated methods; establish guidelines on how observation uncertainties should be reported; and ensure close collaboration with the Water Framework Directive Common Implementation Strategy working group on ecological status (WG ECOSTAT). An expert group advising on best practise is necessary because satellite-based observation capabilities continue to improve over time whereas water quality management relies on stable and transparent methodologies. The expert group should work towards self-certification in the industry, including representation from the downstream Earth observation service sector, and be led by an independent research and policy advisory body (such as the Joint Research Centre).

- **Reference the use of satellite-based Earth observation metrics in the Reporting Guidance (Annex 5) of the revised Water Framework Directive.**

  Particular reference to the use of satellite-derived water quality indicators in assessing phytoplankton biomass (by proxy of chlorophyll-a) and the frequency and intensity of phytoplankton blooms in Annex 5 as well as national and international standards will ensure the provision of monitoring data of equivalent scientific quality and comparability.

- **Convene a conference for EC, Member States, WFD authorities to agree on recommendations of common practices and reporting standards when using satellite-based water quality metrics to support the Water Framework Directive.**

  Provide an opportunity for policy makers to recognise and proactively support the use of already available satellite-based Earth observation derived metrics and capitalise on already established networks of national Earth observation scientists applying relevant derived metrics to the Water Framework Directive requirements.

This white paper results directly from ongoing international Research and Innovation actions funded under Horizon-2020 (see section 9) and building on two decades of EU and (inter)nationally funded research into the use of satellite observations to quantify and monitor trends in water quality in coastal and inland waterbodies. The release of this paper is further prompted by significant EU investment in the Copernicus satellite programme, guaranteeing sustained observation capabilities for decades to come. This paper and its recommendations are supported by a wider group of experts and stakeholders including WFD authorities, research programmes and umbrella organisations listed in section 9.

The recommendations given herein are intended for policy makers at, *inter alia*, DG Environment, national WFD monitoring and reporting authorities as well as delegated authorities and advising organisations (JRC, EEA). Some of the recommended actions, such as the formation of an advisory body, will need support from Member States and could be brought forward in the ECOSTAT working group, to arrive at a strategy for the use of satellite-derived water quality products.

Contents

1. Introduction

The EU Water Framework Directive[4] (WFD), adopted in 2000, is a substantial and ambitious framework legislation that sets out integrative and comprehensive approaches for achieving good ecological and chemical status for all surface waters (rivers, lakes, transitional and coastal waters[5]) and good quantitative and chemical status for groundwater by 2027. Achieving good status for surface waters involves meeting objectives of quality of the biological, hydromorphological and physico-chemical parameters that only slightly deviate from levels normally representative of undisturbed conditions of a waterbody. Some of the quality elements used to assess surface water status, in particular ecological status, can be complemented with satellite observation. These range from water-column measurements (e.g. water transparency and phytoplankton-based indicators) to benthic observations (e.g. abundance and composition of angiosperms).

Approximately 40% of all surface waters have good ecological status based on analysis of in situ samples taken from a network of 130,000 sites across Europe. The number of quality elements contributing to this assessment, however, varies by waterbody and by Member State. In broad terms, only 2% of all surface waters in Europe have all four biological quality elements (BQE1–1 to BQE1–4) included in their status assessment, 56% use one to three BQEs, 19% only use hydromorphological and physico-chemical quality elements and the remaining 23% do not include any elements designed to support an ecological status assessment. The number of waterbodies for which the quality of certain elements is unknown is therefore high. For transparency there is no information for approximately 87% of lakes (including Norway). Phytoplankton is the most reported BQE in lakes and coastal waters and the second-most reported BQE in transitional waters (after benthic invertebrates). Nevertheless, on average the number of waterbodies with unknown status for the phytoplankton element ranged from 58% in coastal waters to 65% in lakes in the second reporting period (Figure 1). Differences between Member States are, however, large (Figure 1), owing to the widely varying number of waterbodies that each Member State reports on.

While justified exemptions to exclude certain quality elements from the assessment exist, there is a wider pattern of unknown biological and non-biological quality elements hinting at difficulties to fulfil the reporting targets of the WFD across Member States. For example, 91% of salinity status for transitional waters is unknown and 96% of thermal conditions status for coastal waters is unknown.

Satellite observation derived metrics can help fill these gaps, particularly with regard to biological quality elements of medium (several km^2) to large-sized surface waters (see further below for technical details and examples). It can also provide added value by quantifying quality elements that are currently not reported by Member States (including short-lived phytoplankton blooms and short-term changes in angiosperm abundance in intertidal areas); improve understanding of temporal and spatial variability of several quality elements within water and above the sediment surface in intertidal and shallow areas; help define environmental reference status of some quality elements using historical satellite data, or establish medium to long-term trends where satellite data do not date back far enough; provide a harmonized approach for monitoring of water quality across Member States and transboundary waters; and support cost-efficiency in monitoring and management practises when implementing the Programme of Measures.

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[4] Water Framework Directive, 2000/60/EC

[5] European Environment Agency, Report no 7/2018. European waters: assessment of status and pressures 2018

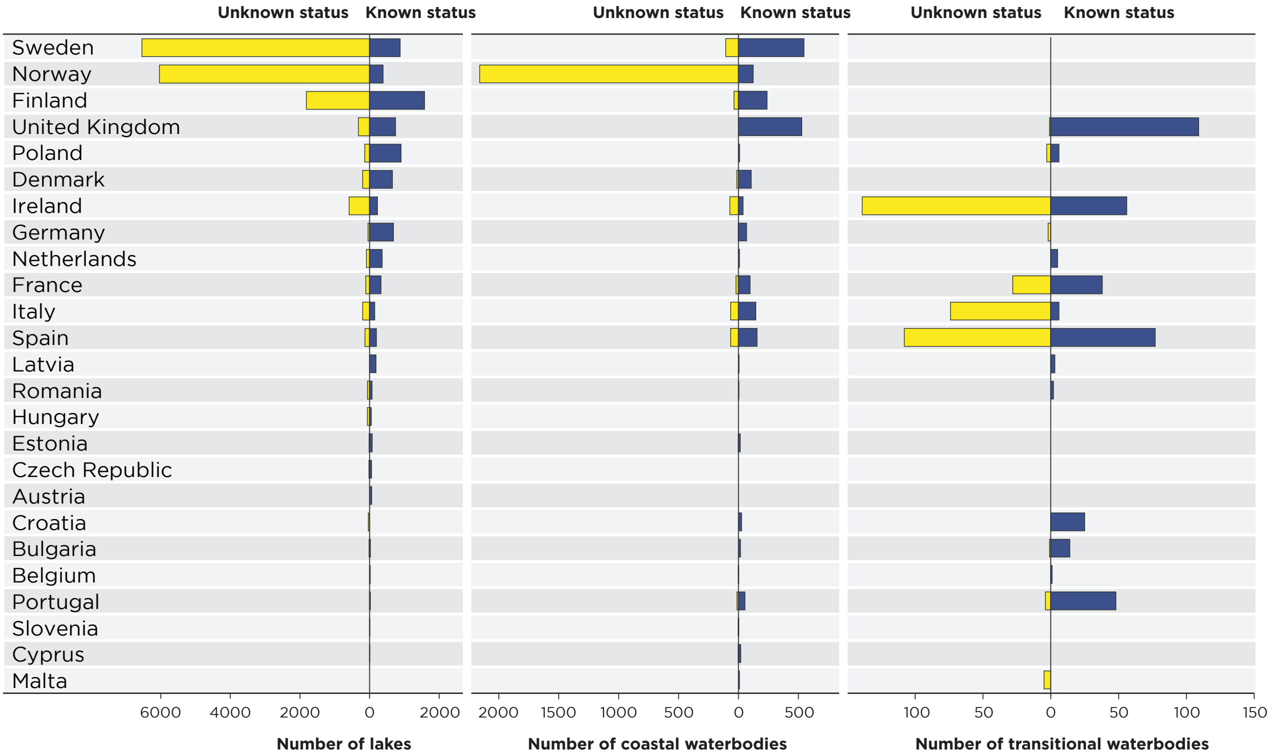

Figure 1: Known versus unknown status for BQE1-1 Phytoplankton in (left) lakes, (middle) coastal and (right) transitional waterbodies. Source of data: WISE-SoW database including data from 26 Member States and Norway (no data for Greece and Lithuania).

2. A growing use of satellite observation for water quality

The water quality metrics included in national assessments using in situ samples are shown in Table 1 alongside suggested proxies that can be derived from satellite observation. With each generation of Earth observation (EO) satellites introduced since the 1990s there has been continuous development to ensure the accuracy of satellite products compared with station sampling, particularly for chlorophyll-a (Chl-a) and vertical transparency[6] and, consequently, their increased use in water quality monitoring (see Box 1).

Table 1: Current in situ metrics and corresponding satellite-derived quality metrics to be considered

WFD requirements	National Systems	Satellite-derived proxies to be considered
QE1 Biological elements		
QE1-1. Phytoplankton		
Abundance and biomass	Extracted chlorophyll-a concentration[i] Biovolume of phytoplankton[i]	Chlorophyll-a concentration from in vivo pigment absorption[ii,iii] Trophic State Index derived from Chlorophyll-a
Composition	Biovolume of cyanobacteria[i] % of cyanobacteria of total biovolume[i] Various other metrics, trophic indices	Phycocyanin (cyanobacterial pigment) concentration[v] Functional size classes (only in oceanic waters)[iv]
Frequency and intensity of planktonic blooms	Not reported / not possible using conventional monitoring	Chlorophyll-a concentration[ii,iii] Phycocyanin (cyanobacterial pigment) concentration[v] Surface accumulations of cyanobacteria[vi]
QE1-2 Other aquatic flora		
Macrophyte abundance	Various trophic indices; Submerged vegetation cover[i] Total areal coverage[i]	Areal cover of floating vegetation
Macrophyte composition	Proportion of taxa	Not from current satellite sensors, but from airborne surveys[vii]
Macroalgal cover and angiosperm abundance	Combination of spatial extent and relative abundance (measured as density) of macrophytes Abundance of macrophytes[viii,ix]	Spatial extent In intertidal areas[x,xi,xii]: spatial distribution of seagrass density of sea grass, total surface area of seagrass beds
QE3. Chemical and physico-chemical elements		
QE3-1. General		
QE3-1-1. Transparency	Secchi disk depth (Dissolved organic carbon also used to characterise lake typology)	Satellite backscatter as turbidity, suspended particulate matter weight or vertical transparency (extinction or Secchi depth)[xiii,xiv]
QE3-1-2. Thermal conditions	Mean water temperature Water temperature range Air temperature	Surface water temperature[xv] (in open water >2 km from land)
QE3-1-4. Salinity	Electrical conductivity Refractometry	Only with regionally tuned models using Coloured Dissolved Organic Matter (CDOM) as freshwater proxy. In marine/ oceans: sea surface salinity
QE3-1-5. Acidification status	pH	Only in oceanic waters: from combining ocean colour, sea surface temperature, sea surface salinity[xvi]

Table references:

[i] Poikane *et al.* 2015,
[ii] For general principles see IOCCG report 17, Greb *et al.* (Eds) 2018,
[iii] Alikas *et al.* 2010,
[iv] Hirata *et al.* 2011,
[v] Simis *et al.* 2005,
[vi] Anttila *et al.* 2018,
[vii] Birk and Ecke 2014,
[viii] Marbà *et al.* 2013,
[ix] Neto *et al.* 2013,
[x] Barillé *et al.* 2010,
[xi] Traganos *et al.* 2018,
[xii] Zoffoli *et al.*, pers. comm,
[xiii] Alikas *et al.* 2017,
[xiv] Alikas *et al.* 2015,
[xv] Layden *et al.* 2015,
[xvi] Sabia *et al.* 2015.

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[6] Examples of statistical accuracy for coastal waters are given in Domingues *et al.* 2008, Gohin *et al.* 2008, Novoa *et al.* 2012, Harvey *et al.* 2015 and Attila *et al.* 2018. For lake waterbodies, examples are given in Bresciani *et al.* 2011, Alikas *et al.* 2015 and Neil *et al.* 2019.

In a recent example of the uptake of satellite products, Sweden used satellite observations (from the MERIS instrument, 2002–2012) to provide phytoplankton (from Chl-a) and transparency (equivalent to Secchi disk depth) metrics for the 2014 WFD status classification. Sweden also includes satellite-based Earth observations of Chl-a for the ongoing 2nd round reporting (2015–2021) for coastal waterbodies. Similarly, Finland used Chl-a time-series of satellite derived data for coastal waterbodies in the 2014 WFD assessment (see Box 1). More recently, Finland introduced satellite-derived metrics to support WFD assessments in the 2015–2021 reporting cycle (see Case study 1: Comprehensive assessment of coastal and inland waterbodies in Finland, in the Appendix).

The examples show that Member States can choose to use satellite products to support implementation of the WFD. A harmonized approach and calibration of methods is, however, lacking, particularly in the light of the vastly improved spatio-temporal coverage that satellite observations bring over conventional sampling for seasonal phenomena such as phytoplankton bloom (see Box 1).

The last river basin management plan report included 2,835 coastal and 782 transitional waterbodies for which macroalgae and angiosperm monitoring falls under the WFD. The proportion of waterbodies with unknown status was high at 78% and 94% for macroalgae and angiosperms, respectively. In France, seagrass beds (marine angiosperms) have been monitored using satellite observations since the 1990s[7] but not as part of WFD monitoring. Satellite time-series can be used to characterise the spatial distribution and density of seagrass, and current satellite capabilities allow mapping of seagrass abundance and coverage at high spatial (10 m) and monthly resolution (see Case Study 2: Intertidal seagrass beds in France, in the Appendix).

Filling existing data gaps is a compelling reason to consider the inclusion of suitable satellite products in monitoring and reporting activities. Subsequently, there may be a need for the Earth observation industry to fulfil the role of data producers, at least in countries where capabilities are currently limited, and for a capacity building programme to bring about informed use of satellite products within the monitoring authorities.

Box 1: WFD reporting of Finnish waterbodies

During the last two Water Framework Directive reporting periods, Finland used satellite products at 300 m resolution to measure Chl-a in 1,513 lakes and 215 coastal regions, to complement information obtained from station-based water quality sampling.

Comparison of classification results between conventional and satellite methods showed good agreement for the 2nd Water Framework Directive reporting period. In over 80% of coastal waterbodies examined in 2014 the resulting ecological status class was the same. The accuracy of satellite information was compared to station sampling resulting in an average difference of 23%, comparable to a ±20% determination uncertainty determined for laboratory-based Chl-a measurements([a,b]).

In the 3rd round of WFD classification, Sentinel-2 satellites were used to estimate Chl-a in approximately 2,000 lakes and 250 coastal waterbodies at 60 m resolution. These satellite results agreed with in situ sampling in over 80% of cases defined as either ‘good or better’ or ‘moderate or worse’. The fine resolution of the satellites allowed 500 small inland waterbodies to be added to the classification, with approximately 10–20 Chl-a estimates in the 2016–2018 period.

Generally, satellite results suggested better water quality than in situ observations, which is due to their improved spatial and temporal coverage. Whereas station sampling takes place during July–August when Chl-a concentrations are highest, satellite observations included the whole assessment period from June to September.

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[7] Barillé *et al*. 2010

[a] Näykki and Väisänen (Eds.). Reports of the Finnish Environment Institute, No. 22/2016 (Finnish)

[b] Attila *et al*. 2018

3. Additional information from satellite observations

The biomass of phytoplankton can be produced using satellite observations using Chl-a as a proxy. Recently, the Centre for Limnology in Estonia used data from the Sentinel-2 multispectral instrument (MSI) at 10 m spatial resolution to observe phytoplankton biomass in Estonian lakes. Phytoplankton biomass dynamics differed markedly between the lakes, showing varying degrees of seasonality (Figure 2). These insights into the seasonality of ecological status provide useful information for the management of these waterbodies, and are not identifiable from conventional monitoring alone. Moreover, the information from satellite products could be used to strategically target sampling activities, bringing some cost-saving potential. For further details and additional examples see Case study 3: Strategic monitoring of lakes in Estonia, in the Appendix.

The occurrence of seasonal phytoplankton blooms increases with eutrophication and the WFD requires Member States to monitor the frequency and intensity of phytoplankton blooms (Annex 5). Currently, only bloom intensity is measured[8,9] because measuring the frequency of blooms has been considered too costly. Revision of the WFD provides an opportunity to address this by explicitly including reference to satellite-derived Chl-a as a cost-effective method to address this component of the legislation. Emerging methods to provide diagnostic information on the presence of cyanobacteria in surface waters from satellite observations[10] would likely provide additional value here, although further validation against in situ observations are needed to come to a robust methodology for blooms that occur in mixed conditions as well as cyanobacteria blooms that may accumulate at the water surface under calm weather conditions.

[8] Carvalho *et al*. 2013

[9] Poikane *et al*. 2015

[10] Anttila *et al*. 2018

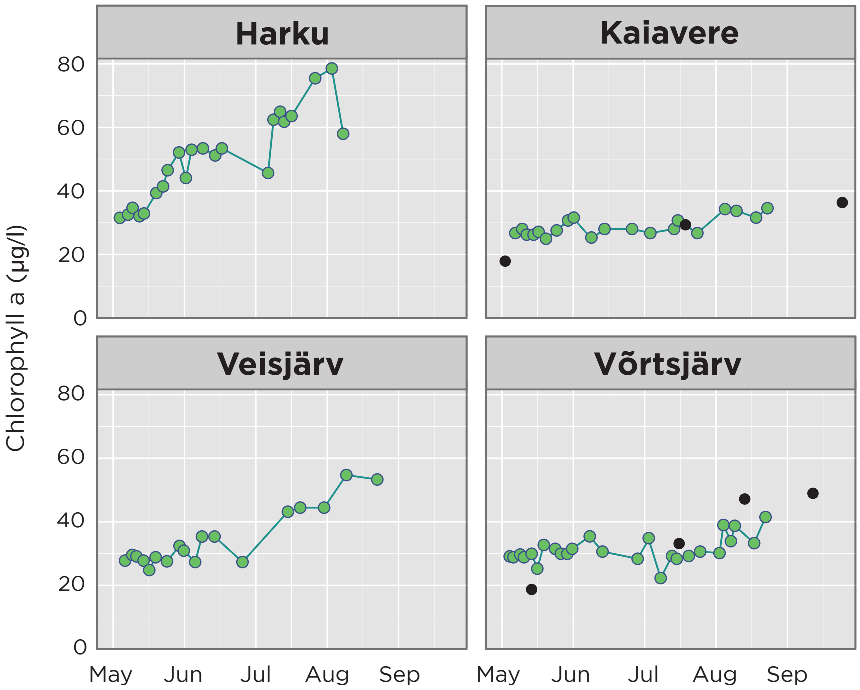
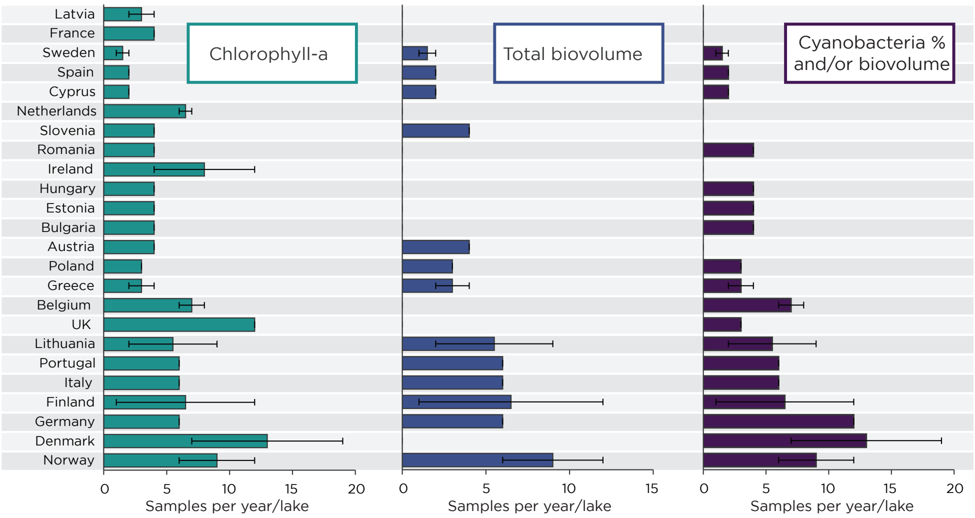


Figure 2: *Seasonal dynamics of chlorophyll-a in selected Estonian lakes which fall under the WFD reporting obligation. Data derived from Sentinel 2 MSI imagery during 2018. Black dots mark chlorophyll-a concentrations in water samples.*

4. Improving spatial and temporal observation coverage

In situ sampling has the advantage of supporting a rich suite of measured quality elements using trusted methodology with high achievable accuracy per sample. An obvious downside in monitoring context, however, is the limited spatial and temporal coverage of in situ observations. Chl-a concentration is recorded as little as once and up to 19 times per year in lakes and 3–20 times per year in coastal waterbodies, with sampling frequencies varying widely between member states (Figure 3). Such sparse information will likely fail to accurately represent the dynamic nature of many waterbodies. Satellite-derived products can help overcome these limitations by providing frequent and spatially extensive information. Datasets of varying temporal (1–16 days) and spatial (10–300 m) resolutions exist to aid in describing the horizontal and temporal dynamics of medium to large waterbodies.

Lakes



Coastal waterbodies

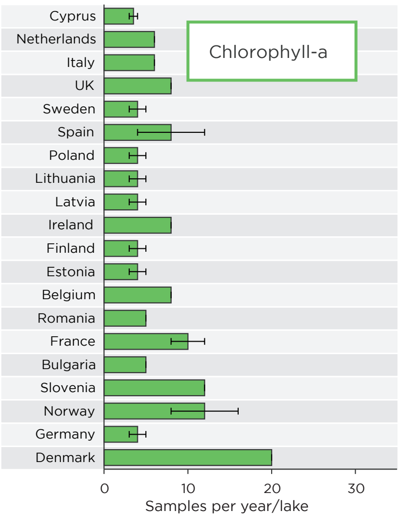


Figure 3: In situ sampling frequency for some Phytoplankton quality elements for lakes (top: left, middle and right) and coastal waterbodies (bottom). Coloured bars indicate the average, black error bars span the minimum and maximum frequency reported. Data collated from WFD Intercalibration technical reports, available on CIRCABC.

Current satellite constellations delivering 300 m resolution images have daily global observations, sufficient to overcome issues of cloud cover in most areas. Such data are particularly useful for large lakes as well as more dynamic transitional waterbodies, where comprehensive assessment from point measurements (in situ sampling) is challenging. Transitional waters can further be delineated to assess the terrestrial influence on coastal systems, which can for example be useful to plan the optimal location of long-term monitoring stations (Figure 4 and further detail in Case study 4: Applying appropriate metrics in transitional coastal waters of Lithuania, in the Appendix).

Accurate assessment of the ecological reference state of a waterbody is one of the most important and challenging tasks of the WFD. Unfortunately, for optical water quality parameters such as Chl-a, methods suitable for lakes and coastal waters start only from 2002 with the launch of the first medium-resolution satellite sensor (MERIS on Envisat) which was in part dedicated to observing these environments. For the monitoring of vegetation including marine angiosperms and turbidity, long-term historical satellite missions such as Landsat (1972–present) and SPOT (1986–present) may also be utilised.

Another aspect of in situ sampling that is difficult to overcome is the associated high cost per individual sample. Site visits and most associated laboratory analysis will remain necessary for those biological, chemical and physico-chemical elements of the assessment which cannot be complemented with satellite products. Cost savings are therefore most likely to result from reduced laboratory analysis of phytoplankton samples, which could at least in part be fulfilled by selecting remote sensing derived metrics. In cases where phytoplankton sampling takes place more frequently than other quality elements, this cost saving could be substantial[11]. Further cost-efficiency could be achieved through strategic optimization of in situ sampling times and locations to capture (or avoid, for baseline monitoring) episodic events. Ultimately, however, cost-savings may not be achieved within the monitoring programmes but rather in the total cost of water quality management, since timely observation of disturbances should lead to more efficient remediation efforts.

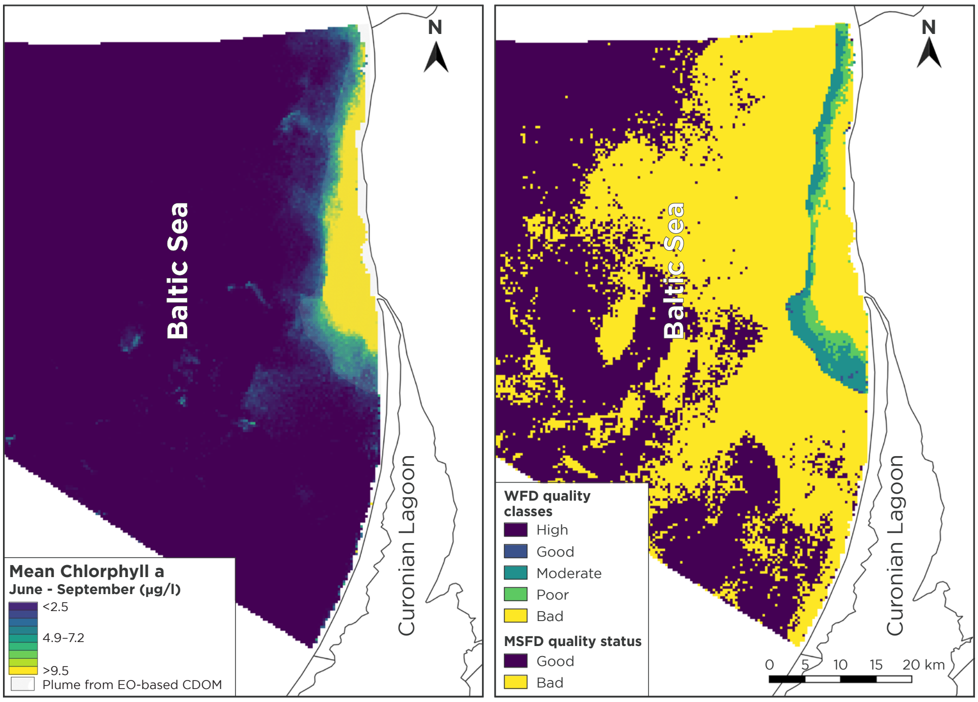


Figure 4: (Left) Map of summer-mean chlorophyll-a concentration and the plume area determined from coloured dissolved organic matter to determine the outflow area of the Curonian Lagoon into the Baltic Sea, from Envisat/MERIS data in 2011. (Right) Combined mapping of WFD and MSFD Environmental Status based on threshold values of Chlorophyll-a for the area included under the respective inland/coastal and marine domains.

[11] Carvalho *et al*. 2019

5. Towards a standardised and harmonised approach

Individual monitoring programmes are determined by Member States in line with the WFD objectives and resources available nationally. Quality elements, sampling methods (including number of samples per waterbody and frequency of sampling), and analysis techniques vary, therefore, both by waterbody and between countries[12]. Satellite observation has the potential to provide a cost-effective, standard, long-term, homogenous methodology that will allow like-for-like comparison of metrics across countries, agencies and industries. Products derived from satellite observation will nevertheless need to meet the same standards of transparency and reproducibility applied to laboratory-derived measurements. There are numerous algorithms that could be applied to satellite data to derive a single quality metric such as Chl-a, often designed to provide the best result for a given water type or region[13]. Continued evolution of satellite capabilities over the last decades has resulted in continuous improvements in satellite products. To ensure that the applied methodologies are stable over time, harmonised metrics need to be addressed as part of a common strategy for the use of satellite Earth observation products.

A major source of encouragement to deliver a harmonised approach to providing satellite-derived water quality indicators will be the management of transboundary waters. Here, a common and independent methodology would provide insight into the management of transboundary waters which can facilitate time sensitive and alternative management interventions between countries (see Box 2).

The creation of a satellite observation water quality intercalibration group should facilitate standardisation of methods and harmonisation of metrics across countries. Standardisation should include elements of how observation methodologies (algorithms) are assessed, how observations from multiple sensors are combined, and how product uncertainties compare with currently used methods. Harmonisation efforts should include the fusion of in situ and remote observations as well as the merging of results originating from complementary methodologies (algorithms), all the while upholding standards of measurement.

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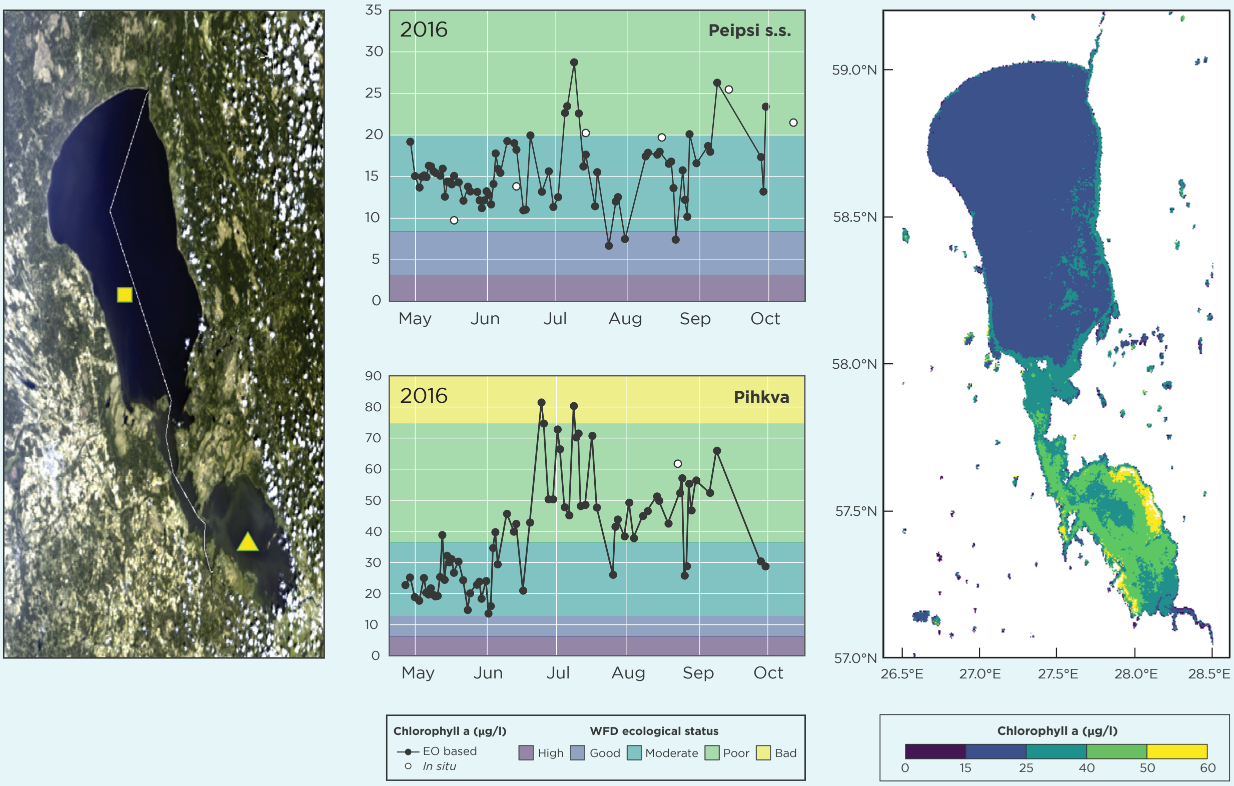
[12] Marbà *et al*. 2013 identify 49 seagrass indicators used in 42 monitoring programmes, including 51 metrics.

[13] Kauppila *et al*. 2016

Box 2: Lake Peipsi

Lake Peipsi straddles the border of Estonia and Russia, and has shown gradual improvement from eutrophication despite recurring annual phytoplankton blooms[a]. While in situ sampling between the countries is coordinated at a basic level, methodologies differ. Environmental status derived from satellite-based Earth observation data provides opportunities for harmonised management, particularly where sampling programmes disagree.



The figures show the Chl-a time series derived from satellite data from stations on the Estonian (square) and Russian side (triangle) of Lake Peipsi. In the Estonian part of the lake, in situ monitoring is performed at six stations, once per month during April–October. In the Russian part of the lake, a joint in situ monitoring event is organized usually once a year in August. The time series in the middle graphs shows the measurements by satellite (filled circles), conventional in situ measurements (open circles) and the thresholds for the WFD status classes (horizontal colours). The 90th percentile of Chl-a values (mapped on the right) over the same period indicates consistently lower concentrations in the northern part of the lake compared to the higher concentrations and relatively inhomogeneous patterns in the southern part where the major inflow enters to the lake.

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[a] Fink *et al*. 2018

6. Holistic assessment and implementation of Programme of Measures

Under Article 5 of the Water Framework Directive, member states are required to carry out a characterisation and impact assessment in six year cycles (2009–2015; 2016–2021). Satellite observation can provide a substantial contribution here, extending information beyond the sampled waterbodies to all medium and large lakes, transitional and coastal waterbodies. This would allow a more holistic estimate of ecological status within a catchment and, through gathering satellite observation data, will represent a marked improvement in approach from inferring risk from land use.

Satellite observation should also improve the implementation of the Programme of Measures (POMs) at local and catchment level. Having a more comprehensive view of lake status in a catchment will help direct POMs to particular (areas in) waterbodies more susceptible to pollution. Tackling such waterbodies will improve them directly but also contribute to solving issues downstream. This can also be used to better provide sufficient information for early detection of deterioration, improve knowledge of the potential extent of an impact, improve monitoring of the effectiveness of POMs, and provide information to support more strategic in situ sampling locations and timings.

For further details, see Case study 5: Evaluating the ecological effects of large-scale restorative projects in The Netherlands and Case study 6: Improving reporting for the EC directives in Italy for further details, in the Appendix.

7. Potential barriers to uptake

The Water Framework Directive requires that multiple biological, chemical and physical elements be measured. Examples of the complementary use of satellite monitoring are given in previous sections and in the Appendix. There are a number of barriers currently slowing the uptake of satellite-derived metrics which need to be addressed. We look beyond any budgetary constraints, since those vary by Member State and will depend on how the recommendations given in this paper are eventually implemented.

- **Satellite observation cannot provide all quality elements required by the WFD. Therefore,** in situ **sampling is necessary and, strictly speaking, makes the satellite products (such as Chl-a, turbidity, macrophytes and angiosperms) surplus to requirement.**

  The solution to this issue requires a change of paradigm. While for satellite observation there are no suitable methods to address the all quality elements, in situ sampling fails to deliver many elements at the observation scale required to effectively monitor waterbodies, leaving many waterbodies without or with incomplete status assessment (Figure 1). The complementary value of satellite products becomes even clearer when we observe the different sampling frequency requirements for some elements: lake phytoplankton biomass (measured using Chl-a) generally requires 3–6 monthly measurements for at least three years of the six year cycle[14]. Satellite observation can replace many of these visits while only a single or annual in situ sampling is needed for most other BQEs (macrophytes, Invertebrates, fish). This approach would yield additional observation data while saving cost.

- **Lack of trust in satellite products compared to conventional assessment methods, where the latter have been inter-calibrated. Laboratory methods can be quality controlled using lab standards and replication, whereas satellite products are validated by comparison to** in situ **observation and may have hidden bias.**

  It is vital to increase user trust in satellite products by showing their consistency with station sampling over areas under status assessment. The case studies reported here provide strong evidence for this. Validation of satellite products must be multi-seasonal and cover all environments where the product will be provided. Extensive validation is often hindered by lack of suitable in situ observations. Existing water sampling strategies in national monitoring programmes may not meet the requirements for accurate satellite validation, for example when observation data are collected at the shoreline. *In situ* monitoring also tends to exclude a radiometry component; this would support the attribution of uncertainties associated with satellite observation since correction of the satellite observation for atmospheric influences is generally considered a prominent source of uncertainty.

[14] Carvalho *et al*. 2013

- **Lack of technical expertise, understanding of satellite-based Earth observation methods and capacity to process and interpret parameters derived from satellite-based observations, within agencies and authorities responsible for monitoring.**

  An emerging industry of European service providers, spurred on by freely available satellite data, may prompt a shift in practice. Sub-contracting and reliance on outside expertise to deliver assessments might alleviate this issue, or satellite data providers may offer the required training. Rethinking and rebalancing budgets for environmental monitoring to capitalise on the benefits of in situ sampling with complementary satellite products could prove essential.

- **Classification systems for status assessment and the interfaces and databases built around them vary in each Member State. Integrating satellite products into these existing data flows has (in individual test cases) proven laborious.**

  This barrier highlights a need for simple 'integrative' products such as spatio-temporal aggregation per waterbody. It also suggests that rethinking the individual approach to monitoring per Member State in favour of regional or centralised efforts may (at least initially) be warranted. Member States would then take on the role of validating, auditing, and further interpreting satellite-derived metrics for the waterbodies that fall under their individual responsibility.

- **Lack of a clear, accepted mapping of satellite-derived metrics against WFD quality elements and associated criteria for their complementary use.**

  Examples provided in this paper and listed in Table 1 show how the state-of-the-art in satellite observation of turbidity or transparency, Chl-a and macrophyte and angiosperm assessment can used as proxies for existing WFD quality elements. It is not claimed that these approaches give full equivalence to existing, intercalibrated methods, even if they result in comparable or better status assessments. The use of fundamentally different observation strategies means that guidance is needed to direct the extent to which satellite products may replace or reduce in situ sampling.

8. Future outlook and recommendations

40% of surface waters are currently in good status, with the remainder to meet good status by 2027. Satellite products can help monitor the effectiveness of management measures, provide more comprehensive assessments of waterbody structure and function, and include waterbodies not currently monitored. Terabytes of land and ocean observations are produced every day from the EU Copernicus space programme satellites, following investment of €7.5 billion between 2008–2020 to *inter alia* monitor land, ocean and atmosphere conditions and provide emergency response capabilities. The constellation of satellites under the EU Copernicus programme is guaranteed until at least 2030 with new sensors ready to replace ageing ones. Member States can therefore rely on having some of the monitoring requirements of their waterbodies met for the foreseeable future by exploiting the shared space assets.

National expertise and international collaboration in developing and applying scientific methods to translate these large volumes of satellite data into useful water quality metrics has also grown over the years. Applications of Earth observation to monitor optical water quality have been published as peer-reviewed papers ensuring methods are scientifically rigorous and results reproducible and robust for use in statutory monitoring and assessments. Funding has predominately come from research activities funded under a number of EU FP7 and Horizon 2020 actions and national activities; product validation activities have thus far been supported by the research community through these activities. In addition, Europe has seen steady growth of its satellite-based Earth observation industry with a number of private enterprises now able to act as brokers of satellite-based Earth observation data and information.

The uptake of satellite-based Earth observation products for standardised monitoring of waterbodies across Member States will require efforts from the Member States as well as the satellite-based Earth observation service industry, supported by continued efforts from the research community. At the European level, agreement about the role of satellite products in supporting the WFD would prompt the development of data standards and harmonisation criteria. At national level, investment in national capability to use satellite observation products is required. Between the Member States there is further need to agree on what methodologies may be adopted to ensure their consistency. For cost-efficiency, these methodologies may need to be supplied by specialised satellite Earth observation service providers with sufficient expertise to provide unbiased information to multiple Member States. There is an overarching requirement to ensure that methodologies are transparent and widely accepted, so that their contribution to reporting of environmental status can be actioned upon.

Satellite observation is not, cannot and should not be seen as a means to replace existing monitoring practises. While cost-savings or increased cost-efficiency can be found, there is far more to be gained in terms of product confidence when both satellite and in situ observations are in place, with in situ efforts organised to support satellite validation. There is, therefore, likely to be an added cost of including satellite products into statutory reporting. However, this cost is likely to be small compared to the existing investment in the Copernicus programme of satellites and services, designed to support activities such as these. Direct cost savings may nevertheless be expected when satellite data help deliver better prioritisation and more efficient catchment management and, in some cases, a more strategic design of in situ sampling programmes. Moreover, and although not explicitly relevant to WFD monitoring requirements, more frequent and wider coverage of algal bloom monitoring using satellite products could have spin-off social and economic benefits by providing early warning of and reducing risks and mitigation costs to the public, water utilities and recreational sectors.

It is therefore recommended to the European Commission, Member States and relevant water management authorities to recognise and encourage the integration of satellite-based Earth observation into national and statutory monitoring for the Water Framework Directive. This can be achieved, firstly, by recognising satellite-based Earth observation as a method in updated Common Implementation Strategy (CIS) guidance for the WFD. For this, we recommend establishment of a relevant working group as part of the CIS ECOSTAT group to deliver CIS guidance to Member States on how they can use satellite observation to make their monitoring more robust and more cost-effective while increasing harmonisation of metrics across countries. This could specifically address the use of satellite observations for currently unreported quality measures, particularly the duration and extent of phytoplankton blooms, which is a largely unfulfilled requirement outlined in Annex 5 of the WFD. We also recommend convening a conference for EC, Member States and relevant water authorities, with the aim to recognise the use of satellite-based Earth observation metrics for the WFD and design a joint plan of actions leading to harmonised use of satellite data and building of institutional capacity.

9. Contributions

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10. Appendix

Case study 1: Comprehensive assessment of coastal and inland waterbodies in Finland

Added value of satellite Earth observation for the WFD

Integration of satellite and in situ data into a comprehensive reporting framework for optical water quality elements of the WFD.

Demonstration case

Finland now uses operational satellite observation data in WFD reporting as complementary information for environmental status assessment. The work is carried out under direct guidance from the Ministry of Environment, and helps address the challenge of reporting on thousands of WFD waterbodies.

Involved government bodies

Finnish Environment Institute (Suomen ympäristökeskus, SYKE)

Finnish Ministry of Environment

Case study details

Rationale / Requirements

Finland reports on a large number (4,617 lakes and 276 coastal) of waterbodies under the WFD. Regional environmental authorities assess the ecological status of their surface waterbodies for subsequent reporting by the Ministry of Environment. SYKE coordinates the national effort by providing guidance and developing computational tools and assessment services. The case for satellite observation to meet the large demand for environmental monitoring of surface waters has long been clear. This case study illustrates how in situ and satellite observations were integrated into a national resource for water quality information for all parties involved.

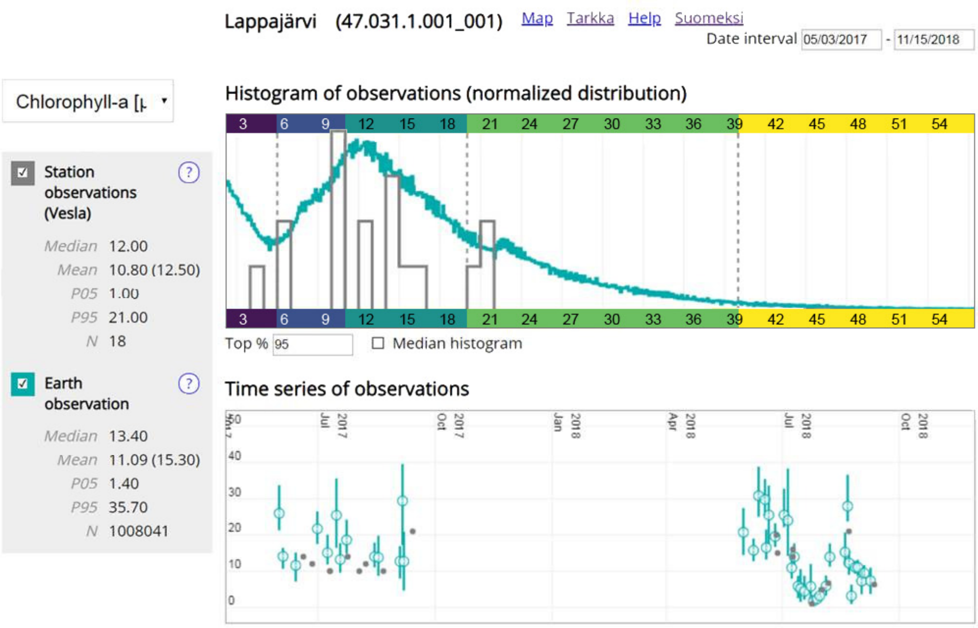
The added value of satellite Earth observation

Finland has put special effort in developing an Earth observation strategy for water quality monitoring, integrating satellite and in situ data into WFD monitoring. Satellite products added to the national WFD assessment system are based on Sentinel-series observations covering 87% of the area of Finnish WFD lakes and nearly all coastal waterbodies.

Combining satellite observations with information from in situ data sources (station sampling and underway sampling from ships) provides significant added value, particularly in those waterbodies where manual sampling yields uncertain assessment results or where station sampling is sparse. Here, satellite observation has shown its strengths since it provides, both spatially and temporally, orders-of-magnitude larger observation volumes. Water quality parameters including chlorophyll-a and (in coastal waters) water transparency (as Secchi depth) acquired through satellite observations are of specific interest. Additionally, data on turbidity and Coloured Dissolved Organic Matter from satellite observations provide information to ecologically classify waterbodies.

While the statistical metrics used in WFD reporting are of the primary interest, complementary data are produced in map format to aid water quality management. For example, chlorophyll-a concentration maps produced annually from satellite observations aggregated over the summer period are made available for most lakes and coastal regions.

The method of delivery was carefully considered to deal with the large data volume coming from satellite observations. A web-based application offers statistical and integrated information on the water quality parameters derived from both satellite and station sampling for a given waterbody. The application provides periodically aggregated statistics, time series and histograms of the distribution of satellite and station sampling datasets over the waterbodies, as well as a map interface.



Lappajärvi (47.031.1.001_001)

Date interval 05/03/2017 - 11/15/2018

Top % 95

☑ **Station observations (Vesla)**

Median	12.00
Mean	10.80 (12.50)
P05	1.00
P95	21.00
N	18

☑ **Earth observation**

Median	13.40
Mean	11.09 (15.30)
P05	1.40
P95	35.70
N	1008041

A view of the web application showing statistics, data distributions (histograms) and time series of station and satellite-derived chlorophyll-a of a coastal WFD region. In the histogram, WFD status classes are indicated by colours (purple: excellent, blue: good, teal: moderate, green: poor, yellow: bad).

For further information

TARKKA website: www.syke.fi/tarkka/en

Case Study 2: Intertidal seagrass beds in France

Added value of satellite Earth observation for the WFD

Deriving seagrass indicators (seagrass bed density and total area) from high-resolution satellite remote sensing, to complement in situ monitoring, improves:

- the length of the measurement time-series (early 1990s – present)
- determining reference values (maximum density/cover in the whole period)
- selection of optimal sampling time from analysis of seasonal variation
- standardization of methods used to map seagrass distribution
- automation of seagrass indicator mapping at the regional to European scale

Demonstration case

Long-term high-resolution remote sensing of intertidal seagrass indicators for water quality monitoring in Bourgneuf Bay along the French Atlantic coast (1991 – 2018).

Involved government bodies

The Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) has been in charge of the implementation of the WFD water quality monitoring in transitional and coastal waters. Water quality indicators include the environmental status of seagrass beds. Seagrass monitoring has been mostly funded by regional Water Agencies.

Case study details

Rationale / Requirements

As the only truly marine angiosperms, seagrasses form a central indicator of the biological quality elements used to define the ecological status of transitional and coastal waters in the WFD. The metrics developed to quantify seagrass ecological status include the total area of the beds, density or abundance and the number of seagrass species, as well as the change of these parameters over time[15]. Due to their widespread geographic extent over Europe, the monitoring of seagrass spatial distribution and temporal dynamics on a national to continental scale calls for new and efficient observation methods.

Satellite products can provide the spatial extent of seagrass beds. This is key information for this habitat that would be difficult and time-consuming to obtain for large meadows with conventional field sampling. The relevance of satellite observation for this metric lies in its capacity to compile a yearly map, whereas in France the corresponding metric has been collected in situ at most every six years. Satellite data can also provide information on seagrass abundance, spatial distribution in terms of percent cover and biomass. Recently, the potential of the Sentinel-2 MSI sensor to map intertidal meadows at 10 m resolution over monospecific seagrass beds of *Zostera noltei* was demonstrated[16]. The main results of this Sentinel-2 study are:

- Sentinel-2 high-resolution time-series (5 days) make it possible to characterize seagrass phenology, and subsequently determine the period of maximum annual development.
- During the peak period of the growth season, spatial distribution of seagrass cover was estimated at 10 m resolution with an uncertainty of 18.4%.
- Multi-sensor satellite constellations can provide long-term high-resolution assessments of seagrass spatiotemporal variability, shifts, and trends along the European coastline.

[15] Marbà *et al*. 2013 identify 49 seagrass indicators used in 42 monitoring programmes, including 51 metrics

[16] Zoffoli *et al*., pers. comm (paper in review)

The added value of satellite Earth observation

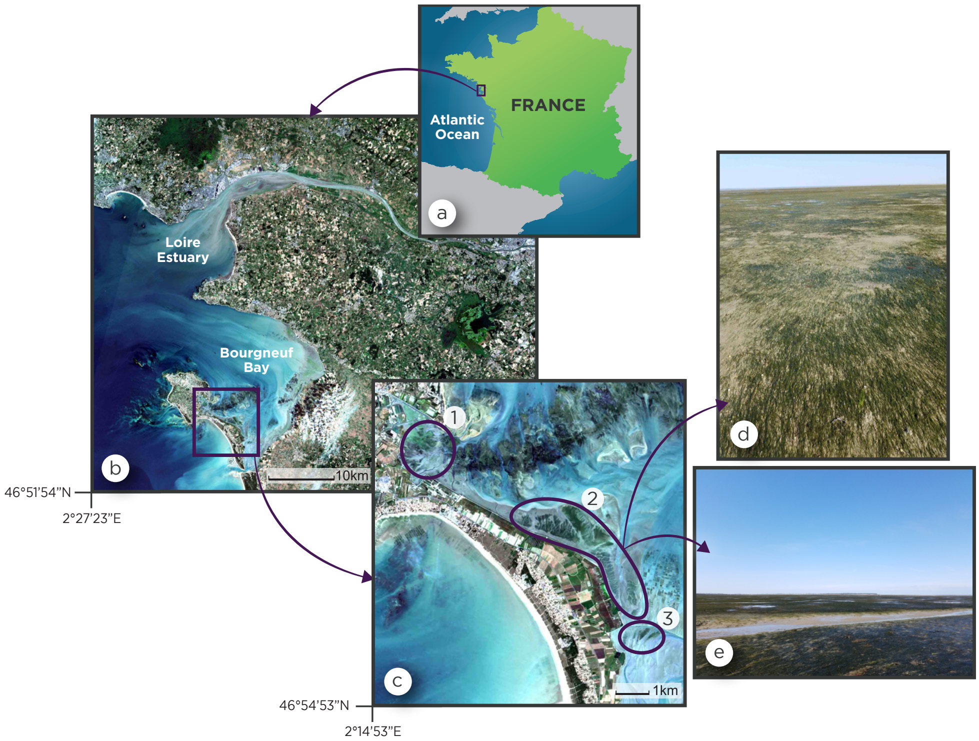
In order to better appraise the added-value of satellite remote sensing, an example of satellite-based monitoring is provided to complement results from the official in situ monitoring program coordinated by IFREMER.

In situ monitoring

A water quality indicator has been developed in France to monitor the ecological status of seagrass beds in intertidal areas. Twelve study sites were selected for monitoring *Z. noltei* beds corresponding to a surface area of about 7,795 ha[17], which is the largest surface of intertidal seagrass beds in Europe. In France, the surface of the beds spanned three orders of magnitude, ranging from 1.2 (at Hossegor) to 4,259 ha (at Arcachon). The indicator developed by IFREMER is computed from three biological metrics determined from in situ sampling: seagrass biodiversity index, percent cover (average of 30 sampling points of 0.25 m^2 each), and the total areal coverage of the beds[17].

The final seagrass indicator is computed as an ecological quality ratio (EQR) corresponding to the averaged relative temporal change in the three metrics. This method is currently the protocol of reference in France. The monitoring strategy is based on annual or multi-annual sampling, performed at low tide during August–September. These months are assumed to correspond to the expected seasonal maximum of seagrass development although inter-annual and seasonal variability remains to be assessed in more detail. As part of the WFD, IFREMER started monitoring in 2007. Since then, biodiversity and percent cover metrics have been acquired every three years from 2007–2010, and every year from 2011–present. It is recommended to monitor total bed area every six years, but data points are missing at many sites due to the large effort and associated cost of monitoring. The total area has been occasionally estimated using photo interpretation of airborne images, or indirectly obtained from published results derived from satellite remote sensing.

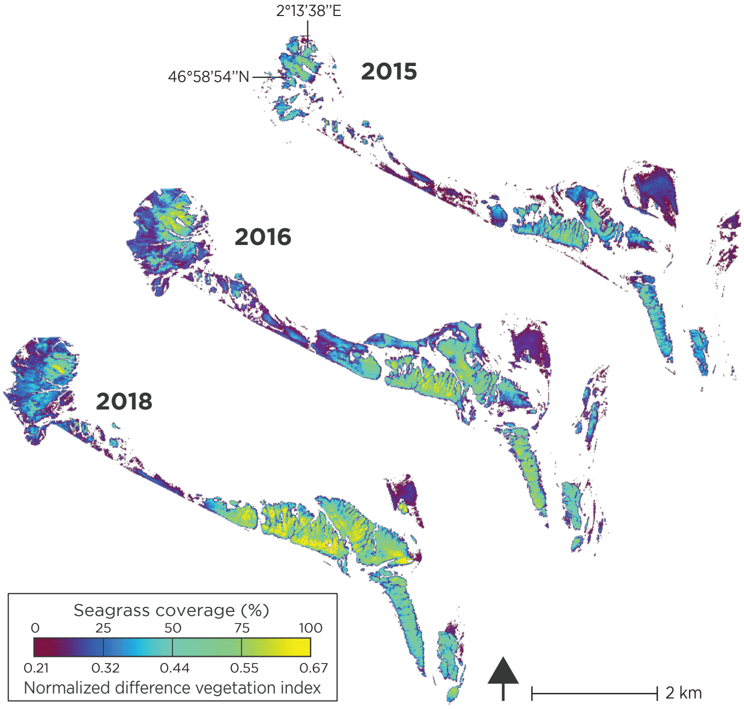
Continuous satellite-derived estimates from 1991 onwards were produced for Bourgneuf Bay, where seagrass bed total areal cover varied from 208–586 ha[18]. In this bay, in situ observations only included seagrass biodiversity and averaged percent cover, observed annually from 2011. The total area of the beds had not been recorded in situ.



Study area: (a) Location of Bourgneuf Bay along the French Atlantic coast. (b) Sentinel-2 MSI image acquired on 16 July 2018 and displayed in RGB composition (R: 665 nm, G: 560 nm, B: 490 nm) showing Bourgneuf Bay in its regional context. (c) The three main seagrass meadows. (d, e) Field view of the seagrass meadow in September 2018.

[17] Auby *et al*. 2018

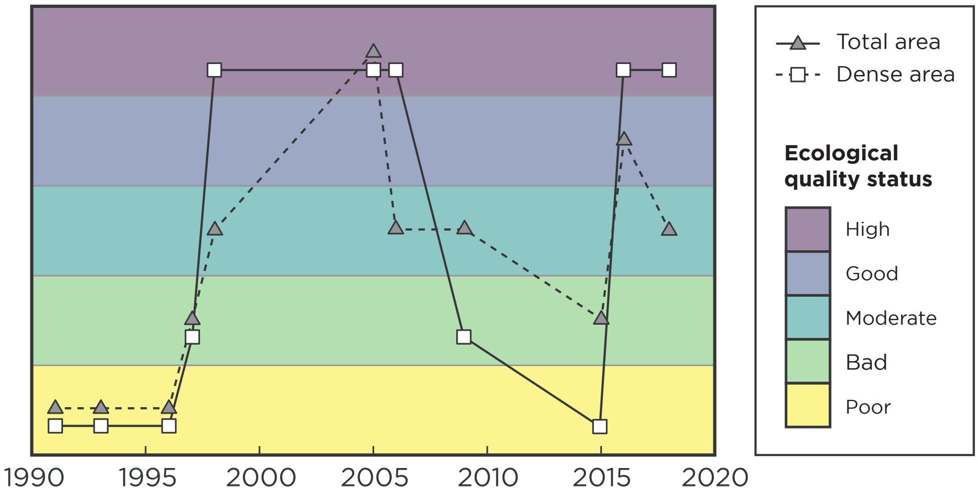
[18] Barillé *et al*. 2010



Satellite-derived maps of seagrass cover in 2015, 2016 and 2018 using high-resolution (10 m) Sentinel-2 MSI images from 30 September 2015, 01 September 2016 and 14 September 2018.

Satellite-based monitoring

In order to complement the missing data on areal cover, a preliminary dataset of the seagrass bed spatial extent measured using high-resolution satellite data was compiled. The spatial extent was computed for seagrass beds with >20% cover[19] as well as for the subarea corresponding to a dense meadow (cover >30%) using radiometric thresholds specifically developed for unambiguous mapping of *Z. noltei*[20,21]. Note that the relatively high-frequency of Sentinel-2 acquisitions (5 days since 2017) now makes it possible to obtain seagrass phenology and seasonal dynamics, thus improving the robustness of annual measurement.



Temporal variation (1990–2018) of the satellite-derived seagrass indicator based on seagrass area in Bourgneuf Bay (France). The colour code corresponds to the Ecological Quality Status (EQS) from high (purple) to bad (yellow) (Duarte et al. 2017). The indicator has been computed for the total area of the seagrass beds (triangles, seagrass cover >20%) and for the subarea corresponding to the dense seagrass meadow (square symbols, seagrass cover >30%).

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CoastObs project: https://coastobs.eu/

[19] Dolch *et al*. 2017

[20] Zoffoli *et al*., pers. comm (paper in review)

[21] Bargain, A. (2012). Ph.D. thesis, University of Nantes, France, 31 October 2012

Case study 3: Strategic monitoring of lakes in Estonia

Added value of satellite Earth observation for the WFD

Satellite data help prioritise lake monitoring efforts under the WFD

Demonstration case

Helping the Centre for Limnology prioritise lakes for inclusion in annual monitoring programmes using input from satellite remote sensing.

Involved government bodies

Ministry of the Environment

Centre for Limnology

Case study details

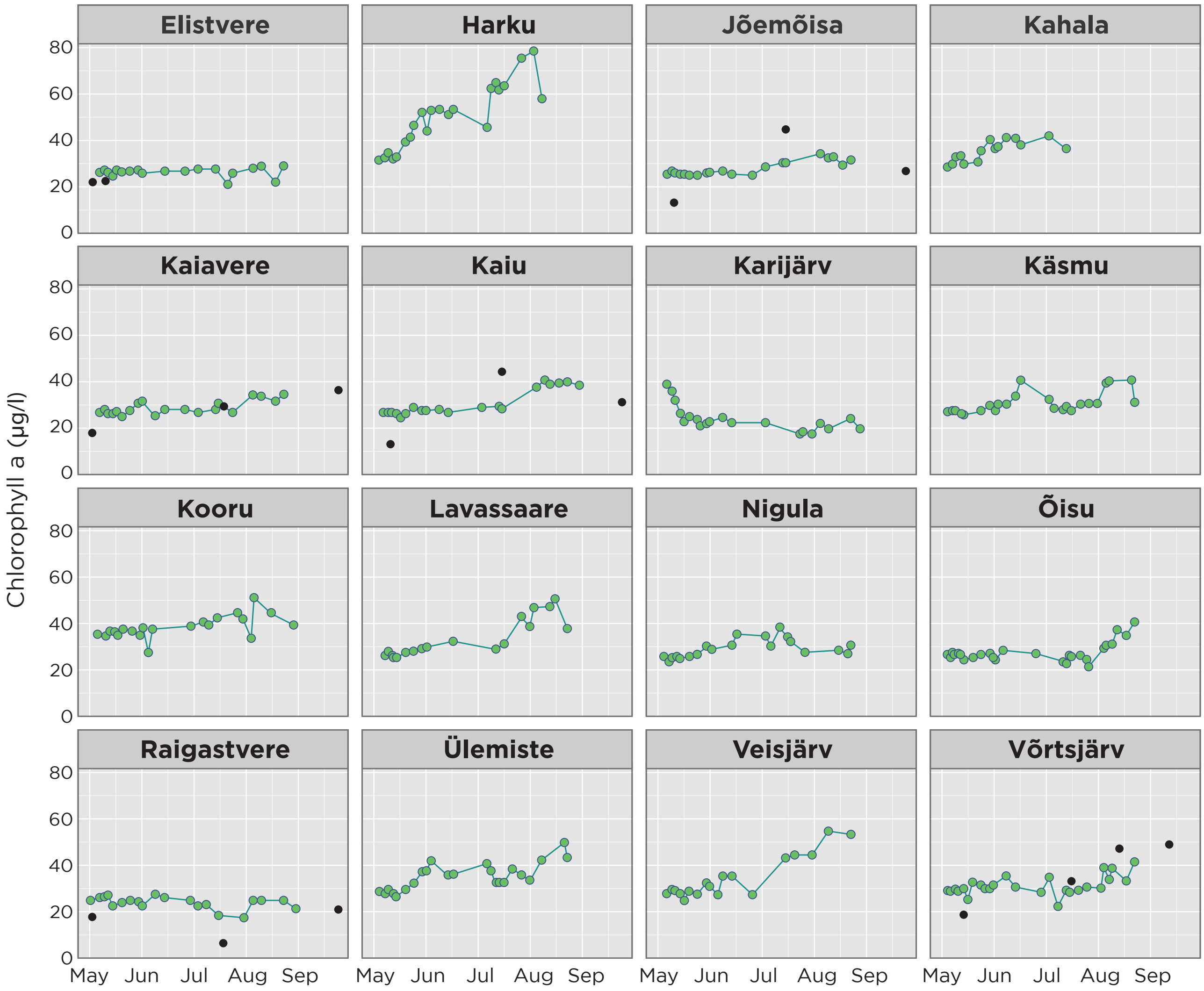
Rationale / Requirements

The Centre for Limnology is the partner of the Ministry of the Environment charged with performing physico-chemical and biological measurements in Estonian lakes. According to WFD regulations, 89 lakes with surface areas larger than 50 ha should be regularly monitored in Estonia. The monitoring programme for smaller lakes (surface area <10 km^2) includes 11 – 30 lakes per year. Eleven of these lakes have been annually monitored since the 1990s while other lakes are monitored with less regularity. To plan the combined monitoring efforts of two institutions, selection takes place at the beginning of each year.

The added value of satellite Earth observation

Satellite data were analysed to assist the experts at the Centre for Limnology to prioritise the lakes for inclusion in the monitoring programme for each year. This enhanced the ability to identify lakes where seasonal dynamics fluctuated more than expected. It also allowed limnologists to select periods of high productivity for lake-specific studies (e.g. gas-exchange, carbon dynamics). In this case-study, satellite data were used to derive estimates for chlorophyll-a, a central parameter describing phytoplankton dynamics, which is an important biological quality element for estimating the ecological status of waterbodies.

The 10 m spatial resolution of the Copernicus Sentinel-2 satellite, which was used, is suitable for characterization of all lakes under the monitoring obligations. The analysis showed varying phytoplankton dynamics between lakes, with and without seasonal blooms. The combination of the two Sentinel-2 satellites in their current constellation was shown to provide frequent temporal (e.g. on average 30 pixels) and spatial coverage of phytoplankton dynamics in all lakes included in the monitoring programme. This proved to be a useful approach to map lakes of interest and identify periods of phytoplankton blooms, when correct design of the in situ sampling programme is critical.



Seasonal dynamics of chlorophyll-a in selected Estonian lakes under WFD reporting obligations from Sentinel-2 satellite during 2018. Black dots denote spectrophotometrically measured (in situ) chlorophyll-a.

Case study 4: Applying appropriate metrics in transitional coastal waters of Lithuania

Added value of satellite Earth observation for the WFD

Supporting delineation of waterbodies and improved water quality assessment for transitional waters.

Demonstration case

In the dynamic Lithuanian coastal waters, satellite data are used to dynamically delineate the spatial extent of the outflow from the Curonian Lagoon, allowing the application of appropriate threshold values for WFD reporting in coastal and transitional waters alike.

Involved government bodies

Environmental Protection Agency (EPA) of Lithuania

Case study details

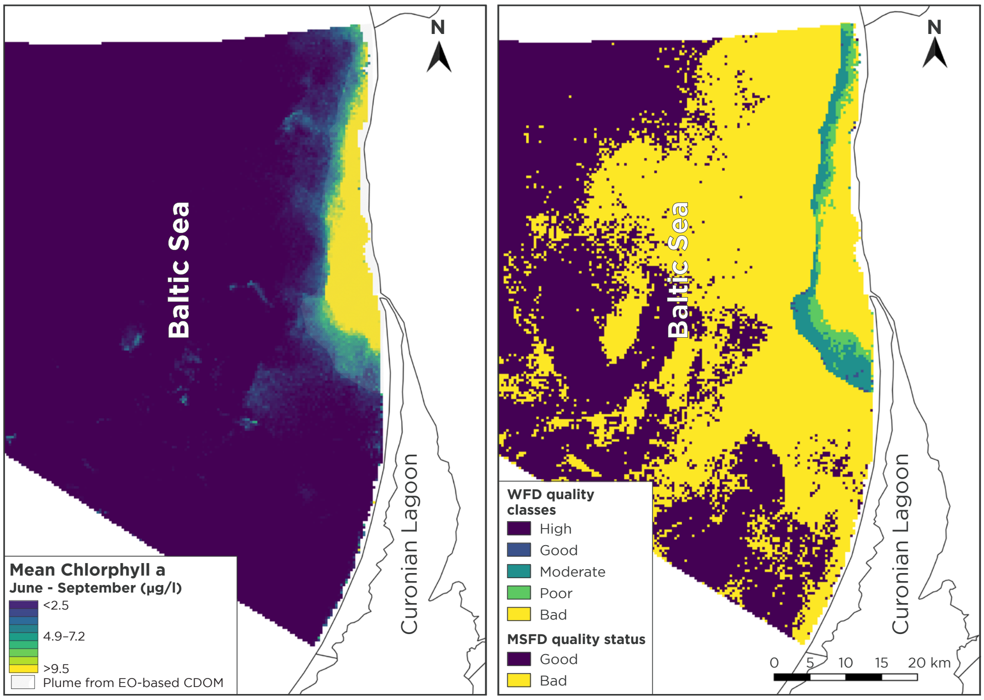
Rationale / Requirements

The national EPA is responsible for monitoring the water quality status of Baltic Sea waters, transitional waters (the Curonian Lagoon and its plume area into the Baltic Sea) and inland waters (lakes and rivers) in Lithuania. The EPA carries out the monitoring of the ecological status in compliance with both the WFD and the Marine Strategy Framework Directive (MSFD, 2008/56/EC). Eutrophication is considered the major pressure for most waterbodies in Lithuania. Chl-a is therefore a key parameter in the monitoring and reporting of environmental status.

The freshwater Curonian Lagoon and Lithuanian Baltic Sea waters fall under respectively the transitional and coastal waters, due to the mixing of water masses via the Sea port channel. The best indicator for the identification of the water masses is considered salinity: transitional waters are characterised by salinity consistently below 7 PSU, while the salinity of coastal waters is around 7 PSU. The criteria and threshold values of Chl-a concentration for transitional waters are based on salinity (Ministry of Environment of Lithuania, No. D1-178, 4th March 2010). For the transitional waters (the Curonian Lagoon itself and plume area) with reduced salinity higher threshold values of Chl-a for good ecological status identification are applied (e.g. 25.7 mg m^{-3}) with respect to the coastal waters (e.g. 4.8 mg m^{-3}). With a point measurement (in situ) approach, comprehensive water quality assessment of transitional waters is challenging as the region is significantly hydrodynamically variable in time and space.

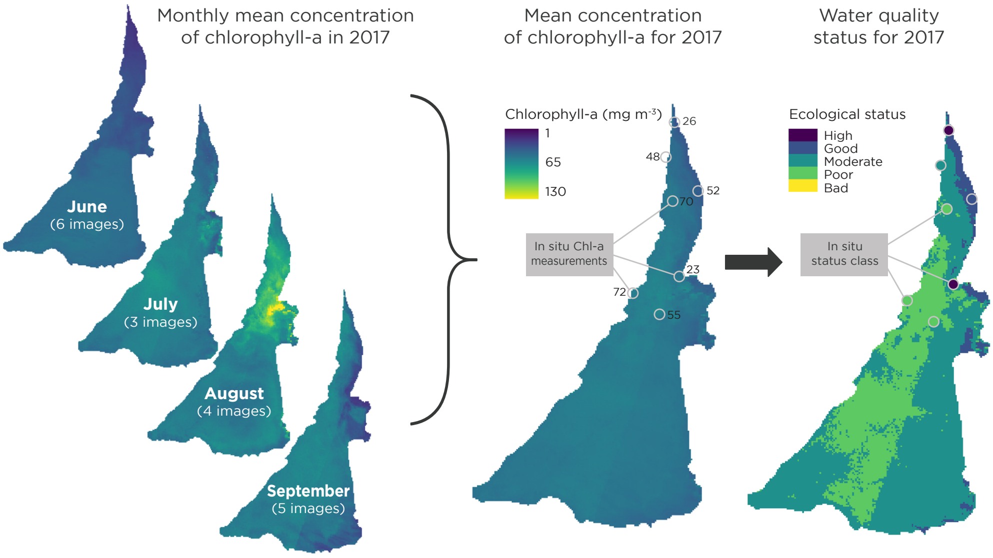
The added value of satellite Earth observation

Earth observation based products provided additional information in both time and space. The absorption of light by Coloured Dissolved Organic Matter (CDOM) is derived from satellite data, as a regionally-tuned proxy of salinity because both are determined by freshwater outflow. This technique supported the delineation of the plume area (lagoon waters feeding into the coastal zone) and coastal waters on an annual basis (using the June–September average values). Water quality assessment can then be optimised using different threshold values of Chl-a for the plume area (ecological quality classes according to the WFD) and for the Baltic Sea waters (good environmental status threshold according to the MSFD), respectively.



Maps of mean chlorophyll-a concentration (left) aggregated for the June-September period and the plume area determined by CDOM derived from satellite observations. (Right) Environmental status of water quality based on threshold values of chlorophyll-a according to the WFD and MSFD criteria for the transitional and Baltic Sea coastal waters, respectively. For this example, 26 MERIS/Envisat images for 2011 were used.

For reporting on the ecological status of the Curonian Lagoon itself the Environmental Protection Agency (EPA) selected satellite products available for the vegetative period (June – September). EPA used satellite-derived Chl-a products from 2017 for the second cycle of MSFD reporting. A comparison of associated water quality status assessment using either in situ or satellite observation shows that in situ observation alone over-estimated water quality compared to estimates derived from satellite. This was especially true in the northeastern part of the Curonian Lagoon, where in situ measurements are rare. Therefore, this case demonstrates the clear added value that satellite products produce for monitoring and evaluating water quality in transitional waters.



Monthly mean maps of Chl-a concentration and subsequently derived ecological status in the Curonian Lagoon, used in EPA reporting for the WFD in 2017. The products are derived from Sentinel-2 (10 m spatial resolution) and Sentinel-3 images (300 m) satellites. In situ measurements of Chl-a and corresponding ecological status classes are overlaid.

Case study 5: Evaluating the ecological effects of large-scale restorative projects in the Netherlands

Added value of satellite Earth observation for the WFD

Detailed analysis of the effectiveness of restorative measures

Demonstration case

Satellite observation data are used to evaluate the ecological effects of large-scale construction in Lake Markermeer designed to ultimately improve ecological status.

Involved government bodies

National Executive Agency Rijkswaterstaat (RWS)

Netherlands Institute of Ecology (NIOO-KNAW)

Case study details

Rationale / Requirements

Lake Markermeer is the second largest lake in the Netherlands, and important for shipping and recreation. The lake ecology is characterized by the effects of frequent wind driven resuspension causing high turbidity and poor light conditions for aquatic vegetation. The fact that there is no riparian zone effects water chemistry and there are consequently limited habitats for fish and macroinvertebrates. The lake regularly fails to meet the WFD ecological targets.

A large construction project is carried out to create new islands, deep water areas and marshland. The target of this project is to increase the ecological status of (part of) the lake, and increase ecological variety. The depths will serve as sinks for suspended silt, decreasing turbidity in parts of the lake. It is expected that the soft shores of the new land areas and the decreased turbidity will stimulate macrophyte growth, creating refuge for macroinvertebrates and fish, while the islands and marshland areas will be attractive to birds.

The conventional water quality monitoring in lake Markermeer takes place at six locations. The MarkerWadden construction project management and national executive agency RWS have set up five additional measurement stations to monitor changes during the construction.

The added value of satellite Earth observation

Even the increased in situ monitoring does not adequately cover the spatial heterogeneity of water quality, but this can be obtained from satellite sources, an example of which is shown. Combined, high detail of measurement from water samples, high-frequency measurements from observation poles and spatial data from satellites will provide comprehensive knowledge of the dynamic water quality. Satellite based water quality maps have been evaluated by NIOO-KNAW, who acknowledge the added value and support the use of satellite data. The responsible executive agency RWS is interested to further study the uptake of new methods in their monitoring programmes.

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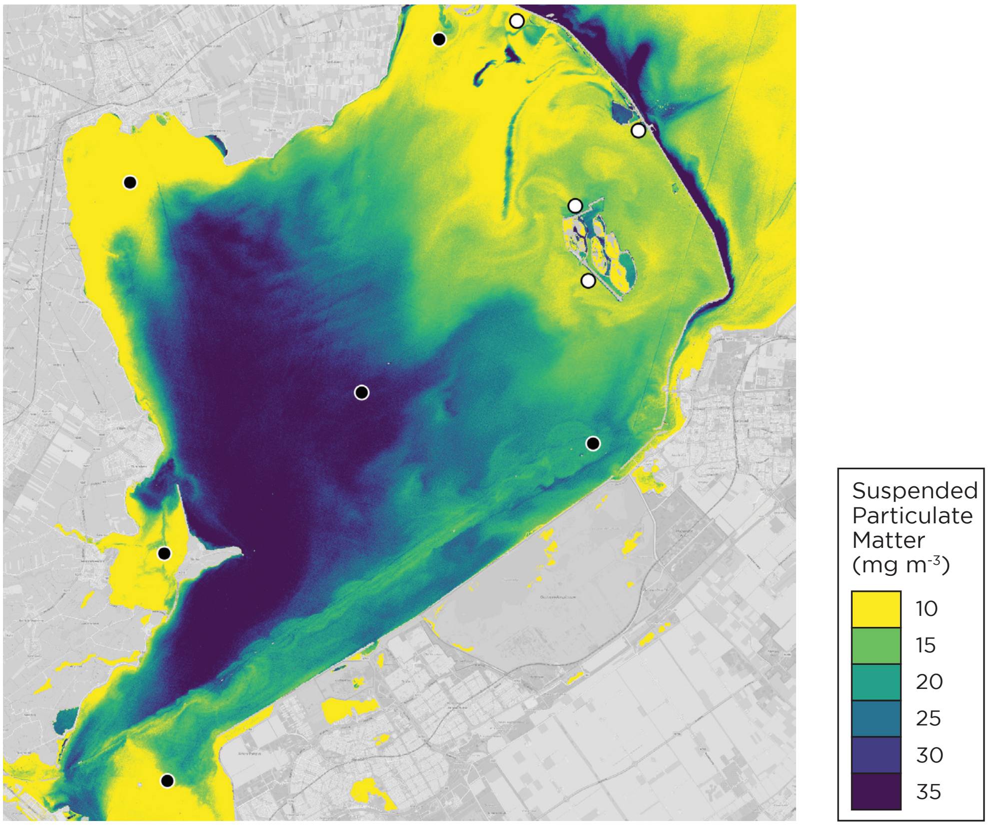


Suspended Particulate Matter (SPM) concentration (mg/m^3) in lake Markermeer. Black circles mark long-term in situ monitoring locations, white dots are new observation poles.

Case study 6: Improving reporting for the EC directives in Italy

Added value of satellite Earth observation for the WFD

Obtain spatial insights in algae bloom dynamics

Demonstration case

Improving spatial and temporal information for phytoplankton monitoring

Involved government bodies

ARPA Umbria, Italy

Case study details

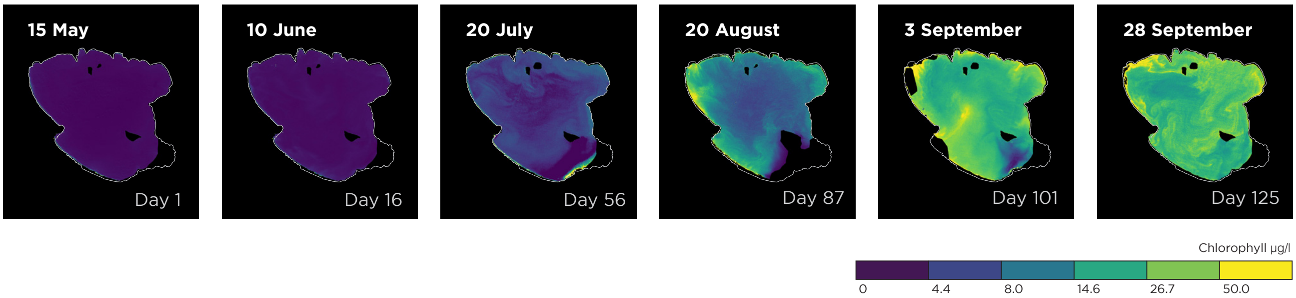
Rationale / Requirements

The Regional Agency for Environmental Protection of Umbria (ARPA-U) is responsible for monitoring water quality status of Lake Trasimeno, the fourth largest lake in Italy. The lake has a diameter of about 11 km, has three small islands and, in the south-eastern area, an open bay colonised by aquatic vegetation. The lacustrine ecosystem is an area of exceptional value for its wealth of flora and fauna and its diversity of species and in 2000 it was declared a protected area (Directive 1979/409/CEE 1979). Ecological constraints are algal blooms of cyanobacteria, reduced conditions of sediments, modification of and decrease in fish community and plankton and recession of common reeds. In recent years, the lake has experienced serious difficulties to recover the ecological equilibrium as recommended by the WFD.

To be compliant with the WFD, ARPA Umbria carries out the monitoring of ecological status of Lake Trasimeno since 1998. Moreover, ARPA-U carries out algal surveillance (Italian law DD n. 2537 of 03/14/2018) as included in the Bathing Directive (2006/7/EC). For WFD monitoring of phytoplankton, ARPA Umbria measures Chl-a at two stations, six times per year. For the Bathing Directive, phytoplankton monitoring consists of counting the number of cyanobacteria cells and measuring related toxin concentrations. These measurements are performed from April to September every month, at 8 shoreline stations, without determining Chl-a concentration.

The added value of satellite Earth observation

As some of the parameters that have to be monitored by law can be determined by remote sensing with reasonable accuracy, satellite-related technologies have been increasingly integrated in the monitoring programme of ARPA Umbria. Typically, the strength of satellite observations lies in their ability to provide high frequency synoptic additional data complementary to the in situ based measurements collected by ARPA Umbria. For this case study, Sentinel-2 and Sentinel-3 data were processed to map Chl-a concentrations that were then used by ARPA-U in their 2018 reporting for the Bathing Directive. In previous reports, Chl-a concentration data had not been used. ARPA-U selected the Chl-a satellite products that coincided with their field sampling as supplementary information on Chl-a status.



Mapped Chl-a products of lake Trasimeno, selected by ARPA-U for the Bathing Directive report of 2018. The products were derived from Sentinel-2 MSI imagery at 10 m resolution. Colour scaling corresponds to the classification thresholds of the WFD phytoplankton biomass indicator.