

ALICE FABBRETTO

Exploiting spaceborne imaging  
spectroscopy in optically complex  
waters for aquatic ecosystems  
mapping



DISSERTATIONES TECHNOLOGIAE CIRCUMIECTORUM  
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Press

Department of Remote Sensing Tartu Observatory, Faculty of Science and Technology, University of Tartu, Estonia

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Supervisors: Associate Professor Krista Alikas, University of Tartu,  
Estonia  
PhD Claudia Giardino, National Research Council, Italy  
PhD Mariano Bresciani, National Research Council, Italy

Opponent: Prof. Ana Belén Ruescas Orient, University of Valencia,  
Spain

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## LIST OF ORIGINAL PUBLICATIONS

This thesis consists of an overview and six publications, which are referred to in the text by their roman numerals. The full texts of the publications are included at the end of the thesis.

- I Giardino, C.; Bresciani, M.; Braga, F.; **Fabbretto, A.**; Ghirardi, N.; Pepe, M.; Gianinetto, M.; Colombo, R.; Cogliati, S.; Ghebrehiwot, S.; Laanen, M.; Peters, S.; Schroeder, T.; Concha, J.A.; Brando, V.E. First Evaluation of PRISMA Level 1 Data for Water Applications. *Sensors* **2020**, *20*, 4553.
- II Bresciani, M.; Giardino, C.; **Fabbretto, A.**; Pellegrino, A.; Mangano, S.; Free, G.; Pinardi, M. Application of New Hyperspectral Sensors in the Remote Sensing of Aquatic Ecosystem Health: Exploiting PRISMA and DESIS for Four Italian Lakes. *Resources* **2022**, *11*, 8.
- III Braga, F.; **Fabbretto, A.**; Vanhellemont, Q.; Bresciani, M.; Giardino, C.; Scarpa, G.M.; Manfè, G.; Concha, J.A.; Brando, V.E. Assessment of PRISMA water reflectance using autonomous hyperspectral radiometry. *ISPRS Journal of Photogrammetry and Remote Sensing* **2022**, *192*, 99–114.
- IV Pellegrino, A.; **Fabbretto, A.**; Bresciani, M.; de Lima, T.M.A.; Braga, F.; Pahlevan, N.; Brando, V.E.; Kratzer, S.; Gianinetto, M.; Giardino, C. Assessing the Accuracy of PRISMA Standard Reflectance Products in Globally Distributed Aquatic Sites. *Remote Sensing*. **2023**, *15*, 2163.
- V **Fabbretto, A.**; Bresciani, M.; Pellegrino, A.; Alikas, K.; Pinardi, M.; Mangano, S.; Padula, R.; Giardino, C. Tracking Water Quality and Macrophyte Changes in Lake Trasimeno (Italy) from Spaceborne Hyperspectral Imagery. *Remote Sensing* **2024**, *16*, 1704.
- VI **Fabbretto, A.**; Bresciani, M.; Pellegrino, A.; Kangro, K.; Greife, A.J.; Panizza, L.; Steinmetz, F.; Kuusk, J.; Giardino, C.; Alikas, K. Exploring the Spectral Variability of Estonian Lakes Using Spaceborne Imaging Spectroscopy. *Applied Sciences* **2025**, *15*, 8357.

## AUTHOR'S CONTRIBUTION

Several co-authors contributed to the papers on which this thesis is based. The author's contribution in presented publications is indicated by their Roman numbers below:

- I** Study co-design, processing of satellite data, simulation of *in situ* data at Top of Atmosphere, validation of PRISMA L1 data by comparison with *in situ* measurements.
- II** Processing of satellite data, atmospheric correction of PRISMA and DESIS images.
- III** Processing of satellite data, atmospheric correction of PRISMA images, validation of PRISMA L2 data by comparison with *in situ* measurements.
- IV** Study co-design, processing of satellite data, validation of PRISMA L2 data by comparison with *in situ* measurements.
- V** Study design leader, processing of satellite data, participation in the field-work to collect *in situ* data, validation of PRISMA, DESIS and EnMAP data by comparison with *in situ* measurements, generation of water quality products, analysis of the ancillary environmental data, lead author in writing the paper.
- VI** Study design leader, processing of satellite data, participation in the field-work to collect *in situ* data, validation of PRISMA and EnMAP data by comparison with *in situ* measurements, generation of water quality products, analysis of the ancillary environmental data, lead author in writing the paper.

## ABBREVIATIONS AND ACRONYMS

6SV	Second Simulation of the Satellite Signal in the Solar Spectrum-Vector
AC	Atmospheric Correction
AERONET-OC	Aerosol Robotic Network – Ocean Colour
AIS	Airborne Imaging Spectrometer
AOT	Aerosol Optical Thickness
ASI	Italian Space Agency
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
CASI	Compact Airborne Spectrographic Imager
CDOM	Coloured Dissolved Organic Matter
CHIME	Copernicus Hyperspectral Imaging Mission for the Environment
Chl-a	Chlorophyll-a
CHRIS-PROBA	Compact High Resolution Imaging Spectrometer aboard the Project for On-Board Autonomy
DESI	DLR Earth Sensing Imaging Spectrometer
DLR	Space Agency of the German Aerospace Center
EnMAP	Environmental Mapping and Analysis Program
EO	Earth Observation
ESA	European Space Agency
FRM	Fiducial Reference Measurement
FWHM	Full Width at Half Maximum
GSD	Ground Sampling Distance
HICO	Hyperspectral Imager for the Coastal Ocean
HYPSTAR	Hyperspectral Pointable System for Terrestrial and Aquatic Radiometry
IOCCG	International Ocean-Colour Coordinating Group
ISS	International Space Station
L1	Level 1
L2	Level 2
MAPD	Mean Absolute Percentage Difference
MSI	MultiSpectral Imager
NASA	National Aeronautics and Space Administration
NIR	Near-infrared
OLCI	Ocean and Land Colour Imager

PACE	Plankton, Aerosol, Cloud, ocean Ecosystem
PANTHYR	Pan-And-Tilt HYperspectral Radiometer
PC	Phycocyanin
PRISMA	PRecursore IperSpettrale della Missione Applicativa
R <sup>2</sup>	Coefficient of determination
RS	Remote Sensing
RMSD	Root Mean Square Deviation
Rrs	Remote sensing reflectance
S2	Sentinel-2
S3	Sentinel-3
SDGs	Sustainable Development Goals
SNR	Signal-to-Noise Ratio
SWIR	Shortwave infrared
TOA	Top Of Atmosphere
TSM	Total Suspended Matter
VIS	Visible
WFD	Water Framework Directive

# 1. INTRODUCTION

## 1.1. Background

Lakes and coastal zones are critical components of Earth's hydrological and ecological systems, as they provide essential ecosystem services such as freshwater storage, biodiversity maintenance, and climate regulation [1–3]. These areas support high levels of biological productivity and are pivotal in global biogeochemical cycles; the importance of these ecosystems is further underscored by their role in mitigating the impacts of extreme weather events and carbon emissions. Over the past several decades, inland and coastal waterbodies have faced escalating environmental stress due to anthropogenic pressures, climate change, and pollution [4–7]. These pressures can lead to biodiversity loss, eutrophication, altered flow regimes, and long-term degradation of ecological functions [8,9]. Such transformations highlight the urgent need for accurate and scalable methods to monitor the ecological health of aquatic ecosystems. Because these impacts are often cumulative and spatially variable, systematic monitoring is required to generate reliable datasets that allow for temporal trend analysis and spatial comparisons across catchments. Within the European Union, this requirement is embedded in the Water Framework Directive 2000/60/EC (WFD), which establishes an integrated framework for the protection of inland surface waters, transitional waters, coastal waters, and groundwater [10,11]. To fulfil this objective, the WFD requires comprehensive and standardised monitoring programs covering the investigation on biological, hydro-morphological and physicochemical conditions: such monitoring traditionally relies on field-based sampling and laboratory analyses [12,13]. While this approach is remarkably precise and accurate, it can be limited in terms of both space and time due to cost, logistical constraints, and the heterogeneity of the aquatic systems.

Remote sensing (RS) offers a complementary approach to WFD implementation, as it improves spatial and temporal coverage and supports management of aquatic ecosystems threatened by anthropogenic and climatic pressures [14–17]. Satellite and airborne sensors provide synoptic, repeatable, and multi-temporal observations at multiple spatial scales, enabling cost-effective surveillance of large and remote areas [18–20]. Optical sensors can capture information on several water quality parameters, for instance turbidity, chlorophyll-a (chl-a) concentration, colored dissolved organic matter (CDOM), total suspended matter (TSM), and on the presence and distribution of submerged and emergent vegetation [21]. These are key factors in the assessment of the ecological status of a waterbody. Overall, RS is not a replacement for traditional field monitoring but a powerful complementary tool.

While traditional multispectral sensors have laid the foundation for large-scale water monitoring, recent advancements in hyperspectral RS, also known as imaging spectroscopy, now is offering unprecedented potential for detailed observation of aquatic environments [22–25]. It provides hundreds of contiguous,

narrow spectral bands typically spanning the visible (VIS), near-infrared (NIR), and shortwave infrared (SWIR) regions of the electromagnetic spectrum, allowing subtle optical differences in aquatic environments to be resolved, which is far beyond the capability of traditional multispectral sensors. This enables more advanced applications in aquatic science such as the characterization of water quality [26], phytoplankton composition [27], and detection of phycocyanin (PC) [28], which is a photosynthetic auxiliary pigment that is abundant in cyanobacteria, whose presence cannot be captured by traditional multispectral sensors, with few exceptions [29]. By capturing data with high spectral resolution, hyperspectral imagery supports the development of new algorithms and insights into aquatic ecosystem dynamics, while maintaining compatibility with existing multispectral approaches. As a result, it offers a powerful and future-proof tool for advancing the precision, scope and extent of aquatic ecosystem monitoring and management. The combination of *in situ* data and hyperspectral RS-derived products supports more robust ecological status classification, enhances spatial representativeness, and allows for rapid response to sporadic and temporary events such as algal blooms [30].

The concept of hyperspectral RS [31] originated from the first airborne hyperspectral imager NASA's Airborne Imaging Spectrometer (AIS) [32] built in early 1980s, the first operational airborne hyperspectral imager Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) [33,34] launched in middle 1980s, and the first commercial airborne hyperspectral instrument Compact Airborne Spectrographic Imager (CASI) [35,36] developed since late 1980s. These instruments demonstrated the scientific potential of contiguous, narrow-band spectral data, which enabled the identification of subtle absorption features associated with vegetation pigments, minerals, and water quality parameters [37]. Their success established imaging spectroscopy as a transformative observational approach and prepared the ground for its transition from airborne to spaceborne platforms. The first practical realization of a hyperspectral imaging spectrometer in space occurred with the launch of NASA's Hyperion instrument onboard the Earth Observing-1 (EO-1) satellite, in 2000. Hyperion provided more than 200 contiguous spectral bands between 400 and 2500 nm at a spatial resolution of 30 m [38–42]. Although conceived as a technology demonstrator, Hyperion operated for nearly two decades and generated a global archive that has been extensively used for land cover mapping, geology, agriculture, and water quality studies. The mission demonstrated both the scientific utility and the technical challenges of spaceborne hyperspectral RS, particularly issues related to radiometric calibration and Signal-to-Noise Ratio (SNR). Following Hyperion, the launch of Compact High Resolution Imaging Spectrometer aboard the PROject for On-Board Autonomy satellite (CHRIS-PROBA) in 2001 marked a milestone in EO and satellite technology [43]. The mission demonstrated how a small, low-cost satellite could perform sophisticated scientific imaging tasks once possible only with large and expensive spacecraft. One of the key achievements of the mission was its on-board autonomy: PROBA-1 was designed to operate with minimal ground control, testing advanced features such as automatic fault detection,

recovery, and attitude control. This autonomy paved the way for the development of future self-managing satellite systems. The CHRIS instrument provided high-resolution hyperspectral and multi-angle imagery, allowing scientists to analyse how light interacts with Earth's surfaces from different directions [44]. Afterwards, several experimental and pre-operational initiatives further advanced the field. The Hyperspectral Imager for the Coastal Ocean (HICO), launched in 2009 and mounted on the International Space Station (ISS), represented the first spaceborne imaging spectrometer specifically optimized for aquatic environments. HICO demonstrated the feasibility of hyperspectral observations of optically complex coastal and inland waters, and it provided a valuable testbed for AC algorithms and aquatic bio-optical retrievals [45–51]. Other demonstrators, such as the Japanese Hyperspectral Imager Suite (HISUI, launched in 2019 on the ISS) are providing additional data and operational experience [52,53].

In more recent years, a series of advanced missions building on these earlier efforts has also been developed in Europe. Notably, the Italian Space Agency (ASI) launched the first proof-of-concept hyperspectral mission, PRecursor IperSpettrale della Missione Applicativa (PRISMA), in 2019. To enable the exploitation of hyperspectral PRISMA data, a pivotal step is the validation of radiance and remote sensing reflectance (Rrs) products. It plays a crucial role in ensuring that the data obtained from the satellite sensor accurately represent the actual conditions of the surveyed waterbody [54]. Validation involves comparing satellite-derived measurements with reliable reference data, such as Fiducial Reference Measurement (FRM) [55]. This process helps to assess the accuracy of the satellite products, identify potential biases, and improve the calibration of sensors and the performance of retrieval algorithms. As a result, validation ensures that radiance and Rrs products are consistent, reliable, and scientifically sound. Another key aspect of validation is maintaining data continuity and comparability across different satellite missions. By confirming that products from various sensors and platforms are consistent, validation supports the creation of long-term, harmonized datasets that are essential for monitoring environmental and climatic changes. Moreover, validation builds confidence among users of satellite data, including researchers, policymakers, and industry professionals. It assures them that the products meet established accuracy standards and can be used for a wide range of applications, such as ocean color analysis and climate modeling. An additional critical step in ensuring the generation of reliable surface Rrs products, suitable for use in water quality retrieval algorithms, is the implementation of an accurate atmospheric correction (AC) [56–58]. This process is required to remove the disturbance of the atmospheric interference from the Top Of Atmosphere (TOA) signal recorded by the sensor. As reported in the International Ocean Colour Coordinating Group (IOCCG) 2010 report [59], AC is very challenging in inland and coastal waters due to the complex interactions of the atmosphere and water. Water-leaving radiance signals are typically weak compared to atmospheric contributions, which can account for more than 90% of the total radiance measured at sensor. Without proper correction for gases, aerosols, and scattering effects, retrieved Rrs values may be significantly biased,

leading to unreliable estimates of water quality parameters such as chl-a or TSM. Accurate AC ensures that the derived surface  $R_{rs}$  reliably represents the optical properties of the waterbody, enabling robust algorithm development, inter-mission comparability, and long-term monitoring of aquatic environments. Particularly in inland and coastal waters, inaccuracies in AC still introduce substantial uncertainties into satellite-derived products, thereby limiting the capability to detect subtle variations within aquatic ecosystems. To quantify these uncertainties, it is essential to assess sensor performance throughout the mission's lifetime to evaluate the quality and reliability of the resulting products. Accordingly, specific validation protocols have been established, typically based on extensive *in situ* measurements acquired concurrently with satellite overpasses, which are representative of the actual conditions at the observed aquatic sites [54,60–63].

While PRISMA is an important technological achievement on its own, its broader value lies in its integration within the constellation of European hyperspectral spaceborne missions. Synergies between PRISMA and other hyperspectral sensors, both current and forthcoming, are of paramount importance for enhancing scientific yield, ensuring improved temporal-spatial coverage, standardized product generation, and international cooperation to foster the development of globally consistent EO strategies. Regarding the European hyperspectral sensors currently in orbit, the German Aerospace Center (DLR) launched the DLR Earth Sensing Imaging Spectrometer (DESI) in 2018 and the Environmental Mapping and Analysis Program (EnMAP) in 2022. Synergies across missions expand temporal coverage and observation density; given the inherent trade-offs between spectral richness and spatial-temporal resolution in hyperspectral systems, no single mission can provide continuous global coverage at both high spatial and temporal frequency. The combined use of PRISMA alongside other spaceborne hyperspectral instruments can overcome these limitations by enabling more frequent monitoring of dynamic phenomena enhancing the ability to capture short-term processes and long-term trends that might otherwise remain undetected by a single platform. The simultaneous availability of diverse but complementary hyperspectral datasets encourages the adoption of harmonized retrieval methods for essential variables. This, in turn, supports the creation of interoperable products that can be used in global environmental monitoring frameworks, climate services, and policy-relevant applications, including those linked to the United Nations Sustainable Development Goals (SDGs) [64]. By aligning mission objectives and technical specifications through cooperative programs, the scientific community can maximize the return on public investment in space-based infrastructure while reducing duplication of effort. Such collaboration is especially significant in light of the increasing challenges posed by climate change, ecosystem degradation, and natural resource management, where comprehensive and harmonized observational data are necessary for informed decision-making [65].

## 1.2. Objectives of this work

The general aim of this thesis is to investigate and leverage the potential of last-generation hyperspectral satellite data for water quality mapping.

Accordingly, three specific sub-objectives have been identified and pursued:

- To assess the radiometric quality of Level 1 Top Of Atmosphere radiance data acquired by PRISMA to evaluate the potential for inland and coastal aquatic remote sensing applications, through comparison with *in situ* measurements distributed globally (**I**).
- To assess the accuracy of PRISMA-derived surface reflectance products over inland and coastal waters, through comparison with *in situ* observations distributed globally (**III, IV, V, VI**).
- To develop water quality applications across diverse study areas that exhibit different optical characteristics, using PRISMA in synergy with existing hyperspectral spaceborne missions. This will involve investigating the spectral features of the main optically active components (**II, VI**), generating water quality products (**II, VI**) and tracking environmental changes (**V**).

## 2. MATERIALS AND METHODS

### 2.1. Satellite data

This chapter provides an overview of three imaging spectroscopy EO missions that provided data for the purposes of this research, i.e. PRISMA, DESIS and EnMAP: these satellite sensors offer similar and complementary capabilities in terms of spatial, spectral, and temporal resolutions and are critical for a wide range of environmental monitoring applications. Additionally, the multispectral satellite missions Sentinel-2 (S2) and Sentinel-3 (S3) will be briefly discussed. These missions complement the hyperspectral data and provide valuable contextual information for analysis.

PRISMA is an Italian hyperspectral EO mission developed by ASI [66–69]. Launched in March 2019, PRISMA combines a hyperspectral sensor with a panchromatic camera, enabling both detailed spectral analysis and moderate spatial resolution imagery, as well as the fusion of the two data sources [70]. In this thesis, only data from the hyperspectral camera were considered. PRISMA's main objective is to support environmental monitoring, precision agriculture and forestry management. The processor used to obtain PRISMA Level 2 (L2) Rrs products is based on the MODTRAN (v 6.0) [71] and uses a multidimensional approach based on look-up tables designed for land applications. L2 products are available in the PRISMA catalogue at different processing levels: namely, L2B (geolocated spectral radiance product), L2C (geolocated reflectance product) and L2D (geocoded and orthorectified version of L2C product). In the various publications, PRISMA L2C and L2D products were used interchangeably as they are equivalent in the selected study areas, where orthorectification is not required. From this point onwards, they will be referred to collectively as L2 products.

DESI is a German hyperspectral imaging spectrometer operated by DLR [72–74]. It was deployed aboard the ISS in October 2018. The mission supports a broad spectrum of applications including urban analysis, crop monitoring, forest health assessment, and coastal studies. Its onboard location on the ISS provides flexible, user-driven acquisition planning, though with more limited coverage compared to sun-synchronous orbiting satellites.

EnMAP is a German hyperspectral satellite mission operated by DLR, launched in April 2022 [75–80]. It is designed to provide high-quality hyperspectral data for environmental research and resource management. EnMAP is focused on deriving biophysical, biochemical, and geochemical variables from Earth surface observations. It has been engineered to address applications in land use monitoring, soil mapping, water quality assessment, and vegetation stress detection. EnMAP is the first of these three sensors to present a specific AC for water targets.

In the following table (Table 2.1), the key characteristics of each hyperspectral sensor are shown.

**Table 2.1.** List of the main features of the PRISMA, DESIS and EnMAP payloads.

	<b>PRISMA</b>	<b>DEGIS</b>	<b>EnMAP</b>
Launch	22 March 2019	29 June 2018	1 April 2022
Coverage	70°N to 70°S	55°N to 52°S	Global in near-nadir mode
Spatial resolution	30 m	30 m	30 m
Spectral resolution	239 bands (400–2500 nm)	235 bands (400–1000 nm)	246 bands (420–2450 nm)
Atmospheric correction	MODTRAN v 6.0 (land based)	PACO (land based)	PACO (land) MIP (water)

In this thesis, ESA’s Copernicus S2 and S3 data were used as an additional reference to validate the hyperspectral data, highlighting the advantages that can be gained by integrating the latter to obtain a more accurate characterization of water quality [26,81–84]. The near-coinciding observations from S2 and S3 have enriched the dataset, as they are a frequent source of data for inland and coastal water RS applications, with a solid track record in terms of calibration and validation [85–88]. In the following table (Table 2.2), the key characteristics of S2 and S3 multispectral sensors are shown.

**Table 2.2.** List of the main features of the S2 and S3 payloads.

	<b>S2</b>	<b>S3</b>
Launch	23 June 2015 (Sentinel-2A) 7 March 2017 (Sentinel-2B)	16 February 2016 (Sentinel-3A) 25 April 2018 (Sentinel-3B)
Coverage	Global coverage every 5 days (S2A+S2B)	Global coverage every 1/2 days (S3A+S3B)
Spatial resolution	10/20/60 m	300 m
Spectral resolution	13 bands (443–2190 nm)	21 bands (400–1020 nm)
Atmospheric correction	Sen2Cor (land based)	L2gen (water based)

Specifications on the spatial, spectral and temporal resolutions of the Rrs data gathered from S2 MultiSpectral Instrument (MSI) and S3 Ocean and Land Colour Instrument (OLCI) are presented in Publication **I** and **VI**.

## 2.2. *In situ* data collection

The *in situ* data used for spaceborne data validation and algorithm parametrization originates from various datasets. These are described in detail in Publications I–VI. The accuracy of the PRISMA Level 1 (L1) and L2 products was evaluated using a combination of radiometric data provided by established observation networks and by dedicated field activities. The validation dataset was designed to maximize spatial coverage and ecological diversity across the study areas, while adhering to recognized protocols for radiometric validation of satellite products [55].

Measurements from the Aerosol Robotic Network – Ocean Color (AERONET-OC) served as a primary reference. AERONET-OC provides measurements of normalized water-leaving radiance measured by CIMEL sun photometers installed on fixed offshore platforms, which offer standardized, quality-controlled measurements across multiple spectral bands, derived from automated radiometric instruments deployed at fixed coastal and inland water sites. These data are widely regarded as a benchmark for satellite ocean color validation due to their strict calibration and quality assurance procedures [89–94].

Hyperspectral *in situ* measurements were obtained from several fixed stations, the first of which is the Pan-And-Tilt HYPerspectral Radiometer (PANTHYR) station located in Venice (Italy) and part of the WATERHYPERNET network [95]. It consists of two TriOS-Ramses hyperspectral radiometers, mounted on a pan-and-tilt pointing system; it autonomously acquires hyperspectral Rrs every 20 minutes during daytime at programmed relative azimuth angles to the sun.

Additional measurements were obtained from the Hyperspectral Pointable System for Terrestrial and Aquatic Radiometry (HYPSTAR) instrument, part of the HYPERNETS network in Venice (Italy) and in Lake Võrtsjärv (Estonia), which consists of hyperspectral radiometers designed for continuous above-water acquisition of Rrs. The HYPSTAR system is equipped with a hyperspectral radiometer featuring dual optical entrances, configured to measure both upwelling water-leaving radiance and downwelling irradiance, allowing for calculation of the water surface reflectance at high temporal resolution (20 minutes intervals) [61–63,96].

Further validation was supported by observations from WISPStation system (located in Lake Trasimeno, Italy [97,98]), which autonomously provides above-water Rrs data in near real-time. High-quality continuous measurements are obtained by recording radiance and irradiance over an extended wavelength range of 350–1100 nm in two viewing directions. All channels are captured using a single spectrometer equipped with an optical multiplexer.

The deployment of autonomous fixed-position optical sensors has also been recognised as an effective method of retrieving optically active constituents [99] as it reveals both inter- and intra-daily changes in parameters' concentrations.

To complement the continuous monitoring networks, ad-hoc field campaigns were organized in several study areas (i.e. Lake Trasimeno in Italy and Lake Peipsi in Estonia). During these fieldworks, radiometric measurements were

acquired using portable hyperspectral instruments, following protocols recommended by the IOCCG for satellite products validation [100]. Field activities were scheduled to coincide with PRISMA overpasses to minimize temporal mismatches. Radiometric data, i.e. above-water Rrs measurements, were collected using WISP-3 instrument [101] in Lake Trasimeno and with TriOS-Ramses instrument [101,102] in Lake Peipsi. The optical range of the WISP-3 is 380–800 nm, with a bandwidth of 4.9 nm; the irradiance is measured with an Ocean Optics CC3 cosine collector and the other two radiometers point at angles of 42° relative to the zenith and the nadir, to measure both radiance from the sky and the water. The TriOS-Ramses [103], equipped with radiance and irradiance sensors too, provides 256 channels operated in the range from 350 to 950 nm. It can be used for hand-held and autonomous applications and can be deployed above or below water. The accuracy of the measurements depends on the sensitivity and the calibration of the spectrometers, and a correct deployment.

In addition to the radiometric observations, ancillary *in situ* data were collected, including water quality parameters, bio-optical measurements, and atmospheric variables, which are essential for the parameterization of the algorithms and for the validation of the water quality products.

The combination of standardized network data and targeted field measurements provided a comprehensive data framework, allowing for an evaluation of both sensor radiometry and AC performance and for the implementation of the models for water quality mapping across a range of aquatic environments.

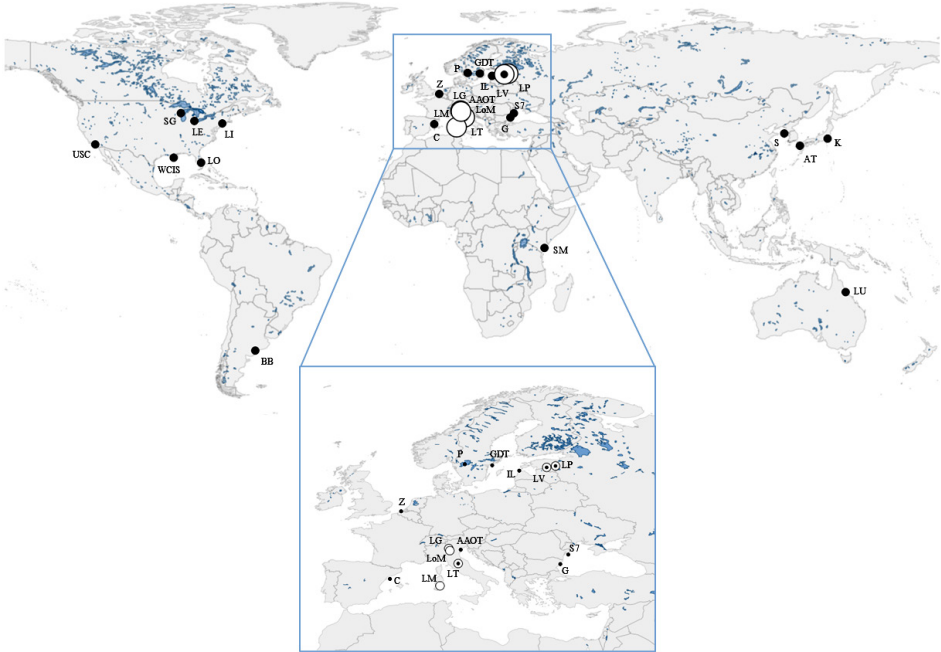
The study areas presented in this thesis are distributed globally, covering six continents, with a denser occurrence in Europe. Table 2.3 below provides a list of the study areas, including their names and acronyms, a brief description of the type of water, details of the devices present and how the images relating to each area were used (e.g., for validation or implementation of an application).

**Table 2.3.** List of the study sites (name and acronym), water type and device present, use in the study.

Site	Water type / Device	Use
Aqua Alta Oceanographic Tower (AAOT)	Optically complex waters with varying concentrations of sediments and CDOM / CIMEL, PANTHYR, HYPSTAR	Validation (I, III, IV)
Ariake Tower (AT)	Turbid waters / CIMEL	Validation (IV)
Bahia Blanca (BB)	Highly turbid waters with high suspended loads / CIMEL	Validation (I, IV)
Casablanca (C)	Clear waters / CIMEL	Validation (I, IV)
Galata (G)	Optically complex waters with varying concentrations of sediments and CDOM / CIMEL	Validation (IV)
Gustav Dalen Tower (GDT)	Optically complex waters with high concentrations of CDOM / CIMEL	Validation (IV)

<b>Site</b>	<b>Water type / Device</b>	<b>Use</b>
Irbe Lighthouse (IL)	Optically complex waters with high concentrations of CDOM / CIMEL	Validation (IV)
Kemigawa (K)	Eutrophic waters, high chl-a concentration values, occurrences of red and blue tide / CIMEL	Validation (IV)
Lake Erie (LE)	Characterized by the presence of algal blooms / CIMEL	Validation (IV)
Lake Garda (LG)	Large deep lake characterised by clear waters / HYPSTAR	Application (II)
Lake Mulargia (LM)	Elevated suspended solids with episodic algal bloom events / WISP-3	Application (II)
Lakes of Mantua (LoM)	Highly productive with coexistence of dense phytoplankton / WISP-3	Application (II)
Lake Okeechobee (LO)	Humic-rich lake/ CIMEL	Validation (IV)
Lake Peipsi (LP)	Divided into three systems, from mesotrophic to hypertrophic conditions / TriOS RAMSES	Validation (VI) Application (VI)
Lake Trasimeno (LT)	Shallow, turbid, eutrophic lake / WISPStation, WISP-3	Validation (I, III, V) Application (II, V)
Lake Vörtsjärv (LV)	Shallow, very turbid, eutrophic lake / HYPSTAR	Validation (VI) Application (VI)
LISCO (LI)	Optically complex waters with varying concentrations of CDOM / CIMEL	Validation (IV)
Lucinda (LU)	Tropical coastal waters of the Great Barrier Reef / CIMEL	Validation (I, IV)
Palgrundén (P)	Oligotrophic state with high CDOM concentration / CIMEL	Validation (IV)
San Marco (SM)	Turbid waters / CIMEL	Validation (IV)
Section 7 (S7)	Optically complex waters with varying concentrations of sediments and CDOM / CIMEL	Validation (IV)
Socheongcho (S)	Turbid waters / CIMEL	Validation (IV)
South Greenbay (SG)	Turbid waters / CIMEL	Validation (IV)
USC Seaprism (USC)	Clear waters / CIMEL	Validation (IV)
WaveCIS (WCIS)	Optically complex waters with varying concentrations of CDOM / CIMEL	Validation (IV)
Zeebrugge (Z)	Highly turbid waters / CIMEL	Validation (I, IV)

To follow, Figure 2.1 shows the spatial distribution of the study areas, with a focus on Europe due to the higher density of points in this region. Black dots indicate validation points, white dots indicate areas where applications have been developed and white dots with a black dot inside indicate areas used for both purposes.



**Figure 2.1.** The location of the study areas, and a focus on Europe. Black dots represent validation points; white dots represent application areas; white dots with a black centre indicate areas used both for validation and for application purposes.

### 2.3. Processing

To conduct the evaluation of the radiometric quality of L1 TOA radiance data acquired by PRISMA, the vector version of the Second Simulation of the Satellite Signal in the Solar Spectrum-vector (6SV) was used to simulate the satellite signal starting from *in situ* measurements provided by AERONET-OC network, PANTHYR and WISPSation. The entire process is explained in Publication I. The PANTHYR and WISPSation data were spectrally resampled according to the bandwidth of PRISMA products, AERONET-OC data were assumed directly comparable to PRISMA as both sensors present around 10 nm bandwidth. A spectral sub-setting of 12 bands was considered in the study to be consistent with the spectral configuration of the CIMEL instrument, and several metrics were calculated: the coefficient of determination ( $R^2$ ), the Root Mean Square Deviation (RMSD) and the Mean Absolute Percentage Difference (MAPD).

To evaluate the accuracy of PRISMA L2 surface Rrs products, the *in situ* data (gathered from AERONET-OC network, WISPStation and fieldworks) were corrected as explained in [104] to remove the sunglint effects, when present; the satellite data were extracted as explained in Publications **III**, **IV** and **V** and the same metrics as in the case of L1 validation were calculated. The same spectral sub-setting of 12 bands was considered and in cases where an image occurred more than once in the dataset (e.g., it was present in two different publications), only the most recent version was selected.

To test alternative AC methods for PRISMA L1 imagery data, corrections were performed with ACOLITE version 20210802.0 [105,106] and POLYMER [51,107] as explained in Publication **III** and **VI**. As before, the same 12 bands were considered for consistency.

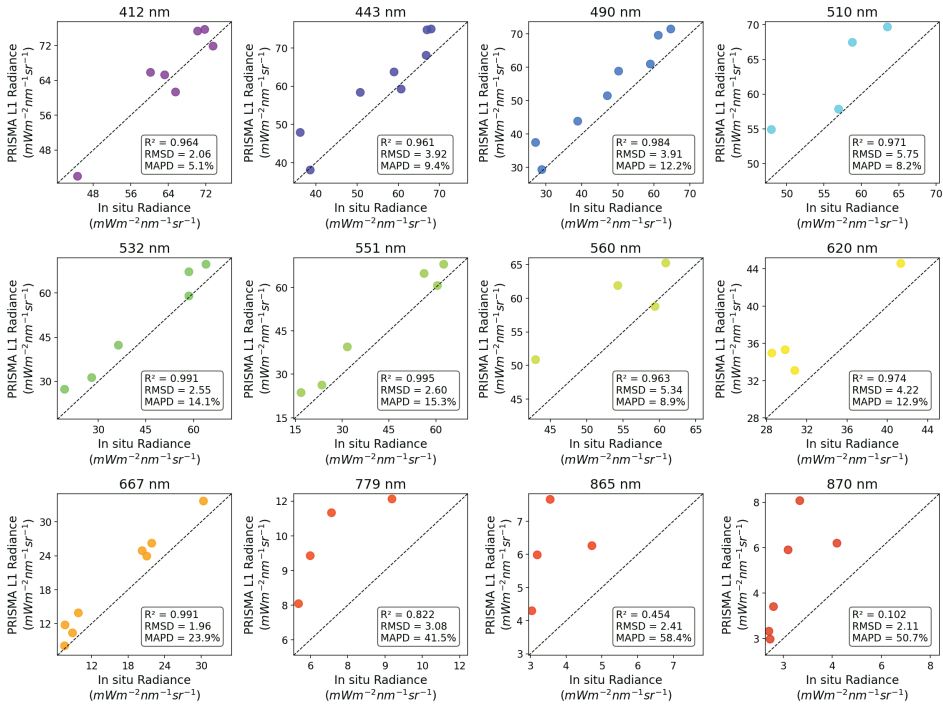
To explore the possibilities offered by using PRISMA in synergy with other hyperspectral sensors (DESI and EnMAP), the procedures dedicated to PRISMA have been standardised and adapted to the other two sensors due to their similar spectral configuration, to obtain a harmonised dataset. To generate water quality products various approaches have been followed: the bio-optical model BOMBER [108] was run to simultaneously retrieve chl-a, CDOM and TSM concentration and the coverage of submerged and emergent macrophytes; value-added products, such as PC concentration maps, were generated through a machine learning model (MDN [28]). Finally, to assess the variability in the water quality parameters and of the aquatic vegetation in a specific case-study, the products were integrated to perform a spatio-temporal analysis. The entire processes are explained in Publications **II**, **V** and **VI**.

### 3. RESULTS AND DISCUSSION

In this chapter, the results are organized following the logical sequence of the three sub-objectives introduced in section 1.2.

#### 3.1. Assessment of PRISMA L1 radiance products (I)

The results of the assessment of the radiometric quality of Level 1 Top Of Atmosphere radiance data acquired by PRISMA over inland and coastal waters are shown in Figure 3.1. The dataset includes data from Publication I.



**Figure 3.1.** Scatterplots between *in situ* and PRISMA L1 radiance data, for each of the 12 bands considered (x-axis shows *in situ* data while the y-axis shows PRISMA L1 data). The dashed black line refers to the 1:1 line.

Overall, most wavelengths (412–667 nm) exhibit strong correlations ( $R^2 > 0.96$ ), low RMSD, and low MAPD, indicating a good agreement between satellite and *in situ* data. However, performance degrades at longer wavelengths (865–870 nm), where  $R^2$  drops sharply (as low as 0.10 at 870 nm), reflecting higher uncertainty and reduced sensor accuracy in the NIR region.

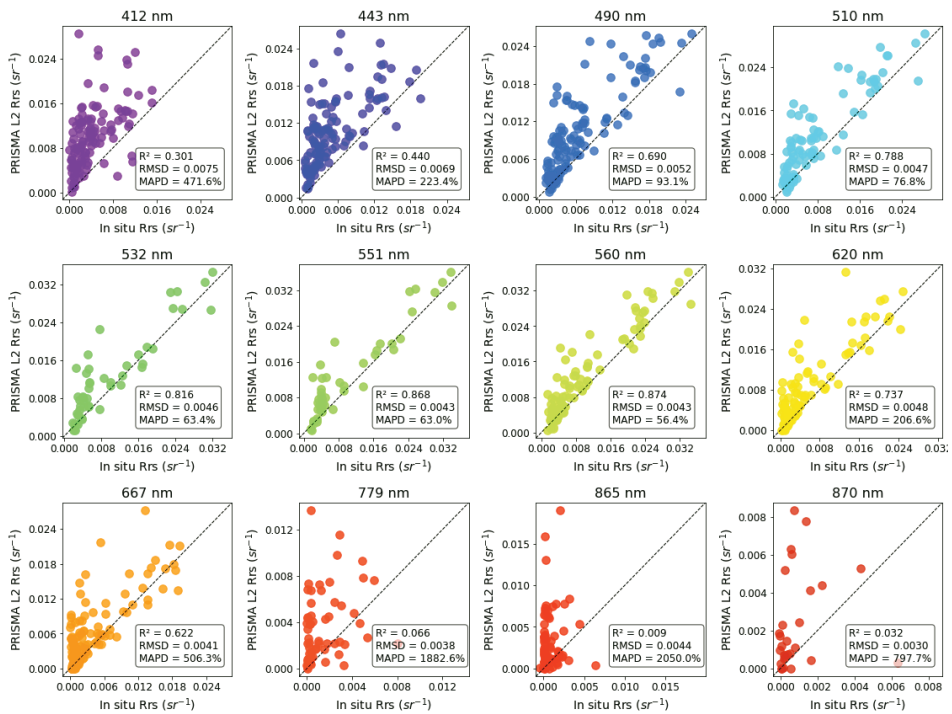
The verification of PRISMA radiometric data accuracy constituted the primary and essential step in enabling all subsequent analyses. This is due to the fact

that robust radiometric performance is a prerequisite for the reliable use of a satellite sensor in quantitative RS, temporal change detection, and multi-sensor comparisons. Discrepancies may arise from using the 6SV model without accounting for the effects of adjacency or sky radiance at the air-water interface.

Moreover, the limited number of match-ups may have constrained the ability to detect differences related to varying illumination or viewing geometries, as reported in other studies where variations in TOA radiances between sensors were attributed to differences in viewing and solar zenith angles [109].

### 3.2. Assessment of PRISMA-derived Rrs products (III, IV, V, VI)

The results of the assessment of the accuracy of PRISMA-derived surface reflectance products over inland and coastal waters are presented into two different plots. Figure 3.2 displays the comparison between the ASI-atmospherically corrected standard L2 products and the corresponding *in situ* measurements. The dataset includes data from Publications III, IV and V.



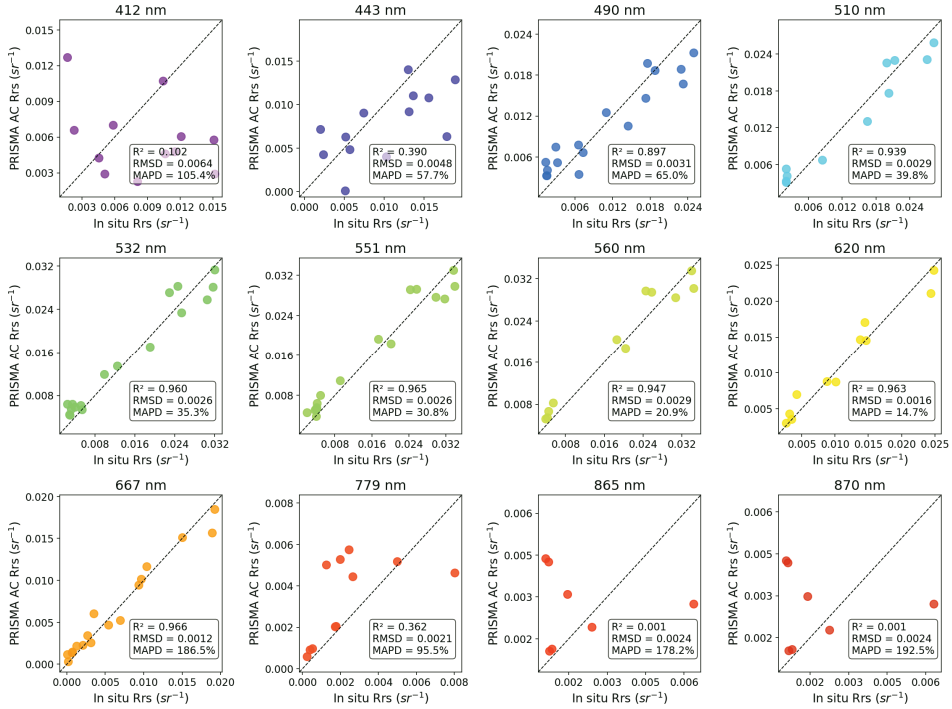
**Figure 3.2.** Scatterplots between *in situ* and PRISMA L2 Rrs data, for each of the 12 bands considered (x-axis shows *in situ* data while the y-axis shows PRISMA L2 data). The dashed black line refers to the 1:1 line.

In the violet-blue region of the electromagnetic spectrum (412, 443 nm)  $R^2$  values are indicating weak correlation ( $R^2 < 0.45$ ), high MAPD values (greater than 220%) indicate that PRISMA L2 products significantly over-estimate the reflectance compared to *in situ* observations. This result suggests that the standard AC algorithm struggles with the violet-blue Rrs possibly due to the complexity of AC or low signal levels. In the blue-green to green region of the spectrum (490–560 nm)  $R^2$  improves substantially (with values between 0.69 and 0.87) and RMSD and MAPD decrease (the last reaching values below 60%). These values indicate that PRISMA L2 performs well in the green-cyan range, which is ideal for monitoring water quality. In the orange-red region of the spectrum (620, 667 nm) the  $R^2$  values are moderate to high ( $R^2 = 0.74$  and  $R^2 = 0.62$  respectively), while the MAPD value begins to increase again compared to the values obtained in the green region. Some overestimation remains in this region. In the NIR region of the spectrum (779–870 nm) very low  $R^2$  (values below 0.1) and extremely high MAPD (up to 2050%) resulted.

PRISMA L2 products fail to reproduce *in situ* values at NIR wavelengths, likely because water Rrs values are extremely low in this region and the signal is dominated by noise. In general, PRISMA L2 data show reasonable agreement with *in situ* measurements in the visible green to yellow range (490–560 nm). Performance drops in the violet-blue (412, 443 nm) and NIR regions, with extremely poor correlation in the NIR region of the spectrum (779–870 nm). The assessment of PRISMA-derived Rrs demonstrates the growing potential of imaging spectroscopy for aquatic ecosystem monitoring, while also highlighting the persistent challenges associated with AC over optically complex waters.

PRISMA products exhibited promising capabilities in retrieving Rrs within the visible range, where uncertainties and biases are lowest. This indicates that, under favourable illumination and viewing geometries, the mission provides sufficient radiometric stability to enable quantitative water quality retrievals. These results revealed that the standard L2 processor, designed for terrestrial applications, produces variable accuracy depending on water type, aerosol conditions, and geometric factors. The current limitations in the PRISMA standard processing chain stem mainly from the lack of water-specific AC and the use of generic aerosol models (i.e. “rural” type) not optimized for maritime or coastal conditions. Adjacency effects, sun-glint, and sky radiance contributions at the air-water interface also introduce residual uncertainties that are not mitigated by the L2 algorithm.

Figure 3.3 illustrates the comparison between PRISMA data corrected for atmospheric effects using alternative AC models, i.e. ACOLITE and POLYMER (hereafter referred to as PRISMA AC) and the corresponding *in situ* measurements. The dataset includes data from Publications **III** and **VI**.



**Figure 3.3.** Scatterplots between *in situ* and PRISMA AC Rrs data, for each of the 12 bands considered (x-axis shows *in situ* data while the y-axis shows PRISMA AC data). The dashed black line refers to the 1:1 line.

The performance varies considerably across the spectrum. At shorter wavelengths (412, 443 nm), the agreement is poor, with very low  $R^2$  (values below 0.4), thus indicating large discrepancies. The results improve significantly from 490 nm onward, especially between 510 and 620 nm, where  $R^2$  values exceed 0.93 and MAPD falls below 40%, reaching the best performance at 620 nm with MAPD under 20%. Similar to the results obtained with L2 products, at NIR wavelengths (779–870 nm), the correlation decreases again, with  $R^2$  tending to zero and MAPD exceeding 170%, suggesting that PRISMA retrievals are unreliable in this region. PRISMA AC products display a similar trend to PRISMA L2: poor agreement in the violet-blue region, promising performance in the green region, and reduced accuracy in the NIR region. Nevertheless, PRISMA AC show better results overall, as it exhibits the same pattern of limitations but with smaller errors. The analysis demonstrates that, when properly corrected using dedicated tools such as ACOLITE or POLYMER, PRISMA data can deliver Rrs suitable for bio-geophysical parameter retrievals. Overall, the results highlight PRISMA’s significant contribution as a pathfinder mission for aquatic hyperspectral RS. The convergence of results across local and global scales confirms its robustness in the visible range and underscores the importance of developing standardized, water-specific AC protocols and validation networks. These efforts will be essential to fully exploit the scientific potential of hyperspectral data for monitoring

inland and coastal water dynamics in the coming decade. Similar results were found in [54,80] when performing AC of Landsat-8, Sentinel-2 and EnMAP images with ACOLITE and POLYMER models.

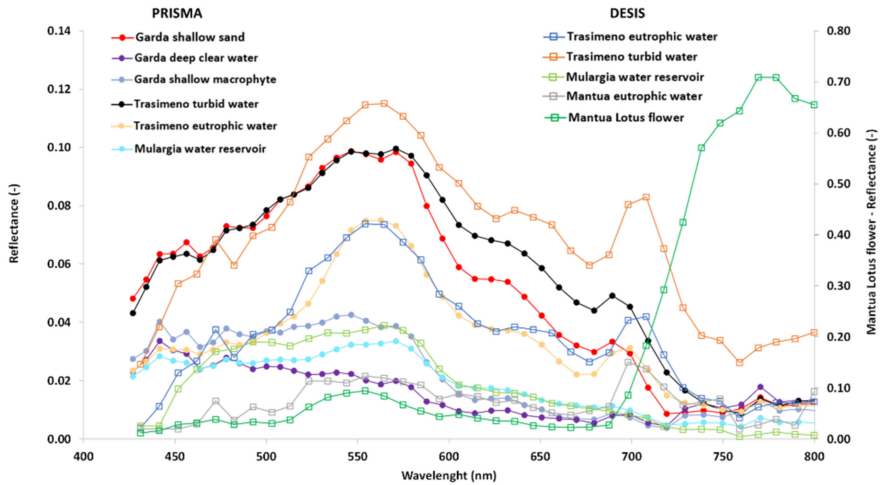
### **3.3. Water quality applications: Synergies with existing hyperspectral spaceborne missions**

Following the validation of PRISMA radiance and Rrs products, DESIS and EnMAP L2 products were also validated (see Figure 5 of Publication V and Figures 2 and 3 of Publication VI). Exploiting synergies with DESIS and EnMAP hyperspectral spaceborne missions has made it possible to explore the spectral variability of Italian and Estonian lakes (II, VI), to generate water quality products (II, VI) and to evaluate a specific case-study of tracking changes in water quality and in the abundance and type of aquatic plants (V). S2 and S3 products were employed to support the discussion on the exploration of spectral variability.

From this point onwards, all the figures (apart from Figure 3.13 and 3.16) are taken directly from the various publications and have been selected to summarise the results obtained in pursuit of the sub-objectives of this thesis.

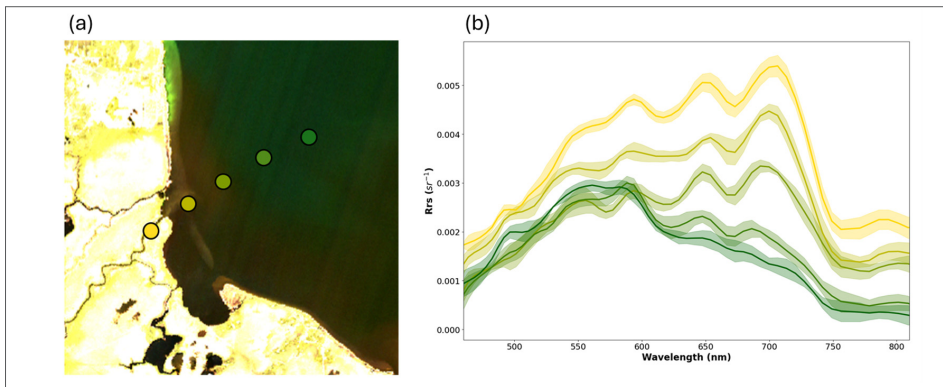
#### **3.3.1. Investigating spectral features (II, VI)**

The focus of the investigation is on assessing the capability of PRISMA, DESIS and EnMAP spaceborne imaging spectrometers to characterize the optical properties and spectral behaviour of diverse water types under varying environmental and trophic conditions. The analysis encompasses the extraction and comparison of spectral signatures, the identification of key absorption and Rrs features linked to the constituents present in the water column, as well as different types of aquatic vegetation. In Figure 3.4 PRISMA and DESIS images show distinct features associated with different gradients of trophic status, water transparency, bottom properties, in addition to emergent aquatic vegetation.



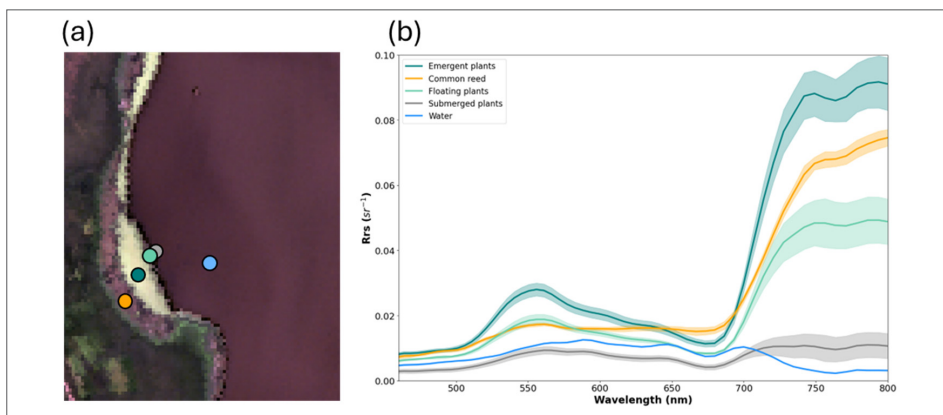
**Figure 3.4.** PRISMA and DESIS water reflectance. The spectra have been extracted to demonstrate the variability of hyperspectral reflectance across the water systems, from shallow to deep, and from clear to eutrophic or turbid and of aquatic vegetation (i.e. lotus flower) collected in the case study lakes investigated (Mantua, Mulargia, Trasimeno, and Garda lakes) (Figure 2, Publication II).

EnMAP image of Lake Peipsi (Figure 3.5) shows the effect of the inflow from the Emajõgi River (Estonia), which connects Lake Võrtsjärv to Lake Peipsi. As the measurement points progress from the river into the lake, where the influence of the inflow gradually diminishes, corresponding changes in the spectral signatures were observed. Initially, the spectra exhibited markedly higher concentrations of TSM, which decreased in magnitude along the transect and reached their lowest levels at the innermost point of the lake, where the river's influence was minimally detectable. This result suggests that the combined spatial resolution and spectral properties of satellite sensors such as EnMAP can support analyses regarding the influence of river discharge into lakes. Therefore, understanding of the hydrological processes in lakes can advance to the level of understanding that has been achieved through many years of monitoring river plumes entering seawater [110].



**Figure 3.5.** (a) EnMAP image acquired on 16 May 2024 at the confluence where the Emajõgi River flows into Lake Peipsi, (b) spectral signatures extracted along a transect crossing the study area. Each curve (corresponding to the points marked in the image using the same color scheme) represents the Rrs values recorded at successive points along the transect (Figure 6, Publication VI).

EnMAP image of Lake Võrtsjärv (Figure 3.6) shows the capability to distinguish between emergent plants, common reeds, floating plants, submerged plants, and water pixels. Based on [111], it is possible to assume that the aquatic vegetation species identified in the image could be *Phragmites australis* (emergent), *Nuphar lutea* (floating), and *Myriophyllum spicatum* (the dominating species among the submerged plants, for at least 20 years [112]).

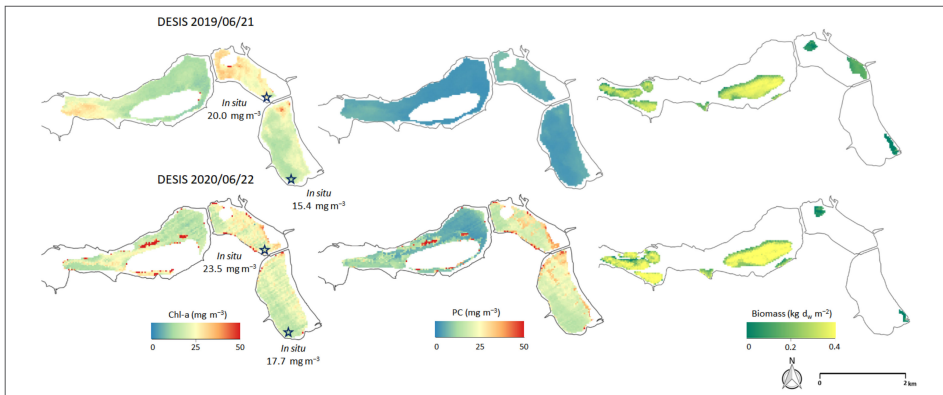


**Figure 3.6.** (a) EnMAP image acquired on 21 July 2024 over Lake Võrtsjärv, (b) spectral signatures extracted from the five ROIs displayed in (a), following the same color scheme (Figure 9, Publication VI).

Once the ability of these sensors to distinguish between different spectral features has been verified, it is possible, for instance, to study eutrophication phenomena in Lake Peipsi (Estonia) [113,114] and Lake Trasimeno (Italy) [115,116], or the evolution of cyanobacterial blooms in Lake Võrtsjärv (Estonia) [112,117] and Mantua lakes (Italy) [118].

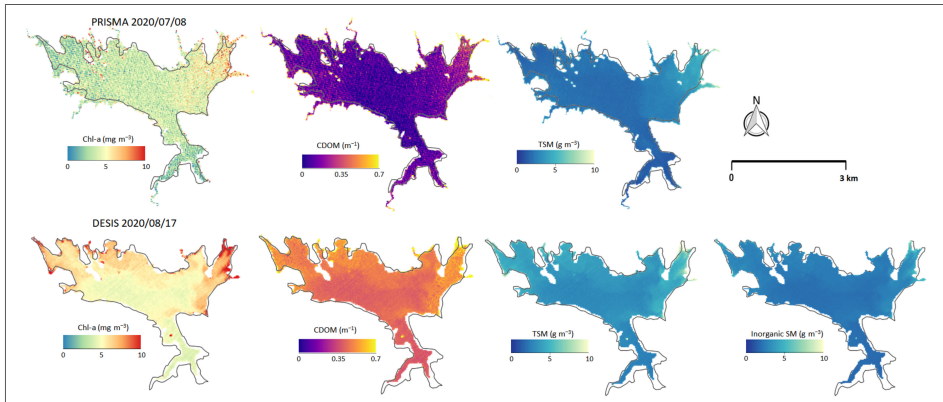
### 3.3.2. Water quality mapping (II, VI)

The water quality products for three Italian lakes (Mantua, Mulargia [119] and Garda [120,121]) were generated using BOMBER, parameterised as explained in II. In Figure 3.7 information of the different primary producers present in the lakes of Mantua are shown, as generated from two DESIS images. The comparison of the products with field data indicated good agreement, as explained in detail in Publication II. The simultaneous mapping of spatial distributions of phytoplankton pigments adds significant value to assessing aquatic ecosystem quality. Chl-a maps reveal a clear increasing gradient from the Superior to the Middle Lake. The lower average PC concentrations in the Superior Lake on 22 June 2020 reflect its fluvial-lacustrine morphology and shorter water residence time, unlike the Middle and Inferior Lakes, where slower currents promote cyanobacterial dominance. Macrophyte biomass products also aid in managing invasive species, such as the lotus flower, which rapidly colonizes the Superior Lake and reaches high biomass levels by June in both years studied.



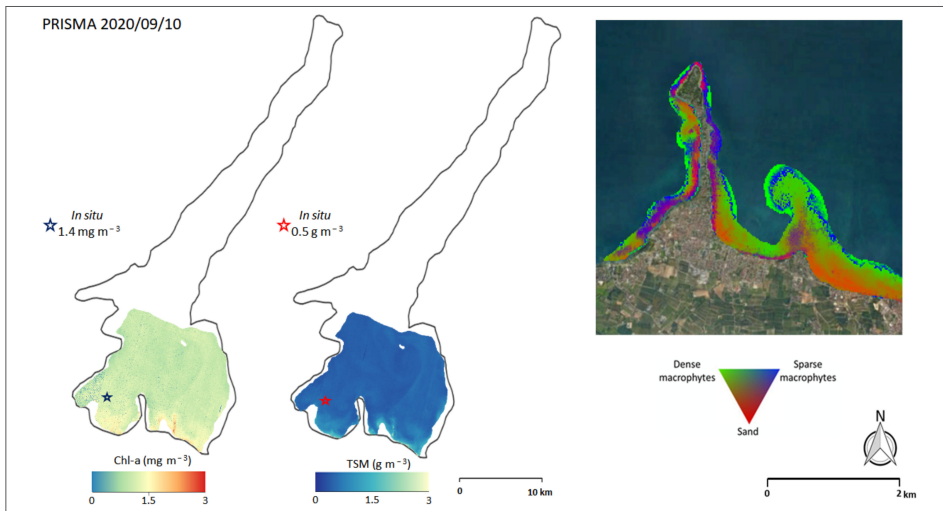
**Figure 3.7.** Maps of concentration of phytoplankton pigments (Chl-a and PC) and of floating-leaved and emergent macrophyte biomass obtained from DESIS images acquired on 21 June 2019 and on 22 June 2020. Blue stars (for Chl-a) are the locations of the *in situ* measurements with fluorimetric probes (Figure 4, Publication II).

In Figure 3.8 water quality maps in terms of chl-a, CDOM, TSM and inorganic Suspended Matter (SM) are shown for Lake Mulargia, as generated from one PRISMA and one DESIS image. The availability of two images acquired one month apart enabled spatial and temporal comparisons, and enabled proposing hypotheses based on the knowledge of the territory, as described in depth in Publication II. All parameters increased in August relative to July. The highest concentrations occurred in the lake's eastern portion, likely due to reduced water circulation, as the tributary enters from the west and the dam lies to the south. Elevated chl-a levels were also observed near the western inflow, probably driven by nutrient-rich tributary waters promoting phytoplankton blooms.



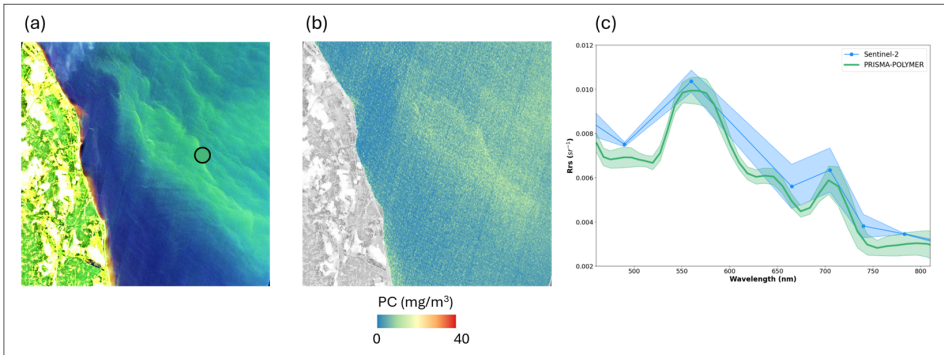
**Figure 3.8.** (Top) Maps of concentration of Chl-a, CDOM and TSM obtained from PRISMA image acquired on 8 July 2020. (Bottom) Maps of concentration of Chl-a, CDOM, TSM and Inorganic SM obtained from DESIS image acquired on 17 August 2020 (Figure 5, Publication II).

In Figure 3.9 water quality and lake bottom maps are shown for Lake Garda, as generated from a PRISMA image. The bottom coverage of the areas around the Sirmione Peninsula in the south portion of Lake Garda was generated with BOMBER applied in “shallow mode” as explained in depth in Publication V. This estimate of the macrophyte coverage of the shallower portion of the Peninsula is in accordance with the results for September 2010 presented in [122] that reported a reduction of the density of the macrophyte meadows compared to the previous decade.

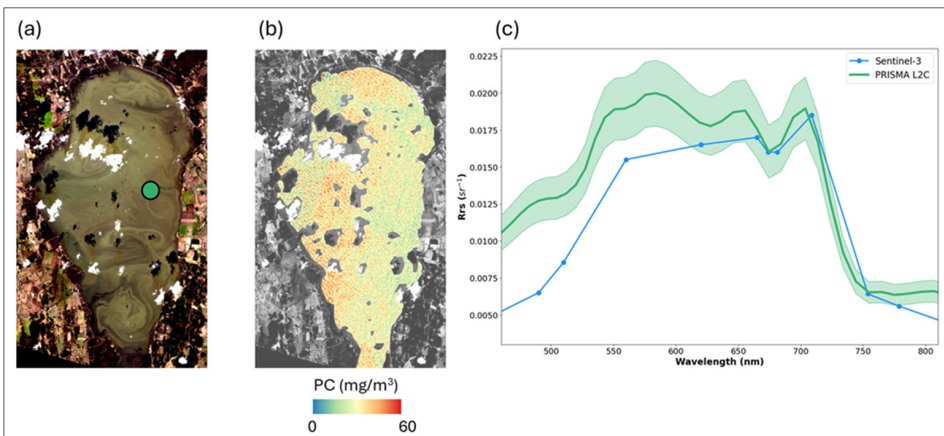


**Figure 3.9.** Maps of Chl-a (left) and TSM (center) concentration, and (right) of the bottom coverage of the Sirmione Peninsula in the south portion of Lake Garda by PRISMA image acquired on 10 September 2020 (Figure 7, Publication II).

PC concentration maps were generated for two Estonian lakes, i.e. Lake Peipsi and Lake Võrtsjärv, running the MDN model on two PRISMA images. The presence of the pigment is also discernible in the spectral signatures obtained from PRISMA imagery; however, due to the lower spectral and spatial resolution, this feature was not detectable in S2 and S3 data, respectively. In Figure 3.10 and 3.11 the maps of PC concentration are shown for Lake Peipsi and for Lake Võrtsjärv, respectively.



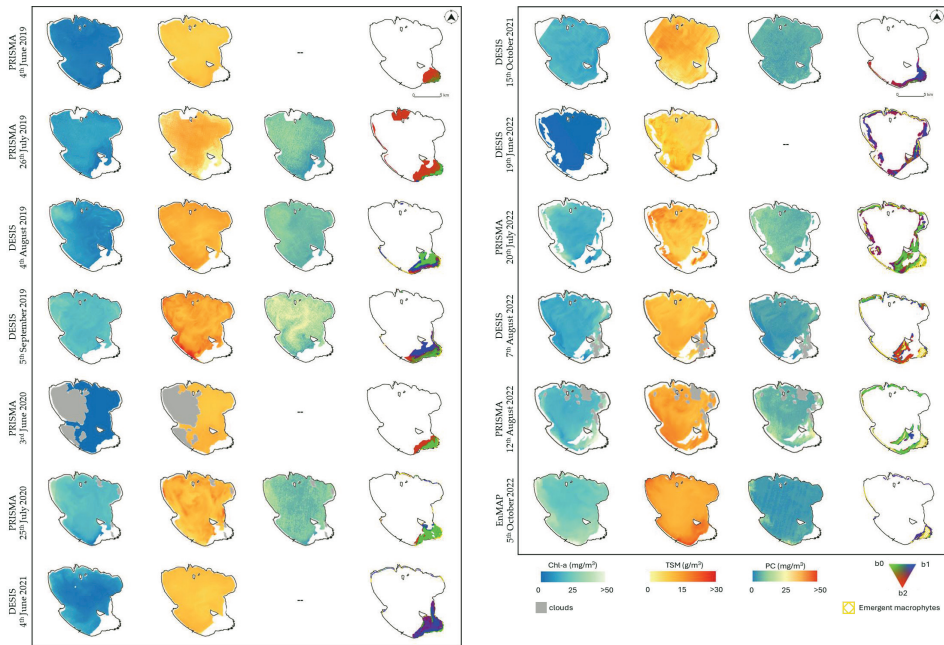
**Figure 3.10.** (a) PRISMA image acquired on 16 August 2022 over Lake Peipsi, (b) PC concentration map, (c) spectral comparison between PRISMA L1 corrected with POLYMER and S2 (17 August 2022), displayed in green and blue, respectively (Figure 7, Publication VI).



**Figure 3.11.** (a) PRISMA image acquired on 4 April 2020 over Lake Võrtsjärv, (b) PC concentration map, (c) spectral comparison between PRISMA L2C and S3 (4 April 2020), displayed in green and blue, respectively (Figure 8, Publication VI).

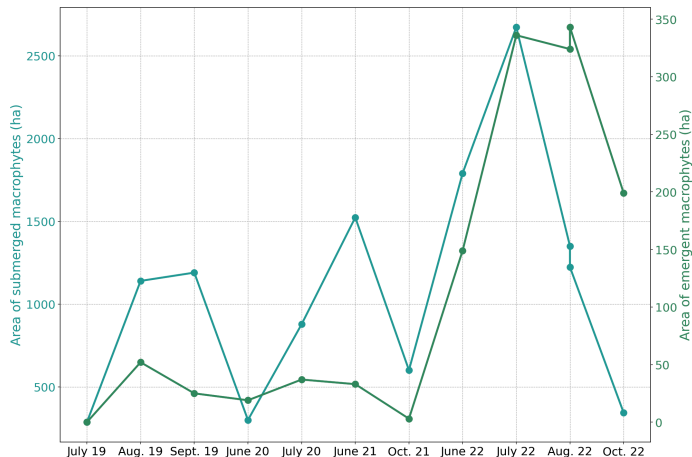
### 3.3.3. Tracking environmental changes (V)

The aim of this study is to present a multitemporal dataset compiled using three spaceborne imaging spectroscopy missions, i.e. PRISMA, DESIS and EnMAP, for enabling aquatic ecosystems mapping. In particular, the study builds on 13 hyperspectral Rrs products of Lake Trasimeno (Italy) covering the summer periods from 2019 to 2022 to assess changes in water quality parameters (chl-a, TSM, PC) and aquatic vegetation coverage and type. The lake area has been divided into optically deep waters and optically shallow waters, according to the criteria explained in Publication V. Figure 3.12 shows the water quality products in the portion of the lake that presented optically deep waters and, in the fourth column, the mapping of the emergent macrophytes (in yellow) and the three types of bottom cover classes (b0: semi-emergent macrophytes, b1: permanently submerged macrophytes, b2: sand) in the portion that presented optically shallow waters. The areas of the images affected by clouds are indicated by the grey color.



**Figure 3.12.** Water quality maps and bottom characterization for the 13 images of the available dataset. From left to right: Chl-a, TSM and PC maps; bottom characterization products, in terms of emergent macrophytes and the three cover classes: b0 (semi-emergent macrophytes), b1 (permanently submerged macrophytes), b2 (sand) (Figure 6, Publication V).

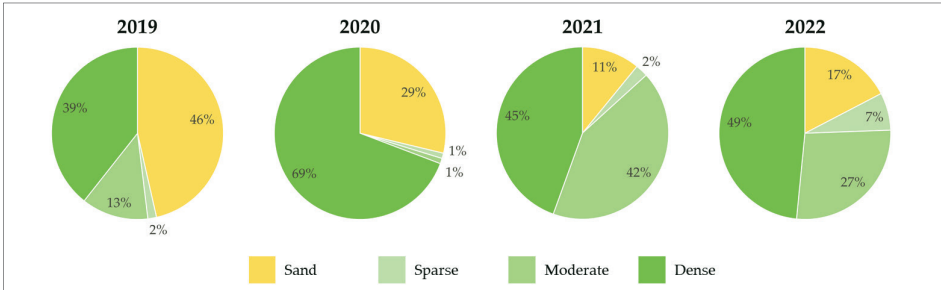
The lowest values of chl-a and TSM are detected in June; higher values, instead, occur in the following summer months: the maximum values are generally observed in September-October. The highest PC values are achieved in September. These results are consistent with the collected *in situ* data (MAPD values below 30% for PRISMA products, MAPD values below 26% for both DESIS and EnMAP products). Regarding the optically shallow water areas, the area of submerged and emergent macrophytes increases over the years. These values reveal that, in addition to the seasonal vegetative cycle with growth starting in early summer and a senescence period in late summer for both submerged and emergent macrophytes, there is an unprecedented increase, in terms of area, in July 2022, leading to an increase of approximately 160% in submerged macrophytes and 600% in emergent macrophytes compared to the average values for the period 2019–2021. The values of the WAVI index show that in 2022, at the maximum area of emergent macrophytes (343 ha, August 2022), the maximum WAVI value was recorded to be 0.38, which corresponds to an increase of about 240% compared to the date with the lowest WAVI value (0.11, October 2021). The area of the submerged ( $b_0 + b_1$ ) and emergent macrophytes retrieved for the period investigated is shown in Figure 3.13.



**Figure 3.13.** Area in hectares of submerged (left axis, aquamarine) and emergent macrophytes (right axis, green) across various dates in the dataset.

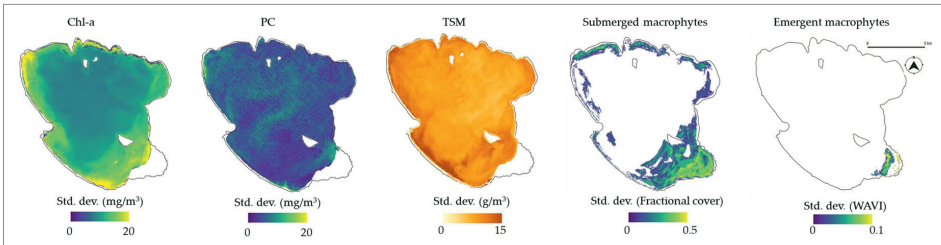
Additionally, a more detailed analysis of the three bottom coverage classes was carried out by calculating the fractional cover by labelling a pixel as “sand” where  $b_2 > 0.66$  (66%) and distinguishing three different classes of submerged macrophytes as follows: sparse ( $0 < b_0 + b_1 < 0.4$ ), moderate ( $0.4 < b_0 + b_1 < 0.7$ ) and dense ( $b_0 + b_1 > 0.7$ ). The results show how the fractional cover of the different classes changed over the study period (Figure 3.14). Un-colonized pixels representing a substrate covered by sand, for instance, decreased considerably in 2021 and 2022, compared to the initial value in 2019. At the same time, the substrate covered by submerged macrophytes increased (moderate and dense classes). To

further interpret these findings, Publication V accounts for additional environmental drivers, including variations in lake level, precipitation, and populations of herbivorous birds feeding on macrophytes.



**Figure 3.14.** Distributions of sand and submerged macrophyte cover classes (sparse, moderate and dense) in the four-year study period. Un-colonized (sand) pixel percentage is represented in yellow; sparse, moderate and dense submerged macrophytes are shown with a gradient of green from lightest to darkest (Figure 7, Publication V).

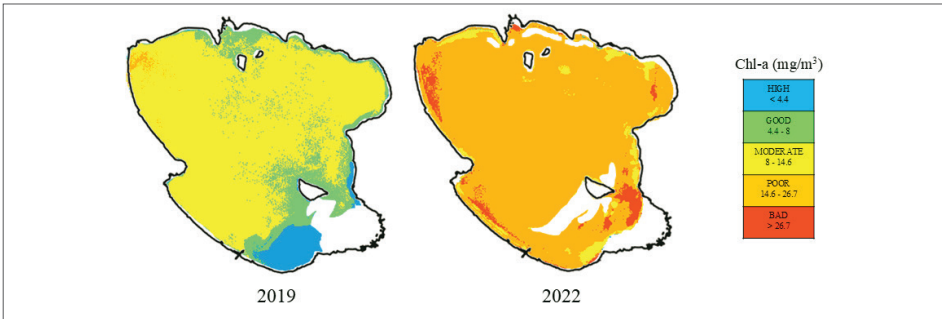
The outcomes of the spatio-temporal analysis are illustrated in Figure 3.15, highlighting the regions exhibiting the greatest variability in water quality parameters (chl-a, PC and TSM), as well as the fractional coverage of submerged macrophytes and the density of emergent macrophytes.



**Figure 3.15.** From left to right, standard deviation maps of Chl-a, PC, TSM, submerged macrophytes' fractional cover and emergent macrophytes' density (WAVI) (Figure 8, Publication V).

The chl-a values show greater variability in the portions of the lake closer to the littoral zone; the PC concentrations show higher variability in open water part of the lake; the TSM concentrations show higher variability close to the tributary inflow in the south-western part of the lake. Macrophytes show higher variability in terms of fractional cover and density in the south-eastern part of the lake where the aquatic vegetation is well established. It is well documented that the loss of aquatic vegetation reduces water transparency by removing the mechanical and biochemical functions provided by macrophytes. Within the limited dataset analysed, average TSM values were generally lower on dates corresponding to greater submerged macrophyte coverage. The extensive proliferation of submerged and

semi-emergent macrophytes observed in 2022 requires continued monitoring, as it likely reflects a substantial decrease in lake levels, coupled with reduced early-June and annual precipitation. A comprehensive discussion is presented in Publication V. Finally, the annual mean chl-a concentrations for the first (2019) and final year (2022) of the study period were classified according to established thresholds representing WFD ecological status classes [123]. Figure 3.16 illustrates the deterioration in the lake's ecological status from 2019 to 2022, characterised by an increase in chl-a concentration and an expansion of optically shallow waters.



**Figure 3.16.** Annual mean classification of WFD ecological status classes for the years 2019 (4 images) and 2022 (5 images). White areas represent optically shallow waters.

## CONCLUSIONS

In conclusion, this thesis successfully demonstrates the potential of last-generation hyperspectral satellite data for water quality mapping, achieving the goal of investigating and leveraging their capabilities in aquatic environment studies. The validation of PRISMA radiance and reflectance products by comparison with ground measurements confirms the overall reliability of these data, particularly in the visible range, where low discrepancies were observed. Although performance limitations persist in the violet-blue and NIR regions, the improvements obtained through independent AC methods highlight the importance of further refining preprocessing algorithms to increase data accuracy across the full spectral domain. The synergistic exploitation of PRISMA, DESIS, and EnMAP imagery proved particularly effective in capturing the spectral variability of optically complex waters across diverse lake systems. Their similar configurations enabled the harmonization of processing and validation procedures, fostering the generation of accurate and comparable water quality products such as chl-a, TSM, and PC, as well as aquatic vegetation indicators. The consistency of these products with field data and their ability to reveal spatial and temporal dynamics, such as seasonal pigment variations and long-term changes in macrophyte coverage, underscore the value of hyperspectral observations for environmental monitoring. Ultimately, this work represents an important step toward the operational use of spaceborne hyperspectral missions for inland and coastal water quality assessment. By establishing standardized processing and validation frameworks, it lays the groundwork for large-scale, harmonized applications in support of forthcoming operational missions such as CHIME, paving the way for more accurate, continuous, and comprehensive monitoring of aquatic ecosystems worldwide. The main findings supporting these conclusions are summarized as follows:

- PRISMA L1 radiances are consistent with the *in situ* measured values observed over water targets in most wavelengths (strong agreement in the range 412–667 nm, with  $R^2 > 0.96$  and MAPD  $< 25\%$ ). The performance degrades at longer wavelengths (865–870 nm,  $R^2$  reaching the value of 0.10). Despite the need for further analysis to be carried out in the NIR spectral region, this promising result encourages the exploitation of PRISMA imagery data for aquatic applications.
- PRISMA L2 standard products show reasonable agreement with *in situ* measurements in the visible green range (490–560 nm,  $R^2$  values between 0.69 and 0.87, MAPD reaching values below 60%). Performance drops in the violet-blue (412, 443 nm, with  $R^2 < 0.45$  and MAPD values greater than 220%) and NIR regions, with extremely poor correlation in the NIR region of the spectrum (779–870 nm,  $R^2$  values below 0.1, MAPD values up to 2050%).
- PRISMA L1 products corrected with independent atmospheric correction methods (ACOLITE and POLYMER) show the same pattern of limitations registered with PRISMA L2 standard products, but with smaller errors.

PRISMA AC data show promising performance in the visible green to yellow range (490–620 nm,  $R^2$  values greater than 0.93, MAPD values below 40%). Performance drops in the violet-blue (412, 443 nm, with  $R^2 < 0.4$  and MAPD values greater than 55%) and NIR spectral regions (779–870 nm,  $R^2$  values tending to zero, MAPD exceeding 170%).

- The synergistic use of hyperspectral data provided by PRISMA, DESIS and EnMAP allows for comprehensive Earth system analysis. These missions form a complementary dataset framework that supports multi-source data fusion and time series analysis.
- Comparable analyses across Italian and Estonian optically different lakes demonstrated that PRISMA, DESIS and EnMAP sensors are effectively able to capture the spectral variability of optically complex waters, gradients in trophic status and vegetation composition.
- The similar spectral configurations of PRISMA, DESIS, and EnMAP enabled the harmonization of processing procedures to simultaneously derive water quality products, i.e. chl-a, TSM, CDOM, and aquatic vegetation coverage and abundance. It also allowed to produce value-added products such as maps in terms of PC, whose spectral feature remains invisible to traditional multi-spectral sensors S2 and S3.
- The water quality products that have been generated for the lakes of Mantua, Lake Mulargia and Lake Garda showed consistent values with the measured *in situ* data.
- The multitemporal analysis of water quality in Lake Trasimeno revealed clear seasonal patterns, with higher concentrations of pigments during late summer and increasing macrophyte coverage over the years. The maps in terms of chl-a, TSM and PC showed the following accuracy: MAPD values below 30% for PRISMA products, MAPD values below 26% for both DESIS and EnMAP products.
- By promoting standardized validation and processing approaches, the study provides a crucial step toward enabling large-scale environmental monitoring with forthcoming hyperspectral missions, including the Copernicus Hyperspectral Imaging Mission for the Environment (CHIME [124,125]).

## SUMMARY

This thesis explores the potential of spaceborne hyperspectral PRISMA data for the assessment of the aquatic ecosystems, with a particular focus on its validation and application, and its integration with other contemporary spaceborne hyperspectral missions, namely DESIS and EnMAP. The study contributes to the advancement of quantitative remote sensing methods for inland and coastal waters, supporting the objectives of the European Union Water Framework Directive and broader environmental monitoring frameworks.

Aquatic environments such as lakes and coastal zones represent essential components of the Earth's hydrological and ecological systems, as they sustain biodiversity, regulate climate processes, and provide essential ecosystem services. Yet these systems are increasingly exposed to multiple anthropogenic pressures, including eutrophication, pollution, and the impacts of climate change. Although traditional field-based monitoring methods are accurate, they are limited in terms of both space and time. Remote sensing offers a complementary, scalable approach in this context, providing synoptic and repeatable observations over vast areas.

The advent of hyperspectral remote sensing has introduced new possibilities for detailed aquatic studies, as it captures continuous spectral information across hundreds of narrow bands. This spectral richness allows for the detection of subtle optical variations linked to water quality parameters and aquatic vegetation, supporting the development of robust monitoring tools and retrieval algorithms.

The main objective of this thesis is to evaluate and exploit the data provided by the ASI PRISMA mission, by investigating the radiometric and surface reflectance products and alternative AC methods, and by testing algorithms for the generation of water quality maps. The ultimate goal is to explore the synergies with DESIS and EnMAP missions operated by DLR for aquatic ecosystem studies at regional and global scales. To the aim, the study builds on *in situ* validation data obtained from international observation networks such as AERONET-OC, HYPERNETS, and WISPStation, complemented by targeted field campaigns. The validation methodology involved the statistical comparison of satellite-derived radiance and reflectance values with *in situ* measurements using standard metrics. The performance of PRISMA L1 Top Of Atmosphere radiance data showed promising results, thus supporting the use of PRISMA products for aquatic studies. PRISMA L2 bottom of atmosphere Rrs products showed reasonable agreement with ground data in the green to yellow wavelengths, although the accuracy declined in the violet-blue and NIR bands due to the difficulties in the AC process. Independent AC methods (ACOLITE and POLYMER) yielded improved results, indicating that tailored algorithms can enhance the retrieval of reliable water reflectance products from PRISMA imagery. The validated data were then used to generate water quality products related to chl-a, TSM, CDOM, PC and mapping of aquatic vegetation and bottom coverage through bio-optical model inversion (BOMBER) and a machine learning approach (MDN).

The synergistic use of PRISMA, DESIS, and EnMAP data proved particularly valuable in expanding the spatial and temporal coverage of hyperspectral observations and improving the continuity of aquatic monitoring. Comparative analyses across Italian and Estonian lakes demonstrated that these sensors are effectively able to capture the spectral variability of optically complex waters and detect gradients in trophic status and vegetation composition. The multitemporal analysis of Lake Trasimeno revealed clear seasonal patterns, with higher concentrations of pigments and suspended material during late summer and increasing macrophyte coverage over the years. The synergistic dataset from PRISMA, DESIS, and EnMAP facilitated the investigation of eutrophication dynamics and the monitoring of spatial transitions from river inflows to open lake areas.

The findings of this thesis demonstrate that hyperspectral satellite missions provide a reliable and versatile framework for the investigation of inland and coastal waters. PRISMA radiometric and reflectance products are consistent and scientifically robust within the visible spectrum, and their integration with DESIS and EnMAP missions enables more comprehensive and frequent monitoring of aquatic ecosystems. These results highlight the potential of imaging spectroscopy to enhance the understanding of aquatic biogeochemical processes, to support long-term ecological assessments, and to inform water management policies.

The study contributes to the development of harmonized validation protocols and processing methodologies, laying the foundation for future large-scale environmental monitoring using forthcoming hyperspectral missions such as CHIME. In conclusion, the thesis establishes that spaceborne hyperspectral remote sensing represents a transformative tool for environmental science, capable of bridging observational gaps between local field studies and global-scale ecosystem assessments. Its integration within operational monitoring frameworks will be crucial for achieving sustainable management of water resources and for addressing the challenges posed by climate change and anthropogenic impacts on aquatic environments.

## SUMMARY IN ESTONIAN

### Satelliidiandmete kasutamine veeökosüsteemide uurimiseks

See väitekirj uurib hüperspektraalse kaugseire potentsiaali veeökosüsteemide seisundi hindamisel. Uuring keskendub PRISMA satelliitsensorile ning selle andmete valideerimisele, rakendamisele ja integreerimisele teiste kaasaegsete hüperspektraalsete missioonidega, eelkõige DESIS ja EnMAP satelliitidega. Töö panustab kvantitatiivsete kaugseiremeetodite arendamisse sise- ja rannikuvete seireks, toetades Euroopa Liidu veepoliitika raamdirektiivi ja laiemate keskkonnaseire raamistike eesmärke.

Veekeskonnad, nagu järved ja rannikualad, on Maa hüdroloogiliste ja ökoloogiliste süsteemide olulised komponendid, kuna need toetavad bioloogilist mitmekesisust, reguleerivad kliimaprotsesse ja pakuvad olulisi ökosüsteemi teenuseid. Samas on need süsteemid üha enam ohustatud inimtegevusest tulenevate survetegurite, sealhulgas eutrofeerumise, reostuse ja kliimamuutuste tõttu. Kuigi traditsioonilised välimõõtmised on täpsed, piiravad neid ruumiline ja ajaline katvus. Kaugseire pakub selles kontekstis olulist täiendust, võimaldades korduvaid vaatlusi laialdastel aladel.

Hüperspektraalse kaugseire areng on avanud uusi võimalusi detailseteks veeökosüsteemide uuringuteks, kuna see tehnoloogia salvestab pidevat spektraalinformatsiooni sadades kitsastes lainepikkuste vahemikes. Selline andmerikkus võimaldab tuvastada ka väikeseid optilisi muutusi, mis on seotud veekvaliteedi parameetrite ja veetaimestikuga, toetades usaldusväärsete seirevahendite ja algoritmide arendamist.

Väitekirja peamine eesmärk on hinnata PRISMA missiooni andmete kasutatavust, uurides radiomeetriliste andmete usaldusväärsust ning testida algoritme veekvaliteedi parameetrite hindamiseks. Lõppeesmärk on uurida PRISMA andmete sünergia DESIS ja EnMAP missioonidega, et toetada veeökosüsteemide seiret nii regionaalsel kui globaalsel tasandil. Uuring tugineb valideerimisandmetele, mis on kogutud rahvusvahelistest vaatlusvõrgustikest nagu AERONET-OC, HYPERNETS ja WISPStation, ning mida täiendavad sihipärased välimõõtmised. Valideerimismetoodika hõlmas satelliitandmete ja kohapealsete mõõtmiste statistilist võrdlust, kasutades mitmesuguseid analüüsimeetodeid. PRISMA L1 atmosfääri ülapiiri kirkuse andmed näitasid paljulubavaid tulemusi, kinnitades nende sobivust veekeskonna uuringuteks. PRISMA L2 peegeldusteguri andmed vastasid hästi maapealsetele mõõtmistele rohelisest kollase lainepikkuste vahemikuni, kuid täpsus vähenes violetses-sinises ja lähiihnapuna piirkonnas. Alternatiivsed atmosfäärikorrektioonialgoritmid (ACOLITE ja POLYMER) andsid paremaid tulemusi, mis viitab kohandatud algoritmide potentsiaalile parandada PRISMA andmete sobivust veekeskonna seireks. Valideeritud andmeid kasutati veekvaliteedi parameetrite, nagu klorofüll-a, hõljum, värvunud lahustunud orgaaniline aine ja fükotsüaniin, hindamiseks, samuti veetaimestiku ja põhjakatte kaardistamiseks, kasutades bio-optilist mudelit (BOMBER) ja masinõppemeetodit (MDN).

PRISMA, DESIS ja EnMAP andmete sünergiline kasutamine osutus eriti väärtuslikuks, laiendades hüperspektraalsete vaatluste ruumilist ja ajalist ulatust ning parandades seire järjepidevust. Itaalia ja Eesti järvede võrdlevad analüüsid näitasid, et need andmed võimaldavad tõhusalt kirjeldada optiliselt keeruliste vete spektraalset varieeruvust ning tuvastada troofilise seisundi, läbipaistvuse ja veetaimestiku gradiente. Trasimeno järve andmetel teostatud analüüsid näitasid selgeid hooajalisi mustreid – suve lõpus tõusid pigmentide ja hõljuva materjali kontsentratsioonid ning makrofüütide levik suurenes aastate jooksul. PRISMA, DESIS ja EnMAP andmestiku kombineeritud kasutamine hõlbustas eutrofeerumise dünaamika uurimist ja ruumiliste muutuste jälgimist jõgede sissevoolualadest avatud järvealadeni.

Väitekirja tulemused näitavad, et hüperspektraalsed satelliidimissioonid pakuvad usaldusväärset ja mitmekülgset raamistikku sise- ja rannikuvete uurimiseks. PRISMA radiomeetrilised andmed on nähtava spektri vahemikus teaduslikult usaldusväärsed ning nende integreerimine DESIS ja EnMAP andmetega võimaldab veeökosüsteemide põhjalikumat ja sagedasemat seiret. Tulemused rõhutavad hüperspektraalsete kaugseireandmete potentsiaali parandada meie arusaama veekeskonna biogeokeemilistest protsessidest, toetada pikaajalisi ökoloogilise seisundi uuringuid ning suunata veemajanduspoliitika kujundamist.

Töö toetab ka ühtlustatud valideerimisprotokollide ja töötlemismetoodikate arendamist, mis on olulised tulevaste hüperspektraalsete missioonide (nt CHIME) rakendamiseks ulatuslikus keskkonnaseires. Kokkuvõttes järeldeb väitekiri, et hüperspektraalne kaugseire kujutab endast olulist tööriista keskkonnateaduses, võimaldades ületada lõhet kohalike välimõõtmiste ja globaalses mastaabis ökosüsteemide seisundi hindamise vahel. Selle integreerimine operatiivsetesse seire- ja raamistikesse on kriitilise tähtsusega, et tagada veevarude säästev majandamine ning reageerida kliimamuutustest ja inimtegevusest tulenevatele keskkonnaprobleemidele veekeskonnas.

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## **PUBLICATIONS**

## CURRICULUM VITAE

**Name** Alice Fabbretto  
**Date of birth** 31.08.1991  
**Nationality** Italian  
**E-mail** fabbrett@ut.ee

### Education

2021–Today University of Tartu, Faculty of Science and Technology,  
doctorate studies  
2020 Politecnico di Milano, Faculty of Environmental and Land  
Planning Engineering, Master’s degree  
2018 Politecnico di Milano, Faculty of Environmental and Land  
Planning Engineering, Bachelor’s degree

### Institution and position held

10.2020–08.2021 National Research Council of Italy (CNR-IREA)  
Early-Stage Researcher

### Scientific and research activity

Hyperspectral remote sensing applications for optically complex waters.

### Additional career information

#### *Supervisor at University of Tartu*

2023/2024 Data Science in Remote Sensing  
2022/2023 Data Science in Remote Sensing  
2021/2022 Data Science in Remote Sensing

#### *Dissertations supervised*

Lodovica Panizza, Master’s degree, 2023. Supervisors: Marco Gianinetto, Mariano Bresciani, Claudia Giardino, Alice Fabbretto, Andrea Pellegrino. “Comparative study of atmospheric correction algorithms for PRISMA products to optimize the retrieval of water quality parameters”. Politecnico di Milano, Faculty of Environmental and Land Planning Engineering.

Andrea Pellegrino, Master’s degree, 2021. Supervisors: Marco Gianinetto, Mariano Bresciani, Claudia Giardino, Alice Fabbretto. “Evaluation of global PRISMA products for water quality mapping”. Politecnico di Milano, Faculty of Environmental and Land Planning Engineering.

## *Awards and scholarships*

2024 – Scholarship named by Juhan Ross.

## *Publications*

- Giardino, C.; Bresciani, M.; Braga, F.; **Fabbretto, A.**; Ghirardi, N.; Pepe, M.; Gianinetto, M.; Colombo, R.; Cogliati, S.; Ghebrehiwot, S.; Laanen, M.; Peters, S.; Schroeder, T.; Concha, J.A.; Brando, V.E. First Evaluation of PRISMA Level 1 Data for Water Applications. *Sensors* **2020**, *20*, 4553. <https://doi.org/10.3390/s20164553>
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- Lima, T.M.A.d.; Giardino, C.; Bresciani, M.; Barbosa, C.C.F.; **Fabbretto, A.**; Pellegrino, A.; Begliomini, F.N. Assessment of Estimated Phycocyanin and Chlorophyll-a Concentration from PRISMA and OLCI in Brazilian Inland Waters: A Comparison between Semi-Analytical and Machine Learning Algorithms. *Remote Sens.* **2023**, *15*, 1299. <https://doi.org/10.3390/rs15051299>
- Pellegrino, A.; **Fabbretto, A.**; Bresciani, M.; de Lima, T.M.A.; Braga, F.; Pahlevan, N.; Brando, V.E.; Kratzer, S.; Gianinetto, M.; Giardino, C. Assessing the Accuracy of PRISMA Standard Reflectance Products in Globally Distributed Aquatic Sites. *Remote Sens.* **2023**, *15*, 2163. <https://doi.org/10.3390/rs15082163>
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## ELULOOKIRJELDUS

**Nimi** Alice Fabbretto  
**Sünniaeg** 31.08.1991  
**Rahvus** Italian  
**E-post** fabbrett@ut.ee

### Haridustee

2021–Täna seni Tartu Ülikool, Loodusteaduste ja tehnoloogia teaduskond, doktoriõpe  
2020 Politecnico di Milano, Keskkonna- ja maakasutusplaneerimise inseneriteaduskond, magistrikraad  
2018 Politecnico di Milano, Keskkonna- ja maakasutusplaneerimise inseneriteaduskond, bakalaureusekraad

### Asutus ja ametikoht

10.2020–08.2021 National Research Council of Italy (CNR-IREA)  
Varajase staadiumi teadlane

### Teadus- ja uurimistegevus

Hüperspektraalne kaugseire optiliselt keeruliste vete puhul.

### Täiendav karjääriinfo

#### *Juhendaja Tartu Ülikoolis*

2023/2024 Andmeteadus kaugseires

2022/2023 Andmeteadus kaugseires

2021/2022 Andmeteadus kaugseires

#### *Juhendatud lõputööd*

Lodovica Panizza, Magistrikraad, 2023. Juhendajad: Marco Gianinetto, Mariano Bresciani, Claudia Giardino, Alice Fabbretto, Andrea Pellegrino. “Comparative study of atmospheric correction algorithms for PRISMA products to optimize the retrieval of water quality parameters”. Politecnico di Milano, Keskkonna- ja maakasutusplaneerimise inseneriteaduskond, bakalaureusekraad

Andrea Pellegrino, Magistrikraad, 2021. Juhendajad: Marco Gianinetto, Mariano Bresciani, Claudia Giardino, Alice Fabbretto. “Evaluation of global PRISMA products for water quality mapping”. Politecnico di Milano, Keskkonna- ja maakasutusplaneerimise inseneriteaduskond, bakalaureusekraad.

## *Auhinnad ja stipendiumid*

2024 – Juhan Rossi nimeline stipendium.

### *Publikatsioonid*

- Giardino, C.; Bresciani, M.; Braga, F.; **Fabbretto, A.**; Ghirardi, N.; Pepe, M.; Gianinetto, M.; Colombo, R.; Cogliati, S.; Ghebrehiwot, S.; Laanen, M.; Peters, S.; Schroeder, T.; Concha, J.A.; Brando, V.E. First Evaluation of PRISMA Level 1 Data for Water Applications. *Sensors* **2020**, *20*, 4553. <https://doi.org/10.3390/s20164553>
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