Technical needs for future Sentinels Water-ForCE

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30.11.2022	V2	Final version for internal review
12.12.2022	V3	Reviewed by project partners (dotSPACE, Water Insight, Groundstation SPACE)

List of Acronyms

CEOS	Committee on Earth Observation Satellites
Chl-a	Chlorophyll-a
CHIME	Copernicus Hyperspectral Imaging Mission for the Environment
CDOM	Coloured Dissolved Organic Matter
ECV	Essential Climate Variable
EO	Earth Observation
FLEX	FLuorescence EXplorer
FLORIS	Fluorescence Imaging Spectrometer
FWHM	Full Width Half Maximum
GALENE	Global Assessment of Limnological, Estuarine and Neritic Ecosystems
GLIMR	Geosynchronous Littoral Imaging and Monitoring Radiometer
HICO	Hyperspectral Imager for the Coastal Ocean
MERIS	MEdium Resolution Imaging Spectrometer
MM/MS	Multi-Mission/Multi-Sensor
MODIS	Moderate Resolution Imaging Spectroradiometer
MSI	Multi Spectral Imager
NAP	Non Algal Particle
NIR	Near InfraRed

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OLCI	Ocean and Land Color Imager
OLI	Operational Land Imager
PACE	Plankton, Aerosol, Cloud, ocean Ecosystem mission
PFT	Phytoplankton Functional Type
PRISMA SG	PRecursore IperSpettrale della Missione Applicativa Second Generation
Rrs	Remote Sensing Reflectance

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1 Executive summary

This document gives an evaluation of technical needs (e.g., spectral and spatial resolution) to make future Sentinel sensors more suitable for inland and coastal **water quality** monitoring. To this aim, we performed a multi-source review of documents providing innovative technical solutions for satellite missions that would be specifically designed (e.g., the Earth Explorer GALENE) for observing aquatic ecosystems. The participation in workshops on development of optical satellite missions and community network interactions also allowed to follow the progress on EO technology (e.g., Sentinel-2 NG, Sentinel-3 NGO) that might contribute to the observations of water quality in inland and coastal waters. The main recommendations on sensor features found in such analysis can be summarised as follow: hyperspectral sensor with **contiguous bands from UV to NIR** with an average **band width of 5 nm** possibly **augmented by a SWIR** imaging spectrometer with a **spatial resolution from 5 up to 33 m;** as spectral and spatial resolution are the core sensor priorities the **temporal resolution needs to be as high as is financially possible**. A 4°-5° fixed westward tilt is also recommendable for glint avoidance, multi-angular polarimeter and night observations have been also suggested within the ESA Earth Explorer 11. The value of **multi-mission/multi-sensor capabilities** was also discussed to cover the variety of resolutions needed to observe aquatic ecosystems while dedicated studies would be needed to quantitatively support our findings. It should be finally noted

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that, similar to the other Water-ForCE documents, this report provides inputs for the Water-ForCE Roadmap.

2 Introduction

Inland and coastal water ecosystems are environmentally important, provide multiple ecosystem services and are vital for human consumption, irrigation, sanitation, transportation, recreation and industry. In the past decades, these ecosystems have experienced high stress from various human impacts as well as climate change (Hartmann et al., 2013). Changes in the water cycle and temperature leading to new mixing regimes, habitat shifts along with increasing eutrophication and pollution are some of the major environmental threats of these environments.

Remote sensing techniques may be used for acquiring timely, frequent synoptic information, from local to global scales, of inland and coastal waters. Satellite based measurements of physical and biochemical parameters in these waters mainly rely on the interpretation of the spectral reflectance, which is used to retrieve water components, floating materials, water depth and bottom properties.

Satellite observations have been successfully applied for mapping inland and coastal waters for about 50 years (e.g., Strong, 1974; Wang and Shi, 2008; Stumpf et al., 2012; Bresciani et al., 2014; Matthews and Odermatt, 2015; Tyler et al., 2016; Pahlevan et al., 2017; Pahlevan et al., 2018; Wang and Yang, 2019). Overall, these studies focused on the retrieval of water reflectance, physical parameters (e.g., water colour, turbidity, diffuse attenuation coefficient, water clarity), suspended and dissolved water quality components such as chlorophyll-a (Chl-a) concentration (commonly used as a proxy of phytoplankton biomass), phycocyanin as proxy for cyanobacterial biomass, coloured dissolved organic matter (CDOM) and total suspended matter (TSM). Moreover, shallow water remote sensing, enabling for example the retrieval of benthic composition, bathymetry, fractional cover of substrate types (e.g., Kutser et al., 2020 and reference herein) and observations of floating materials (e.g., scum, floating

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vegetation, pollen, plastic), have been also widely supported by satellite observations (e.g., Guo et al., 2017; Topouzelis et al., 2021; Hu et al., 2023). In particular, for the specific purposes of water quality monitoring most of the applications have been supported by multispectral sensors and ocean colour radiometers as following:

- Multispectral Landsat data have been systematically used to have long-term lake water quality information on synoptic scale (Olmanson et al., 2008; Kallio et al., 2008; Kutser, 2012). More recently, the synoptic, fine-scale and high-frequency retrieval of these parameters has become possible because of the latest generation of medium to high spatial resolution multispectral sensors onboard Landsat-8 and Sentinel-2 satellites. Successful examples of the use of these new sensors are provided by for mapping corals, Giardino et al., (2014), Toming et al., (2016) and Kutser et al., (2016) for subalpine and boreal lakes, Dörnhöfer et al., (2016) for oligotrophic lakes, Vanhellemont and Ruddick (2014) for coastal turbid waters, Brando et al., (2015) for river plumes, Zoffoli et al., (2021) for intertidal seagrass meadow and Lobo et al., (2015) for rivers.
- For large water bodies, coarse and medium spatial resolution data gathered from ocean colour satellite sensors (e.g., MODIS, MERIS, OLCI) have been considered to offer suitable spectral, radiometric and temporal resolutions for aquatic studies (Savtchenko et al., 2003; Rast et al., 1999; Nieke et al., 2012). In particular, MERIS and OLCI, with their spatial resolution of about 300 m and dedicated spectral bands for detecting Chl-a in turbid waters, have been successfully used for studying lakes and coastal waters from 2002 (e.g., Odermatt et al., 2012); MERIS and OLCI also provided the retrieval of the lake water leaving reflectance (and related chlorophyll-a and turbidity products) for the global assessment of the impact of climate change on lakes, within the ESA CCI Essential Climate Variable (ECV) project (Carrea et al., 2022).

Despite the successful history of remote sensing applications for aquatic ecosystems, mostly in terms of water quality, current satellite radiometers are designed to observe the global ocean or land surface and thus not specifically designed for observing coastal and

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inland waters. The current land and ocean sensors are not optimised for these complex aquatic environments and consequently are not likely to perform as well as a dedicated sensor would (Palmer et al., 2015). Consequently, deriving coastal and inland aquatic applications from these existing sensors remains challenging (Mouw et al., 2015). Most of the challenges in inland and coastal water observations are due to their optical complexity and diversity, the fine scale to coarse spatial scale of water-related processes, with the obvious high degree of change. The trade-offs between spectral, spatial, radiometric and temporal sampling often mean that no single sensor or platform can provide all of the needs for any single user community or application (Muller-Karger et al., 2018).

3 Assessment of technical requirements

Several sources have been examined in order to gather the requirements on the technical needs for future Sentinel missions for aquatic ecosystems. Moreover, a dedicated analysis for suggesting the implementation of spectral bands for S2-NG has been performed.

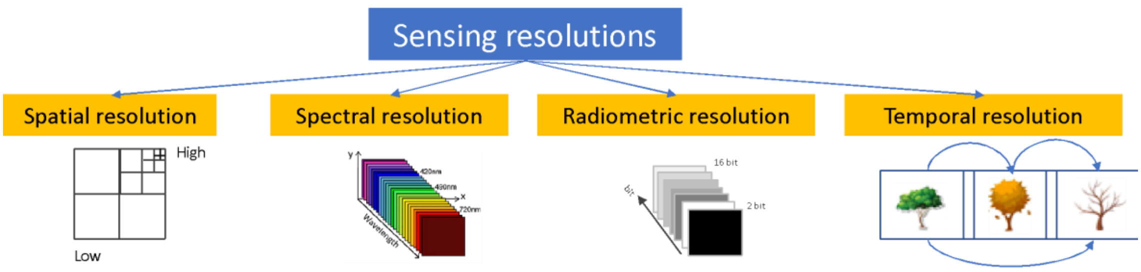

Figure 1 Principal resolutions used in satellite remote sensing for describing main elements of the imagery data.

The next sections summarise the needs we reviewed for future Copernicus satellite missions for aquatic ecosystems mapping, particularly focusing on water quality. The technical needs are collected from different sources, aim to cover the resolutions which usually define satellite data (Figure 1) and are defined as following:

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i) Spatial resolution determines the **size of the area being measured on the ground**. It has consequences for imaging water bodies and understanding of related processes, which might be characterised by a patchy distribution as well as interesting a small portion of water bodies (e.g., river plumes, algal blooms, floating matters, bottom substrates and wetlands parameters).

ii) Radiometric resolution determines **the lowest interval of radiance** or reflectance that the sensor can **reliably detect and discriminate per spectral band**. When the spectral and spatial resolution increase, the signal relative to noise in the data decreases (as less photons are captured). Notably, the water leaving signal at the satellite sensor is a small part of the total measured signal (composed of the water leaving signal plus the reflections at the air-water interface plus the signal from reflected sun and skylight in the atmosphere), hence radiometric resolution should be sufficient **to detect relevant levels at surface systems levels** variables through a set of atmospheric and air water interface conditions and solar angles. In addition, temporal **radiometric stability** is a key requirement to ensure consistent water quality products.

iii) Temporal resolution determines the **revisit time** of the sensor over the same area and should be able to represent the **high dynamics of ecosystems processes** in both deep and shallow water processes that might occur over diurnal, seasonal, and annual cycles. Temporal resolution also drives the compilation of satellite data archives to develop **time series** for understanding phenology and trend analysis.

3.2 CEOS Feasibility Study

In order to identify the requirements for aquatic ecosystem Earth observing capability, the CEOS study (Dekker, Pinnel et al., 2018) comprehensively considered the sensor ability to measure the following water quality indicators; notably this list corresponds also to feedback received at the Water-ForCE Workshop (WP2 and WP4) on *in situ* calibration and validation of satellite products of water quality and hydrology (Simis et al., 2021):

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- algal pigment concentrations of Chl-a, accessory pigments, cyanobacteria pigments,
- algal fluorescence (especially Sun-induced Chl-a fluorescence at 684 nm),
- suspended matter, possibly split up into organic and mineral matter,
- coloured dissolved organic matter and discriminate terrestrial from marine CDOM,
- spectral light absorption and backscattering of the optically active components,
- transparency of water such as Secchi disk depth, vertical attenuation of light and turbidity.

Then, for optically shallow waters:

- water column depth (bathymetry),
- substratum type and cover (e.g., muds, sands, coral rubble, seagrasses, macro- algae, corals, etc.) as well as plants floating at or just above the water surface.

For estimating the atmospheric composition and for residual sun glint correction (if sun glint mitigation measures are insufficient) it is also required to have spectral bands to measure O_3, NO_2, water vapour and aerosols as well as have some bands in the nearby infrared and/or SWIR for sun glint correction.

The results indicate that a dedicated sensor of aquatic ecosystems could be a multispectral sensor with around **26 bands in the 380-780** nm wavelength range. Then another **band at 810** nm is recommended to improve the retrieval of high concentrations of particulate matter (e.g., up to 70 gm^{-3}) in CDOM-rich waters (Kutser et al., 2016). There is a slight decrease in the water absorption coefficient around 810 nm and therefore any material that is scattering light (e.g., phytoplankton, dissolved mineral particles) creates a peak there. The usefulness of this band is especially useful in very dark CDOM-rich waters where the reflectance peak at 700-710 nm, that is typically used for mapping phytoplankton biomass (Gitelson, 1992) is still strongly affected by CDOM absorption (Kutser et al., 2016). Moreover, about **15 spectral bands between 360-380** nm **and 780-1400** nm are needed for removing atmospheric and air-water interface effects.

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Then, a sensitivity analysis was made to derive recommendations concerning radiometric sensitivity; the results indicate: i) maximum radiances over dark water bodies: **100 mW m^{-2} sr^{-1} nm^{-1}** in the blue and 20 mW m^{-2} sr^{-1} nm^{-1} in the red; maximum radiances for monitoring extremely turbid waters, bleached corals, and shallow waters with bright sand: 400 mW m^{-2} sr^{-1} nm^{-1} in the blue and 200 mW m^{-2} sr^{-1} nm^{-1} in the red; radiometric sensitivity NEDeltaL: in the range 0.005 mW m^{-2} sr^{-1} nm^{-1} (optimal) and 0.010 mW m^{-2} sr^{-1} nm^{-1}.

For polarisation, the CEOS study looks at PACE (Plankton, Aerosol, Cloud, ocean Ecosystem mission) (Gorman et al., 2019) requirements for which the upper limit for polarisation sensitivity is 1% while it is recommended that it be characterised to within 0.2% to reduce uncertainty in TOA radiances due to polarisation to less than 0.1% for a large majority of global ocean cases.

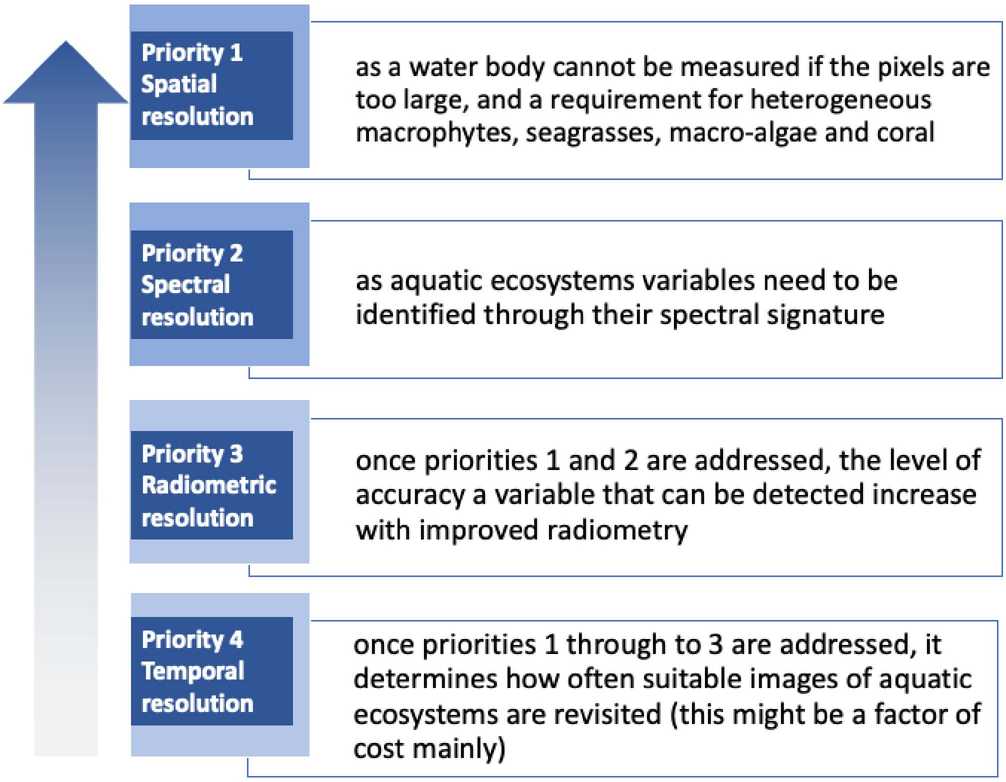

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Figure 2 Prioritization of resolutions based on the feasibility study for an aquatic ecosystem EO system (Dekker, Pinnel et al., 2018).

The CEOS requirements are very close to defining an **imaging spectrometer with spectral bands between 360 and 1000 nm** (suitable for Si based detectors), possibly **augmented by a SWIR** imaging spectrometer. In that case, the spectral bands would ideally have **5 nm spacing** and Full Width Half Maximum (FWHM), although it may be necessary to go to 8 nm wide spectral bands (between 380 to 780 nm where the fine spectral features occur -mainly due to photosynthetic or accessory pigments) to obtain sufficient signal relative to noise. A noise equivalent radiance difference (**NEΔL**) at **~ 0.005 $mWm^{-2}sr^{-1}nm^{-1}$** (optimal) and 0.010 $mWm^{-2}sr^{-1}nm^{-1}$ is, in fact, recommended. The **spatial resolution of** such a **global mapping mission would be between ~17 and ~33 m** enabling imaging of the vast majority of water bodies (lakes, reservoirs, lagoons, estuaries etc.) larger than 0.2 ha and ~25% of river reached globally (**at ~17 m resolution**) **whilst maintaining sufficient radiometric resolution**. As **spectral and spatial resolution are the core sensor priorities** (Figure 2), the **temporal resolution needs to be as high as is technologically and financially possible**. In fact, although high revisit frequency is probably not critical for applications focused on benthic mapping and inventory, it is critical for tracking processes such as algal blooming and coral bleaching.

3.1 Related publications

Gege and Dekker (2020) studied the measurement requirements of spectral resolution and radiometric sensitivity to enable the quantitative determination of water constituents and benthic parameters for optically deep and optically shallow waters. In particular, the spectral and radiometric variability was investigated by simulating Remote Sensing Reflectance (Rrs) spectra of optically deep water for twelve inland water scenarios; for optically shallow waters, Rrs changes induced by variable water depth are simulated for fourteen bottom

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substrate types, from lakes to coastal waters and coral reefs. The required radiometric sensitivity is derived for the conditions that the **spectral shape of Rrs** should be **resolvable with** a **quantization of 100 levels** and that **measurable reflectance differences at least one wavelength** must occur at **concentration changes in water constituents of 10%** and **depth differences of 20 cm**.

The results for **deep waters** overall showed that the spectral details of Rrs are most pronounced from about 480 to 600 nm and from 630 to 730 nm: in these regions, spectrally highly resolved measurements with **resolutions below 2.5 nm** should be used to gather spectral information. The lack of spectral details in Rrs makes spectrally highly resolved measurements in the NIR of little use, **except for high NAP** concentrations at specific spectral regions with local minima of pure water absorption; the most pronounced minimum at 810 nm corresponds to the spectral region used by Kutser et al. (2016) in black lakes.

In case of shallow waters, the results indicate that the **spectral interval** used for deriving information about the bottom **becomes narrower with increasing water depth**. Common to all bottom substrates is the upper boundary: above near 740 nm, light reflected at the bottom is detectable only in waters of typically less than 1 m depth. The spectral range **from 500 to 600** nm allows the measuring of light reflected from the bottom substrates **at 10 m** water depth. The width of this interval depends on the bottom albedo: the **darker the substratum**, the **narrower the range**; the **brighter the substratum** (e.g., bright sand or bleached coral), the **wider the spectral range and the greater the depth** at which a measurable signal is present.

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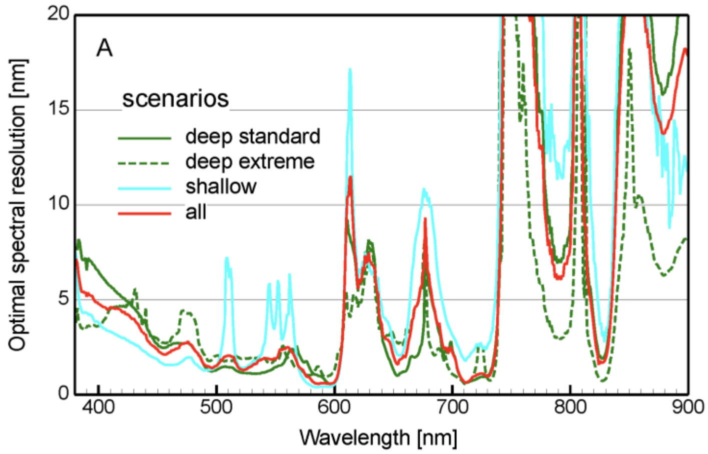

Figure 3 Medians of the optimal spectral resolutions for capturing the details of Rrs spectra simulated according to different scenarios of water conditions (from Gege and Dekker, 2020).

The optimal spectral resolution depends on wavelength (Figure 3). It ranges from **0.6 to 4.8 nm** in the **400-600 nm**, from **0.7 to 11.5 nm** in the **610-735 nm**, and increases significantly at 740 nm, exceeding 20 nm in wide spectral intervals. The **averages** across all scenarios **are 2.9 nm from 400 to 735 nm** and **13.8 nm from 740 to 900 nm**. The spectral pattern is similar for the standard and extreme scenarios of optically deep water, whilst the **optically shallow water scenarios produce more variable values in the 500 to 580 nm range**.

3.3 Sentinel-2 Next Generation

ESA initiated in 2018 an architectural design study to prepare the development of the next generation of the optical component of Sentinel-2 and Sentinel-3. This encompasses the next generation of the Multi Spectral Imager (MSI), Ocean and Land Color Imager (OLCI) and Sea and Land Surface Temperature Radiometer (SLSTR) observations (Löscher et al., 2020). In particular, within the temporal frame of Water-ForCE we had the opportunity to explore a series of technical requirements for Sentinel-2 NG. In fact, despite being designed as land

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imager, Sentinel-2 NG will offer, similarly as it is happening with Sentinel-2 (Figure 4), valuable data for mapping aquatic ecosystems.

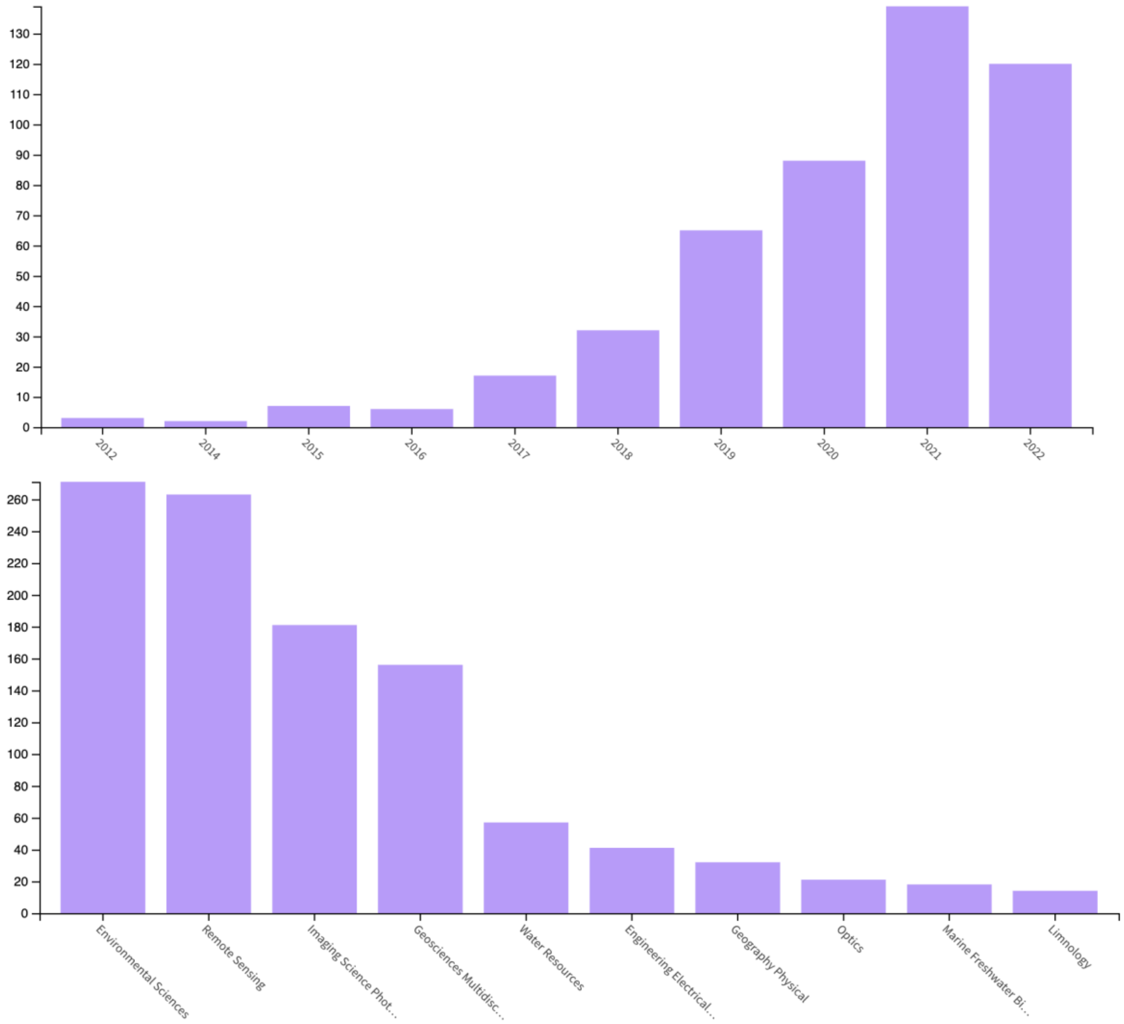

Figure 4 Web of Science (WoS) results for the keyword search 'Sentinel-2 AND Water quality'. A total of 480 publications were found; top: the number of documents by year; bottom: the results grouped according to the 10 most relevant WoS categories.

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Within the Water-ForCE project an activity has been hence promoted to interact with the community to follow the progress of S2-NG development. In particular, the potentiality of S2-NG for aquatic applications can be summarised as follows. Most of the requirements are based on Giardino et al. (2021) refined within the regularly WP2 project meetings and project workshops (e.g., 'Shallow water and floating matter remote sensing', Milano, 20-21/10/2022: https://waterforce.eu/workshops/shallow-water).

Spatial resolution: The potentiality of having a set of S2-NG bands with a spatial resolution of 5 m will be an added value for applications dealing fine scale mapping such as shallow waters and floating matter, two thematic fields for which a finer spatial resolution has a higher priority than an improved radiometry (e.g., high SNR). Although the **5 m pixel is intended for three visible bands only (Blue, Green and Red)** it could improve the delineation of **bottom types** in heterogeneous benthic habitats (Figure 5 and Figure 6) while it could be also crucial for mapping the **floating materials** such as scum, emerging/floating vegetation, plastic and pollen that may show a rather patchy distribution or narrow filaments that are narrower than pixels of current sensors. For example, a recent study from Taggio et al. (2022) demonstrated how the pan-sharpened hyperspectral data remotely sensed by **PRISMA at 5 m** spatial resolution enabled it to identify plastic targets offshore. Kutser (2004) showed that 30 m spatial resolution images of hyperspectral Hyperion sensor are too coarse for mapping cyanobacterial scum on the water: if scum patches are smaller than pixel size the resulting reflectance is a mixture of scum (scum layer bears similarities to reflectance of vegetation on land) and relatively clear water. The resulting spectrum has a peak between 700 and 710 nm. This is typical to waters with high biomass (mixed into the water column) (Gitelson, 1992). Consequently, the inadequate spatial resolution causes misunderstanding in interpreting cyanobacterial bloom images where floating on the water surface scum is identified as subsurface high biomass. The same problem occurs with 10 m spatial resolution of current Sentinel-2 sensors. Thus, the 5 m spatial resolution of S2-NG would allow much more accurate mapping of cyanobacterial blooms and other floating material, while, even if limited to three visible bands it can of

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course provide useful data for narrow water bodies (e.g., rivers, streams, fiords and bays, ports, aquaculture).

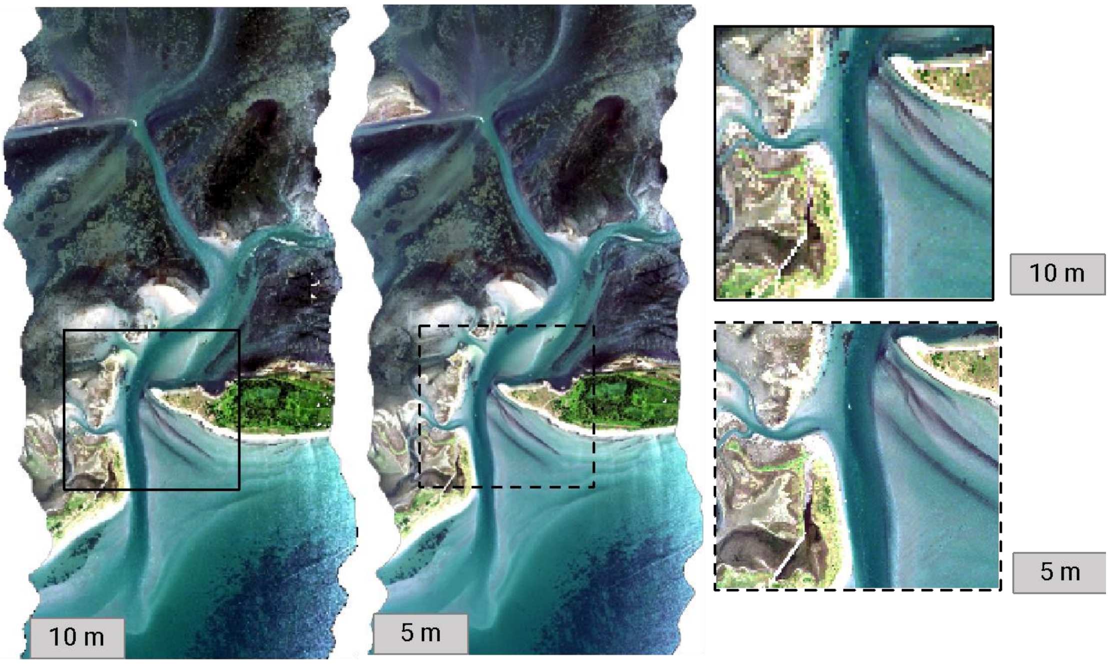

Figure 5 True colour imagery of a complex transitional ecosystems (Italy) where grey boxes indicate the pixel size: in this example they are at 10 m (left) and 5 m (right); the zooms show improved details for an area of about 1 km by 1 km (maps were generated downscaling airborne images gathered at 1 m ground sampling distance).

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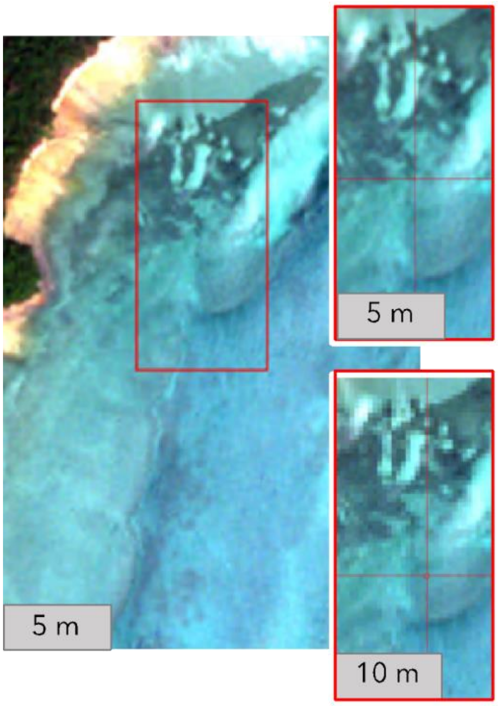

Figure 6 Left: True colour imagery of a coral reef ecosystems (Lampi Island, Myanmar) where grey boxes indicate the pixel size: in this example RapidEye are at 5 m spatial resolution; the zooms show improved details for an area of about 300 m by 900 m at 5 m and at 10 m (the second generated downscaling RapidEye data).

Spectral resolution: The following new spectral bands for S2-NG are proposed to improve the aquatic ecosystem mapping; the bands have been initially presented in the Water-Force Deliverable 2.2 (Analysis of current Copernicus water quality portfolio) and then further refined as follows.

- a '**Carotenoid**' band at 470 or 473 nm (as we know it was proposed for terrestrial plant and it can also support the phytoplankton recognition (Lee et al., 2007; Dekker et al., 1991);
- a '**Phycocyanin'** band at 620 nm (cf. Figure 7). A further 'Phycocyanin'-related band at 650 nm for phycocyanin algorithm (note: S2 has band 4 at 665 nm) (Kutser 2004; Lee et al., 2007; Dekker et a., 1992);
- a '**particulate material**' band at 810 nm band (Kutser et al., 2016) (cf. Figure 7);

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- a band at 1070 nm for extremely turbid water and floating matter (Knaeps et al., 2015; Knaeps et al., 2021; Moshtaghi et al., 2021);
- the existing Sentinel-2 MSI bands, plus those proposed here (620 nm, 650 nm and 810 nm) would also be good for **mapping shallow water** (Botha et al., 2013);

It would be good to have an UV band to help in **glint removal**, and to provide a second reference point **for atmospheric correction** (Cairo et al., 2020; Frouin et al., 2019; Kutser et al., 2013).

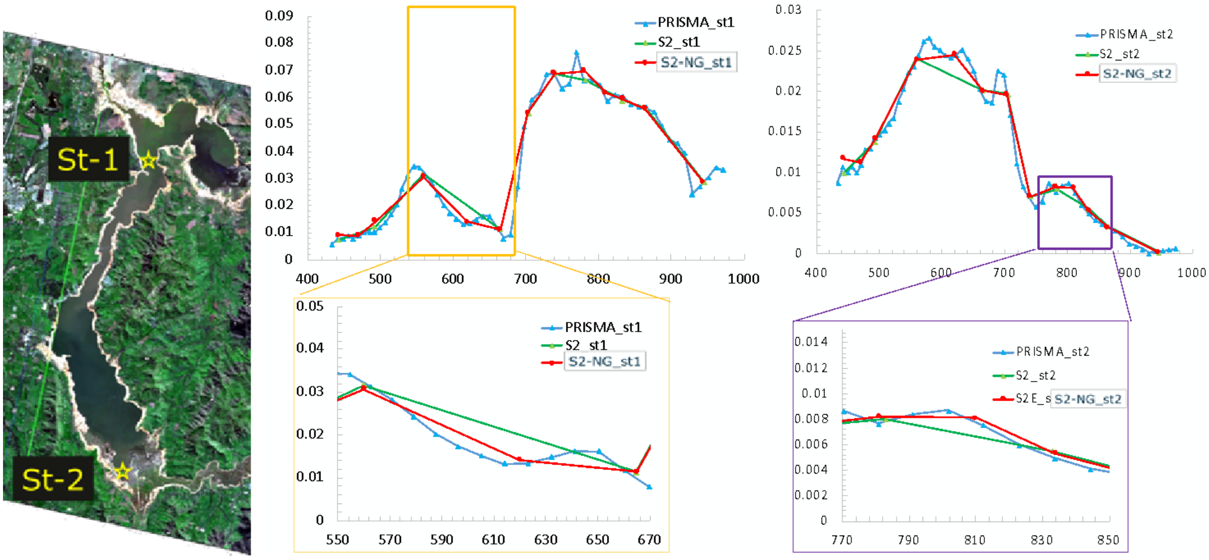

Figure 7 PRISMA image of Lake Hume in which St-1 is affected by the presence of cyanobacteria and St-2 by darker waters: the graphs show the Rrs spectra: in blue PRISMA, in green S2-MSI and in red S2-NG in which the band at 620 nm and at 810 nm are added to show how they improve the retrieval of water components (more appreciable in the zooms on key wavelength ranges).

Temporal resolution: the 5 days revisit (that in case of overlapping orbits becomes in the order of 3 days) with a sensing time of common Sun-synchronous land imagers (e.g., Sentinel-2, Landsat, PRISMA) is assumed reasonable for most of the applications (even if a consultation with stakeholders would be needed). Keeping S2-NG at the same overpassing

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time of S2 and Landsat is also valuable for being consistent to these missions in performing both retrospective studies and water quality monitoring and reporting. In the example provided in Figure 8 a sensing time between 11:00 and 12:00 local solar time is representative for most of the daylight conditions, apart from early morning and late afternoon where lower and higher phytoplankton pigments concentrations are observed, respectively.

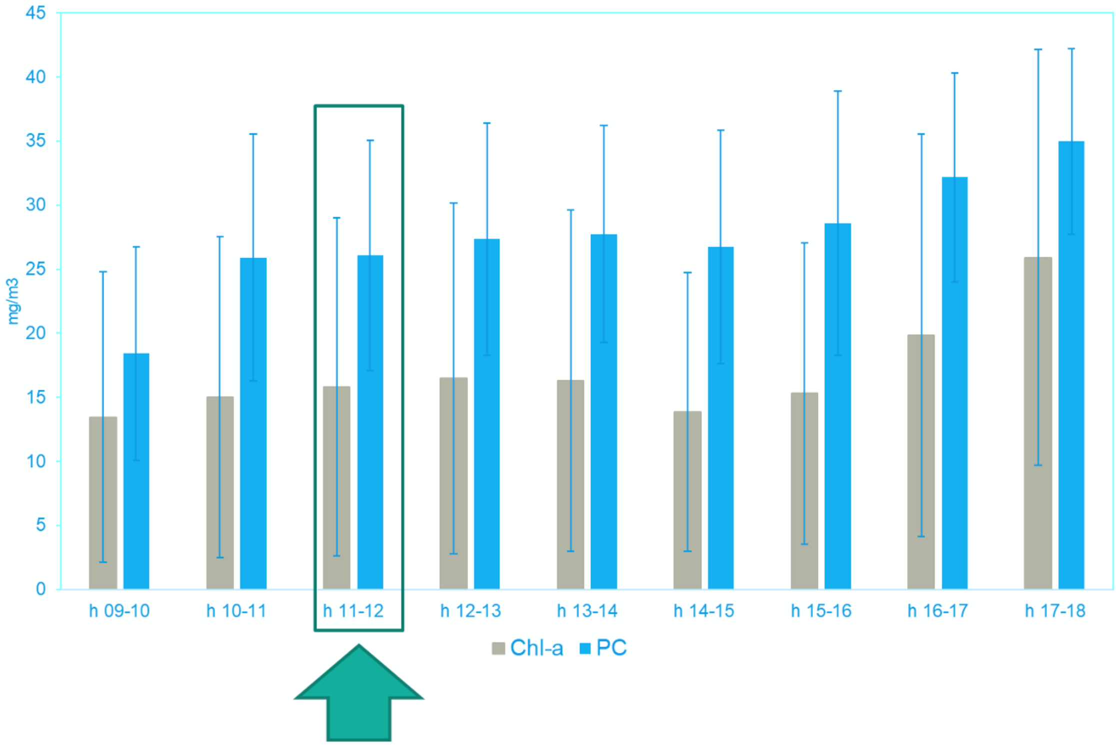

Figure 8 Two-years averages (with standard deviation) of chl-a and PC concentration in a turbid lake (Trasimeno, Italy) over hourly steps; the S2 sensing time is indicated with the green arrow.

For sake of completeness the recommendations listed above for S2-NG should be further investigated to assess, in addition to listed advantages, how they could impact on mission costs and data exploitation. It could be useful to measure the impact of increasing to 5 m the spatial resolution on data rating and on sensor swath, which will likely be narrower for

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5 m than for 10 m. Ongoing and future studies supporting the S2-NG developing phases have hence to be considered to update and revise this section.

3.4 GALENE

In occasion of the last call of ESA Earth Explorer 11 a proposal has been submitted with the name **Global Assessment of Limnological, Estuarine and Neritic Ecosystems** (GALENE) (Chami et al., 2022) to gain understanding on water and ecosystems properties and dynamics.

The proposal, that was unfortunately not selected to enter pre-feasibility study, was motivated by some specific need for aquatic ecosystems such as to advance understanding, to predict coastal and inland water dynamics and to define strategies for risk mitigation for which new versatile satellite-based approaches were considered necessary to provide evidence-based scientific data in a timely and reliable manner. The following societal challenges and applications were identified for GALENE.

- Support the needs of water managers and many end-users:
  - Conventions Ramsar, OSPAR and HELCOM, European Union Directives, United Nations Water Integrated Monitoring Initiative, Global Environment Monitoring System for freshwater.
- Various research and application fields:
  - global ***monitoring*** of inland water availability, quality and vulnerability in view of UN-Sustainable Development Goals;
  - ***carbon cycling*** across terrestrial-aquatic boundaries;
  - ***biodiversity*** and benthic community assessments;
  - ***status, functioning and resilience of aquatic ecosystems*** under environmental change and anthropogenic disturbances;
  - source, accumulation and sinking zones of ***plastic litter***;
  - ***ship security***, maintenance dredging, monitoring of erosion and sedimentation processes;

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- ***natural hazard assessment***, sea-level rise;
- fisheries ***management***, aquaculture activities.

The main mission features are indicated below, while Figure 9 shows key elements of the GALENE as presented by Chami et al. (2022).

- Global Earth coverage of inland and coastal waters < 50 km from the coastline
- **Dynamic sampling** of aquatic ecosystems in various dimensions:
  - Spectral: **hyperspectral** adjustable bands
  - Temporal: target pointing capability for **> 1 measurement per day**
  - Spatial: **from 2.5 m to 20 m and 100 m**
  - Angular: **5 to 10 viewing angles**
  - Observation: **night-time measurements** capability for turbidity, **daytime polarimetry**

Payload	350 - 450 kg / Power: 300 W
Hyperspectral Instrument (HSI)	120 bands [0.38 - 1.7 µm] – adjustable spectral resolution (3 nm VIS, 10 nm IR, 20 nm SWIR), SNR ~800, GSD: 30 m
Panchromatic camera (PAN)	[0.38 – 0.9 µm], Minimum radiance: 10^{-5} W m^{-2} sr^{-1} / GSD: 5 m
Multi-Angular Polarimeter (MAP)	12 viewing angles, +/- 60° nadir, 6 polarized bands (5 VIS + 1 NIR), GSD: 100 m, Noise-equivalent polarized reflectance: 10^{-4}
Swath/ Revisit / Tilt	250 km / 10 days / Tilt ~45° across-track
Lifetime	5 years
Payload	350 - 450 kg / Power: 300 W

Mission features	Added value
Polarimetry	Hydrosols composition (mineral vs biogenic)
Night observation	Turbid water dynamics
Hyperspectral	Benthic habitats, phytoplankton composition
Radiometry	Observation of very dark waters (majority of Earth inland waters)
Earth coverage	Areas < 50 km from the coastline, high latitude waters
Daytime revisit	At least two times per day (pointing capability)

Figure 9 Main characteristics of GALENE: on left the missions' features, on right the added value derived from these features.

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3.5 MARLISE

A concept for a dedicated marine litter satellite mission (MARLISE) was proposed at the Living Planet Symposium 2022 (more info in 'VITO web-page, Dec. 2022'). A feasibility study, financed by ESA-PRODEX was successfully finished providing an overview of the priority use cases, technical requirements for the mission and a first proposal for an instrument and mission concept.

The proposal was motivated by the need for a better understanding of the whereabouts, sources and sinks of marine (plastic) litter. Marine plastics are widely recognized as a major and urgent global environmental problem, with a major negative impact on marine life and leading to global economic loss, as well as posing risks on human health. On 3 March 2022, at the 5th UN Environment Assembly (UNEA-5) a historic resolution named **"End Plastic Pollution" was adopted** to **end plastic pollution** and forge an international legally binding agreement by 2024. **Monitoring, reporting and review mechanisms** are critical for the success of such a Global Plastics Treaty. The MARLISE concept proposed may lead to the development and full deployment of a marine plastics monitoring satellite system, called for by, and in support of the Treaty. MARLISE can fill the large gap in the knowledge on the amounts, sources and pathways of plastic litter, because current efforts only assure very partial observations.

The primary use cases were identified through a literature review and interviews with 30 stakeholders and experts from various (international) organisations and different countries, including 23 stakeholders from 10 different European countries.

As a result, three primary use cases are considered:

- Large scale monitoring of beach litter
- Monitoring of litter accumulations in coastal/estuarine fronts and coastal windrows
- Monitoring/detection of landfills

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Observational requirements, common to the primary use cases, were compiled as follows:

- Spectral range: **26 spectral bands** in the range **400 nm – 2350 nm**
- Spectral resolution: **bandwidths** of **10 nm – 20** nm for most bands
- Radiometric resolution: high signal to noise ratio (**SNR> 200** for a reference radiance)
- Spatial resolution: **1 – 3 m GSD (wavelength dependent)**
- Spatial range: Swath: **8 km – 12 km**

3.6 Spaceborne imaging spectroscopy

Following the launch of Hyperion which was followed a few years later by Chris-PROBA and HICO, a new generation of spaceborne hyperspectral sensors (e.g., PRISMA, GaoFen-5, DESIS, EnMap, HISUI), is now available for improving water resources monitoring, while future missions are also under development (e.g., CHIME, SBG, PRISMA-SG). In such framework, Hestir et al. (2015) showed how bio-optical algorithms, specifically developed for assessing water quality in optically complex water systems, perform best if they can make use of sensors providing measurements across numerous discrete narrow bands, forming a contiguous spectrum. For example, Zolfaghari et al., 2021, showed that when developing algorithms applicable to different optical water conditions is considered, the performance of models (in this case a multilayer perceptron neural network) applied to hyperspectral data (including HICO and PRISMA) surpasses that of those applied to multispectral datasets (with median biases of ~73%, 93%, 126%, and 83% for OLCI, MSI, OLI, and Landsat Next, respectively.) For example, PRISMA overall shows accurate Top-Of-Atmosphere (TOA) radiances (Giardino et al., 2020; Cogliati et al., 2021) and it provides promising valuable data for aquatic ecosystems mapping (Niroumand-Jadidi et al., 2020; O'Shea et al., 2021; Bresciani et al., 2022; Taggio et al., 2022).

Nonetheless, the challenge of atmospheric correction along with a sub-optimal radiometry (Braga et al., 2022) suggest that further technical needs would be required for operational

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use of satellite imaging spectroscopy in the field. Among the others there is the need of improving the radiometry as, over marine waters, the PRISMA SNR is lower than both HICO and Landsat SNRs, while it's at level of Sentinel-2 SNR (Figure 10); such weakness might impact on the retrieval of bio-geochemical parameters (Gege and Dekker 2020).

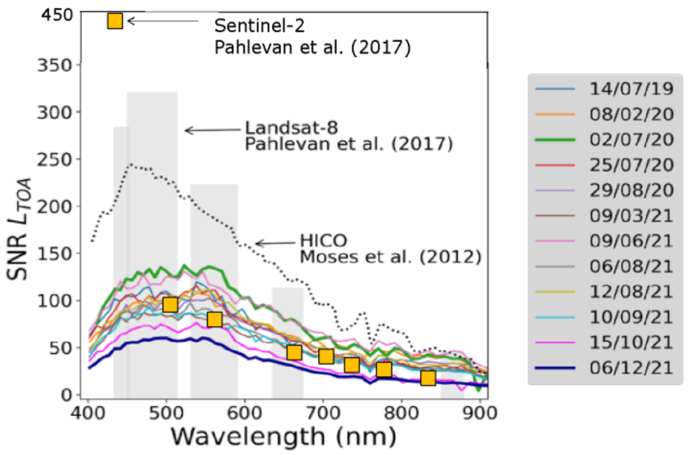

Figure 10 SNRs of PRISMA TOA radiances (L_{TOA}) calculated over sea water (i.e. AAOT AERONET site) for 12 scenes with thicker lines indicating those acquired with maximum and minimum Sun zenith angles. SNRs estimated for HICO (Moses et al., 2012), Landsat-8 and Sentinel-2 (the last two both from Pahlevan et al., 2017) are given as a qualitative reference (figure adapted from Braga et al., 2022).

To improve the SNR, **PRISMA-Second Generation (SG)** will offer ad-hoc tasking with higher integration time, while for **CHIME there will be the possibility of spectral/spatial binning**. Then, SBG also has a spatial resolution of 30 m and, to take into account the user needs from the water community from the decadal survey, the sensor will be **tilted 4°-5° westward** to mitigate the glint contamination, while PRISMA and PRISMA-SG might take advantage of the rolling platform, while for CHIME this is not discussed yet. In general, a **4°-5° fixed westward tilt** is recommended to **minimise the sun-glint** effects, for observing water targets. Notably, differently from existing spaceborne imaging spectroscopy, both **PRISMA-SG, CHIME and SBG will be global orbiting archiving missions**, so that a lot of services

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might be developed with hyperspectral technology in the near future by also both considering a pixel size ranging between **10 m (PRISMA SG, spotlight mode) to 30 m (SBG)**, and the ESA-NASA mission **cooperation efforts for CHIME and SBG,** to improve the temporal observational capabilities of a single mission.

3.7 Coarser spatial resolution satellites

Despite a key requirement for aquatic ecosystem mapping is a medium to high resolution, hence a class of sensor with GSD of the order of 5-30 m, the advantage of using coarse spatial resolution data with high revisit time is also valuable for mapping meso-scale processes. To the aim MERIS first and OLCI now have provided valuable data and supporting management and science relevant applications. For example, MERIS and OLCI provide a unique dataset for the ECV Lakes in terms of reflectance, Chl-a and turbidity (Carrea et al., 2022). In view of supporting a multi-mission approach the relevant elements of future missions that will contribute to develop Services for water quality are shortly presented.

Sentinel-3 NG

As said in Section 3.3, an architectural design study to prepare the development of the next generation of the optical component of Sentinel 3-NGO was initiated by ESA in 2018. With respect to OLCI it is under discussion to improve the **spatial resolution to 150 m** at least for coastal areas, inland waters and land, **with a goal of 100 m** (Cipollini et al., 2022). Furthermore, the inclusion of two UV bands and three SWIR bands at the same spatial resolution as the visible bands is under investigation. The SWIR bands will allow for an improvement of the atmospheric correction over turbid water regions, a better glint correction and improved cloud screening. The UV bands will also allow for a better aerosol characterisation and atmospheric correction over highly turbid waters.

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FLEX

The FLuorescence EXplorer (FLEX) mission (Drusch et al., 2016) will provide global maps of vegetation fluorescence that can reflect photosynthetic activity and plant health and stress **at spatial resolution of** 300 m. FLEX will carry the high-resolution Fluorescence Imaging Spectrometer (FLORIS), which will acquire data in the **500 - 780 nm spectral range**. It will have a sampling of 0.1 nm in the oxygen bands (759–769 nm and 686–697 nm) and 0.5-2.0 nm in the red edge, chlorophyll absorption and PRI (Photochemical Reflectance Index) bands so it might provide interesting data for observing also phytoplankton. It will in fact operate in tandem with Sentinel-3 so that the full visible spectra, including blue bands will be measured by OLCI. The **FLEX-S3 configuration** will overall provide relevant parameters on phytoplankton (such as algal pigments and quantum yield) to be simultaneously retrieved; by considering that thermal observations will be also available application on meso-scale ecosystems processes might be developed. **It is scheduled to launch in 2025**.

PACE

The NASA Plankton, Aerosol, Cloud, ocean Ecosystem mission (PACE) (Chami et al., 2022), currently in the design phase of mission development, aims to extend and improve NASA's over 20-year record of satellite observations of global ocean biology, aerosols (tiny particles suspended in the atmosphere), and clouds. PACE is scheduled to **launch in 2024** and will advance the observations on the distribution of phytoplankton, tiny plants and algae. It will also continue systematic records of key atmospheric variables associated with air quality and Earth's climate. PACE will **measure light (and colour)** over a **broader spectrum - and a finer resolution** - than ever before. This means that not only will PACE be able to identify how much phytoplankton is present, but the kind of phytoplankton that is there. Despite focusing on oceans, and pixel **size of 2.5 km** (up to 3 km for polarimetric data), larger inland and coastal water bodies will benefit from PACE observations.

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GLIMR

The Geosynchronous Littoral Imaging and Monitoring Radiometer (GLIMR) (Salisbury, 2022) has been selected as a space-based instrument under the NASA Earth Venture Instrument. GLIMR will be launched in the 2026-2027 time frame into a geosynchronous orbit where it will be able to monitor a wide area, **centred on the Gulf of Mexico**, portions of the south-eastern United States coastline, and the Amazon River plume for up to **15 hours a day**. From this vantage point, the hyperspectral ocean colour radiometer will measure the reflectance of sunlight from optically complex coastal waters in narrow wavebands. GLIMR will be able to gather many observations of a given area each day, a critical capability in studying phenomena such as the lifecycle of coastal phytoplankton blooms and oil spills in a way that would not be possible from a satellite in a low-Earth orbit. Given its unique spatial and temporal resolution, GLIMR will be highly **complementary to other low-Earth orbit satellites** that observe the ocean and coastal zones.

Such investment might indicate a route for future Copernicus missions on geostationary orbits as in the coastal environment the optical properties can vary on temporal scales that are shorter than the near-polar orbiting satellite temporal resolution (~1 image per day), which does not allow capturing most of the coastal optical variability (Bracagalia et al., 2021). Despite geostationary orbit presents new or more critical algorithmic challenges (e.g., atmospheric correction algorithms will need to be improved for high zenith angle) (Ruddick et al., 2014) and the typical spatial resolution is rather coarse, the sensors as GLIMR are here mentioned because by combining the high temporal resolution of geostationary sensors with the typically higher spatial resolution of polar-orbiters surely provide new water resources services to be developed (e.g., oil spill, lifecycle of phytoplankton blooms).

3.8 Very High Resolution Satellites

Within Water-ForCE we would suggest limiting Copernicus imaging satellites to the spatial resolution to 5 m, as for instance planned for three S2-NG visible bands (see section 3.2),

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without requiring further improvement of the spatial resolution. Within the project, it was discussed how the Very High Resolution (**VHR**) satellites (e.g., Pléiades, SPOT6/7, which might also include imaging spectroscopy as the **Planet Hyperspectral Satellite**) might continue to be **part of the private sector,** as it has been providing valuable data for multiple commercial services. Copernicus might instead support this private business by working on multi mission initiatives to come to a common calibration quality of sensors and quality of atmospheric correction tools.

Launching VHR satellites and providing high resolution products might be a risk of damaging private incentives. If Copernicus provides products and services based on VHR data, many private businesses might stop. As Copernicus is also intended to support European space business and by considering the excellence of the sector (e.g., Planet), we would hence agree not pushing for VHR, despite the usefulness of it for mapping fine scale features and processes that also interest aquatic ecosystems.

3.9 Miscellaneous

For sake of clarity, we avoid covering the following points, while we think they are worth mentioning as further contribution to the deliverable.

- **Atmospheric correction:** although not presented here, main uncertainties in inland water quality remote sensing come from atmospheric correction and adjacency effects (e.g., Pahlevan et al., 2021), and perhaps from unknown vertical stratification state. Technical needs presented in this report provide some inputs to mitigate this problem but for a comprehensive analysis please refer to the project deliverable 'D2.3 Atmospheric Correction'.
- **Radar remote sensing:** we do not cover this technology, while supporting it as in case of inland and coastal waters it also provided useful information (e.g., shallow water mapping, wind fields, currents, detection of floating material mapping, water body mapping) (e.g., Bresciani et al., 2014; Amadori et al., 2021).

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- **New missions:** although not presented here, more plans on new missions **dedicated to inland and coastal waters** observations exist. One of those is **AquaWatch Australia** to co-design and build an extensive network of purpose-designed Earth observation satellites and ground-based sensors to monitor the quality of Australia's rivers and coastal and inland waterways with real-time data and predictive analysis. Technical details of the mission are not available yet, but Water-ForCE will follow AquaWatch Australia for being updated on this topic.
- **Field infrastructures:** *In situ* measurements of reflectance are required for the inter-comparison and the synergistic exploitation of the current and expected satellite missions. Along with traditional field campaigns and cruises, an increasing number of autonomous hyperspectral radiometers, including those that can be operated on ferries (Qin et al., 2017; Brando et al., 2016), have been proved to support qualification of satellite data (e.g., Braga et al., 2022). As technical need of future Sentinels for the water continuum we hence support the need of these hyperspectral infrastructures (cf. HYPERNETS, MONOCLE and EOMORES H2020 projects) with global contributors and covering coastal, transitional and inland waters (including rivers) as they enable improved analysis of the satellite sensors performances. For example, an increased number of match-ups between satellite overpasses and field measurements will allow more robust statistical analyses, providing further information on the performance under varying observation geometry, atmospheric conditions and across various optical water types.

4 Conclusions, recommendations

A series of technical requirements have been presented -for comprehensive observations of aquatic ecosystems (on e.g., water bio-geochemistry, shallow water properties, detection and recognition of floating matter). Most of that applies to Sun synchronous VIS-NIR-SWIR

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optical polar orbits satellites, although geosynchronous satellites and thermal remote sensing are mentioned. In summary, the principal findings were the following:

- **Spatial resolution**: **from 5 up to 33 m**.
- **Spectral and radiometric resolutions**: **hyperspectral**, with contiguous bands from UV to NIR with an average **band width of 5 nm** (up to 8 nm) and possibly augmented by a SWIR imaging spectrometer. The radiometric resolution should be able to provide a **NE∆L at ~ 0.005 mWm-2sr^{-1}nm^{-1}** (up to 0.010 mWm^{-2}sr^{-1}nm^{-1}).
- **Temporal resolution**: as spectral and spatial resolution are the core sensor priorities the temporal resolution needs to be **as high as is financially possible**. A high temporal resolution could be obtained by a constellation of Earth observing sensors, while **mission's cooperation** (e.g., CHIME and SBG) for having sensors in multiple orbits and orbit types help to solve this issue. **Night-time** observations (e.g., proposed GALENE) and **geostationary** satellites (e.g., GLIMR) will also support valuable applications and new services in an improved temporal domain.
- **Additional sensors**: Thermal remote sensing (e.g., Copernicus LSTM Expansion mission, Landsat), dedicated satellite missions (e.g., FLEX) and additional instruments (multi-angular polarimeter, PAN camera) collected in synergy with optical observations are also encouraged to support new applications, services and to improve the discrimination and/or characterization of aerosol types, heights, and/or optical thickness (as recommended in 'Deliverable 2.3 Atmospheric Corrections').
- **Glint avoidance:** Satellite sensors that have been designed for use over water bodies have opted for either tilt or roll for sun glint avoidance to increase the fraction of glint free acquisitions; for example, OLCI has a 12 degrees westward roll to avoid sun glint. The LEO sensor we considered by CEOS key for aquatic ecosystem processes will need to be carefully designed to avoid sun glint as much as possible given that low latitudes earth observation will be a crucial component of this sensor mission with its abundance of shallow water tropical ecosystems such as coral reefs,

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tropical seagrasses etc. Sun glint avoidance thus will be a combination of (for polar orbiting LEO) overpass time and tilt of the sensor so that in case of SBG a **4°-5° fixed westward tilt has been recommended.**

In addition to defining and implementing new technical needs, a **multi-mission/multi-sensor (MM/MS) capabilities** (Figure 11) is a further solution to **cover the variety of resolutions needed to observe aquatic ecosystems**. Actually, both the features of current Sentinel and the Sentinel expansion missions, have been reviewed in the project deliverable 'D1.3 Links between missions-services-applications' for demonstrating their support for the inland water sector. The MM/MS approach has been also opening multiple scenarios for improved and novel applications. To this aim, the recommendations on **e.g., data interoperability** (e.g., Helder et al., 2018)**, common set of spectral bands** (for enabling easier algorithms adaption), **per instrument inter-band consistency, sensors intercalibration**, etc. have to be considered to fully exploit MM/MS capabilities (cf. ESA S2NG / S3NG SynOpto WS, 2022-11-29/30).

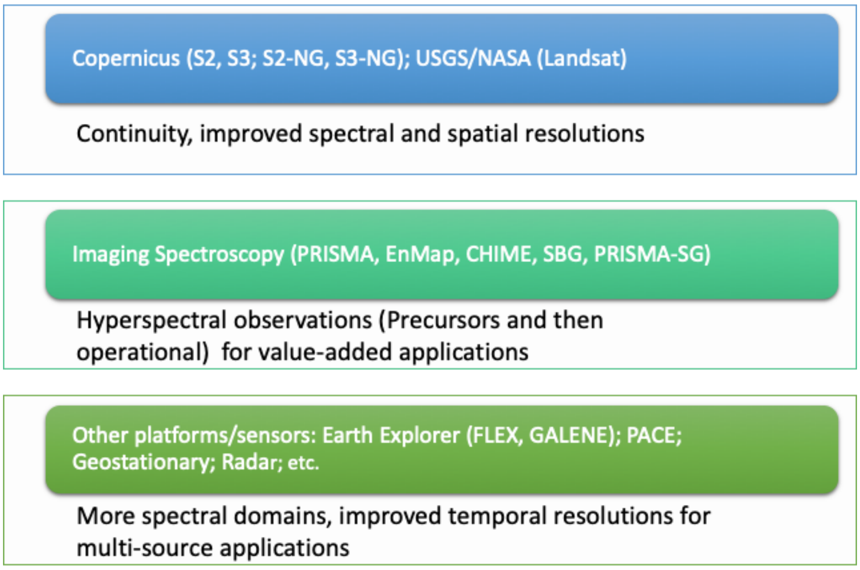

Figure 11 An overview of sensors and missions discussed in the deliverable, in view to exploit MM/MS capabilities.

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