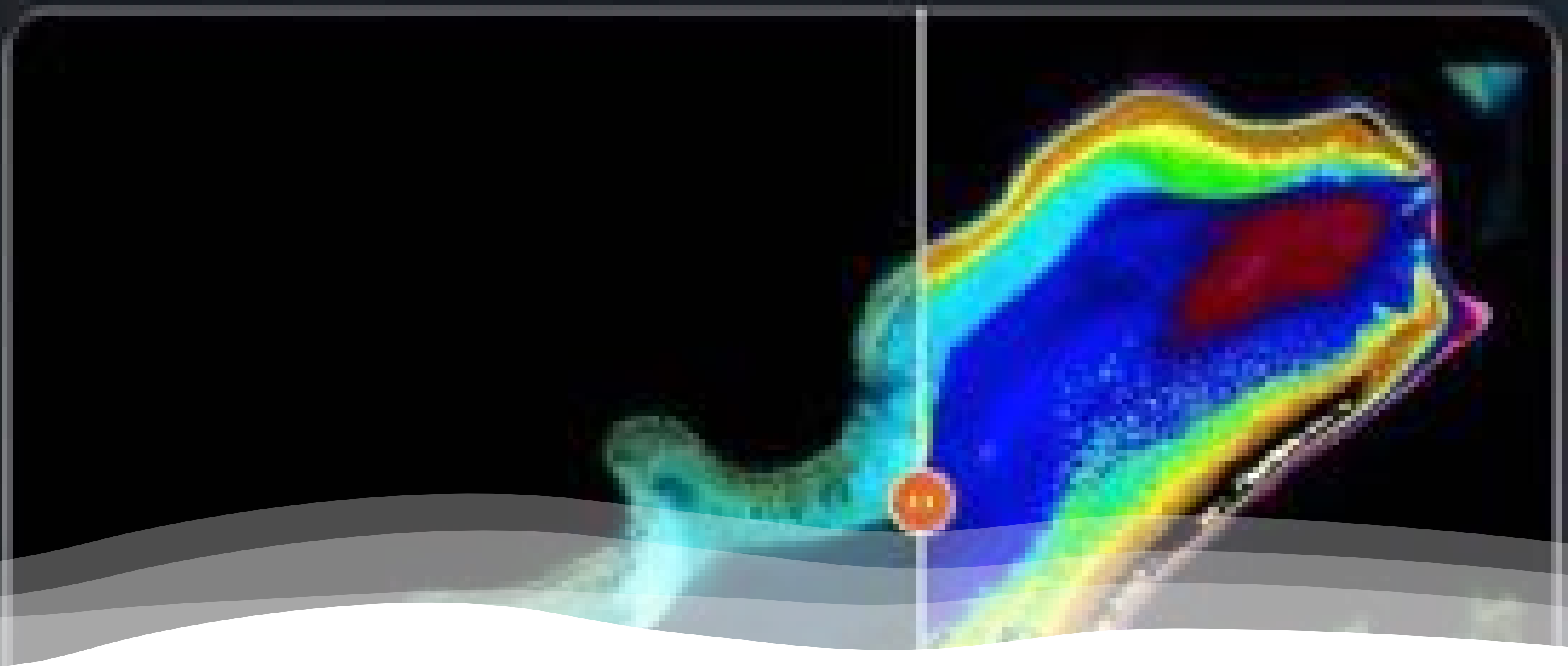


Claudia Giardino, Laura Zoffoli

Tools for shallow water mapping

2026 IOCCG Summer Lecture Series

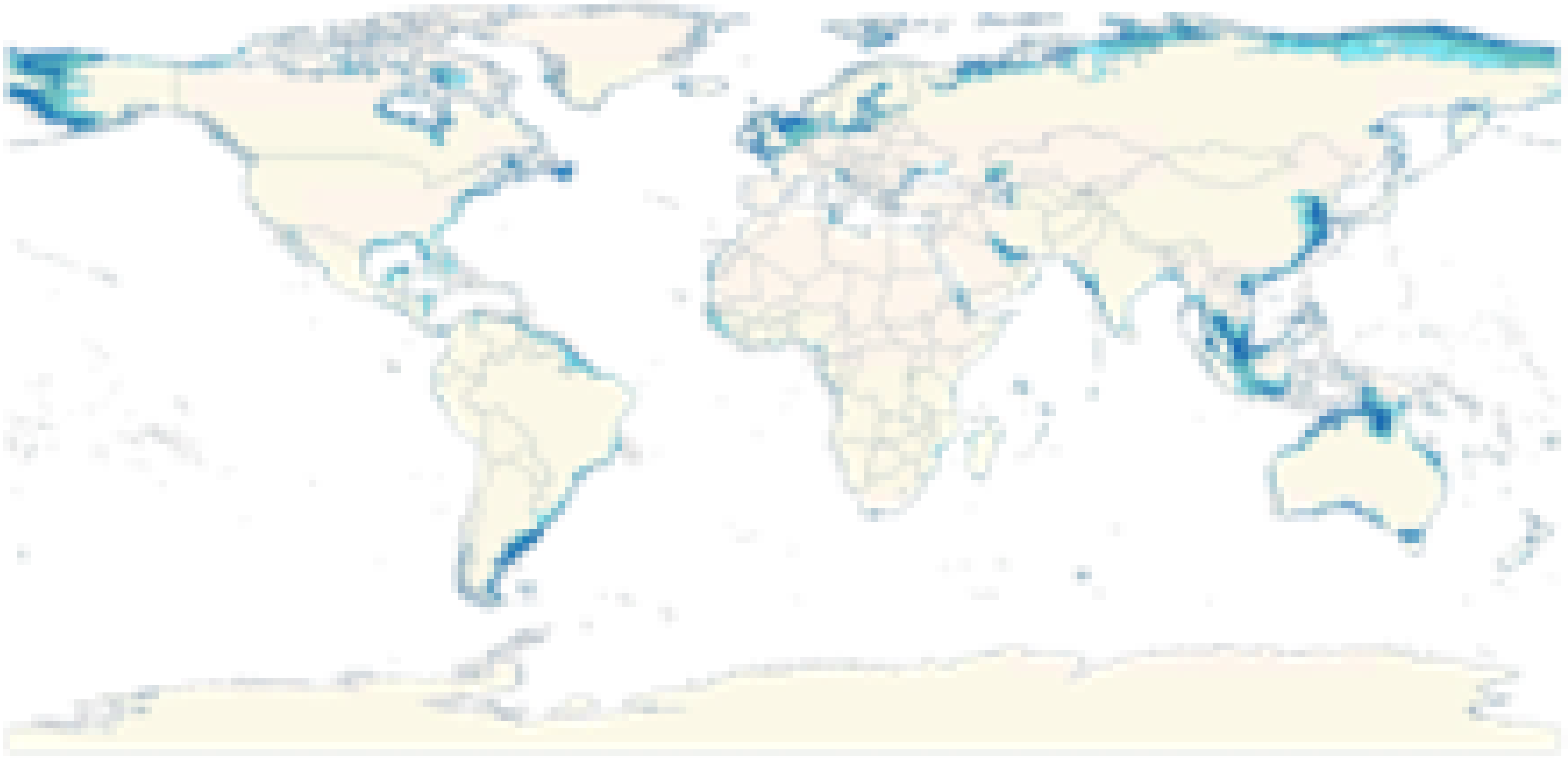
Frontiers in Ocean Optics and Ocean Colour Science: 5 – 19 July 2026

Italian National Research Council

Presentation outline

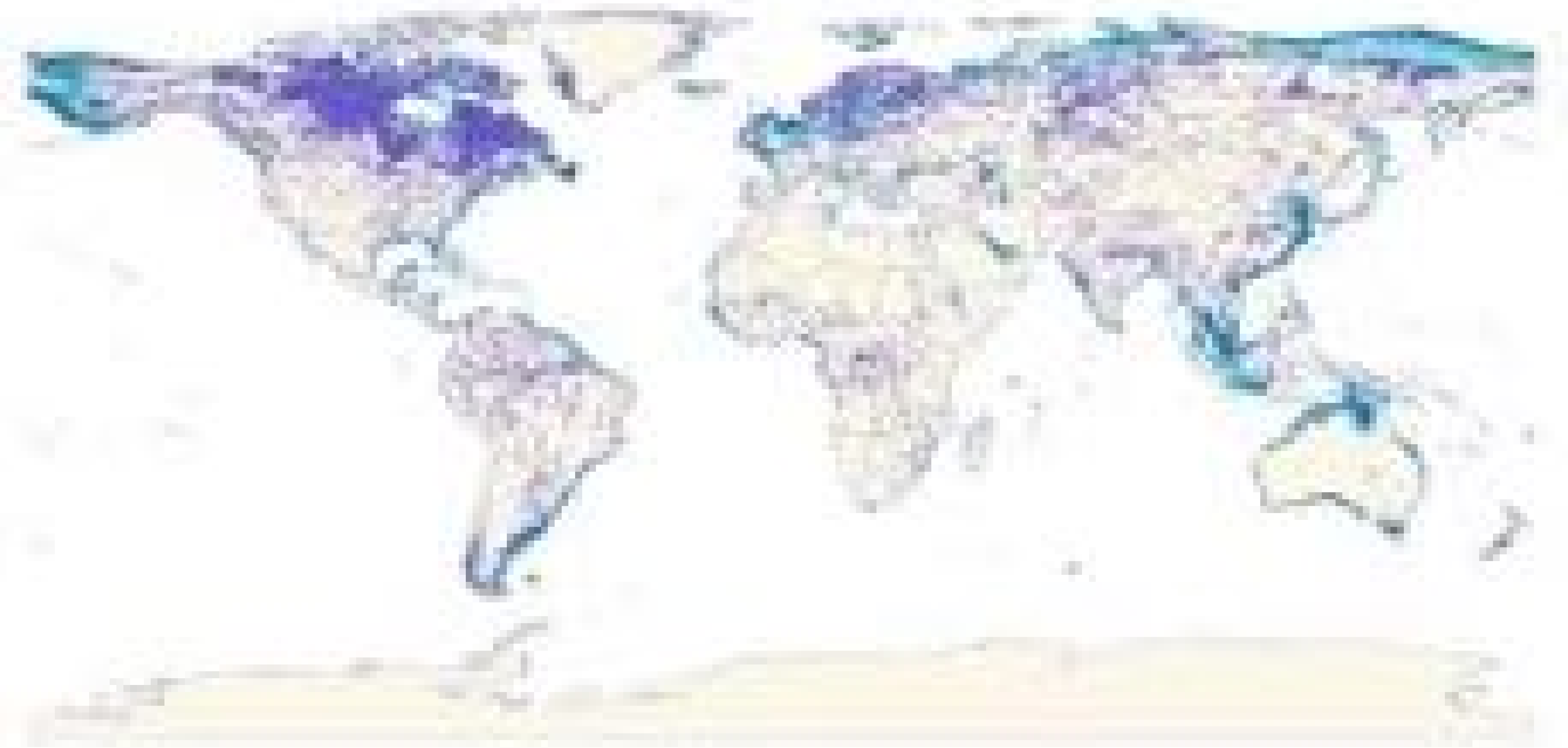
- **Scientific rationale**
- **Methods**
based on few publications
- **Software/Tools**
BOMBER
WASI
Sen2Coral - SWAMPy
- **Applications**
based on 3 studies
- **SWAMPy**

Global relevance



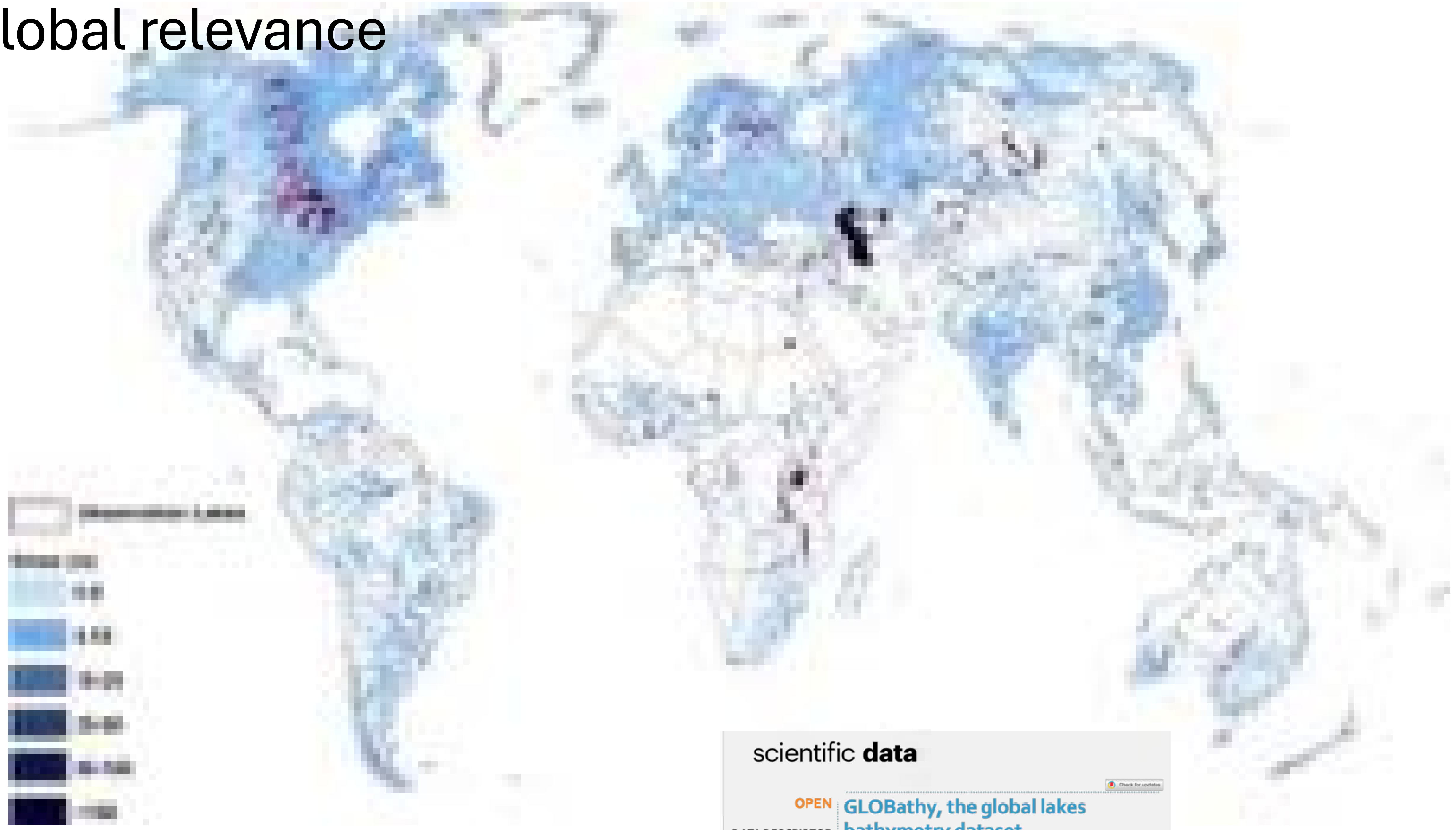
Coastal regions where the sea bottom depth is less than 50 m (data source: GEBCO Grid 2021)

Global relevance



Inland water ecosystems addedd (e.g. lakes, rivers, ponds, streams, wetlands) Data source: GLWD-1 and GLWD-2

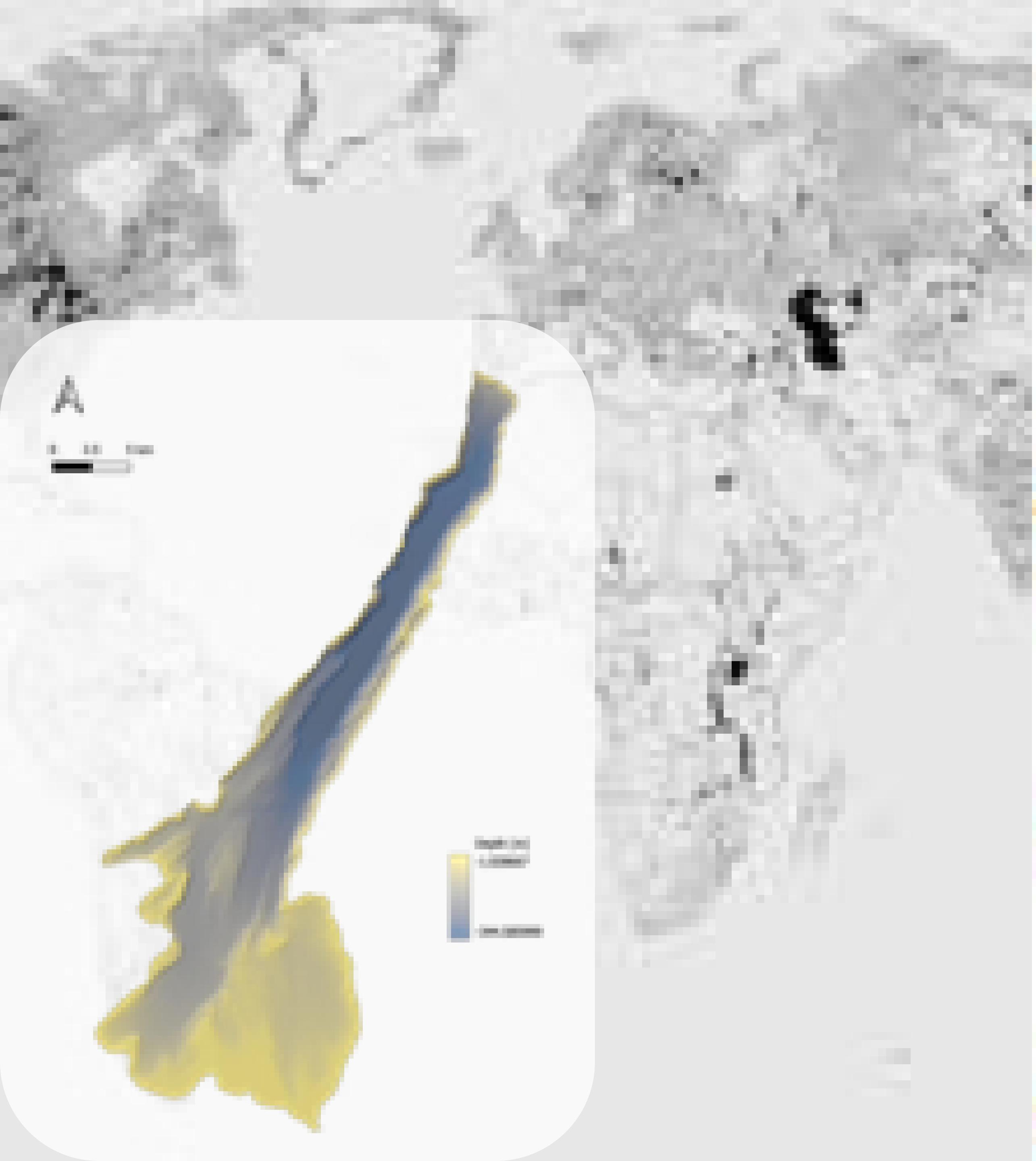
Global relevance

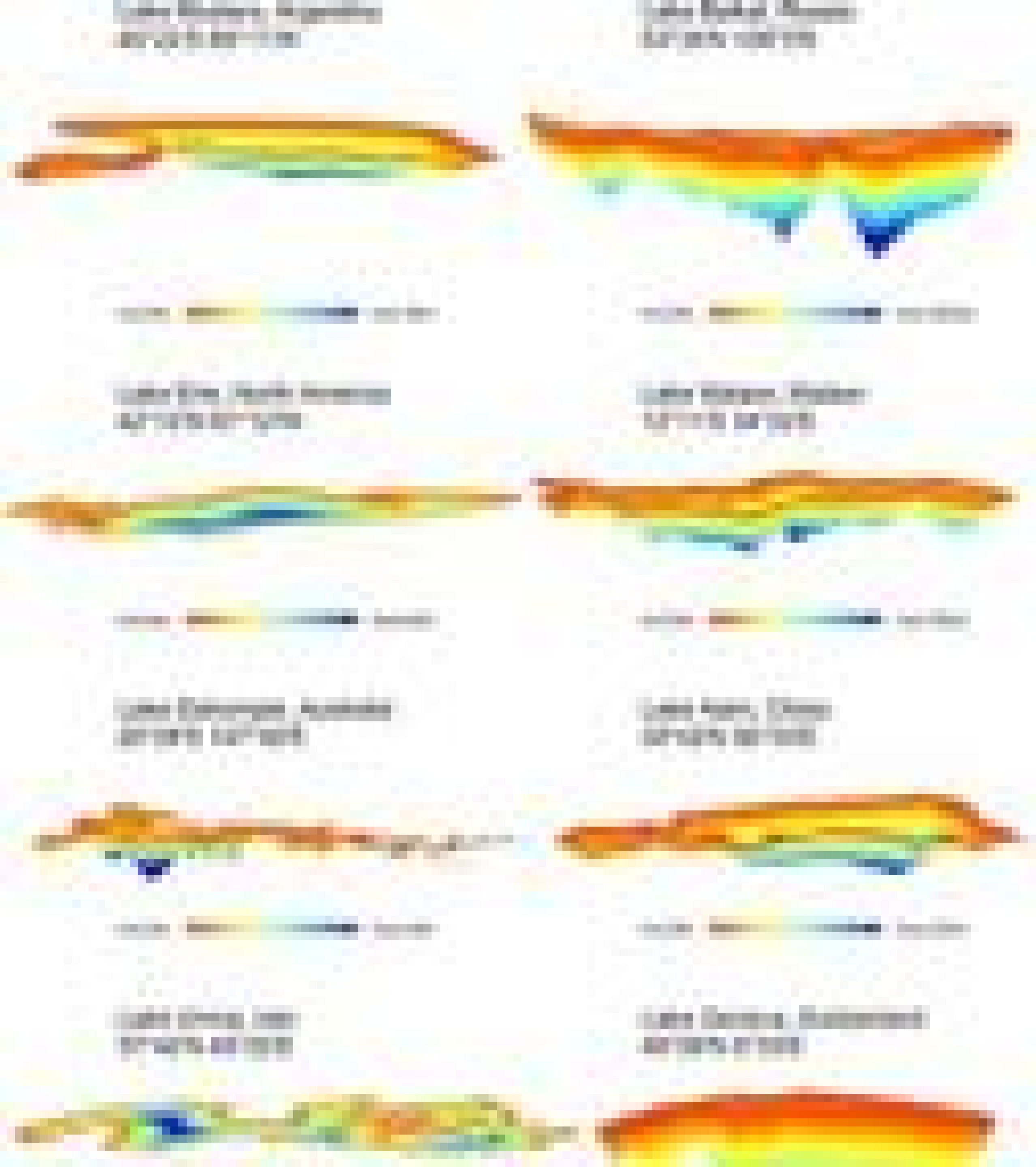


scientific **data**

OPEN
DATA DESCRIPTOR

GLOBathy, the global lakes bathymetry dataset





Value of coastal ecosystems

Coastal ecosystems are supporting numerous physical and biological processes, act as recreational, leisure, and tourism centres and overall provide a wide range of valuable ecosystems services.

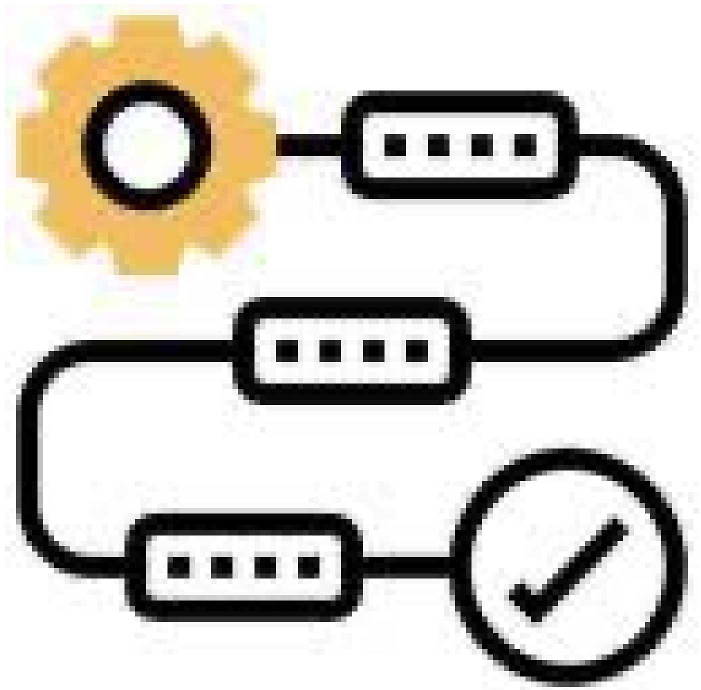
Benthic habitat offer a plethora of values, including biodiversity, mitigation of coastal erosion

The satellite component

Earth Observation satellites offer valuable data for **high frequency fine scale** mapping **at local to global scales** for a variety of **research and applications** for (optically) **shallow water** mapping

Approaches

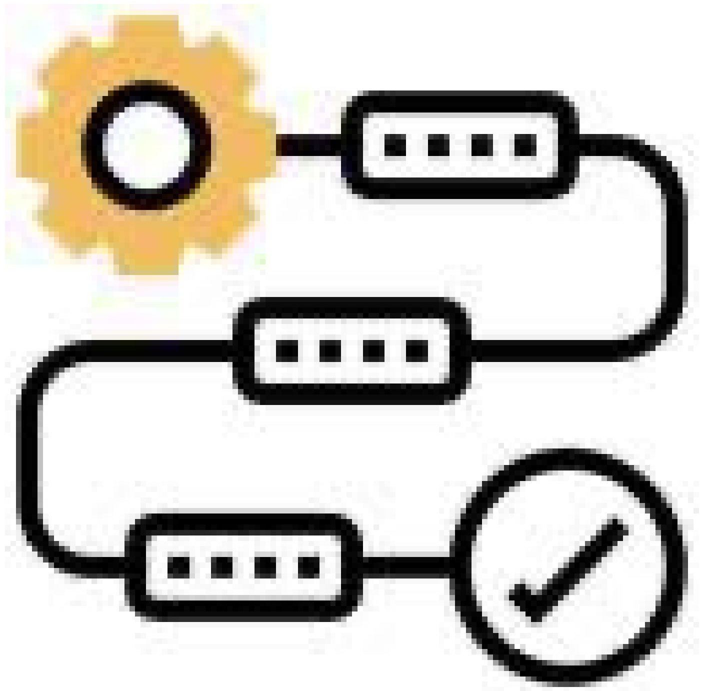
Kutser et al., 2020
Dekker et al., 2011



Giardino et al., 2012
Gege 2004, 2014
Gege et al., 2025
Hedley et al., 2009

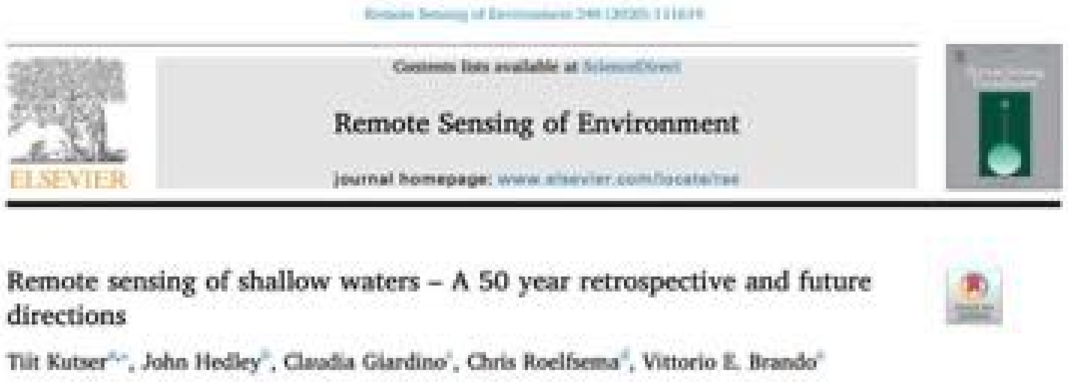
Approaches

Kutser et al., 2020
Dekker et al., 2011



Giardino et al., 2012
Gege 2004, 2014
Gege et al., 2025
Hedley et al., 2009

Approaches (Kutser et al. 2020)


Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

ELSEVIER

Remote sensing of shallow waters – A 50 year retrospective and future directions

Tiit Kutser, John Hedley, Claudia Giardino, Chris Roelfsema, Vittorio E. Brando

Navigation and Infrastructure

Bathymetry data is essential for **navigation safety**, **planning** fish or algae **farms**, marine protected areas, and designing nearshore infrastructure like **ports** and **wind farms**. All marine activities and **maritime spatial planning** require accurate depth data.

Ecological Indicators

Species composition of benthic habitats serves as important **indicators of water quality and ecological state**. Seagrasses provide crucial coastal protection, **biodiversity** support, and influence water circulation and sedimentation processes. **Benthic macroalgal** communities similarly **stabilize coastlines** and serve as indicators of ecological status.

Carbon Processing

Substantial **carbon processing** takes place in coastal zones, with **benthic habitats** like seagrass beds and coral reefs serving as **critical processors of land-based fluxes** ranging from nutrients to pollutants.

Coral Reef Conservation

Coral reefs, among Earth's most diverse ecosystems, are declining globally due to climate change, ocean acidification, and pollution. Many reefs lie in remote locations, making **remote sensing a valuable component of the management toolkit**

Approaches (Kutser et al. 2020)

Active Sensors

LIDAR: Used since the late 1960s for shallow coastal water research, capable of mapping substrata and biological habitats down to ~30m depth.
Synthetic Aperture Radar (SAR): Uses microwave signals that cannot penetrate water deeper than a millimeter, but can provide indirect information about seabed morphology through surface wave patterns.

Multispectral Sensors

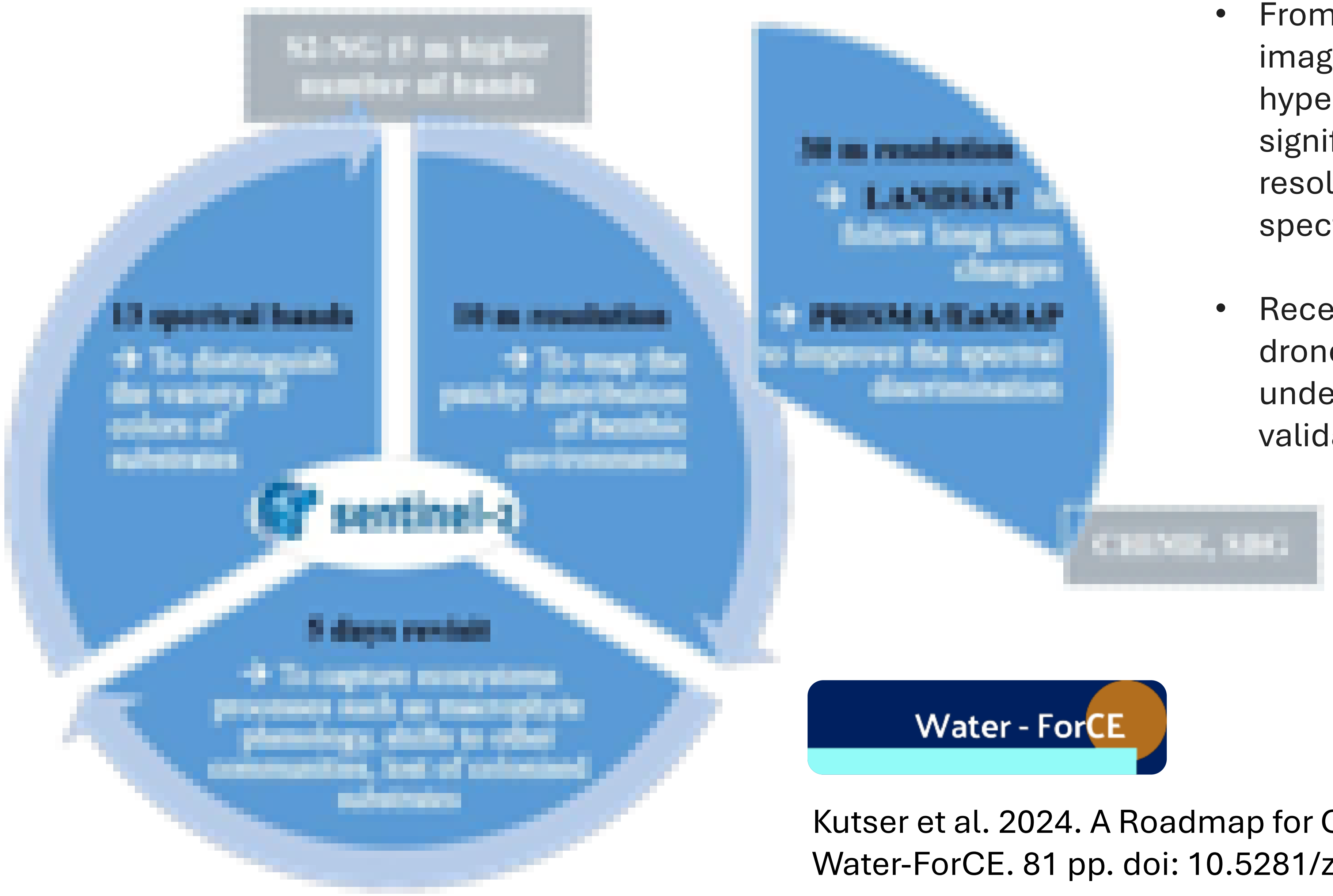
Landsat series: The primary sensor available in the 1970s, with improved radiometric resolution from Landsat-8 and beyond
SPOT: Launched in 1986 with better spatial resolution but only two visible spectral bands
High-resolution sensors: IKONOS, QuickBird-2, WorldView series achieving spatial resolutions down to 1.24m multispectral and 0.31m panchromatic 5 (**commercial**)
Sentinel-2: **Provides 10m resolution with 5-day revisit capability, becoming key for bathymetric and benthic mapping**

Ocean Color Radiometers

Including SeaWiFS and MERIS/OLCI, used for regional-scale shallow water mapping despite **lower spatial resolution.**

Hyperspectral Sensors (hundred of bands (30m):
Spaceborne: Hyperion, **DESIS**, **PRISMA, EnMAP** and HICO on ISS (100m)**.**
Airborne: AISA, AVIRIS, APEX, CASI, HyMap, HySpex, MIVIS, PHILLS, PRISM **with ~10nm spectral resolution and 1m or smaller pixels**

Approaches (Kutser et al. 2020)



Technology Evolution

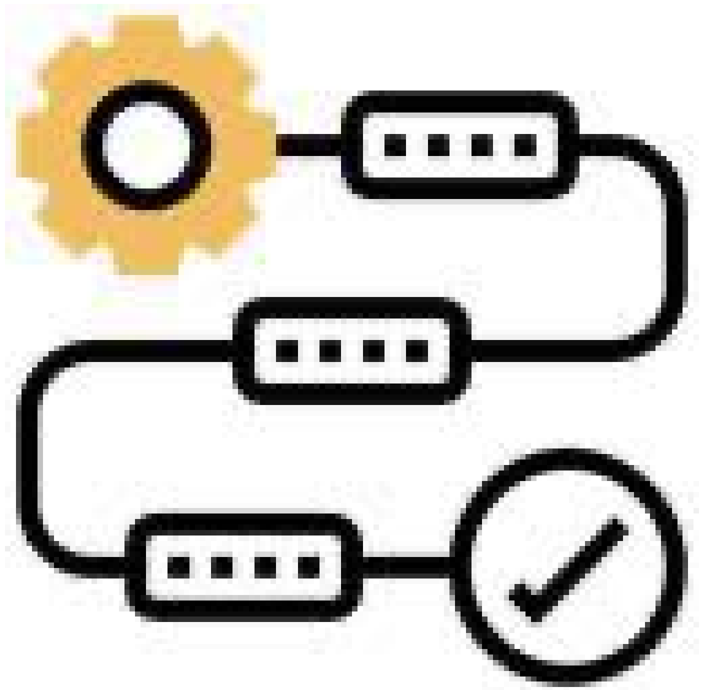
- From early Landsat multispectral imagery in the 1970s to modern hyperspectral sensors, with significant improvements in spatial resolution (down to 0.31m) and spectral capabilities
- Recent developments include drone-based systems and underwater spectrometers for field validation.

Water - ForCE

Kutser et al. 2024. A Roadmap for Copernicus water services. Water-ForCE. 81 pp. doi: 10.5281/zenodo.10847654

Approaches

Kutser et al., 2020
Dekker et al., 2011



Giardino et al., 2012
Gege 2004, 2014
Gege et al., 2025
Hedley et al., 2009

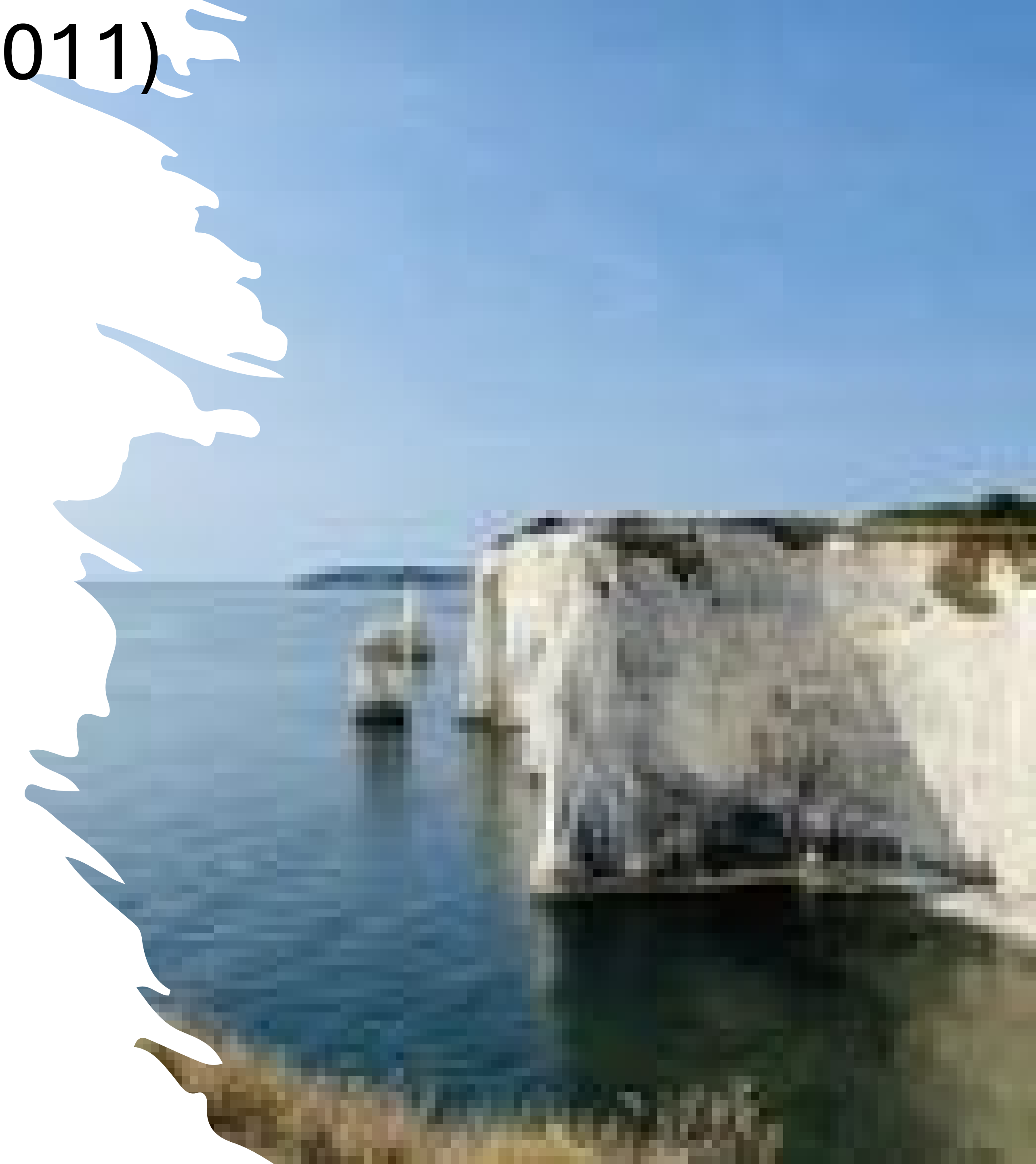
Approaches (Dekker et al. 2011)


LIMNOLOGY and OCEANOGRAPHY: METHODS

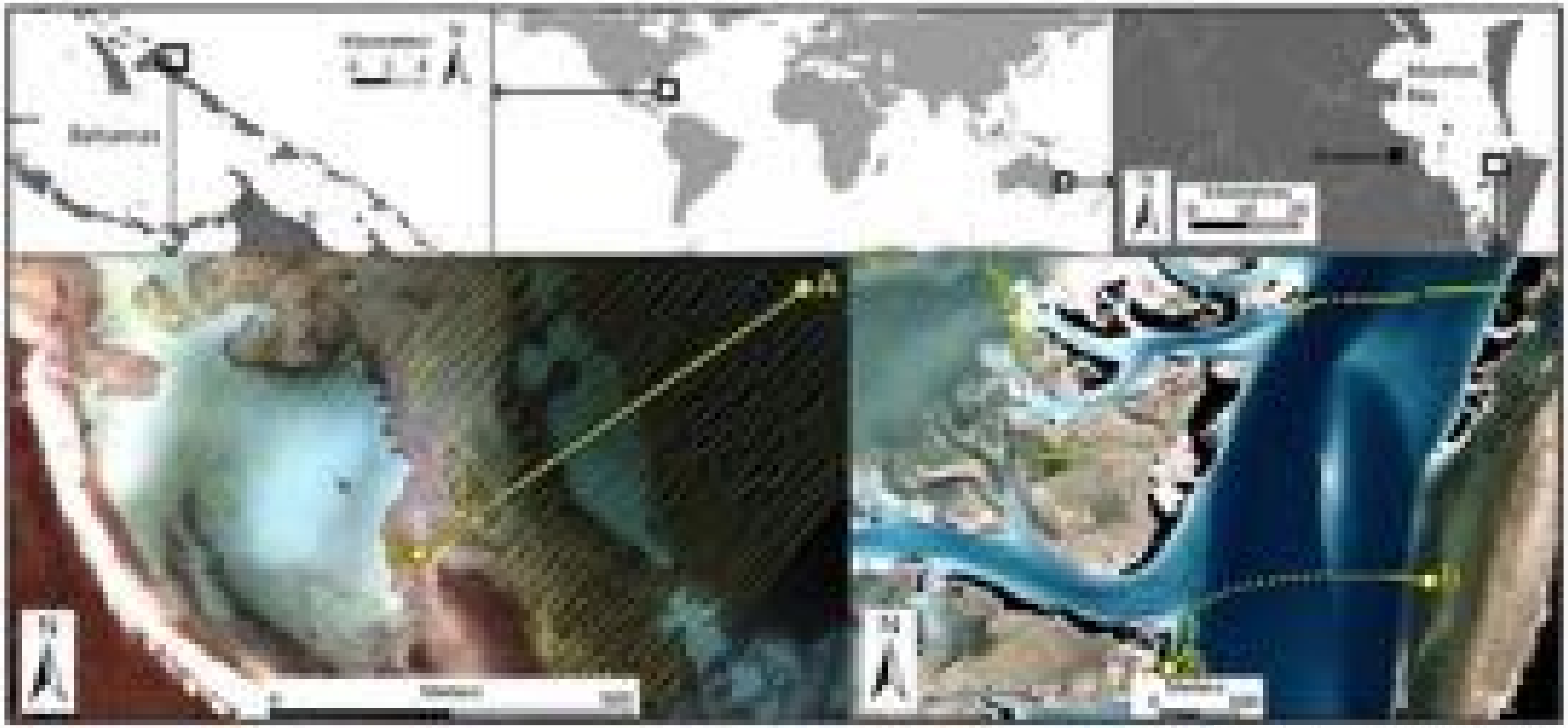
Intercomparison of shallow water bathymetry, hydro-optics, and benthos mapping techniques in Australian and Caribbean coastal environments

Arnold G. Dekker, Stuart R. Phinn*, Janet Anstee, Paul Bissett, Vittorio E. Brando, Brandon Casey, Peter Fearns, John Hedley, Wojciech Klonowski, Zhong P. Lee, Merv Lynch, Mitchell Lyons, Curtis Mobley, and Chris Roelfsema*

- **Science, resource management**, and defense need algorithms capable of using airborne or satellite imagery to accurately map bathymetry, water quality, and substrate composition in **optically shallow waters**.
- Although **a variety of inversion algorithms are available**, there has been limited assessment of performance and no work has been published **comparing their accuracy and efficiency**.

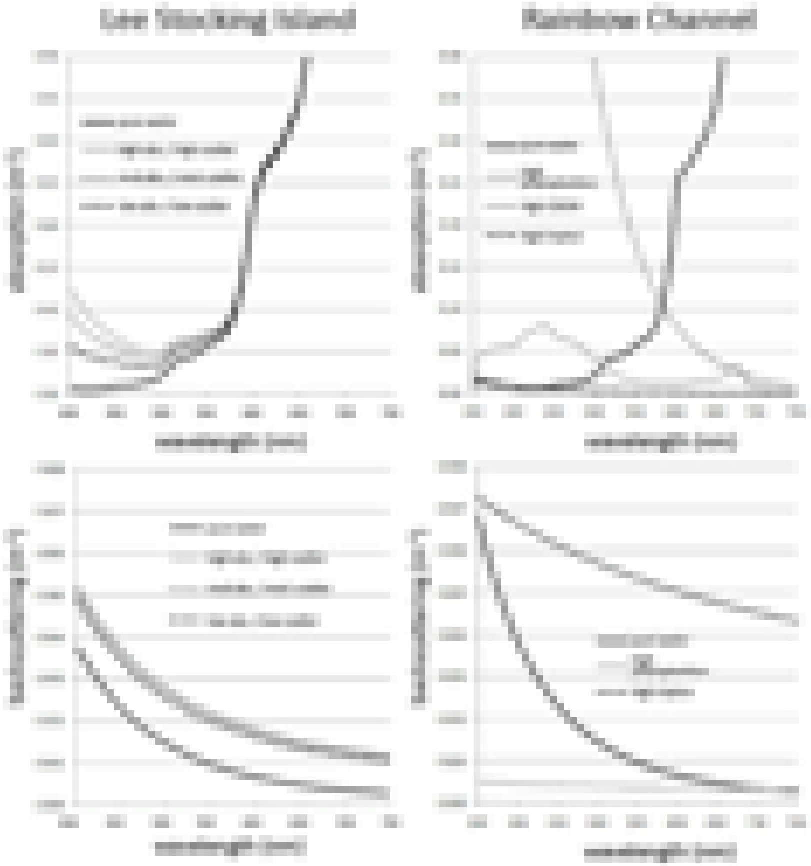


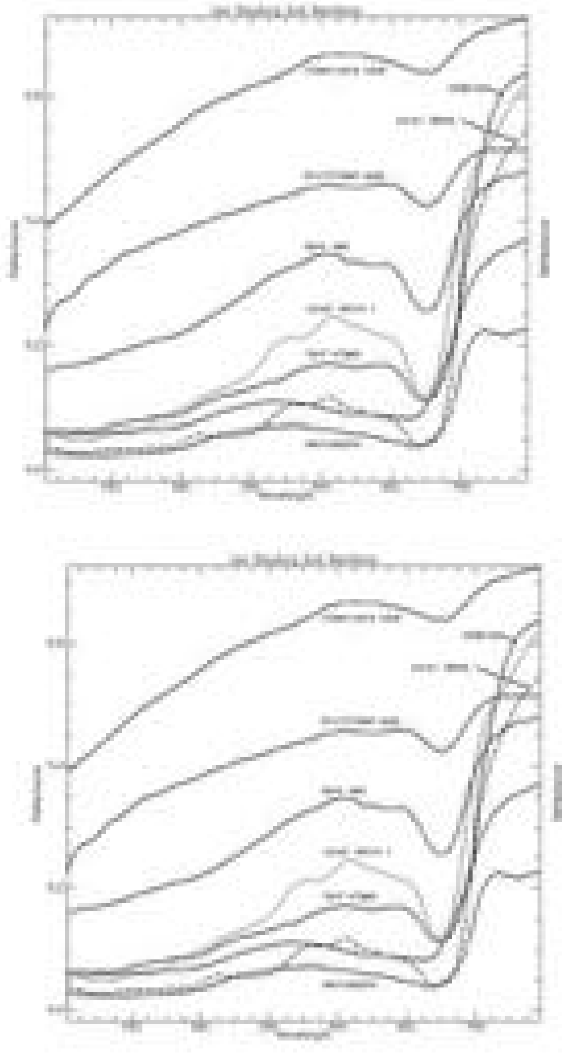
Approaches (Dekker et al. 2011)



Site	Sensor Type	Pixel Size	Spectral Band: - Number - Range - Width	Acquisition Date	Corrections Applied
Lee Stocking Island, Bahamas	Ocean PHILLS	1.3 m	- 128 bands - 400 - 1000 nm - 4.6 nm wide	17 May 2000	Geometric Radiometric Atmospheric correction using TAFKAA to R_{rs}, trim to 72 bands, 5 nm wide between 402.4 and 747.5 nm (Mobley, Sundman et al. 2005)
Rainbow Channel, Moreton Bay, Australia	CASI-2	4.0 m	- 30 bands - 441 – 847 nm - 10 nm wide in 500-680 nm - 20 nm wide in > 680 nm (Brando et al. 2009)	2 July 2004	Geometric Radiometric Atmospheric correction using c-WOMBAT-c to R_{rs} (Brando et al. 2009)

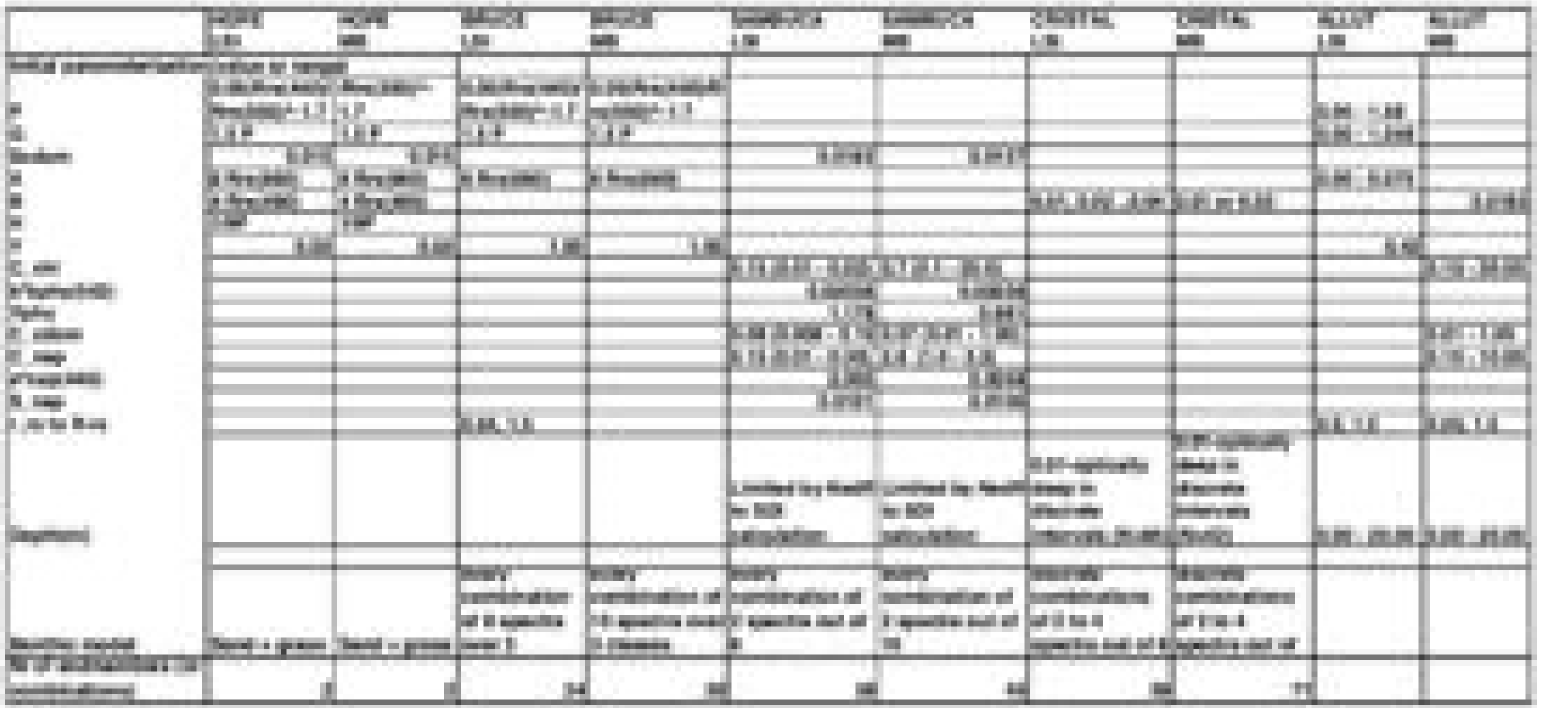
Approaches (Dekker et al. 2011)





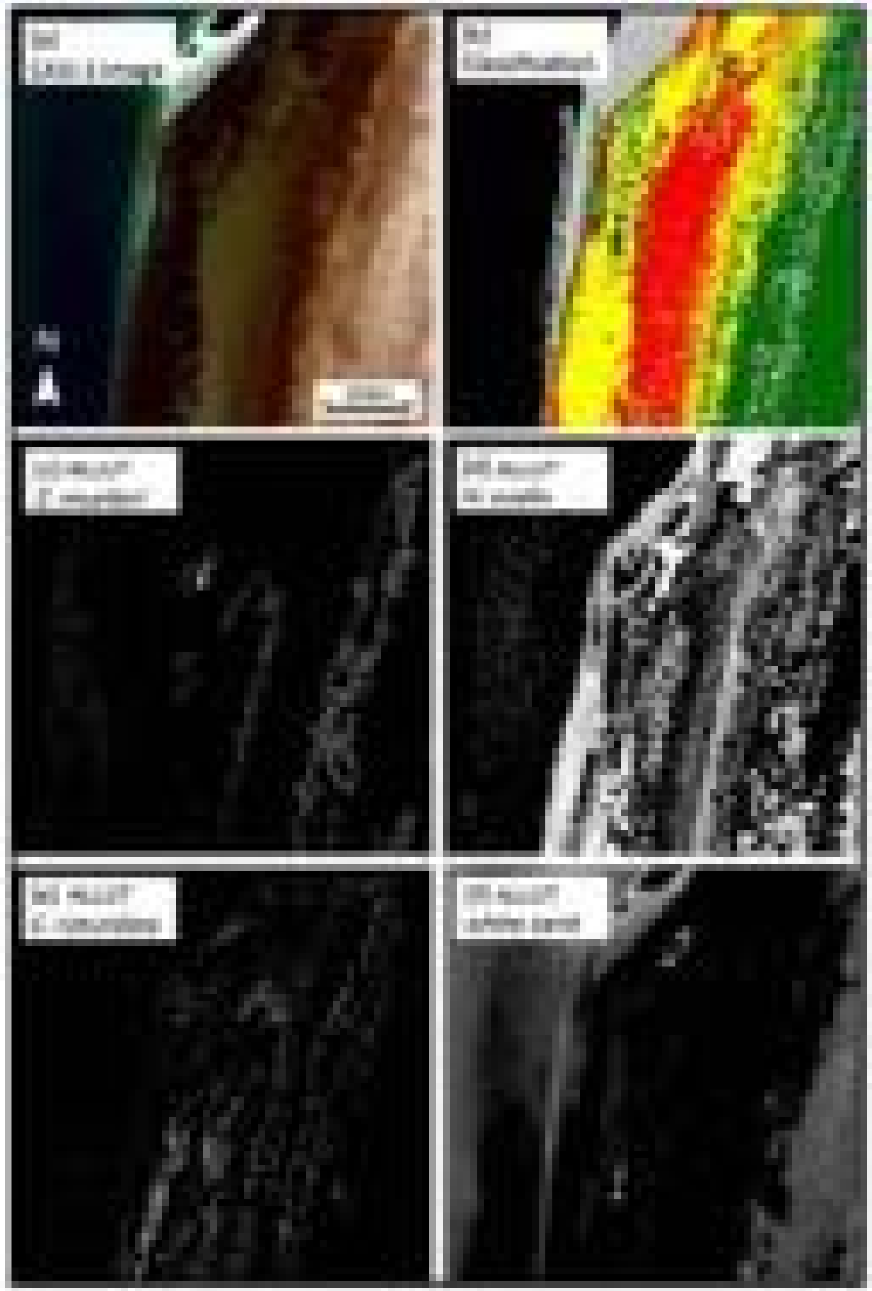
Approaches (Dekker et al. 2011)

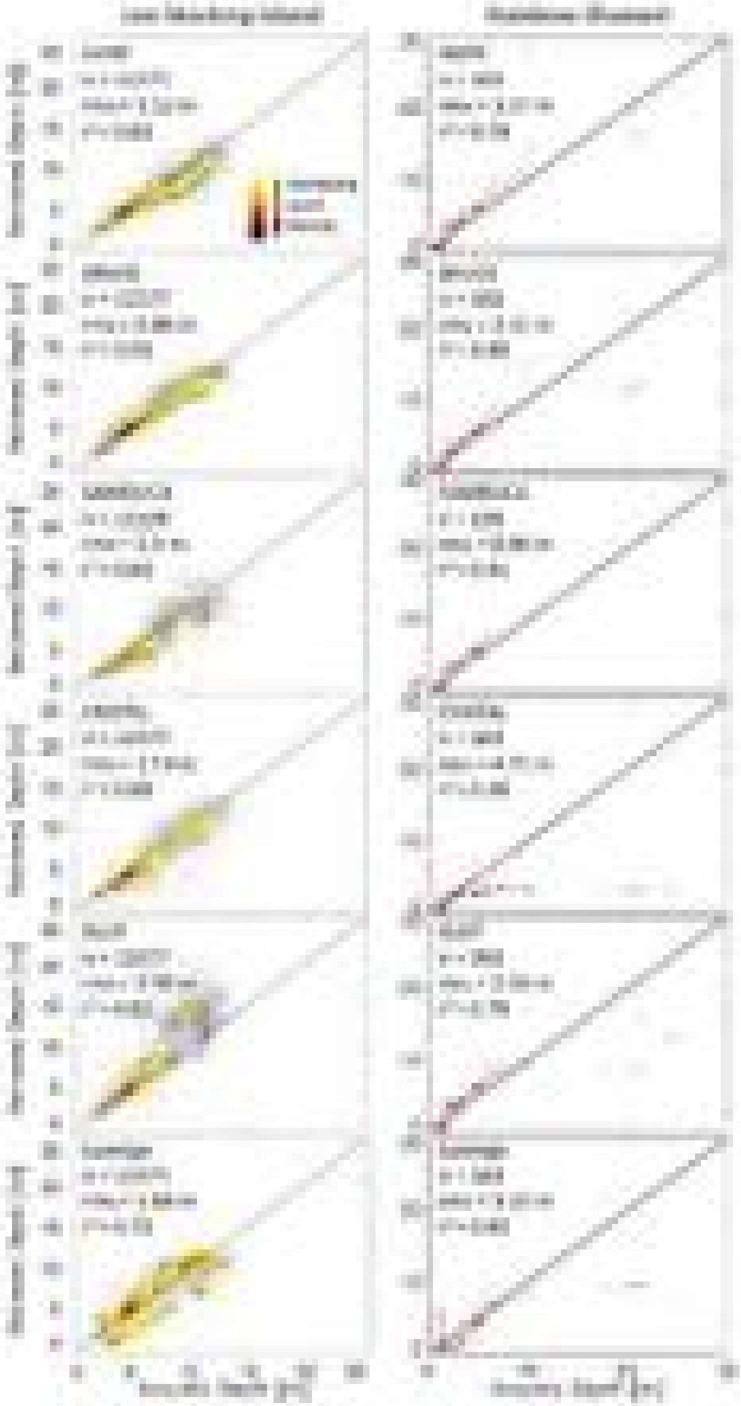
All these methods rely on some form of spectrum matching of modeled reflectance spectrum using a set of bathymetry, bottom classification, and water column IOPs values, optimized to match the image Rrs spectra



HOPE, BRUCE, SAMBUCA	spectrum matching via a nonlinear search that determines the optimal parameter values for their semi-analytical model (Lee et al., 1999, 2001)
CRISTAL	spectrum matching by searching through a precomputed database of Rrs spectra (Mobley et al. 2005; Mobley and Bissett 2011)
ALUT	adaptive LUT method for creating an effective LUT for parameterizing the semi-analytical model and then applies spectrum matching (Hedley et al., 2009)

Approaches (Dekker et al. 2011)





Approaches (Dekker et al. 2011)

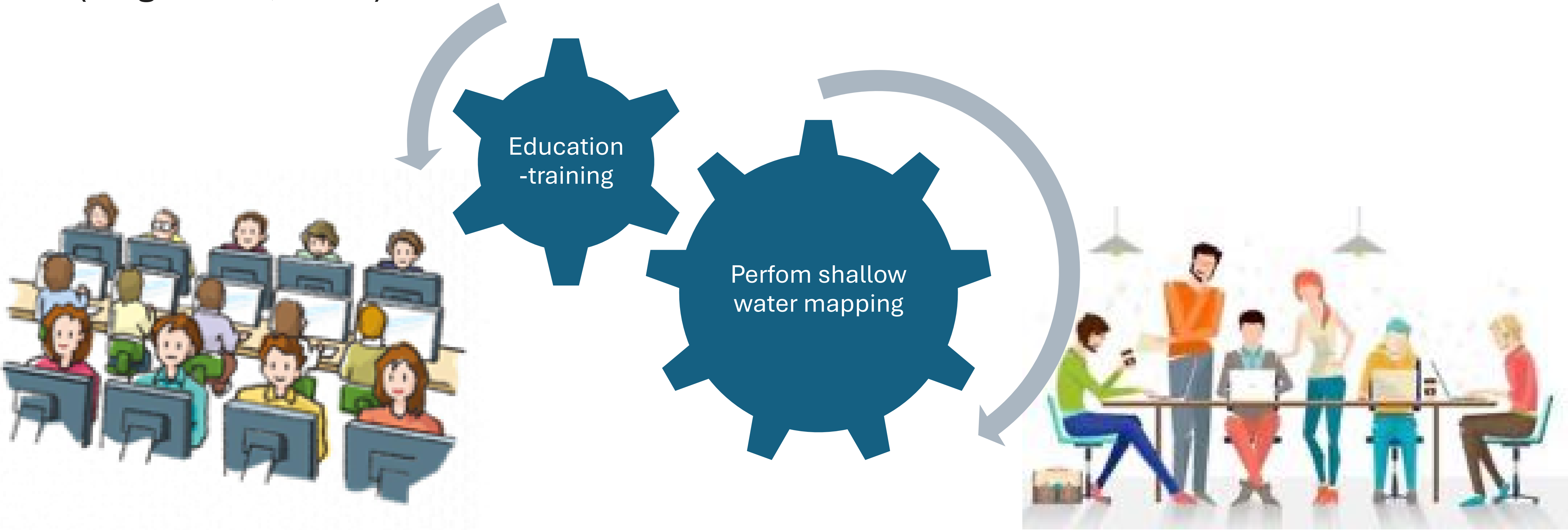
Algorithm	Site	Processor	Pre-processing time	Image processing time	pixels processed per second	Program Code
HOPE	LSI	2.66 GHz		48 mins	156.39	C
HOPE	MB	2.66 GHz		90 mins	157.01	C
BRUCE	LSI	2.40 GHz		12 hours	10.43	C++
BRUCE	MB	2.40 GHz		15 hours	15.70	C++
SAMBUCA	LSI	*		1147 hours*	0.11	IDL/ENVI
SAMBUCA	MB	*		628 hours*	0.38	IDL/ENVI
CRISTAL	LSI	2.00 GHz	45 hrs	23 mins	326.38	Fortran95
CRISTAL	MB	2.00 GHz	135 hrs	22 mins	642.32	Fortran95
ALLUT	LSI	3.00 GHz	4 mins 12 s	2hrs 2 mins	61.53	C++
ALLUT	MB	3.00 GHz	6 mins 48 s	2hrs 32 mins	92.97	C++

The assessment showed that

- all inversion methods provided moderately accurate retrievals of bathymetry, water column inherent optical properties, and benthic reflectance in waters less than 13 m deep with homogeneous to heterogeneous benthic/substrate covers
- higher accuracy retrievals were obtained from locally parameterized methods
- no method compared here can be considered optimal for all situations.

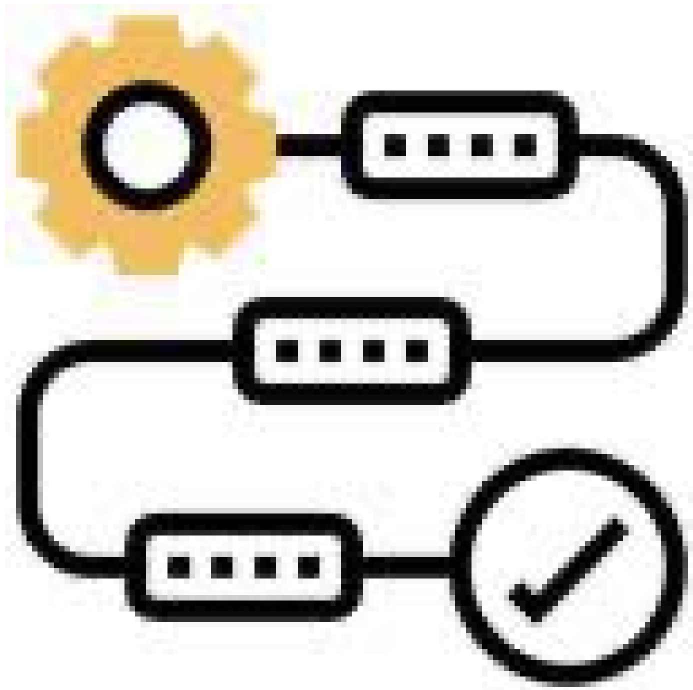
Tools/software for shallow waters mapping

Although many algorithms for inverse modelling of water leaving radiance and reflectance exist (IOCCG, 2006, Dekker et al., 2011), no publicly available software was available for long time that can be regionally optimized by the user (Gege et al., 2014)



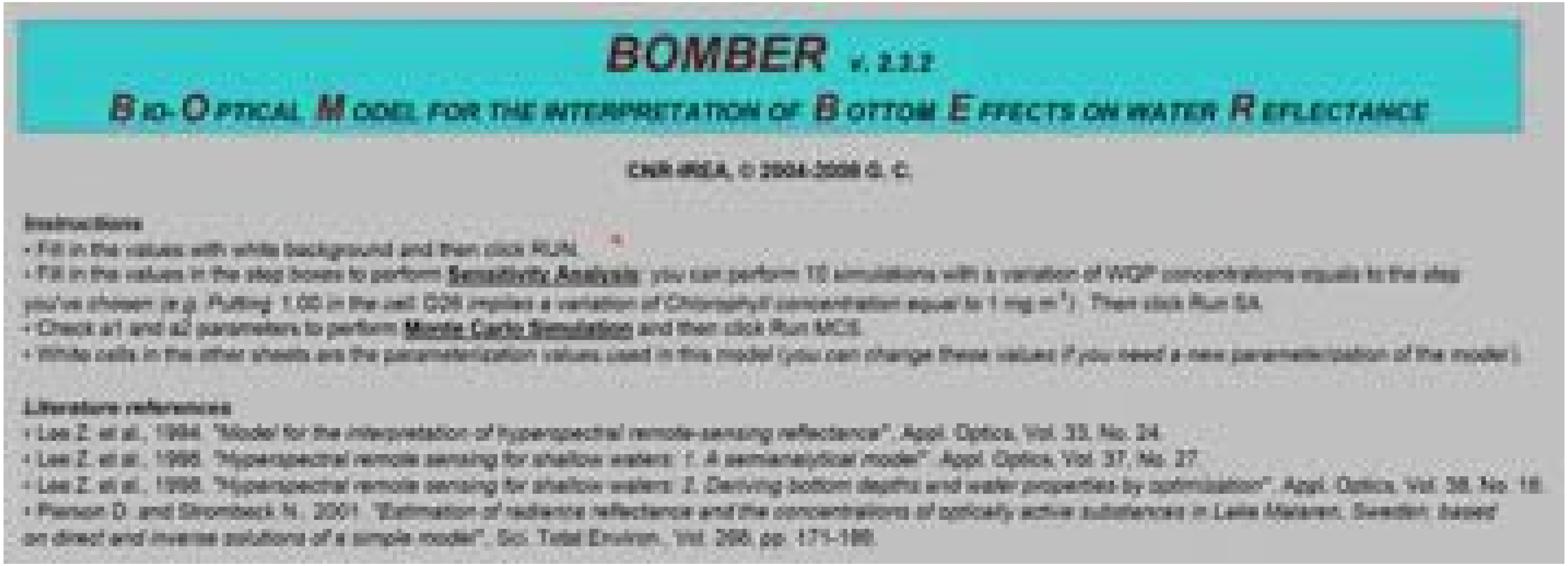
Approaches

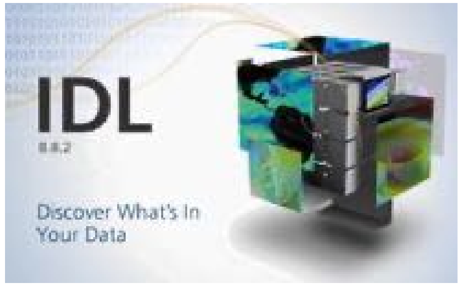
Kutser et al., 2020
Dekker et al., 2011



Giardino et al., 2012
Gege 2004, 2014
Gege et al., 2025
Hedley et al., 2009

BOMBER





BIO-OPTICAL MODEL BASED TOOL FOR ESTIMATING WATER QUALITY AND BOTTOM PROPERTIES FROM REMOTE SENSING IMAGES

BOMBER

Computers & Geosciences

BOMBER: A tool for estimating water quality and bottom properties from remote sensing images

Claudia Giardino, Gabriele Candiani, Mariano Bresciani, Zhongping Lee, Stefano Gagliano, Monica Pepe

Highlights

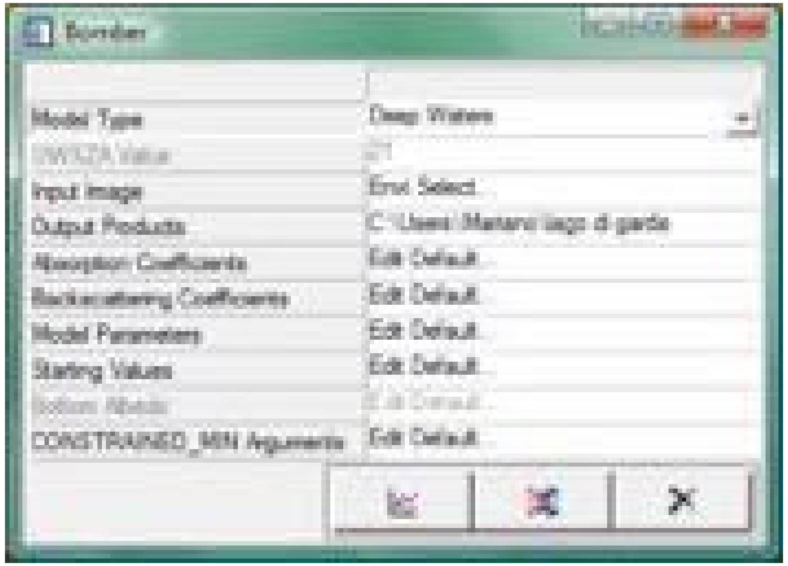
► A software package simultaneously retrieves properties of water column and bottom from remotely sensed imagery. ► The tool implements an optimization technique to invert a bio-optical model for deep and shallow waters. ► The software is programmed in IDL and runs as an add-on tool for the image processing software the ENVI+IDL. ► A series of GUIs allow the user to parameterize the bio-optical model and to run the inversion.

It is based on Lee et al., 1999, 2001)

HOPE, BRUCE, SAMBUCA

CRISTAL

ALUT



Model Type – *Deep and shallow Waters*

Input: Parameterisation

Bio-optical modelling

$$R_{rs} = I \frac{R(0-)}{Q(1-\gamma R(0-))}$$

Above water surface

Below water surface

$$R(0-) = R(0-)^{dp}\left(1 - A_0 e^{\left(-\left(\frac{1}{\cos(\vartheta_w)} + \sqrt{D_0^C\left(1+D_1^C u\right)}\right)\kappa H\right)}\right) + A_1 \rho e^{\left(-\left(\frac{1}{\cos(\vartheta_w)} + \sqrt{D_0^B\left(1+D_1^B u\right)}\right)\kappa H\right)}$$

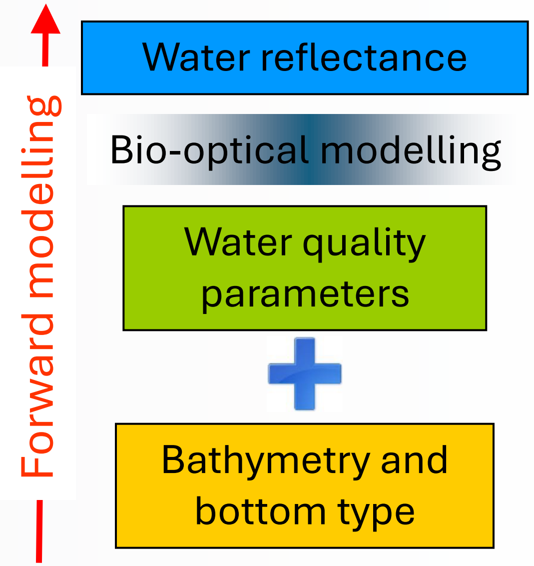
$$R(0-)^{dp} = \left(g_0 + g_1 \cdot u^{g_2}\right)\cdot u \quad \text{con} \quad u = \frac{b_b}{a + b_b}$$

$$a = a_w + a_{CHL} + a_{SPM} + a_{CDOM}$$

$$a(\lambda) = a_w + a_\Phi(\lambda, chl-a) + a_{NAP}(\lambda, SPM) + a_{CDOM}(\lambda, a_{CDOM}(440))$$

$$b_b = b_{bw} + b_{bCHL} + b_{bSPM}$$

$$b_b(\lambda) = b_{bw}(\lambda) + b_{b\Phi}(\lambda, chl-a) + b_{bNAP}(\lambda, SPM)$$



Bio-optical modelling

$$R_{rs} = I \frac{R(0-)}{Q(1-\gamma R(0-))}$$

$$R(0-) = R(0-)^{dp}\left(1 - A_0 e^{\left(-\left(\frac{1}{\cos(\vartheta_w)} + \sqrt{D_0^C(1+D_1^C u)}\right)\kappa H\right)}\right) + A_1 \rho e^{\left(-\left(\frac{1}{\cos(\vartheta_w)} + \sqrt{D_0^B(1+D_1^B u)}\right)\kappa H\right)}$$

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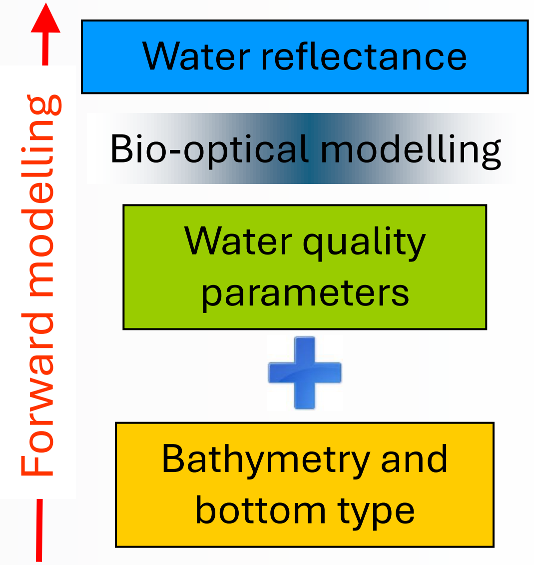

Bio-optical modelling

$$R_{rs} = I \frac{R(0-)}{Q(1-\gamma R(0-))}$$

$$R(0-) = R(0-)^{dp}\left(1 - A_0 e^{\left(-\left(\frac{1}{\cos(\vartheta_w)}+\sqrt{D_0^C\left(1+D_1^C u\right)}\right)\kappa H\right)}\right) + A_1 \rho e^{\left(-\left(\frac{1}{\cos(\vartheta_w)}+\sqrt{D_0^B\left(1+D_1^B u\right)}\right)\kappa H\right)}$$

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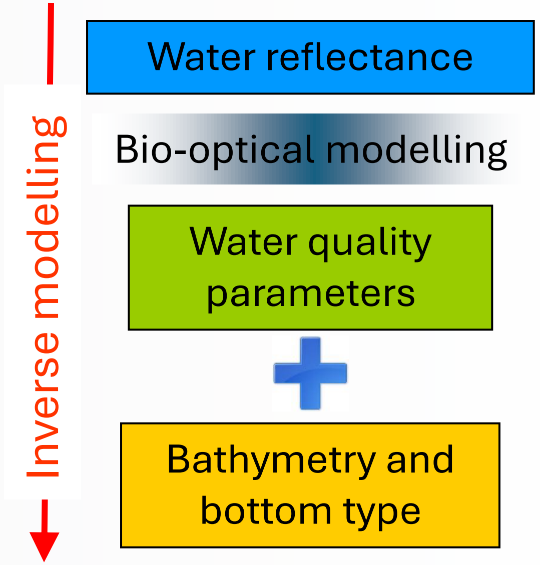

Bio-optical modelling

$$R_{rs} = I \frac{R(0-)}{Q(1-\gamma R(0-))}$$

$$se \quad H \to \infty \Rightarrow R(0-) = R(0-)^{dp}$$

$\Rightarrow 0$ $\Rightarrow 0$

$$R(0-) = R(0-)^{dp}\left(1 - A_0 e^{\left(-\left(\frac{1}{\cos(\theta_w)} + D_0^C\left(1+D_1^C u\right)\right)\kappa H\right)}\right) + A_1 \rho e^{\left(-\left(\frac{1}{\cos(\theta_w)} + D_0^B\left(1+D_1^B u\right)\right)\kappa H\right)}$$

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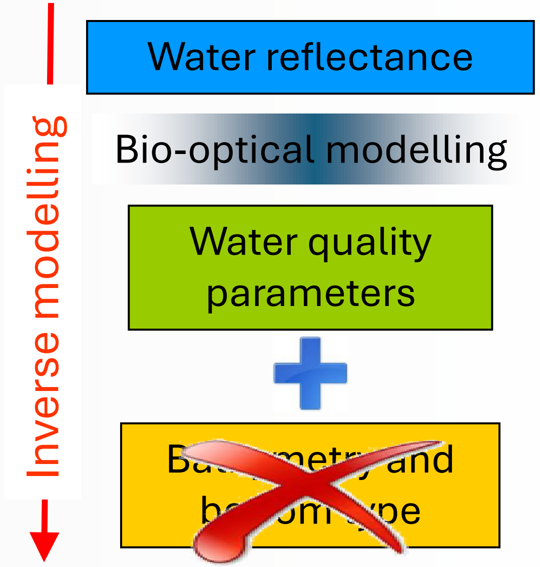
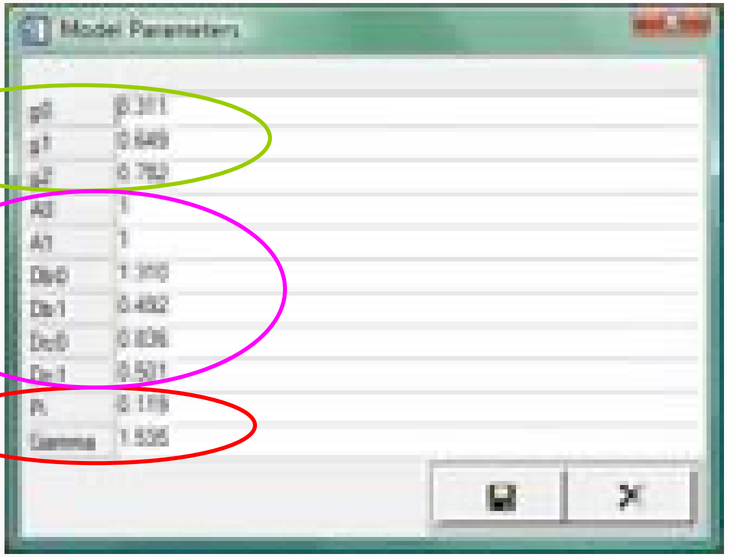


Air/water interface e other scalars

$$\frac{L_u(0+,\vartheta,\phi)}{E_d(0+)} = R_{rs} = I\,\frac{R(0-)}{Q(1-\gamma R(0-))} = \Pi\,\frac{R(0-)}{(1-\gamma R(0-))}$$



Deep waters

$$R(0-)^{dp} = \left(g_0 + g_1 \cdot u^{g_2}\right) \cdot u$$

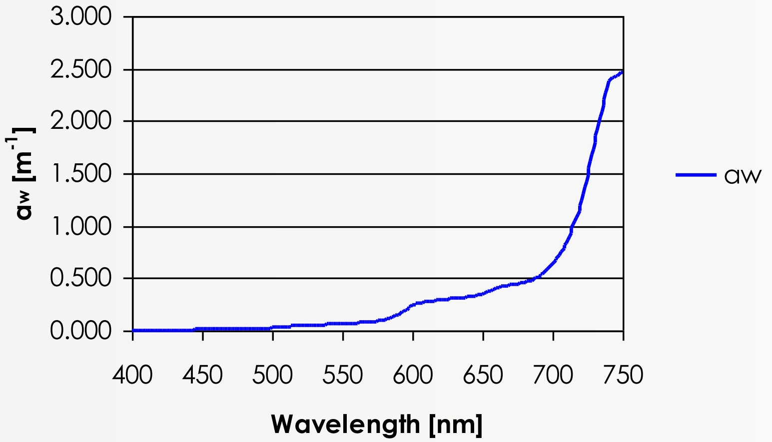
Shallow waters

$$R(0-) = R(0-)^{dp}\left(1 - A_0 e^{\left(-\left(\frac{1}{\cos(\vartheta_w)} + \sqrt{D_0^C (1 + D_1^C u)}\right)\kappa H\right)}\right) + A_1 \rho e^{\left(-\left(\frac{1}{\cos(\vartheta_w)} + \sqrt{D_0^B (1 + D_1^B u)}\right)\kappa H\right)}$$

Water absorption

$$a(\lambda) = a_w + a_\Phi(\lambda, chl-a) + a_{NAP}(\lambda, SPM) + a_{CDOM}(\lambda, a_{CDOM}(440))$$

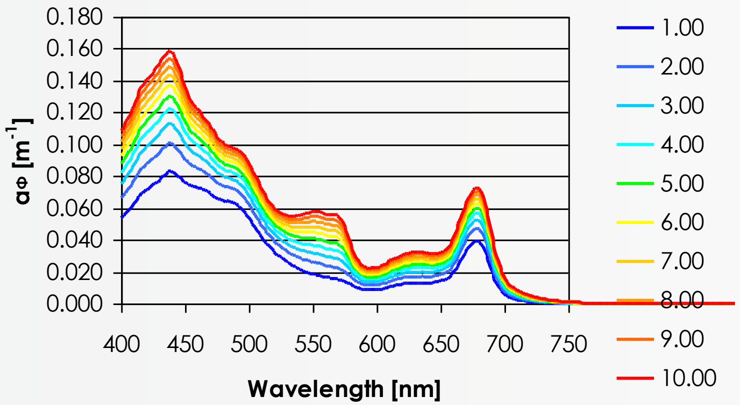
$$a_w = Smith \,\&\, Baker(1981), Pope \,\&\, Fry(1997)$$



Phytoplankton absorption

$$a(\lambda) = a_w + a_\Phi(\lambda, chl-a) + a_{NAP}(\lambda, SPM) + a_{CDOM}(\lambda, a_{CDOM}(440))$$

$$a_\Phi(\lambda, chl-a) = \left(A(\lambda)\cdot chl-a^{-B(\lambda)}\right)\cdot chl-a$$

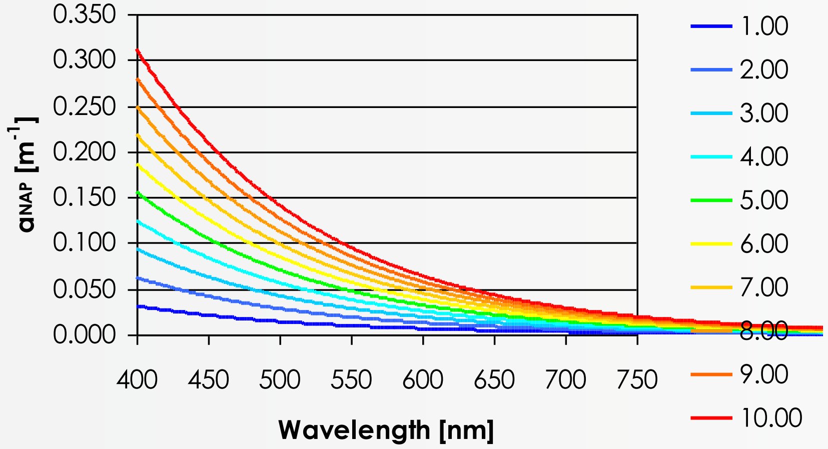


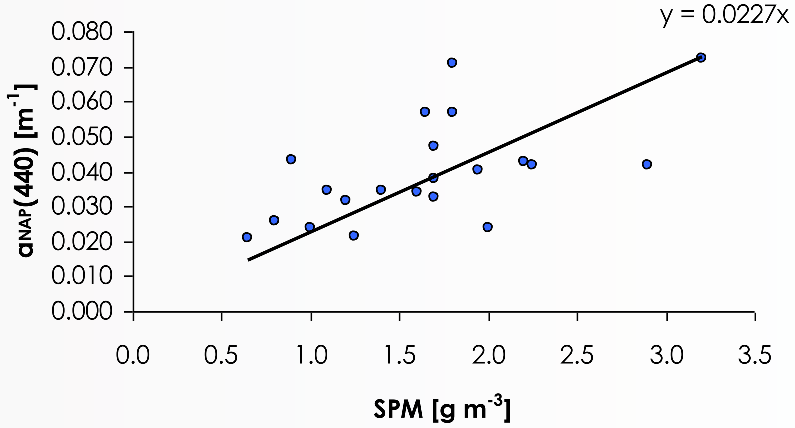
Wavelength [nm]	A [-]	B [-]
400	0.055	0.429
425	0.076	0.453
450	0.077	0.517
475	0.068	0.633
500	0.055	0.599
525	0.030	0.469
550	0.019	0.111
575	0.012	-0.192
600	0.008	0.152
625	0.011	0.114
650	0.013	0.190
675	0.035	0.387
700	0.006	0.155
725	0.001	0.769
750	0.000	1.024

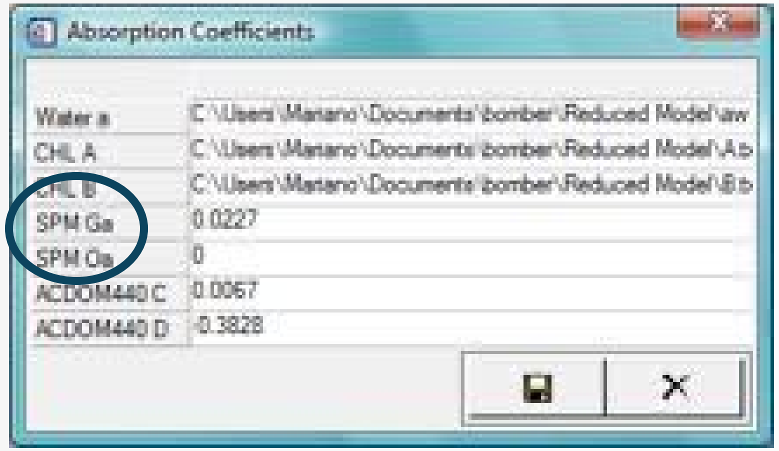
Suspended matter absorption

$$a(\lambda) = a_w + a_\Phi(\lambda, chl-a) + a_{NAP}(\lambda, SPM) + a_{CDOM}(\lambda, a_{CDOM}(440))$$

$$a_{NAP}(\lambda, SPM) = a_{NAP}(440) \cdot e^{-S_{NAP}\cdot(\lambda-440)} = (\mathrm{G_a} \cdot \mathrm{SPM} + \mathrm{O_a}) \cdot \mathrm{e}^{-S_{NAP}\cdot(\lambda-440)}$$



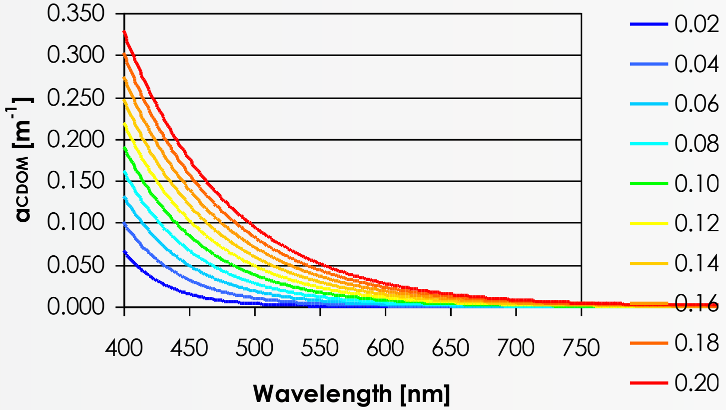


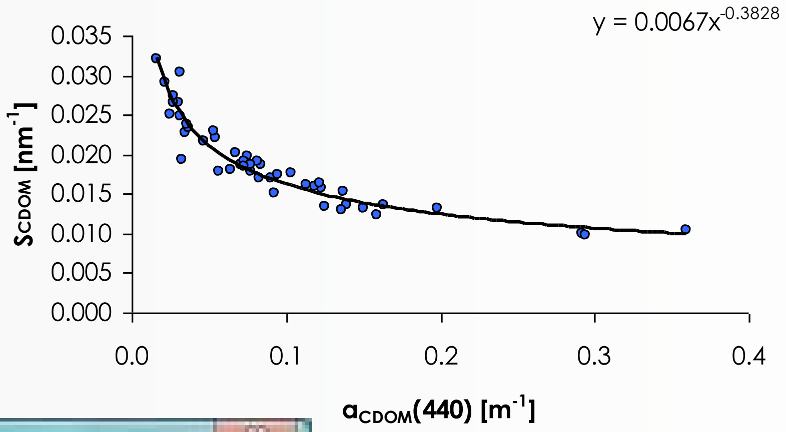


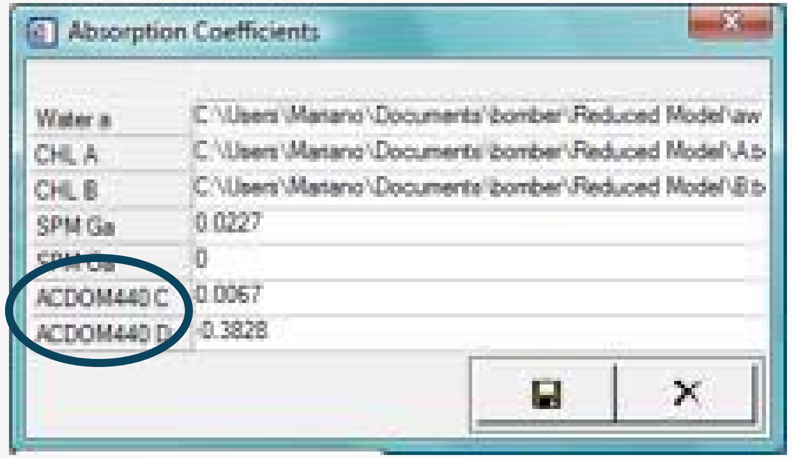
CDOM absorption

$$a(\lambda) = a_w + a_\Phi(\lambda, chl-a) + a_{NAP}(\lambda, SPM) + a_{CDOM}(\lambda, a_{CDOM}(440))$$

$$a_{CDOM}(\lambda, a_{CDOM}(440)) = a_{CDOM}(440) \cdot e^{-S_{CDOM} \cdot (\lambda - 440)} = a_{CDOM}(440) \cdot e^{-C \cdot a_{CDOM}(440)^{-D} (\lambda - 440)}$$



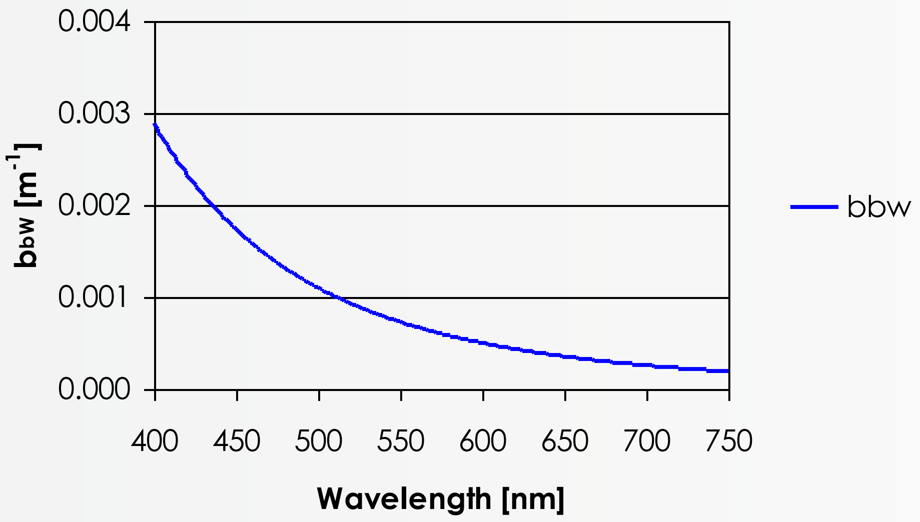


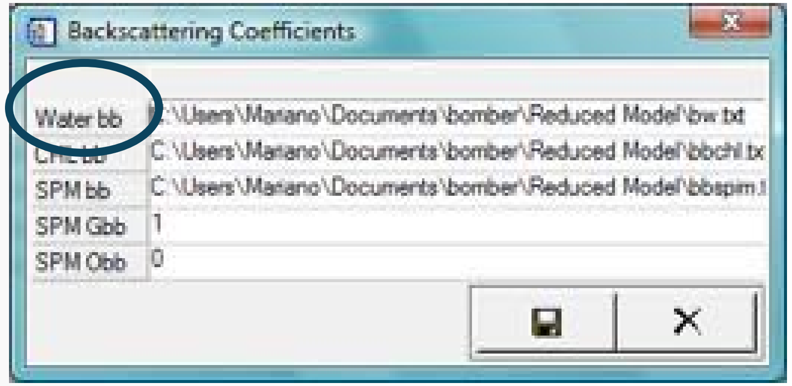


Pure water back-scattering

$$b_b(\lambda) = b_{bw}(\lambda) + b_{b\Phi}(\lambda, chl-a) + b_{bNAP}(\lambda, SPM)$$

$$b_{bw} = Morel(1974), Dall'Olmo \,\&\, Gitelson(2006)$$

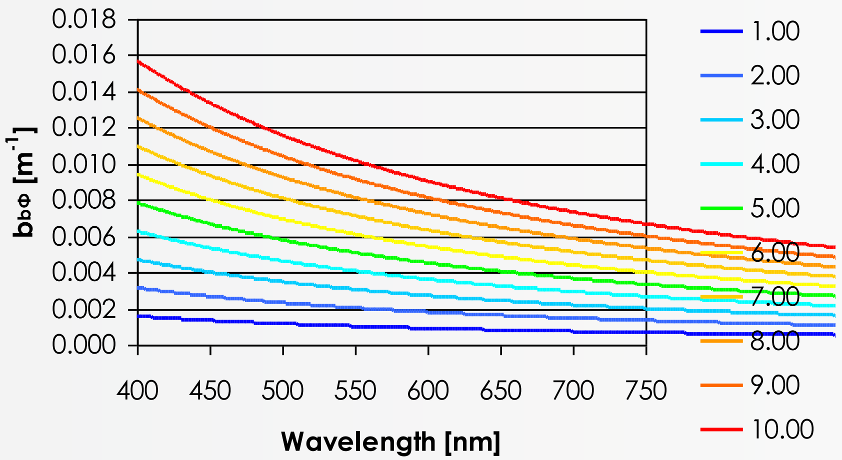


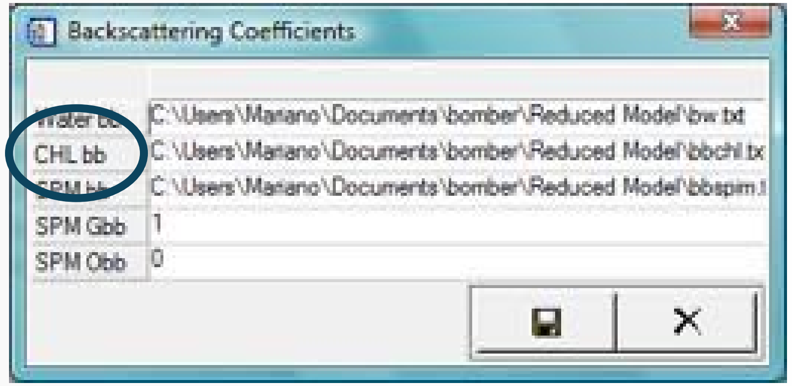


Phytoplankton back-scattering

$$b_b(\lambda) = b_{bw}(\lambda) + b_{b\Phi}(\lambda, chl-a) + b_{bNAP}(\lambda, SPM)$$

$$b_{b\Phi}(\lambda, chl-a) = 0.00138\left(\frac{440}{\lambda}\right)^{1.35885} \cdot chl-a$$

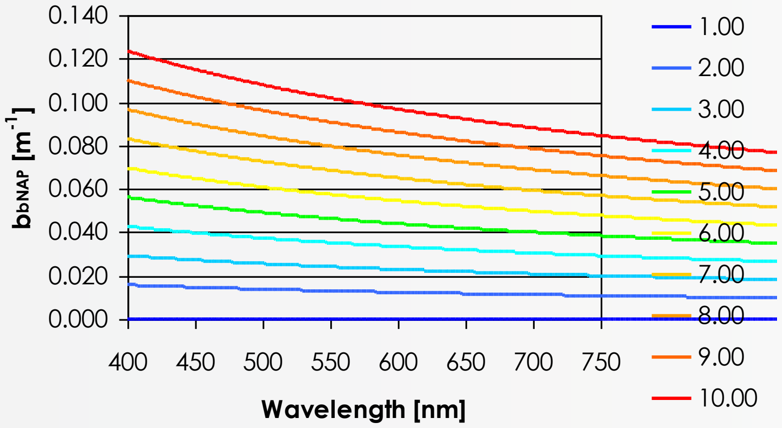


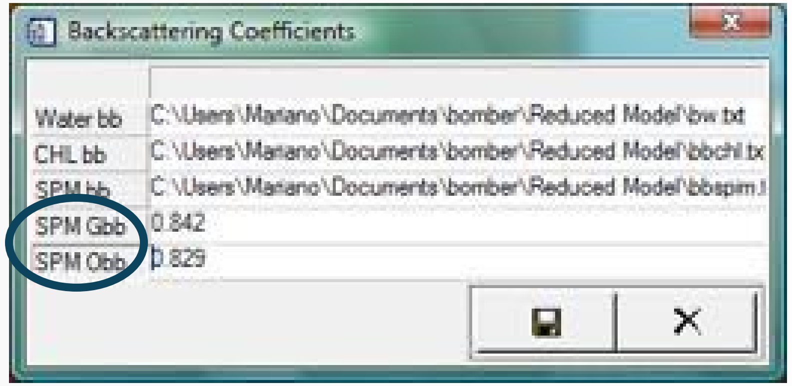


Suspended matter back-scattering

$$b_b(\lambda) = b_{bw}(\lambda) + b_{b\Phi}(\lambda, chl-a) + b_{bNAP}(\lambda, SPM)$$

$$b_{bNAP}(\lambda, SPM) = 0.01271\left(\frac{440}{\lambda}\right)^{0.60265} \cdot (0.842 \cdot SPM - 0.829)$$





Bottom reflectance

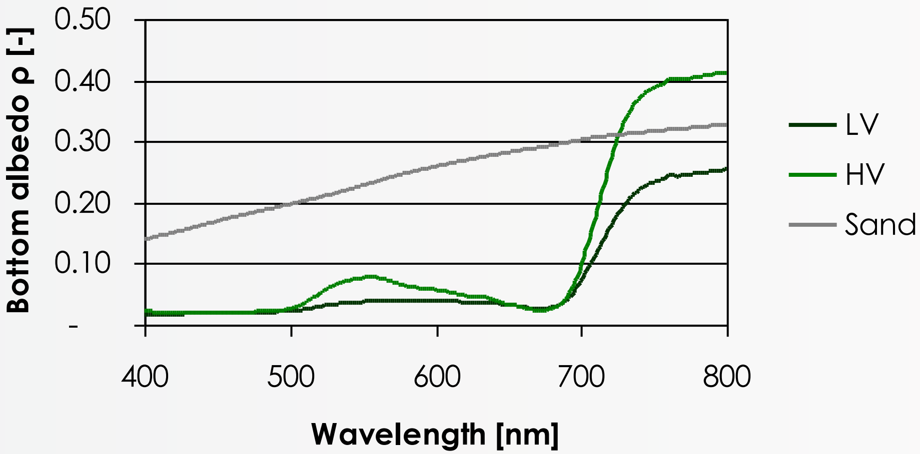
$$R(0-) = R(0-)^{dp}\left(1 - A_0 e^{\left(-\left(\frac{1}{\cos(\vartheta_w)} + \sqrt{D_0^C\left(1 + D_1^C u\right)}\right)\kappa H\right)}\right) + A_1 \rho e^{\left(-\left(\frac{1}{\cos(\vartheta_w)} + \sqrt{D_0^B\left(1 + D_1^B u\right)}\right)\kappa H\right)}$$

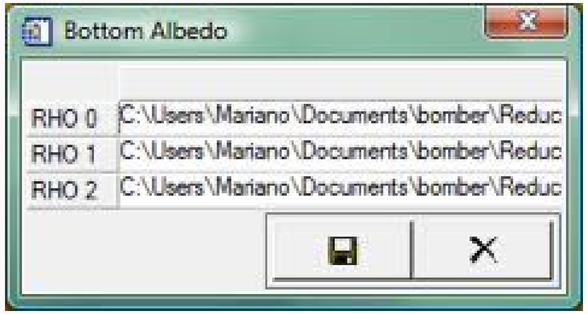
$$\rho = b_0 \rho_{sand} + b_1 \rho_{SV} + b_2 \rho_{HV}$$


Sand

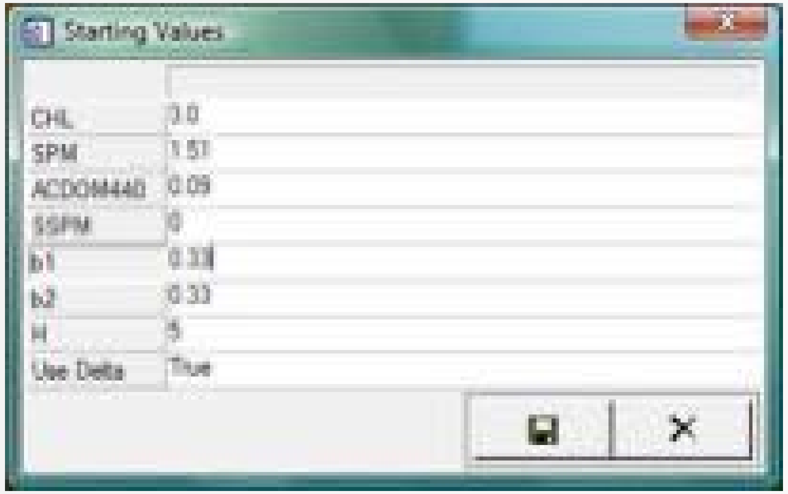

Vallisneria spiralis

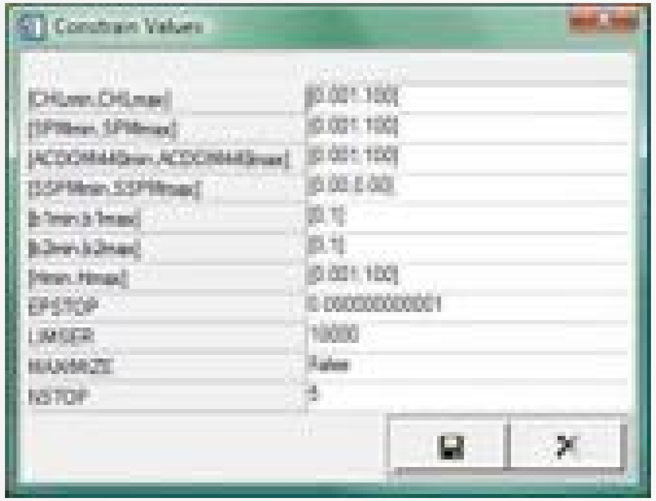

Characee

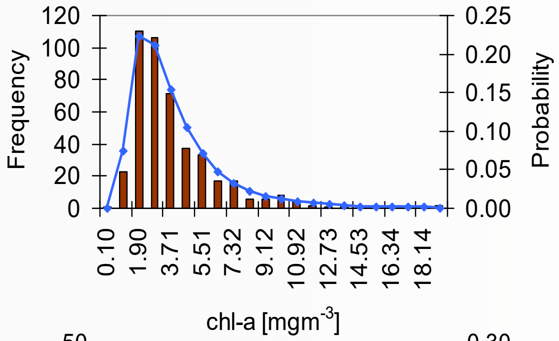


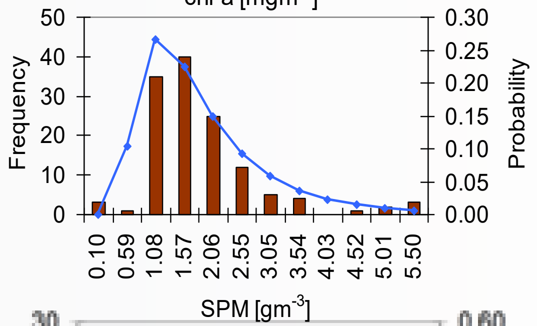


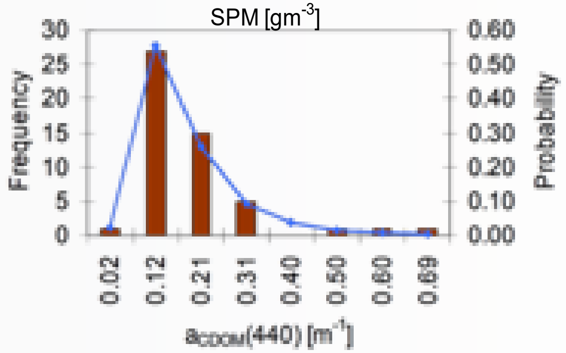
Starting values and optimaztion parameters











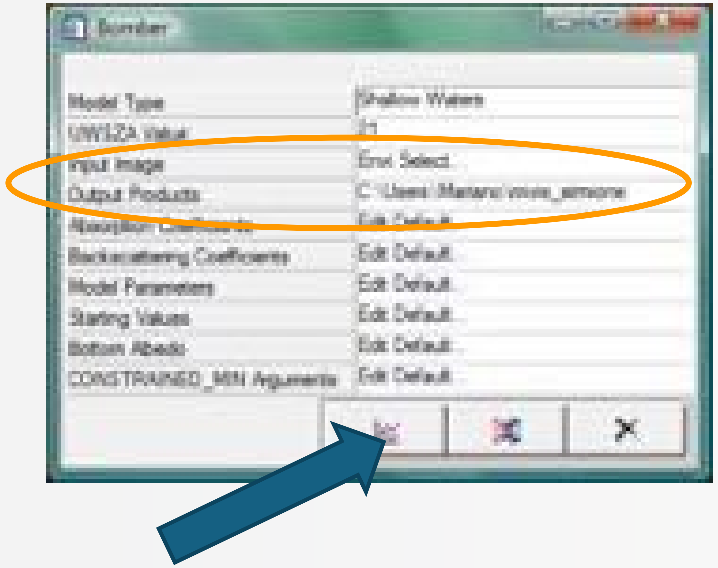
Run on single spectra

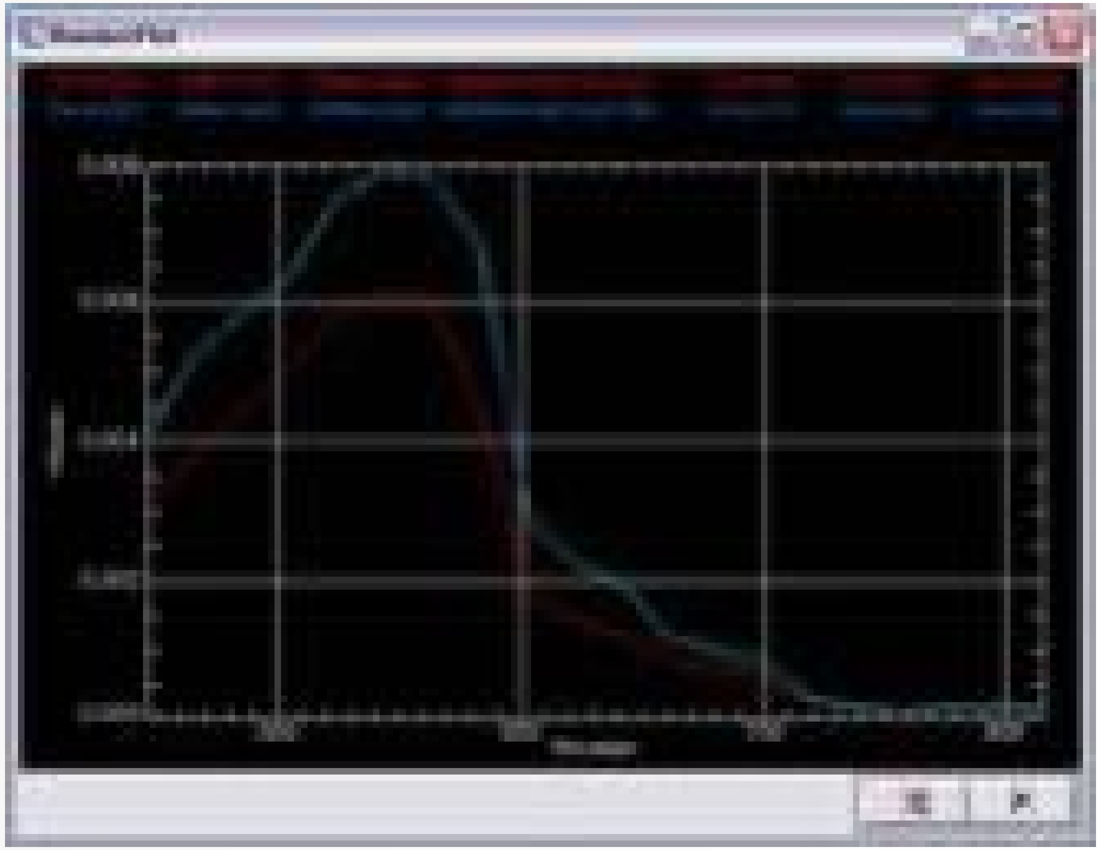
DEEP WATERS

$$Obiettivo = \min_{CHL,SPM,a_{CDOM}(440),S_{SPM}} \sqrt{\sum_{i=1}^{N} \left[\left(R_{rs}^{I}(\lambda_i) - \Delta \right) - R_{rs}^{B}(\lambda_i) \right]^2}$$

SHALLOW WATERS

$$Obiettivo = \min_{CHL,SPM,a_{CDOM}(440),S_{SPM},H,b_0,b_1,b_2} \sqrt{\sum_{i=1}^{N} \left[\left(R_{rs}^{I}(\lambda_i) - \Delta \right) - R_{rs}^{B}(\lambda_i) \right]^2}$$





Starting Reflectance

Image Reflectance

Model Reflectance

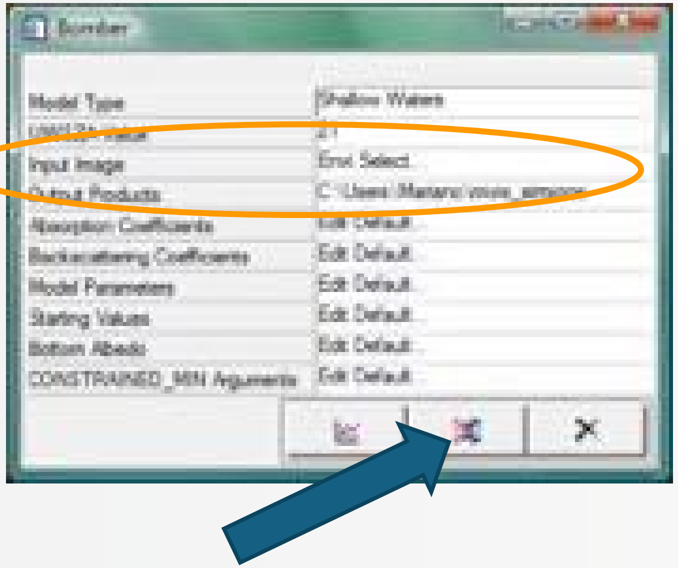
Run on imagery data

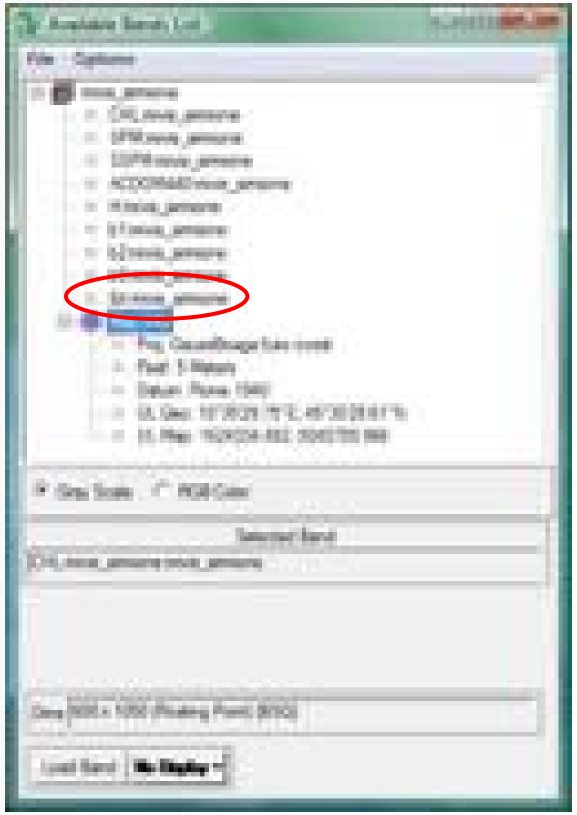
DEEP WATERS

$$Obiettivo = \min_{CHL, SPM, a_{CDOM}(440), S_{SPM}} \sqrt{\sum_{i=1}^{N} \left[\left(R_{rs}^{I}(\lambda_i) - \Delta\right) - R_{rs}^{B}(\lambda_i)\right]^2}$$

SHALLOW WATERS

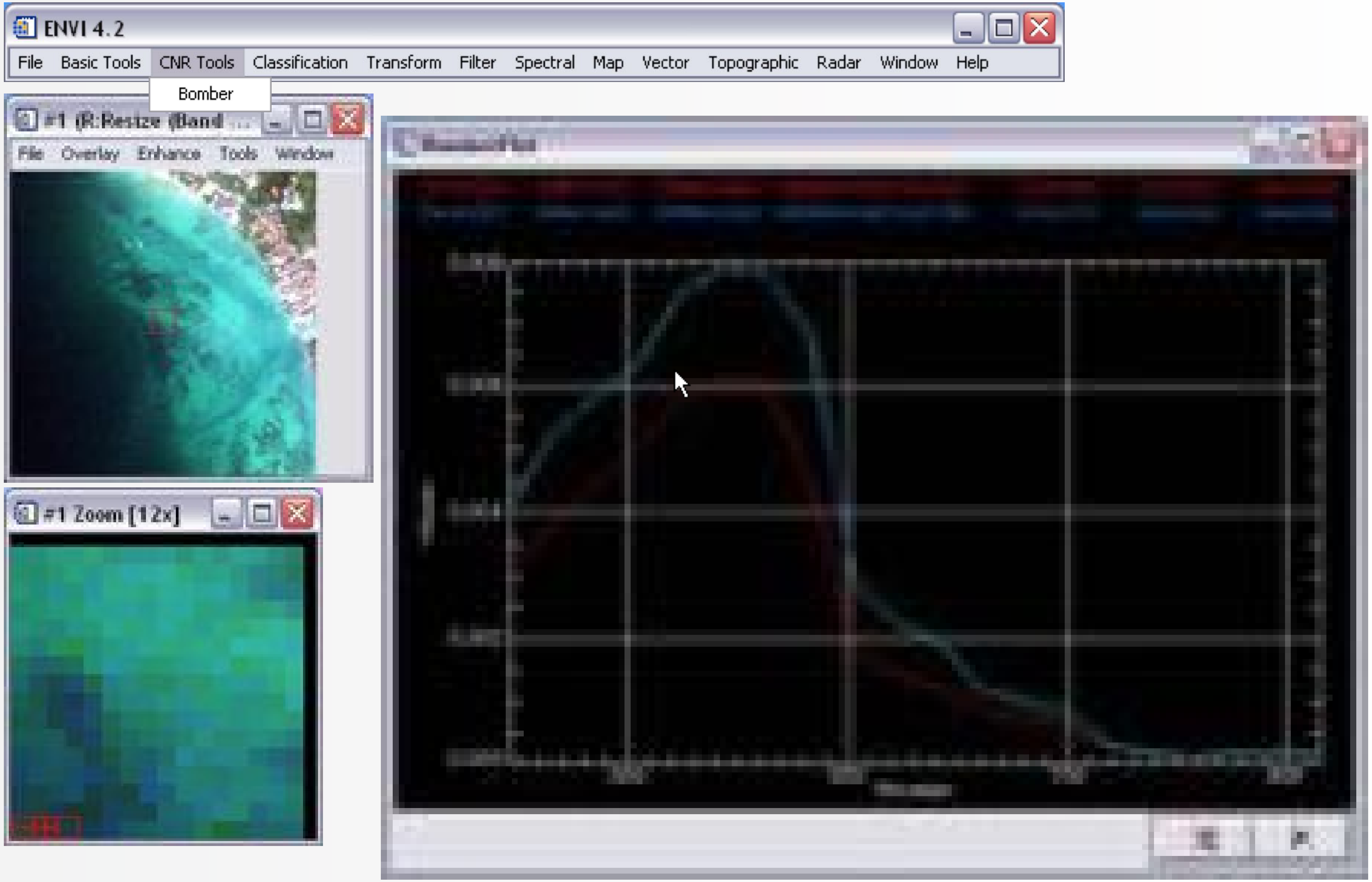
$$Obiettivo = \min_{CHL, SPM, a_{CDOM}(440), S_{SPM}, H, b_0, b_1, b_2} \sqrt{\sum_{i=1}^{N} \left[\left(R_{rs}^{I}(\lambda_i) - \Delta\right) - R_{rs}^{B}(\lambda_i)\right]^2}$$





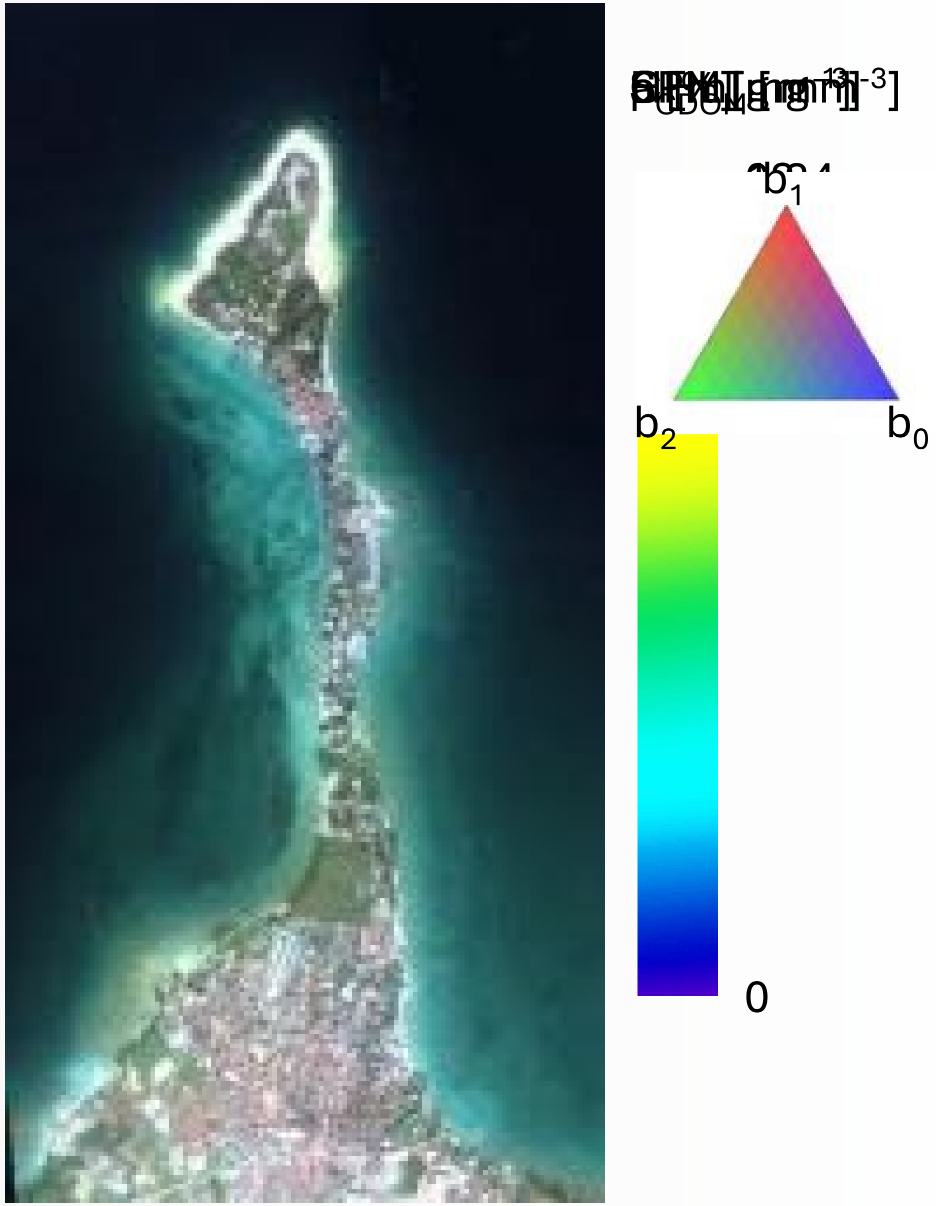
$$err = \frac{\delta}{\sqrt{\sum_{i=\lambda_{min}}^{\lambda_{max}} \hat{R}_{rs}^{2}(\lambda_i)}}$$ con $$\delta = \sqrt{\sum_{\lambda_{min}}^{\lambda_{max}} \left(R_{rs}(\lambda) - \hat{R}_{rs}(\lambda)\right)^2}$$

Output


ENVI 4.2
File
Basic Tools
CNR Tools
Classification
Transform
Filter
Spectral
Map
Vector
Topographic
Radar
Window
Help
Bomber
#1 (R:Resize (Band ...
File
Overlay
Enhance
Tools
Window
#1 Zoom [12x]

Output

1. Chlorophyll (CHL)
2. Suspended Particulate Matter (SPM)
3. Coloured Dissolved Organic Matter (a_{CDOM})
4. Bottom depth (H)
5. Bottom albedo (ρ):
   a. % Low albedo Vegetation (b_1)
   b. % High albedo Vegetation (b_2)
   c. % Sand (b_0)



WASI

Computers & Geosciences
Volume 30, Issue 5, June 2004, Pages 523-532

The water color simulator WASI: an integrating software tool for analysis and simulation of optical in situ spectra

Peter Gege

Computers & Geosciences
Volume 62, January 2014, Pages 208-215

WASI-2D: A software tool for regionally optimized analysis of imaging spectrometer data from deep and shallow waters

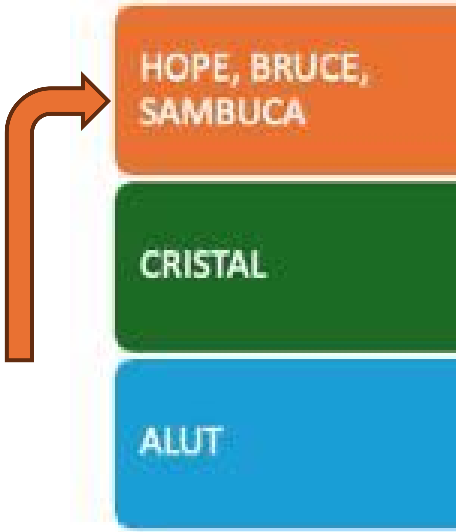
Peter Gege

Highlights

- Free image processing software for multi- and hyperspectral data.
- Deep and shallow waters.
- Wavelength dependent sun and sky glint correction.
- Easy adaptation to different environments and sensors.

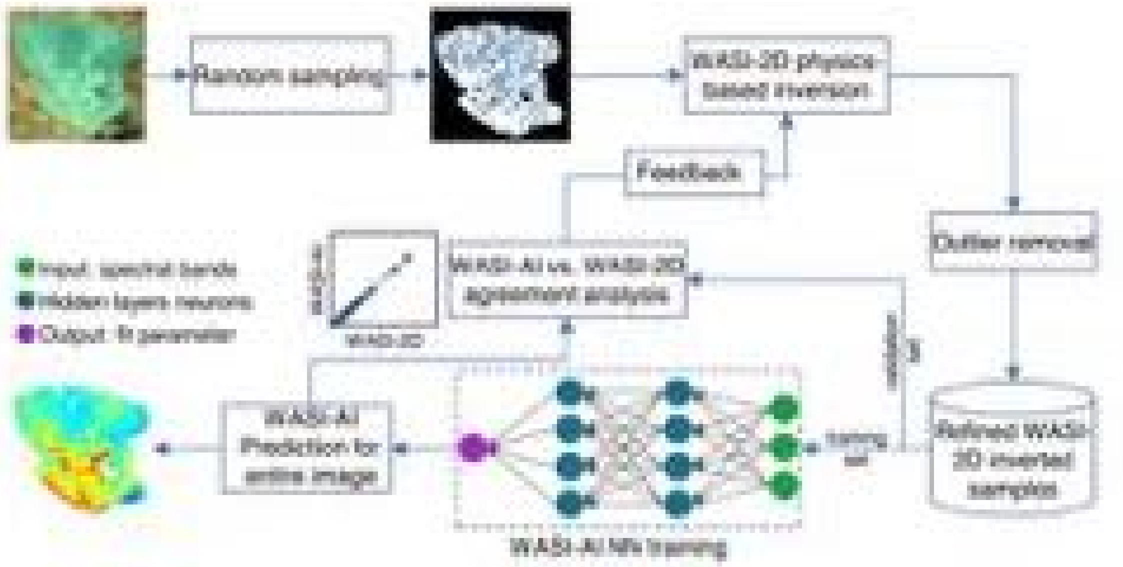
«Although many algorithms for inverse modelling of water leaving radiance and reflectance exist (IOCCG, 2006, Dekker et al., 2011), no publicly available software was available for long time that can be regionally optimized by the user.

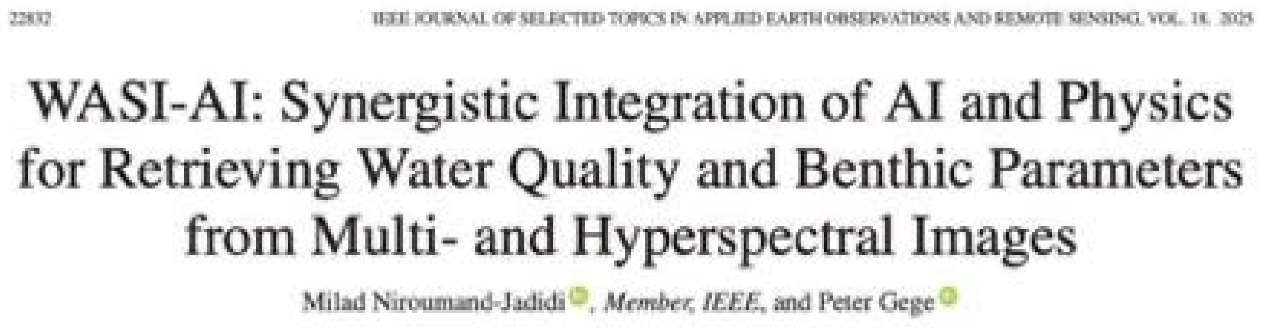
The first software of this kind, BOMBER, was developed only recently (Giardino et al., 2012). … . A similar tool is presented in this paper, WASI-2D. It is based on the Water Colour Simulator WASI (Gege, 2004, Gege and Albert, 2006), …»



WASI

WASI





22832 IEEE JOURNAL OF SELECTED TOPICS IN APPLIED EARTH OBSERVATIONS AND REMOTE SENSING, VOL. 18, 2025

WASI-AI: Synergistic Integration of AI and Physics for Retrieving Water Quality and Benthic Parameters from Multi- and Hyperspectral Images

Milad Niroumand-Jadidi, *Member, IEEE*, and Peter Gege

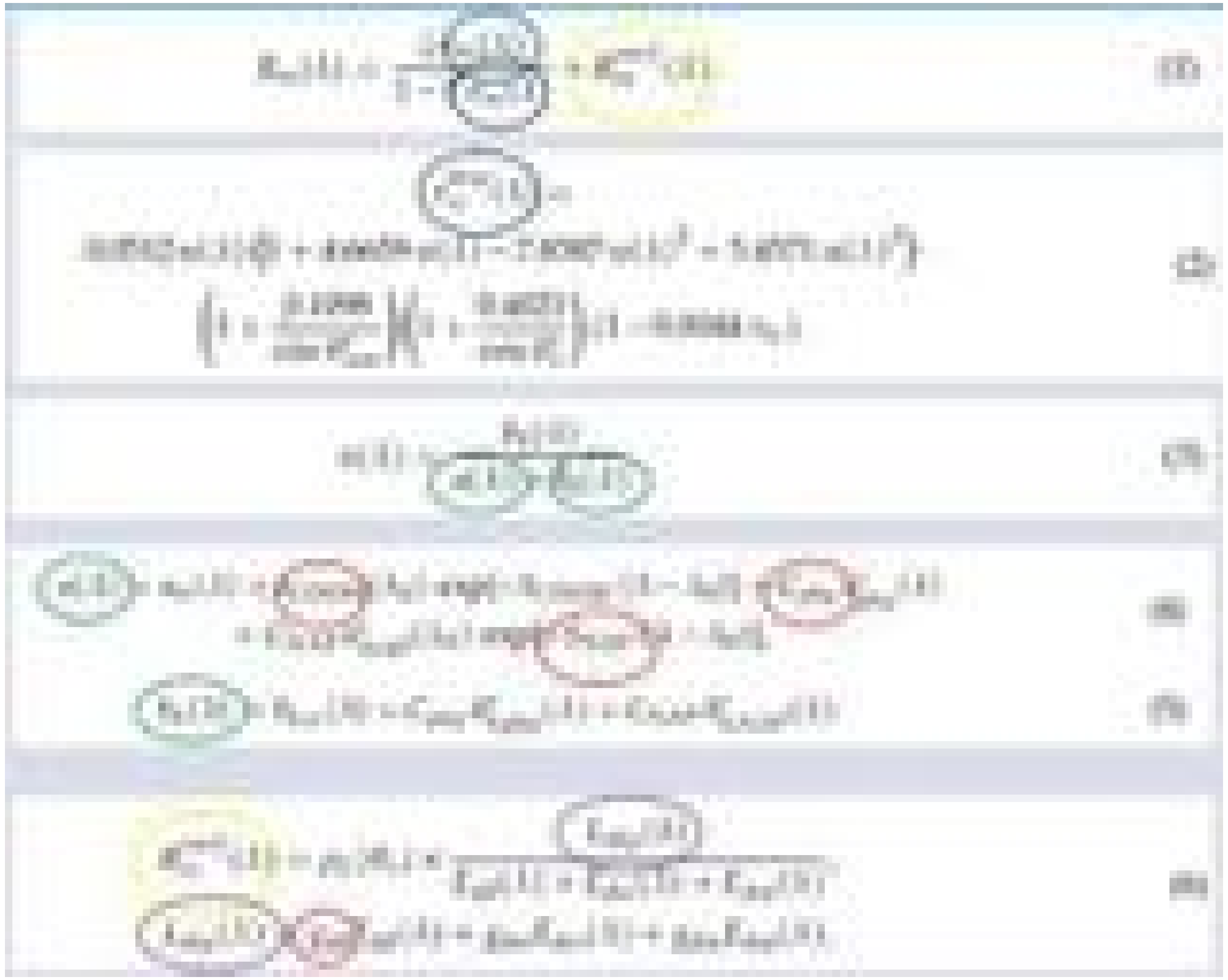
- WASI-AI uses the physics-based WASI two-dimensional (2-D) (WASI-2D) module of WASI to retrieve the unknown biophysical parameters for a small subset of image pixels selected at random.

- A portion of the inverted samples is used to train neural networks (NNs). The trained NNs are then applied to predict the unknown biophysical parameters for all water pixels of the image.

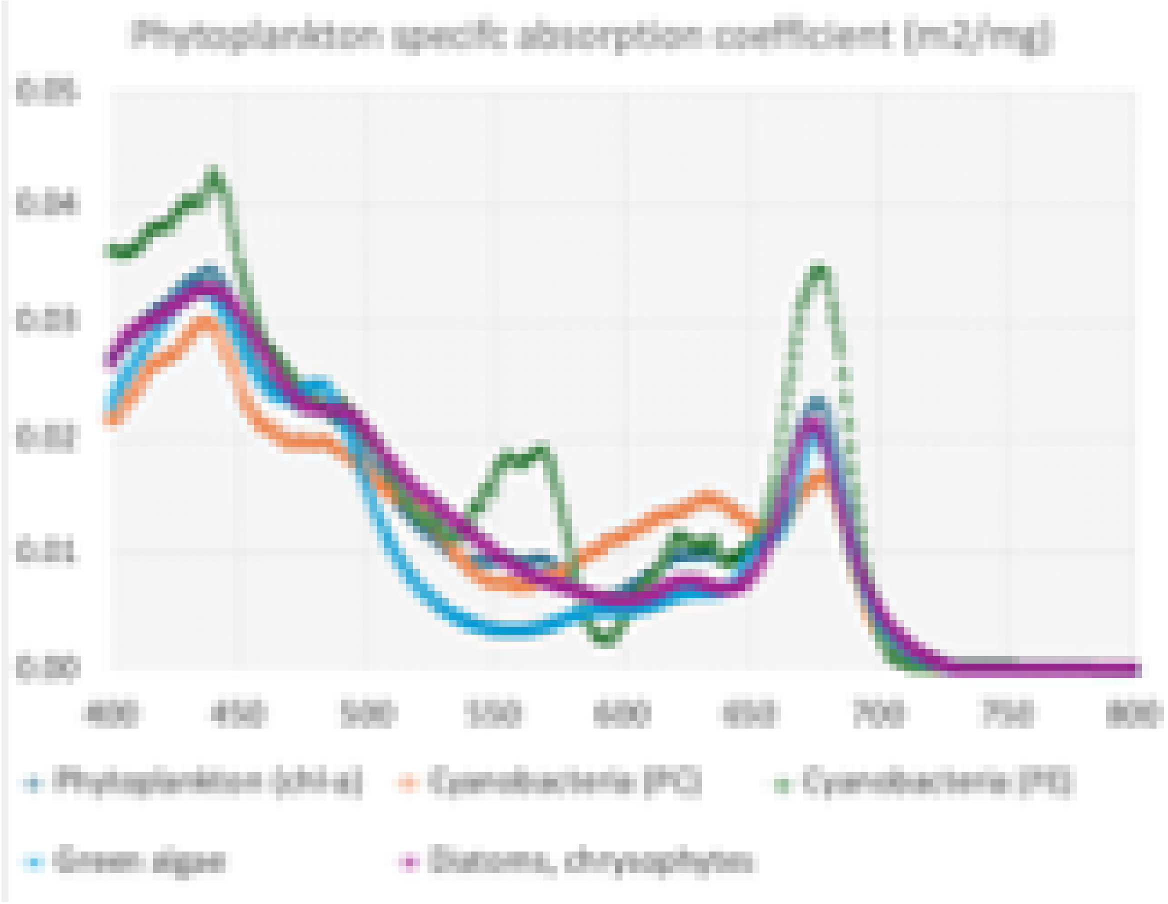
- The remaining portion of samples is used to assess the agreement between WASI-AI and WASI-2D and allow recognizing spectral ambiguity and optimizing inverse modeling parametrization.

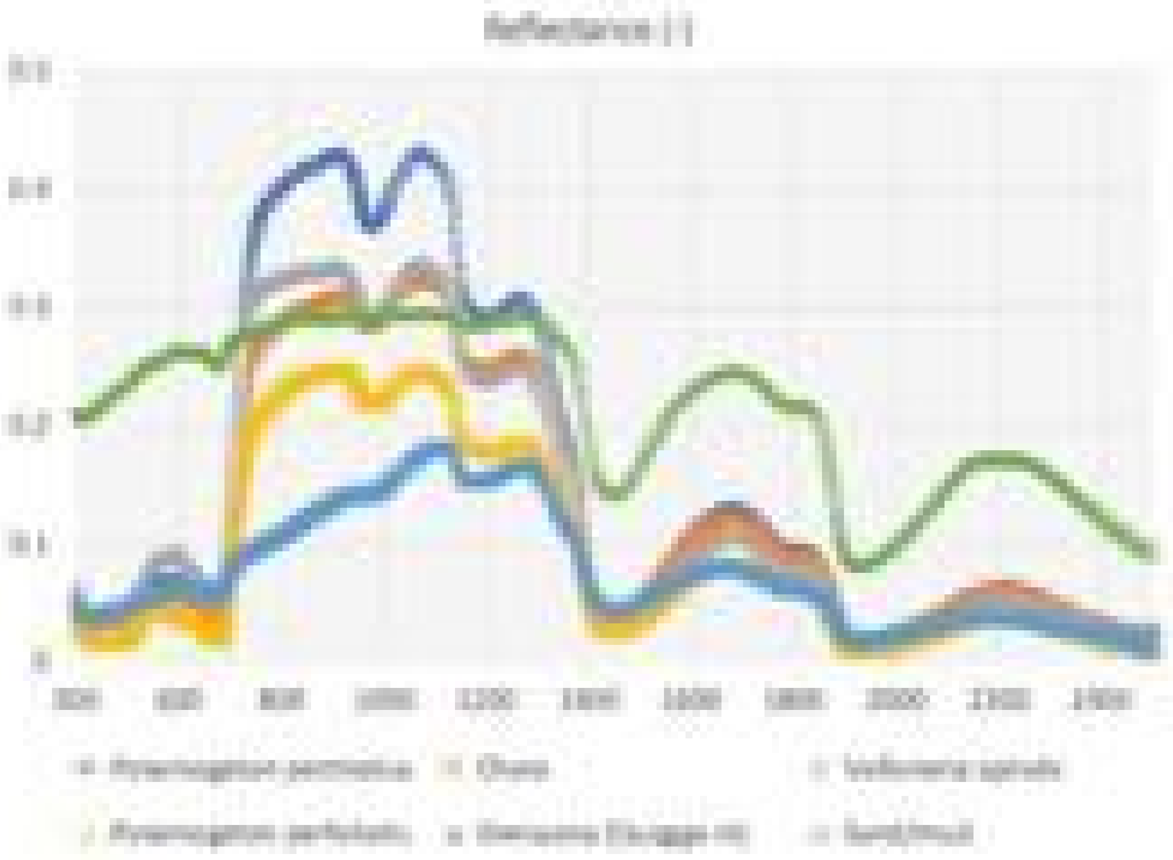
- The integration of AI significantly speeds up the inversion, reducing the processing time of a single image from hours/days to mere minutes.

WASI

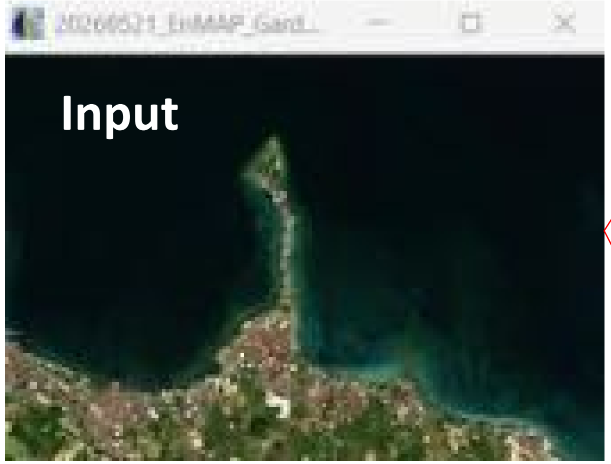


Model parametrisation





WASI



EnMAP L2A Lake Garda (Italy)
21 May 2026

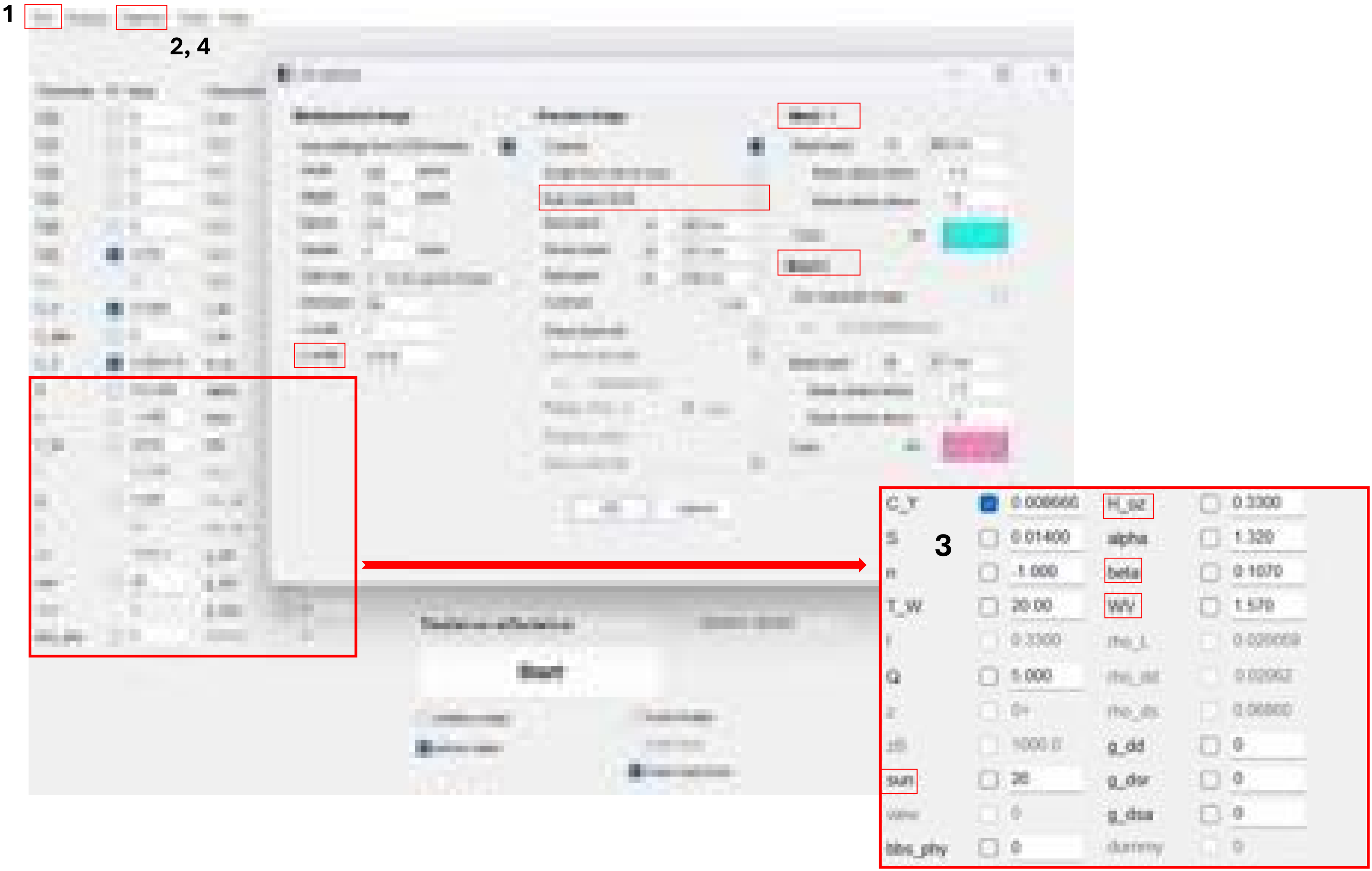
First step

1. Load the image from «File»

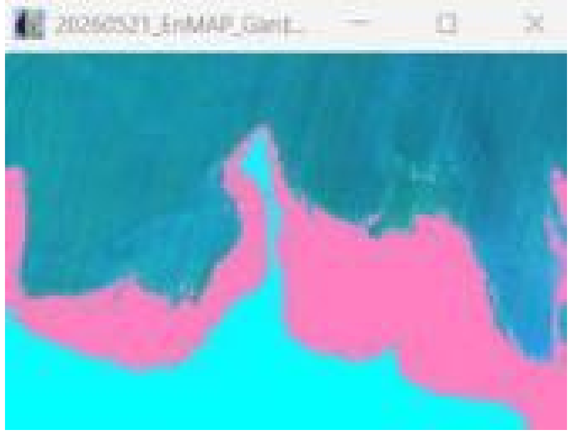
2. In the 2D options, set the image's y-scale, the bands to display the true colour and the mask values"

3. Add Sun zenith, Aerosol Optical Depth (beta), Water Vapor (WV) and the Ozone (H_oz) values from the metadata of the sensor

4. In Options -> Inverse calc. -> Fit tuning: set the spectral range



Deep waters



Before characterising the **shallow water**, you need to configure the **deep water**

The "C" parameters refer to the specific absorption coefficients of phytoplankton:
(0) = Phyto
(1) = Cryptophytes
(2) = Cyanobacteria
(3) = Diatoms
(4) = Dinoflagellates
(5) = Green algae

C(X) refers to TSM
C(Y) refers to CDOM

Shallow waters

Leave the default settings for deep water and proceed to shallow water

The “f” parameters refer to bottom parameters:
(1) = Sand
(2) = Silt
(3) = Seagrass
(4) = Mussel
(5) = Macrophyte

zB refers to Bottom depth

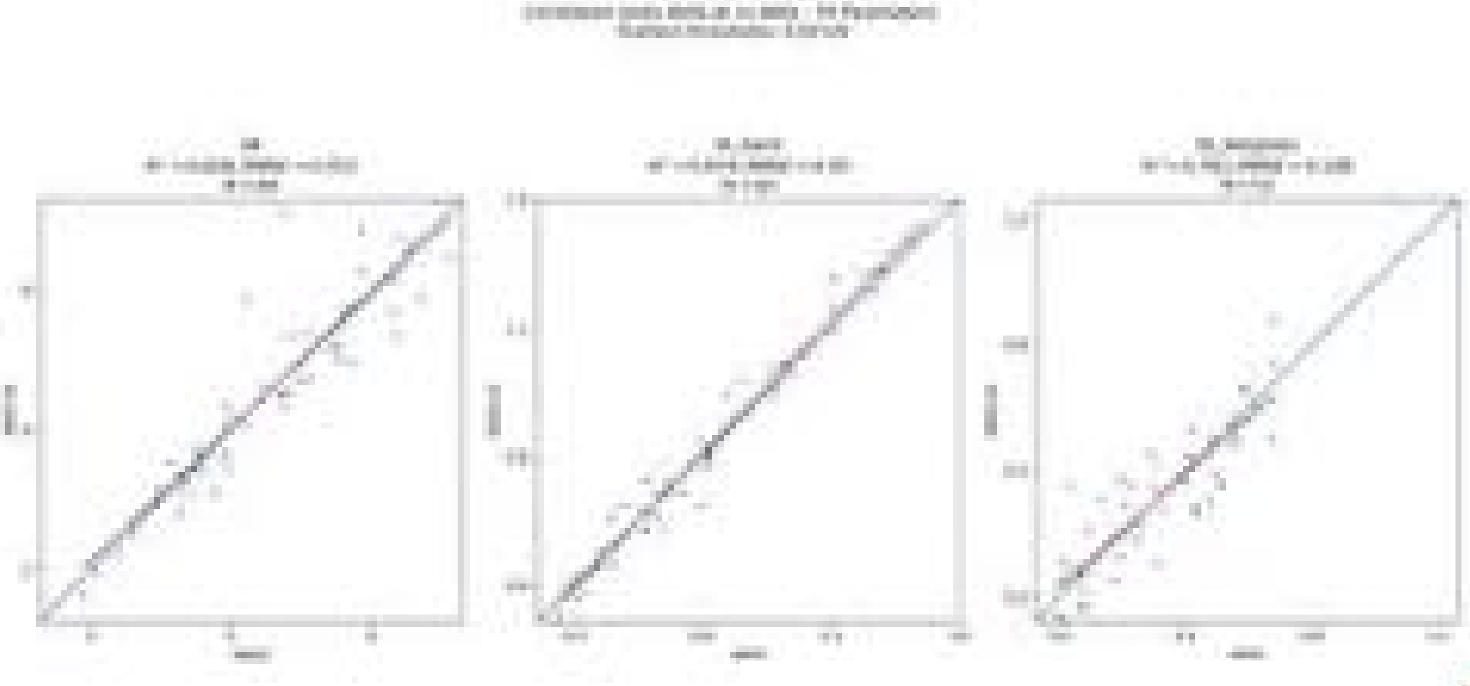
Mask

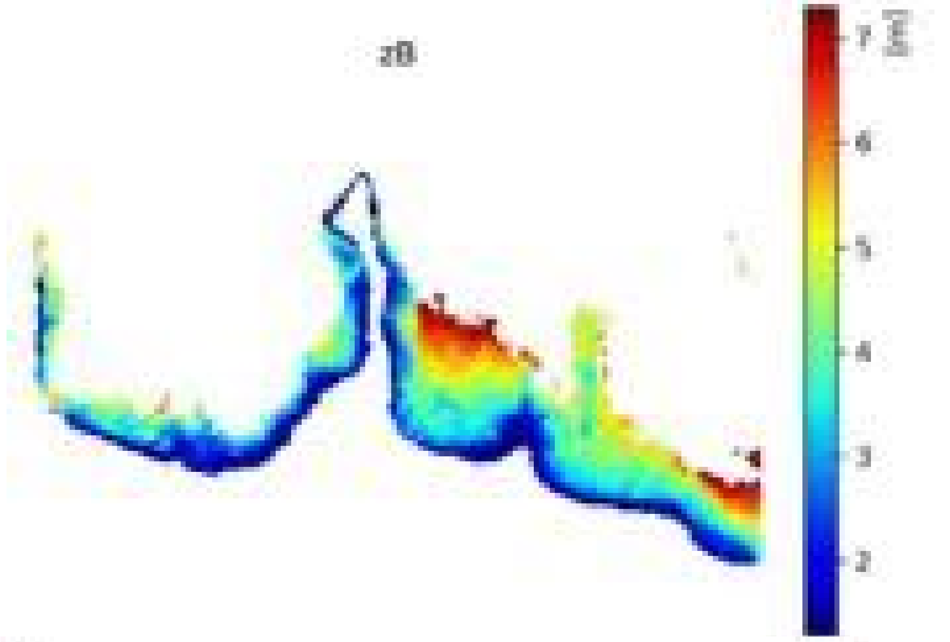
Leave the default settings for deep water and proceed to shallow water

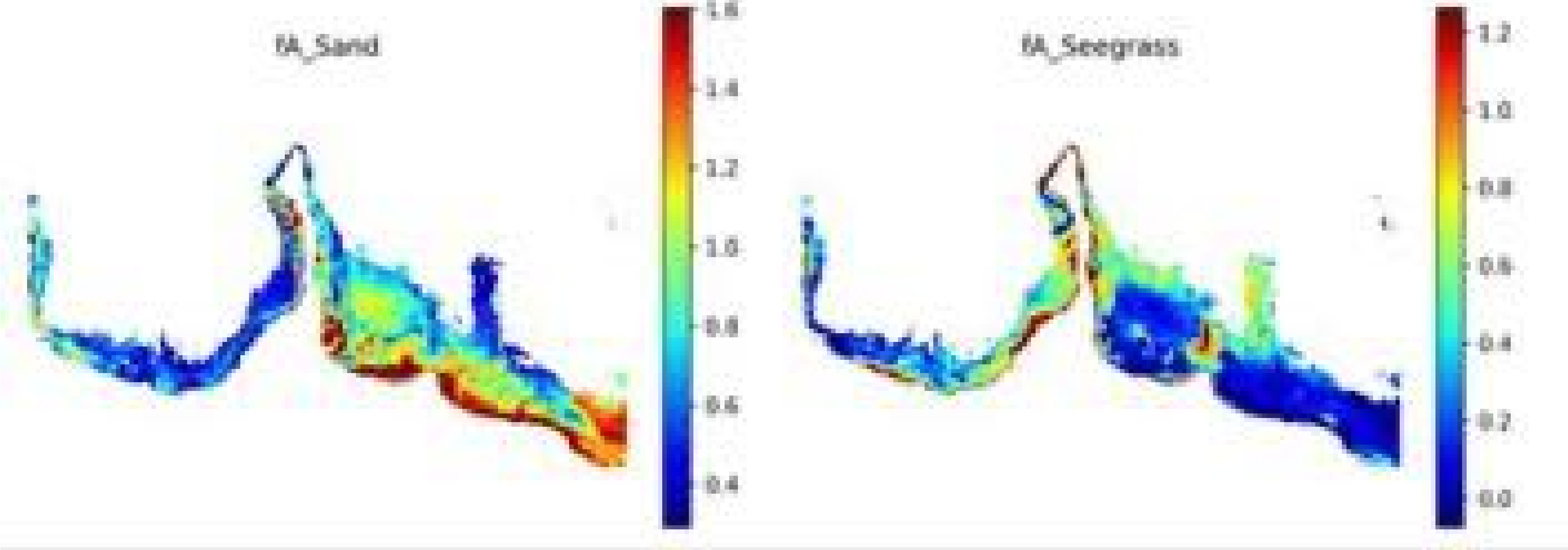
The "f" parameters refer to bottom parameters:
(1) = Sand
(2) = Silt
(3) = Seegrass
(4) = Mussel
(5) = Macrophyte

zB refers to Bottom depth

Output







The correlation plots (**between WASI (AI) and WASI**) of the fit parameters make it possible to identify spectral ambiguities and thus optimize the parameterization of inverse modeling.

SEOM S2-4Sci Land and Water

https://sen2coral.argans.co.uk/

ELSEVIER

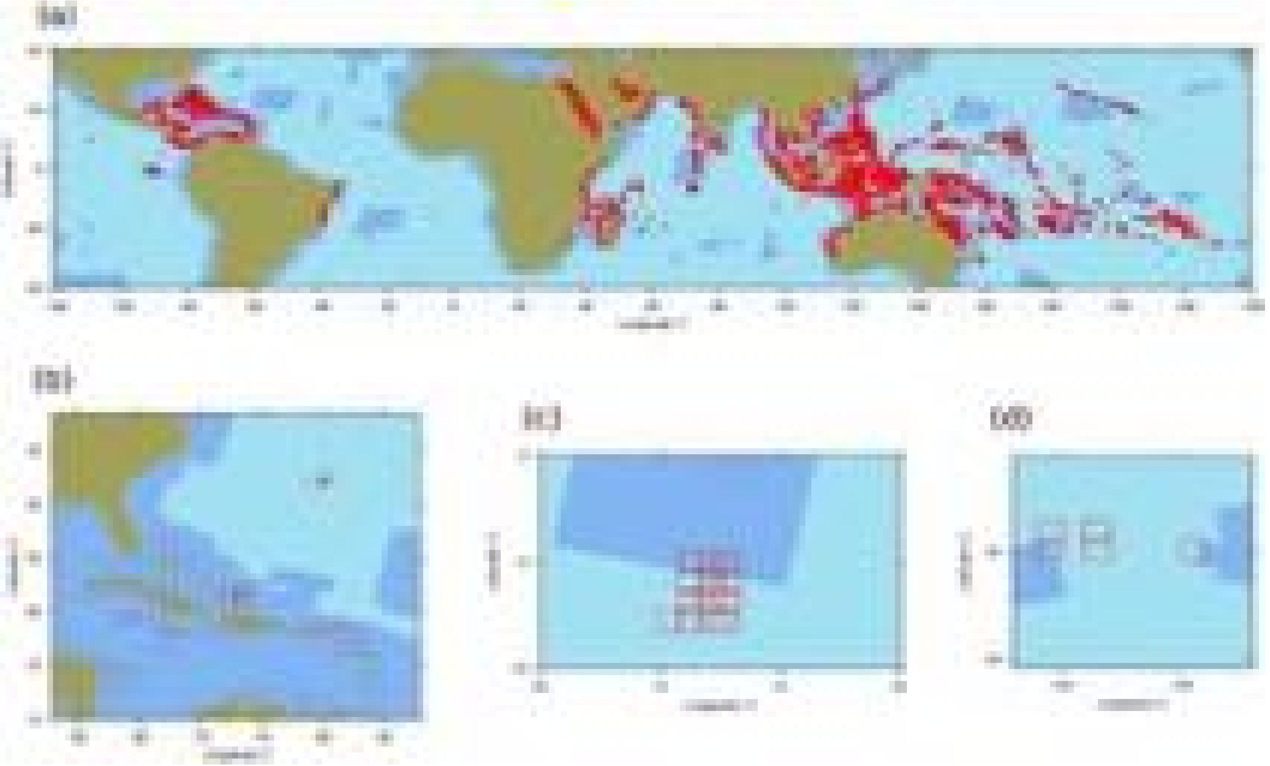
Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Coral reef applications of Sentinel-2: Coverage, characteristics, bathymetry and benthic mapping with comparison to Landsat 8

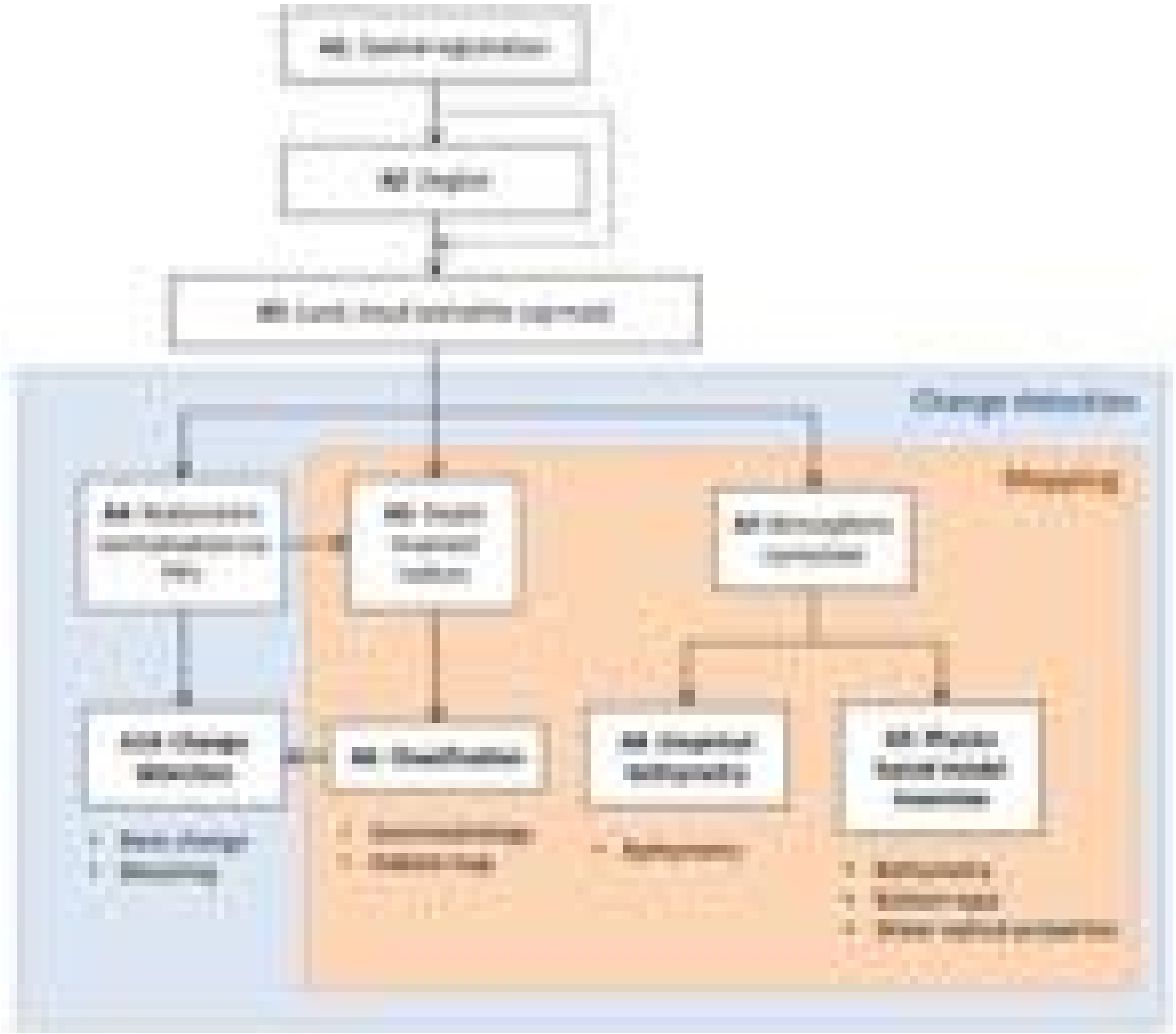
John D. Hedley[a,*], Chris Roelfsema[b], Vittorio Brando[c], Claudia Giardino[c], Tiit Kutser[d], Stuart Phinn[b], Peter J. Mumby[e], Omar Barrilero[f], Jean Laporte[g], Benjamin Koetz[h]



Highlights

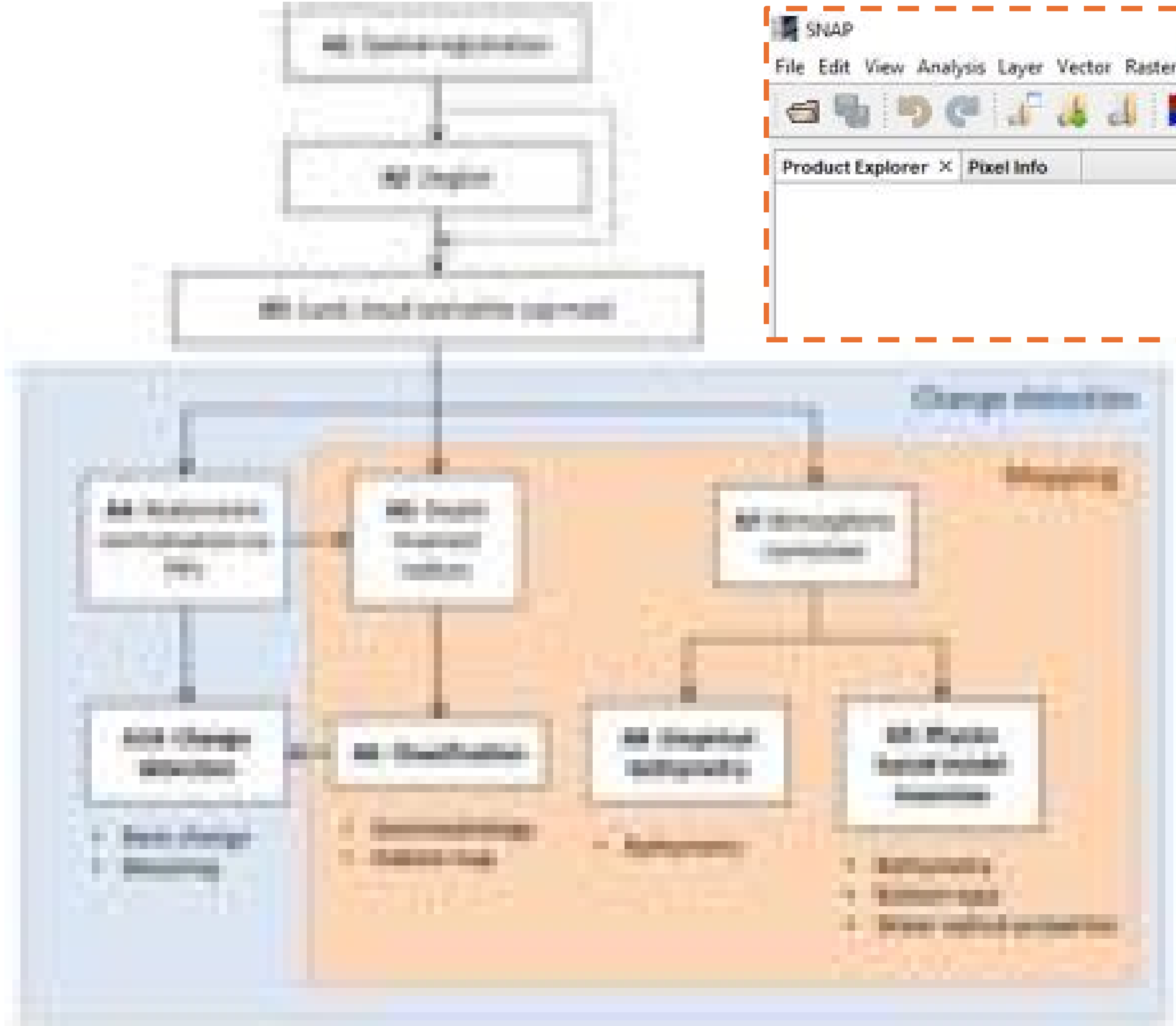
- Despite being a land mission Sentinel-2 images nearly 90% of the World's reefs.
- Sentinel-2 provides excellent results for bathymetry and benthic mapping.
- Sentinel-2 has advantages over Landsat 8 and high spatial resolution sensors.
- Coral bleaching is visible in Sentinel-2 images.
- We recommend an acquisition plan review with the aim to cover all reefs globally.

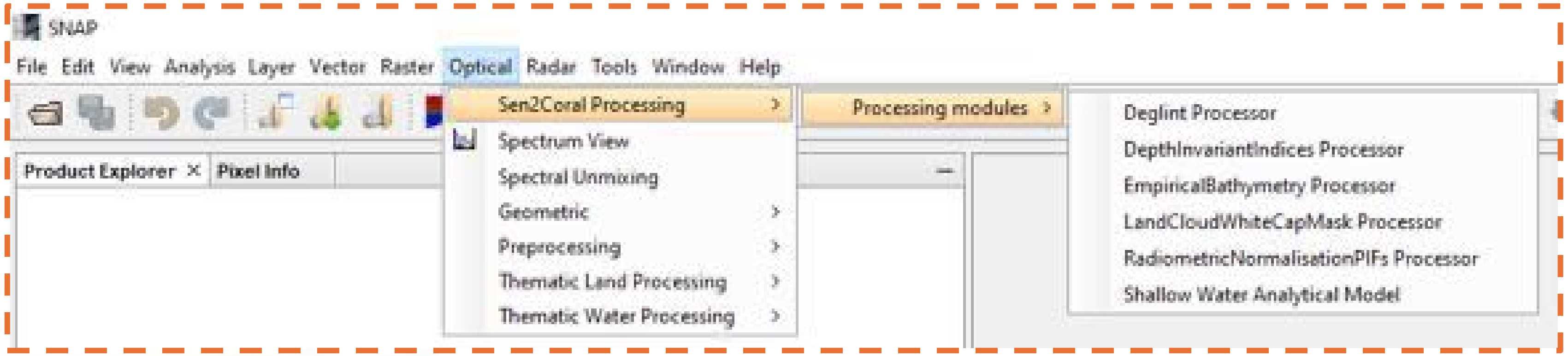
A coral reef remote sensing processing chain



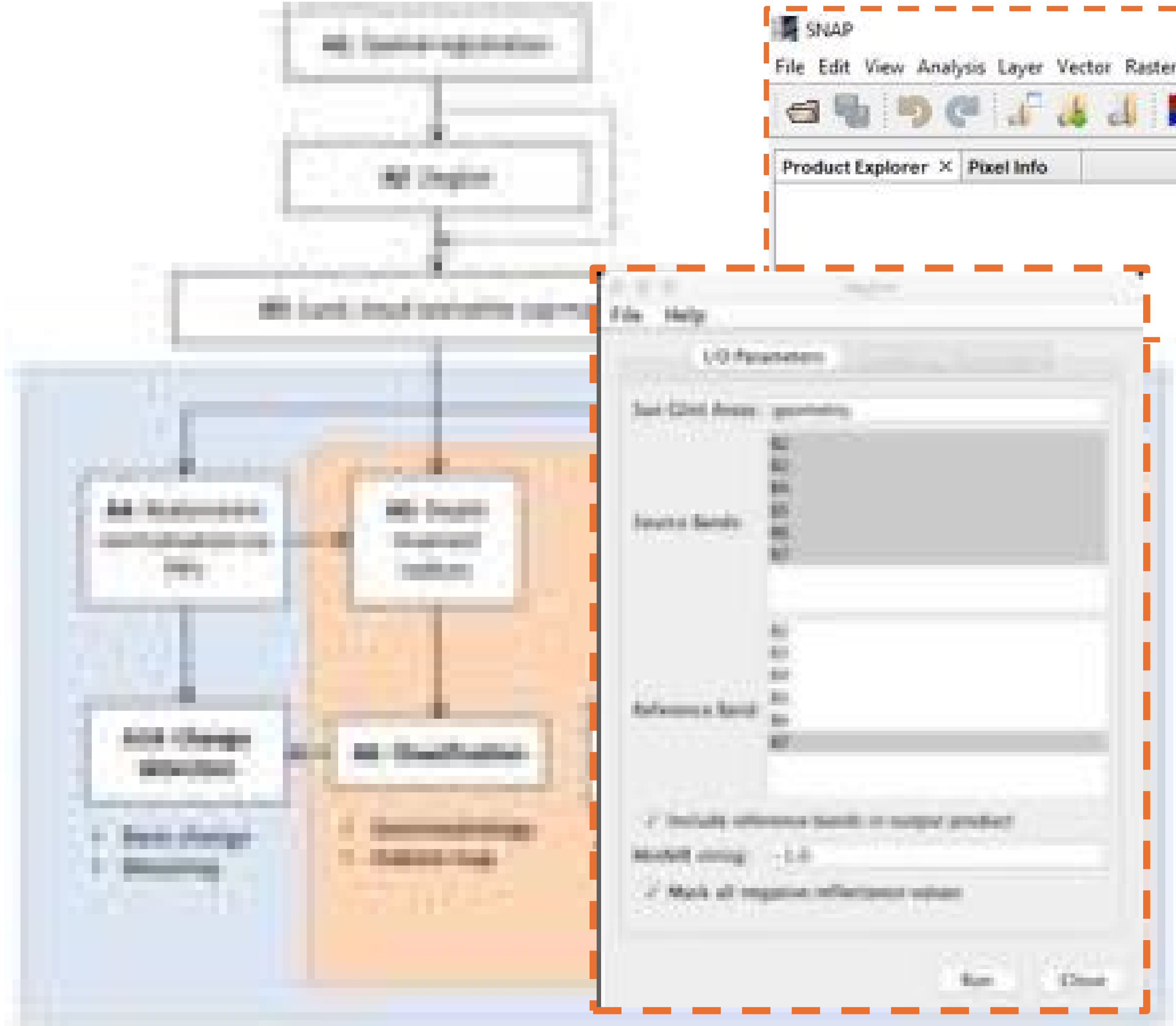
- Consistent with web resources, e.g. UNESCO Remote Sensing Handbook for Tropical Coastal Management
- Basic (pre-)processing tools
- Plus “state-of-the art” model inversion method

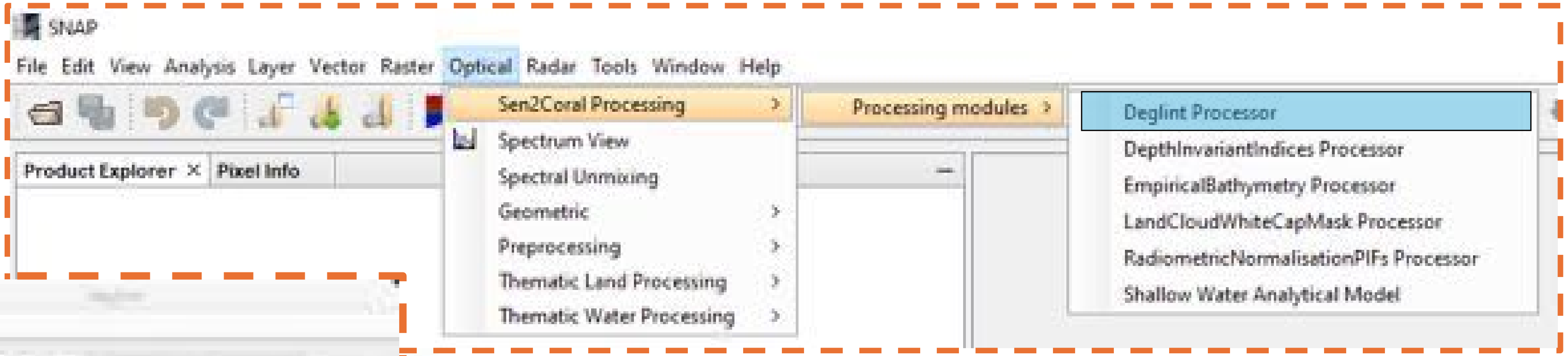
Sen2Coral processing chain in SNAP





Sen2Coral: deglint module





A2 : Deglint

Removes sun glint reflected from waves by using a NIR band

- Essential component of the tool box
- Improves visual appearance
- In shallow areas can over-correct because of subsurface NIR reflectance (makes pixels dark)
- Result is noisy - relies on good spatial and temporal band registration

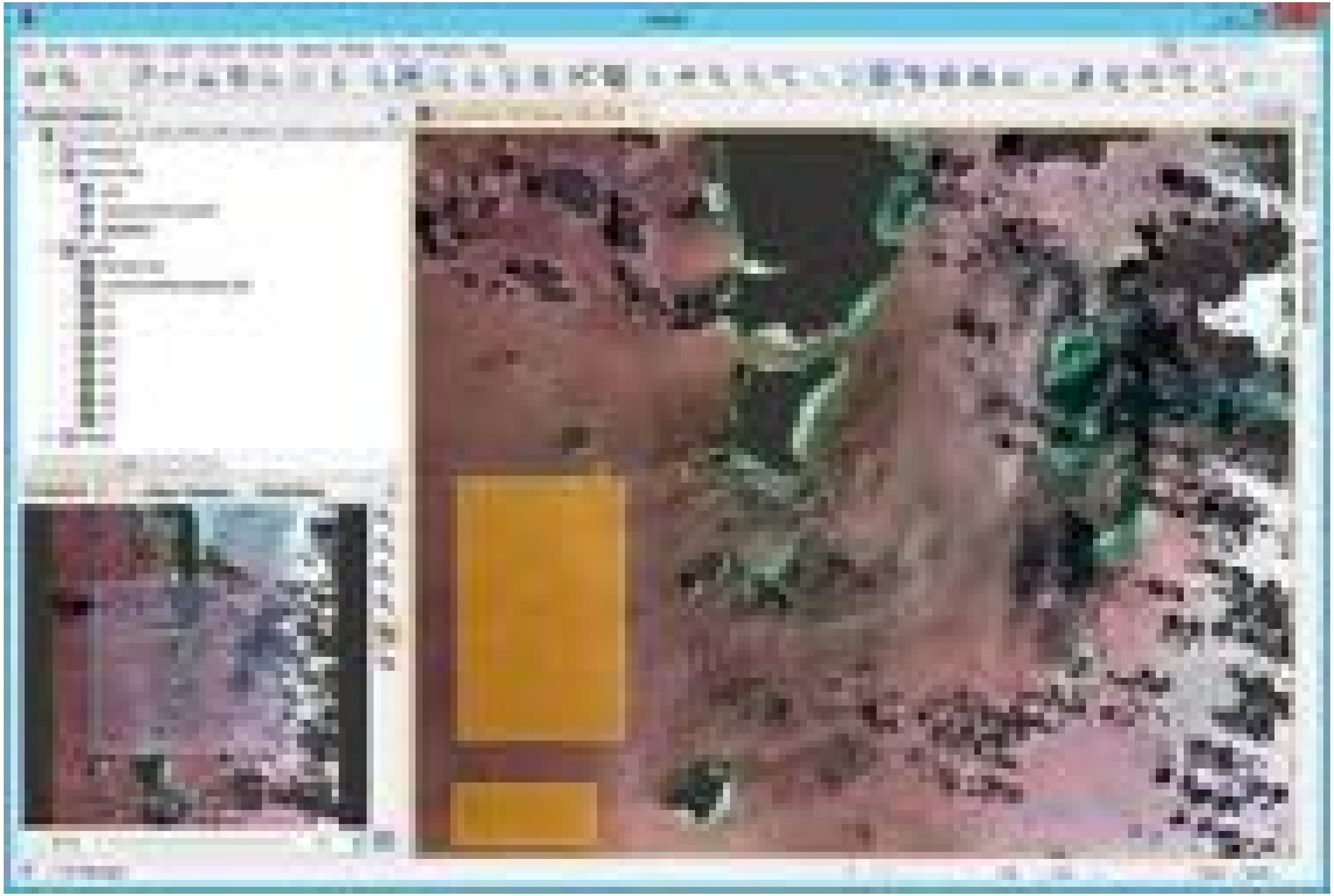
Deglint: Specific issue with Sentinel 2

<u>glint is frequently caused by waves smaller than the 10 m pixels.</u>

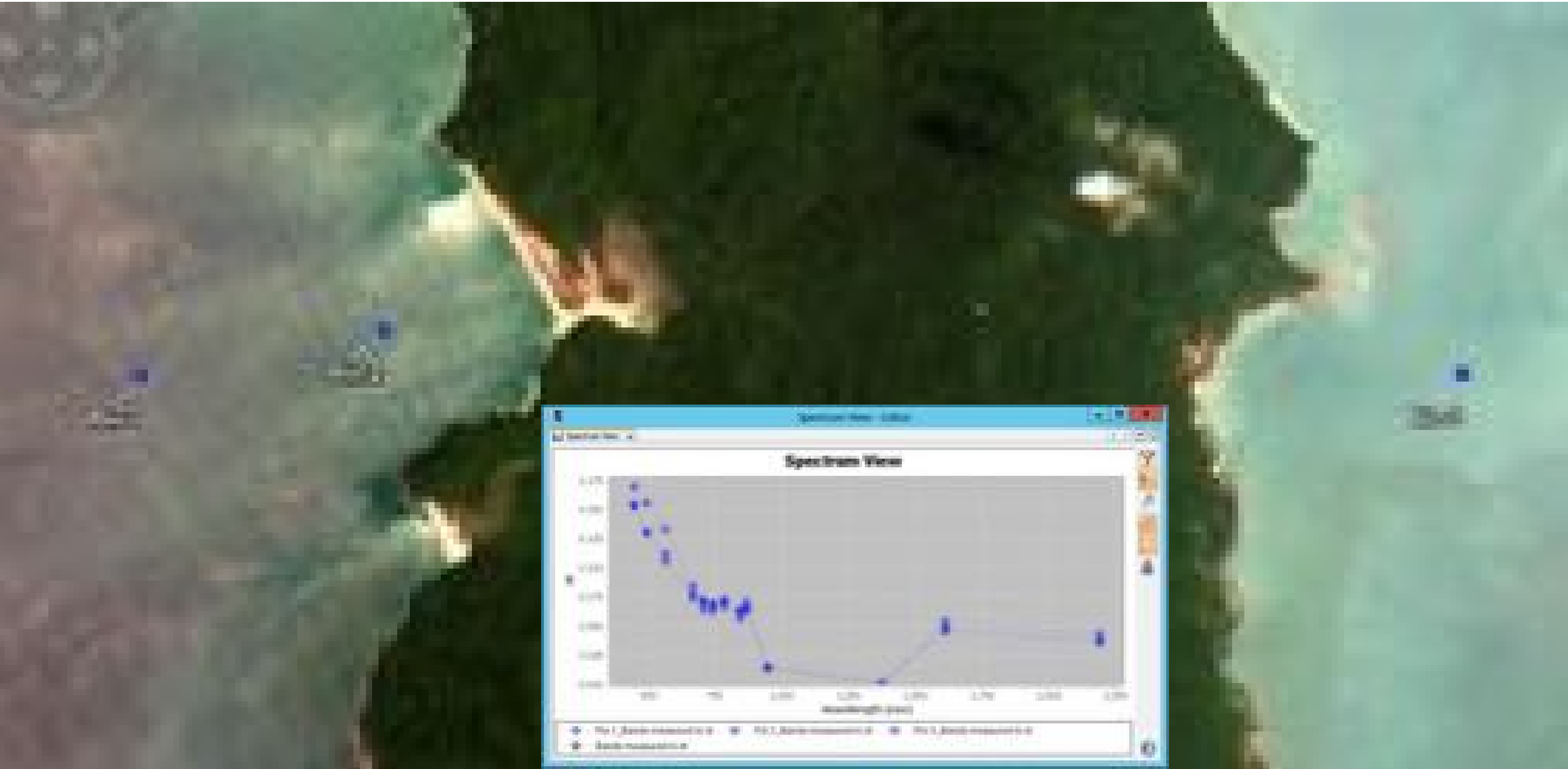
- Can't be corrected by this method because no basis to characterise the relationship.
- This component exists in many images - difficult to get a radiometrically correct surface correction.

This is more like "large pixel" sensor regime - MERIS etc. these correct for glint using Cox and Munk equations of surface slopes from wind speed - not valid in shallow waters.

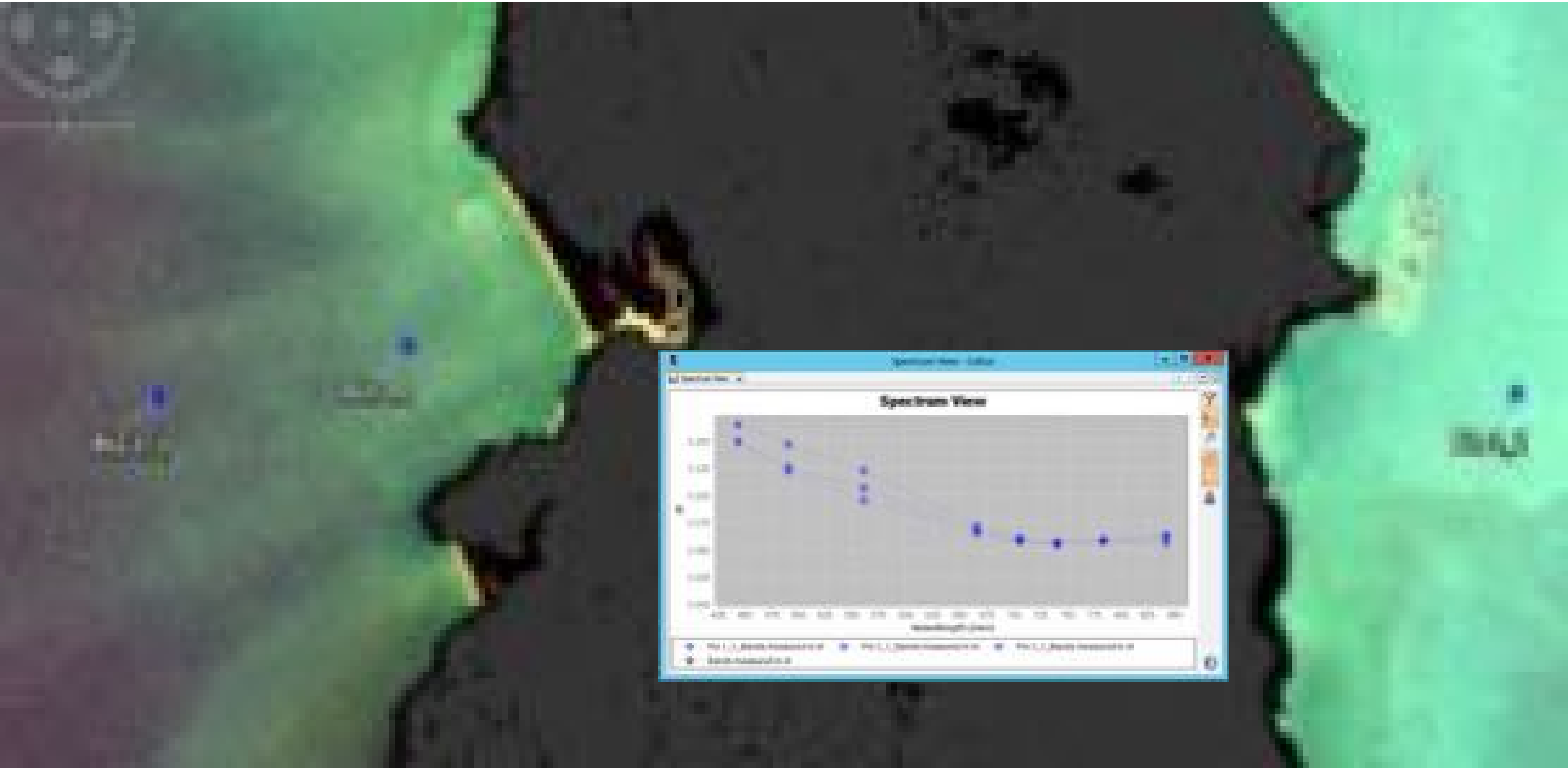
Sen2Coral: deglint module



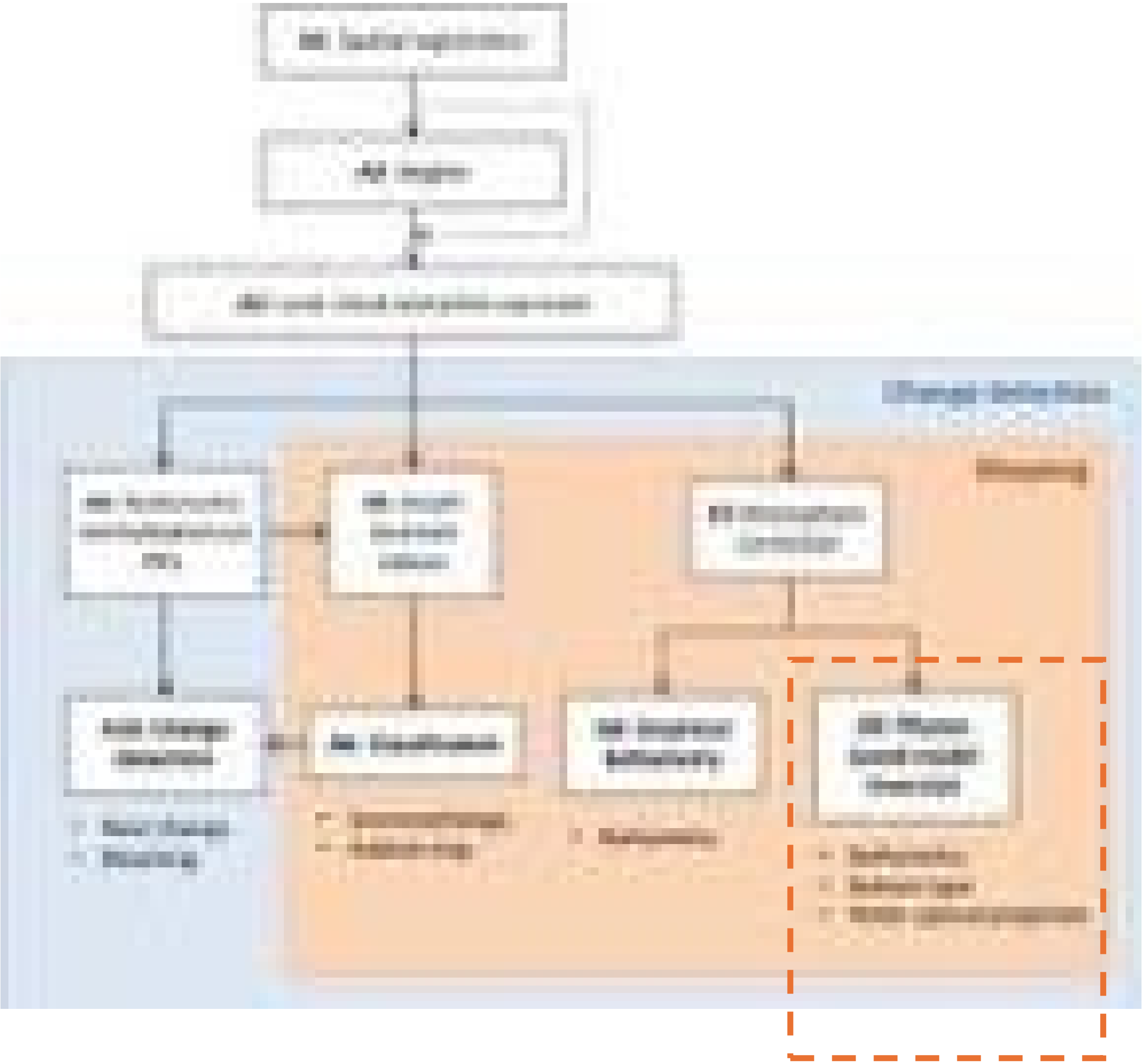
Sen2Coral: deglint module



Sen2Coral: deglint module



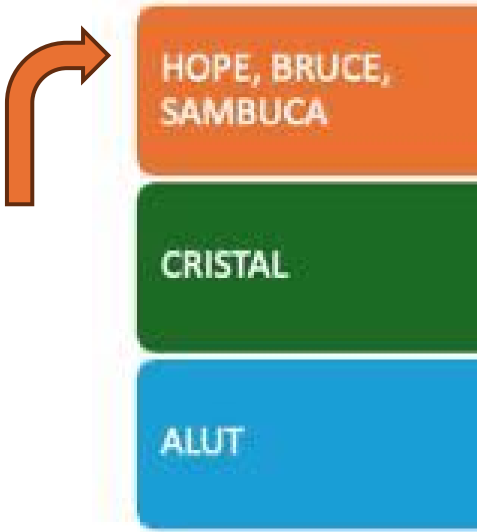
Sen2Coral: Physics based model inversion module



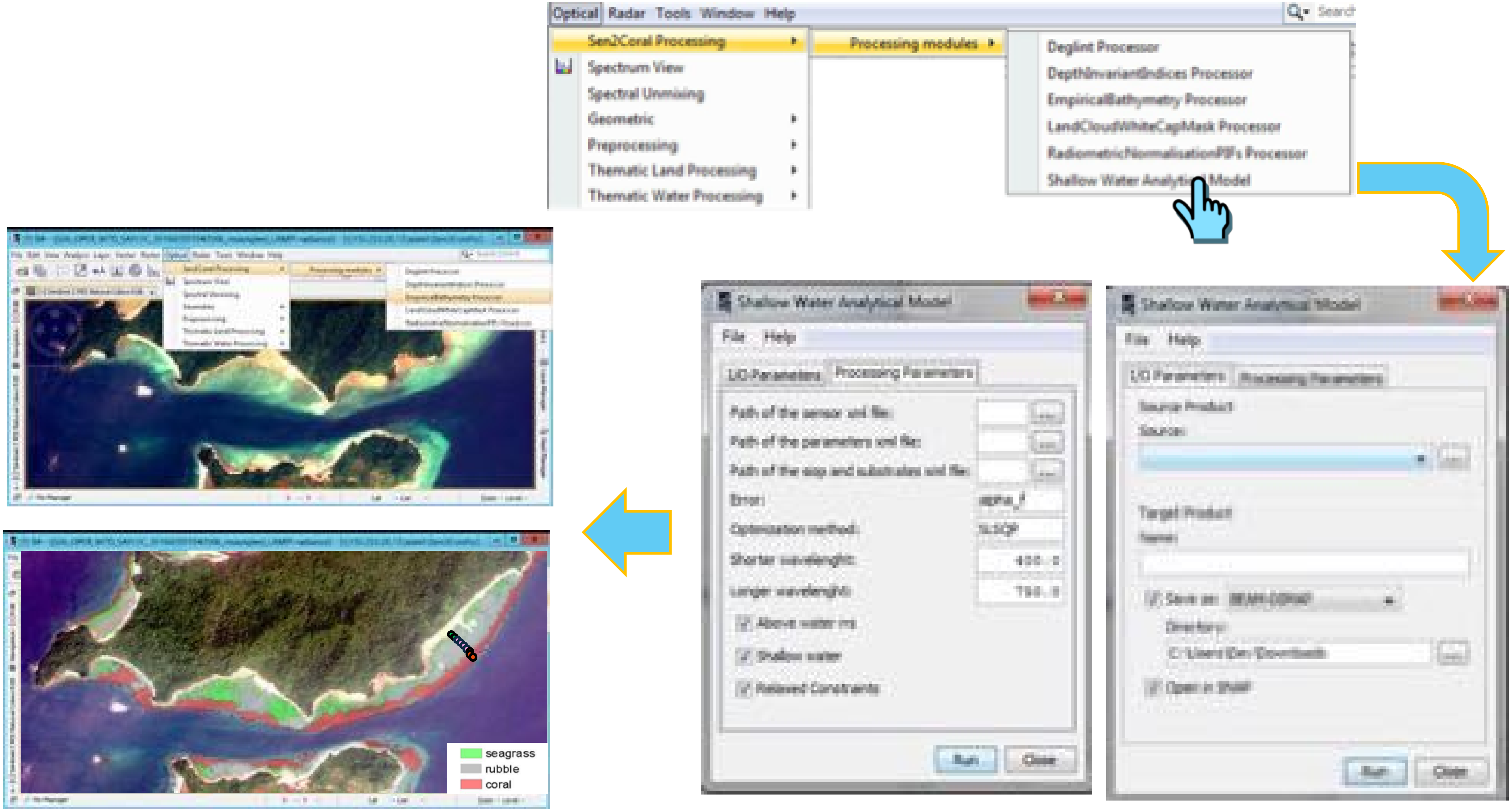
- Built on Lee et al. (1998, 1999);
- Linear mixed distribution of up three different substrates as in BOMBER (Giardino et al., 2012);
- Quality control procedure based (e.g. Substrate Detectability Index) and the characteristics of the instrument as in SAMBUCA (Brando et al., 2009);
- Uses of a relax constrain hypothesis (Petit et al. 2017) for modelling the contribution of the substrates in bottom reflectance

SWAMPy

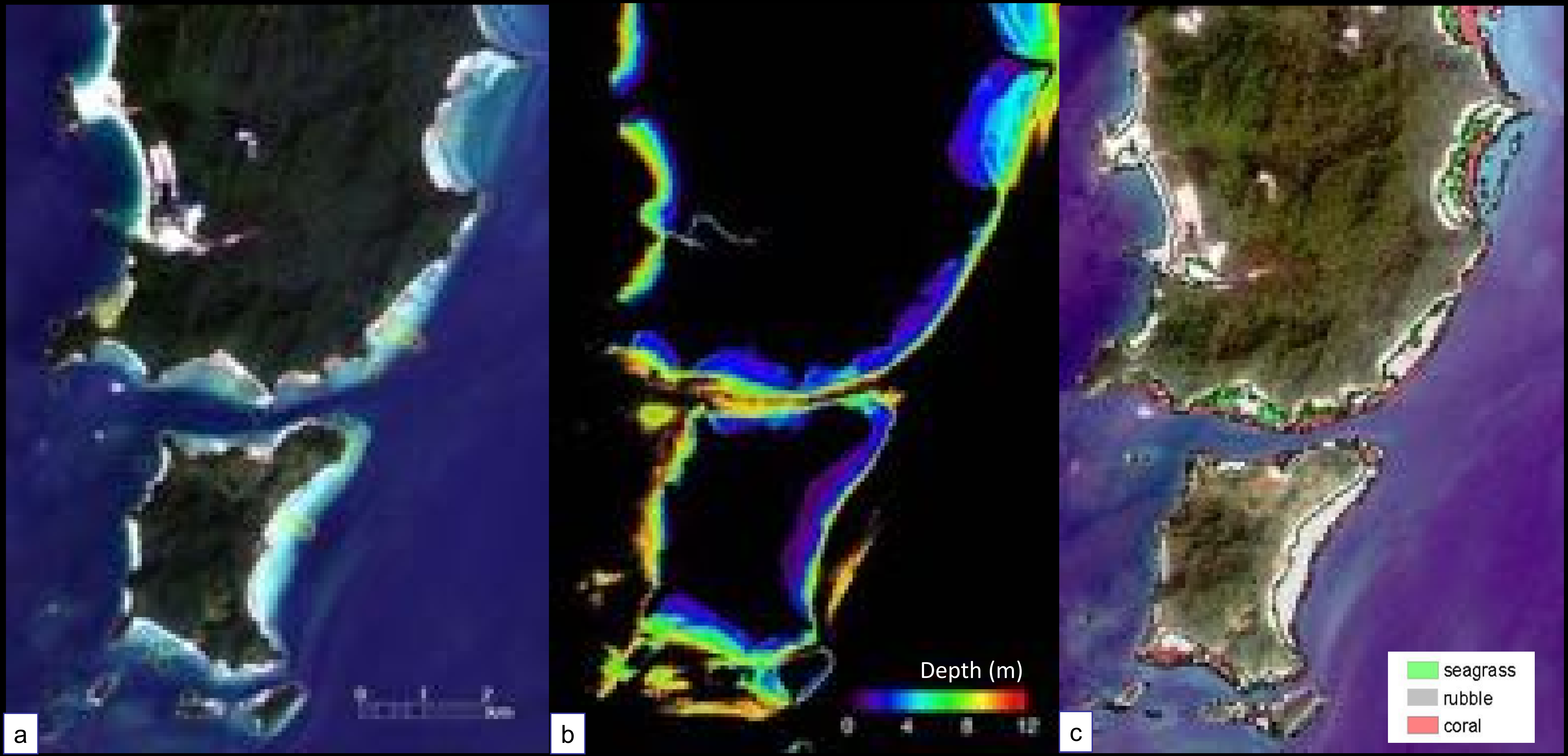
python™



Sen2Coral: Physics based model inversion module



Sen2Coral: Physics based model inversion module



Shallow or deep waters ?

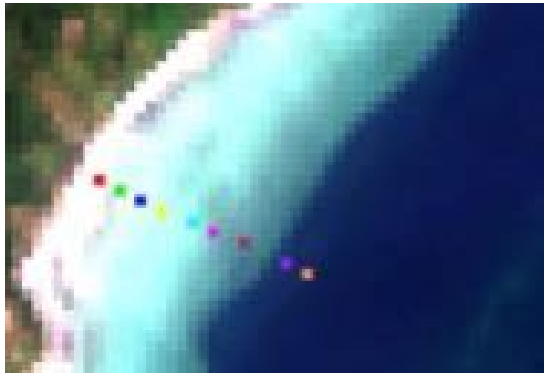
Shallow *vs* deep waters

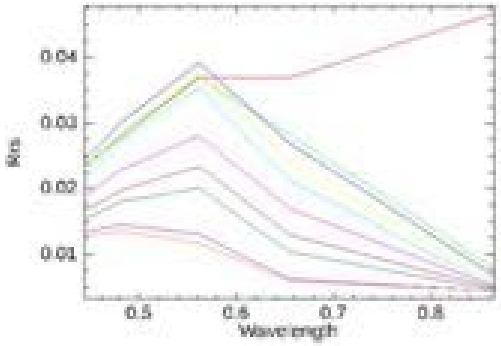
Brando et al. 2009

$$\mathrm{SDI} = \max\left(\left| r_{rs}^{\mathrm{model}} - r_{rs}^{dp\_\mathrm{model}} \right| / \mathrm{NE}\Delta r_{rsE} \right)$$

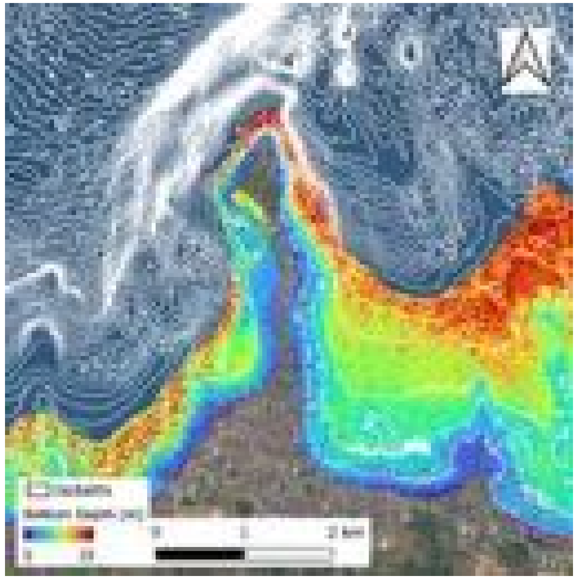
- “optically shallow waters” where the signal from the substratum is directly measurable and is ~ 5 NEΔrrsE at the band of maximum penetration (SDI > ~ 5)
- “quasi-optically deep waters”, where the contribution from the substratum is weak at the is between 1 and 5 NEΔrrsE (i.e. 1 < SDI < 5)
- “optically deep waters”, where no signal from the substratum is measurable (i.e. SDI = 0).

Spectral indexes

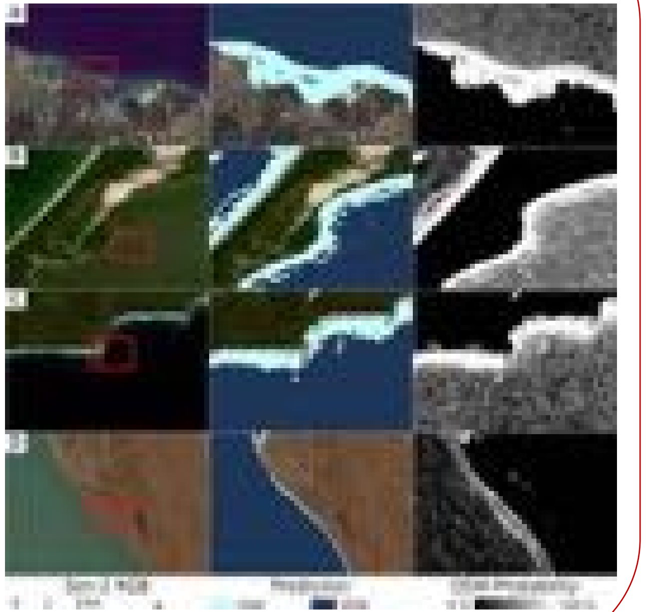




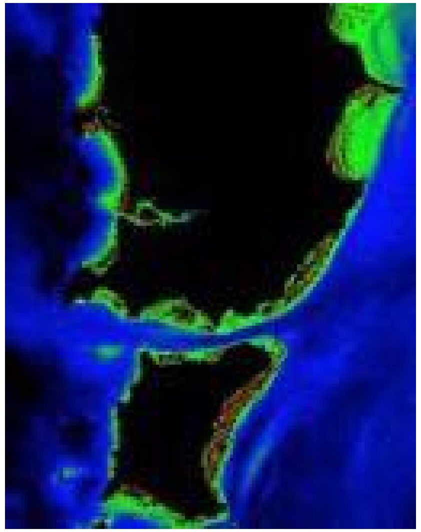
A priori

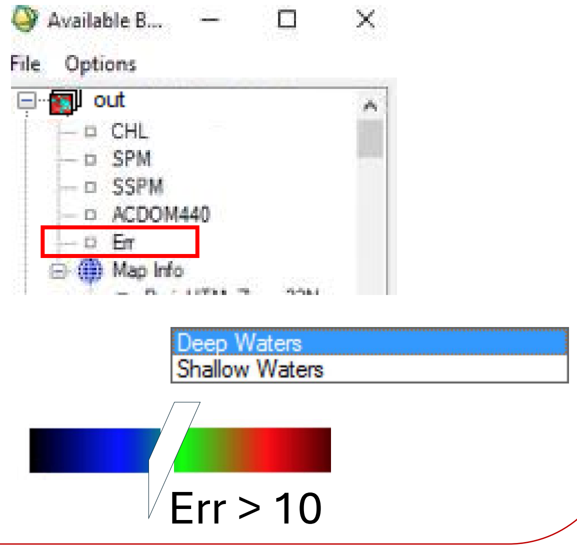


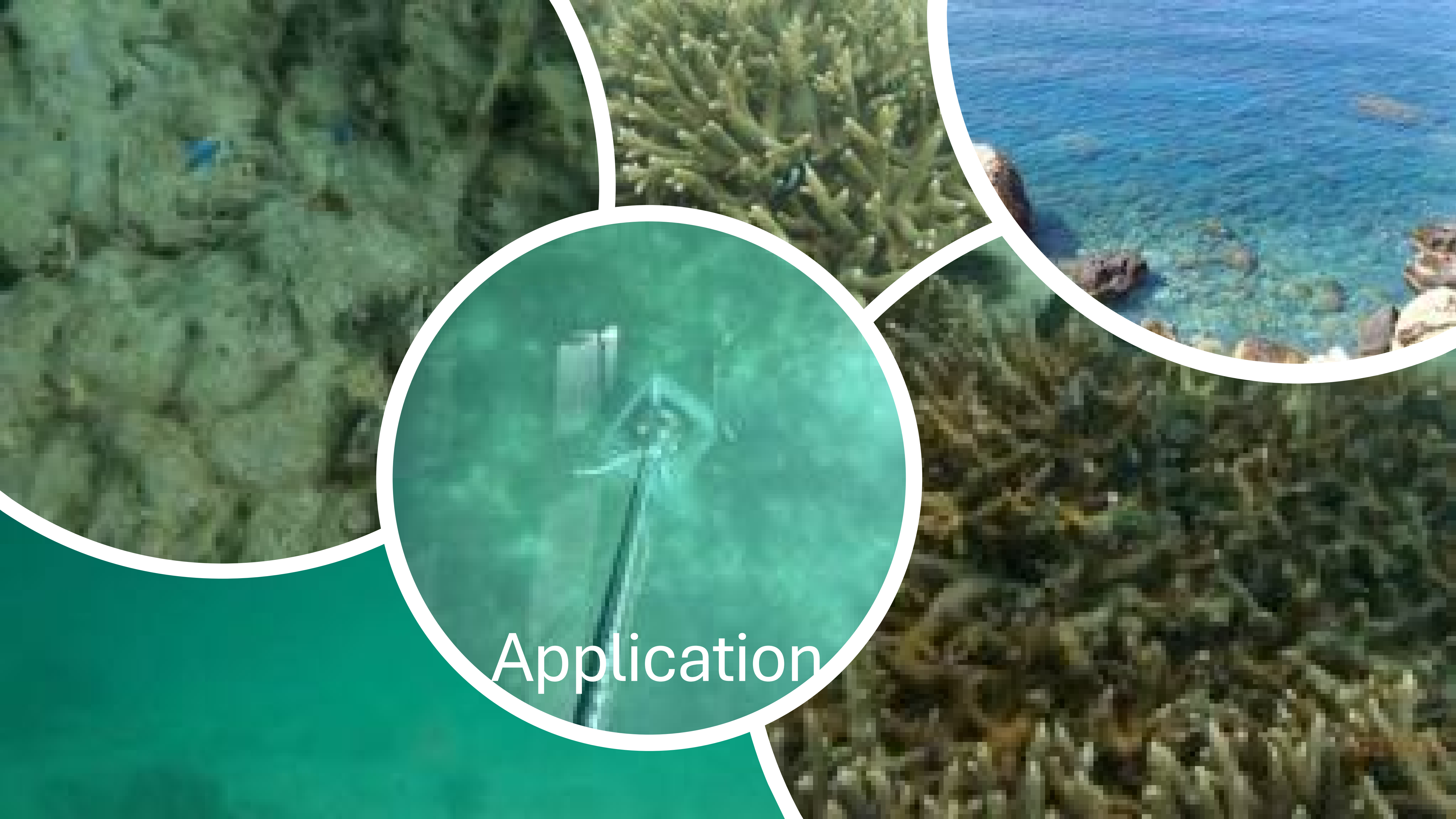
Richardson et al. 2024



Giardino et al. 2015, 2016






Application

Shallow-tropical benthic habitat mapping from in situ and satellite observations in Lampi Island Marine National Park

OIKOS

MOECAF

Cooperazione Italiana allo Sviluppo

Project: Enforce local capacities for the Environmental Conservation and Tourism Development in the Myeik Archipelago (COAST)

Period: 2014-2017

Sector: Natural Resources

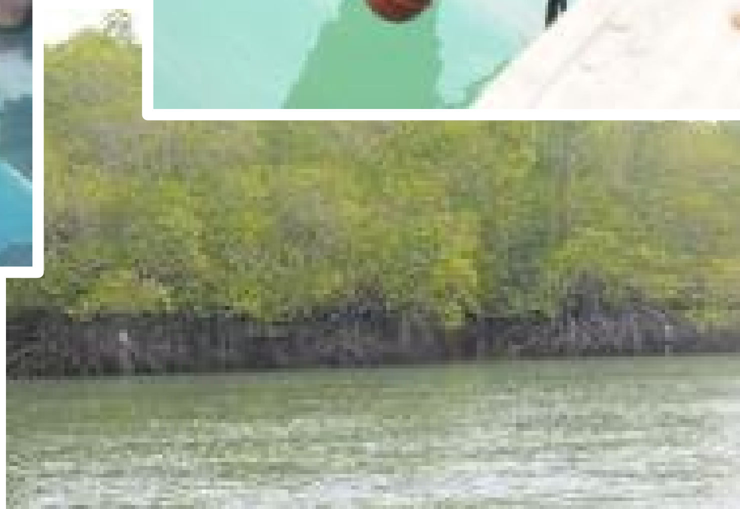
Country: Myanmar

Partner: Nature and Wildlife Conservation Division (Forest Department – Ministry of Environmental Conservation and Forestry)

Stydy area and field campaign (Feb 28 – Mar 4, 2015)

152 measurement points

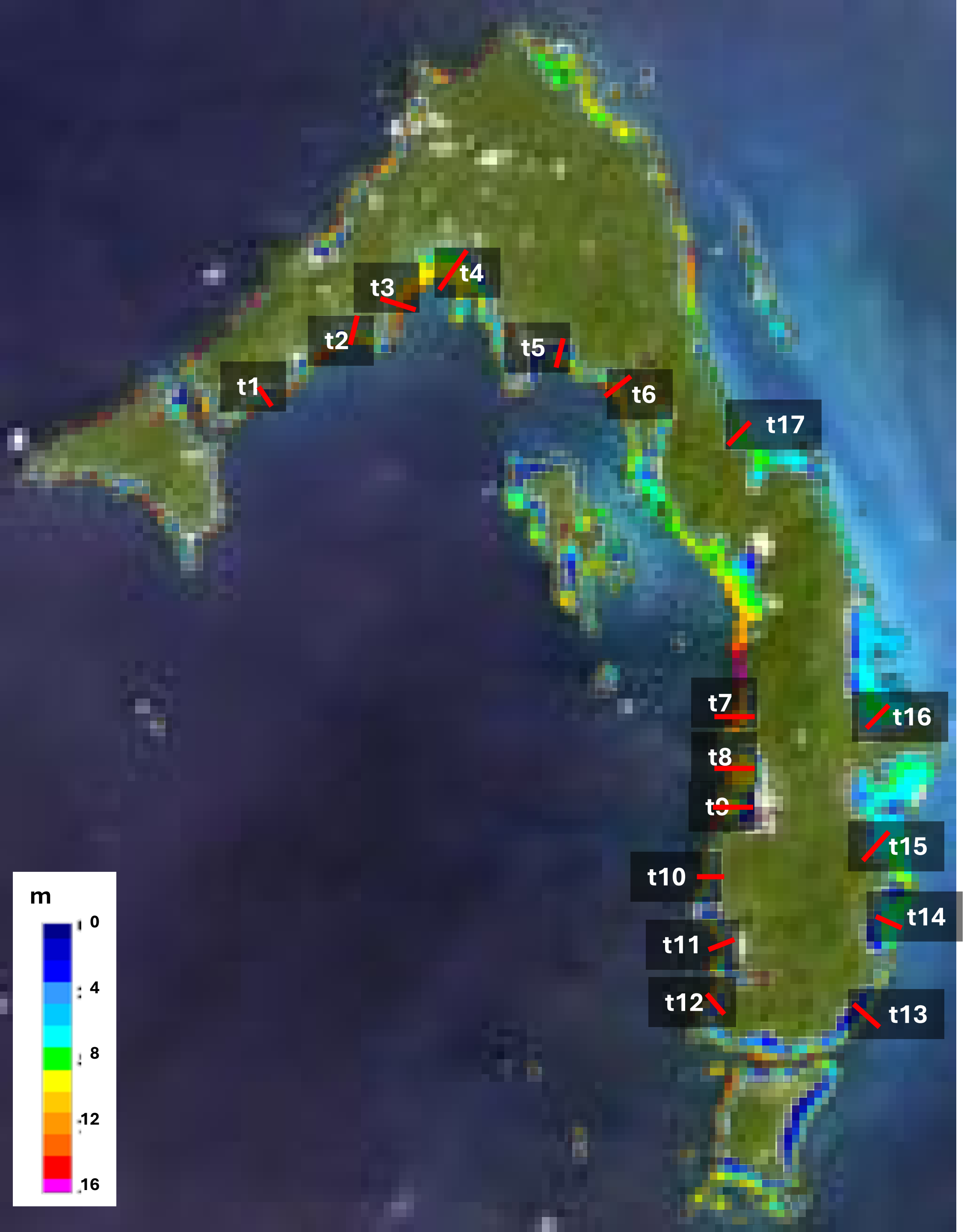
- Bottom cover typology
- Bottom depth
- Water quality parameters
- Water Reflectance

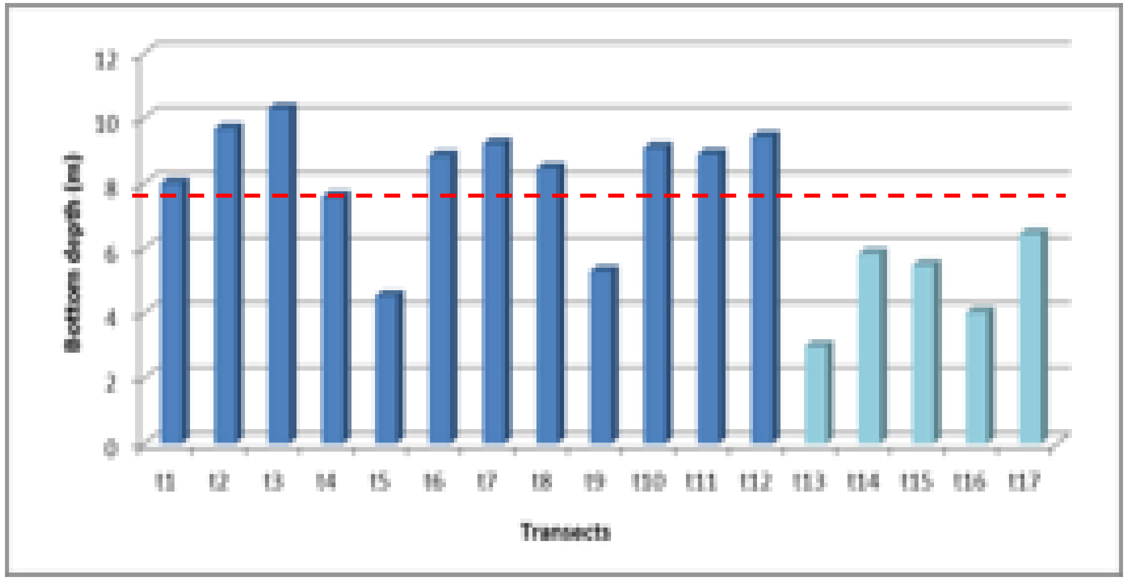


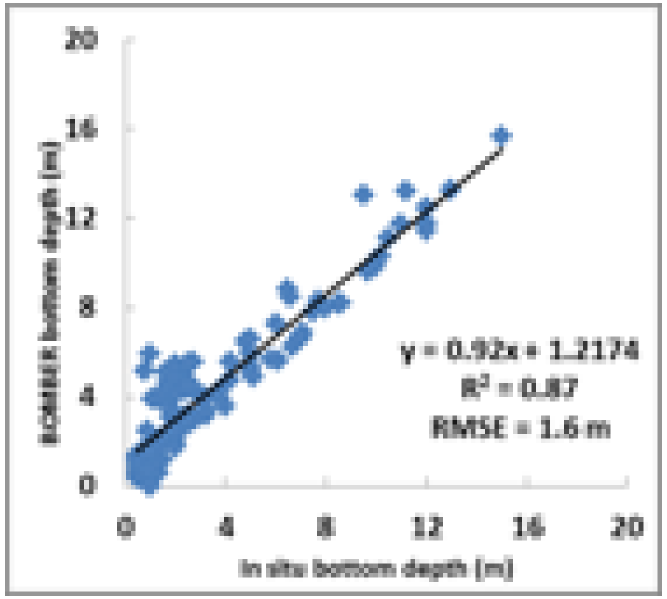
152 stations

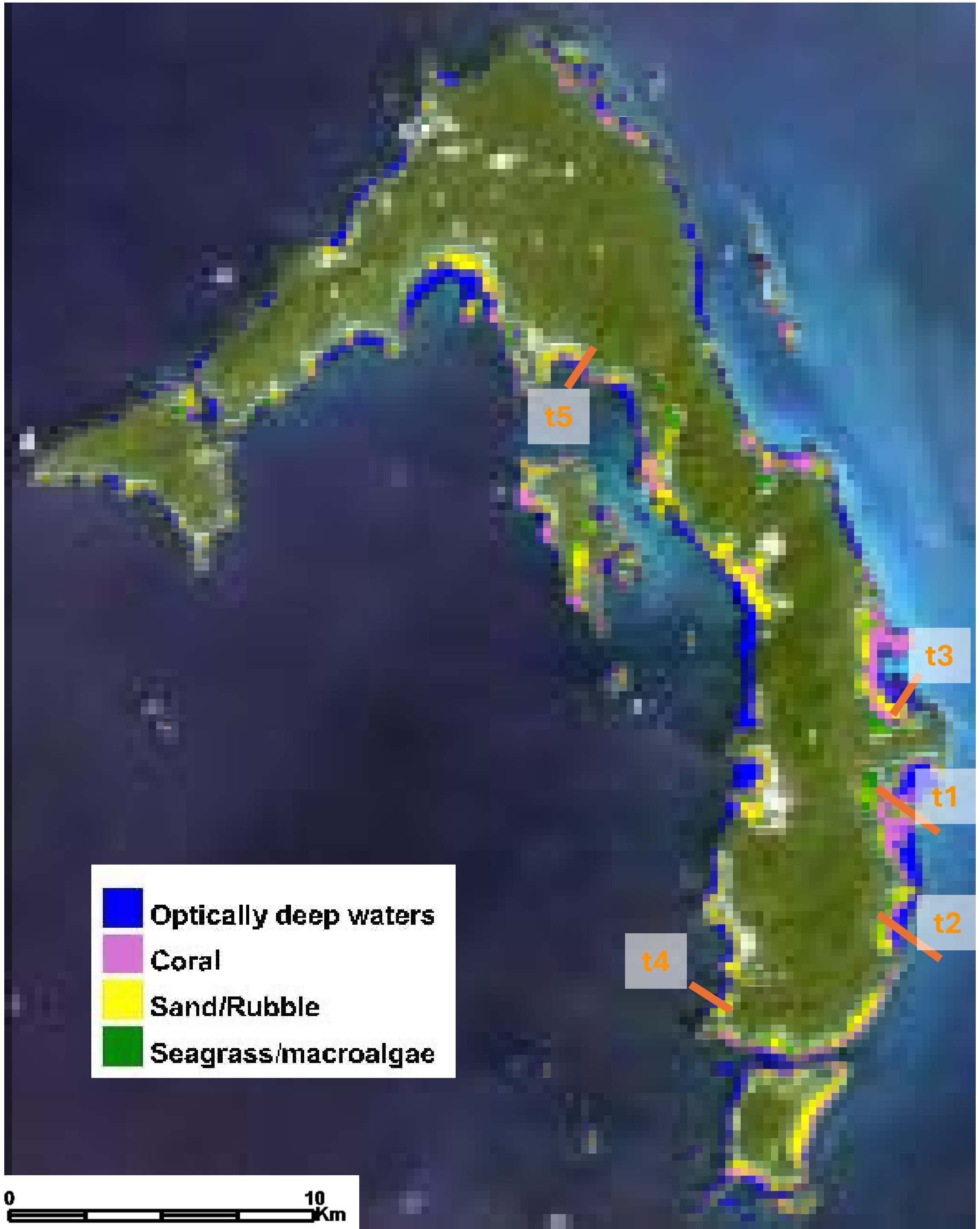
Mangroves forests

Match-up with with L8-OLI (28/02/2015)


t1
t2
t3
t4
t5
t6
t7
t8
t10
t11
t12
t13
t14
t15
t16
t17
m
0
4
8
12
16


Bottom depth (m)
0
2
4
6
8
10
12
Transects


y = 0.92x + 1.2174
R^2 = 0.87
RMSE = 1.6 m
In situ bottom depth (m)
0
4
8
12
16
20



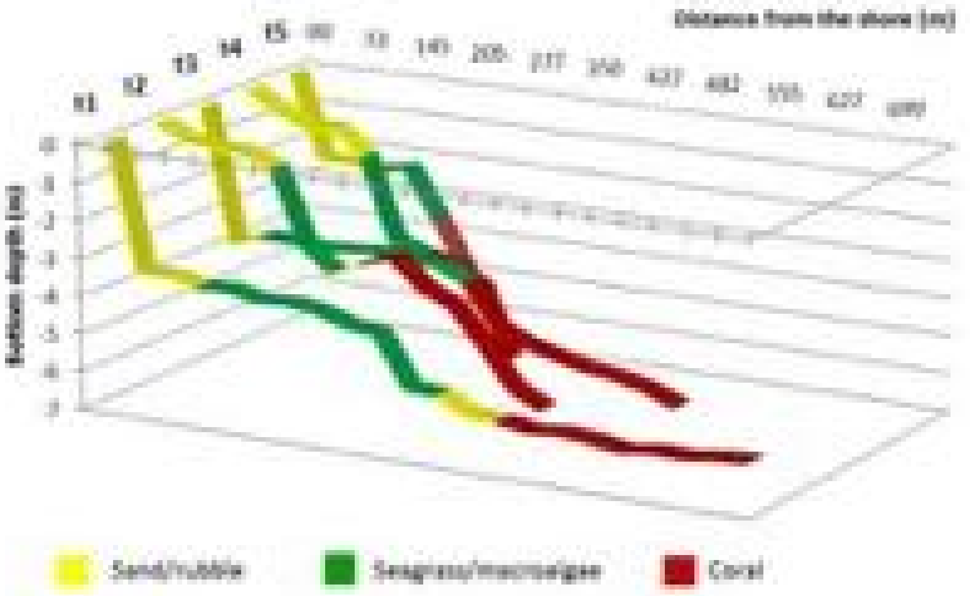
Landsat-8

	Ground truth: Optically deep waters	Ground truth: Coral	Ground truth: Sand/rubble	Ground truth: Seagrass/ macroalgae	Total	User accuracy
Image: O. deep Waters	40	10	7	2	59	68%
Image: Coral	1	24	6	0	31	77%
Image: Sand/rubble	0	6	46	1	53	87%
Image: Seagrass/macroalgae	0	1	2	3	6	50%
Total	41	41	61	6	149	
Producer accuracy	98%	59%	75%	50%		

Overall accuracy	76%
Cohen's Kappa	0.65

Substrates spatial distribution - 2015

Class	Optically deep Waters	Coral	Sand/ Rubble	Seagrass/ macroalgae
Area (km^2)	25.8	14.2	29.7	6.2



https://allencoralatlas.org/

Submerged vegetation and bathymetry mapping using EnMAP image of the Gulf of Oristano (Italy)

Study area

- The coastal areas of the Gulf of Oristano host seagrass habitat colonised mainly by *P. oceanica,* followed by *Cymodocea nodosa*
- The Gulf of Oristano is vulnerable to both natural and anthropogenic hazards. The main activities are fishing, shellfish farming, and other economic activities related to the production of local specialties (eg *bottarga)*

Submerged habitat

- The coastal areas of the Gulf of Oristano host seagrass habitat colonised mainly by *P. oceanica*, followed by *Cymodocea nodosa*
- The Gulf of Oristano is vulnerable to both natural and anthropogenic hazards. The main activities are fishing, shellfish farming, and other economic activities related to the production of local specialties (eg *bottarga)*

- *Posidonia oceanica*, an indigenous plant in the Mediterranean Sea, dominates seagrass meadows throughout the Italian shores.

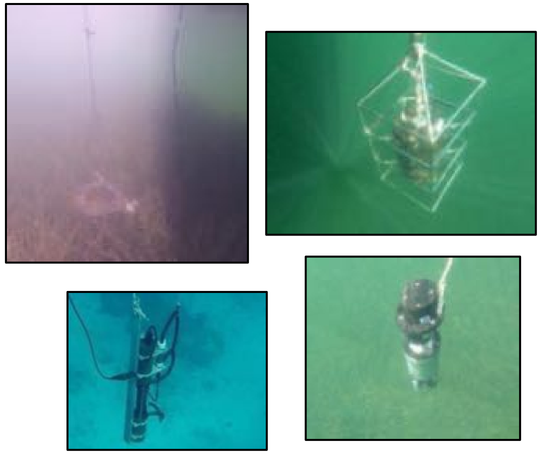
- Due to the sensitivity of *P. oceanica* to environmental changes, the study of seagrass cover and its evolution over time can help conservation and management initiatives on maintaining the biodiversity of the ecosystem.

Field campaign

Radiometric measuraments (WISP-3, Satlantic and Full range Spectra Evolution)

GPS localization of different substrates

Water samples for lab analysis (abs, Chl-a, TSM, CDOM)

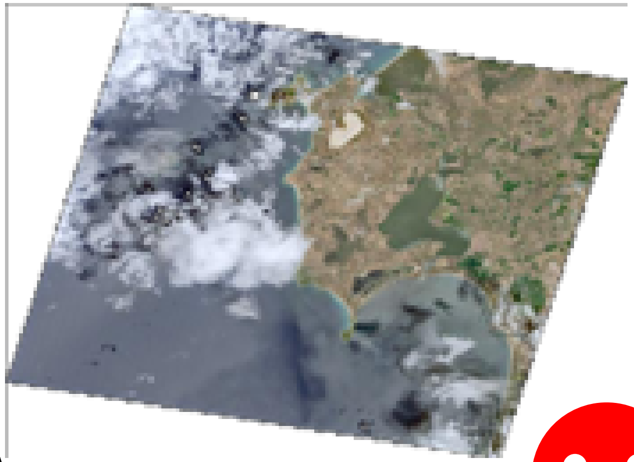


Water column depth, Z90, Fluorimeter, back-scattering

EnMAP data-set

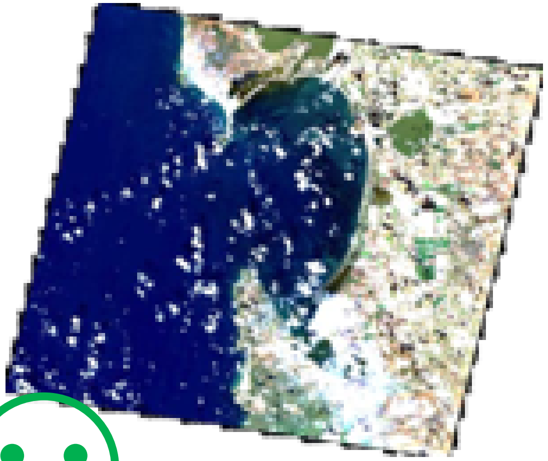
11/07/2024

14/07/2023



22/07/2023

26/05/2024

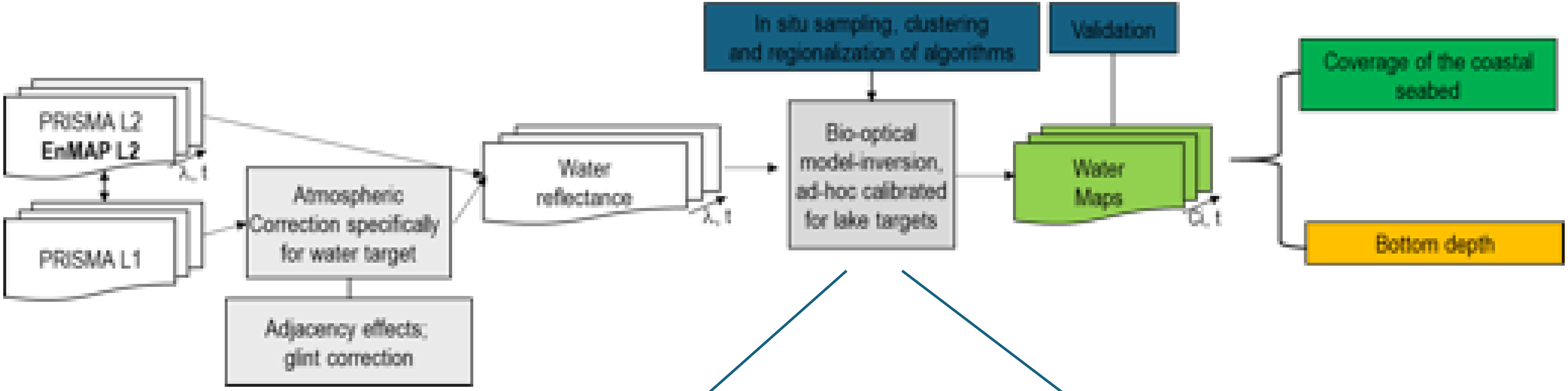


25/05/2024

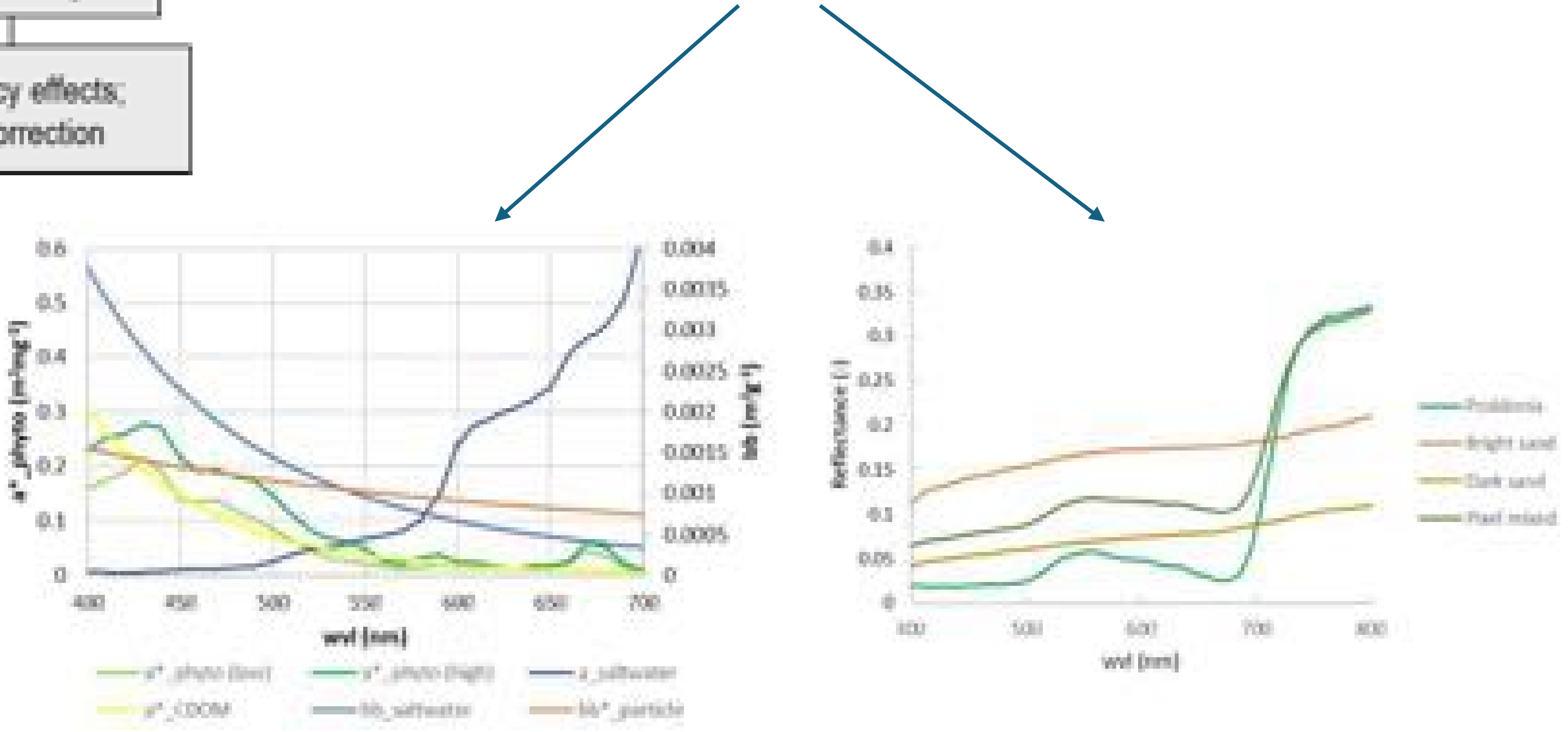
29/05/2024

18/09/2024

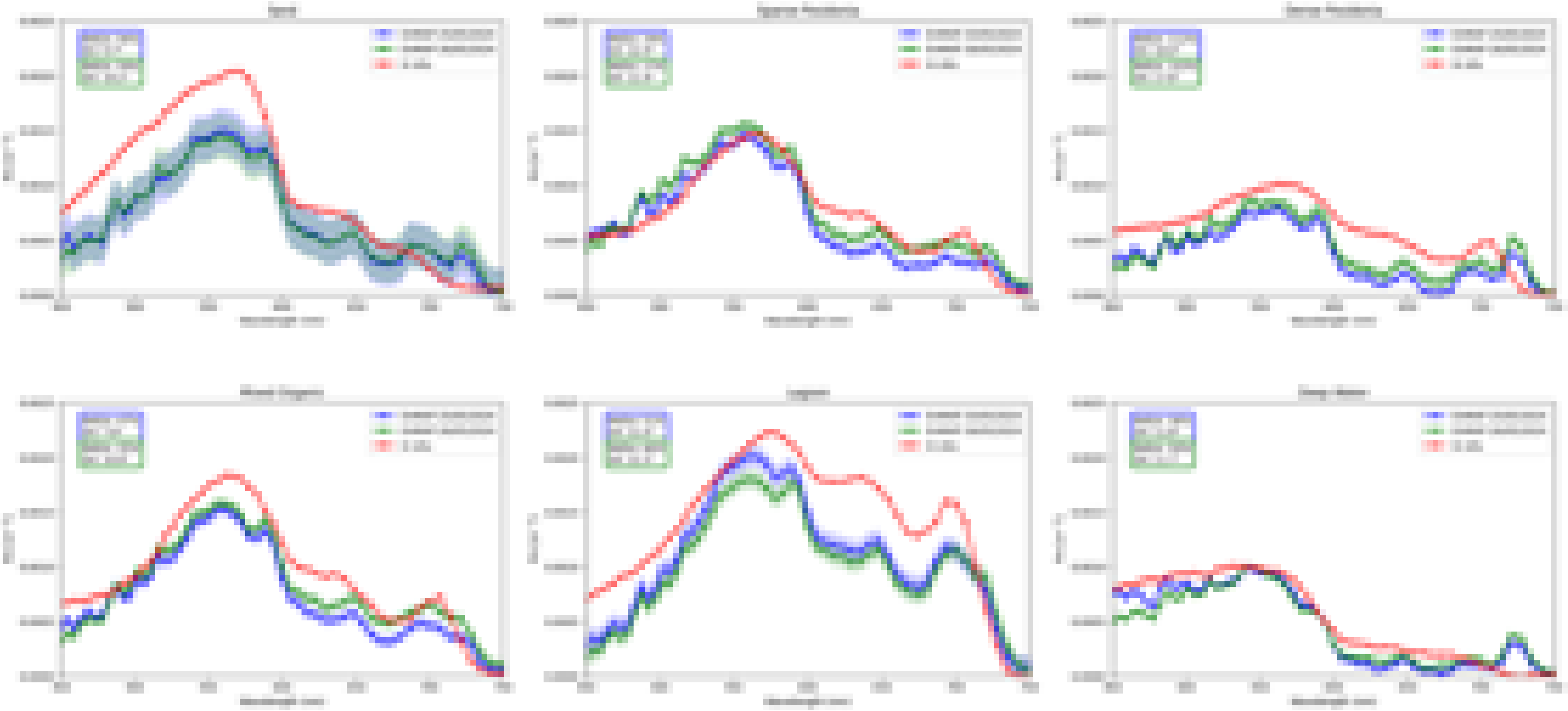
Methodology



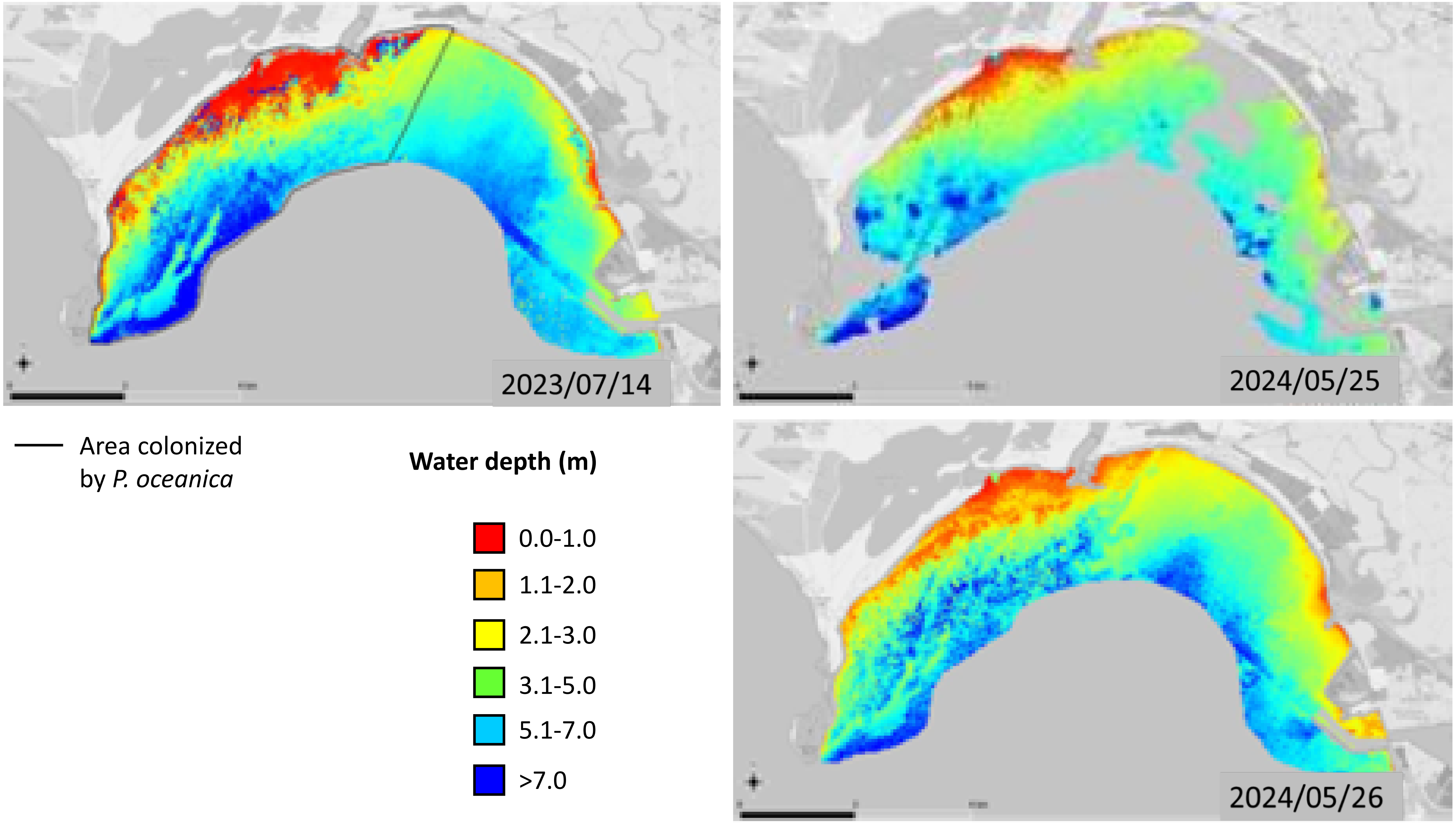
Chl-a (mg/m^3)= 0.4 (±0.3)
TSM (g/m^3)= 1.2 (±1.5)
CDOM (m^{-1})= 0.1 (±0.1)



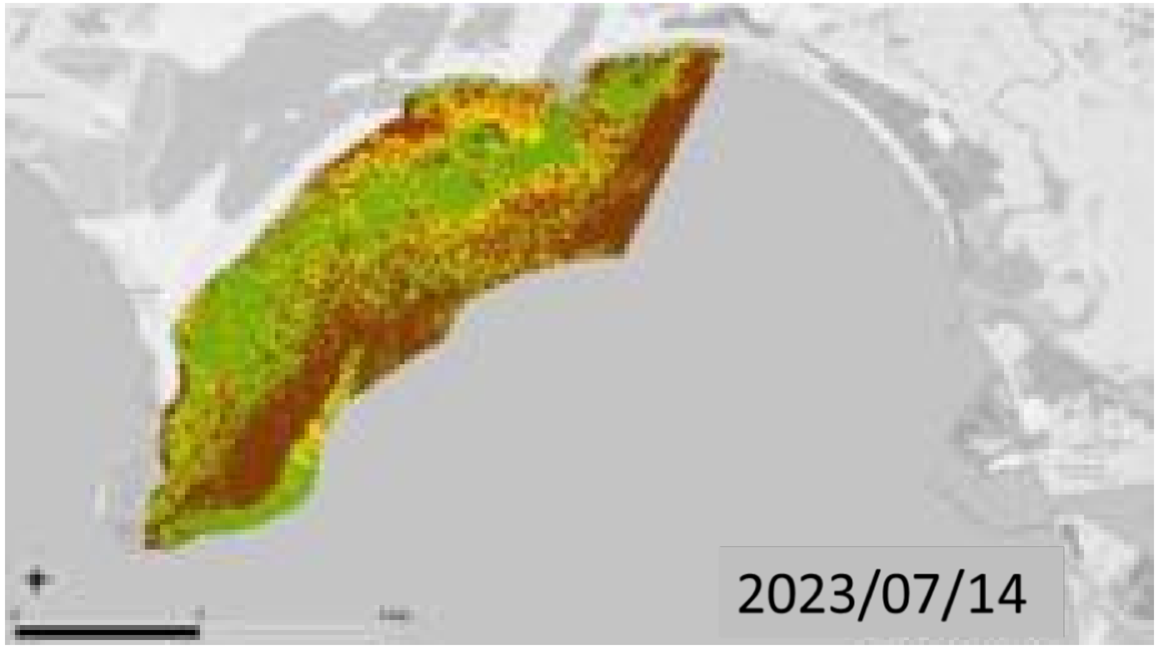
Rrs match-up (25-26 may 2024)

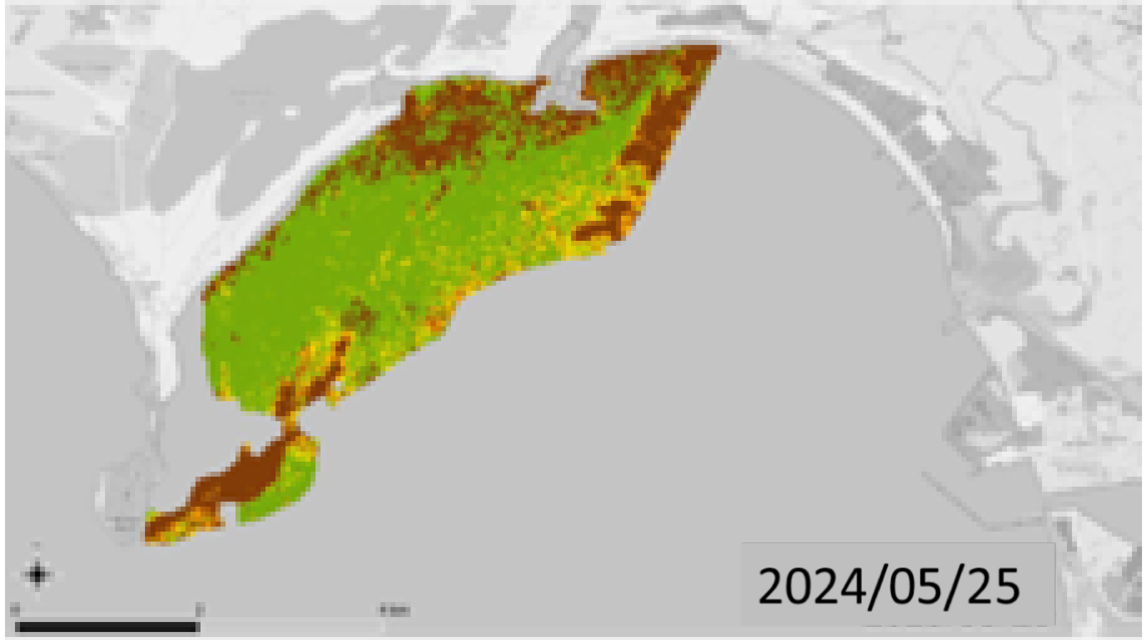


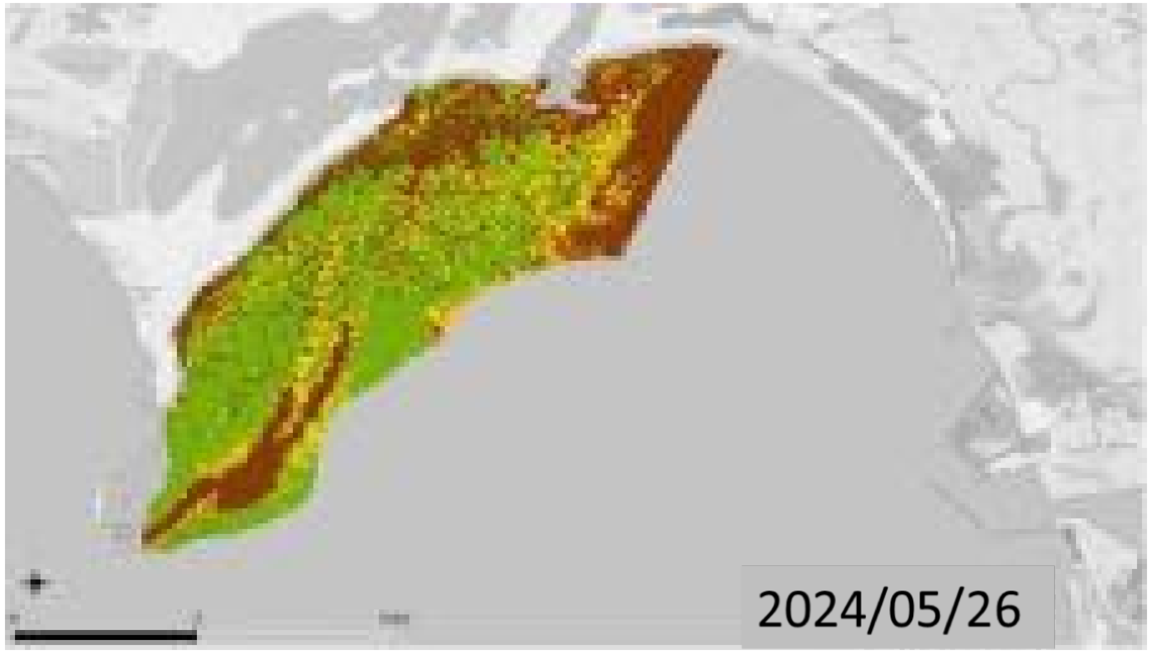
Products


2023/07/14
2024/05/25
2024/05/26
Area colonized by *P. oceanica*
Water depth (m)
0.0-1.0
1.1-2.0
2.1-3.0
3.1-5.0
5.1-7.0
>7.0

Products



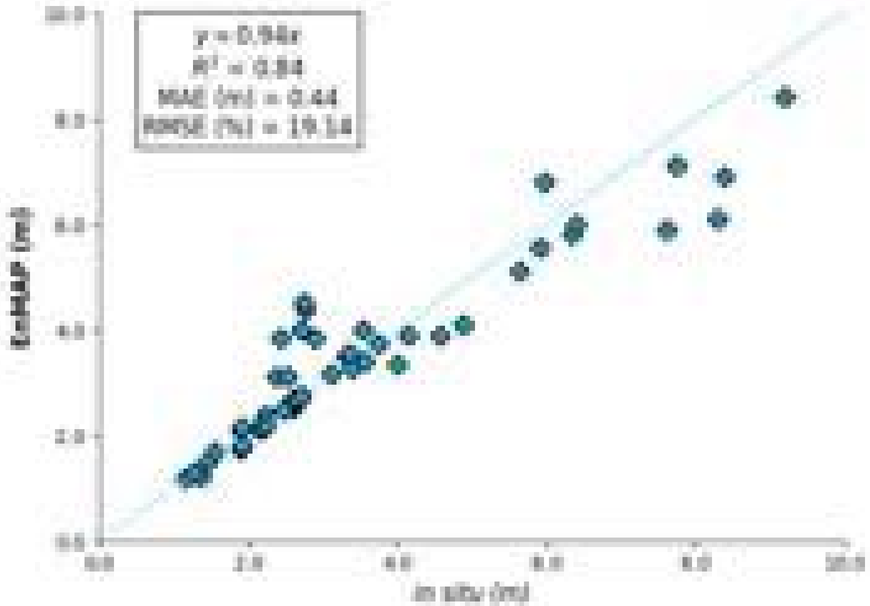




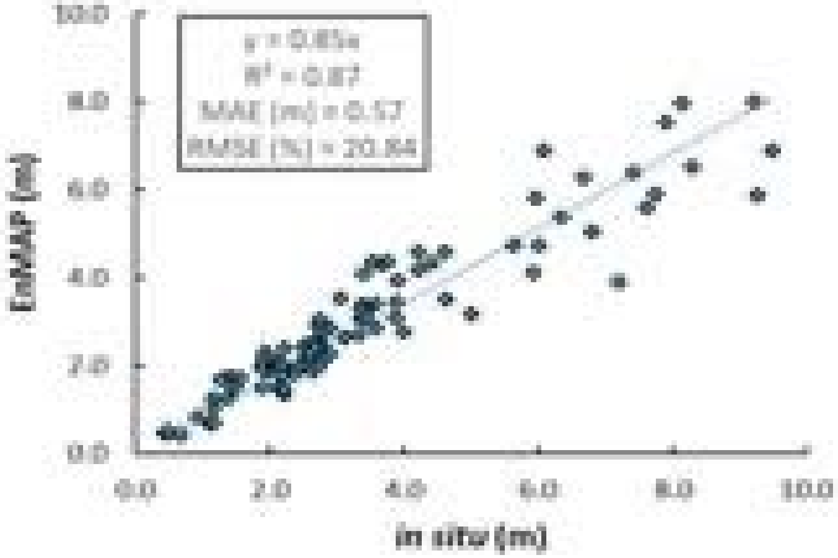
- Bare sediment (sand) with phanerogams (*Posidonia oceanica*) **<30%**
- Mixed substrate with sand and phanerogams (*Posidonia oceanica, Cymodocea* spp.) between **30% - 50%**
- Substrate with phanerogams (*Posidonia oceanica*) **>50%**

Product validation

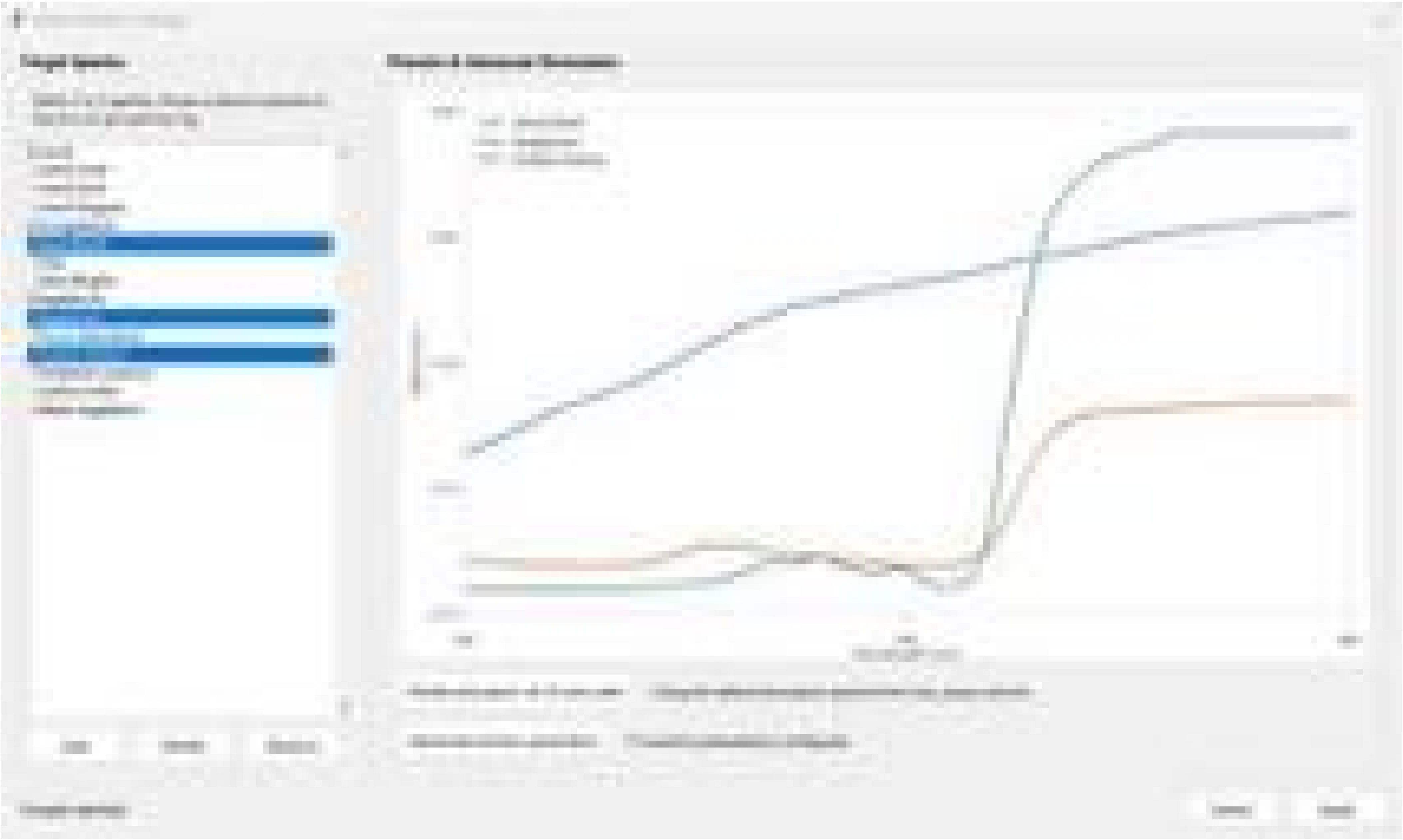
EnMAP-Bomber 25 May 2024						
		Posidonia	Sand	Mixed organic	Deep Water	TOT
in situ	Posidonia	19				19
	Sand	3	11			14
	Mixed organic	3	1	6		10
	Deep Water				6	6
	TOT	25	12	6	6	49
				Overall Accuracy		86%

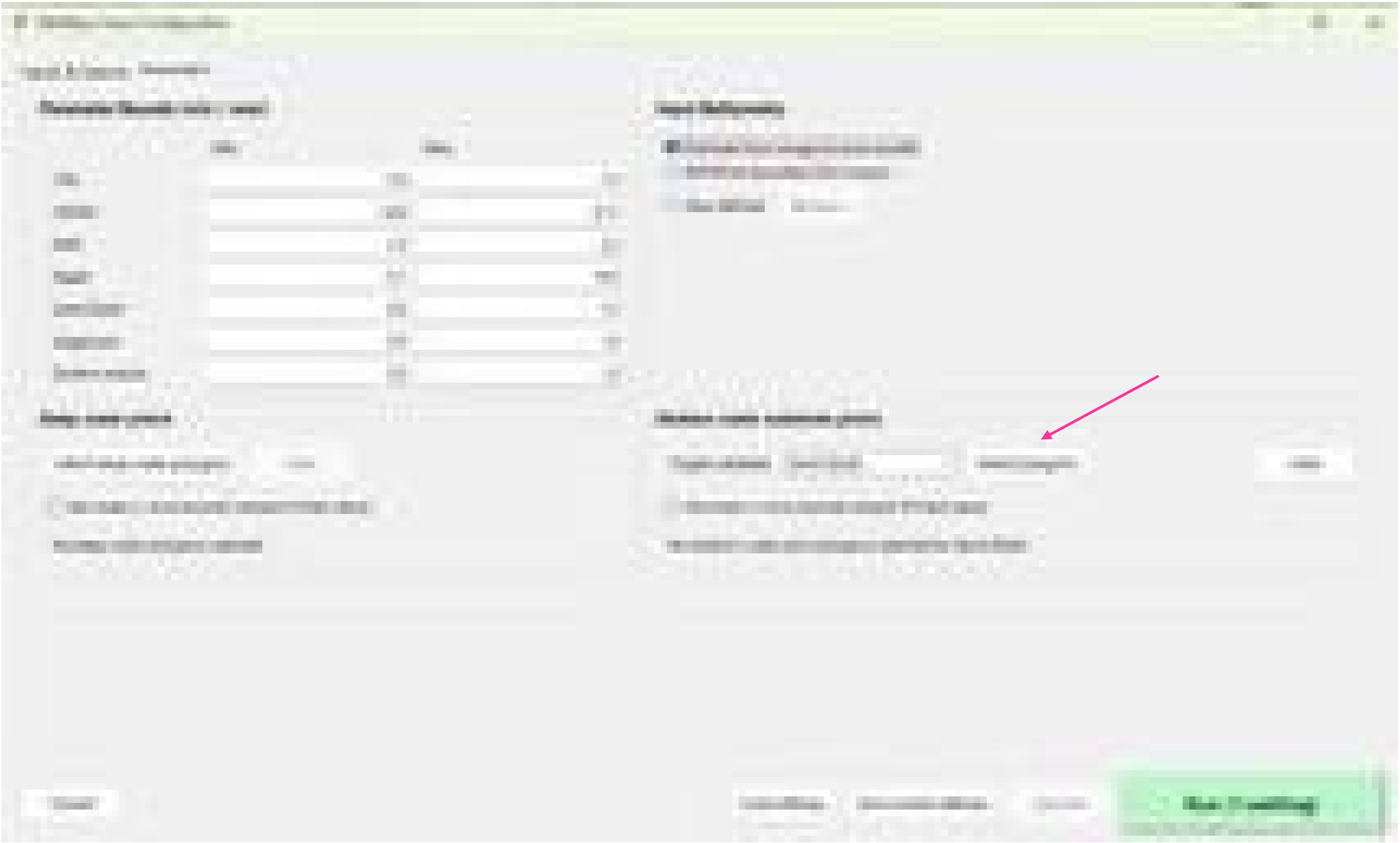


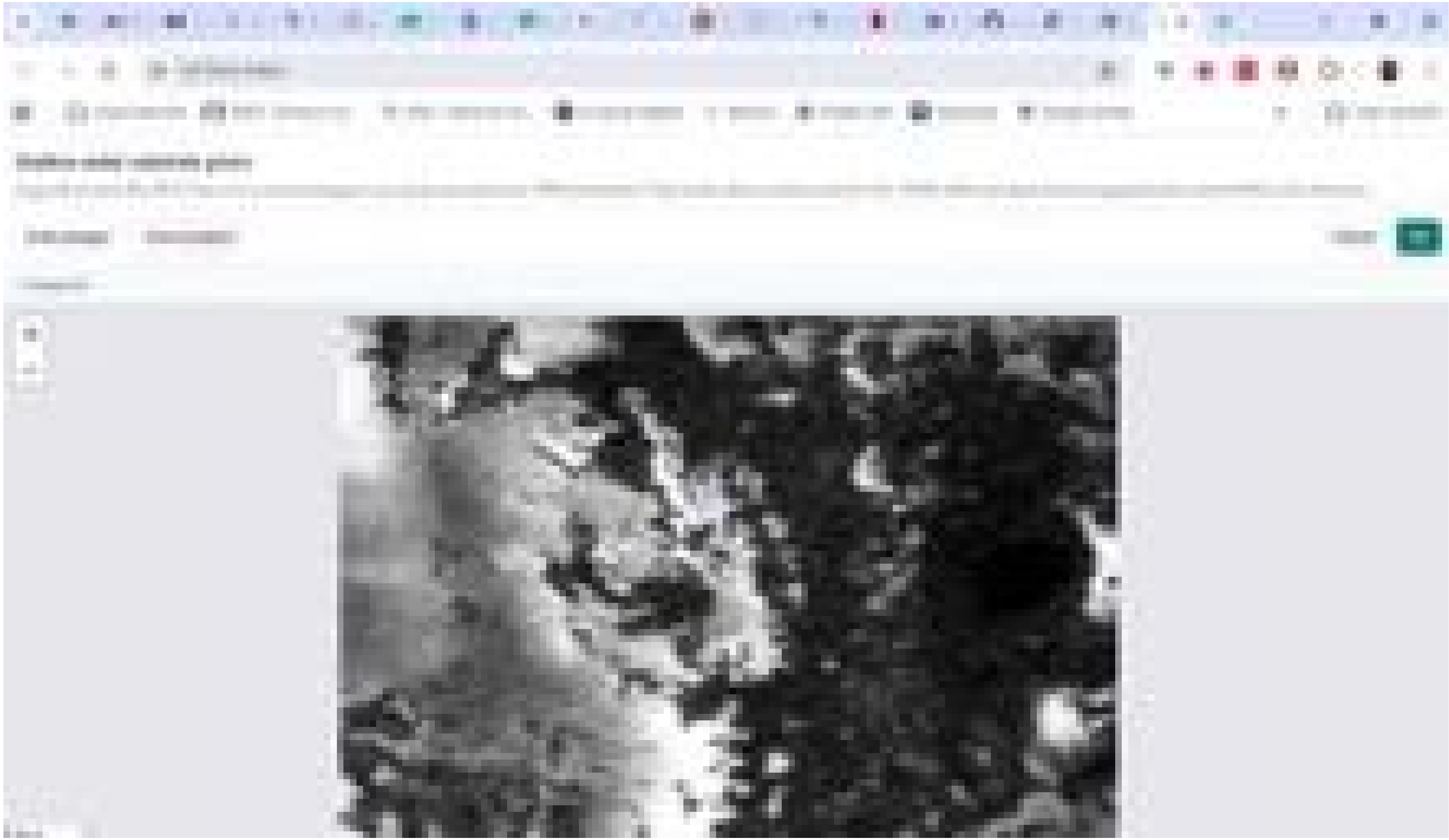
EnMAP-Bomber 26 May 2024						
		Posidonia	Sand	Mixed organic	Deep Water	TOT
in situ	Posidonia	16	2	2		20
	Sand		14	2		16
	Mixed organic	2	1	10		12
	Deep Water				8	8
	TOT	17	17	14	8	56
				Overall Accuracy		84.1%



SWAMpy v2026.04



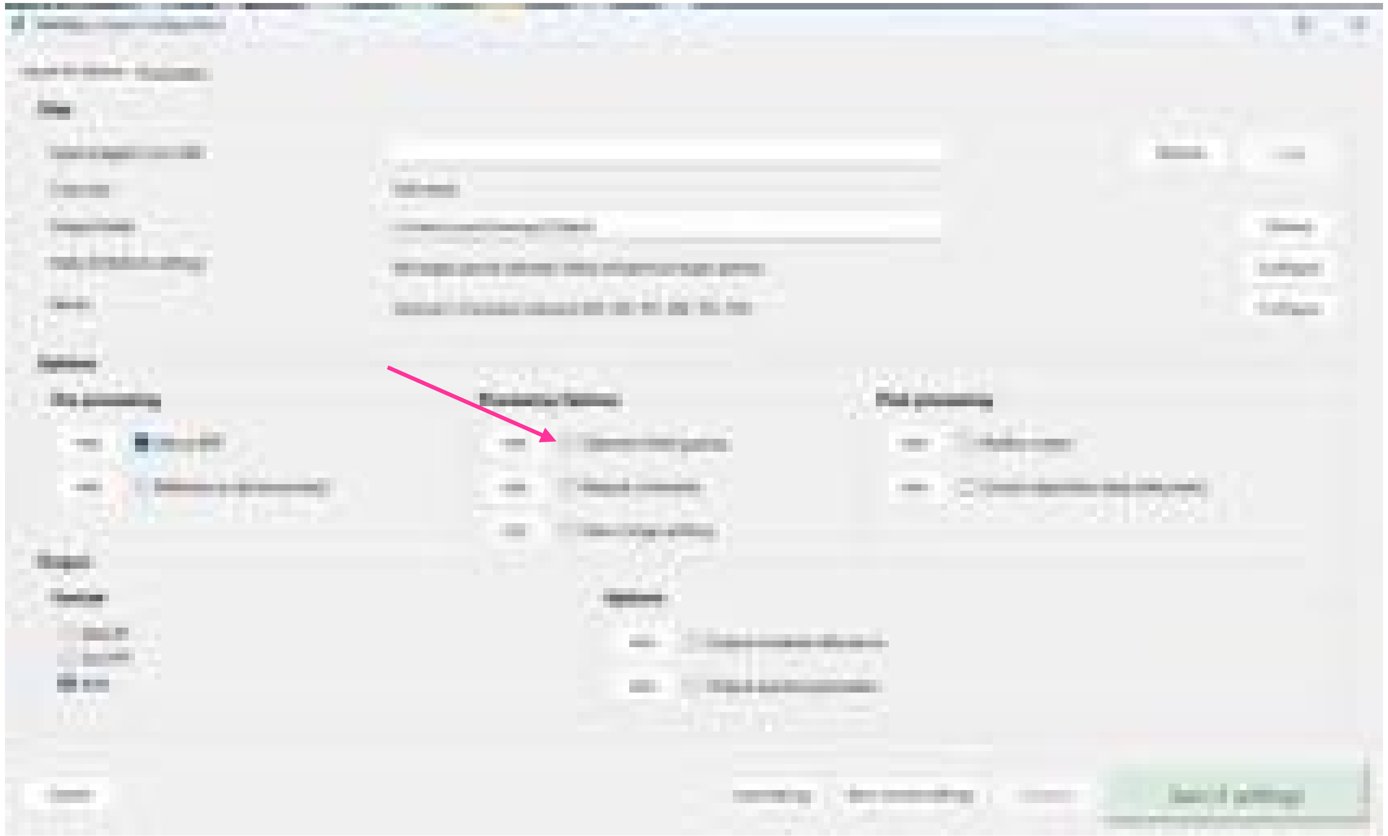




Optimization schemes highly dependent on initial guesses

- Default: Initial guess for each parameter, set to the median of its specified range

- Advanced option: pixel-wise initial guess selection (“optimise initial guesses”)



Optimise initial guesses

Ranges defined by the user

z	25% Mean 75%
x_{ij}	25% Mean 75%
[Chl]	25% Mean 75%
[CDOM]	25% Mean 75%
[NAP]	25% Mean 75%
(optional)	Min Max

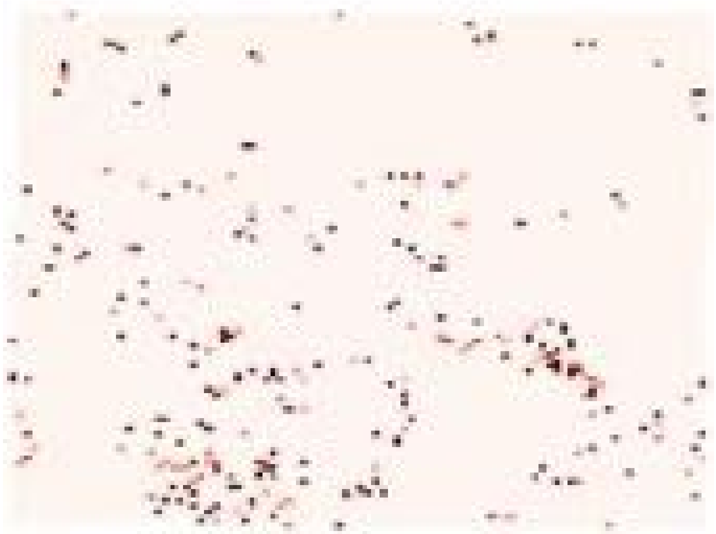
Forward model for all possible combinations 3^5

5^5 combinations

For each pixel, difference between satellite Rrs and forward modeling ➔min value, initial guesses for this pixel

Initial guess depth

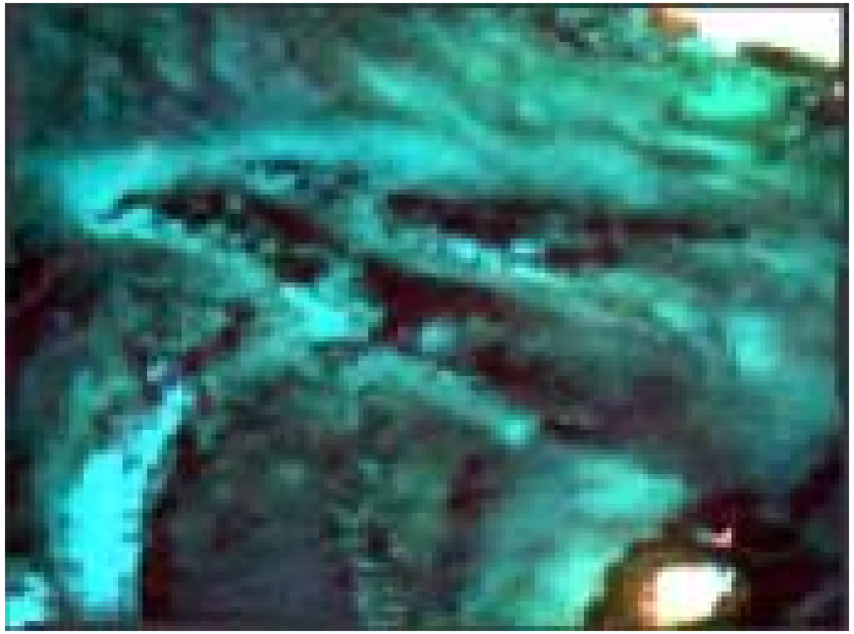
Initial guess vegetation

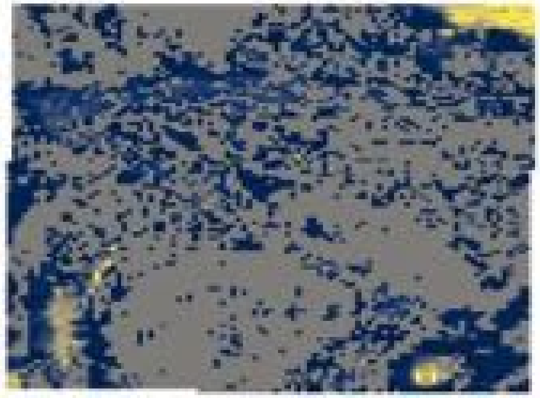


- Rerun the algorithm in suspicious pixels

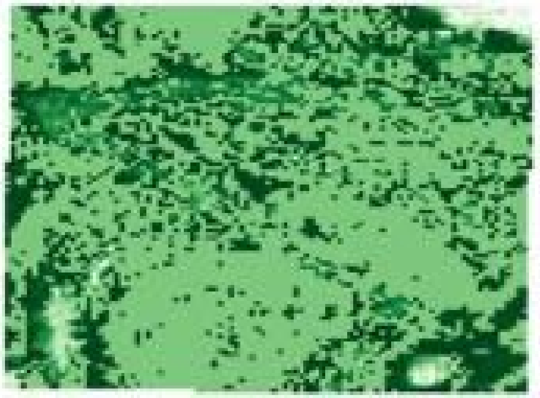
Failures in retrievals in very dark areas

RGB





Sand

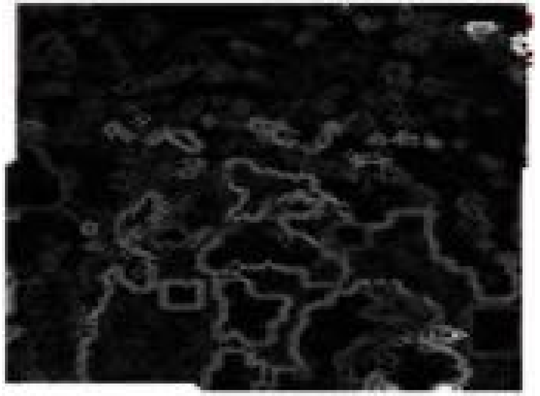


Vegetation

Depth

Identification of suspicious pixels

- Detection of sharp slopes in depth, not expected for natural shallow waters
- ➔ SDI < 1 **AND** steep slopes with the pixel neighbor ➔ boundary pixels



Boundary pixels

From boundary pixels, suspicious pixels are identified as those who share similar SDI and depth as boundaries

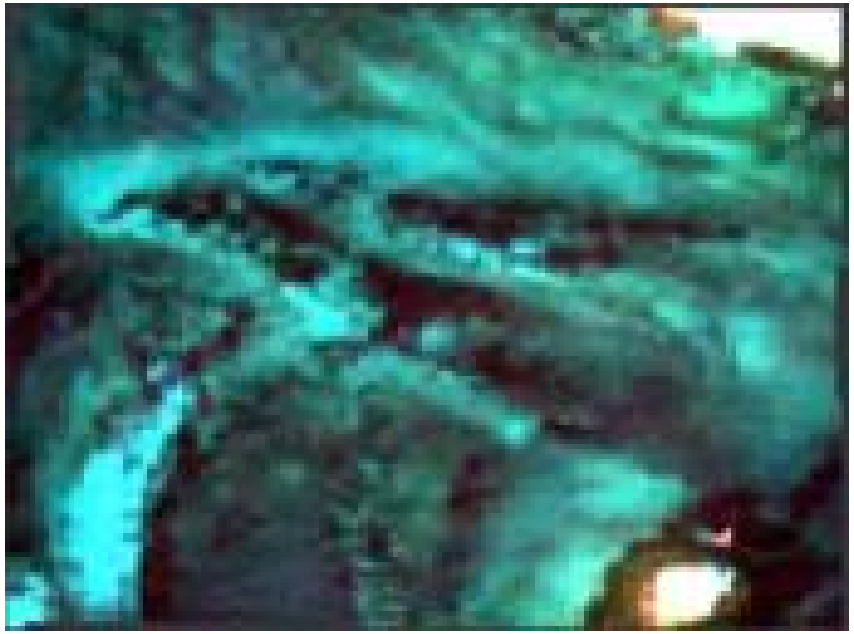
Suspicious pixels

- For suspicious pixels, SWAMpy is re-ran using:

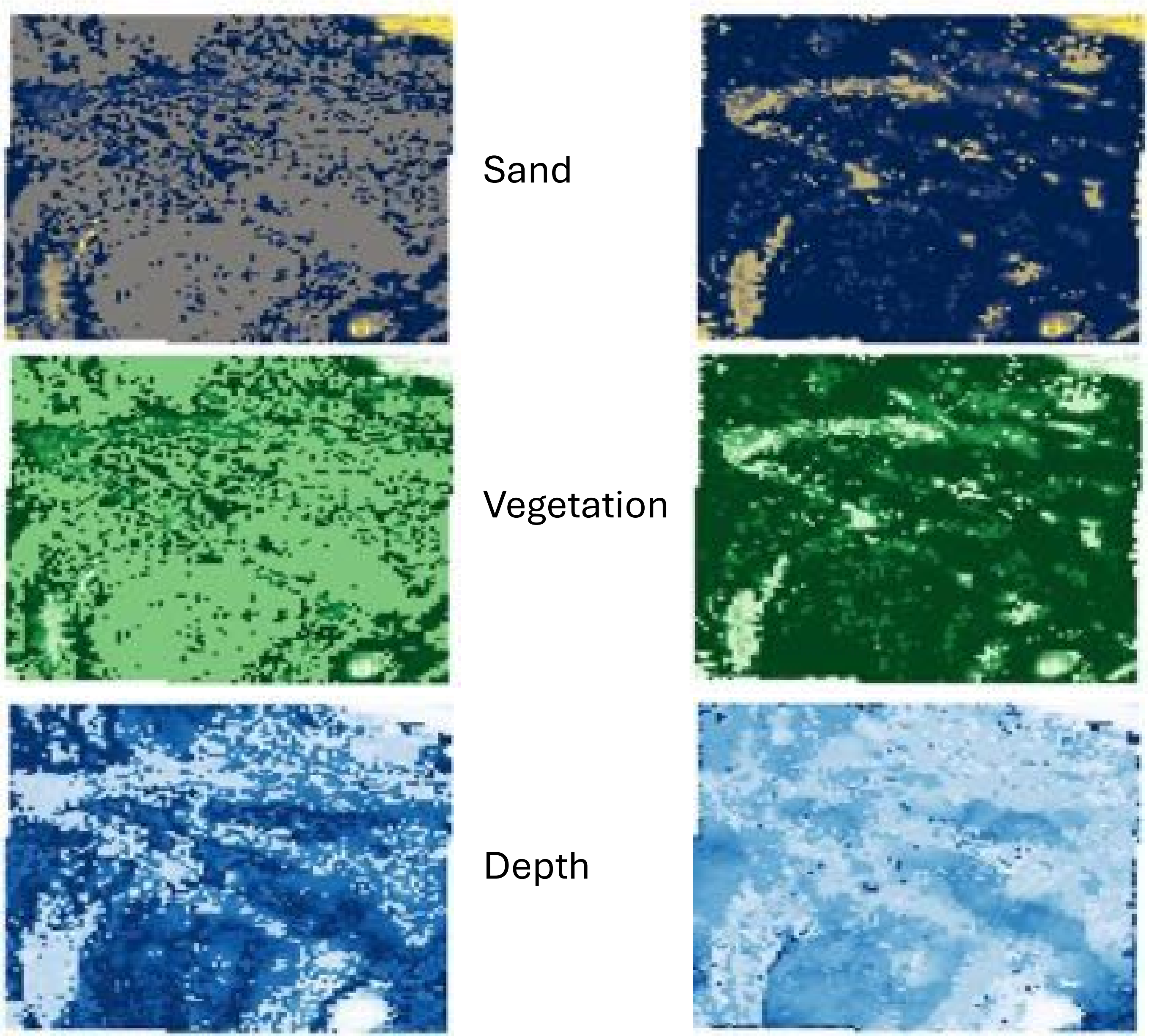
 - initial guesses of depth, Chl, CDOM and NAP: results of the closest confident pixel

- Range of variability (except for substrate) ± 10% of the initial guess

RGB



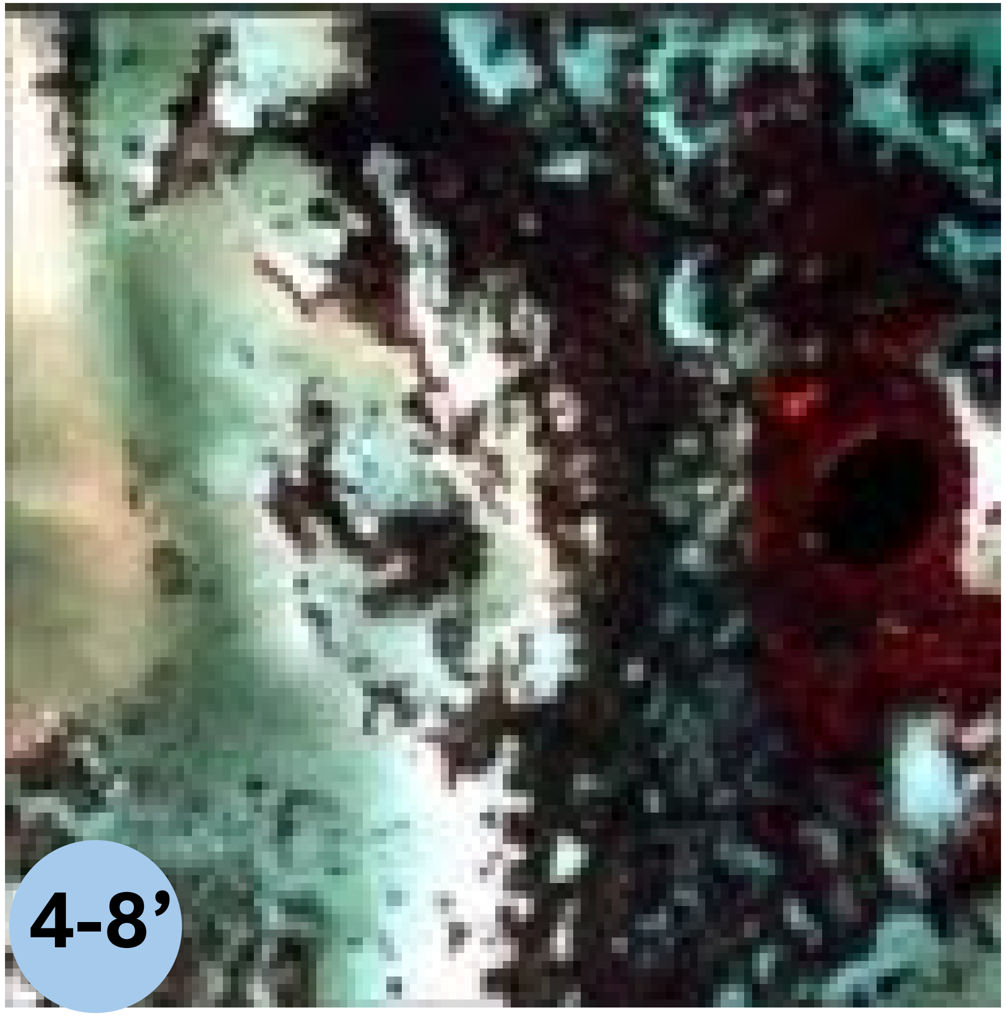
Before **After**



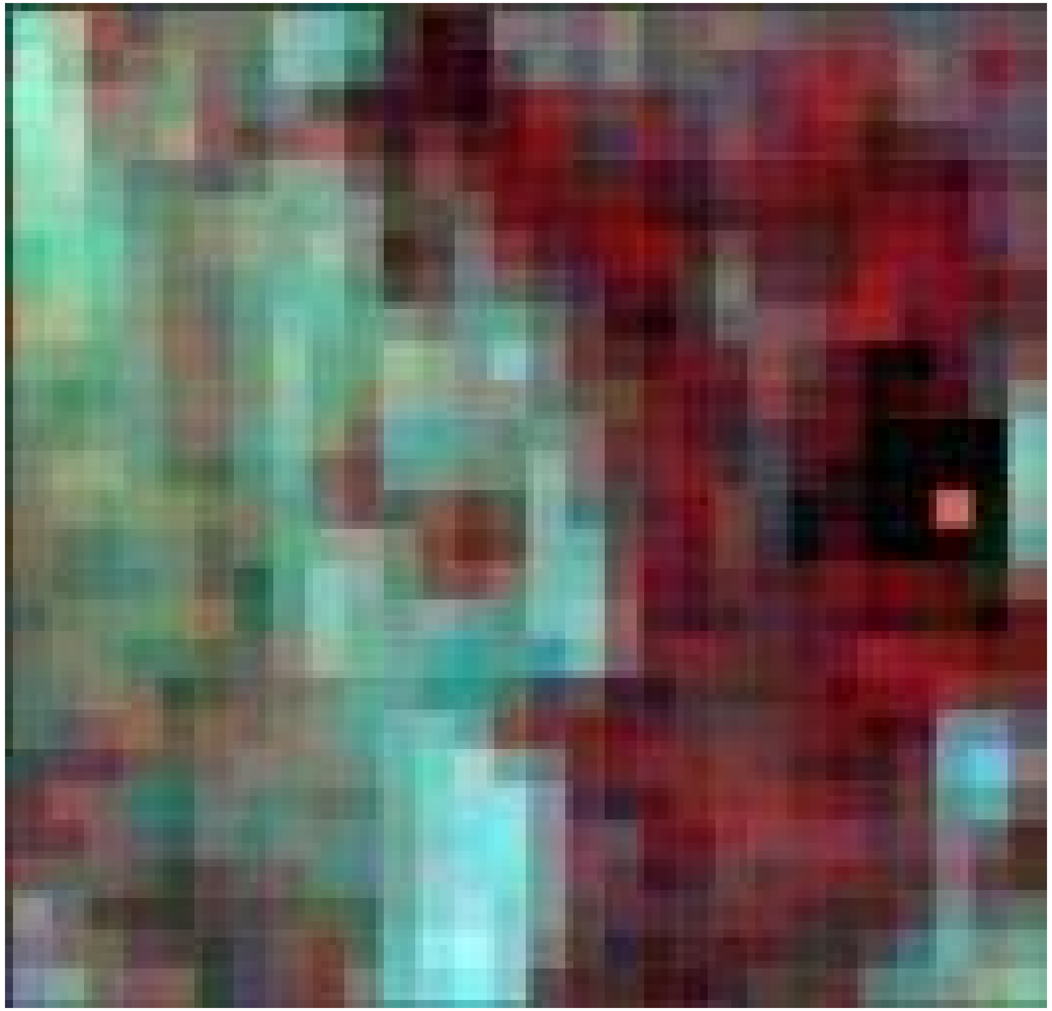
Qualitative evaluation of changes in optimization settings

Evaluate the impact of spatial and spectral information

WorldView3: 2 m pixel



Sentinel2: 10 m pixel

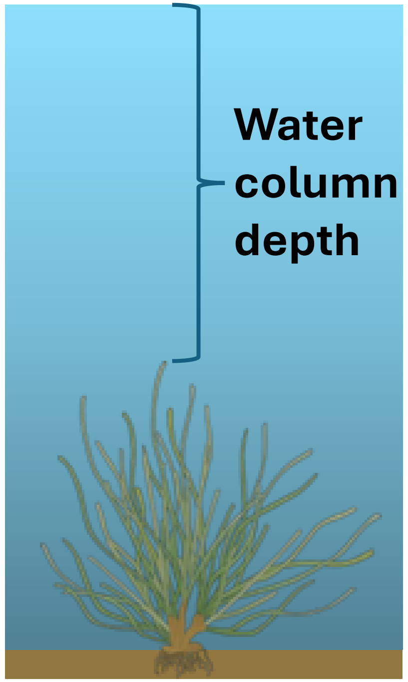


4

4-8’

Evaluate the impact of using bathymetry as input

Depth = water column depth



1 13’

In your console:

```
cd Swampy
conda activate Swampy2026
python launch_swampy.py
```

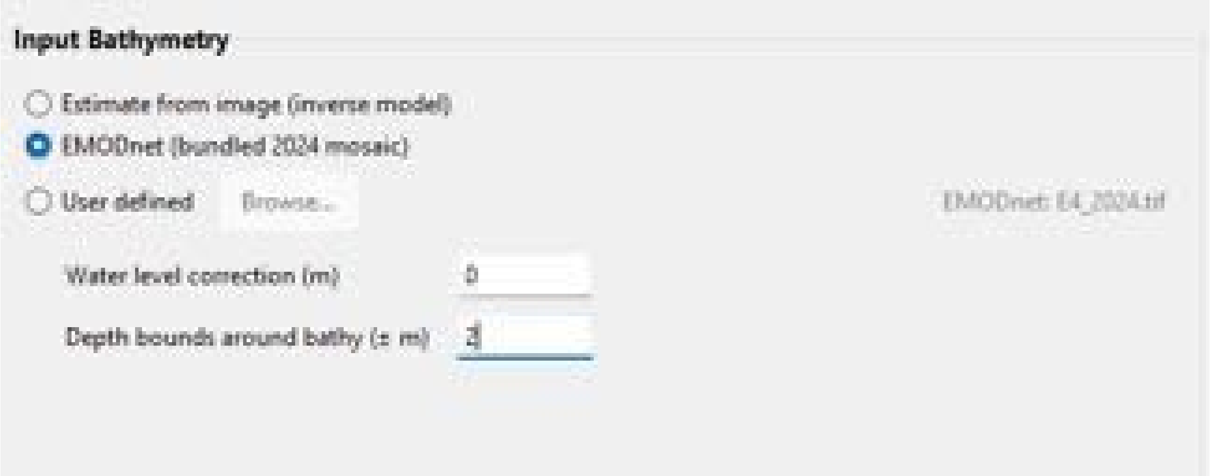
Common parameters

- Image input: S2B_MSI_2025_09_04_10_18_09_T32TQR_L2W.nc
- Water & Bottom settings: Mixed vegetation and Sand (Dark)
- Sensor: Sentinel-2 (select Bands 443 to 704 nm)
- Parameters:
  - AOCs/IOPs: default

Different inputs

  - Only in one of the runs, «Input Bathymetry», EMODnet

Attention to regions with high tide coefficients!



Questions to guide interpretation

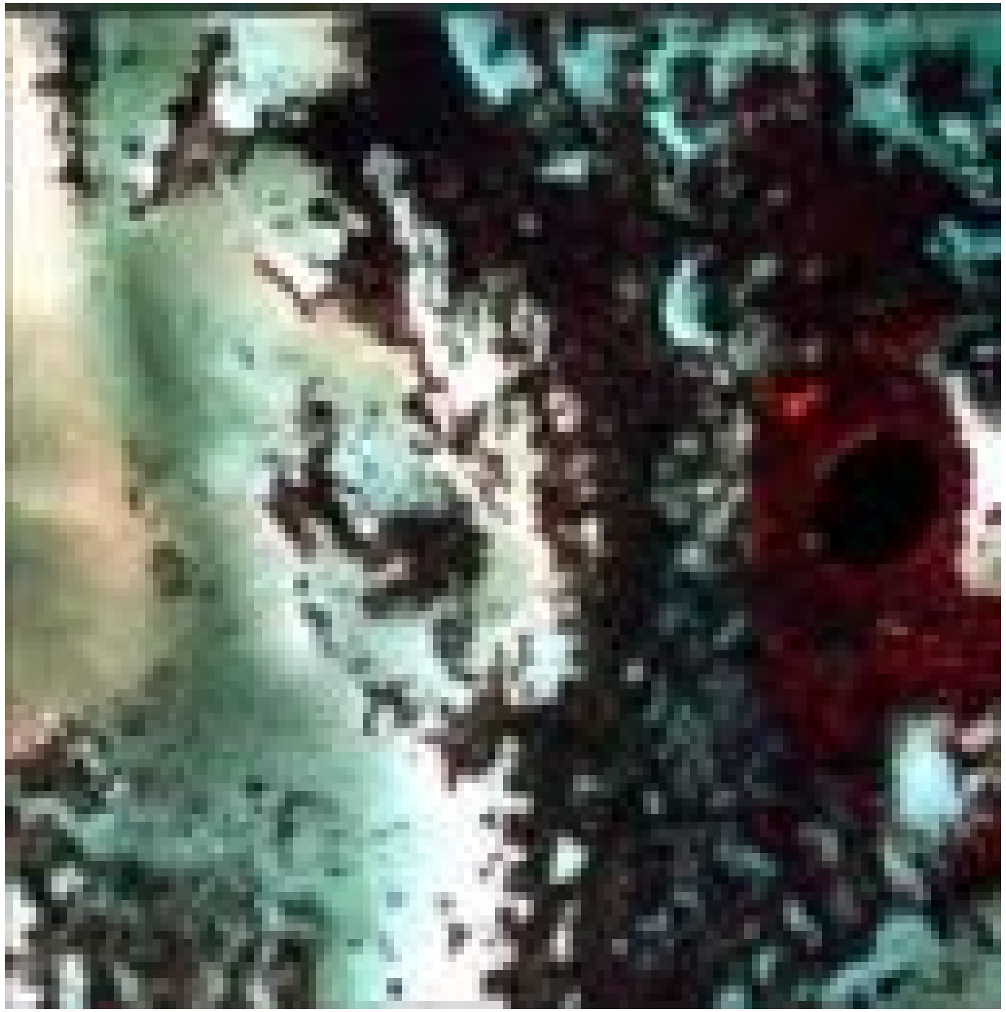
- Using EMODnet bathymetry as a reference dataset, how accurately does the model retrieve bathymetry?
- Do the use of bathymetry improve the bottom cover retrievals for sand and vegetation? If so, in which zones is the impact more evident?
- Are there any limitations inherent to using bottom depth as an input?

Evaluate the impact of bottom endmembers

2

4-8’

Evaluate the impact of bottom endmembers



In your console:

```
cd Swampy
conda activate Swampy2026
python launch_swampy.py
```

Common parameters

- Image input: WorldView3_2019_07_03_11_43_12_L2W.nc
- Sensor: Worldview-2 (select Bands 478 to 659 nm)
- Relaxed constraints; Info: standarise between 0 and 1
- Parameters:
  - AOCs/IOPs: depth: 10m. Leave the othes as default

Different inputs

- Water & Bottom settings:
  - Sand (dark)
  - *Sargassum*
  - *Zostera marina*

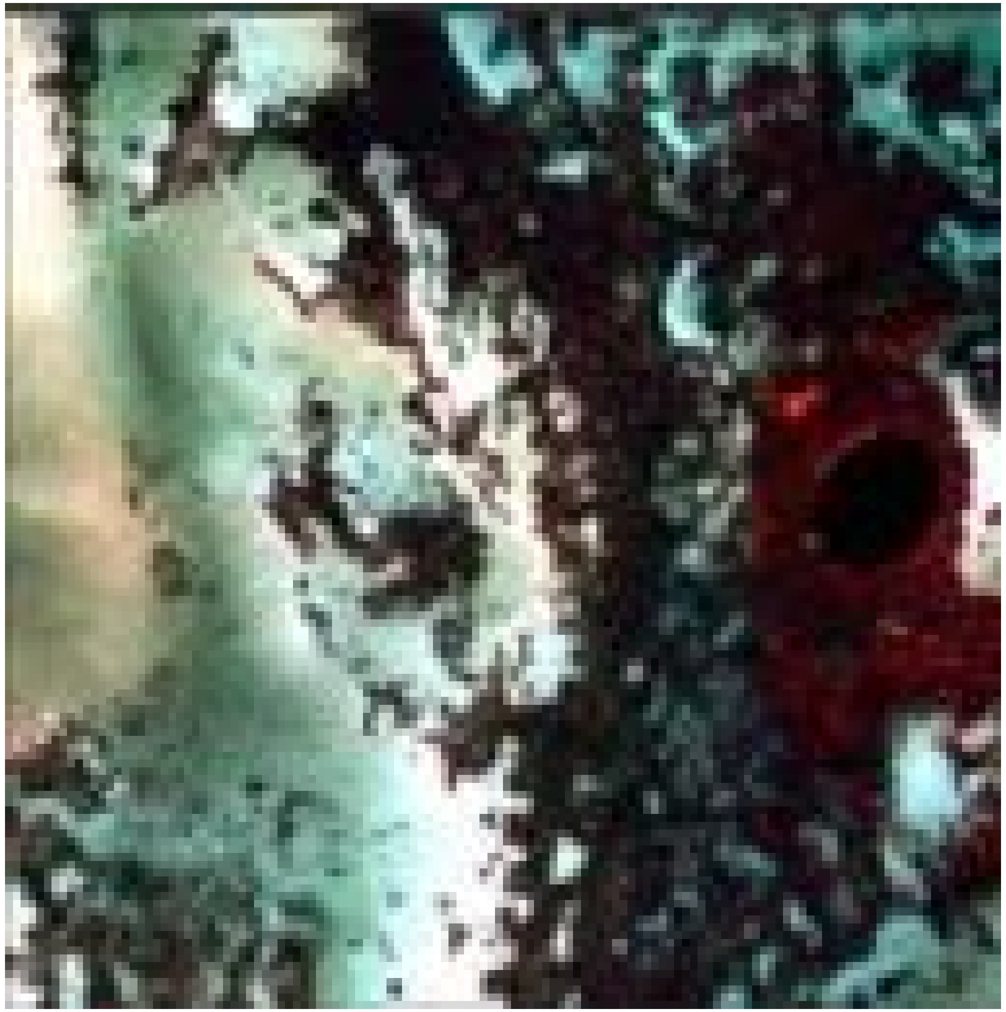
vs.

  - Mud
  - *Sargassum*
  - *Posidonia oceanica*

Questions to guide interpretation

- Does the overall spatial pattern of macroalgae and seagrass distribution correspond to their expected distribution?
- From a qualitative perspective, is there any evidence of overestimation or underestimation in the bottom-cover retrievals according to the spectral library used?

Evaluate the impact of bathymetry



3 4-8’

In your console:

```
cd Swampy
conda activate Swampy2026
python launch_swampy.py
```

Common parameters

- Image input: WorldView3_2019_07_03_11_43_12_L2W.nc
- Sensor: Worldview-2 (select Bands 478 to 659 nm)
- Water & Bottom settings: Sand (Dark), *Sargassum*, *Z. marina*
- Parameters:
  - AOCs/IOPs: default

Different inputs

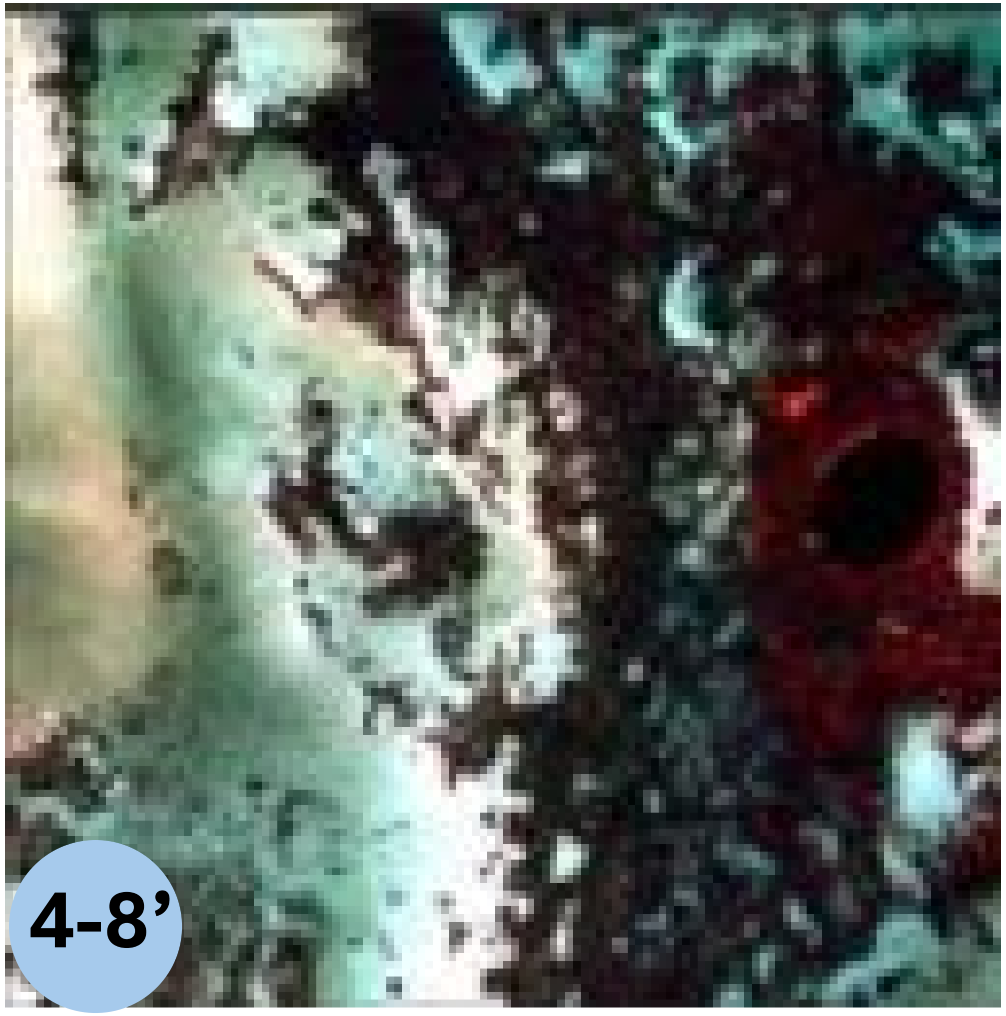
- Only in one of the runs, «Input Bathymetry», User defined: Litto3D_1m.tiff

Questions to guide interpretation

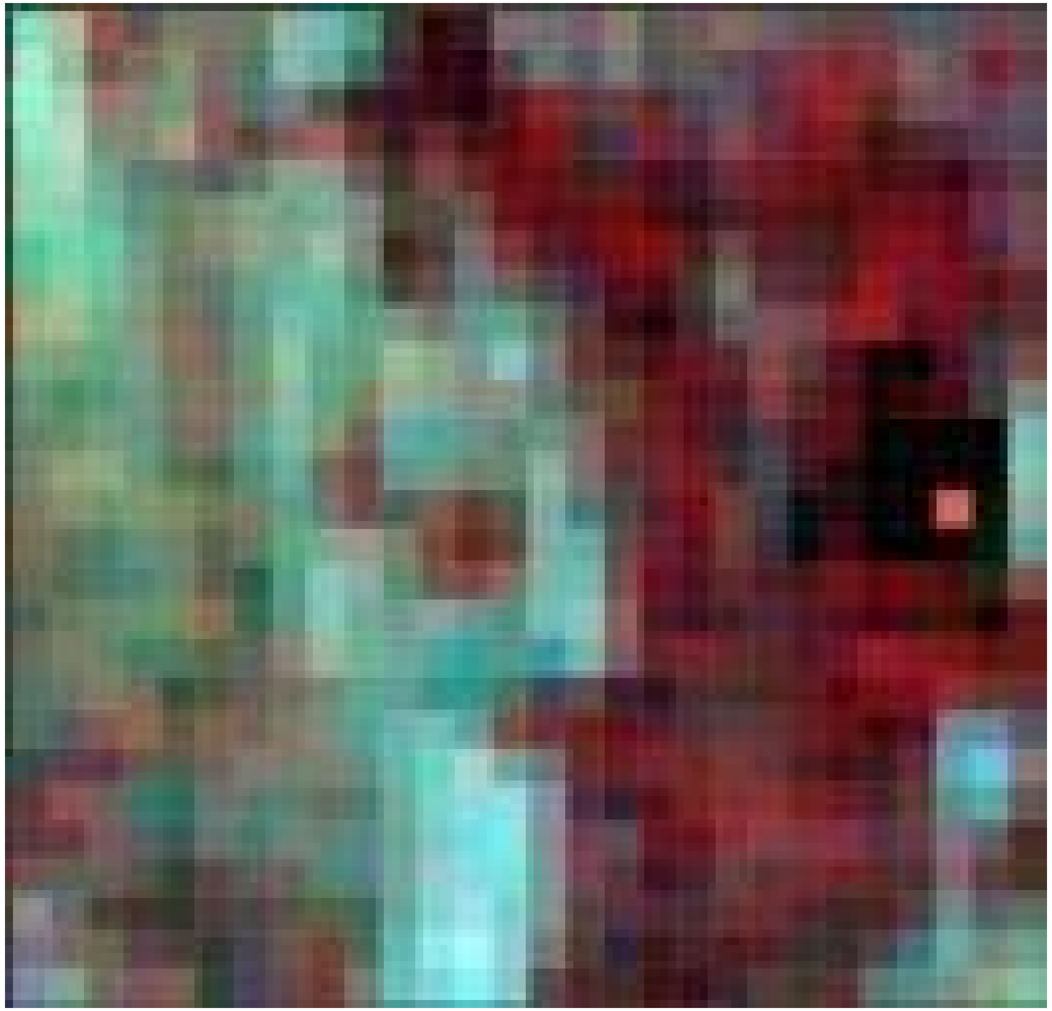
- Using bathymetry as a reference dataset, how accurately does the model retrieve bathymetry?
- Do the use of bathymetry improve the bottom cover retrievals for the three substrates? If so, in which zones is the impact more evident?
- Are there any limitations inherent to using bottom depth as an input?

Evaluate the impact of spatial and spectral information

WorldView3: 2 m pixel



Sentinel2: 10 m pixel



4

4-8’

In your console:

```
cd Swampy
conda activate Swampy2026
python launch_swampy.py
```

Common parameters

- Water & Bottom settings: Sand (Dark), *Sargassum*, *Z. marina*
- Relaxed constraints; Info: standarise between 0 and 1
- Parameters:
    - AOCs/IOPs: depth: 10m. Leave the othes as default

Different inputs

- Image input: S2A_MSI_2019_07_11_11_18_13_T30TVT_L2W.nc
- Sensor: Sentinel-2 (select Bands 443 to 704 nm)

- Image input: WorldView3_2019_07_03_11_43_12_L2W.nc
- Sensor: Worldview-2 (select Bands 478 to 659 nm)

Questions to guide interpretation

- Does the overall spatial pattern of macroalgae and seagrass distribution correspond to their expected distribution?
- From a qualitative perspective, is there any evidence of overestimation or underestimation in the bottom-cover retrievals?
- What is the impact of including the 620 nm band on the discrimination between seagrass and macroalgae?

Thanks!