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Satellite-based monitoring of cyanobacteria in bathing waters

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List of abbreviations

BWD	Bathing Water Directive
EEA	European Environment Agency
ETC/ICM	European Topic Centre for Inland, Coastal and Marine Waters
EU	European Union
HAB	Harmful Algae Bloom
IT	Information Infrastructures
MERIS	Medium Resolution Imaging Spectrometer
MS	Member States
RMSE	Root Mean Squared Error
US EPA	United States Environmental Protection Agency
US	United States
UWWTD	Urban Waste Water Treatment Directive
WFD	Water Framework Directive
WHO	World Health Organization
WISE SoE	Water Information System for Europe State of Environment
WISE	Water Information System for Europe

Key messages

- Although cyanobacteria are not subject to the regular quantitative monitoring prescribed by the Bathing Water Directive (BWD), the blooms frequently create the need for issuing temporary advice against or prohibition of bathing.

- There are some bathing waters in Europe that obtain a high-quality status although they suffer from cyanobacterial blooms. This is because the quantification of bathing quality status is solely based on two hygienic parameters, *Echerichia coli* and Intestinal enterococci.

- The health risks of bathing in waters where blooms occur is questioned in the BWD review, so regular monitoring and reporting on cyanobacteria is expected for bathing waters at risk of cyanobacterial blooms. In addition, the detection of probable cyanobacteria proliferation before the event shall help managers to prevent the health risks posed to bathers well in advance.

- All standard monitoring strategies for cyanobacteria require on-site water sampling and subsequent analysis in the lab. Monitoring is expensive and demanding for personnel and often associated with a time delay between sampling and availability of results, which opens a time window of several days for potential adverse health effects on bathers.

- Satellite-based detection of cyanobacteria from the European satellites Sentinel2 and Sentinel3 is attractive for bathing water security as they provide high spatial and temporal coverage over Europe, are quickly available, and the costs do not have to be borne by the organizations that monitor the bathing water quality.

- Semi-quantitative or categorial indicators derived from satellite images are easily interpretable by bathing water managers. However, although remote sensing with the satellites has been documented to show a high skill set for cyanobacterial bloom detection, satellite-borne information comes with uncertainty and can lead to both, false positive warnings and false negative warnings.

- For practical implementation, a hierarchical monitoring approach may be considered where an algal bloom that is detected by satellite is triggering further monitoring and management reactions. Such an adaptive monitoring approach would allow to focus the cost and personnel-intensive in-situ sampling only on places where blooms most probably occur.

1 Introduction

Increasing our knowledge on organic pollution by nutrients and pollutants of emerging concern, such as microplastics, viruses and pharmaceuticals, points to the need to potentially expand the elements systematically monitored and reported under the BWD. Relevant information and policy options for enhancing the level of protection afforded by the BWD may be derived also from other initiatives such as ongoing revisions of the UWWTD and WFD. In addition, WHO (2018) recommends an inclusion of harmful algal blooms (cyanobacteria) monitoring to the BWD for years and suggests this to be based on local experience and circumstances – indeed not all Member States are equally affected. The WHO also suggests to increase the spatio-temporal coverage of the existing bacteria samplings (an increase in the annual number of sampling efforts and extending the sampling period beyond the bathing season).

Such proposals are also discussed in the ongoing BWD evaluation process. Therefore, we might expect that the monitoring of the occurrence of cyanobacteria will be systematically included in the implementation of the BWD in future. In this report, we provide basic information about the relevancy of cyanobacteria for bathers, how this phenomenon is monitored today and what are the current challenges in monitoring, especially utilizing satellite techniques.

This scoping study evaluates the potential of satellite remote sensing for monitoring cyanobacterial abundances from space, which may facilitate an improved, cost-effective bathing site monitoring with respect to the detection of cyanobacterial blooms. These techniques may also help in their timely forecasting and in assessments of risks as directed by BWD (Annex III).

2 Why cyanobacteria are relevant for bathing waters and how is this assessed

Cyanobacteria, also called blue-green algae, grow in lentic aquatic environments and are part of the phytoplankton in lakes, ponds and reservoirs. Their typical ecological niche comprises of high concentrations of nutrients, namely phosphorus, warm water temperatures and high irradiance. Accordingly, in central Europe, they mostly occur during high summers in nutrient-rich water bodies. Under these conditions, the eco-physio-logical features of cyanobacteria are providing them with a competitive superiority in comparison to other algae (Carey et al. 2012), due to their ability to:

- use elemental nitrogen (N_2) as a nitrogen source (by nitrogen fixation) and grow under conditions of low to zero concentrations of inorganic reactive nitrogen;
- realise high growth rates at high water temperatures (particularly above 24°C; Rigosi et al. 2015) where other algae become physiologically restricted;
- optimise light harvesting by chromatic adaptation and buoyancy control;
- resist grazing from zooplankton because of their filamentous or colonial morphologies.

If the ecological conditions are favouring cyanobacteria, they often proliferate to high abundances and form mass developments, so-called algal blooms. Such cyanobacterial blooms are often associated with a so-called “scum” formation given the fact that their cells are buoyant. Such cyanobacterial scum formations are extremely distracting for swimming and perceived as very bad water quality by the public. Some species potentially produce toxins that pose health risks to humans and interfere with ecosystem functioning. Water managers therefore usually associate cyanobacterial proliferations with a *harmful* algal bloom (HAB). Such algal blooms massively deteriorate water quality due to high turbidity and low transparency, toxin production, scum formation, as well as anoxia arising from decaying blooms.

Since bathing can be a realistic way of exposure to cyanobacterial blooms and toxins, the EU Bathing Water Directive (BWD) includes suggestions for minimizing health risks from cyanobacteria on bathers. This

Directive lays down provisions for (i) the monitoring and classification of bathing water quality, (ii) the management of bathing water quality, and (iii) the provision of information to the public on bathing water quality. The BWD is focused on hygienic indicators and evaluates the two target parameters outlined in Table 1.

Table 1 Key indicators of the EU Bathing Water Directive (BWD) for assessing the water quality of identified inland bathing sites. (*): Based upon a 95-percentile evaluation, (**) Based upon a 90-percentile evaluation, see Annex I and II in EU (2006) for details.

Parameter	Excellent quality	Good quality	Sufficient quality	References
Intestinal enterococci (cfu/100 ml)	200 (*)	400 (*)	330 (**)	ISO 7899-1 or ISO 7899-2
Escherichia coli (cfu/100 ml)	500 (*)	1 000 (*)	900 (**)	ISO 9308-3 or ISO 9308-1

As these indicators do not inform about cyanobacterial abundances and the associated potential health risks, Article 8 of the BWD contains a separate statement dedicated to cyanobacterial blooms:

Article 8: Cyanobacterial risks

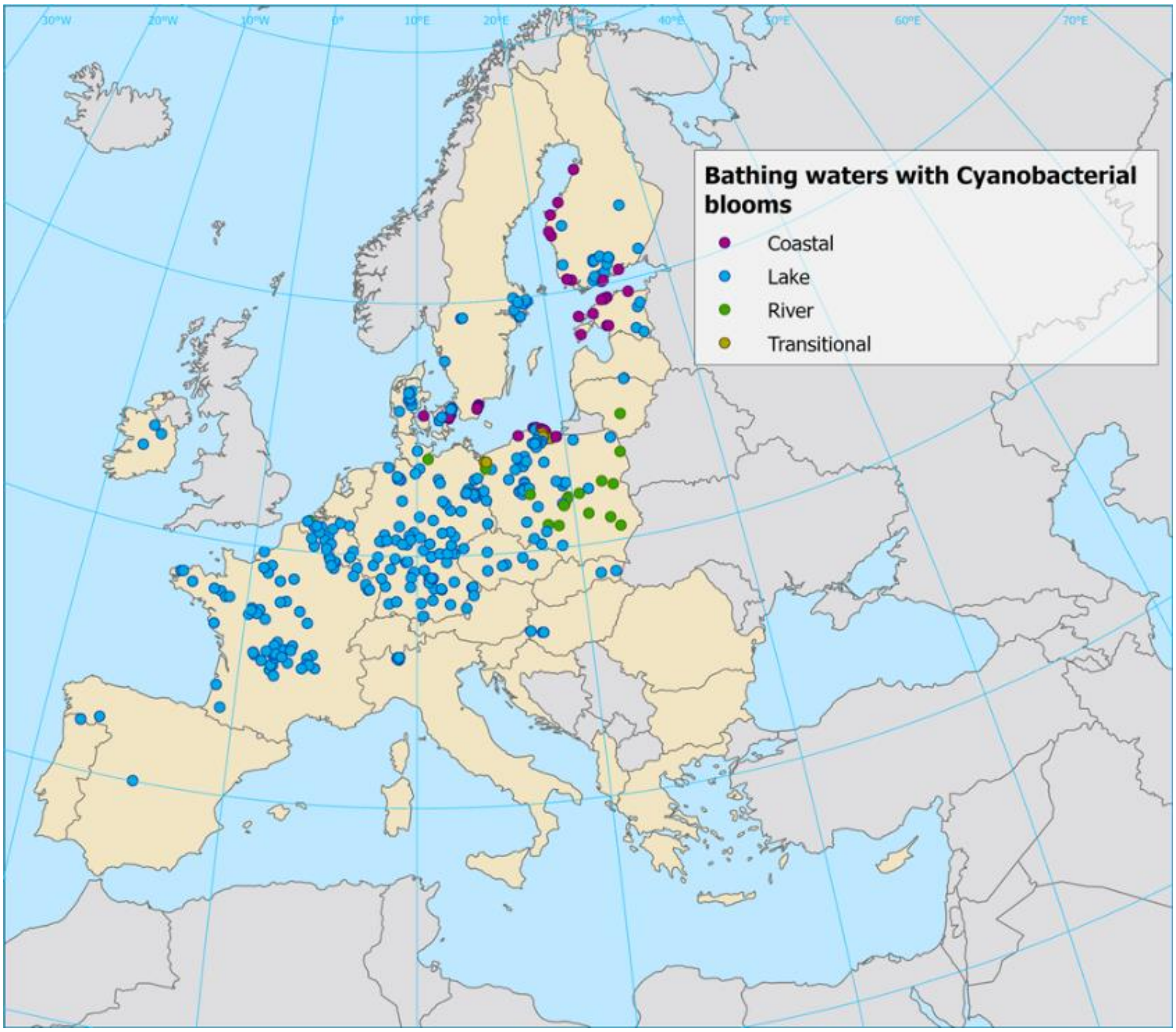
1. When the bathing water profile indicates a potential for cyanobacterial proliferation, appropriate monitoring shall be carried out to enable timely identification of health risks.
2. When cyanobacterial proliferation occurs and a health risk has been identified or presumed, adequate management measures shall be taken immediately to prevent exposure, including information to the public.

Although this article is pointing out the risks from cyanobacteria it remains imprecise in terms of monitoring, assessment or thresholds. BWD also suggests that an assessment of the potential for proliferation of cyanobacteria should be included into the bathing water profile (Annex III), but similarly, it does not give any further methodological advice.

To conclude, clear legal guidance or management actions are missing. The Member States handle the cyanobacterial risks differently and no harmonized procedure is available. In fact, many countries just report the key indicators mentioned in Table 1. In Germany, for example, cyanobacterial abundance is not regularly monitored at bathing sites although some states do so and others do not, given the fact that bathing site monitoring is regulated at a state or community level. Also, some countries do assess cyanobacteria but do not report back to the EEA and therefore no full assessment of their impact can be documented.

At the same time, there is evidence that cyanobacterial blooms are occurring at numerous bathing sites throughout Europe and are not at all an exceptional or a rare event. While Map 1 shows the bathing sites with clearly reported bloom periods, there are almost a thousand bathing sites in total with some reported descriptive indications of the occurring issue. We can expect even a larger share of bathing sites to be affected, since the reporting of the cyanobacteria issues is voluntary for the Member States, and not all cases are thus covered in the data sets available to the EEA and EU. Besides the bacteriologically based bathing water quality indicators mentioned above, the inclusion of monitoring for cyanobacterial blooms would be therefore an important aspect of a comprehensive health assessment of bathing sites.

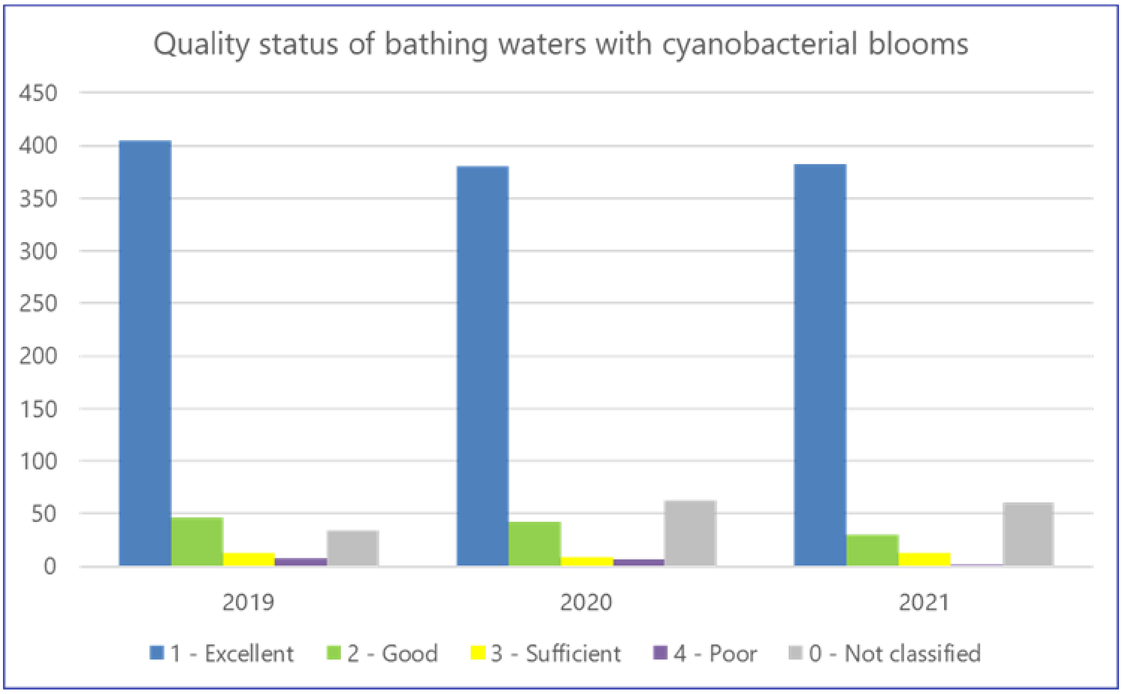
Map 1 Reported occurrences of cyanobacteria blooms in Member States, Switzerland and Albania over the period 2018–2021 by bathing water categories



Note: Not all Member States report on cyanobacterial blooms and monitoring efforts on cyanobacterial blooms at bathing sites are heterogeneous within the EU.
Source: ETC/ICM, based on the Status of bathing water 2022 dataset (EEA 2022)

Interestingly, the occurrence of cyanobacterial blooms is often taking place in water bodies that have a high bathing water quality according to the bacteriological indicators mentioned in Table 1. In fact, 80 % of sites reported with cyanobacteria proliferation were at the same time classified as having excellent bathing water quality (Figure 1). This points to a potential safety gap: since cyanobacteria monitoring and reporting on its occurrence is not mandatory, an unknown number of bathing sites may harbour non-recorded and non-reported, respectively, cyanobacteria mass developments with potential health risks.

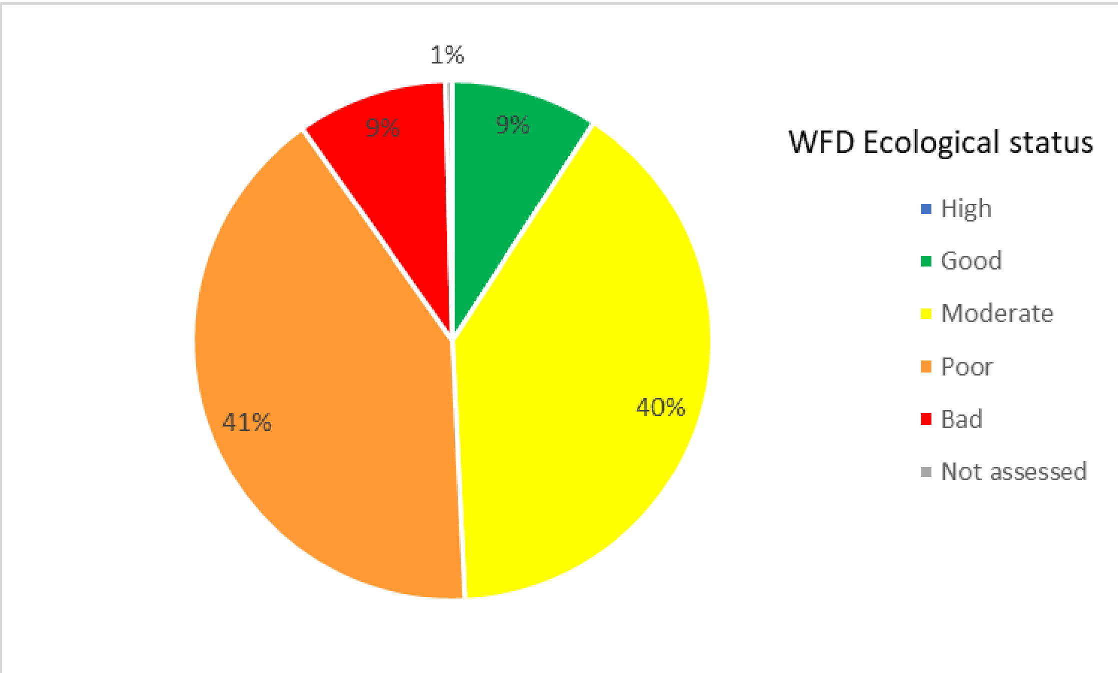
Figure 1: Classification of bathing water sites with cyanobacterial blooms according to the mandatory bacteriological quality indicators given in Table 1



Source: ETC/ICM, based on the Status of bathing water 2022 dataset (EEA, 2022)

The occurrence of cyanobacterial blooms is often taking place at bathing waters situated at WFD water bodies of a poor (188 or 41 % of bathing waters) or moderate (184 or 40 % of bathing waters) ecological status. None of the bathing waters with a reported cyanobacterial bloom is situated on a WFD surface water body with a high ecological status and only 42 (or 9 %) of bathing waters with a cyanobacterial bloom are located on WFD surface water bodies with good ecological status (Figure 2).

Figure 2: WFD ecological status of bathing waters with a reported cyanobacterial bloom at least once in the period 2018–2021



Source: ETC/ICM, based on the Status of bathing water 2022 dataset (EEA,2022)

3 Water quality deterioration and health risks induced by Cyanobacteria

Cyanobacteria are generally considered as an indicator of low water quality and the share of cyanobacteria in the overall phytoplankton community is also evaluated in the European Water Framework Directive as a critical water quality component. High abundances of cyanobacteria tend to form visually distracting surface scum formations on waters that interfere with its touristic uses such as swimming or fishing. Their high physiological activity in terms of primary production and respiration lead to large daily fluctuations of pH and oxygen, potentially dangerous to fish and other water organisms. After their proliferation, decaying biomass depletes oxygen at the sediment-water-contact zone, inducing hypoxic or even anoxic conditions leading to mass kills of benthic organisms or fish.

Table 2 Overview of prominent cyanotoxins with respect to toxicity and occurrence

Toxin category, mode of intoxication	**Examples of toxins**	**Toxin-producing Cyanobacteria**	**Typical symptoms and diseases**
Hepatotoxins (main target: Liver), ingestion	Microcystin, Nodularin	Microcystis, Phormidium Aphanizomenon, Dolichospermum, Oscillatoria, Planktothrix	Diarrhoea, Liver inflammations, haemorrhage, weakness
Neurotoxins (main target: Neural system), ingestion	Anatoxin, Saxitoxin, β-Methylamino-L-Alanine	Dolichospermum, Aphanizomenon, Oscillatoria, Planktothrix, Cylindrospermopsis	Paralysis, muscle twitching, salivation, numbness
Dermatoxins (main target: Skin), skin contact	Lyngbyatoxin, Aplysiatoxin, Lipopolysaccharides	Cylindrospermopsis, Planktothrix, Lyngbya, Oscilatoria	Skin irritations, dermatitis, allergy, fever, respiratory interference
Cytotoxins (main target: Liver), ingestion	Cylindrospermopsin	Cylindrospermopsis, Dolichospermum, Aphanizomenon, Oscillatoria, Planktothrix, Lyngbya	Inflammations of inner organs, haemorrhage, dermatitis

Source: Summarized from Sanseverino 2017

Table 3 Guidelines for safe use of bathing sites with respect to risks from cyanobacterial blooms

Alert level	Decision criteria	Potential health risks	Management reaction
Relatively low probability of adverse health effects	• > 20,000 cells ml $^{-1}$ cyanobacteria ***or*** • >10 µg l^{-1} Chl a with dominance of cyanobacteria	Short-term health impacts, e.g. skin irritation, gastrointestinal illness	Risk information at bathing site, inform relevant authorities
Moderate probability of adverse health effects	• > 100,000 cells ml $^{-1}$ cyanobacteria ***or*** • >50 µg l^{-1} Chl a with dominance of cyanobacteria	Potential long-term health effects. Short-term health impacts, e.g. skin irritation, gastrointestinal illness	Monitoring for scum formation Discourage bathing Risk information at bathing site, inform relevant authorities
High probability of adverse health effects	Sum formation of a cyanobacterial bloom at bathing site and/or risk of ingestion or aspiration	Potential for acute poisoning. Potential long-term health effects. Short-term health impacts, e.g. skin irritation, gastrointestinal illness	Control of human contact to scum formations, potential closing of bathing site public health investigations. Risk information at bathing site, inform relevant authorities

Source: Summarized from WHO 2003

Their ability to produce a variety of cyanotoxins make cyanobacteria a major health concern. Intoxication of humans, cattle and other animals have been documented (WHO 2003) and a variety of toxins from cyanobacteria can be at play. An overview over the most relevant cyanotoxins is provided in Table 2. It is well evidenced that cyanotoxins display a heterogeneous group of toxins with a wide range of toxic effects, modes of intoxication, and taxonomic occurrence within cyanobacteria.

Since recreational use of waters is a major and likely way of exposure to cyanobacteria and cyanotoxins, the WHO has dedicated a specific guideline to this issue that is also setting thresholds for cyanobacteria abundances as given in Table 3 (WHO 2003), setting the alert level framework for monitoring and managing cyanobacteria in recreational water bodies in WHO (2021).

Also, in the EU legislation on drinking water supply, cyanotoxins are mentioned where microcystins are used as a primary proxy for cyanobacterial health risks. The WHO (2017) has defined a critical threshold for drinking water at the concentration of 1 µg/l for microcystin-LR.

4 Occurrence of cyanobacterial blooms: primary drivers, contemporary observations and future trends

Cyanobacteria benefit from warmer water temperatures and a high phosphorus loading (Carvalho et al. 2013, Rigosi et al. 2015, Carey et al. 2012). Regarding nutrients, nitrogen concentrations are less decisive because many cyanobacterial species can fix elemental nitrogen and therefore phosphorus is the main limiting nutrient for cyanobacterial proliferations (Schindler et al 2014). Accordingly, global warming as well as eutrophication exacerbate the formation of cyanobacterial HABs. Since the warming effects on lakes also induce processes favouring phosphorus loading, climate warming often acts not only directly by elevating water temperature but also by increasing phosphorus availability and trophic state (Moss et al., 2011). Climate warming and eutrophication can therefore enter a self-enhancing cycle and synergistically induce major water quality deteriorations (e.g. Kosten et al. 2012, North et al 2014). The very data-rich study of Carvalho et al. 2013, which was focused on more than 1500 European water bodies, indicated that cyanobacterial bloom frequency increases particularly strongly in the range of total phosphorus between 20 and 50 µg/l.

Indeed, large scale global assessments of phytoplankton blooms in inland waters by remote sensing clearly indicated an increasing incidence of bloom frequency (Ho et al. 2019). Particularly strong increases were noted in the years since 2010, which points to the importance of globally increasing temperatures as a driver (Hou et al. 2022). Notably, the increase in bloom frequency corresponded spatially with fertilizer application and agricultural fertilizer use can clearly be identified as a dominant driver of bloom frequency increase (Hou et al. 2022). Besides the evidence for increasing algal bloom occurrences worldwide, these two studies also demonstrate the abilities of satellite-based observations of phytoplankton dynamics.

The extrapolation of these trends in empirical observations raise the expectation that harmful algal blooms will further increase within this century. This expectation is supported by future increasing fertilizer application due to agricultural intensification and population growth (Mogollón et al. 2018a, b); which is forecasted to be in the range of +51 to +86 % by the year 2050 in the case of Phosphorus (Mogollón et al. 2018a), the major limiting nutrient of aquatic primary production (Schindler et al. 2008). Similarly, global forecasts for lake water temperature show a consistent warming with higher water surface temperatures, longer stratification durations and reduced mixing, which all support these expected positive trends in cyanobacterial blooms (Kosten et al. 2012, Woolway et al. 2021).

In conclusion, the issue of harmful algal blooms by mass developments of cyanobacteria are very likely to increase substantially in the future, which will require a more careful inclusion of cyanobacterial blooms into the management of bathing sites with respect to public health. This points towards the urgent demand for novel monitoring strategies that can be applied at affordable costs with a reasonable reliability as well as a consistent, harmonized framework for algal bloom detection and corresponding health management strategies for bathing sites.

4.1 Current monitoring and assessment of cyanobacterial mass developments in the EU

All standard monitoring strategies for cyanobacterial require on-site water sampling and subsequent analysis in the lab by either biological, chemical or molecular methods, which are summarised in Table 4. The requirement of collecting water samples make these monitoring methods expensive and demanding in personnel, lab, and financial resources. Usually, they come into practice only on demand, e.g. if bathers or authorities provide warnings, and are definitely not employed at every sampling occasion of the respective water body. They are also often associated with a time delay between sampling and availability of results, which opens a time window of several days for potential adverse health effects on bathers in case of toxic blooms. Further attributes of the different monitoring strategies refer to their specificity and required resources like lab infrastructures, experts or information infrastructures (IT).

Since the EU BWD does not specify the method of detection, cyanobacterial blooms are detected by diverse approaches and current practices differ between Member States, often even between states or communities. Accordingly, harmonisation of the method of detection would be helpful for a better comparability among EU members, facilitating an EU-wide evaluation of results.

Table 4 Overview of different monitoring techniques for cyanobacterial blooms and phytoplankton biomass, extended from Sanseverino et al. 2017

Target	Method	On-site samping required	Specificity	Comments
Cyanobacteria cells	Microscopic inspection	Yes	Very high, with taxonomic composition	Algal expert required, with intermediate delay
Cyanobacteria pigments	Fluorescence probe (phycocyanin)	Yes	High, specific for cyanobacteria, no taxonomic composition	Probe required, no delay
Cyanobacteria pigments	Probe-based real-time monitoring & data transfer	No	High, specific for cyanobacteria, no taxonomic composition	No delay, high maintenance, IT infrastructures
Cyanobacteria pigments	HPLC	Yes	High, specific for cyanobacteria, no taxonomic composition	Specified lab required, with longer delay
Cyanobacteria pigments	Remote sensing	No	Intermediate, specific for cyanobacteria, no taxonomic composition	Only available at satellite overcasts without cloud cover, intermediate delay
Cyanobacteria toxins	HPLC, ELISA, …	Yes	High, but only toxin concentration, no biomass or taxonomic information	Specified lab required, with longer delay
Cyanobacteria genes	PCR techniques	Yes	Very high, with taxonomic composition and toxin production potential	Specified lab required, with intermediate delay
Total phytoplankton	Microscopic inspection	Yes	Very high, with taxonomic composition	Algal expert required, with intermediate delay
Total phytoplankton	Cytometer	Yes	High, with taxonomic composition	Specified lab required, short delay
Chlorophyll a	Probe	Yes	Low, Chlorophyll can also originate from other algae	Probe required, no delay
Chlorophyll a	HPLC or photometry	Yes	Low, Chlorophyll can also originate from other algae	Lab required
Chlorophyll a	Probe-based real-time monitoring & data transfer	No	Low, Chlorophyll can also originate from other algae	No delay, high maintenance, IT infrastructures
Chlorophyll a	Remote sensing	No	Low, Chlorophyll can also originate from other algae	Only available at satellite overcasts without cloud cover, intermediate delay

4.2 Current handling of cyanobacterial blooms in the BWD

Only bacteriological parameters are the obligatory water quality indicators for bathing waters. On the other hand, monitoring of cyanobacterial blooms is addressed ambiguously in the BWD. On the one hand, health risks from cyanobacteria are mentioned and immediate action and monitoring in case of their incidence is foreseen but, on the other hand, the monitoring of cyanobacteria is not included in the standard monitoring protocol, thus left for the Member States to be handled differently.

At the same time, clear evidence exists that many bathing water sites are affected by cyanobacterial blooms and health risks cannot be ruled out. In fact, 80 % of bathing sites with cyanobacteria blooms receive an excellent grade because the bacteriological indicators are either lower than the prescribed limit values (see Figure 1) or have no significant impact on the final grade according to the rules in BWD. This points to a potential safety gap if cyanobacterial proliferations remain undetected (or even not monitored at all) and bathing activities proceed in waters with harmful blooms. Monitoring techniques for cyanobacterial blooms or, more generalised, algal blooms, are diverse and no harmonized protocol exists among Member States.

5 Satellite-based methods for cyanobacteria detection and their applicability for BWD

Space-borne detection of water quality has already been employed for many years and is primarily focused on the marine environment. Here, satellite-based monitoring is very beneficial due to the broad (global) spatial coverage of satellite imagery. Although the primary water quality indicators are similar between marine and inland waters, e.g. turbidity, transparency, and chlorophyll a, most inland waters require a fine spatial resolution unless only very large lakes are targeted. The Copernicus-satellites Sentinel 2 and Sentinel 3 provide a new generation of remote sensing products that are well suited for inland waters and their potential in inland water monitoring is not yet fully exploited by water authorities and EU legislation.

5.1 Technical background of the Copernicus Programme

The key characteristics of the available satellites comprise the spatial resolution, temporal return rate and the spectral resolution of the respective optical instruments. There is a trade-off between spatial resolution and return rate: the larger the spatial resolution the more frequent images can be taken. The spectral resolution, i.e. the number and band width of the recorded spectral bands, determine the detection abilities for different optical features, for example, to differentiate between the two pigments chlorophyll a and phycocyanin. While the former occurs in all algae, the latter is specific for cyanobacteria. Chlorophyll a has high light absorption between 400–450 nm and 660–690 nm, Phycocyanin absorbs exclusively between 500 and 590 nm, where chlorophyll is mostly optically inactive. Accordingly, optical detectors that are sensitive in these different bands can differentiate cyanobacteria from other algae. The basic features of the relevant satellites and sensors of the Copernicus Programme are summarised in Table 5. Further relevant satellites are provided by the NASA satellite programme including Landsat 5 and 8 and MODIS.

Table 5 Technical features of Sentinel 2 & 3 satellites of the Copernicus Programme

Satellite	Sensor	Spatial resolution	Return rate	No. of spectral bands	Historical coverage
Sentinel 2 A/B	MSI	10…20 m	ca. 5 days	13 bands between 442 to 2202 nm	From 2015 (S2A) & 2017 (S2B) onwards
Sentinel 3 A/B	OLCI	300 m	1…2 days	21 bands between 400 and 1020 nm	From 2016 (S3A) & 2018 (S3B) onwards

For water bodies of a larger size, say > 1 km^2, the OLCI instrument on Sentinel3 offers an optimal sensor as its spatial resolution fits to the water body and the return rate of 1–2 days is very high. For smaller water bodies, only Sentinel2-products can be used, which come along in roughly weekly resolutions.

Data products from the Sentinel satellites are provided by the Copernicus Service platform and are freely available. Note also that the Copernicus Land Service even has a water quality product that provides information on chlorophyll and water temperatures for a set of larger lakes in Europe and elsewhere (look at https://land.copernicus.eu/global/products/lwq).

5.2 Advantages and disadvantages of satellite-based methods for cyanobacteria detection in comparison to classical methods

Satellite observations provide advantages that classical methods cannot compete with. This refers to the spatial representation and temporal coverage but also to costs and work effort, which are all relevant aspects in governmental monitoring programmes. An overview of strengths and limitations are provided in Table 6.

Table 6 Advantages and disadvantages of satellite-based monitoring of inland waters

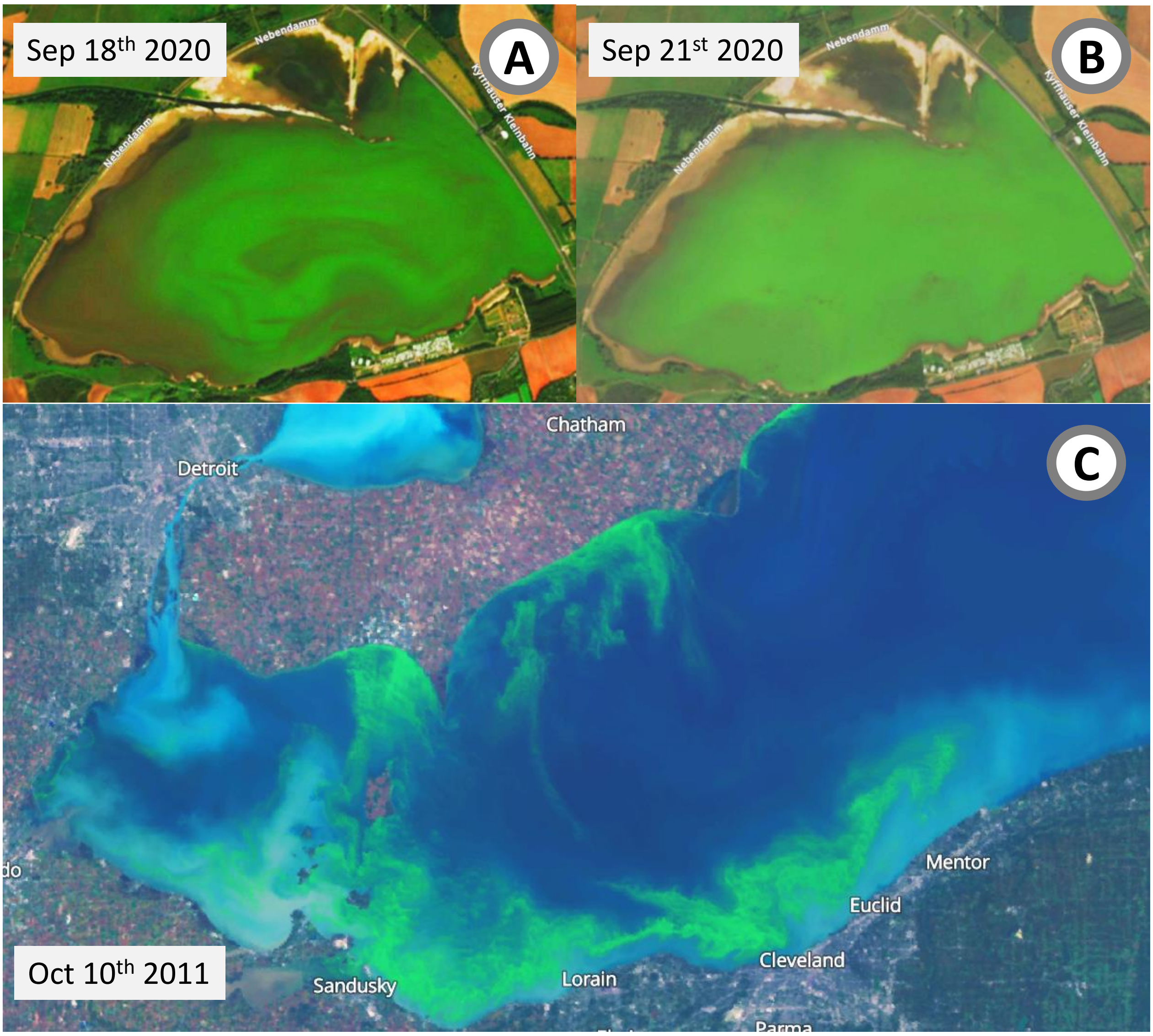
Category	**Advantages and strengths**	**Limitations and disadvantages**
Spatial coverage	Full spatial coverage instead of point information, assessment of lake-wide averages or spatial distributions	Only surface layer is assessed by satellites, no depth information is provided. No data in case of cloud cover
Temporal coverage	High sampling frequency according to the return rate of the satellites (1…5 days)	Fixed overcast No data in case of cloud cover
Target variables	Optically sensitive target variables are chlorophyll, phycocyanin, transparency, reflectance and temperature	No information on other variables like nutrients, pollutants, conductivity, pH, oxygen and other limnological or biogeochemical characteristics
Effort & resources	Data are available free of charge and within 1–2 days after satellite overcast, broad support from EU- or nationally supported IT-infrastructures. Basic information from Copernicus Land Services	Complex data processing is required, multiple algorithms exist and selection of the right algorithm requires expert knowledge. Advanced competences in geospatial data handling

A major limitation of satellite-based methods is cloud cover or any other atmospheric interference (e.g. sunlight, fog), which blocks the optical interaction between sun, water body and satellite. Depending on the region and season this can be a real bottleneck, e.g. at coastal regions in northern and central Europe or mountainous regions. On the other hand, central continental European areas are well suited for satellite observations, particularly during the main vegetation period between April and September. The problem of cloud cover also interacts with the satellite system when in use. If Sentinel3 products are applicable (i.e. the targeted water body is large enough in surface area), cloud cover is a less sensitive issue given the high return rate. Cloud cover is a more sensitive issue when Sentinel2 is used as this satellite returns only every 5th day. In regions with frequent cloud cover, accordingly, the advantage of high temporal resolution of satellite overcasts cannot really be exploited.

Although cloud cover is a crucial factor, the potential for high temporal coverage is a decisive advantage as algal blooms are often taking place at time scales of several days to a few weeks. Since many classical monitoring protocols employ monthly sampling frequencies, they often overlook blooms. In the case of bathing waters, this harbours the risk of intoxications and exposure to algal blooms of bathers simply because they are not detected in the monitoring regime in place.

A similar statement can be made with respect to spatial coverage. Unless cloud cover is interfering with satellite overcasts, the satellite images provide spatially resolved information. This is of high importance for algal blooms that are notoriously heterogenous (e.g. Ortiz & Wilkinson, 2021; Chaffin et al. 2021) so that classical sampling strategies, which mostly sample just at one point per lake (usually the deepest point), run a high risk of missing a bloom: they simply sample the wrong location at a given time. A very prominent example was the massive algal bloom in Lake Erie in 2011, but also smaller lakes in Europe show spatial heterogeneity, sometimes even with very fast changes between heterogenous and rather homogeneous patterns) under these conditions. Classical point sampling is likely to not be representative for the current status. A spatially resolved satellite image or the calculation of lake-wide average values based on remote sensing products appears more appropriate for a reliable bloom detection.

Figure 3: Satellite images of a cyanobacterial bloom in Kelbra Reservoir in Thuringia, Germany (A and B) from September 18th and 21st 2020, i.e. only three days apart, showing fast changes from heterogeneous to homogeneous spatial distribution. Another example of a strongly spatially confined cyanobacterial bloom (C) is observed in Lake Erie (Envisat MERIS) in 2011.



Source: https://apps.sentinel-hub.com/eo-browser.

Even though satellite-borne monitoring has a number of advantages there are still features that can only be assessed by classical monitoring techniques. These refer firstly to the target variables because remote sensing can only detect such variables that are optically active (see Table 6). Water quality determinants such as nutrients, dissolved salts or pH and dissolved gases cannot be assessed by satellites (but also not relevant for the BWD). With respect to phytoplankton, remote sensing is well suited for total biomass (measured as chlorophyll a) or cyanobacterial abundance (measured as phycocyanin) but cannot provide taxonomically resolved phytoplankton community composition, which can only be assessed by microscopic inspection and cell counting. Finally, remote sensing can only look at the surface of the water bodies and basically reflect the water status of the upper layer (from surface down to Secchi Depth) while classical monitoring can also sample water from deeper layers. This can be relevant in the case of subsurface blooms although they rarely interfere with bathing activities but are nevertheless important water quality determinants.

A potential problem for many users of satellite products arises from the highly diverse methodology in data processing. The optical measurements of the satellite require a complex data processing chain that include atmospheric corrections, cloud detection, pixel identification and other aspects. The application of different processing chains ends up in different values of the target values and the usefulness of these alternative processing routes is not easily interpretable for non-experts and we are still lacking a harmonized, transferable set of algorithms. Also, satellite-borne monitoring data come along with uncertainty (as all monitoring techniques do) and this can lead to both, false positive warnings (indicating the presence of an algal bloom although there isn't one) and false negative warnings (indicating there is no bloom although there is one). It will therefore make sense to consider a hierarchical and adaptive application of the satellite-based monitoring as already been proposed for the US by EPA 2019. The methodology for satellite-based bloom detection is laid out in Coffer et al. (2021b), which propose to use this methodology for identifying lakes or portions of a lake that are more prone to cyanobacterial blooms in order to assist in the prioritization of sampling resources and mitigation efforts.

5.3 Application potential and accuracy of Copernicus products for inland water monitoring of cyanobacterial proliferations

A quantitative assessment of remotely monitored cyanobacterial proliferations is not easy to achieve because the major target variable from the satellite is the concentration of the cyanobacterial pigment phycocyanin. But this pigment is not included in standard samplings of water authorities and even in scientific monitoring programmes hardly included because its measurement protocol requires a separate line of extraction and is therefore additional work. Some monitoring programmes at least measure cyanobacterial biovolume based on cell counts or use fluorescent probes for measuring phycocyanin fluorescence. Although all these variables (phycocyanin concentration, cyanobacterial biovolume, phycocyanin fluorescence) are well suited for cyanobacteria monitoring and usually show high correlations, their quantitative values are different and a comparison always requires a proper intercalibration with an established standard.

For practical applications, however, cyanobacterial bloom detection is not requiring a fully quantitative estimate of pigments or biomass. Instead of quantitative precision it is more important to provide robust status descriptions. This can also be realised by semiquantitative classifications that result in categorial output variables, e.g. classifiers of no/minor/intermediate/strong cyanobacterial proliferations. Of course, such a categorial classification of monitoring products could only be established if a harmonized approach is developed that is based in extensive field observations and empirically based categorial classifications. Such a harmonised system is not available in the EU at present and requires the involvement of water experts from the Member States, e.g. in the form of an expert group, a project team, or a workshop.

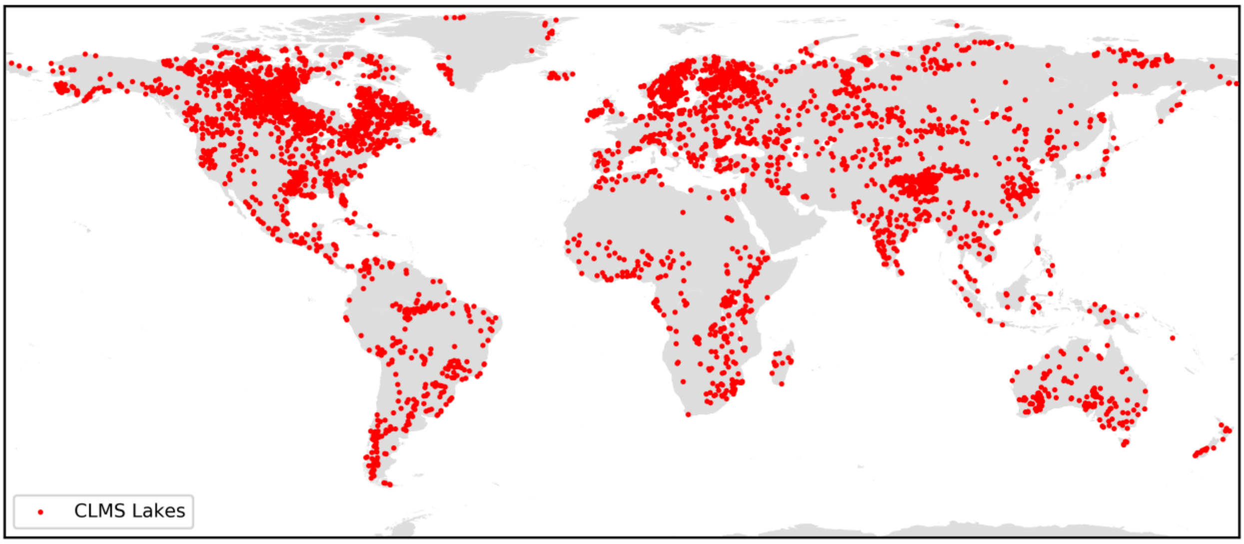
An interesting option for improving the observational data basis for on-site information could be realised by involving bathing guests in a citizen science approach. This is nicely exemplified in a Portuguese mobile App that allows visitors to give feedback on bathing water quality and potential bloom formation (Infopraia, see https://infopraia.apambiente.pt/). The information is then made public via the App so that citizens can inform themselves where the best water quality is available and will avoid bloom affected sites. This not only provides useful information but also reduces health risks. Last but not least, the obtained information via the App can be compared to satellite-based products (in that case semi-quantitative would be sufficient) and hence can be directly used for ground truthing and optimisation of processing algorithms.

Another issue in the practical application of satellite-based detection of cyanobacterial proliferations is the complex processing routines required to translate the spectral satellite-borne information into a measure of cyanobacterial abundance. These routines (e.g. atmospheric correction, etc… see chapter 5.2) require expert knowledge that is usually not available in water authorities. The applicability of satellite-based techniques in governmental monitoring programmes is therefore often mediated by specialised companies that provide professional processing services including visualisation and analysis tools. These companies bridge the gap that often exists between the opportunities provided by Copernicus satellites and the monitoring demand of water authorities and environmental administrations (e.g. visit https://earsc.org/). When analysing the applicability of satellite products in cyanobacterial monitoring the services of such companies need to be considered and are therefore included in the case studies introduced in chapter 5.3.3.

5.3.1 Copernicus Land Services for water quality

The Copernicus Land Service provides lake water quality information products (see https://land.copernicus.eu/global/products/lwq) at global level for a set of more than 4200 lakes, among them many high priority water bodies within EU states (Map 2). This programme also provides a validation report where in-situ data are used for a validation of the underlying data processing algorithms and inform about the accuracy and reliability of the satellite products.

Map 2 Map of lakes included in the lake water quality sector of the Copernicus Land Service. More than 4200 lakes are included, among them 1100 lakes from Europe.



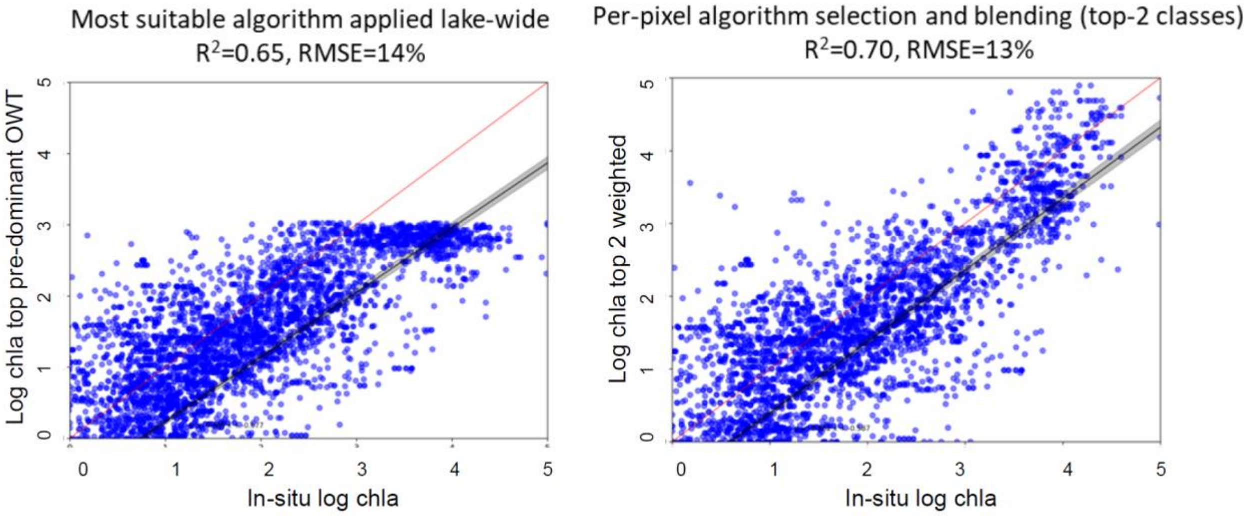
Source: https://land.copernicus.eu/global/products/lwq; Copernicus Service information [2022]. The products were extracted from the land service of Copernicus, the Earth Observation program of the European Commission. The Calimnos production chain was initially developed within UK NERC GloboLakes and has been further developed with core collaboration between PML, University of Stirling, Brockmann Consult and HYGEOS in the Copernicus Land Monitoring Service, H2020-TAPAS, H2020-EOMORES, and ESA CCI Lakes.

The approach of the Copernicus service is based in the definition of 13 optical water types (OWT's) that allow to optimise the algorithms according to systematic properties of the water bodies, for instance with respect to their water colour (e.g. affected by the content of humic substances).

A broad scale evaluation of this approach yielded a relatively high reproducibility of observed chlorophyll values with an $R^2 = 0.65…0.70$ and a relative RMSE of 13…14 % (Figure 4). This level of accuracy is in a range that makes satellite-derived chlorophyll estimates definitely applicable in governmental water quality monitoring including bathing water safety.

Unfortunately, the Copernicus Programme only provides estimates of chlorophyll and is not yet producing information on cyanobacteria. An extension of this Copernicus service towards including cyanobacteria abundance would further increase the applicability of Sentinel-products in lake and reservoir water quality monitoring.

Figure 4: Comparison of measured in situ chlorophyll a concentration (in µg L^{-1}) and satellite-based chlorophyll. Note the log_{10}-scale of both axes. Left: Application of OWT-specific algorithm to the whole water body, right: pixel-wise application of OWT algorithms, i.e. within a given water body different OWT-algorithms may be applied given the specific optical properties, which allows a better reproduction of very high chlorophyll values by the satellite-borne values. OWT = optical water type



Source: Buchhorn, M. et al. (2020)

5.3.2 State-of-the-art in research and evaluation of scientific literature

Research studies employing remote sensing of water quality are numerous and still growing in number (Dornhöfer & Oppelt, 2016). Besides turbidity and transparency, also chlorophyll and cyanobacteria are often analysed and a rich body of scientific literature exists. An overview of some studies exploring the predictability of in-situ chlorophyll and cyanobacteria concentrations by different satellite products are summarized in Table 7. As a matter of fact, older studies used satellites of the previous generation, predominantly Medium Resolution Imaging Spectrometer (MERIS) data from Envisat, but in recent years, studies using Sentinel 2 and 3 data products have increasingly been published. Overall, predictability of chlorophyll and cyanobacteria is very different among these studies although no consistent trend can be identified with respect to the specific satellite used, i.e. both Sentinel 2 and 3 appear to be equally suited for deriving these target variables. The accuracy of the satellite-based information of course also depends on the algorithms and with ongoing optimisation of algorithms, predictability should consolidate at a reasonable level that fits to monitoring requirements, as already pointed out in chapter 5.3.1.

In conclusion, the predictability of chlorophyll and cyanobacteria by Copernicus satellites is sufficient to be used for water quality monitoring purposes. This is even more valid when it comes to algal bloom identification as here the precise quantitative value is not decisive (e.g. it is not important whether chlorophyll is at 100 or 200 µg L^{-1}), but it is important to differentiate between blooming and non-blooming algal states (e.g. whether the chlorophyll value is, say, 10 or 100 µg L^{-1}). It should be noted that most scientific applications are still lake-specific or include only a few lakes and the corresponding methodology is optimised for these specific case studies. It should be stressed, therefore, that the transferability of these approaches remain to be tested and evaluated. In that respect, the Copernicus service with its broad empirical data basis and high number of water bodies included (see chapter 5.3.1) is probably a better approach to obtain reliable and transferable algorithms than single-lake focused analyses in most scientific papers.

Table 7: Collection of scientific literature focused on phytoplankton detection by different satellite-based techniques, extended from Dornhöfer & Oppelt (2016); r = correlation coefficient, RMSE = root mean square error, R^2 = determination coefficient, WFD = Water Framework Directive, *Airborne, hyperspectral sensor

Authors	Sensors	Parameter	Range	Accuracy	Study Area	Time	Process
Bresciani et al., 2011c	MERIS	Chl-a	0–20 mg m^{-3}	-	Perialpine lakes	2003–2009	WFD monitoring
Gómez et al., 2011	CHRIS MERIS	Chl-a Cyano	0–250 mg m^{-3} 0–250 mg m^{-3}	RMSE: 8.6 mg m^{-3} RMSE: 12.92 mg m^{-3}	Albufera of Valencia (Spain)	2001–2005	WFD monitoring
Hunter et al., 2010b	CASI-2*, AISA*	Chl-a Cyano	0-> 150 mg m^{-3}	R^2: 0.832 R^2: 0.984	Loch Levan, Esthwaite water (UK)	13, 26 April, 22 August 2007	Monitoring cyanobacterial blooms
Kauer et al., 2015	MERIS	Chl-a $K_{d(PAR)}$	0–100 mg m^{-3} 0–3 m^{-1}	R^2: 0.92 R^2: 0.82	Lake Peipsi, Lake Võrtsjärv (Estonia)	2005–2009	Phytoplankton primary production model
Keith et al., 2012	HyperOCR*	Chl-a	2–90 mg m^{-3}	R^2: 0.97	49 lakes in New England (USA)	15–17 Sept. 2009	Trophic status assessment, CWA mon.
Mattews, 2014	MERIS	Chl-a Cyano Surface scum area	1–500 mg m^{-3} 1–50 % 0.01–10 %	r: 0.72 -	50 lakes in South Africa	2002–2012	Time series analyses, trends, monitoring blooms
Ogashawara, 2019	Sentinel 3	Phycocyanin Chlorophyll	0.1-ca. 800 mg m^{-3} 0.1-ca. 600 mg m^{-3}	R^2: 0.08-0.41 (same day) R^2: 0.01-0.50 (same day)	Lake Erie (US, Canada)	2016–2018	Phytoplankton and Cyanobacteria monitoring
Palmer et al., 2015a	MERIS	Chl-a Phenology features	0-> 60 mg m^{-3} Days, rates	R^2: 0.97 0.58< R^2 < 0.84	Lake Balaton (Hungary)	2002–2012	Phytoplankton phenology, spatio-temporal trends and changes
Sòria-Perpinyà et al. 2020	Sentinel 2	Phycocyanin		Calibration: R^2 = 0.84, n = 21 Validation: R^2 = 0.78; n = 55;	Albufera of València lagoon (Spain)	2016–2017	Bloom detection

Sòria-Perpinyà et al. 2021	Sentinel 2, Sentinel 3	Phycocyanin	0.1–1040 mg m^{-3}	Calibration Sentinel2: R^2 = 0.67…0.94 Sentinel 3: R^2 = 0.66…0.96 Validation Sentinel2: R^2 = 0.35…0.92 Sentinel 3: R^2 = 0.62…0.96	Various lakes in Spain	2017–2018	Water quality monitoring, bloom detection
		Chlorophyll a	0.5–705 mg m^{-3}	Calibration Sentinel2: R^2 = 0.47…0.93 Sentinel 3: R^2 = 0.5…0.93 Validation Sentinel2: R^2 = 0.21…0.91 Sentinel 3: R^2 = 0.23…0.91			
Viso-Vázquez et al 2021	Sentinel 2	Cyanobacteria (cells ml^{-1})	0-223000 cells ml^{-1}	R^2 = 0.71–0.88	A Baxe Reservoir (Spain)	2018	Phytoplankton biomass estimates
		Chlorophyll	0.7–111 mg L^{-1}	R^2 = 0.71–0.80			
Wu et al., 2015	MODIS	Cyanobacterial bloom area	100–800 km^2	-	Lake Taihu (China)	2000–2011	Cyanobacterial blooms and wind speed
Yan et al. 2022	Sentinel 2	Cyanobacterial bloom area	0–250 km^2	R^2 = 0.99 RE = 3 %	Lake Chaohu (China)	2016–2020	Bloom area detection and quantification

5.3.3 Case study examples of cyanobacterial detection

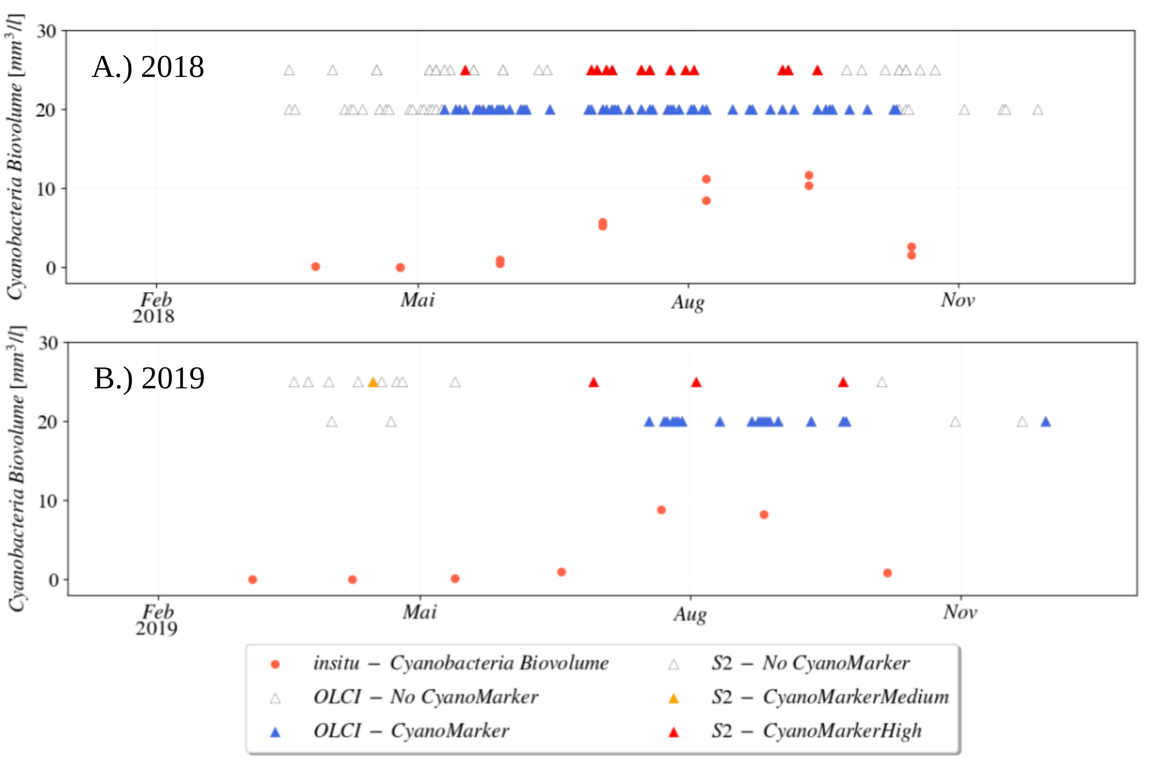
Two case studies are embedded in this report in order to demonstrate how potential satellite-based information on cyanobacterial proliferations relate to field observations. Also, the examples show a potential way of data visualisation towards decision-making bodies by using semi-quantitative indices. In both cases, the data processing was realised by freely available software (SNAP[1] and CALVALUS2[2]) and the level of cyanobacterial abundance was given as a semi-quantitative indicator.

5.3.3.1 Lake Dobersdorf

Lake Dobersdorf is a medium-sized (312 ha surface area) eutrophic lake in Northern Germany. It has an official bathing site, which frequently has problems with cyanobacterial blooms. Sampling of the water authority (Landesamt für Landwirtschaft, Umwelt und ländliche Räume Schleswig-Holstein) is routinely undertaken on a monthly basis.

In this case study, Sentinel3-based (OLCI) as well as Sentinel2-based data were processed and an indicator value (CyanoMarker) calculated. For Sentinel3, the algorithm just separates cyanobacteria-dominated state vs. a condition with no or low cyanobacteria. For Sentinel2 (S2), a three-level indicator (No/Medium/High cyanobacterial occurrence) is generated.

Figure 5: Lake Dobersdorf in Northern Germany as an example for satellite-based detection of cyanobacterial proliferations



Note: The satellite information is given in a qualitative output variable (CyanomMarker) derived from Sentinel2 (S2) and Sentinel3 (S3) satellite data.

Source: In situ Data (Cyanobacterial biovolume) were provided by Landesamt für Landwirtschaft, Umwelt und ländliche Räume Schleswig-Holstein. Satellite data were derived from modified Copernicus Sentinel data [2018–2019 from Sentinel-3 OLCI and Sentinel-2 MSI, data processing was performed by Kerstin Stelzer, Brockmann Consult GmbH

[1] http://step.esa.int/main/toolboxes/snap/
[2] https://github.com/bcdev/calvalus2

With the onset of the growth of cyanobacteria in Lake Dobersdorf in June 2018 and July 2019 also the satellite-based indicators point towards cyanobacterial proliferation. The satellite-based indicator has some uncertainty and false positive as well as false negative cases occur although the majority of satellite scenes comply to observations. This clearly demonstrates that it is an advantage to utilize all available satellite information (i.e. all satellite overcasts should be included) for a given lake in order to provide full information of the status. A major advantage of the satellite-based information is the far higher temporal resolution compared to the monthly field observations. Given this far better temporal coverage, the above mentioned false-positive/false-negative indicator values remain only marginally problematic as the overall information generates a very clear pattern showing the emergence of this cyanobacterial bloom in Lake Dobersdorf. A reasonable reaction by decision-makers to this information could be, for example, to trigger an in-situ monitoring effort during the time of the cyanobacterial occurrence and to release a warning to bathers.

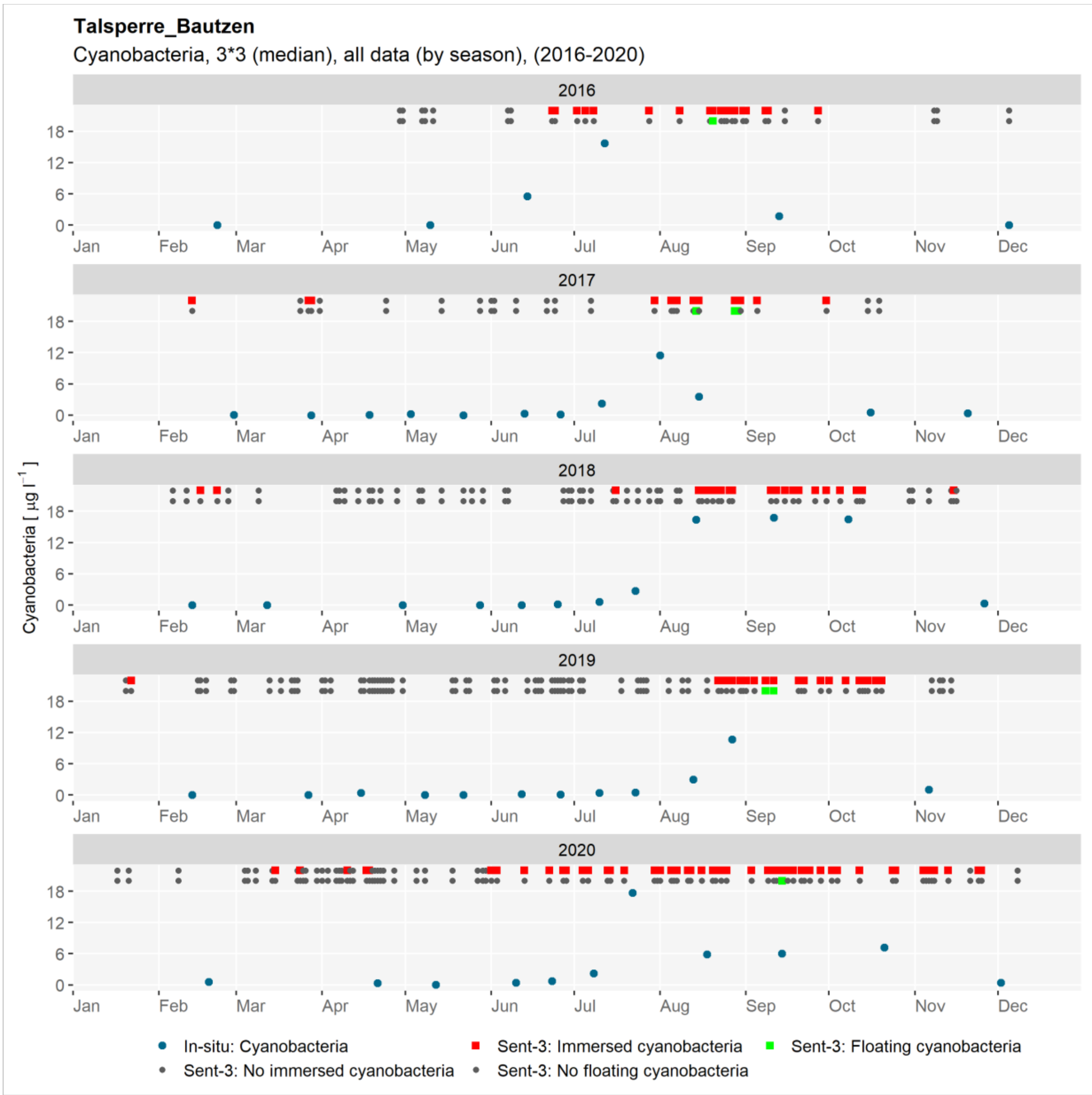
5.3.3.2 Bautzen Reservoir

Bautzen Reservoir is located in south-eastern Germany in the state of Saxony. It is frequently used by tourists, anglers and swimmers as it has an official bathing site as well as tourist infrastructures including a camping site and rentable cottages. The reservoir is relatively large with approximately 580 ha at full storage and suffers from a high nutrient loading from the surrounding catchment resulting regularly in heavy, scum-forming cyanobacterial blooms.

Given the large size of Bautzen Reservoir, it is well suited for Sentinel3-based monitoring having a spatial resolution of 300m. The processing of Sentinel3-data provides also the opportunity to differentiate between immersed and floating (i.e. scum-forming) cyanobacteria. Again, the satellite-based information was provided as a categorial variable for cyanobacterial occurrence, which complied well with the observational data from in-situ sampling of cyanobacterial biovolume (Figure 6). Although, also in this case some false positive or false-negative indicator values occur, their frequency is lower than in Lake Dobersdorf and the overall pattern of cyanobacterial proliferation from Satellite-derived information (in particular the indicator for immersed cyanobacteria) is highly consistent with the field observations. Note, however, that observational in situ-data just inform us about cyanobacterial biovolume and do not provide information on scum-formation.

The satellite-based information comes along with a far higher temporal coverage and thus informs decision makers more frequently than in-situ sampling. This is a major benefit of the satellite product, which can be exploited for triggering in-situ monitoring, early warning, or further management reactions.

Figure 6: Occurrence of Cyanobacteria (in-situ data: Reservoir authority of Saxony, LTV Sachsen) in Bautzen Reservoir, Saxonia, for the period 2016–2020 and detection of cyanobacteria by Sentinel 3-based (Sent-3) remote sensing



Note: The algorithm differentiates between immersed and floating (i.e. scum-forming) Cyanobacteria, processing platform: Calvalus C2RCC (Case-2 Regional CoastColour) v1.0, processing: T. Schröder, UFZ, Department Lake Research (supported from BIGFE-Project, Deutsche Raumfahrtagentur im DLR e.V., Grant Nr. 50EW2101A).

Source: In-situ data from State Dam Administration of the Free State of Saxony (Landestalsperrenverwaltung des Freistaates Sachsen).

6 Synergies with other EU legislation, potential obstacles, and ways to improvement

The assessment of the water quality in water bodies is not only relevant for bathers but also for other human uses and for sustaining ecosystem services. This refers particularly to provisioning services like drinking water or irrigation water supply, as well as biodiversity and ecosystem health.

Large synergies can be expected between the BWD and the European Water Framework Directive (WFD). The major goal of the WFD is to obtain a good ecological status of surface waters and the assessment of the ecological status requires a structured and harmonized monitoring strategy that is fully implemented in all Member States. All standing water bodies larger than 50 ha are subject to the WFD and are regularly monitored. Many official bathing sites are at water bodies that belong to this group and would benefit from the results of the WFD-based monitoring, which, among others, also include the assessment of cyanobacterial proliferation. In fact, a structured exchange of data from both EU directives would release a major synergy for both, as it would improve the information base and reduce costs due to multiple usage of monitoring results. For example, a cyanobacterial bloom registered in the WFD-monitoring should be submitted to the authorities in charge of the BWD. Most importantly, it should also be stressed that, based on the WFD-based monitoring, many bathing sites are classified as susceptible to cyanobacterial proliferation and at the same time get a high-quality grade in the BWD-based assessment because the mandatory bacteriological quality indicators (see Table 1) are non-alerting. In such a case, the BWD would report a high bathing water quality while the WFD may report a bad ecological status due to cyanobacterial blooms (see Figure 2). In consequence, a bather would be exposed to health risks without being informed although the relevant information is available in other administrative or managerial bodies. The reporting of WFD-based monitoring results should be coordinated with BWD reporting and assessment of bathing water adopted accordingly.

At present, the WFD-based monitoring is taking place mostly as in-situ monitoring but in many Member States (e.g. Belgium or Ireland[3]) a process is underway to include also satellite-based techniques as a monitoring instrument. In Finland, given the huge number of lakes, remote sensing of chlorophyll is already implemented in the ongoing WFD monitoring by the Finish Environmental Institute SYKE[4]. A remote-sensing based detection of cyanobacteria is under implementation for monitoring of the Baltic Sea and could similarly be used for lakes. A white paper from Papathanaopoulou et al. (2019) comprehensively illustrates the benefits of satellite-based remote sensing for WFD-based monitoring and their arguments are similarly applicable for utilizing remote sensing within the BWD. In the perfect setting, any satellite-based water quality information of a given water body would be made available to both Directives to maximise synergies and cost-efficiency.

Not least, other environmental data flows of the EU that collect water data can provide a good basis of knowledge to be shared between different legislative aims, including addressing the health risks to bathers under the BWD. Most notably, the Water Information System for Europe (WISE) is a platform that collects water data from Eionet reporting countries, including the State of Environment Water Quality (WISE-6) data flow that also collects the raw monitoring results of cyanobacteria. 856 monitoring sites have been reported by a total of 13 countries where monitoring of cyanobacteria biomass (or cyanobacteria proportion) is taking place. Although limited to only some Eionet countries and thus not spatially representative for the whole EU, it provides a good starting point for centralising more monitoring data,

[3] https://www.irishtimes.com/news/environment/pollution-police-look-to-space-to-monitor-over-800-irish-lakes-1.3702129

[4] https://www.syke.fi/en-US/Research__Development/Research_and_development_projects/Projects/Water_quality_detection_using_Sentinel_and_Landsat_satellite_series_on_Finnish_lakes_and_coastal_watersBaltic_Sea_VESISEN
https://www.syke.fi/en-US/Open_information/Open_web_services/EO_web_map_services

to be used in synergy with satellite-based methods of cyanobacteria monitoring. The WISE data flow depends on the future monitoring programmes implemented by European countries.

Finally, satellite-based assessment of chlorophyll and cyanobacteria in surface waters can support other water-related policies at EU level as optional instruments, e.g. for:

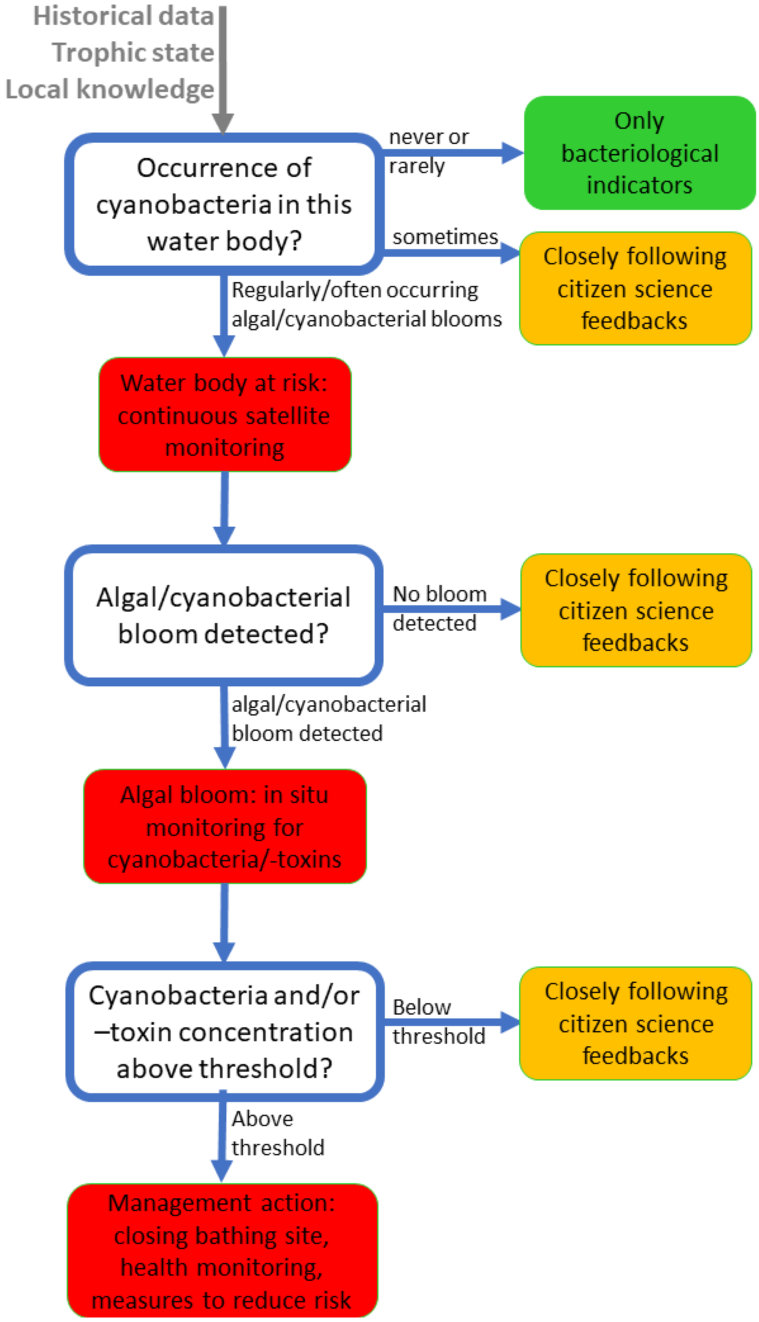
- water quality monitoring of drinking water reservoirs and supporting observational data for water safety plans for these water bodies. Satellite-based monitoring of water bodies used as drinking water source has also been proposed in the US and is consistently elaborated in Coffer et al. (2021a);
- impact assessment of management measures in agricultural practices;
- supporting observational data for causal analyses in case of ecosystem crashes, pollution spills or fish kills.

7 Conclusions and suggestions for using remote sensing in BWD implementation

- There is broad evidence that many bathing water sites are affected by cyanobacterial blooms with potential adverse effects on bathers due to exposure to cyanotoxins.
- The assessment of bathing water quality should also include the detection of cyanobacterial proliferation in order to reduce health risks for bathers. The current practice in many places is only focusing on the mandatory bacteriological target variables (Table 1) and emerging cyanobacterial blooms remain undetected.
- Copernicus services by Sentinel2 and Sentinel3 offer satellite-borne information on chlorophyll and cyanobacterial proliferation enabling the detection of algal blooms in general and cyanobacterial blooms in particular. For the latter, a semi-quantitative or categorial indicators may be considered because it is easier to derive, more robust, and directly interpretable for water managers.
- Remote sensing offers huge advantages with respect to spatial and temporal coverage of monitoring data for bathing sites. Satellite data from the Copernicus Programme are available with only little time delay (1–2 days) and the costs do not have to be borne by the organizations that monitor the bathing water quality. But the processing of these data requires an IT infrastructure and expert knowledge with a limited availability. Also, satellite-borne monitoring data come along with uncertainty (as all monitoring techniques) and this can lead to both, false positive warnings and false negative warnings. It will therefore make sense to consider a hierarchical monitoring approach where an algal bloom that is detected by satellite is triggering further monitoring and/or management reactions. Such an adaptive monitoring approach is outlined below in Figure 7 and would allow to focus the cost and personnel-intensive in-situ sampling only on places where blooms are emerging on the satellite-based products. A similar approach is proposed by the US EPA for the monitoring of recreational waters involving satellite-based techniques (EPA 2019, see also: https://www.epa.gov/cyanohabs/monitoring-and-responding-cyanobacteria-and-cyanotoxins-recreational-waters).
- An adaptive monitoring approach as outlined in Figure 7 also includes the monitoring of cyanobacteria and/or toxin concentrations after management measures implemented for risk reduction and to confirm that a site can be re-opened for bathing.
- Consider the implementation of an expert group or a project team that develops science-based guidelines for the application of remote-sensing techniques and an avenue for an EU-wide harmonised procedure for the utilisation of satellite products. Maybe a workshop on these issues would be a good next step. It should also be noted that substantial experience and knowledge is present in companies working on EO services and it may be helpful to make their knowledge available in this process by integrating them into the group of experts.
- The existing data about cyanobacteria proliferations, provided by governmental monitoring within the WFD as well as scientific monitoring programmes, may be used to initiate a research project that uses these available data for quantifying the robustness, reliability, and uncertainty of satellite-borne monitoring products in order to identify the most useful processing algorithms and provide meaningful definitions of thresholds.
- Contributions from citizen science can be implemented by mobile apps that allow bathers to transmit information on bathing water quality with respect to algal blooms. This information can be used twice – on the one hand the app informs other bathers about the current state at a given bathing site, and on the other hand, the submitted data can be used to ground-truth satellite information or for triggering satellite-borne monitoring or even on-site sampling by classical methods.
- Substantial synergies can be achieved between the BWD and the WFD, since both target on cyanobacteria. Alone the reporting of results from WFD-monitoring to the relevant managing authorities of bathing water can close current information gaps with respect to cyanobacterial proliferation. This can be supported by other water data flows of the EU, namely WISE SoE – Water

Quality, providing raw monitoring results. Both Directives would benefit from satellite-based information on algal blooms, possibly by targeting on chlorophyll as well as cyanobacteria. It should be noted that some Member States have already started activities on using remote sensing techniques within WFD-related monitoring and it will be helpful to integrate their experience into the BWD-related processes.

Figure 7: Suggested workflow for an adaptive monitoring approach that involves satellite-based monitoring only if a certain risk can be identified. Only in the case of an ongoing bloom more intense in-situ sampling efforts are triggered.



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