Analysis of current Copernicus water quality portfolio

Project Identification	
Project Full Title	Water scenarios for Copernicus Exploitation
Project Acronym	Water-ForCE
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History of Changes		
Date	**Version**	**Comments**
03.05.2021	V0	First Concept (FvB/IGB)
03.15.2021	V0.1	Revised Version by the following partners: VITO, UTartu, FvB/IGB
21.05.2021	V0.2	Revised Version by the following partners: EMU, UTartu, PML, FvB/IGB
14.06.2021	V.0.3	Revised Version by the following partners: VITO, WaterInsight, USTIR, CNR, FvB/IGB
29.06.2021	V.0.4	Revised Version by the following partners: UTartu, PML, VITO, CNR, FvB/IGB
23.07.2021	V.1	Final Version (FvB/IGB)

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List of Acronyms

AATSR	Advanced Along-Track Scanning Radiometer
ACIX	Atmospheric Correction Inter-comparison eXercise
a_{phy}	Phytoplankton Absorption Coefficient
a_{tot}	Total Absorption Coefficient
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High-Resolution Radiometer
B_{bp}	Particulate Backscattering Coefficient
C3S	Copernicus Climate Change Service
CCI	Climate Change Initiative
CDM	Coloured Dissolved Matter
CDOM	Coloured Dissolved Organic Matter
CEOS	Committee on Earth Observation Satellites
Chla	Chlorophyll-*a*
CGLMS	Copernicus Global Land Monitoring Service
CMEMS	Copernicus Marine Environment Monitoring Service
CMIX	Cloud Masking Intercomparison eXercise
DIAS	Data and Information Access Services
DOC	Dissolved Organic Matter
EO	Earth Observation
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GCOS	Global Climate Observing System
GLWD	Global Lakes and Wetlands Database
HELCOM	Helsinki Commission
HPLC	High Performance Liquid Chromatography
HR OC	High Resolution Ocean Colour
K_d	Diffuse Attenuation Coefficient
L3	Level 3
L4	Level 4
LIMNADES	Lake Bio-optical Measurements and Matchup Date for Remote Sensing
LMCS	Land Monitoring Core Service
LSWT	Lake Surface Water Temperature
MERIS	Medium Resolution Imaging Spectrometer
MODIS	Moderate-Resolution Imaging Spectroradiometer
MSI	Multispectral Imager
NASA	National Aeronautics and Space Administration
NERC	United Kingdom Natural Environment Research Council
NOAA	National Oceanic and Atmospheric Administration
NRT	Near Real Time

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OC TAC	Ocean Colour Thematic Assembly Centre
OLCI	Ocean and Land Colour Instrument
OWT	Optical Water Types
PAR	Photosynthetically Available Radiation
PRISMA	PRecursore IperSpettrale della Missione Applicativa,
R_{rs}	Remote Sensing Reflectance
R&D	Research and Development
SDG	Sustainable Development Goal
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SLSTR	Sea and Land Surface Temperature Radiometer
SPM	Suspended Particulate Matter
SST	Sea Surface Temperature
SST TAC	Sea Surface Temperature Thematic Assembly Centre
TEP	Thematic Exploitation Platforms
TSI	Trophic State Index
TSM	Total Suspended Matter
UAV	Unmanned Aerial Vehicle
UN	United Nations
VIIRS	Visible Infrared Imaging Radiometer Suite
WP	Working Package
WPC	Water Production Centres
ZSD	Secchi Disk Depth

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Executive Summary

The Horizon2020 project Water scenarios For Copernicus Exploitation (Water-ForCE) will develop a Roadmap for Copernicus Inland Water Services. The Roadmap will assess the current state of water related services provided by six existing Copernicus Services and will provide an optimal way forward for satisfying different user and stakeholder communities.

The current report provides detailed inventory of relevant water quality products provided by different Copernicus Services and identifies gaps in the current product portfolio. The water related services are currently in a very dynamic state. For example, the Copernicus Marine Environment Monitoring Service started to provide coastal products just a few weeks ago and there are further developments in inland water services provided by the Copernicus Land Monitoring Service. Therefore, this report provides insights for the final analysis on the gaps and recommendations for future developments which will be provided in the Roadmap.

The analysis carried out in preparing this report pointed out several bottlenecks which inhibit users to obtain a clear and complete picture of all products made available by the Copernicus Services:

- Lack of harmonization / standardization between the documentation, metadata, products and delivery system among different Copernicus Services.
- Lack of a centralized portal for easy access to water quality related products from different Copernicus Services - the search engine of the current portal (https://www.copernicus.eu/en/services-portfolio) does not deliver the products of interest.
- Insufficient data for calibration and validation activities of current and future water quality related products.
- Need for improvement of algorithms for atmospheric correction.

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- Need for more spectral bands (and/or better spatial resolution) in satellite sensors.
- Lack of data-awareness with the wider community.

There is also a need for more higher-level water quality products (e.g. primary productivity, nutrients availability, phycocyanin). Limnologist working in local lakes usually require higher spatial and temporal resolution of products than are currently provided.

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1. Introduction

1.1 Water-ForCE

The Horizon-2020 project Water-ForCE (Water scenarios For Copernicus Exploitation) will develop a Roadmap for Copernicus Inland Water Services

The Roadmap will contain:

- Analysis of user communities' landscape
- Analysis on how Copernicus water services can support policy development and monitoring of their implementation
- Gap analysis of the Copernicus water-related service portfolio
- Identification of future higher level biogeochemical products
- Technical requirements for future Copernicus sensors to improve the water0-related service portfolio
- Proposal for organising in situ measurement networks to validate Copernicus remote sensing and modelling products and to provide complementary data not collected by remote sensing
- Proposal on how to define relationships between Core Services and Downstream services
- Recommendation on the evolution of a water service (via the creation of a new service, or the improvement of water services under current Copernicus services, or through a better integration of water-related products)

The Water-ForCE project is coordinated by the University of Tartu (Estonia) with 20 participating organisations from all over Europe. It connects experts in water quality and quantity, in policy, research, engineering and service sectors.

This report is part of Work Package 2 (WP2) "Water quality continuum" which focusses on the water quality related products from inland to coastal waters.

1.2 Purpose of the document

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Water is an essential resource for humankind, providing essential goods and services underpinning the United Nations (UN) Sustainable Development Goals (SDGs). Alcamo (2019) identified that many different SDGs could be combined to bring mutual benefits in achieving the targets set for environmental issues especially water quality. The Synthesis Report of SDG 6 showed that there is a lack of available and reliable data to meet the requirements of the SDG 6 indicators (UN, 2018). Satellite Earth observation (EO) data have been evaluated to be a source of information for locations where the ground-based information is lacking or limited (Anderson 2017), and Copernicus Land Service products have indeed contributed to the most recent data drive for SDG6.3 monitoring (albeit reported within SDG6.1). In Europe, there is also increasing uptake of satellite EO for water-related ecosystem monitoring, modelling, and forecasting of environmental issues to support decision-making.

A growing number of studies have demonstrated that inland and coastal water quality can also be adequately measured using second-generation moderate-resolution satellite EO sensors, in operation since the early 2000s (Giardino et al., 2007, 2012, 2014, 2015, 2016; Dekker et al., 2005; Kutser et al., 2006a,b,c, 2013; Vahtmäe and Kutser, 2007, 2013, 2016). There are no satellite sensors that have been specifically designed for inland water quality remote sensing (Palmer et al., 2015; Mouw et al., 2015). Nevertheless, the improvement of sensors designed for land and coastal water monitoring (Sentinel-3) and land remote sensing (Landsat-8 and Sentinel-2) allows water quality products for smaller aquatic systems to be developed.

Overall, satellite water quality products (water temperature and optical products) are split across three Copernicus services: Copernicus Marine Environment Monitoring Service (CMEMS), Copernicus Climate Change Service (C3S), and Copernicus Global Land Service (CGLS) which is part of the Land Monitoring Core Service (LMCS). Water quality is included in the scope of C3S (as Lake water-leaving Reflectance is part of the Lakes Essential Climate Variable) but has thus far not been included. Water plays a crucial role

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in the Copernicus Emergency Service, but water quality is not currently part of this, either. Furthermore, there is some alignment between C3S, CGLS/CMEMS and the European Space Agency (ESA) Climate Change Initiative (CCI), where C3S focusses on regularly updating climate data records, CGLS/CMEMS on operational near real-time production and CCI contributing a Research and Development (R&D) component aimed to support climate research.

1.3 Content of the Report

This document presents the status of water quality related products within the Copernicus services and how any identified gaps are being addressed in the wider services and R&D landscape, particularly in Europe. The main products related to water quality are first summarized (section 2) followed by existing development plans for future products (section 3), resulting in a list of initial gaps and limitations (section 4). The major requirements from the expert group on EO of water quality and from the expert group on in situ water quality data are described in section 5 and additional resources to support the development of water quality products are described in section 6. Finally section 7 presents a list of recommendations to be taken up in the roadmap.

Concomitant to production of this review of Copernicus Water Quality products, WP1 is currently analysing stakeholder and user needs from research to policy perspectives and the international working group on water quality remote sensing experts (D2.1) and the in situ water quality experts group (D.4.1) continues to analyse gaps in Copernicus water quality products. Consequently, this report forms a snapshot of the requirement analysis and gap assessment which will be developed with these two expert groups (D2.1 and D4.1) within the scope of the Roadmap.

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2. Current Copernicus products

A detailed explanation of the Copernicus Programme and related Services can be found on the Copernicus website https://www.copernicus.eu/en/copernicus-services. In this section water quality products from the three Copernicus services (CMEMS, CGLS and C3S) will be introduced with their respective metadata information. The review of the available products is important for the evaluation of the current state of the water quality related products. Metadata information about products include geographic coverage, estimated parameters, temporal coverage, frequency of data processing and other characteristics of the products.

2.1 Copernicus Marine

Through the CMEMS (https://www.copernicus.eu/en/copernicus-services/marine), Copernicus provides a long list of satellite EO products for water quality including expert products such as Inherent Optical Properties and remote sensing reflectance (R_{rs}) as well as products which can directly inform ecological management such as chlorophyll-*a* (Chla) concentration, sea surface temperature (SST), Secchi depth (ZSD), photosynthetically available radiation. These products are generated within the Ocean Colour Thematic Assembly Centre (OC TAC) and the Sea Surface Temperature Thematic Assembly Centre (SST TAC).

The OC TAC operates the European Ocean Colour component, providing worldwide global and regional (Arctic, Baltic, Black Sea, European North West Shelf Seas, Iberia Biscay Ireland Regional Seas and the Mediterranean) state-of-the-art satellite ocean colour products based on Earth Observation Ocean Colour missions. OC TAC relies on current and legacy Ocean Colour satellite sensors: the Medium Resolution Imaging Spectrometer (MERIS), from the ESA, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate-Resolution Imaging Spectroradiometer (MODIS) from National Aeronautics and Space Administration (NASA), the Visible Infrared Imaging

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Radiometer Suite (VIIRS) from National Oceanic and Atmospheric Administration (NOAA) and the ESA Sentinel 3 Ocean and Land Colour Instrument (OLCI). Products from OC TAC are divided into OPTICS and CHL groups, discussed below.

The CHL is the phytoplankton chlorophyll-a concentration (a proxy of phytoplankton biomass, units mg m^{-3}). The OPTICS products include all other variables retrieved from ocean colour sensors such as total absorption coefficient (a_{tot}), phytoplankton absorption coefficient (a_{phy}) and the particulate backscattering coefficient (b_{bp}), the diffuse attenuation coefficient of light at 490 nm (K_d), ZSD, R_{rs}, PAR, CDM, and SPM. However, from this list of products, water quality users can be interested in the following: K_d, ZSD, PAR, CDM, and SPM. The OPTICS products have varying availability between geographic regions. It is important to highlight that the completeness and accuracy of the products are not yet at their full potential. For example, the Baltic Sea products include only Chla and R_{rs} and the correlation of these products with *in situ* data is very low (R^2=0.24 for Chla) according to CMEMS product validation document (Brando et al., 2021a) (https://catalogue.marine.copernicus.eu/documents/QUID/CMEMS-OC-QUID-009-048-049.pdf).

The SST TAC provides state of the art level 3 (L3) and 4 (L4) products of surface sea temperature. These are provided operationally in near real time, and multi-year reprocessed products. The full list of current available near real time products is present in the following table:

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Table 1 - List of products available at CMEMS

Region	Product	Reference	Parameters	Temporal Coverage	Spatial Resolution	Temporal Resolution	Update Frequency
Artic	Optics	009_046	R_{rs} K_d a_{tot} CDM a_{phy} SPM	May/2016 - Present	1km	Daily	Daily
Artic	Optics	009_089	K_d	May/2016 - Present	1km	Monthly	Monthly
Artic	Chla	009_047	Chla	May/2016 - Present	1km	Daily	Daily
Artic	Chla	009_087	Chla	May/2016 - Present	1km	Monthly	Monthly
Artic	SST	010_008	SST	Jul/2018- Present	6km	Daily	Daily
Artic	SST	010_014	SST	Mar/2015 - Present	25km	Weekly	Weekly
Baltic Sea	Optics	009_048	R_{rs}	May/2016 - Present	1km	Daily	Daily
Baltic Sea	Chla	009_049	Chla	May/2016 - Present	1km	Daily	Daily
Baltic Sea	Chla	009_050	Chla	Jan/2019 - Present	1km	Daily	Daily
Baltic Sea	SST	010_007b	SST	Jan/2016 - Present	2km	Daily	Daily

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Baltic Sea	SST	010_009a	SST	Jan/2016 - Present	2km	Daily	Daily
Baltic Sea	SST	010_009b	SST	Aug/2010 - Present	2km	Daily	Daily
Baltic Sea	SST	010_032	SST	Jan/2019- Present	2km	Daily	Daily
Black Sea	Optics	009_042	R_{rs} K_d CDM a_{phy} B_{bp}	May/2016 - Present	1km	Daily	Daily
Black Sea	Optics	009_043	K_d	May/2016 - Present	1km	Monthly	Monthly
Black Sea	Chla	009_044	Chla	May/2016 - Present	1km	Daily	Daily
Black Sea	Chla	009_045	Chla	May/2016 - Present	1km	Daily + Monthly	Daily
Black Sea	Chla	009_050	Chla	Jan/2019 - Present	1km	Daily	Daily
Black Sea	SST	010_006	SST	Jan/2008 - Present	1km	Daily	Daily
Black Sea	SST	010_009a	SST	Jan/2016 - Present	2km	Daily	Daily
Black Sea	SST	010_009b	SST	Aug/2010 - Present	2km	Daily	Daily

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Black Sea	SST	010_013	SST	Jan/2008 - Present	1km	Daily	Daily
European North West Shelf Seas	Optics	009_034	R_{rs} K_d CDM a_{phy} B_{bp}	May/2016 - Present	1km	Daily	Daily
European North West Shelf Seas	Optics	009_092	K_d	May/2016 - Present	1km	Monthly	Monthly
European North West Shelf Seas	Chla	009_036	Chla	May/2016 - Present	1km	Daily	Daily
European North West Shelf Seas	Chla	009_037	Chla	Jul/2019 - Present	1km	Daily + Monthly	Daily
European North West Shelf Seas	Chla	009_050	Chla	Jan/2019 - Present	1km	Daily	Daily
European North West Shelf Seas	Chla	009_090	Chla	May/2016 - Present	1km	Monthly	Monthly
European North West Shelf Seas	SST	010_009a	SST	Jan/2016 - Present	2km	Daily	Daily
European North West Shelf Seas	SST	010_009b	SST	Aug/2010 - Present	2km	Daily	Daily
European North West Shelf Seas	SST	010_025	SST	Jan/2018 - Present	2km	Daily	Daily
Global	Optics	009_030	R_{rs} ZSD K_d CDM B_{bp} SPM	May/2016 - Present	4km	Daily	Daily

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Global	Optics	009_083	R_{rs} ZSD K_d CDM B_{bp} SPM	May/2016 - Present	4km	Daily + Monthly	Daily
Global	Chla	009_032	Chla	May/2016 - Present	4km	Daily	Daily
Global	Chla	009_033	Chla	May/2016 - Present	4km	Daily + Monthly	Daily
Global	SST	010_005	SST	Sep/2017- Present	28km	Daily	Daily
Global	SST	010_010	SST	Jan/2016 - Present	11km	Daily	Daily
Iberia Biscay Ireland Regional Seas	Optics	009_034	R_{rs} K_d CDM a_{phy} B_{bp}	May/2016 - Present	1km	Daily	Daily
Iberia Biscay Ireland Regional Seas	Optics	009_092	K_d	May/2016 - Present	1km	Monthly	Monthly
Iberia Biscay Ireland Regional Seas	Chla	009_036	Chla	May/2016 - Present	1km	Daily	Daily
Iberia Biscay Ireland Regional Seas	Chla	009_037	Chla	Jul/2019 - Present	1km	Daily + Monthly	Daily

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Iberia Biscay Ireland Regional Seas	Chla	009_050	Chla	Jan/2019 - Present	1km	Daily	Daily
Iberia Biscay Ireland Regional Seas	Chla	009_090	Chla	May/2016 - Present	1km	Monthly	Monthly
Iberia Biscay Ireland Regional Seas	SST	010_009a	SST	Jan/2016 - Present	2km	Daily	Daily
Iberia Biscay Ireland Regional Seas	SST	010_009b	SST	Aug/2010 - Present	2km	Daily	Daily
Iberia Biscay Ireland Regional Seas	SST	010_025	SST	Jan/2018 - Present	2km	Daily	Daily
Mediterranean Sea	Optics	009_038	R_{rs} K_d CDM a_{phy} B_{bp}	May/2016 - Present	1km	Daily	Daily
Mediterranean Sea	Optics	009_039	K_d	May/2016 - Present	1km	Monthly	Monthly
Mediterranean Sea	Chla	009_040	Chla	May/2016 - Present	1km	Daily	Daily
Mediterranean Sea	Chla	009_041	Chla	May/2016 - Present	1km	Daily + Monthly	Daily

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Mediterranean Sea	Chla	009_050	Chla	Jan/2019 - Present	1km	Daily	Daily
Mediterranean Sea	SST	010_004	SST	Jan/2008 - Present	1km	Daily	Daily
Mediterranean Sea	SST	010_009a	SST	Jan/2016 - Present	2km	Daily	Daily
Mediterranean Sea	SST	010_009b	SST	Aug/2010 - Present	2km	Daily	Daily
Mediterranean Sea	SST	010_012	SST	Jan/2008 - Present	1km	Daily	Daily

Source: https://marine.copernicus.eu/about/producers

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2.2 Copernicus Global Land Service (CGLS)

The Lake Water Products (lake water quality, lake surface water temperature) provide a semi-continuous observation record for a large number (nominally 4,200 for water quality) of medium and large-sized inland water bodies (lakes, reservoirs, and some lagoons and riverine wetlands). The monitored waterbodies are delineated according to the maximum water extent product of ESA CCI Land Cover (v.4, 150m resolution) and identified against existing spatial databases of inland waterbodies, notably the Global Lakes and Wetlands Database (GLWD) and Hydrolakes. The waterbodies were selected based on shape and size criteria that favour larger stretches of open water. Several waterbodies of specific environmental monitoring interest were added per user requests or to align with existing efforts, notably GMES for waterbodies in Africa. The CGLS service consists of three water quality parameters: turbidity, trophic state index and lake water-leaving reflectance. Chla and total suspended matter are expected to be added within the 2021-2023 service framework. All water products in the CGLMS are provided as 10-day aggregate periods, using averages for turbidity, TSI and temperature, and the most representative spectrum of lake water-leaving reflectance.

Within the list of datasets from Copernicus Global Land service the following water quality related products are available:

- Lake Surface Water Temperature
- Lake Water Quality 100m (to be restarted in 2021)
- Lake Water Quality 300m
- Lake Water Quality 1km (discontinued)

2.2.1 Lake Surface Water Temperature

The Lake Surface Water Temperature (LSWT) Version 1 consists of two components: a historical dataset of Collection 1km LSWT from 2002 until 2012 generated from the Advanced Along-Track Scanning Radiometer (AATSR) instrument on Envisat and a Near

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Real Time (NRT) dataset of 1km LSWT from the Sea and Land Surface Temperature Radiometer (SLSTR) instrument on Sentinel-3A from the April 2018 until present.

DATA DESCRIPTION	
Data type	Grid
Projection	Regular latitude/longitude grid (EPSG:4326) with the ellipsoid WGS 1984 (Terrestrial radius=6378km).
Horizontal coverage	Global
Horizontal resolution	The resolution of the grid is 1°/120.
Vertical coverage	Surface
Vertical resolution	Single level
Temporal coverage	Envisat MERIS - From May 2002 to March 2012 Sentinel 3 OLCI - From Nov 2016 to present
Temporal resolution	10 days
File format	NetCDF
Conventions	Climate and Forecast (CF) Metadata Convention (v1.6)
Versions	v.1.1
Update frequency	10 days

MAIN VARIABLES		
Name	Units	Description
Lake surface water temperature	K	Lake surface skin temperature, weighted average over the aggregation period

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2.2.2 Lake Water Quality 100m

The 100m products are derived from the Sentinel-2 Multispectral Imager (MSI), primarily designed for land applications although some properties of water bodies can also be observed. The algorithms used to derive the input for the optical lake water products are implemented in the *Calimnos* processing chain.

DATA DESCRIPTION	
Data type	Grid
Projection	Regular latitude/longitude grid (EPSG:4326) with the ellipsoid WGS 1984 (Terrestrial radius=6378km).
Horizontal coverage	Europe and Africa
Horizontal resolution	The resolution of the grid is 1°/1113.2 or approximately 100m.
Vertical coverage	Surface
Vertical resolution	Single level
Temporal coverage	From January 2019 to March 2020
Temporal resolution	10 days
File format	NetCDF
Conventions	Climate and Forecast (CF) Metadata Convention
Versions	v.1.1
Update frequency	Archive only
MAIN VARIABLES	

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Name	Units	Description
Trophic State index	-	Trophic state index (TSI) obtained from chlorophyll-*a* observations, averaged over the observation period. The TSI has a value of 0, 10, 20, 30, 40, 50, 0, 70, 80, 90, or 100 corresponding to the classes given in Carlson (1977), where 0-40 are oligotrophic, 40-60 mesotrophic, 60-80 eutrophic, and 80-100 hypereutrophic. Note: for the initial 100m products, TSI was only included as a placeholder, pending product optimization. Production is expected to be restarted in 2021.
Turbidity	NTU	A proxy for underwater light conditions, with turbidity increasing with particle concentrations.
Water-leaving reflectance	-	Fully normalized water-leaving reflectance for all wavebands in the source product, following atmospheric correction.

2.2.3 Lake Water Quality 300m

The 300m products are derived from Envisat MERIS and Sentinel-3 OLCI L1b data. The algorithms used to derive the input for the optical lake water products are implemented in the *Calimnos* processing chain and were tuned and validated within 13 predefined optical water types (OWT) in the NERC (UK) GloboLakes project (Spyrakos et al. 2017).

DATA DESCRIPTION	
Data type	Grid

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<table>
<tr><td>Projection</td><td colspan="3">The product is displayed in a regular latitude/longitude grid (plate carrée) with the ellipsoïd WGS 1984 (Terrestrial radius=6378km).</td></tr>
<tr><td>Horizontal coverage</td><td colspan="3">Global - 4264 medium and large-sized lakes</td></tr>
<tr><td>Horizontal resolution</td><td colspan="3">The resolution of the grid is 1°/448 (approximately 250m)</td></tr>
<tr><td>Vertical coverage</td><td colspan="3">Surface</td></tr>
<tr><td>Vertical resolution</td><td colspan="3">Single level</td></tr>
<tr><td>Temporal coverage</td><td colspan="3">Envisat MERIS - From May 2002 to March 2012
Sentinel 3 OLCI A/B - From May 2016 to present</td></tr>
<tr><td>Temporal resolution</td><td colspan="3">10 days</td></tr>
<tr><td>File format</td><td colspan="3">NetCDF</td></tr>
<tr><td>Conventions</td><td colspan="3">Climate and Forecast (CF) Metadata Convention (v1.4)</td></tr>
<tr><td>Versions</td><td colspan="3">v.1.4</td></tr>
<tr><td>Update frequency</td><td colspan="3">10 days</td></tr>
<tr><td colspan="4">MAIN VARIABLES</td></tr>
<tr><td>Name</td><td>Units</td><td colspan="2">Description</td></tr>
<tr><td>Trophic State index</td><td>-</td><td colspan="2">Trophic state index (TSI) obtained from chlorophyll-a observations, averaged over the observation period. The TSI has a value of 0, 10, 20, 30, 40, 50, 0, 70, 80, 90, or 100 corresponding to the classes given in Carlson (1977), where 0-40 are oligotrophic, 40-60 mesotrophic, 60-80 eutrophic, and 80-100 hypereutrophic.</td></tr>
</table>

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Turbidity	NTU	A proxy for underwater light conditions, with turbidity increasing with particle concentrations.
Water leaving reflectance	-	Fully normalized water-leaving reflectance for all wavebands in the source product, following atmospheric correction.

2.3 Copernicus Climate Change Service (C3S)

Within the list of datasets from Copernicus Climate Change Service the following water quality related products are available:

- Lake surface water temperature from 1995 to present derived from satellite observations.
- Ocean colour daily data from 1997 to present derived from satellite observations.

2.3.1 Copernicus Climate Change: Lake surface water temperature

This dataset provides mid-morning daily values for lake surface water temperature generated from the Along Track Scanning Radiometer (ATSR) and Advanced Very High-Resolution Radiometer (AVHRR) sensors. The retrieved temperatures have been bias adjusted for consistency between sensors using overlap periods and uncertainty and quality levels based on statistical confidence levels are also provided. The dataset contains only observations and therefore gaps in time and space may be present.

Most of the lake surface water temperature data in this dataset have been developed within the United Kingdom Natural Environment Research Council (NERC) GloboLakes project.

DATA DESCRIPTION	
Data type	Gridded

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Projection	Regular latitude-longitude grid	
Horizontal coverage	Global	
Horizontal resolution	0.05° x 0.05°	
Vertical coverage	Lake surface	
Vertical resolution	Single surface layer	
Temporal coverage	June 1995 to August 2019	
Temporal resolution	Daily (with gaps)	
File format	NetCDF-4	
Conventions	Climate and Forecast (CF) Metadata Convention v1.6, Attribute Convention for Dataset Discovery (ACDD) v1.3	
Versions	4.0	
Update frequency	Annually	
MAIN VARIABLES		
Name	Units	Description
Lake surface water temperature	K	Daily gridded temperature of the water at the surface of the inland water body.

Source:
https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.d36187ac?tab=doc

2.3.2 Copernicus Climate Change: Ocean Colour daily data

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The files from this dataset contain global daily composites of merged sensor products: SeaWiFS, MERIS, MODIS Aqua, VIIRS, and OLCI (the latter included only in version 5). Note that R_{rs} and Chla data are only available over cloud- and ice-free areas.

This dataset is produced using the processing chain developed by the Ocean Colour component of the European Space Agency Climate Change Initiative project (ESA OC-CCI). Version 5.0 of the dataset is produced by the C3S service whereas previous versions are brokered from ESA OC-CCI.

VIIRS, MODIS, SeaWiFS and MERIS R_{rs} were derived from a combination of NASA l2gen (for basic sensor geometry corrections, etc) and HYGEOS Polymer v4.12 (for atmospheric correction). OLCI R_{rs} were sourced at L1b (already geometrically corrected) and processed with Polymer. Derived products were computed with the standard algorithms through SeaDAS, therefore, additional parameters such as inherent optical properties (IOPs) were derived using the standard SeaDAS algorithm. A fuzzy water classifier was used to identify 14 OWT (Jackson et al. 2017). The final chlorophyll is a combination of OCI, OCI2, OC2 and OCx, depending on the water class memberships.

DATA DESCRIPTION	
Data type	Grid
Projection	Regular latitude-longitude and sinusoidal grids
Horizontal coverage	Global
Horizontal resolution	Sinusoidal equal-area grid: 4km x 4km Regular latitude-longitude grid: 0.042° x 0.042° (4km x 4km at the Equator)
Vertical coverage	Surface
Vertical resolution	Single level

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Temporal coverage	From September 1997 to present		
Temporal resolution	Daily and Monthly		
File format	NetCDF		
Conventions	Climate and Forecast (CF) Metadata Convention v1.6, Attribute Convention for Dataset Discovery (ACDD) v1.3		
Versions	v5.0: Updated processing chain; use of OLCI data; SeaWIFS replaced with MERIS as reference sensor. v4.2: Data for Chla and R_{rs}; based on reprocessed satellite data and updated processing chain. v3.1: Data for Chla only; ends in September 2018.		
Update frequency	Quarterly with a 9-12 month delay behind real time		
MAIN VARIABLES			
Name	Units	Description	
Mass concentration of chlorophyll-a	mg m-3	Mass chlorophyll-a per unit of volume of near-surface water.	
Remote sensing reflectance	sr-1 (per steradian)	Fraction of the downwelling solar irradiance reflected by the ocean surface at a given wavelength. It is the basic input used to derive chlorophyll-a concentrations (as well as other ocean colour products). Here, estimates of R_{rs} measured at six wavelengths (410, 443, 490, 510,	

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		555, and 670 nm) are provided as separate variables in the NetCDF files.

Source: https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-ocean-colour?tab=overview

2.4 General Overview

Overall, the CMEMS has more water quality related products compared to CGLS and C3S, including a range of products targeted at the scientific community (such as the a_{tot}, a_{phy}, B_{bp}, and R_{rs}). Products such as K_d, ZSD, PAR, CDM, SPM, Chla and SST are more likely to be favoured by the water quality monitoring user community, depending on the availability of on the geographic coverage of these products. These products have a relatively high spatial resolution for coastal/ocean applications (> 1km or 300m,). C3S currently offers three global products related to water quality (Lake Surface Temperature, Rrs and Chla concentration). The Rrs and Chla have a spatial resolution of 4km and do not extend to inland waters. Within the product there are other derived products which are not listed as a main parameter such as IOPs retrieved from Seadas and 14 Water Classes based on the classification strategy described by Jackson et al. (2017). Thus, there are basically three different services providing water colour products for coastal and Inland waters - CMEMS, CGLMS, C3S. Up to recently CGLS was the only one that provided the service with moderate (100 m) spatial resolution, whereas CMEMS coastal products have very recently become available for Europe.

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3. Future Plans

In this section we provide an overview about the near-future plans for the expansion of water quality products within the three services and the ambitions for the growth of the water quality products.

CMEMS launched on May 5th 2021 the High-Resolution Ocean Colour (HR OC) Products for the Coastal stripes of 20km for all European Seas which can be accessed via the CMEMS portal (https://resources.marine.copernicus.eu/?option=com_csw&task=results). These products are level 3 and level 4 products, generated from the processing of Sentinel 2A and 2B images, including the following at 100 m spatial resolution:

- R_{rs}
- Turbidity
- SPM
- B_{bp}
- Chla

These products are available for daily, monthly, and daily gap filled resolutions.

- L3_NRT_1D: Daily products contain all valid data of the acquisition day, with averaging where tiles overlap.
- L4_NRT_1M: monthly products contain averages of all daily input products within the respective month. This is applicable for the following parameters: Turbidity, SPM, CHL, B_{bp}.
- L4_MY_1D: daily products contain gap filled daily products. Gap filling is performed by temporal-spatial interpolation. Products contain Turbidity, SPM, CHL, B_{bp}.

With the launching of this product, another plan for the CMEMS is the possibility to merge Sentinel 3 derived products with the newly developed Sentinel 2 products. An

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ambition for this service is the production of global HR-OC products, since they are now only available for the Europeans seas.

The CGLS plans to re-start processing a set of 200 Sentinel-2 A/B MSI tiles in 2021, with a 100 m product resolution. These products will contain Rrs, Chla and TSM/Turbidity with the algorithms to produce biogeochemical products aligned with those of existing Sentinel-3 OLCI products. A number of future ambitions for this service can be derived from the tender document for the 2021-2023 framework, although it is not yet known when they will start:

- The inclusion of additional water quality products including: cyanobacteria surface bloom, Chla concentration, Total Suspended Matter (TSM).
- Per-pixel product uncertainties and quality flags.
- Extended validation of Sentinel 2 and Sentinel 3 derived products.

Meanwhile, the ESA CCI+ programme continues into its next project phase during 2021, further exploiting current and past satellite data records to provide long time series, for example by including MODIS into the time series to bridge observation gaps between the MERIS and OLCI sensors at medium resolution. With its focus on data quality against the GCOS requirements rather than operational service provision, and the overlap in processing systems between CCI Lakes and CGLS, it should be expected that product improvements from the CCI lake surface water temperature and lake water quality efforts find their way to the operational service. This then triggers the need for regular archive reprocessing. For lake surface water temperature this is done in the C3S whereas for water quality no plan for reprocessing has been identified in the current service framework.

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4. Needs and Recommendations from the Expert Panel (WP2 and WP4)

This section presents an overview of the discussion in the first two expert panels organized by the Water-ForCE consortium. The first expert panel was organized by the WP2 on 23 of February 2021 in which a list of water quality remote sensing experts was established. The second expert panel was organized by WP 4 in cooperation with WP2 on 17, 18 and 20th May 2021 and invited in situ water quality experts and water quality remote sensing experts to promote integration between these two communities of experts. This meeting also received contribution from several relevant projects, investigating data interoperability, new observation methodologies, and a range of usage scenarios.

4.1. Requirements and recommendations by in situ water quality experts

4.1.1 Spatial data needs

The first need for satellite EO data is the need for higher spatial resolution products, especially for inland aquatic systems. Considering that lakes cover 3.7% of the Earth's non-glaciated land area (Verpoorter et al., 2014) and that the number of small lakes is much higher than the number of large lakes (Cael, and Seekell, 2016) there is a significant need for higher spatial resolution water quality products. In addition to the desire for higher spatial resolution products, several other water quality parameters were highlighted for a possible future product. One emerging need from the *in situ* observation community is the need to detect (micro)plastics in the water. While the use of Chla, SPM and Colored Dissolved Organic Matter (CDOM) were used to indirectly identify the concentration of microplastics in water (Piehl et al., 2020) more investigations are needed to directly estimate microplastic from satellite data. A further highlighted need was for Dissolved Organic Matter information in the Copernicus water quality products. This information is currently only available for selected products in

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CMEMS. Considering the widespread brownification in inland water systems, especially in boreal lakes (Monteithet al., 2007; Gamor et al., 2014), the elevated concentrations of CDOM derived from terrestrial sources are important for the understanding of these ecosystems (Kritzberg et al., 2020). Moreover, high concentrations of CDOM in inland waters may cause regime shifts from autotrophic to heterotrophic conditions, depending on whether light and nutrient conditions favour phototrophs. Therefore, the Copernicus Global Land service water quality product would benefit from including a CDOM product, if a globally validated approach can be found.'

A summary of desirable water quality products is as follows:

- Dissolved matter composition
- Light absorption and scattering properties
- Nutrient availability
- Particle size distribution
- Particulate matter weight or composition
- Phycocyanin
- Phycoerythrin
- Phytoplankton composition
- Primary production
- Turbidity
- Vertical light attenuation or transparency
- Water colour indices
- Benthic habitats

4.1.2 – Other *in situ* water quality experts needs

In addition to possible new satellite EO products, the *in situ* water quality experts highlighted that there are some gaps in order to improve the use of EO data. Major needs are related to specific training for data collection, data management, data sharing as well as training for the use of satellite EO data.

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- Training for collecting data that can be used for remote sensing calibration and validation is needed.
- Common vocabulary between *in situ* water quality community and remote sensing community is needed.
- Funding opportunities for installing spectroradiometers in the existing infrastructures.
- Capacity building for satellite EO data users – Training should be provided to capacitate users to: 1) select the appropriate product; 2) use products.

4.2. Requirements and recommendations by the water quality remote sensing experts

To fully understand the optical processes among the space-atmosphere-water system and to improve algorithms for water quality retrieval, a more rigorous framework of processing satellite data is needed (CEOS, 2018). To do that, information on concentrations and knowledge of optical properties of optical active components in water and atmosphere are essential. Additionally, it is important to have protocols to measure an optical parameter or optical property in order to reduce the uncertainty of using different methodologies. This is also required for the water quality parameters used for calibration and validation. For example, Chla can be measured by spectrophotometric, fluorometric (*in vivo* or *in vitro*) or by HPLC methods. Thus, the need to have measurement uncertainty data which will be essential for the collection of suitable data for calibration and validation of satellite products.

4.2.1 *In situ* data needs

- Wider collection of hyperspectral radiometry (from fixed autonomous stations and ad hoc).
- Open water data (away from shore)for Chla, TSM and turbidity at global scale.

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- Transect spectroradiometric data to assess the adjacency effect, particularly for small water bodies.
- A water quality database with metadata and quality-controlled data available for satellite EO algorithm developers.
- *In situ* data collected close to the time of satellite overpass.
- Costs for automated measurements should be reduced to allow larger scale data collection.

4.2.2 Other water quality remote sensing experts needs

- Handle overlap between inland, marine and transitional water, harmonized approach needed for water quality retrieval and atmospheric correction.
- Regularly repeating round robin exercises for algorithm candidates (atmospheric correction (e.g. the Atmospheric Correction Inter-comparison eXercise - ACIX), in water, cloud/pixel identification (e.g. the Cloud Masking Intercomparison Exercise - CMIX).
- *In situ* database (QA/AC data and metadata) open for algorithm developers
- Atmospheric correction assessment focussed on different optical water types, small and/or narrow inland waterbodies where adjacency effects are predominant, and shallow areas.
- Dedicated field campaigns and data sharing arrangements needed throughout EU funding programs.

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5. Initial analysis on Gaps and Limitations

When assessing the Copernicus products for water quality it became apparent that there is no centralized database for the management of Copernicus Products and product documentation. Harmonization of documentation formats and content would aid users in finding the right data for their application. Despite this current shortcoming, in this section we present an overview of initial gaps and limitations observed during the assessment of the products.

It has to be stressed that certain remote sensing products are rather universal and others are less so. For example, a SST algorithm developed in one region or for one waterbody works nearly everywhere (Fiedler et al 2014). On the other hand, biogeochemical (ocean colour) products, like Chla, Rrs and other products derived from the Rrs, are highly site specific and often even seasonal (Simis et al. 2017, Ligi et al. 2017).

5.1. Product consistency

Based on the current water quality products available from CMEMS, CGLS and C3S (see section 2), as well as the standard processing done at EUMETSAT, we observe a lack of consistency between products related to water quality. Products in CMEMS have been optimised for specific regions. The comparison among services showed that only Rrs and SST (or LST) are present in all three Copernicus services. Chla concentration could be a third common product since it is calculated for the computation of the TSI product provided by the Copernicus Global Land Service, and is expected to become included during the 2021-2023 service framework. Overall, there is a need for a centralized database to standardize the accessibility of water quality related products and documentation from the Copernicus Services as well as the adoption of a standard procedure for the production of similar products.

To achieve a higher level of consistency, various efforts could be considered:

- assess options to include the same product set across water domains

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- assess continuity of retrieval performance between the existing products across marine and inland water domains
- common validation data sets and methodology between the service components
-

5.2 spatial resolution

CMEMS products are generated for open parts of the regional seas and, therefore, cannot be used to address management issues of complex coastlines(e.g. archipelagos). Moreover, the optical complexity of some coastal waters and inland waters are optically complex and the biogeochemical parameters are usually complex to retrieve (Brockmann et al., 2016). Thus, it is important to the validate the use of algorithms developed for the open parts of the sea in optically complex waters. This limitation can be minimized by the newly launched CMEMS product to monitor European coastal areas (in service since May 2021 - a few weeks before the delivery of this document, see Section 3 of this document). Thus, a significant step forward has been made already although the performance of the products in different coastal waters needs to be assessed.

Regarding the spatial resolution of the CGLS products, it is unlikely that a higher than 1km resolution in lake surface water temperature would be achieved for the global service very soon as this will require new spaceborne assets. The CCI+ Lakes and CGLS projects have nevertheless identified at least 2000 waterbodies for which lake surface water temperature is likely achievable. The CCI+ Lakes water quality products are also provided at 1km resolution, which is suitable for large and medium lakes and is done to provide a common format between ice, temperature and water colour products. In the operational context of CGLS, both 300m and 100m products are defined. The 100m product is not expected to reach global coverage anytime soon, given the high computational effort and associated cost, but is being launched for 200 Sentinel-2 MSI

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tiles in 2021 to further support product valuation and to build user interest. These processes will likely inform the future coverage of the 100m service.

5.3 Dissolved carbon

The Copernicus Services do not currently address dissolved organic carbon (DOC), which is a key component in modelling the role of waterbodies in the global carbon cycle. More than 90% of carbon in lakes is in DOC (Wetzel 2001). Lake carbon content mapping is also relevant for the drinking water industry - coagulants and other chemicals used in water treatment are expensive and need accurate dosage. A major challenge in addressing the dissolved carbon component in lakes is that the relationship between DOC and lake colour varies in time and space. There have been studies demonstrating empirical correlations between the coloured dissolved organic matter fraction (CDOM), which in turn is included in the light absorption budget observed by remote sensing sensors (Kallio 1999: Kutser et al. 2005a,b; Zhu et al. 2014). CDOM (or the less specific CDM) products exist in the Copernicus portfolio (provided by CMEMS, C3S), but only for the marine environment, and these lack validation data (Toming et al. 2020). Therefore, as a first step to determining the role of inland waterbodies in the global carbon cycle and carbon fluxes between the land and sea, targeting the accurate global retrieval of CDOM from water colour remains a key gap in the current services. There are clear challenges in the retrieval of CDOM across water bodies, ranging from high uncertainty in the retrieval of water-leaving reflectance in blue bands where CDOM absorption is strongest, the absence of observations in the UV, and optical ambiguities between CDOM and phytoplankton absorption components to overcome. Whilst performance of CDOM retrieval across global lakes remains unproven, the most likely route towards inclusion of CDOM in the inland water services would therefore be through a dedicated R&D component in the ESA CCI+.

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5.4.- Absence of shallow waters products

Benthic macroalgal communities, seagrass beds, coral reefs are essential for many organisms as habitats, mating and nursery grounds, feeding areas and refuge. They stabilise and protect coastlines and their cover and shifts in it are indicators of ecological status of the coastal environments. Generally, exchange of matter between land and waterbodies takes place in the coastal zone. Benthic algal cover, seagrass beds and coral reefs are critical as processors of land-based fluxes ranging from nutrients to pollutants. Substantial carbon processing takes place in coastal zone. There are carbon budgets for land, but the role of coastal waters in the carbon cycle (e.g. the amount of carbon fixed by benthic habitats) is not known (Kutser et al. 2020).

Coastal bathymetry and habitat mapping in inland and marine waters are critical for spatial planning, carbon cycle studies, fisheries, aquaculture and many other purposes. Thus, there is a strong need in different shallow water products for many uses. Sentinel-2 can be used in production of shallow water products such as submerged aquatic vegetation, seagrass beds and coral reefs (Hedley et al. 2018). However, there are currently no shallow water products in the Copernicus portfolio which could be addressed by the CGLS.

5.5. Sensor specifications

The first satellite sensor designed specifically for Inland and coastal water remote sensing, GALENE, was proposed for the Earth Explorer 11 mission, but was not funded. There have been (Hyperion) and are (*PRecursore IperSpettrale della Missione Applicativa* - PRISMA) hyperspectral sensors in space and their usefulness in inland and coastal water remote sensing has been demonstrated (Brando and Dekker 2003; Kutser et al. 2003, 2004, 2006; Giardino et al., 2020, Niroumand-Jadidi et al., 2020). However, these are scientific demonstration missions that do not provide global coverage. Therefore, an alternative option to get necessary information with global coverage and reasonable

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revisit times is to improve next versions of current Copernicus satellites like Sentinel-2 and Sentinel-3.

Sentinel 2 MSI was not designed for aquatic applications. Nevertheless, it has been used for shallow (both inland and coastal) water applications (Hedley et al 2018; Kotta et al. 2018) as well as inland water quality monitoring (Toming et al. 2016; Ogashawara et al., 2021). On the other hand, hyperspectral studies on water quality, algal blooms, and shallow water studies have demonstrated (Giardino et al. 2014, 2015, 2020; Kutser 2004; Kutser et al. 2003, 2020) that there are spectral bands which would vastly improve the capabilities of similar multispectral sensors in future.

Some suggestions for additional Sentinel 2 – MSI spectral bands are:

- A narrow spectral band around 620 nm would be needed for the development of cyanobacteria water column-biomass products.

- A band centred at 470 or 473 nm nm with 20 nm bandwidth for the estimation of carotenoid.

- A 810 nm band as a good indicator of particulate material (if the particular material is phytoplankton (like in most lakes) then the peak height correlating with the Chl-a).

- A narrow spectral band around 1070 nm would be needed for the identification of plastic in water (Moshtaghi, 2021).

These additional bands would also be good for mapping shallow water habitats and to improve retrieval of substrate type.

- The signal to noise ratio needs to be improved for dark waters. The Feasibility Study for an Aquatic Ecosystem Earth Observing System (CEOS, 2018) recommended for the radiometric sensitivity a noise equivalent radiance difference (NEΔL) in the range 0.005 mW m^{-2} sr^{-1} nm^{-1} (optimal) and 0.010 mW m^{-2} sr^{-1} nm^{-1}.

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- Higher temporal resolution (daily revisit time) to allow monitoring water quality where the dynamics can change rapidly or where cloud cover is frequent.
- Off-nadir viewing angles to avoid sun glint.

5.6 Atmospheric correction

More than 90% of the signal measured above water at satellite altitude results from interaction within the atmosphere. Therefore, it is important to remove the atmospheric effects from the water-leaving radiance signal. Small uncertainties in atmospheric correction can be significant in the interpretation of the water-leaving signal. Unfortunately, atmospheric correction remains one of the major challenges for aquatic remote sensing, especially in optically complex waters and near land (De Keukelaere, 2018; Warren et al., 2019; Pahvelan et al., 2021). The major known challenges are:

- Lack of R_{rs} in situ measurements from locations (from both inland and coastal waters) representing a range of optical water types and atmospheric conditions (Warren et al. 2019) to inform the development of improved atmospheric correction procedures.
- Addressing and validating the removal of sun glint.
- Contributions of adjacent land to the signal measured over water bodies.
- Addressing bottom reflection, particularly in optically shallow water.
- Identification of cyanobacteria scum or floating macrophytes and avoiding the interpretation of affected pixels as water-column observations.
- Lack of a strategy to meet the desired and achievable requirements for accuracy and stability of the aquatic reflectance as specified by GCOS (currently under review).

5.7. Water quality product validation

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Validation of coastal and inland water quality products has been flagged as challenging by the Copernicus services. While the global CMEMS product for Chla shows validation metrics such as R^2=074, RMSD = 0.34, bias = 0.02 (Garnesson and Bretagnon, 2021). Oceanic waters are much more homogenous than coastal and Inland waters. Yet, there Is more in situ validation data available for oceans than for coastal and Inland waterbodies. Radiometric observations to validate the water-leaving reflectance product are particularly lacking which lead the community to establish a database named LIMNADES (Lake Bio-optical Measurements and Matchup Date for Remote Sensing) to share research data.

Regular monitoring is carried out in a large number of inland and coastal waters, although not equally so across regions of the world. Exploiting statutory monitoring data in validating satellite products would seem an obvious move. However, the data is not always easily findable, accessible and caution is needed when using such monitoring data as they may be of suboptimal quality from the remote sensing validation point of view. For example, EUMETSAT matchup protocols for Sentinel-3 OLCI require maximum 1 hour time difference between the *in situ* measurements and satellite overpass, which can be extended to 3 hours. In certain cases to enlarge the number of matchups (https://www.eumetsat.int/media/44087). This time window cannot be followed in statutory water quality monitoring programs. Similarly, positioning metadata are less likely to follow the precise requirements for satellite validation, particularly in horizontally heterogeneous environments. In situ sampling strategies and laboratory analysis methods are known to vary between countries or regional sea agreements; satellite validation ideally requires these measurement uncertainties to be known and reported. Having a set of *in situ* sampling stations with a consistent set of instrumentation and uniform sampling methodology would be ideal from the perspective of validating Copernicus water quality products, but also single data

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resources with metadata on sampling time, location, measurement protocols and uncertainties are valuable.

Thus, we listed the following limitations in relationship to product validation:

- Lack of suitable *in situ* data for calibration and validation of Copernicus products
- Lack of a coordinated database of *in situ* water quality data with well described metadata which could be accessed for algorithm development and validation.
- Lack of information about the uncertainty of the product for regional or local purposes.

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6. Additional satellite EO development of water quality related products

In this section, on-going R&D projects related to the development and improvement of water quality products are described. These on-going projects are advancing the development of water quality satellite products and could fill some of the gaps observed at current Copernicus water quality products from CMEMS, CGLS and C3S.

6.1 Lakes Climate Change Initiative

The ESA Climate Change Initiative (CCI) is a programme set out to create and improve climate data records of the Essential Climate Variables (ECVs). The ESA Lakes_cci is a multi-disciplinary project (https://climate.esa.int/en/projects/lakes) combining expertise to exploit data to create the largest and longest possible consistent climate data record for the variables included under the Lakes ECV by the Global Climate Observing System (GCOS). Version 1.0 of the database covers 250 globally distributed lakes with a temporal coverage, depending on the thematic variable, ranging from 1992 up to 2019. The dataset is planned to expand to 2000 lakes in version 2.0, expected in 2021. All satellite-derived products from Lakes_cci are provided with per pixel uncertainty estimates (ESA, 2020). The thematic variables included in Lakes_cci are:

- Lake Surface Water Temperature
- Lake Water-Leaving Reflectance, and derived Chla and turbidity
- Lake Water Level
- Lake Water Extent
- Lake Ice Cover
- Lake Ice Thickness (in a future release)

To derive these products, over 30 satellite sensors are considered, and synergies between the products are analysed to produce the highest possible product consistency. For example, lake ice cover and water surface temperature, using thermal bands available on some of the satellite sensors, informs the masking of Lake Water-Leaving

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Reflectance products. In terms of water quality, the major R&D components of Lakes_cci are to accurately estimate per-pixel uncertainties and to generate stable records from a combination of MERIS, MODIS, and OLCI observations, addressing inter-sensor bias and algorithm consistency.

6.2 H2020 CERTO

The Horizon 2020 Copernicus Evolution – Research for Transitional-water Observation (H2020 CERTO - https://certo-project.org) is currently preparing a harmonization of Copernicus water quality products across the continuum of oceans, seas, coasts, estuaries, lagoons, rivers and lakes.

CERTO focuses on: methods to optically classify waters, using satellite observations, together with existing and new *in situ* data; improvements to remove the atmospheric signal, particularly problematic in near-coastal and transitional waters, including optically shallow and intertidal zones. . The main output of the project will be a prototype processing chain for satellite EO data that can be implemented across all three Copernicus services: CMEMS, CGLMS-CGLS and C3S.

6.3 H2020 MONOCLE

The Multiscale Observation Networks for Optical monitoring of Coastal waters, Lakes and Estuaries project (MONOCLE - https://monocle-h2020.eu) is developing essential research and technology to lower the cost of acquisition, maintenance, and regular deployment of *in situ* sensors. The MONOCLE sensor system will establish firm links between operational satellite EO and essential environmental monitoring in inland and transitional water bodies. These aquatic ecosystems, which are particularly vulnerable to direct human impacts, represent areas of the weakest performance in current satellite EO capability, despite the major technological advances in recent decades. At the same time, these areas are of great economic importance and are crucial to sustainable food, energy, and clean water supply. MONOCLE focusses on sensor

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technology that can directly aid in the validation of satellite derived water colour, based on radiometry, automation, as well as low-cost sensors to assess vertical properties of the water column and to fill EO observation gaps (with drones and smartphones). Some of the sensors are suitable for integration into citizen science activities, to better observe the micro-scale of aquatic ecosystems and their tributaries.

6.4 H2020 HYPERNETS

The objective of the HYPERNETS project http://hypernets.eu/from_cms/summary is to develop a new lower cost hyperspectral radiometer and associated pointing system and embedded calibration device for automated measurement of water and land bidirectional reflectance. The instrument will be tested in a prototype network covering a wide range of water and land types and operating conditions. Quality controlled data with associated uncertainty estimates will be provided automatically for the validation of all optical satellite missions. Preparations will be made a) for the new instrument design (and associated calibration service) to be commercialized with an expected lifetime of at least 10 years and b) for the networks to be further expanded to become the main source of surface reflectance validation data for all spectral bands of all optical missions for at least the next 10 years.

6.5 H2020 PrimeWater

The PrimeWater Project (https://www.primewater.eu/) aims to make inland water quality information derived from satellite EO or satellite technologies more accessible and usable across the water sector. The project connects the scientific community with stakeholders who can benefit from having water quality forecasts such as those dealing with potable water production, recreation, hydropower, aquaculture, environmental protection, water resources management and emergency planning. PrimeWater is trying to understand the social and institutional factors in the water industry that drive

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adoption of new approaches such as water quality forecasting. This is being done using behavioural analysis methods which can direct a stronger uptake of innovative approaches. The intent is to have an operational web-based platform which can provide different water users with continuous monitoring of critical environmental parameters such as turbidity and algal blooms, as well as produce forecasted water quality characteristics in reservoirs and lakes.

6.5 H2020 WQeMS

The Copernicus Assisted Lake Water Quality Emergency Monitoring (WQeMS) aims to provide an operational Water Quality Emergency Monitoring Service to the water utilities industry in relation with the quality of the 'water we drink' (https://wqems.eu/). Therefore, it will focus its activities on monitoring of lakes valued by the water utilities for the delivery of drinking water. Sentinel data (i.e. Sentinel -2 and Sentinel-1) will be exploited for quality monitoring at a fine spatial resolution level, following validated processes with in situ data. The proposed WQeMS will exploit the Copernicus Data and Information Access Services (DIAS ONDA), instead of setting up its own download and processing infrastructure. Linkages with the existing Thematic Exploitation Platforms (TEPs), such as the Hydrology TEP for monitoring flood events and the Food Security TEP for supporting the sustainable intensification of farming from space will be pursued. Following cases are to be treated in real time in cooperation with drinking water production companies (public and private): - Slow developing phenomena (business-as-usual scenario), such as geogenic or anthropogenic release of potentially polluting elements through the bedrock or pollutants' leaching in the underground aquifer through human rural activities, may influence water quality. Changes in the monitored chemical dissolved substances may be then detected. - Fast developing phenomena (e.g. floods spilling debris and mud or pollutant spills of chemicals in the lakes or algal bloom and potential release of toxins by cyanobacteria) produce huge quantities of

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contaminants at a short time interval bringing sanitation utilities at the edge of their performance capacity. Monitoring of the extent of the effluents in the lake; thus, providing a warning about the risk of water contamination, assist in mitigating impact, both for the water drinking water production and the environment.

6.6 H2020 CALLISTO

CALLISTO aims to bridge the gap between Copernicus Data and Information Access Services (DIAS) providers and application end-users through dedicated Artificial Intelligence solutions (https://callisto-h2020.eu/). It will provide an interoperable Big Data platform integrating satellite EO data deriving from the Data and Information Access Services (DIAS) with crowdsourced, geo-referenced and distributed data from various sources. All data will be served in Mixed Reality environments.

CALLISTO aims to exploit satellite data, Unmanned Aerial Vehicle (UAV) observations, in-situ hyperspectral data and water quality measurements to allow virtual presence at the Water Production Centers (WPC), offering an improved and continuous water quality monitoring. CALLISTO will also exploit Artificial Intelligence (AI) technologies to process air quality data close to WPCs and to estimate potential implications to water quality.

6.7 H2020 DCS4COP

The Data Cube Service for Copernicus project (DCS4COP) addresses the challenges of handling big data volumes, integrating data streams from different sources and generating high-quality information from the novel sensors of the Sentinel satellite series by implementing the Copernicus Water DataCube Service as a first application (http://dcs4cop.eu/)

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This new service model will integrate Sentinel data and user supplied data in a DataCube system that allows for tailor-made integration of data and information services into the users' business environment.

6.8 H2020 CoastObs

CoastObs aims at using satellite remote sensing to monitor coastal water environments and to develop a user-relevant platform that can offer validated products to users including monitoring of seagrass and macroalgae, phytoplankton size classes, primary production, and harmful algae as well as higher level products such as indicators and integration with predictive models. To fulfill this mission, we are in dialogue with users from various sectors including dredging companies, aquaculture businesses, national monitoring institutes, among others, in order to create tailored products at highly reduced costs per user that stick to their requirements.

With the synergistic use of Sentinel-3 and Sentinel-2, CoastObs aims at contributing to the sustainability of the Copernicus program and assisting in implementing and further fine-tuning of European Water Quality related directive.

6.9 ESA EO4SD programme

EO4SD – Earth Observation for Sustainable Development – is a new ESA initiative which aims to achieve a step increase in the uptake of satellite-based environmental information in the IFIs regional and global programs. It will follow a systematic, user driven approach in order to meet longer-term, strategic geospatial information needs in the individual developing countries, as well as international and regional development organizations. Specifically, for water resource management the EO4SD will seek to demonstrate the benefits and utility of EO services in response to stakeholder requirements for water resources monitoring and management at local to basin scales.

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6.10 H2020 CAL/VAL

Copernicus CAL/VAL Solution: Sentinels are a new family of missions including a range of technologies, such as radar and multi-spectral imaging instruments for land, ocean and atmospheric monitoring, providing robust data for Copernicus Services. Although Sentinel calibration and validation (Cal/Val) activities are instrumental to each mission, they face some limitations. To overcome these, the EU-funded CCVS project will define a comprehensive solution for all Copernicus Sentinel missions. The project will propose an updated specification of Cal/Val requirements as well as an overview of existing Cal/Val sources and means and a gap analysis identifying missing elements and required developments. Focusing on responsibility, cost and schedule aspects, CCVS will also design a roadmap for implementation of the Cal/Val solution.

6.11 EUMETSAT

Under the Copernicus Programme, EUMETSAT provides EO data, products and support services to the Copernicus information services and user communities, with a focus on marine, atmosphere and climate. In the marine context, this role encompasses operating the Sentinel-3, Jason-3 and Sentinel-6/Jason-CS satellites. EUMETSAT produces Level 1 and Level 2 data such as:

The Level 1B products are:

- TOA (upwelling) radiances [$mW.m^{-2}.sr^{-1}.nm^{-1}$],
- Calibrated to geophysical units
- Ortho-geolocated onto the Earth's surface.

The Level 2 products are:

- Water reflectance in 16 bands
- Chla from Open and Complex Water approaches
- ADG at 443 nm

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- TSM
- K_d at 490 nm
- PAR

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7. Recommendations for the Roadmap

The main recommendation for the Roadmap is to highlight the need of an independent service for Water which will harmonize protocols, documentation, and data organization among the currently products offered by different services. Additionally, this new service should create a centralized database to collect and distribute the Copernicus products related to water quality and water quantity (D3.2). It is important to highlight the need for development of new products as well as the need for the computation of uncertainties of existing products. Table 2 summarizes the main recommendations for the Roadmap.

Table 2 – List of recommendations for the Roadmap

ID	Gaps & limitations	Needs	Recommendation
Product 1	The protocols, documentation, and data organization of water quality related products from different Services are not harmonized.	Create standard documentation among different services, create a centralized database.	Creation of a service to focus on Water (e.g. Copernicus Thematic Hub Water) where protocols from all services will be harmonized.
Product 2	The offered products are not complete for the monitoring of water quality, especially in environments used for water supply. More products are needed.	Development of products for shallow waters, and additional water quality parameters such as primary production, microplastic, nutrients, other phytoplankton pigments.	Support more product development
Product 3	Products for shallow water are limited	Understanding and development of shallow water products.	Support more research and development on shallow water

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			remote sensing.
Processing 1	Large uncertainty in atmospheric correction	Assessment of atmospheric correction (AC) under different atmospheric and water conditions	Atmospheric correction round robin exercises for AC validation under different atmospheric and water conditions
Processing 2	Larger atmospheric uncertainty near coast and shoreline due to adjacency effects	Atmospheric corrections that can deal accurately with adjacency effects	Development and performance assessment of atmospheric corrections that can correct for adjacency effect
Sensor 1	Cyanobacteria related products at 20-30m resolution	Additional spectral band at 620 nm on satellite sensors	Additional Sentinel-2 E spectral band at 620 nm. Hyperspectral satellite (e.g. CHIME)
Sensor 2	Carotenoids related products at 20-30m resolution	Additional spectral band at 470 nm	Additional Sentinel-2 E spectral band at 470 nm. Hyperspectral satellite (e.g. CHIME)
Sensor 3	Macroplastic related products at 20-30m resolution	Additional spectral band at 1070 nm on satellite sensors	Additional Sentinel-2 E spectral band at 1070 nm. Hyperspectral satellite (e.g. CHIME)
Sensor 4	Particles related products in very-absorbing waters at 20-30 nm resolution	Additional spectral band at 810 nm on satellite sensors	Additional Sentinel-2 E spectral band at 810 nm. Hyperspectral satellite (e.g. CHIME)
Sensor 5	Substrate type mapping in shallow waters	Additional spectral bands (i.e. Sensors 1 and 2 and listed	Additional Sentinel-2 E spectral band at 620 and 650 nm.

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		above) on satellite sensors	Hyperspectral satellite (e.g. CHIME)
Calibration and Validation 1	Lack of systematic in-situ data	Collection of automated data.	Use of new autonomous sensors such as: DNA identification, flow through absorption meters, flow cytometers with optical characterisation capabilities.
Calibration and Validation 2	Lack of systematic in situ R_{rs} data	Collection of automated data.	Use of new autonomous hyperspectral spectroradiometers for the acquisition of R_{rs} information. Include in regular monitoring programmes.
Calibration and Validation 3	Limited value of regular in situ monitoring programmes to validation.	Time series of water quality data to match-up with satellite passages, including key variables, strategic locations	Harmonize existing measurements by inter-comparison exercises (of protocols, calibrations and instruments). Increase 'satellite literacy' with key agencies to promote more support for remote sensing cal/val.
Capacity Building 1	Lack of knowledge on EO products by end-users	Training on the use of EO products	Support training for end-users at academic and non-academic events.

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