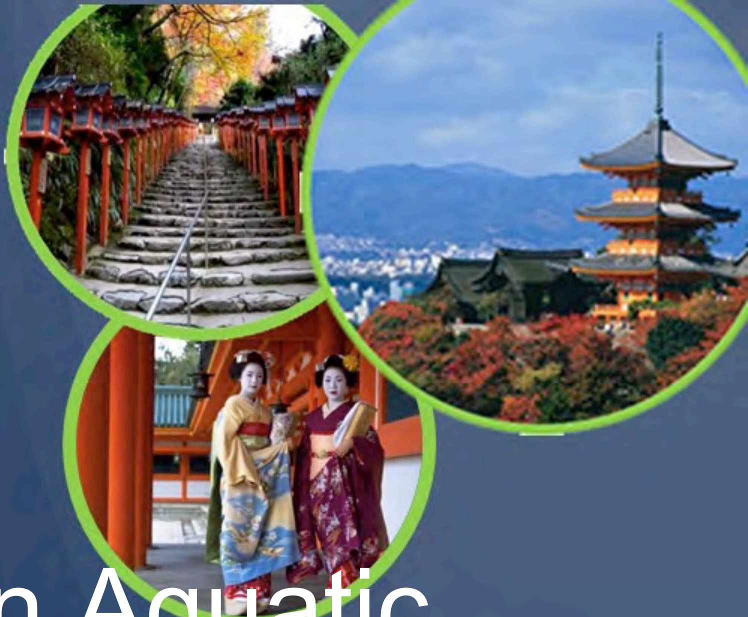
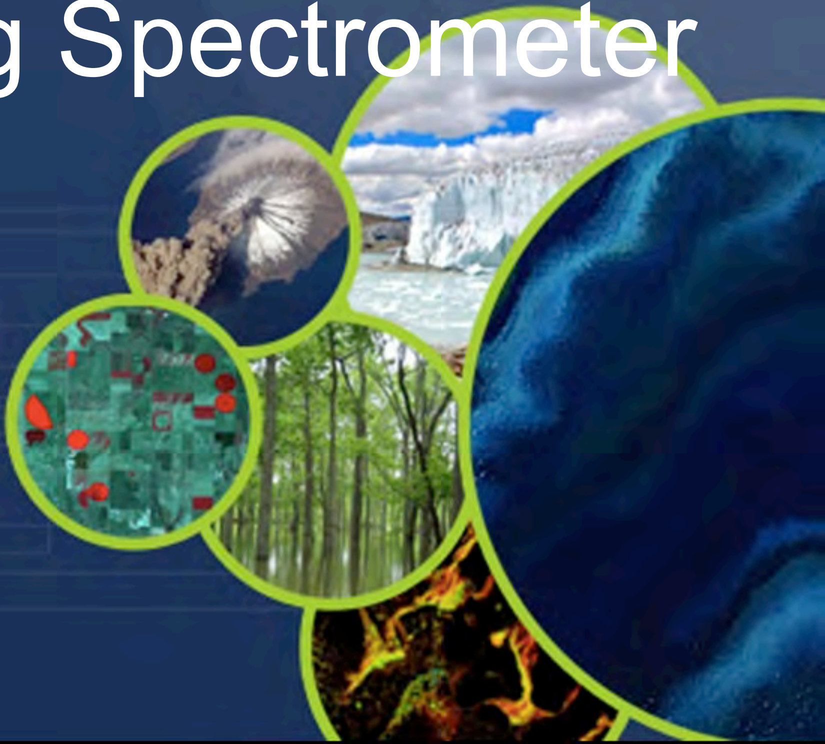
Committee on Earth Observation Satellites



Feasibility Study for an Aquatic Ecosystems Imaging Spectrometer



Ad-Hoc Working Group CEOS

Presented by A.G. Dekker

IOCS 2017 Lisbon, Portugal

Scope of the Feasibility Study Imaging Spectrometer for (non-Ocean) Aquatic Ecosystems

- The CEOS response to (GEOSS) Water Strategy recommendations was endorsed by CEOS at the 2015 CEOS Plenary.
- This study addresses original recommendation C.10 : A feasibility assessment to determine **the benefits and technological difficulties of designing a hyperspectral satellite mission focused on water quality measurements**:
- The GEO AquaWatch community proposed to extend the scope to: **(i) a dedicated imaging spectrometer or (ii) augmenting designs of spaceborne sensors for terrestrial and ocean colour, to allow improved inland, near coastal waters, benthic and shallow water bathymetry applications**.
- Augmenting designs of spaceborne sensors for terrestrial and ocean colour applications could be **a cost-effective pathway to addressing the same science and societal benefit applications**
- Focus is on a **global mapping mission**

Scope of the Feasibility Study
Imaging Spectrometer for Aquatic Ecosystems

Three activities defined in this feasibility study:

1. An assessment of the benefits and technological difficulties of designing a global satellite mission focused on inland, estuarine, deltaic and near coastal waters - as well as mapping macrophytes, macro-algae, seagrasses and coral reefs and shallow water bathymetry- at significantly higher spatial resolution than 250m.
2. To examine threshold and baseline observation requirements for sensors suitable for aquatic ecosystems to inform CEOS Agencies
3. That the GEO Water community define inland and near-coastal water quality and benthic habitat essential variables, including an assessment of relative priority, linked to defined economic, social and environmental benefits. This information would be of great value in informing investment decisions.

CEOS Team "Feasibility Study Imaging Spectrometer":

Lead: CSIRO - Arnold Dekker; Coordinator: DLR - Nicole Pinnel

Members: (for non-CEOS organisations the country is given)

CNES	Marie-Jose Lefevre & Xavier Briottet
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EOMAP	Thomas Heege (Germany)
CNR	Federica Braga, Claudia Giardino & Vittorio Brando (Italy)
NASA	Kevin Turpie & Nima Pahlevan
CSA	Martin Bergeron & Maycira Costa
USGS	Thomas Cecere
WaterInsight	Steef Peters (Netherlands)
TNO	Andy Court (Netherlands)
CSIRO	Hannelie Botha & Antonio Robles-Kelly

Supporting sponsors:

(NSO)	Mark Loos & Joost Carpaaij
(EC)	Astrid-Christine Koch & Catharina Bamps

Current Status:

April 2016	Team created
May 2016	Contents established
June 2016:	Self-nomination process chapter leads and co-authors
Sept. 2016	Summary presented at (CEOS-SIT) Oxford UK
Nov 2016	CEOS Plenary: Full draft approximately 80 % ready
April 2017	All information required (especially simulations of benthos-water column-airwater interface and atmosphere) written
May-June 2017	Editing to a draft report suitable for review

Table of Contents:
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1. *Strategic direction for studying inland waters, coastal waters, benthos and shallow water bathymetry*
2. *Science and Applications Traceability Matrix and resulting sensor requirements*
3. *Instrument, platform and mission design considerations*
4. *Aquatic ecosystem earth observation enabling activities*
5. *Summary, conclusions, recommendations*
6. *References*

Appendix A: The forward bio-optical and atmospheric simulations

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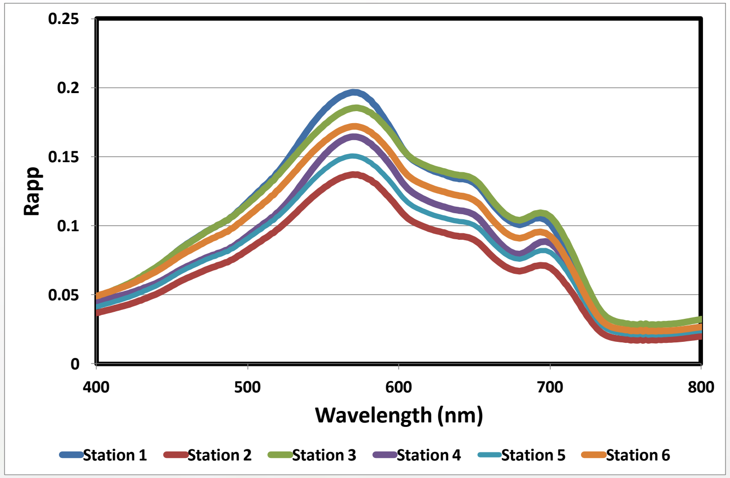
Appendix A: The forward bio-optical and atmospheric simulations

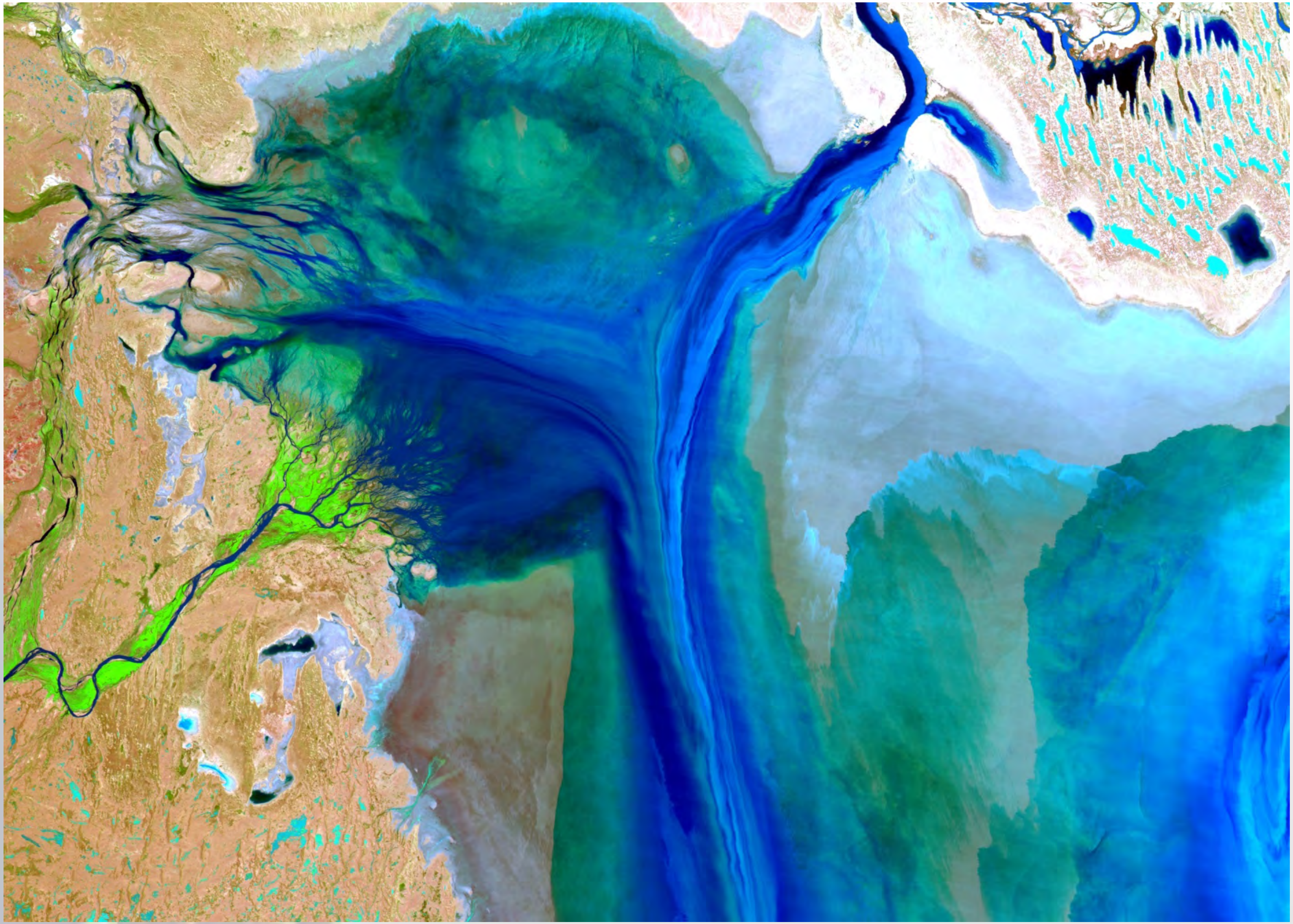
Inland waters: not so simple:
land-water boundaries;
lakes at -140 to 4500 m altitude

- Reflectance

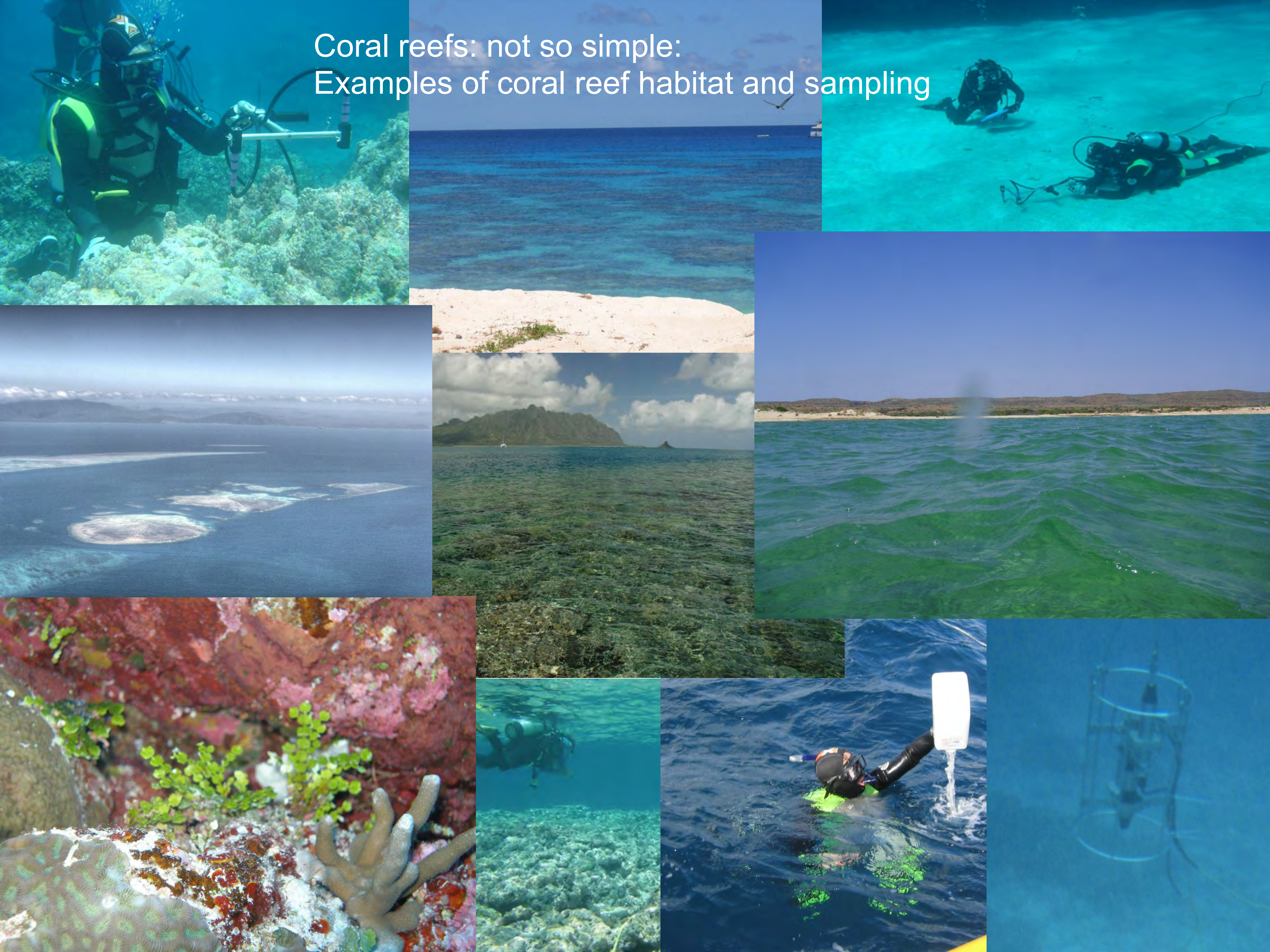


CSIRO

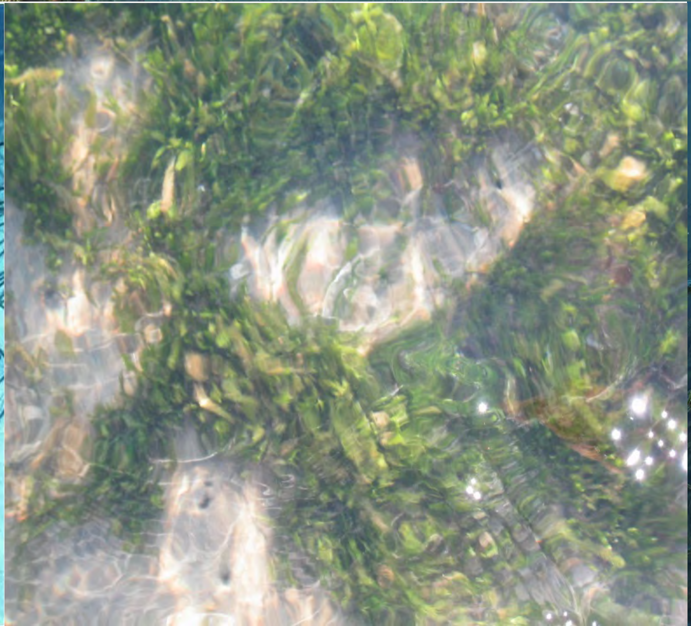
Salt lakes- not so simple (Lake Eyre- Australia after floods)



Coral reefs: not so simple:
Examples of coral reef habitat and sampling

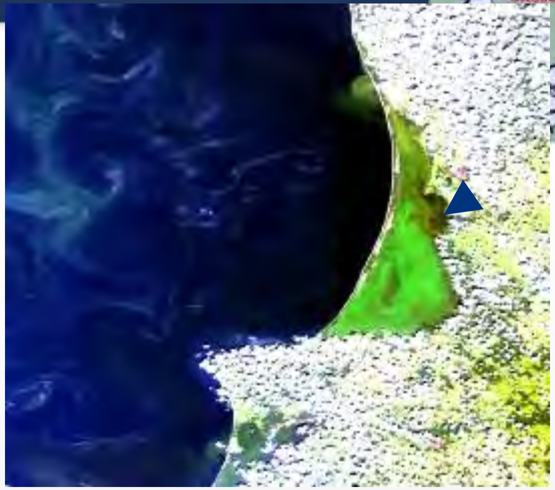


Seagrass and intertidal: not so simple:

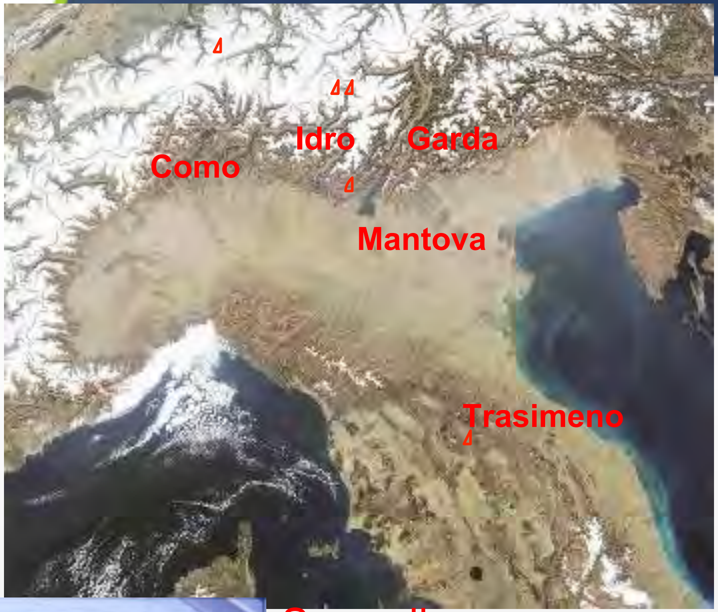


Coastal and inland Harmful Algal Blooms
Not so simple (courtesy C. Giardino CNR)

Curonian lagoon

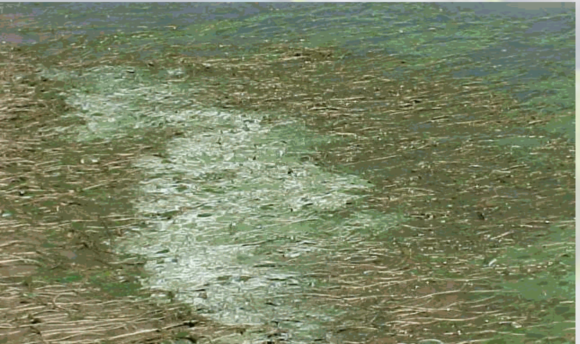


Italian lakes



Sporadic homogeneous blooms with vertical migration in oligo-meso trophic lakes

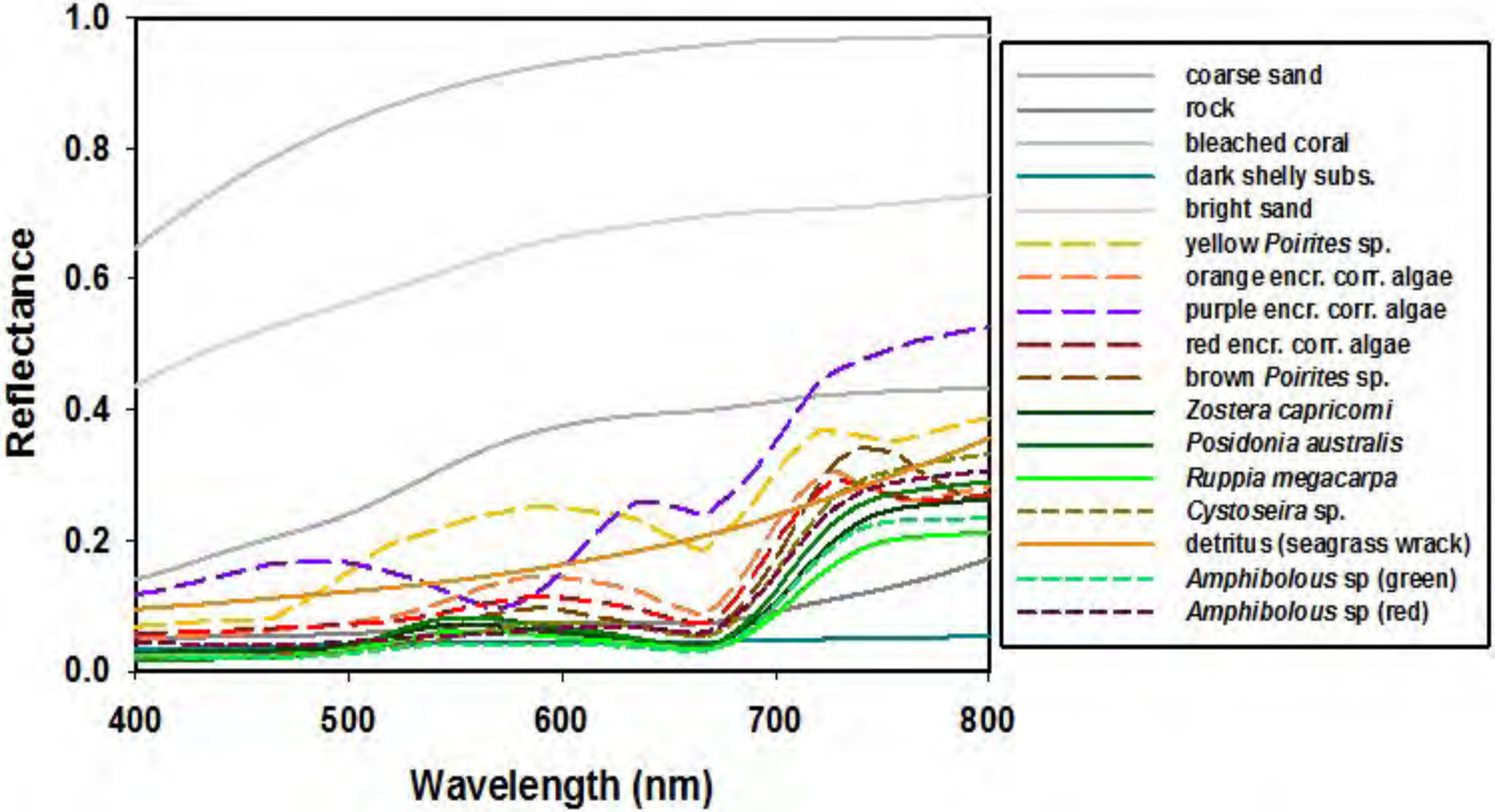
Frequent and intense heterogeneous bloom in hypertrophic lakes



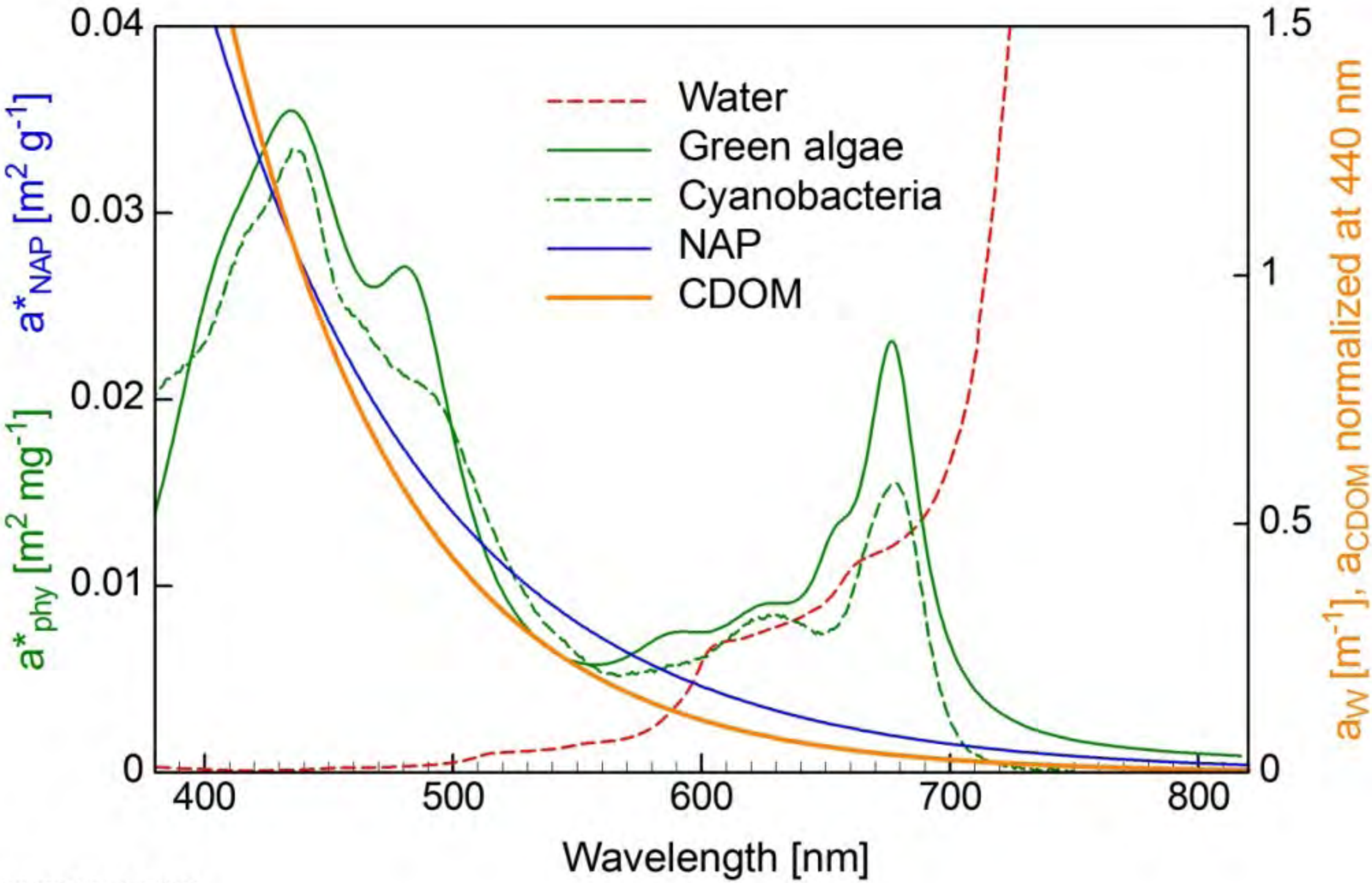
Frequent and intense homogeneous bloom in hypertrophic lakes with scums

Frequent homogeneous bloom in meso-eurtrophic lakes without scums

Substratum spectra: seagrass & coral reef environments used as parametrisation for simulations of Rrs (note the large spectral variability)



Input specific inherent optical property (IOP) data for Rrs simulations (note the large spectral variability)



Note that all simulations shown next are examples of a much fuller set of simulations in the appendix (~ 80 pages)

Scenario	X-	X+	Y-	Y+	C-	C+
Extreme	low TSM	high TSM	low a_{CDOM}	high a_{CDOM}	low CHL	high CHL
	Lake Garda	Lake Taihu	Lake Garda	Finnish lakes	Italian lakes	Lake Taihu
TSM [g m^{-3}]	0.1	300	1(0.2-20)	2(0.5-5)	1(0.2-20)	50(10-300)
a_{CDOM} [m^{-1}]	0.1(0.04-2)	1(0.2-3)	0.04	10	0.1(0.04-2)	1(0.2-3)
CHL [mg m^{-3}]	1(0.1-10)	20(1-1000)	1(0.1-10)	5(1-10)	0.2	1000
S [nm^{-1}]	0.014 (0.01-0.02)	0.014 (0.01-0.02)	0.014 (0.01-0.02)	0.014 (0.01-0.02)	0.014 (0.01-0.02)	0.014 (0.01-0.02)

The simulations keep the extreme value constant and change other model parameters within a realistic range. Note that some water constituents are not completely independent (e.g. high CHL prevents very low a_{CDOM} values as CDOM is also a degradation product of phytoplankton).

The iterated model parameters include TSM, a_{CDOM}, CHL, and the slope of CDOM absorption (S).

Simulation results Rrs (normalized) for a range of inland to coastal water types

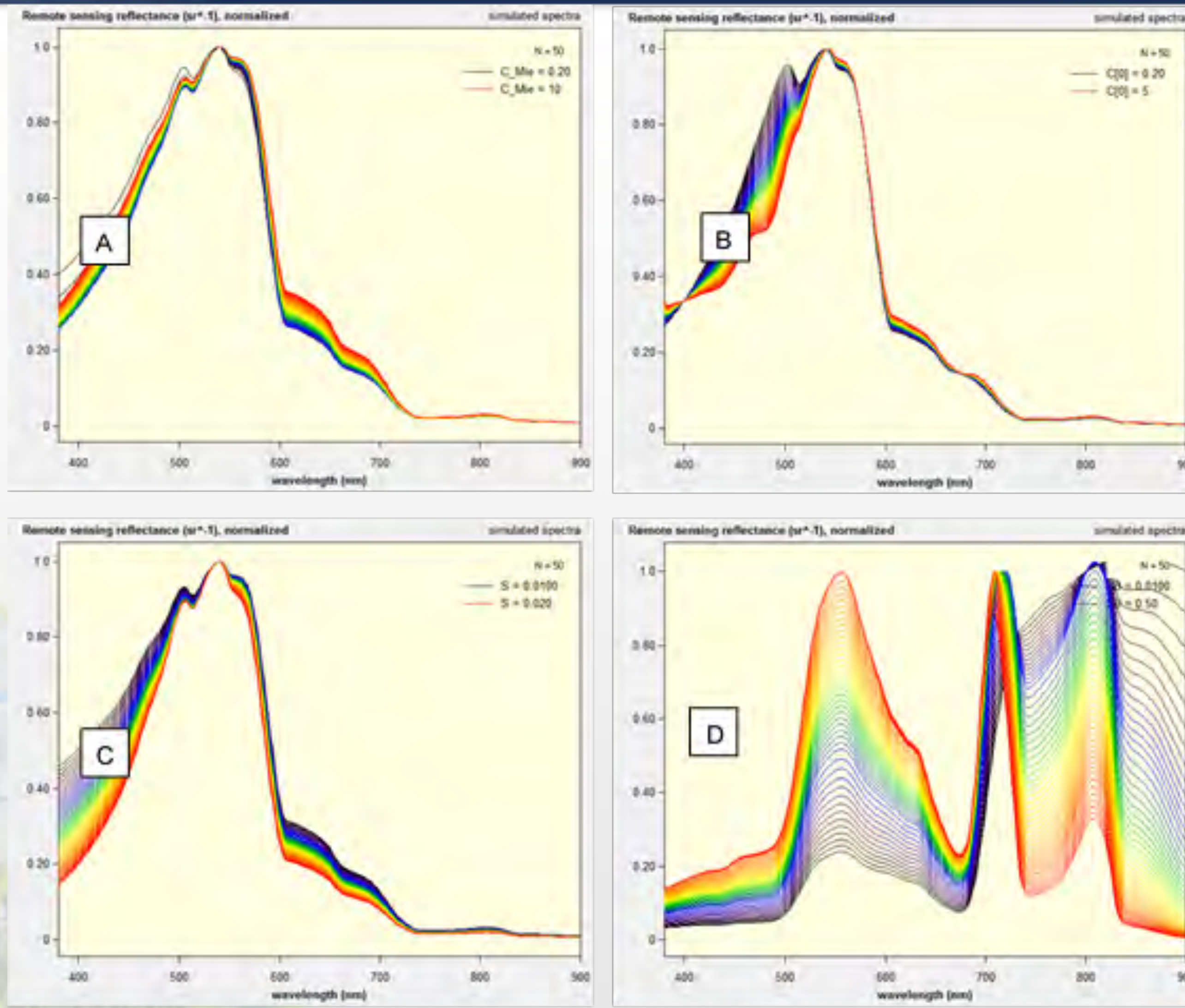


Figure 1: Normalized remote sensing reflectance for (A) TSM range 0.2 - 10 mg/l, (B) CHL range 0.2 – 5 µg/l, (C) S_{CDOM} range 0.010 – 0.020 nm^{-1}, (D) depth range 0.01 – 0.5 m.

Simulation results of spectral resolution for a range of inland to coastal water types (Y-axis is spectral resolution in nm)

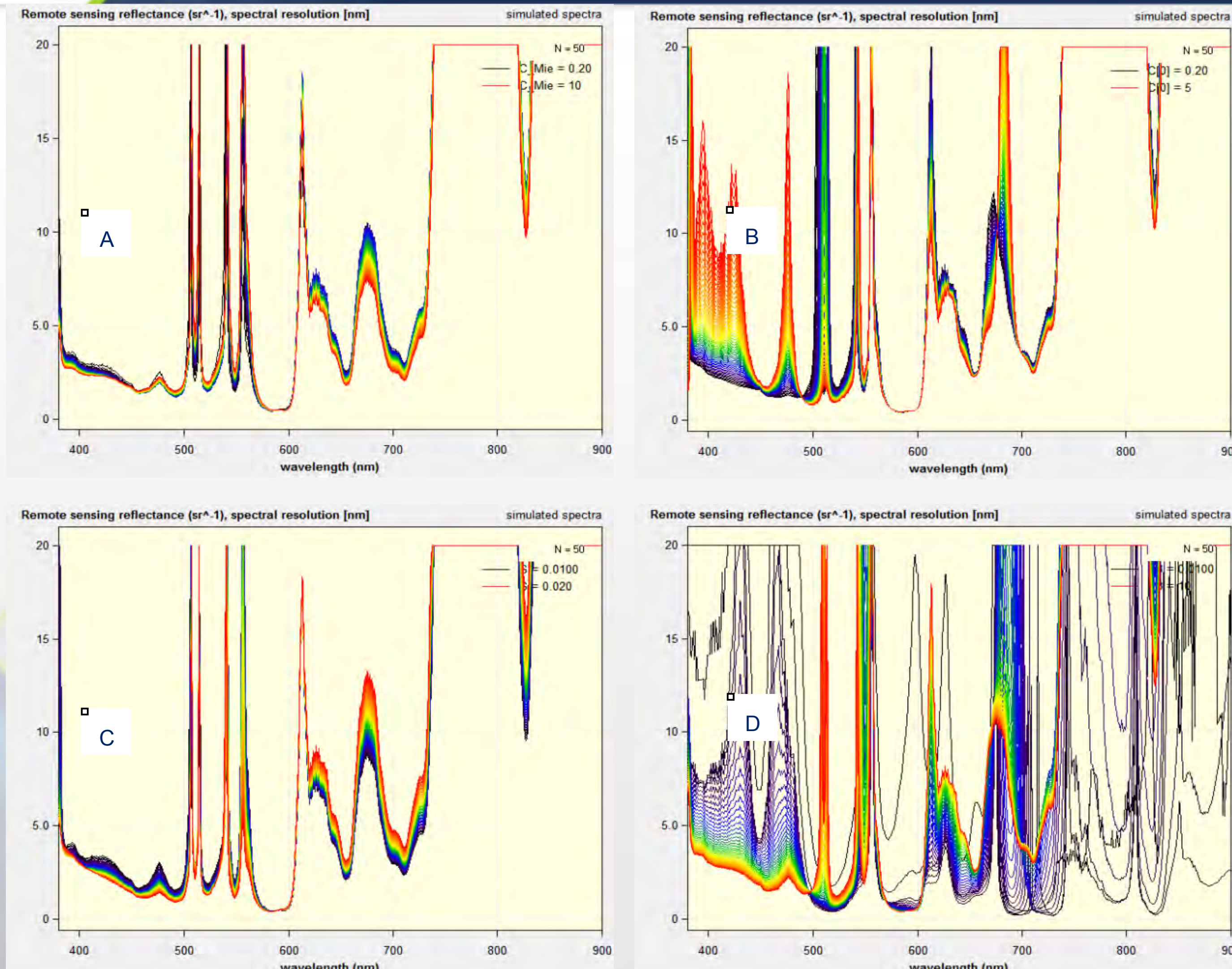


Figure 10: Spectral resolution for
(A) TSM range 0.2 - 10 mg/l, **(B) CHL range 0.2 – 5 µg/l,**
(C) S_{CDOM} range 0.010 – 0.020 nm^{-1}, **(D) depth range 0.01 – 10 m.**

1^{st} and 2^{nd} derivatives of Rrs

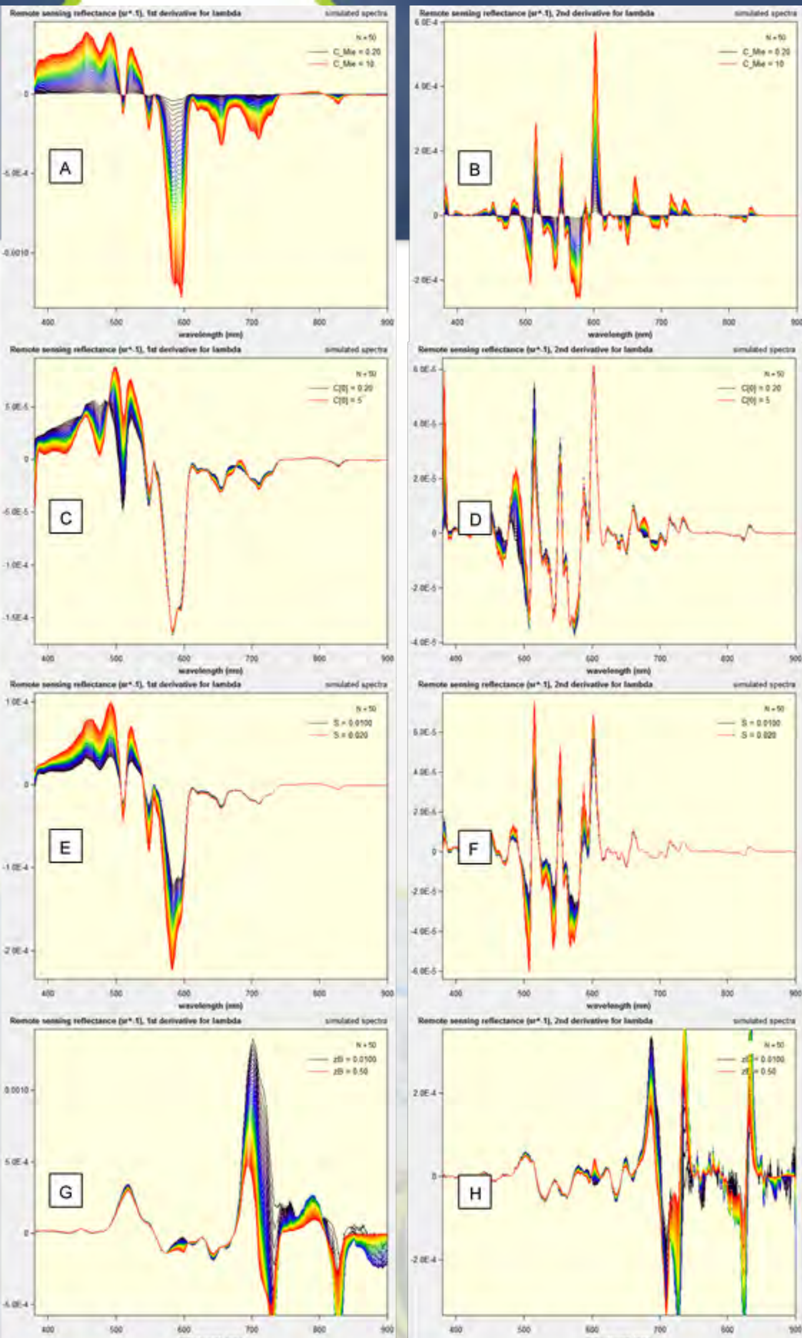


Figure 1: First (left column) and second (right column) derivatives of remote sensing reflectance for (A, B) TSM range 0.2 - 10 mg/l, (C, D) CHL range 0.2 – 5 µg/l, (E, F) S_{CDOM} range 0.010 – 0.020 nm^{-1}, (G, H) water depth range 0.01 – 0.5 m.

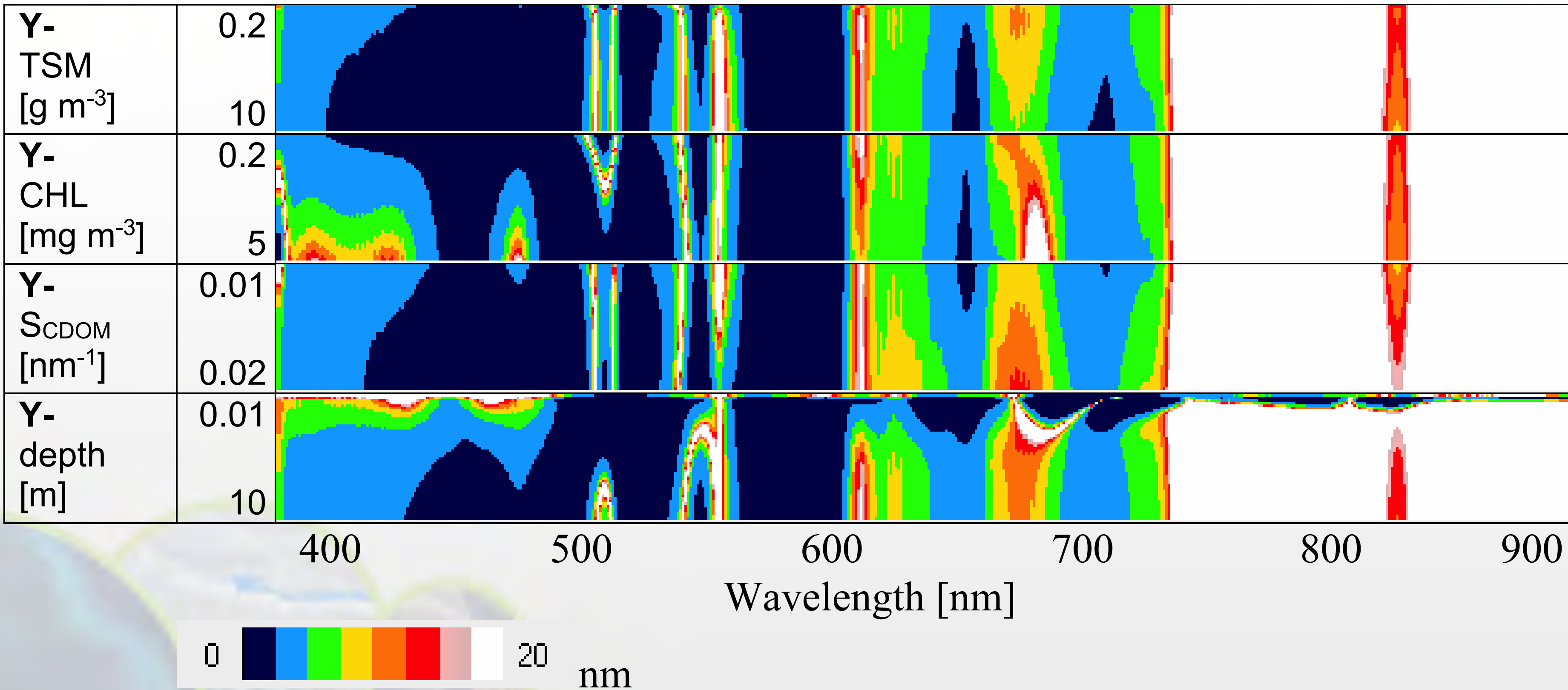
1^{st} and 2^{nd} derivatives of Rrs for a range of inland to coastal water types

1^{st} derivative: where reflectance peaks and troughs occur as a f(max, min) in light absorption,

2^{nd} derivative: where reflectance shoulders appear as a f(max, min) in light absorption

Note that these include pure water absorption effects

Spectral resolution (in 2.5 nm steps) required to resolve change at low to high variable concentration (standard OAC scenario-optically shallow water)



Simulations showing how max change in NeDR and it's spectral location varies with changing concentrations (standard OAC's concentrations scenario)

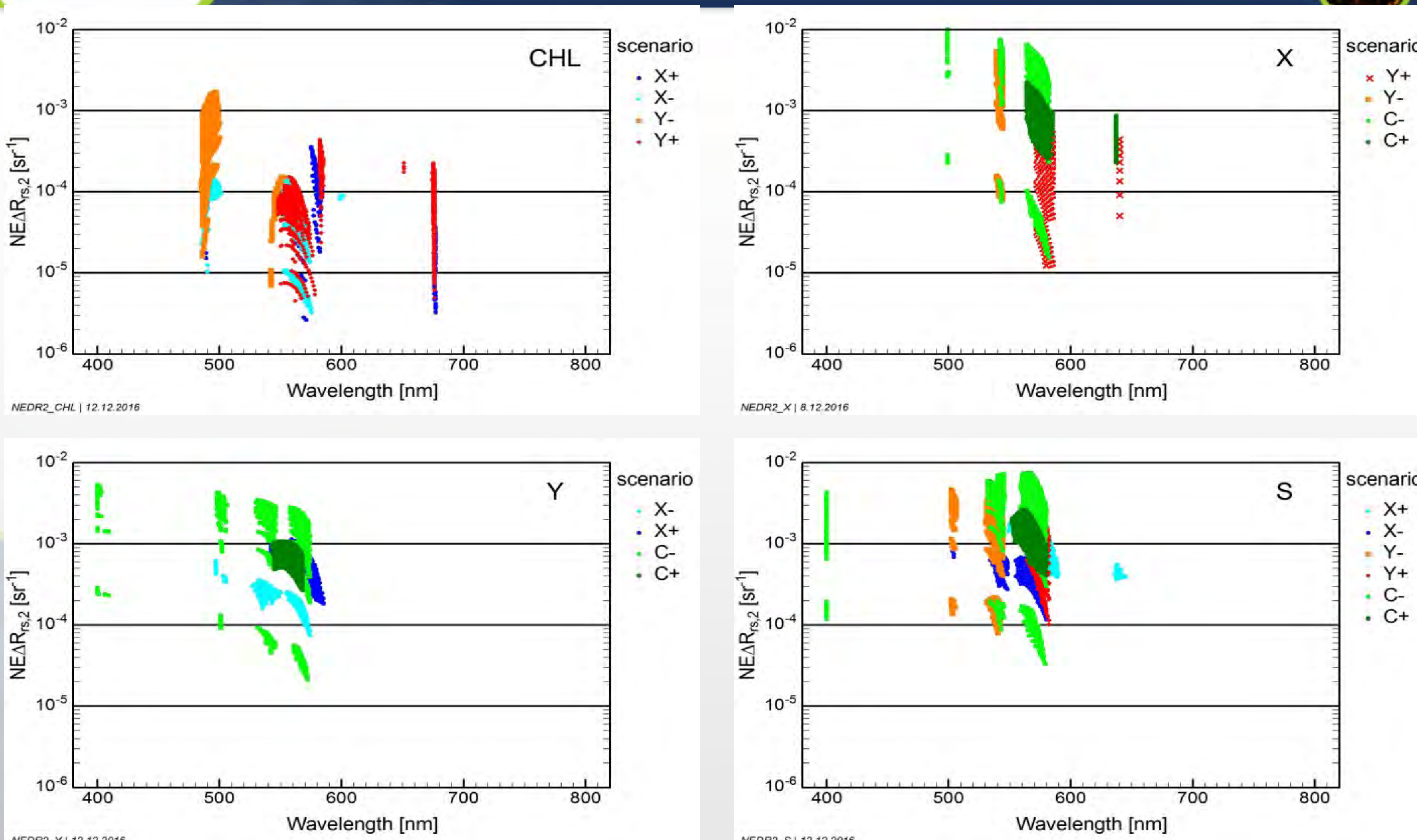


Figure 35: Maximum change of R_{rs} for a 10% change of CHL, x=TSM, Y=CDOM, S=CDOM slope for the standard OACs range scenarios.

Simulations showing how max change in NeDR and it's spectral location varies with changing concentrations (extreme concentrations scenario)

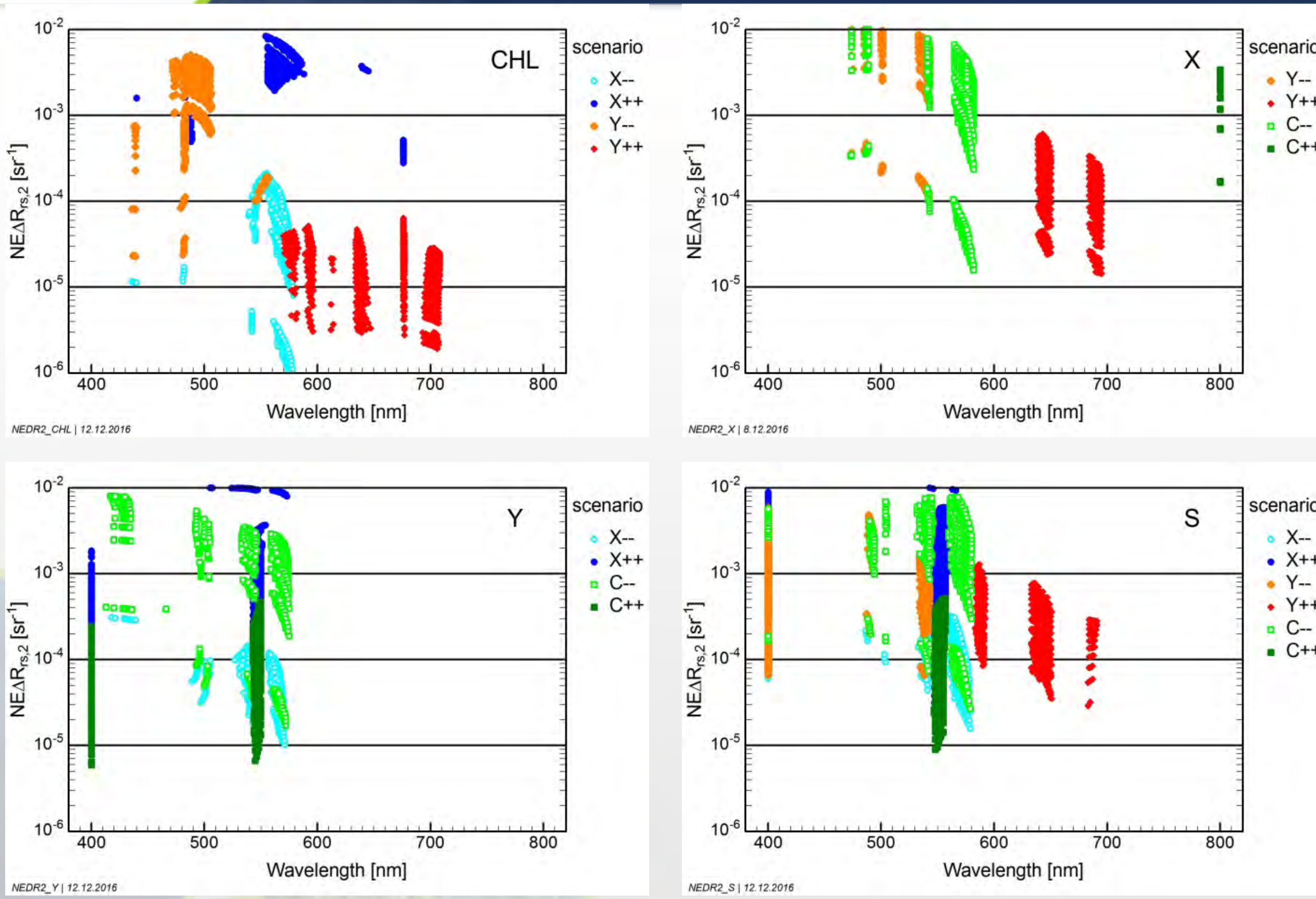
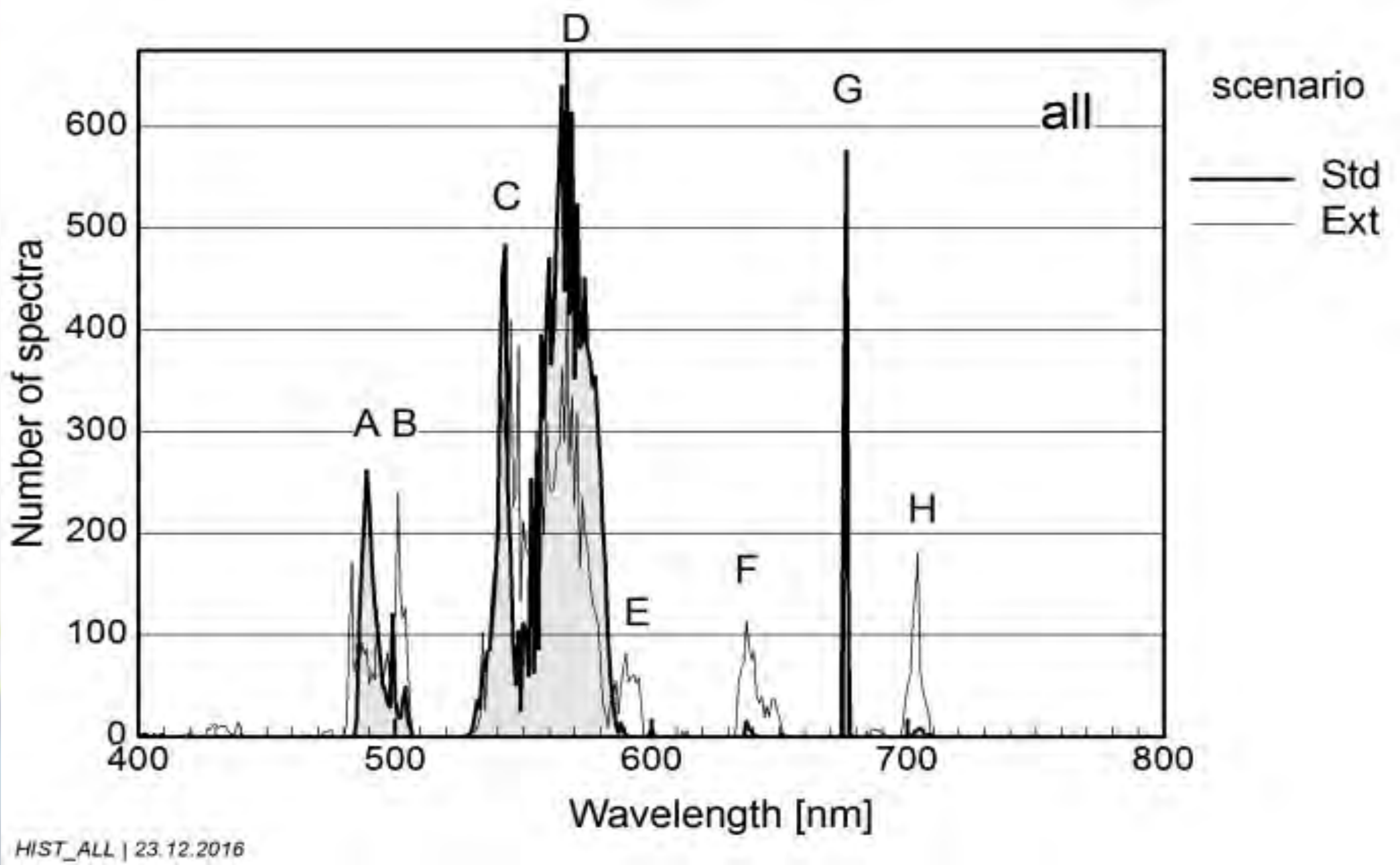


Figure 36: Maximum change of R_{rs} for a 10% change of the parameter indicated top right for the extreme scenarios.

Possible augmentation bands to multispectral land sensors (note that this analysis method poorly resolves areas where spectral peaks shift)



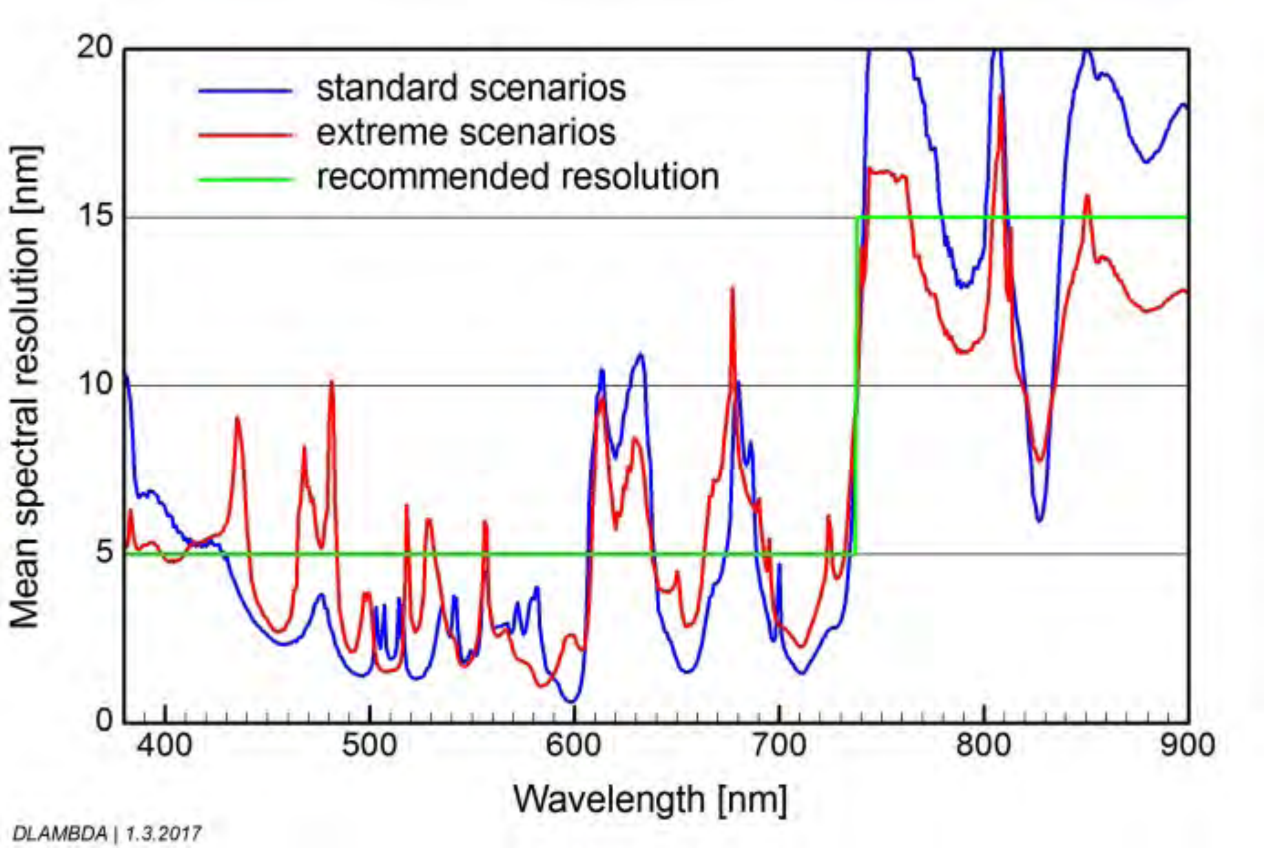
The sum of the histograms for CHL, CYA, TSM, CDOM and S(CDOM). The labels A to H indicate the most sensitive spectral regions.

Trade-off between spatial, spectral and radiometric resolution

The priority in specifications for an aquatic ecosystem imaging spectrometer (or many multi-bands sensor is from 1 to 4:

1. Spatial resolution (as not getting a pure aquatic pixel avoids any measurement at all)
2. Spectral resolution (to discriminate between all the variables)
3. Radiometric resolution: should be as high as possible given priorities 1 and 2
4. Temporal resolution (varies from once a season to hourly intervals) can be solved by LEO+GEO and /or constellations of LEO's

Summary of Results: spectral resolution recommendation based on simulations



the recommended spectral resolution of a hyperspectral sensor based on these simulations is 5 nm (+/- 3 nm) from 380 to 737 nm, and 15 nm from 737 to 900 nm.

Summary spectral bands & resolution from: (i) multiple types of simulations, (2) spectral pigment features (from phytoplankton, macrophytes and other benthos), and algorithm requirements

Center nm	FWHM nm	Application
+/- 385	6	CDOM ; NAP
+/- 425	8	CDOM ; Blue Chl-a absorption band reference band ; NAP
443	8	Blue Chl-a absorption maximum
+/- 475	7	Accessory pigments ; Blue Chl-a absorption band reference band ; NAP
+/- 490	8	Chl band-ratio algorithm (in clear waters)
+/- 510	6	Chl band-ratio algorithm (in clear waters) ; NAP ; red tide
+/- 542	8	Suspended sediments (as most algal pigments absorptions are low);
+/- 555	8	Suspended sediments (as most algal pigments absorptions are low); Cyanophycoerythrin
565	8	Cyanophycoerythrin in vivo absorption maximum
+/- 583	8	Phycoerythrin ;cyanophycocyanin reference band
624	8	Cyanobacteria (specifically phycocyanin), suspended sediment,
+/- 640	16	NAP, cyanophycocyanin reference band
655	3	Chl-b
670	7	Fluorescence line height (FLH) baseline; red chl-a absorption peak suitable for chlorophyll in highly turbid or CDOM rich water
676	7	Chlorophyll in vivo absorption maximum; Fluorescence line height
683	3	Chlorophyll fluorescence (FLH)band
+/- 700	8	FLH baseline; HABs detection; NAP in highly turbid water; reference band for 2 or 3 band Chl-a algorithms
+/- 710	8	FLH baseline; HABs detection; NAP in highly turbid water; reference band for 2 or 3 band Chl-a algorithms
+/- 748	9	NAP in highly turbid water; emerse macrophytes and kelp and other floating vegetation

Note that for the algal pigment absorption maxima we have included reference bands for the 3 band pigment absorption and fluorescence line height approaches. Physics based spectral inversion methods do not need these pigment reference bands. When the band center has a +/- sign it means that the wavelength center is not critical and may vary by about 5 nm.

Recommended spectral bands for atmospheric correction purposes as well as Non Algal Particulate matter concentration estimation.

+/- 730	Sun and sky glint/NAP/atmospheric correction
+/- 740	Sun and sky glint/NAP/atmospheric correction
+/- 750	Sun and sky glint/NAP/atmospheric correction
+/- 770	Sun and sky glint/NAP/atmospheric correction
+/- 865	Atmospheric correction
1240 or 1238	Atmospheric correction (*MODIS* or VIIRS)
1640 or 1600	Atmospheric correction(*MODIS* or VIIRS)
2130 or 2257	Atmospheric correction (M*ODIS* or VIIRS)

Table 6.2.

Spatial resolution for inland waters is a key driver for specifications

Ground sampling distance requirements showing resolvable size class and total cumulative number and area coverage of the world's lakes (based on assumptions using Verpoorter et al. (2014) dataset). (Courtesy E.L. Hestir & Mark Matthews)

Size Class	Required GSD*	% Total Area	Total number	
≥ 10 km^2	1054 m	44	25,976	Focus of current and future OC sensors
≥ 1 km^2	333 m	60	353,552	
≥ 0.1 km^2	105 m	80	4,123,552	Focus of this study
≥ 0.01 km^2	33 m	90	27,523,552	
≥ 0.002 km^2	15 m	100	117,423,552	

*Calculated using a box of 3 x 3 pixels sufficient to resolve the specified lake size

Ground sampling distance requirements showing the resolvable river width class and cumulative number of total river reaches of the world's rivers from Pavelsky et al. (2012) dataset.

River Reach Size Class (width)	Required GSD*	Total number of reaches	Percent of total reaches
1.5 km	500	2,877	< 0.1%
≥ 1 km	333	8,483	<1%
≥ 0.5 km	167	35,420	1%
≥ 0.1 km	33	382,466	12%
≥ 0.05 km	17	766,303	24%
≥ 0.01 km	3	2,576,452	81%

*Calculated using a box of 3 x 1 pixels sufficient to resolve the width of the river reach

Focus of current and future OC sensors

Focus of this study

Spatial & spectral resolution requirements

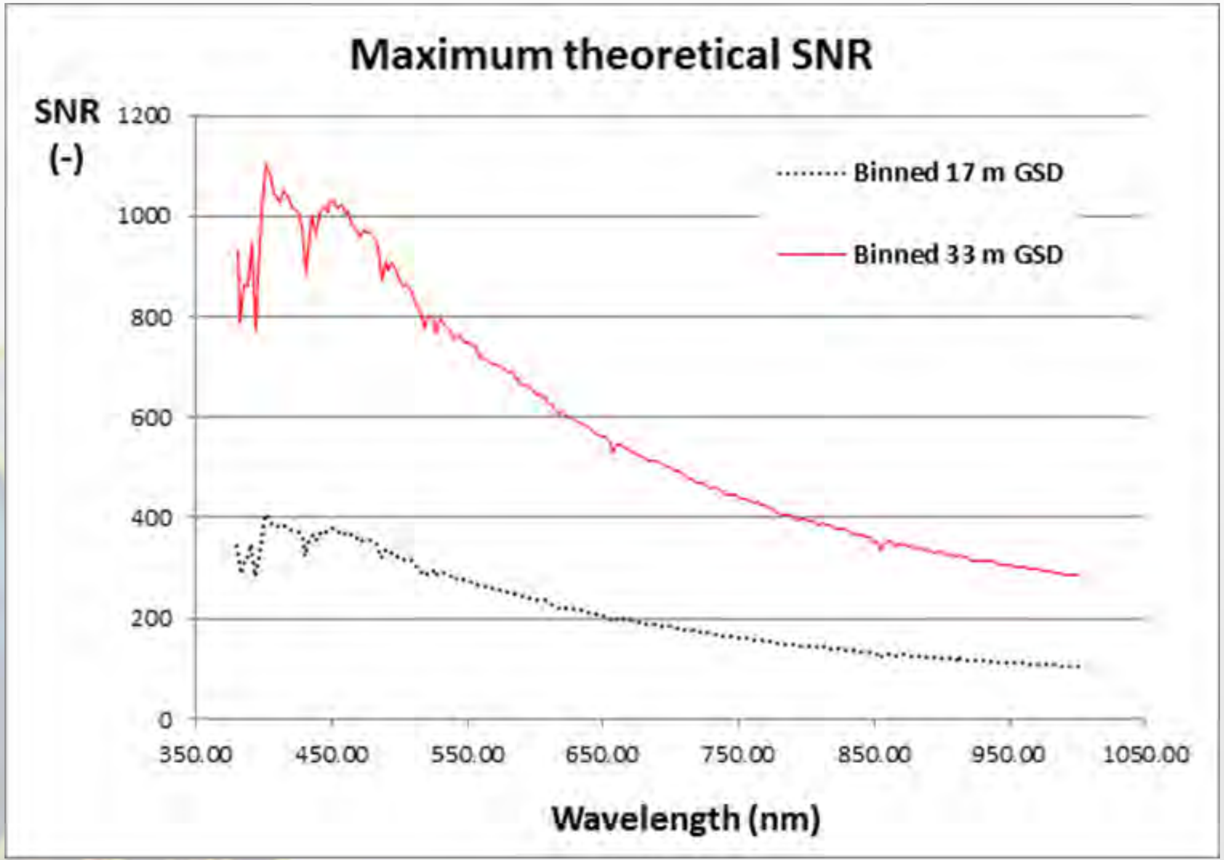
The minimum spatial resolution requirement for inland water bodies can be categorized for large lakes and for smaller water bodies:

- A GSD of 300 m can observe the majority of the world's lake surface area (but is a small fraction of the total number of lakes)
- The Sentinel-3 series of satellites has 22 spectral bands, high SNR and a GSD of 300m and is thus adequate for large lakes.
- A sensor with a minimum GSD of 15-17 m would enable observations for ~25% of global river reaches and 90 to 100% of lakes 0.2 ha or larger.
- The focus should be around 5 to 8 nm spectral intervals and a GSD of about 17 m, whilst a GSD of 30 m could be a compromise between costs and S:N (= close to experimental sensor ENMAP Specs)

A simulation of achievable radiometric resolution within constraints of spectral and spatial resolution in terms of SNR (By M. Bergeron CSA)

Raw Ground Sampling Area of 5.66 and 11 m binned (3 bins) to 17 and 33 m;

- Raw Spectral Sensing Interval of 2.66 nm binned (3 bins) to 8 nm;
- Assumes typical TOA radiance at 42 degrees SZA from Zia Ahmad (2012);
- a 30 cm aperture for the fore optics.



CEOS Report
"Feasibility Study Imaging Spectrometer":

Society needs detection, assessment and monitoring of aquatic ecosystems :

UN SDG's 6, 14 and 15 contain aquatic ecosystem variables specifically.

Coral reefs, seagrasses, macro-algae, macrophytes (freshwater) could all possibly be measured with a fixed set of multispectral bands for each separate application

However…..

- When measuring optically active water constituents over large ranges (optically deep water case) and needing to measure the substratum/benthic spectra through a water column (optical shallow water case), there is not one specific multispectral band set that will be able to do it all- **strong indication imaging spectrometry will be required**.

On the other hand …..

- By augmenting planned **land sensors spectrally** or **ocean sensors spatially**, cost-effective solutions for observing aquatic ecosystems could be achieved.

Cost-effective enhancements to planned land sensors to make them much more suitable for inland and coastal water quality , submerged vegetation and benthic measurements.

As new versions for Landsat and Sentinel-2 are foreseen, a cost effective manner to enhance these global sensors for inland and near-coastal water remote sensing is to add a few spectral bands and to increase the spatial resolution where possible.

Sentinel-2 : if all 13 Sentinel 2 bands could be 10 m spatial resolution that would be a significant benefit for inland water remote sensing.

For S-2 and Landsat some extra spectral bands (8 to 10 nm wide) such as at the cyanophycocyanin and red chlorophyll-a suitable wavelengths centered at 624 and 676 nm resp. would significantly enhance their suitability as global missions for inland and coastal water quality as well as shallow water bathymetry, submerged vegetation and benthos measurements.

CEOS Report
“Feasibility Study Imaging Spectrometer”:

Suggestions for improvements appreciated

Also see Wesley Moses Presentation:

Tuesday 15:35 Breakout Workshop 4.(Auditorium I) RS of Inland and Coastal Waters: title “Sensors” and compare……….

Arnold Dekker

Director SatDek Ltd

Satellite based Discovery of Environmental Knowledge

Honorary Professor - Australian National University

Adjunct Professor - University of Queensland

Honorary Science Fellow - CSIRO, Australia

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  - *1.2.1. RS of Inland waters and variables*
  - *1.2.2. RS Coastal and optically shallow waters*
- *1.3. Introduction to the physics of light interaction in water bodies*
- *1.4. Introduction to algorithms to derive information from RS data*
- *1.5. Benefits to society / societal impacts*
- *1.6. What we propose to do*

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- *2.2. Science question per application*
    - *2.2.1. Inland waters*
    - *2.2.2. Aquatic macrophytes in wetlands*
    - *2.2.3. Estuarine, deltaic and lagoon waters*
    - *2.2.4. Seagrass, coral reefs, kelp*
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- *2.3. Science and applications traceability matrix (inland waters & wetlands, estuarine, delta's and lagoons, seagrassess and coral reef, kelp, shallow water bathymetry)*

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  - *2.4.1. Bio-optical simulations of remote sensing reflectance and water leaving radiance*
    - *2.4.1.1. Theory*
    - *2.4.1.2.Spectral intervals and resolution*
    - *2.4.1.3. Radiometric sensitivity (SNR , NEdL and NEdR)*
  - *2.4.2. Top of atmosphere simulations (SNR , NEdL and NEdR)*
  - *2.4.3. Spatial resolution and geometric accuracy requirement*
  - *2.4.4. Temporal resolution requirements*
  - *2.4.5. Atmospheric, adjacency effect and air-water interface correction requirements*
  - *2.4.6. Summary of sensor specifications*

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- *2.6. Proposed modifications to planned future sensors to make them more suitable for (non-oceanic) aquatic ecosystems*
  - *2.6.1. Modifications to planned land sensors*
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- *3.2. Geostationary orbit sensors*
- *3.3. Scanning time and coverage*
- *3.4. Atmospheric and air-water interface corrections*
    - *3.4.1. Aerosols*
    - *3.4.2. Ozone and* NO_2
    - *3.4.3. Water vapour*
    - *3.4.4. Sun glint avoidance and mitigation strategies*
    - *3.4.5. Polarization*
    - *3.4.6. Adjacency effect*

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- *3.5.1. Straylight*
- *3.5.2. Striping*
- *3.5.3. Linearity response*
- *3.5.4. Polarisation*
- *3.6. Calibration and validation*
  - *3.6.1. Pre-launch calibration and characterization*
  - *3.6.2. Post-launch calibration and validation*
- *3.7. Platform requirements incl. geometric stability*
- *3.8. Ancillary data requirements*
- *3.9. End-to-end simulation*

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4. Aquatic ecosystem earth observation enabling activities

- *4.1. Introduction*
- *4.2. Studies for algorithm development*
  - *4.2.1. Atmospheric correction*
  - *4.2.2. Air-water interface correction*
  - *4.2.3. In water algorithms*
    - *4.2.3.1. Optically deep waters*
    - *4.2.3.2. Optically shallow waters*

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"Feasibility Study Imaging Spectrometer":

4.3. In situ Instruments

- *4.3.1. Spectroradiometers (AOP sensors) above and underwater*
- *4.3.2. IOP sensors*
- *4.3.3. Biogeochemical sensors*

- *4.4. Sources of uncertainties*
- *4.5. Field campaigns and priorities for calibration/validation research*
- *4.6. Interdisciplinary science studies (data-data fusion, model-data fusion, model-data assimilation)*

5. *Summary, conclusions, recommendations*
6. *References*

Appendix A: The forward bio-optical and atmospheric simulations