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Towards Earth Observation supported monitoring of freshwater biodiversity	

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1 Description of ESS pilot

1.1 Scientific case

Lake Marken is considered a Heavily Modified Water Body according to the Water Framework Directive terminology (Lammens et al., 2008). It was separated from Lake Ijsselmeer with the creation of the dam "Houtribdijk" in 1976, which also negatively affected its biodiversity. Damming and regulation of the water table prevented the lake from developing in a natural way including the lack of development of emergent vegetation (Lammens et al., 2008). Other pressures are high nutrient loads and overexploitation of fish. In the 1970s phosphorous concentrations were very high (0.2-0.3 mg L^{-1}) but started to decrease in the 1980s (<0.1 mg L^{-1}). Despite this reduction in phosphorous the ecosystem and hence biodiversity did not improve.

Particles trapped in Lake Marken remain in suspension during long periods, which leads to decreased light penetration in the water column which in turn hampers the development of underwater vegetation. Because of this low light availability, production in the lake is mainly taken place in the pelagic rather than in the benthic zone. Primary consumers in turn are dominated by benthic macroinvertebrates (mainly by the Quagga mussel *Dreissena rostriformis*) that rely heavily on pelagically produced organic matter. The food web in the lake is thus rather simple in comparison to more natural freshwater lakes and shows a high trophic incoherence (Tack et al., 2023).

Different measures took place in recent years, especially on improvement of habitat diversity, in the lake. Best example of this has been the creation of islands in 2016 in the north-western part of the lake, the Marker Wadden. The final two islands were finished in 2022 (Irwin, 2023). The Marker Wadden offer spawning areas, islands and natural shores such as wetlands and beaches so that many plants and animals can thrive, and this will improve biodiversity. Another function of the islands is to reduce the amount of wind fetch in the north-western part of the lake to improve light conditions under water and hence, stimulate the growth of the underwater vegetation. The coming years should make clear if this measure (and other measures as well) was successful or not, but Marker Wadden will surely provide important lessons for other restoration and rewilding projects (Marker Wadden project, 2020).

BIOMONDO provides data that can be used to investigate if the islands reduced the wind fetch on the lake and whether this has led to a better lighting climate underwater. The EO products on turbidity from before and after the creation of the islands can show this. Until now we have not been able to see if turbidity has dropped because dredging activities were taking place. 2023 is probably the first year for which this can truly be investigated. The early adopter for this pilot study is Rijkswaterstaat, the executive organization of the Dutch Ministry of Infrastructure and Water Management, responsible for the management of Lake Marken. RWS is also responsible for the Natura 2000 management plans of national waters and responsible for the achievement of the Natura 2000 objectives. In addition, RWS is running the monitoring programs for evaluation of the different policies. The main policy frameworks are the European Nature Directives (Habitat and Birds with

Natura2000), the Water Framework Directive (WFD) and the EU 2030 Biodiversity strategy.

1.2 Science/Policy Traceability Matrix

The Science/Policy Traceability Matrix (SPTM) compiled for BIOMONDO lists six major drivers related to the decline of freshwater biodiversity, including pollution and eutrophication, habitat changes, invasive species, climate change impact, overexploitation, and effects resulting to driver interaction or unknown drivers. Pilot 1 aims to explore objectives related to eutrophication. The full science/policy track of this objective is summarized in Figure 1.

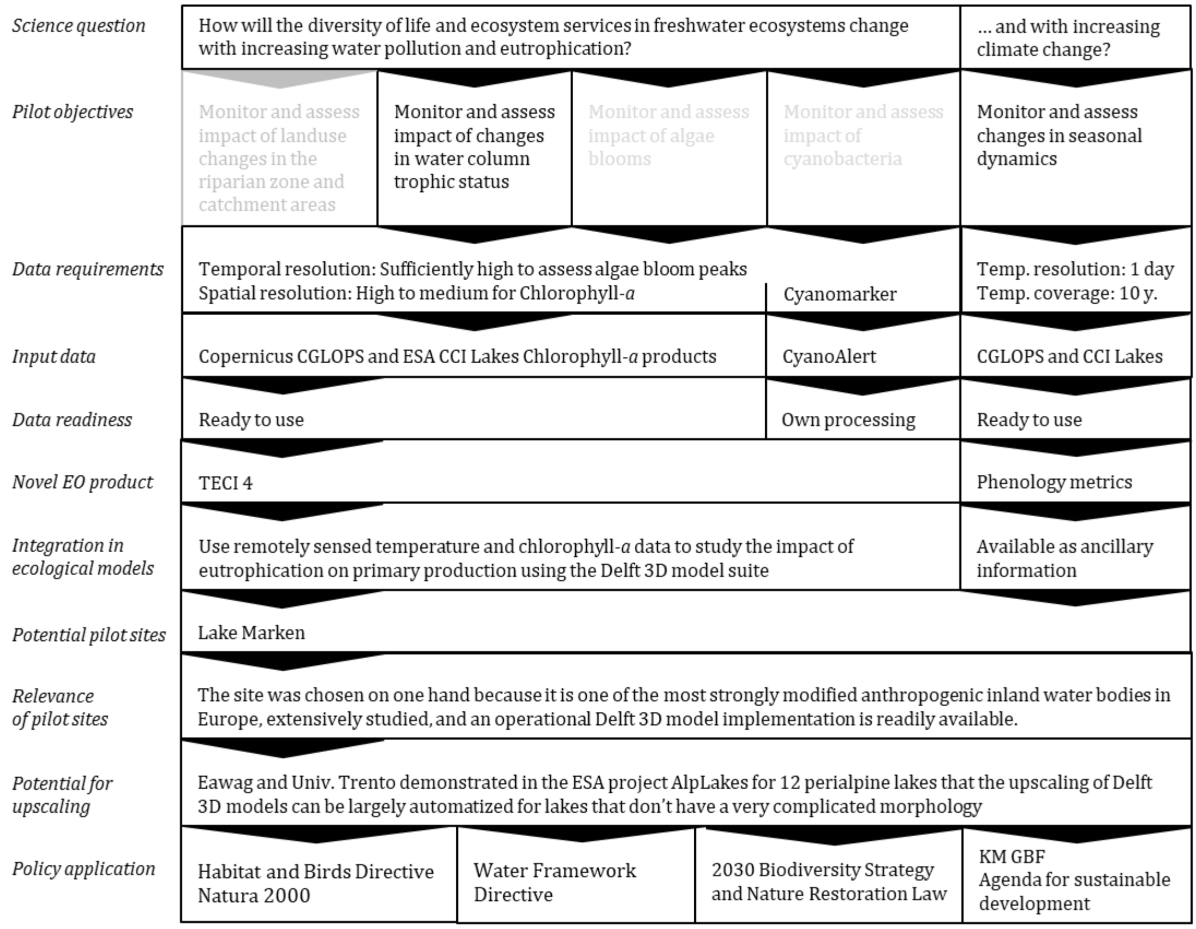

Figure 1 Graphical summary of the Science/Policy Traceability Matrix for pilot study 1 (modified from BIOMONDO WP1 SPTM).

1.3 Test sites

Pilot 1 was limited to Lake Marken as the sole test site, because the deployment of the corresponding models is relatively laborious and requires a high level of local adaptation. The description here is compiled from the BIOMONDO Requirements Baseline

(BIOMONDO_D1.1_RequirementsBaseline_v2.1.pdf) and Experimental Dataset (BIOMONDO_D2.4_ExperimentalDatasets_v1.0.pdf) reports.

1.3.1 Lake Marken

Lake Marken, or Markermeer, is a 680 km^2 large lake in the Netherlands. It is second in size to Lake IJssel, which lies between Lake Marken and the North Sea, and is separated from them only by dams. Lake Marken has an average depth of 3.6 meters and a maximum depth of 5 meters. It has an open connection to Lake Gooi and Lake Eem in the south, and it is connected by sluices to Lake IJssel and its main tributary, the river IJssel, which is a distributary of the Rhine River (Figure 2). Lake Marken and Lake IJssel are artificial freshwater lakes, which were created in a shallow bay of the North Sea, the Zuiderzee. Plans to turn Lake Marken into the Markerwaard polder were abandoned in 2003, and it has now become an ecological and recreational site on its own.

Lake Marken, Lake IJssel and their border lakes are all Ramsar and Natura 2000 sites. Owing to the way they were constructed, the lakes are “heavily modified” according to the definition of the Water Framework Directive (WFD). As with many freshwater lakes, the Markermeer-IJsselmeer system has unique biochemical properties that influence its ecological health and sustainability. The lakes are characterized by relatively high turbidity, high nutrient concentrations, and a complex food web that supports a diverse range of plant and animal species. While Markermeer and IJsselmeer share many similarities in terms of their physical and chemical properties, there are some notable biological differences between them. One key difference is the composition of the plankton community. Markermeer has been shown to have a higher abundance of small-sized phytoplankton compared to IJsselmeer, which tends to have a higher proportion of larger phytoplankton species (Noordhuis et al. 2014).

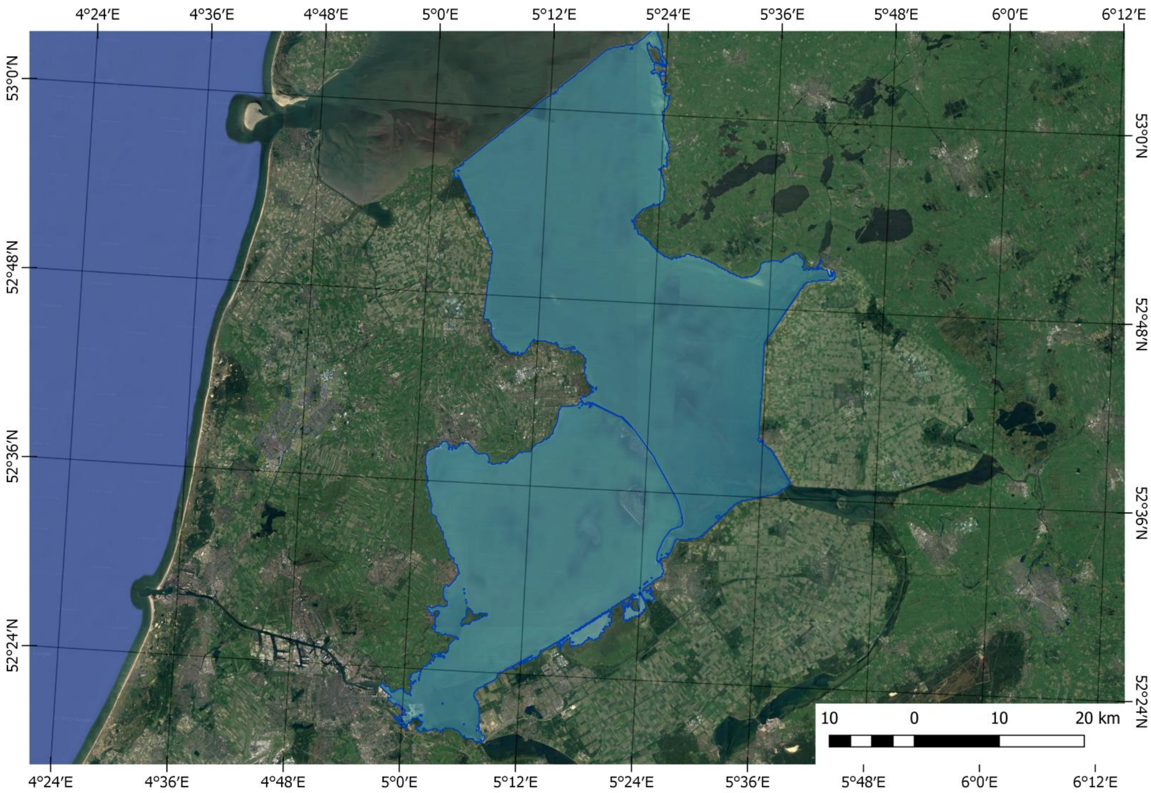

Figure 2 Pilot Site Lake Marken (bottom) and Lake Ijssel (top).

1.4 Methods

The Delft3D model developed by Deltares is a hydrodynamical-water quality model that calculates biogeochemical processes such as primary production and nutrient dynamics in a 3D spatio-temporal context (BIOMONDO D2.2 ATBD v2.1.docx). Different parameters are included to force the model and several of them originate from point based in situ measurements. In BIOMONDO, we have used the model to estimate chlorophyll-a and primary production for the years 2016 and 2020 using either, as originally implemented, in situ air temperature from the Dutch national weather service or, as explored in this pilot, EO based Lake Surface Water Temperature (LSWT) as forcing. In this way, we produced modelled data for Chlorophyll-a and Net Primary Production for the years 2016 and 2020. The different model outputs were then compared with each other, to EO data products of chlorophyll-a, and to in situ data of both chlorophyll-a and primary production.

The LSWT products used in the pilot are gap-filled CCI Lakes data. To comply with Pilot 1 and Pilot 2 needs, these were generated by running DINEOF (Data Interpolating Empirical Orthogonal Functions (Alvera-Azcárate et al., 2011) for the lake datasets, using quality levels 4 and 5 only, generating gap-filled daily LSWT products. Matchup comparison of DINEOF interpolated CCI LSWT with in situ bulk temperature measurements taken at max. 0.5 m depth in Lakes Mälaren and Marken agreed with biases < 0.5 ° and RMSEs between 1.14 and 1.29° (BIOMONDO_D2.3_PVR_v2.0.pdf). Given the selected test sites' size and dynamic range of more than 20°, we expect these product specifications to be fit for purpose. A submission of the gap filled daily LSWT products to the Pangaea data repository is in progress. LSWT data for the period of September 1999 to September 2020 were processed for Lake Marken.

1.5 Expert consultations

The main findings of BIOMONDO pilot 1 were discussed with various scientific and policy experts. Table 1provides an overview of the consultation meetings held for the assessment of the main findings.

Table 1 List of experts providing feedback on the main findings of pilot 1.

Name	Institution	Meeting dates
Marcel van den Berg	Rijkswaterstaat	26 Aug 2023
Ruurd Noordhuis	Deltares	26 Aug 2023
Lièn Klugkist	Deltares	26 Aug 2023
Advisory Board		
• María Vallejos	Univ. Buenos Aires	Maternity leave
• Erin Hestir	UC California, Merced	30 Aug 2023
• Lisa Rebelo	IWMI /DE Africa	30 Aug 2023
• Ole Seehausen	Univ. Bern	7 Sept 2023

2 Scientific impact

2.1 Main findings and contribution to current knowledge level

The EO products generated for and used in Pilot 1 comprise LSWT and chlorophyll-a concentration. In general, both parameters are of vital importance for any ecological study of lakes and can all be strong indicators of lake status and change. It was shown that the EO based chlorophyll concentrations were in line with the in-situ measurements, and the fact that the EO data is spatially and temporally continuous is then a strong improvement and complement to sparse in situ monitoring data and many more lakes can be covered. EO products, tailored to fit user needs and provided in analysis ready data format, have the potential to contribute to many research fields and serve as input to ecological models. In combination with a set of tools for easy access and visualisation of data, the scientific contribution and impact potential becomes impressive.

Pilot 1 focused on investigation of the effects of eutrophication on water quality using Lake Marken as a test site. The parameter in focus was primary production. Primary production allows us to investigate ecosystem functioning (which directly influences biodiversity) because it provides information on the carrying capacity within the lake. Delft3D model-based calculations of primary production were generally in line with the observations (in situ). The modelled primary production using either in situ air temperature or EO based LSWT as forcing was compared and different spatial, temporal and seasonal patterns could be seen. In general, the use of LSWT products as input into the Delft3D model generated a slightly smoother temporal variability in the primary production, which is realistic as the variability in water temperature exhibits less variation than air temperature. To describe in-water conditions, it is assumed that LSWT products provide better input for the hydrodynamic part of the Delft3D model than the in-situ temperature data because LSWT products capture spatial heterogeneity while in case the model is forced with in situ temperature, this is assumed to be the same anywhere in the lake. The two different forcing alternatives generated some temporal and spatial differences and shifted lows and highs when compared. Finally, a correlation analysis between in situ measured primary production data from 2020 and modelled primary production using either in situ air temperature (blue) or EO based LSWT (orange) as forcing was made and the result can be seen in Figure 3. The different approaches did not lead to major differences in modelled level of primary production even though a slight general improvement can be seen for the EO forced results. This is expected as primary production is not only dependent of temperature but also (and more important) on the availability of light and nutrients. Interestingly, these parameters, or at least proxies of these parameters, could also be derived from EO data and potentially serve as input to the model.

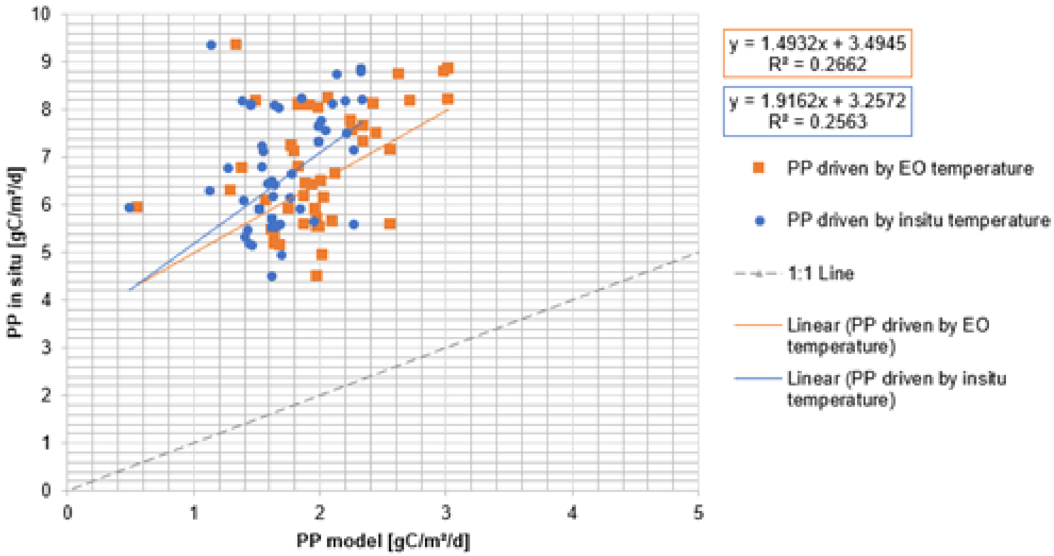

Figure 3 Comparison between in situ measured primary production and modelled primary production using either in situ air temperature (blue) or EO based LSWT (orange) as forcing.

Although chlorophyll-a and primary production are important parameters to understand biodiversity dynamics, they don't immediately show the effects on biodiversity, and in this case the diversity of phytoplankton. The advantage of EO products is that these data have full spatial coverage. However, distinguishing between species is not possible with these data. In situ data on the other hand are useful to make this distinguishment but they often lack the spatial component. Often, both methods also show gaps in time, although improvements have been made in recent years with online in situ sensors and satellites with a more frequent overpass time. Models, like the one used in this pilot, can spatially and temporally (e.g. daily) calculate several water quality and ecological parameters. The Delft3D model contains information on different phytoplankton species, allowing to see if changes in the diversity of phytoplankton occur. In Figure 4 below we show Delft3D hydro-dynamic-water quality coupled calculations for the green algae in green, diatoms in or-ange and one cyanobacterial species (*Microcystis*) in blue using the weather service's air temperature (upper graph) and remotely sensed LSWT (lower graph).

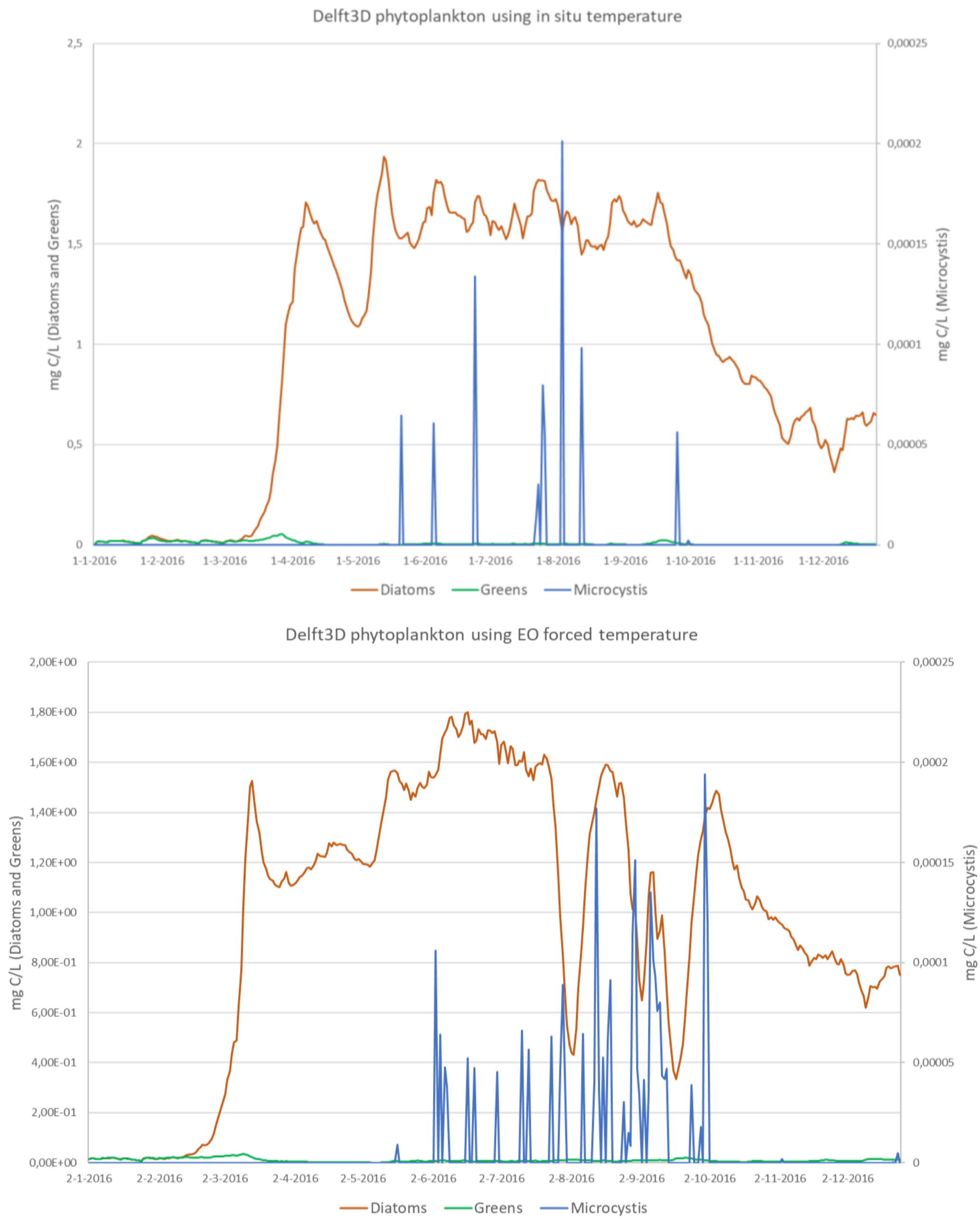

Figure 4 Delft3D calculations of different phytoplankton species for Lake Marken (location Zuid-Oost) in 2016 using either in situ (upper graph) or EO LSWT (lower graph) temperature.

Using temperature obtained from EO data as input into the model results in a stronger up and down dynamics in the phytoplankton calculations (compare for example the diatoms). This resembles the field situation better as algae groups tend to dominate and disappear during the year. For example, diatoms tend to bloom in early spring, disappear later in the year and then bloom again (Tõnno et al., 2016). The EO temperature forced scenarios also show more peaks of Microcystis than the *in-situ* temperature scenario. This looks more realistic because Microcystis does tend to prevail once it has been blooming and does not disappear quickly. In 2016, Microcystis was only found in August and September, so in both Delft3D calculations Microcystis tends to appear too soon (although the field campaigns have a frequency of once per month, so much information is lacking). Figure 4

2.2 Potential for large-scale application

Delft3D does not go beyond the phytoplankton when studying biodiversity. Other models can go further up the food chain of freshwater systems. Examples are PCLake and Ecopath (mostly applied in marine systems, Steenbeek et al., 2016). PCLake describes the relationships between biotic and abiotic factors in lakes (Janse, 2005). Originally, the model described a completely mixed water body with no vertical and horizontal water transport and thus meant for shallow, non-stratifying lakes (Janse, 2005). Later, a vertical dimension was added so that it could be applied to deep lakes as well. This vertical dimension comprises of an epi- and hypolimnion (Janssen et al., 2019). Food chain models usually lack a spatial component, i.e., the outcome is usually applicable to the whole ecosystem without showing the spatial variation within it. In the last years however, models such as PCLake, PISCES, SELMA and DEB have been coupled to hydrodynamic models within the Framework for Aquatic Biogeochemical Models (FABM, 2023) to allow for 3D calculations (Hu et al., 2016).

Future developments would include the coupling of Delft3D and a food chain model to provide insights into biodiversity of organisms higher in the food chain in a spatially explicit way. Delft3D would provide data on hydrodynamics, nutrients and primary production to the food chain model, allowing for insights into the spatial heterogeneity of for example macrophytes, fish and birds. A future EO product for macrophytes would allow either a direct input into the food chain model or validation of it.

Another development to be considered for the future is the use of Flexible Mesh (Mogé et al., 2019). With FM we are capable of handling curvilinear grids that provide very good performance in terms of computational speed and accuracy. In addition to this, the grid may also consist of triangles, quads, pentagons, and hexagons. This provides optimal modelling flexibility and ease in setting up new model grids or modifying existing ones, or locally increasing resolution. This is therefore very useful to apply to water systems with islands since water flow can now more accurately be calculated.

During the user consultation it was mentioned that the EO spatial resolution is too coarse for Lake Marken (and IJsselmeer). The users hope that in the future Sentinel-2 data will be used. Wind as EO product was also discussed since wind drives algae dynamics in the lake. The current EO product for wind is not accurate, instead the approach of EAWAG to use hindcast meteo data would be more feasible (see below). EAWAG also uses Delft3D in certain freshwater studies. The operational Delft 3D model for physical processes in Lake Geneva was initially deployed in 2016 (Baracchini et al., 2020). In subsequent years, analogous, manual implementations of Delft 3D were added for other large lakes in Switzerland, namely Lake Biel, Greifensee and Lake Zurich. In parallel a MITgcm model was implemented for Lake Geneva, for comparisons with the Delft 3D model (Datalakes project, 2023). In 2021-2023, the AlpLakes project funded by ESA allowed Eawag, CNR and the University of Trento to develop an automatic optimization for some of Delft 3D's model parameters, strongly reducing the time needed for model deployment. In doing so, we also revised the vertical heat dissipation by Delft 3D, to effectively use Sentinel-2 estimated Secchi depth products as near-real time simulation input. The AlpLakes operational web platform offers tracking the dominant water pathways with particle tracking tools, which, for example, can be used for hindcasting and forecasting of observed algae bloom patterns. The approach was tested for 12 large, perialpine lakes (AlpLakes project, 2023), and a publication on the hydrodynamic modelling process is in preparation. With this work, we have strongly reduced the scaling effort required for 3D hydrodynamic modelling, to efforts in the order of weeks per lake. Accurate bathymetry and meteorological data remain a strict requirement for model adaptation, and a high level of expertise is required, for increasingly complex basin morphologies. The most important limitation is however that our upscaling efforts have not yet addressed biological processes, which come with significant additional challenges.

In BIOMONDO we tried to use EO LSWT products to investigate if this would lead to different water quality model outcomes. Future activities could include the use of EO derived chlorophyll-a products as a direct input into the model. The model would be forced with spatial explicit chlorophyll-a data, instead of using point location data (with the consequence that this concentration applies to the whole water body). The model in turn would fill up gaps between satellite overpasses and it could be used for scenario analyses. This data assimilation has been tried in the FP7 project CoBiOS (focussing on Kd; CORDIS, 2023).

3 Policy impact

3.1 Relevant policy goals and targets

Water is essential for natural ecosystems and the interlinkages between water, energy, food and health are highlighted by recent nexus initiatives (e.g., Water-biodiversity, Water-Energy-Food, Climate-Biodiversity-Health). The availability of acceptable freshwater quantities and qualities vary substantially across the globe. Uneven patterns of supply and rising water-stress from climate change is impacting food security and biodiversity. Global, regional and national policies and strategies have for quite some time had specific goals for freshwater, especially in relation to the ecosystem services provided such as safe drinking water and sanitation (Goal 6 of the 2030 Agenda for Sustainable Development, see 3.1.5).

From a policy perspective Pilot 1 results and products are relevant for the support of several strategies and monitoring frameworks, with goals and targets to halt and reverse the loss of biodiversity and to move towards sustainable use of water. The relevant European policy frameworks as identified in the Pilot 1 SPTM are the EU Nature Directives (Habitat and Birds, with Natura2000, EC 2017), the WFD (EC, 2014) and the EU 2030 Biodiversity Strategy (EC, 2021). On a global level the results have potential to support the development of indicators for the targets of the 2030 Sustainable Development Agenda (UN GA, 2015) and the KM-GBF (CBD, 2022a and b), as well as improving data for Ramsar site assessments and monitoring.

Comprehensive, objective, continuous in space and time and scale independent information to monitor progress towards biodiversity targets and goals are lacking in many areas including freshwaters (BIOMONDO_RequirementsBaseline_v2.1.docx). The focus of Pilot 1 has been to derive EO based products and to test Delft3D integration. The results showed the potential for improvements to hydrodynamical-water quality modelling (section 1.3 and 2.1) by including different EO based information to force modelling.

In the following sections (3.1.1 to 3.1.5), the main policies and strategies relevant to Pilot 1 are summarised and can be viewed as an update to the descriptions in the BIOMONDO Requirements baseline document. Section 3.3 outlines a show case with examples of relevant results. In section 3.4 the potential policy utility and impact of the Pilot 1 results are assessed and described in relation to the added value for related biodiversity strategies and monitoring frameworks. It focuses on the usefulness for current policies and describes how the products and results can be used by managers for decision making including the potential for development of indicators.

3.1.1 Nature Directives – Habitat (and Birds) directives and N2000

According to the Natura 2000 website (European Commission, 2021):

"Natura 2000 sites are selected with the aim of ensuring the long-term survival of species and habitats protected under the Birds and the Habitats Directive.

Natura 2000 sites have been designated specifically to protect core areas for a sub-set of species or habitat types listed in the Habitats and Birds Directives. They are deemed to be of European importance because they are endangered, vulnerable, rare, endemic or *present outstanding examples of typical characteristics of one or more of Europe's nine biogeographical regions. In total, there are around 2000 species and 230 habitat types for which core sites need to be designated as Natura 2000 sites."*

The Markermeer & IJmeer Natura 2000 area has been designated based on habitat types and Habitats Directive species, including breeding and non-breeding bird species. Detailed information is included in the Natura 2000 factsheet, Goal/Habitat types, Habitat Directive species for the Markermeer & Ijmeer site (Natura 2000 in the Netherlands, 2023). The boundary of the Ramsar site Markermeer / IJmeer is equal to the Natura 2000-site with the same name. In 2014 the two separate Ramsar Sites IJmeer and Markermeer were merged into a single site within the Natura 2000 boundary, increasing its area by 131 ha.

The establishment of the Marker Wadden islands has created new habitat for migrating birds of which some are listed as vulnerable in the EU Birds directive and highlighted as being important for improving the ecological character and boosting the biodiversity of the Ramsar site.
As already mentioned above, EO data representing transparency can potentially be used to monitor the effects on the lake ecosystems from the mitigation measures employed (Marker Wadden, see sections 1.1 and 3.3).

3.1.2 Water Framework Directive (WFD)

According to the Water Framework Directive (WFD; EC, 2014):

"Waters must achieve good ecological and chemical status, to protect human health, water supply, natural ecosystems and biodiversity."

The Water Framework Directive (WFD), adopted and implemented in 2000, is the main EU directive for member states reporting on the ecological condition of European surface and ground waters. The objective of WFD is to establish a framework to protect surface water and contribute to the provision of the sufficient supply of good quality surface water and groundwater as needed for sustainable, balanced and equitable water use.

The WFD is based on the natural river basin approach to manage water and to improve the chemical and ecological status. The abundance of aquatic flora and fish fauna, the availability of nutrients, and aspects like salinity, temperature and pollution by chemical pollutants and excess nutrients defines the ecological status. Morphological features, such as quantity, water flow, water depths and structures of the riverbeds, are also considered. Surface water status is assessed using biological quality factors such as composition, abundance (and biomass) of phytoplankton and other aquatic flora, benthic invertebrate and fish fauna.

Chlorophyll-a is one of the parameters used to assess the status related to 'Phytoplankton' and EO based chlorophyll-a products are already used in several countries to support the classification. Chlorophyll-a is also included in the EO product suite of BIOMONDO for Pilot 1.

Different indices are used in different countries, and many were initially developed to reflect effects of eutrophication. This is further discussed in section 3.4, which includes some feedback from the expert consultations. In addition to the biological quality factors, the following general physical-chemical quality factors are included in the WFD assessment:

- Transparency
- Thermal conditions
- Oxygenation conditions
- Salinity
- Acidification status
- Nutrient conditions

As mentioned in section 1.3.1 the test site Lake Marken is “heavily modified” according to the definition of the WFD. It has unique biochemical properties that influence its ecological health and sustainability. The ecological status (ecological potential) as reported in the 2nd River Basin Management plan, 2016 (European Environment Agency, 2023), is classified as “Moderate”, whereas the chemical status is “Failing to achieve good”. The objective of the WFD is to ensure that measures are put in place to facilitate also for heavily modified surface waters to achieve “Good” status. Mitigation measures employed at Lake Marken (Marker Wadden) are hoped to improve both the water quality, nutrient and light conditions and in extension the biodiversity of the lake.

3.1.3 EU 2030 Biodiversity strategy

Excess nutrient run off to inland waters and the sea can cause or exacerbate eutrophication and algal blooms, which can be toxic to organisms and impact biodiversity in freshwater ecosystems.

The EU 2030 Biodiversity Strategy (EC, 2021) emphasises the importance of work to reduce causes of eutrophication and to apply suitable mitigation measures:

“The Commission will increase ongoing policy implementation and enforcement efforts in order to reduce by at least 50% nutrient losses from nitrogen and phosphorus fertilisers, while ensuring that there is no deterioration in soil fertility. The aim is to reduce nutrient pollution to amounts within safe planetary boundaries, in line with the targets set by the EU Biodiversity Strategy for 2030, the Farm to Fork Strategy and the Zero Pollution Action Plan.”

The Pilot 1 products and results can support the targets of the “Pillar 1, Protect Nature” and “Pillar 2, Restore Nature”. Specifically, Target 13, of the Nature Restoration Plan, stipulates that “The losses of nutrients from fertilisers are reduced by 50%, resulting in the reduction of the use of fertilisers by at least 20%”. In addition, Target 3, “Effectively manage all protected areas, defining clear conservation objectives and measures, and monitoring them appropriately”, can be seen as highly relevant as it stresses the need for monitoring of applied management efforts. Indicators for the targets are under development.

EU policy needs in the biodiversity domain were analysed by the KCEO Deep dive called Earth Observation in Support of EU Policies for Biodiversity with the aim to verify how and to what extent existing EO products and services meet these needs, highlight existing gaps and provide recommendations on future evolution (Camia et al. 2023). Suggested improvements included more regular and frequent updates of existing products, longer and consistent time series, and refining of aggregated land cover classes for the mapping of ecosystem types to be able to drive the assessment of habitats and ecosystem condition. Satellite observation requirements and current availability of dataset and future needs to address the targets and indicators of the EU Biodiversity Strategy are provided in a list in an annexed Excel-file. For most targets and indicators there is only a “partial match”, which means that there is scope for further development, especially since the temporal resolution of available EO products often do not match user requirements. We believe that the results of the BIOMONDO pilots can contribute as they provide improvement to the temporal and spatial resolution of the needed products.

3.1.4 Kunming-Montreal Global Biodiversity Framework

The aim of the Kunming-Montreal Global Biodiversity Framework (KM-GBF) with its developing monitoring framework of targets and indicators is to halt and reverse the loss of biodiversity, sustain water-related ecosystem services, and support SDG 6 and the other Sustainable Development Goals. The KM-GBF is recognising Inland Waters as a realm of its own in addition to terrestrial, coastal and marine ecosystems. The final KM-GBF includes four goals for 2050 that are supported by 23 targets, which aim to be completed by 2030. The aim of Goal A and some of its targets and headline indicators are of most relevance to Pilot 1. The first eight targets aim specifically at reducing threats to biodiversity.

In August 2023, guidance notes for each of the 2030 Targets were published (Convention on Biological Diversity, 2023) and will be updated periodically. The main purpose of the material is to provide an overview of each target and to serve as a resource for national target setting exercises and highlighting implications as well as identifying adopted indicators to monitor progress.

Several targets relate to Pilot 1 - eutrophication. Target 7 requires reduction to pollution risks by for example by reducing excess nutrients lost to the environment by at least half, including through more efficient nutrient cycling and use (7a). In addition, target 2 stipulates that by 2030, 30 % of degraded ecosystems in each realm are under effective restoration and Target 3 that by 2030, at least 30% of all ecosystems in each realm are effectively conserved and managed.

A review of the KM-GBF to identify indicators to track the state of terrestrial biodiversity show innovation potential for satellite remote sensing (Timmermans & Kissling, 2023). This indicates that also the results of the BIOMONDO pilots could contribute in a similar way to freshwater biodiversity monitoring by providing data to feed into biodiversity indicators.

3.1.5 2030 Agenda for Sustainable Development and Ramsar convention

Several of the goals of the 2030 Agenda for Sustainable Development with its 15 goals (SDGs) need better information for the target indicators to track progress towards sustainability. As already mentioned above the main relevant water related goal is SDG 6 - Clean water and sanitation. The SDG 6 Synthesis Report 2023 is a blueprint for building action plans to accelerate progress on water and sanitation (Water Action Agenda, United Nations, 2023). The report is a concise guide to delivering concrete results – offering actionable policy recommendations to get the world on track to achieve SDG 6: to ensure availability and sustainable management of water and sanitation for all by 2030.

The report is divided into five sections to help the acceleration framework based on the obstacles blocking progress, of which one is data and information, or rather, “Not enough data”. In too many countries, policymakers lack credible and timely data for decision-making due to inadequate monitoring and reporting, and insufficient resources. To accelerate progress and to fill this gap it is pointed out that “Earth observation technologies and improved data practices, such as standardization and disaggregation, can enhance decision making and reduce inequalities”.

The SDG Indicator 6.6.1 Change in the extent of water-related ecosystems over time has two custodian agencies, UNEP and Ramsar Secretariat. Currently a 2023 revision of the SDG 6.6.1 EO support Sheet is undertaken, coordinated by CEOS, see also discussion in section 3.4.

When it comes to the Pilot 1 results and the potential for using EO to monitor effects of the mitigation efforts like the establishment of the Marker Wadden Island, the SDG goals 6, 9, 12, 13 14 and 15 are concerned (Knowledge and Innovation Programme Marker Wadden, 2023).

3.1.6 The EBV cube – the link between biodiversity observations and biodiversity change

The Essential Biodiversity Variables (EBVs) are defined as the derived measurements required to study, report, and manage biodiversity change, focusing on status and trend in elements of biodiversity, and should play the role of brokers between monitoring initiatives and decision makers. They provide the first level of abstraction between low-level primary observations and high-level indicators of biodiversity change that different policies require for assessments of status and monitoring of effects of and responses to different management decisions (GEO BON, 2023). For example, the EBV class “Ecosystem functioning” has three EBVs that are described as follows:

- Primary productivity - The rate at which energy is transformed into organic matter primarily through photosynthesis.
- Ecosystem phenology - Duration and magnitude of cyclic processes observed at the ecosystem level, such as in vegetation activity, phytoplankton blooms, etc.
- Ecosystem disturbances - Abrupt deviances in the functioning of the ecosystem from its regular dynamics.

Primary productivity is an EBV for which Pilot 1 can contribute enhanced information through the combination of EO data and hydro-dynamic water quality modelling.

3.2 BIOMONDO Experimental dataset

The datasets available for building show cases and methods for viewing the data and products stored in the BIOMONDO Freshwater Laboratory are introduced below and in BIOMONDO_D2.4_ExperimentalDatasets_v1.0.pdf.

For Pilot 1, the experimental datasets presented and discussed with the Early Adopters consist of:

- Lake Surface Water Temperature from EO
- Turbidity and chlorophyll-a concentration from EO
- Modelled biological parameters – EO and in situ forced
- Modelled warming tolerance of occurring species per lake
- Water quality parameters and temperature from in situ measurements

All produced EO based and modelled datasets have been included in the BIOMONDO Freshwater Lab. The lab allows the user to work with and combine different information sources to analyse and compare model output with observations made in-situ or by Earth Observation. The central part of the BIOMONDO Freshwater Laboratory is the BIOMONDO Viewer and its functionalities. The Viewer enables easy access, visualization of and to work with the experimental datasets, and it was essential for the demonstration and consultation sessions. The Viewer also serves as good demonstration and show case of how the results and outputs of the ESS Pilots could be integrated into decision systems on the management side, either as external web-based tool or by integrating data in the organisations existing systems. Figure 5 shows the Viewer and gives an example of the chlorophyll-a from Delft3D Biological EO forced dataset for Lake Marken. Such time series can be generated and analysed for any location (orange and red dots) or region defined by the user.

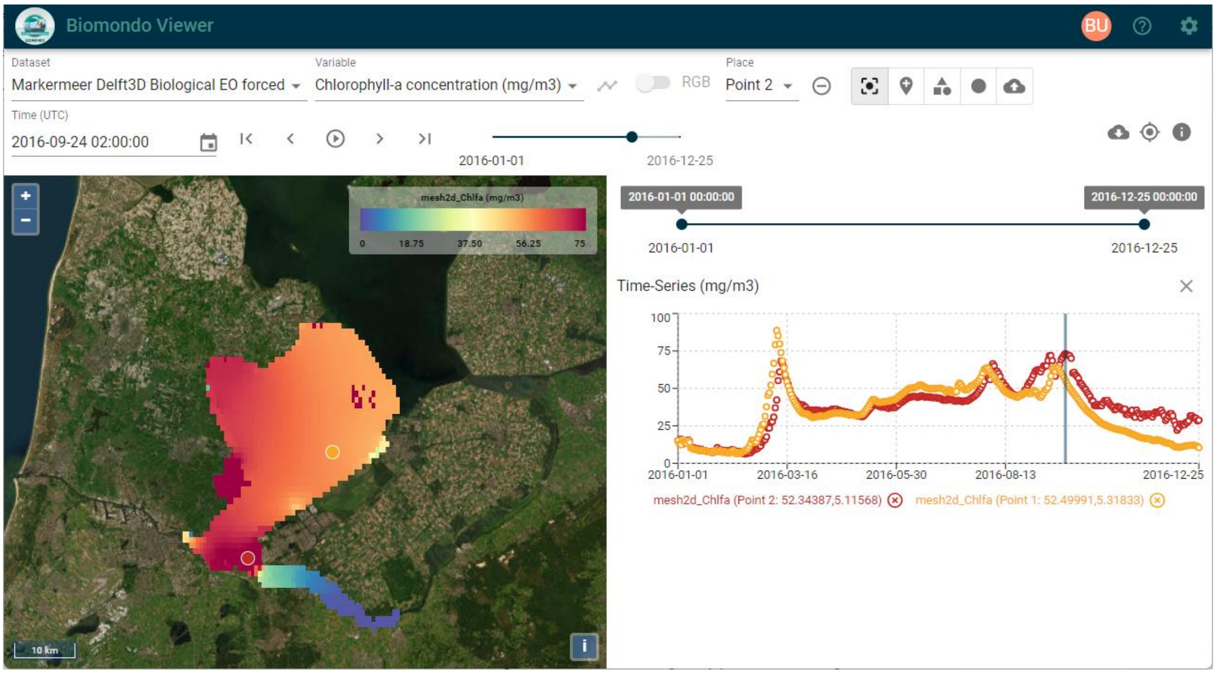

Figure 5 BIOMONDO Viewer showing chlorophyll-a from Delft3D Biological EO forced dataset for 2016-09-24.

In addition, thematic ecosystem change indices (TECIs) that provide information on the extent and intensity of changes in ecosystems has been developed and demonstrated to the Early Adopters. The developed TECIs for Pilot 1 are based on the analysis of the EO datasets listed above and are designed to capture land use or water quality changes. TECIs can support the interpretation of big datasets and provide valuable information for understanding the drivers and impacts of ecosystem change. Figure 6 shows an example for the Lake Marken data described above. The summers of 2006, 2018 and 2020 correspond to higher TECI scores compared to the other years, indicating high probabilities that these years have higher certainties of anomalies and also that lake surface temperature is a main contributor to the higher TECI score.

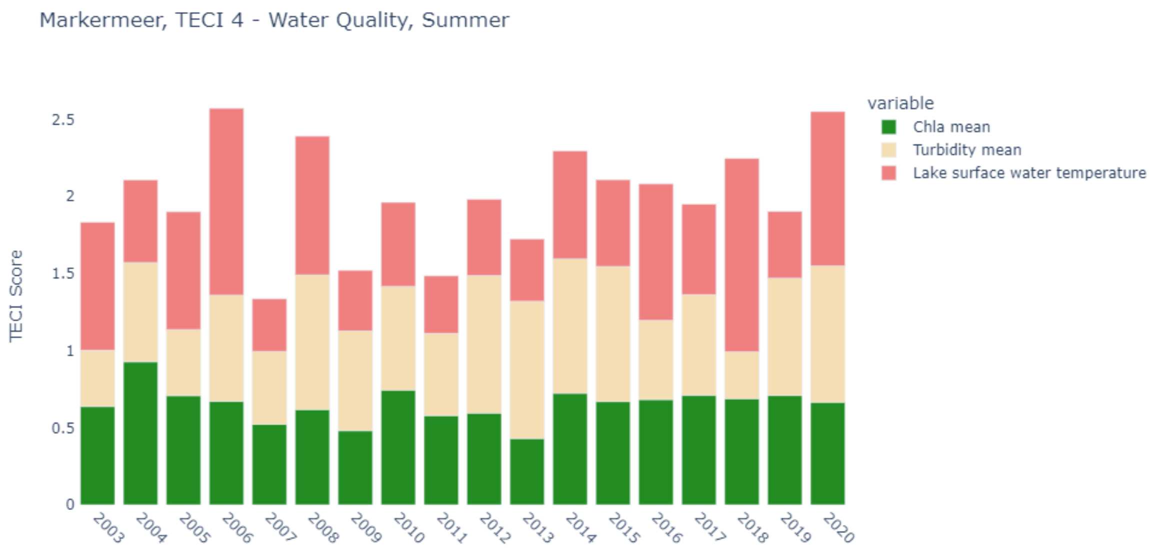

Figure 6 Score of TECI 4 – Water Quality for summer months, Lake Marken.

The experimental datasets, the EO based products and TECI examples were presented in consultation meetings (see Table 1) to discuss and assess the impact and utility for policy in general and to inform the showcase presented in section 3.3 below.

3.3 Pilot 1 Show case – Monitoring effects of mitigation measures

This show case exploits the potential of the experimental data developed for Pilot 1 and the ability to address policy priorities related to drivers of biodiversity change including effects of mitigation measures, both positive and negative. The show case has been developed in collaboration with the Early Adopters from Deltares and Rijkswaterstaat and have included detailed presentation of the pilot results and discussion about how these products can support relevant policy priorities and be integrated in decision support systems. The show case demonstrates the potential usefulness and practical application of the Pilot work and results to provide improved input data to monitor effects of mitigation measures, e.g. Marker Wadden project, which has as a goal to halt biodiversity loss and boost biodiversity of the site and improve water quality.

3.3.1 Policy context and information needs

The EU Nature Directives (Habitat and Birds) require appropriate management of protected areas and the WFD calls for measures to be put in place to improve the ecological status of European freshwater bodies. In addition, the EU Biodiversity Strategy and its Nature Restoration Law requires mitigation actions to be put in place to improve aspects of protected areas to maintain and improve biodiversity.

An example of such measures is the large-scale restoration project Marker Wadden project (see also section 1.1). Sand, clay and silt from Lake Marken were used to create an archipelago of 10,000 ha consisting of islands, marshes and mud flats. The aim was to improve water quality by increasing the water transparency and ecological status as well as to boost the biodiversity, by reducing wind impact and provide sheltered areas at island edges and rifts for wintering birds and fish spawning grounds and nurseries, which in turn provide food for the migrating birds. Research shows that a huge number of birds have discovered the nature of Marker Wadden, that insects are abundant, and that the underwater life is extremely varied (Dutch Society for Nature Conservation, 2023). This is relevant for the objectives of the Habitat and Birds directives but also as an example of using Nature-based solutions (NbS).

'There is global recognition that Nature-based Solutions can protect, manage, and restore natural or modified ecosystems, as well as providing human well-being and biodiversity benefits. However, there is still a lack of NbS projects being implemented at scale. Marker Wadden is considered as an iconic example of such large-scale Nature-based Solution, and its lessons can be of great value for scaling up efforts globally.' (Quote from EcoShape director Stefan Aarninkhof at KIMA 2022 conference; Rijkswaterstaat, 2022).

The early adopter, RWS, is responsible for the Natura 2000 management plans of national waters and the achievement of the Natura 2000 objectives. In addition, RWS is running the monitoring programs for evaluation of the different policies. RWS has also been the organization that was responsible for the first monitoring program of the Marker Wadden (KIMA).

The policy goals of the Marker Wadden project were threefold:

1. Improving the ecological qualities and recreational uses of Lake Marken and thereby contributing to a Future Proof Ecological System (FPES)
2. Developing a bird paradise with optimal contribution to the Natura 2000 objectives for Lake Marken and the Netherlands
3. Learning, monitoring effects, and innovating

In 2023, KIMA 2.0 started under the lead by Deltares. The focus will be on lessons and questions related to the functioning of Marker Wadden as an engine for sustainable development of the entire Lake Marken and the sustainable conservation of the Marker Wadden, both in a physical sense and in terms of natural values. The interaction between the ecological processes that take place on the islands, in the underwater landscape between the islands and the lake around Marker Wadden are therefore the centre for attention. The aim is to gain more insight into the food and silt flows between Marker Wadden and the surrounding area, the role of water level regimes in the development of a robust and climate-adaptive reed marsh, and to draw up an action perspective for the maintenance of the islands. Field monitoring will be integrated with modelling and experimental research using developed methods and experiences at KIMA1.0. For more information about KIMA 2.0, please visit KIMA2.0: Met Marker Wadden naar een robuust en klimaatadaptief Markermeer – TKI Delta technologie.

3.3.2 Lake Marken's Biodiversity Revival: The Role of Marker Wadden in nature restoration of a man-made lake

The Pilot 1 show case address the potential use of EO derived products that can complement in situ monitoring efforts and provide temporal and spatially continuous information on the effects of Marker Wadden project on both water quality in the vicinity of the new islands and in the entire Lake Marken. The main EO derived product to illustrate this potential is turbidity but also chlorophyll-a and suspended particulate matter (SPM) can be used as they in combination affect the light climate and thereby the potential for different species (e.g. phytoplankton, macrophytes and fish) to increase in both diversity and in abundance.

We can show that overall patterns of turbidity in Lake Marken change after the restoration activities, especially southwest of the Marker Wadden islands. However, detailed patterns need to be evaluated over time and seasonal patterns investigated as wind direction and speed has a strong influence on turbidity because of the relative shallowness of Lake Marken. The ratio of chlorophyll-a to SPM (chl/SPM) is also important. If the decrease of chlorophyll is not as strong as the decrease of total suspended matter (chl/spm ratio increased), this would suggest better food quality of suspended matter to filter feeders on the next level in the foodweb (de Rijk et al., 2022).

EO before mitigation project

Lake Marken is a man-made lake created in 1975 due to its separation from Lake IJsselmeer by a dam (Houtribdijk). The damming and regulation of the water level prevented the lake from developing in a natural way. For example, it does not have flood plains because the dikes create an abrupt transition from land to water (Lammens et al. 2008). The lake is very shallow and strong winds during the autumn period lead to resuspension of material form the bottom of the lake. This resuspension is partly responsible for the poor visibility in the lake, next to modifications in phytoplankton species composition due to oligotrophication (i.e. smaller phytoplankton cells that are more evenly spread over the water column). This shift in phytoplankton composition led to dominance of algae that have a lower food quality and therefore the carrying capacity of the lake for birds and fish dropped (Noordhuis et al. 2014).

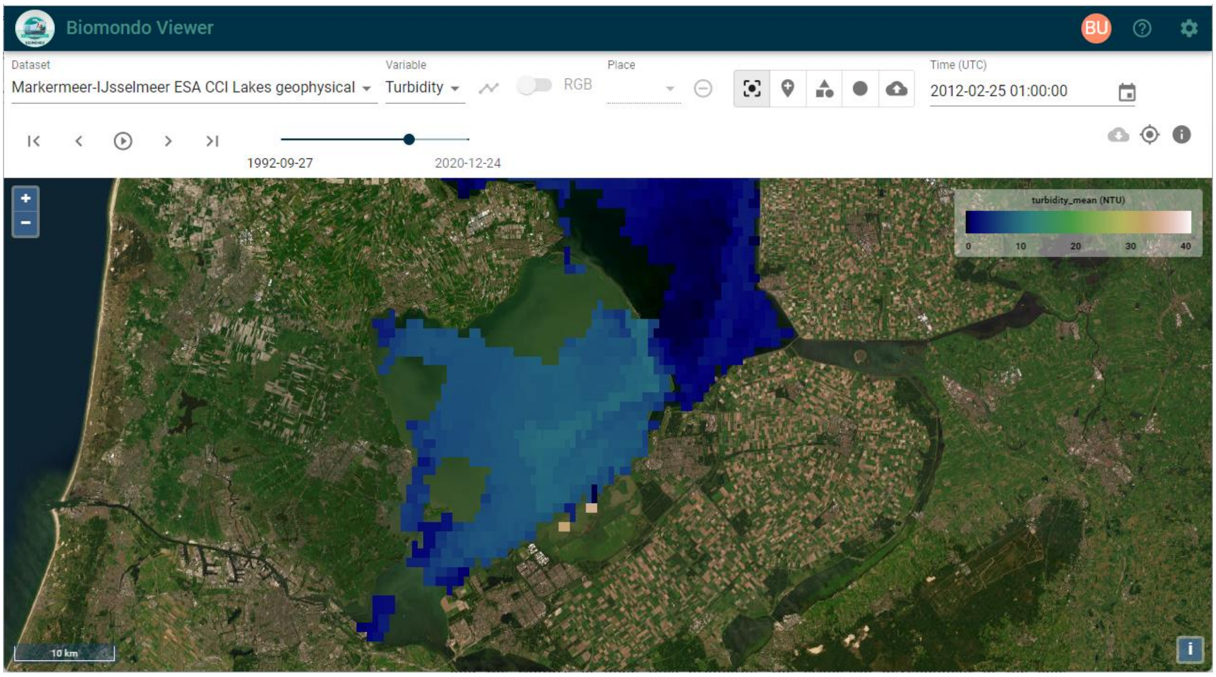

Figure 7 Image from the BIOMONDO Viewer showing spatial turbidity variations in 2012-02-25 in the Lake Marken **before** the establishment of the Marker Wadden islands.

Mitigation - activities

Marker Wadden has been constructed to reduce the turbidity of Lake Marken by sheltering and capturing mud, thus promoting the ecological development of the lake (Noordhuis et al., 2023). As described above, extensive efforts were made to establish the five main islands of the Marker Wadden (Figure 8).


Figure 8 Left: Aerial photo of the early stages of the establishment of the Marker Wadden islands (September 2016, credit: Peter Leenen/Straystone Pictures, from Irwin, 2023). Right: Aerial photo of the results of the establishment of the Marker Wadden islands in 2023 (credit: Robbert Frank Hagens/Alamy, from Irwin, 2023).

In the spring of 2016 effects of the dredging activities related to the initial stages of the establishment of the Marker Wadden islands can be seen in the EO turbidity product as lighter plumes southwest of the works (Figure 9).

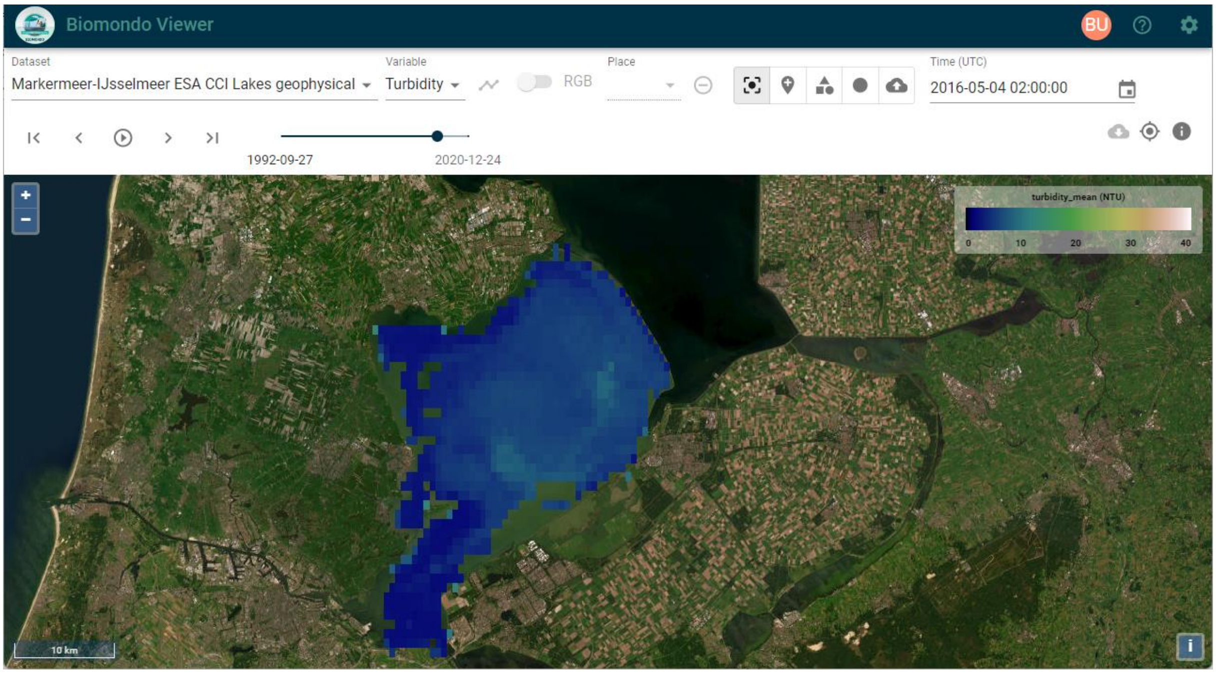

Figure 9 Image from the BIOMONDO Viewer showing spatial turbidity variations 2016-05-04 in the Lake Marken **during** the establishment of the Marker Wadden islands. Plumes from dredging activities are clearly visible.

EO after mitigation project

The KIMA programme was completed in 2022 and the results summarised in a synthesis report (de Rijk et al. 2022). Influence of the Marker Wadden on the mud fluxes (and turbidity) in Lake Marken has been determined through a combination of measuring and modelling. A small but permanent decrease in turbidity by the capture of mud by the islands has been established.

A satellite image of turbidity from 2021 (Figure 10) shows a different pattern with lower values in the area southwest of the Marker Wadden islands. This can be compared to 2012 (Figure 7) before mitigation activities and 2016 (Figure 9) during mitigation activities.

To support KIMA 2.0 and ongoing monitoring relevant to Natura2000 and Ramsar as well as the WFD status assessments, spatially and temporally continuous EO based products for turbidity derived for Pilot 1 could provide valuable and useful information to assess fluctuation and patterns, both over the years and over seasons.

Such products also have potential to aid in the development of indicators of biodiversity change related to climate change impacts on habitats that are relevant for the European and global monitoring frameworks like the EU 2030 Biodiversity Strategy and KM-GBF.

In 2023, the developments at the Marker Wadden went from the construction to the management phase (both in terms of physics and natural values). Within KIMA 2.0 the following research questions will therefore be addressed:

1. How can management and future constructions be performed effectively to initiate and optimize food flows (nutrients such as carbon and phosphate or distribution of organisms such as fish) between Marker Wadden and the surrounding area?

2. How can silt be used for the management and maintenance of land-water transitions in a sustainable way, considering vegetation succession, nature objectives and the food flows between Marker Wadden and the surrounding area?
3. What is the effect of different water level variants and the management of the islands on the development of a robust reed marsh?

For exchange of food flows and the maintenance of a robust reed marsh, the water level, especially the dynamics of the water level in the lake, is decisive. Currently, the high production on the islands is not yet clearly exploited outside the archipelago. Currently, there is no identifiable food flow such as juvenile fish production within the islands after which it enters the lake, which in turn contributes to the food supply of the islands' breeding birds (question 1). The formation of a flow of nutrients from the reed marshes to the lake also depends on the details of management and maintenance (question 2) and water level dynamics (question 3). Both the extent to which reed marshes can develop, cyclical control with water levels where compartments (i.e. water bodies within the islands) can be temporarily closed, and the development of aquatic plant fields and their spatial coherence determine biological production and the extent to which it can radiate out on a larger scale around the islands.

Monitoring will be an important activity within KIMA 2.0. Its action plan mentions that the following parameters in the water will be monitored: Water currents, suspended solids, nutrients (N and P), phytoplankton, zooplankton, fish, macro-invertebrates and macrophytes.

KIMA 2.0 will mainly focus on what is happening in and directly around the archipelago, but the WFD and Natura2000 goals will still be applicable to the whole lake. As such, continuation of collecting data lake wide will remain valuable and therefore EO data on the parameters PP, chlorophyll-a, LSWT etc should be provided in the future.

KIMA 2.0 wants to investigate the interaction between water level dynamics and vegetation development (see KIMA questions above). The expansion (or reduction) of reed could be visualized using satellite images which, in relation to in situ investigation of the same, could save much time. Also, from satellite images water levels could be retrieved and directly coupled to the vegetation data to investigate its interaction. EO water level data could also be used as validation for the Delft3D hydrodynamics module.

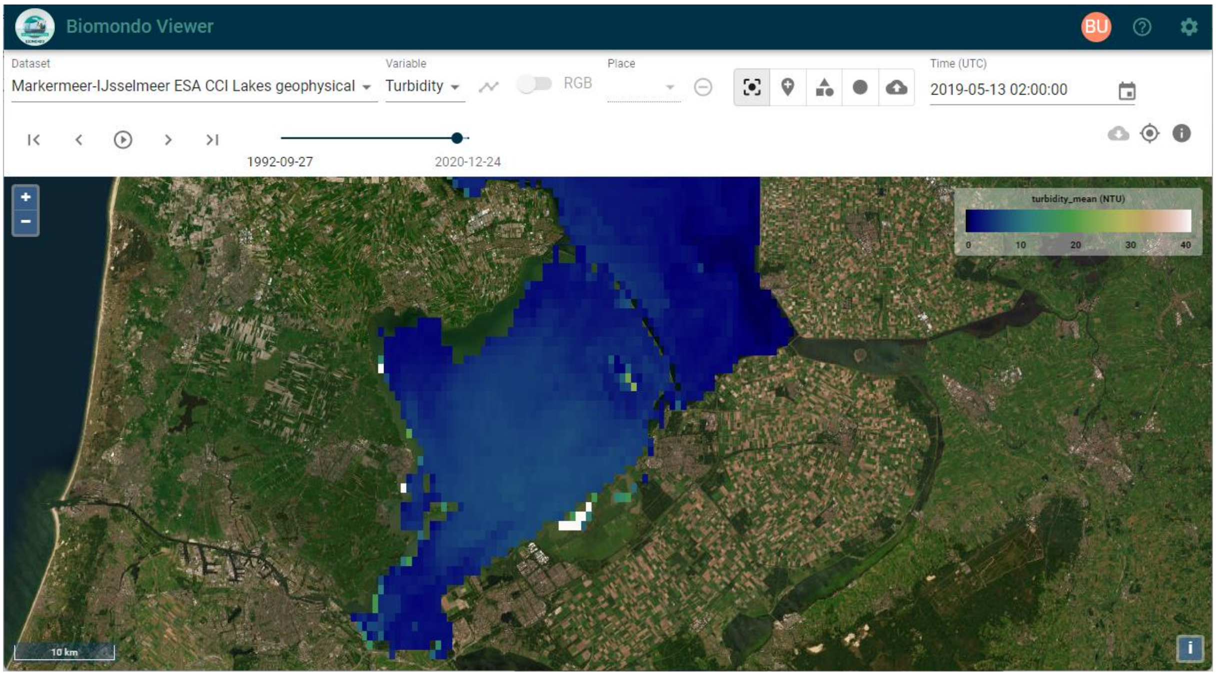

Figure 10 Image from the BIOMONDO Viewer showing spatial turbidity variations 2019-05-13 in the Lake Marken **after** the establishment of the Marker Wadden islands.

One of the goals of the Marker Wadden project has been to improve the water quality, especially to decrease the turbidity as high levels are associated with poor conditions for many fish species and macrophytes. An improvement has been noted along the shores of the islands, but more research and monitoring are needed to know whether this is happening on a larger scale. However, the synthesis report (De Rijk et al. 2022) describes several aspects that indicate the success of the project so far. Within the islands major contributions to biodiversity have been achieved. Fish spawn in the shallower areas, partly protected by the macrophytes in the different water basins that also contain much zooplankton (Irwin, 2023). The islands also provided new nesting sites for several bird species such as terns, sea gulls and duck species (47 nesting species in 2021, Irwin (2023)).

3.4 Assessment of policy utility and impact

Hydrodynamic modelling is an essential method to study scenarios for hydro-environmental problems, such as pollutant water discharges, sediment transport and lake eutrophication. The performance and reliability of such modelling, including the Delft3D suite, are dependent on the quality of the input data. The Pilot 1 results have shown that by including EO-based temperature values that are spatially and temporally continuous in the modelling we start to see spatial variation also in the output results including estimation of primary production, algal composition and algal blooms. This is seen as an improvement compared to for example using air temperature from a station on land to force the model.

The EU Nature Directives and the WFD calls for measures to be put in place to improve habitats, biodiversity and the water quality of European water bodies. As demonstrated in the Pilot 1 showcase there is also potential to study changes in turbidity due to mitigation measures. The possibility for mangers and experts to explore the EO input data and derived products from model integration in the Viewer were highlighted in the consultation meetings as very valuable as it can contribute to new knowledge for improved decision making.

There is a need to monitor the subsequent changes to the ecological character (N2000, Ramsar and national directives) from mitigation measures. EO based products that are comprehensive, objective, continuous in space and time and scale independent have great potential to support such needs.

With respect to Natura 2000 management plans and objective, the EO based products, and the novel experimental datasets, which all are linked to EBVs and biodiversity change drivers, and the output from the models could be used to support regular assessments of ecosystem conditions and changes within Natura 2000 areas. Another potential use could be to demonstrate inclusion of validated EO data products, in combination with models and in-situ data, in Natura 2000 SCI assessments and SCA status and change reporting.

The type of application demonstrated in Pilot 1 could also support the objectives of the EU Biodiversity Strategy 2030 by providing improved information for indicators to monitor targets (e.g., Target 3, Target 13, see section 3.1.3) as stipulated by the KCEO Deep Dive on EO in support of EU policies for biodiversity (Camia et al. 2023).

In addition, the results have global relevance as the KM-GBF require improved input information for the ongoing development of indicators for the framework targets (section 3.1.4). As stated by Timmermans & Kissling (2023), "No detailed user requirement analysis of Satellite Remote Sensing (SRS) products has yet been performed in the GBF context, which limits the capacity of the scientific community to contribute to the development of new SRS products and workflows that can be used in biodiversity indicators." We have shown that water quality and hydrodynamic model outputs can be improved by EO derived parameter forcing, which could provide improved knowledge of the possibilities of integrated products for biodiversity monitoring.

The SDG 6 goal with its indicator 6.6.1 Change in the extent of water-related ecosystems over time, also require improved input data for lakes on changes both to surface areas and water quality. Currently there are two quality elements, turbidity and trophic state, available in the Freshwater Ecosystem Interactive Map at 300 m resolution that have been produced by the Copernicus Land Service (UN Environment, 2023). In the EO support sheet for SDG 6.6.1 (under development by CEOS, see also CEOS, 2023) it is highlighted that there is a need to integrate multi-spectral sensor data (L8/S2) into current ocean colour based WQ data processing and temperature from thermal sensors need to be explored as an additional proxy of water quality. The results of BIOMONDO Pilot 1 show some of the potential to use current EO-based temperature values that are spatially and temporally continuous; with the planned improved ESA Lakes Climate Change Initiative (Lakes_cci): Lake products, the utility of the results should further increase.

Feedback from consultation meetings indicated that the BIOMONDO Viewer is "a nice to have tool that could for sure contribute to a better understanding of the ecosystem functioning in the lakes".

In summary the Pilot 1 results show potential for use in monitoring of the lake water quality status using integration of EO derived parameters with modelling. The improvement of the output results from the Delft3D model using LSWT (and potentially chlorophyll-a and turbidity) to force the model provides a different spatial and temporal view of the dynamics of the water quality state of Lake Marken which can help managers to make more informed decisions regarding prioritisation of actions and better understanding of the complex ecosystems. The use of EO products on turbidity and chlorophyll-a could also support appropriate monitoring of the success/effects of mitigation measures such as the creation of islands, removal of barriers for fish and creation of low-wind areas for development of macrophytes.

To support KIMA 2.0 and ongoing monitoring relevant to Natura2000 and Ramsar as well as the WFD status assessments, spatially and temporally continuous EO based products, derived for Pilot 1 could provide valuable and useful information. They also have potential to aid in the development of indicators of biodiversity change related to climate change impacts on habitats that are relevant for the European and global monitoring frameworks such as EU 2030 Biodiversity Strategy and KM-GBF.

In summary the contributions to improved decision making, biodiversity management and conservation lies in the integration of EO based products in modelling and processes for mitigation aimed at water quality improvements. For this the BIOMONDO viewer can provide visualisation support. Validated EO LSWT products, in combination with models and in situ data, as well as water quality parameters especially turbidity were used to demonstrate that these data and methods can:

- be used to improve output results from the Delft3D model using LSWT to force model outputs and provide continuous spatial and temporal views of the dynamics of the water quality in Lake Marken
- support research to determine how best to monitor the effects of mitigation efforts in order to improve lake water status addressed in the WFD, as well as the monitoring objectives of Natura2000 and Ramsar
- aid in the development of indicators and attribution of biodiversity change (EU Biodiversity Strategy, KM-GBF)
- help reduce information gaps and determine risk, vulnerability and resilience of freshwater fish species (EU Climate Adaptations Strategy)
- support prioritisation of lakes and freshwater ecosystems in need of restoration and thereby support restoration targets of the EU 2030 Biodiversity Strategy
- potentially be applied to determination of risk for spread of invasive alien species
- provide data and information to GBIOS and support the achievement of the KM-GBF targets

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