Mapping of photosynthetic pigments in Spanish inland waters using MERIS imagery

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Centro de Estudios Hidrográficos del CEDEX. SPAIN
ESA Project AO-594

“Development of an Operational System for direct Thematic Mapping of Photosynthetic Pigments in Lakes using MERIS. Application to the Spanish reservoirs”.

Main steps

1. Reservoir Classification (1999)
2. Selection of several experimental reservoirs (1999-2000)
3. Field radiometric studies in selected reservoirs (2001-2002)
1. Reservoir Classification (1999)

In our centre (CEDEX) we have an extensive database with information for those variables and access to European databases as members of the European Thematic Centre for Inland Waters (ETC/IW) of the EEA.

We also have been made limnological studies of most of the reservoirs in the last twenty years. Also, since 1988 we have studied the water quality of almost all the reservoirs using the TM sensor of Landsat-5.

From this information, integrated in a matrix of data, the reservoirs were classified in several categories using a conglomerate analysis method.
2. Selection of several experimental reservoirs (1999-2000)

Once established a classification of the reservoirs we selected at least one reservoir representing each one of the four or five major classes obtained.

Due to the large size of the country, the selection is make among the reservoirs of central Spain (included in one scene of 575 x 575 km), provided that all the classes are represented in this area.

This will represent an economy of imagery and a simplification of the sampling scheme for the calibration of the models.
3. Field radiometric studies in selected reservoirs (2001-2002)

The objective was to study the spectral response of the natural waters in order to determine the most appropriate wavelength intervals for discriminating between different photosynthetic pigments.

Special emphasis was made in investigating the usefulness of the chlorophyll absorption and fluorescence channels, for an accurate estimation of chlorophyll concentration.

The field radiometric data has been transformed into the nominal channel configuration of MERIS.

The aim is to define models relating the photosynthetic pigment concentrations (PPC) with the water reflectance for one or several wavelength intervals.

An accurate atmospheric correction is required. To achieve that goal, field radiometric measurements are taken the same dates of image acquisition in order to determine the radiance in the visible channels and thus refine the correction algorithms to obtain the reflectance values.

Based in the radiometric studies, models have been proposed, relating PPC with the reflectance for one or several channels or channel ratios.

In some cases the band ratios is changed by normalized differences to prevent errors derived from negative values in some areas.

Once defined the models, their parameters will be calibrated with the MERIS imagery. Eventually, the model definition will be modified for attaining a better fit with the satellite data.

The second year, the models are being applied in the whole set of reservoirs for validation purposes.

For the calibration and validation of the models, field measurements of the parameters of interest have been taken in the selected reservoirs the dates of image acquisition.

Apart from chlorophyll concentrations and other PPC, determinations will be made for transparency measures (Secchi disk depth) as well as suspended and dissolved solids and dissolved organic matter.

Data for other parameters as nutrient concentration, pH or conductivity will be also taken in order to explain the variability observed in those parameters affecting the optical properties of water. The determinations make at the Water Quality Laboratory of CEDEX.

Also, the taxonomy and the relative abundance of different phytoplankton groups is determined for the sampling dates.

The final result of the project is obtaining thematic maps from the algorithms, directly after the acquisition of the imagery. Thus providing information on the trophic state of the reservoirs throughout the year and allowing a rapid diagnostic of the quality of inland waters. It will serve also to know the different behaviour of the reservoirs in terms of eutrophication processes monitoring and phytoplankton composition assessment, related to the characteristics (geology, climate and nutrient sources) of their catchment areas.

These results obtained will be of great interest in two fields:

As a water management tool, demonstrating the usefulness of remote sensing data for an accurate estimation of the trophic state of inland waters at a regional level.

As a scientific research tool, permitting the study of the eutrophication processes in a whole complex system of interconnected water bodies and the identification of the main driving forces of these processes.

Both two aspects are very important in a country like Spain where the scarcity of water of enough quality for human uses is a problem.
The third stage of the project comprised the development of algorithms for photosynthetic pigment mapping with MERIS, obtained from an extensive field campaign carried on 36 inland water bodies throughout the years 2001-2002.

1500 reservoirs in Spain
120 reservoirs (80% of water stored)
can be studied using MERIS FR images
An extensive field campaign was carried out in reservoirs and lakes in order to obtain a database of Rrs spectra, photosynthetic pigments concentration and phytoplankton composition.

The sampled water bodies cover a wide range of environmental conditions, trophic levels and phytoplankton communities.
MATERIALS AND METHODS:

- Two visits to each water body in the period sep. 2001 – oct. 2002
- Two sample points per reservoir

Radiometric measurements:

All measurements made with an ASD-FR spectroradiometer

- Above water Remote Sensing Reflectance (Rrs), following Fargion and Mueller (2000). See the next figures for details of measurement procedure and calculations (FOV=8º). Estimation of the reflected skylight contribution to the measured radiance according to Mobley (1999), based on measurements of skylight radiance, wind speed and solar zenithal angle.

In-water measurements

- Upwelling radiance (Lu) at surface
- Upwelling and Downwelling diffuse irradiance (Eu and Ed), using a fiberoptic extension and cosine receptors in a lowering frame
- Derived quantities: R, Q, and absorption coefficients according to Hojerslev (2001)
Spectrophotometry

Using a integrating sphere and the ASD FR as detector

*In vivo* absorption coefficients of phytoplankton, detritus and CDOM

Pigment concentration measurements

Vertical profiles: Temperature, conductivity and induced fluorescence of chlorophyll a, CDOM (Coloured Dissolved Organic Matter) and phycobiliproteins (phycocyanin and phycoerytrin)

HPLC determinations of chlorophyll and carotenoids in the first optical depth

Phytoplankton composition and biomass (1st optical depth)

The water samples for analytical laboratory measurements are taken in the first optical depth for the PAR radiation. According to Gordon and McCluney (1975), this depth (also called penetration depth) is where 90% of the remotely sensed light originates.
ABOVE WATER RADIOMETRY

Optical fibre

FOV 8

Spectralon 25%

ASD-FR

Diffuse sky radiance

$\phi = 135^\circ$

Diffuse sky radiance

$L_{sk}$

Wavelength (nm)

Upwelling surface irradiance

$E_d (W m^{-2})$

Wavelength (nm)

Spectralon irradiance

$Es$

Wavelength (nm)

$W (m^{-2}sr^{-1})$

$W (m^{-2}sr^{-1})$

$W (m^{-2}sr^{-1})$

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Above Water Measurement Device

Optical fibre

Observation Zenithal angle Controller

Spectralon 25%

Azimuthal angle from Sun position Controller

$\theta = 40^\circ$

$\phi = 135^\circ$
ASD Spectro-radiometer on the working boat
Reflectance Calculation

\[ R_{rs} = \left( L_{sfc} - \rho L_{sky} \right) / E_s \]

\( \rho \) computed from \( \theta \) and \( U \)
IN WATER RADIOMETRY

A) DOWNWELLING Irradiance Attenuation Profile

B) UPWELLING Irradiance Attenuation Profile
INTEGRATED SAMPLING DEPTH CALCULATION

\[ K_{d\text{PAR}} = 0.60 \quad Z_{\text{int}} = 1 / 0.60 \quad (1^{st} \text{ optical thickness}) \]

\[ y = 136.97e^{-0.6013x} \]

\[ R^2 = 0.9997 \]

EUPHOTIC ZONE DEPTH (1%) : \( 4.606/0.6 = 7.70 \) m

EUPHOTIC ZONE MIDPOINT (10%) : \( 2.303/0.6 = 3.85 \) m

INTEGRATED SAMPLE DEPTH : 1.67 m
SUBSAMPLING FROM INTEGRATED SAMPLE

- Suspended solids
- Phytoplankton
- Filtration for CDOM
  - Freezing -23 °C
  - Nucleopore filters 0.22 µm
- Vacuum filtration
  - 150 mm Hg
  - 6 Filters GF/F 25 mm
- Particle absorption
  - Freezing -23 °C
- Phycobilines calibration
  - Drying
  - Liquid N² freezing
- HPLC
**INTEGRATED SAMPLE DATA**

- **Cond.** 230.2 µS/cm
- **Temp.** 21.7 °C
- **[chl a]** 6.3 µg/l
- **[CDOM]** 2.1 µg/l

**INTEGRATED SAMPLE DATA**

- **Temp.** 21.7 °C
- **[chl a]** 6.3 µg/l
- **[FC]** 21.6 µg/l
- **[FE]** 0.8 µg/l
The pigments studied have been selected after a bibliographic review of previous radiometric research and attending to their importance for distinguishing between different phytoplankton groups (mainly chlorophytes, blue-green algae, diatoms and dinoflagellates). Possible candidates, apart from chlorophylls, are phycocyanin, pheophytin and certain xanthines (fucoxanthin, zeaxanthin, etc.).

(from: Phytoplankton pigments in oceanography; Edited by S.W. Jeffrey, R.F.C. Mantoura and S.W. Wright; SCOR/UNESCO, 1997)
### Summary of some signature pigments useful as markers of main algal groups

<table>
<thead>
<tr>
<th>Pigment</th>
<th>Algal group or process</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. Chlorophylls</strong></td>
<td></td>
</tr>
<tr>
<td>Chl <em>a</em></td>
<td>All photosynthetic microalgae (except Prochlorophytes)</td>
</tr>
<tr>
<td>Chl <em>b</em></td>
<td>Green algae: chlorophytes, prasinophytes, euglenophytes</td>
</tr>
<tr>
<td>Chl <em>c</em> family</td>
<td>Chromophyte algae</td>
</tr>
<tr>
<td><strong>B. Carotenoids</strong></td>
<td></td>
</tr>
<tr>
<td>Alloxanthin</td>
<td>Cryptophytes</td>
</tr>
<tr>
<td>Fucoxanthin</td>
<td>Diatoms, prymnesiophytes, chrysophytes, raphidophytes, several dinoflagellates</td>
</tr>
<tr>
<td>Lutein</td>
<td>Green algae: chlorophytes, prasinophytes</td>
</tr>
<tr>
<td>Peridinin</td>
<td>Dinoflagellates</td>
</tr>
<tr>
<td>Violaxanthin</td>
<td>Green algae: chlorophytes, prasinophytes; eustigmatophytes</td>
</tr>
<tr>
<td>Zeaxanthin</td>
<td>Cyanophytes, prochlorophytes, rhodophytes, chlorophytes eustigmatophytes (minor pigment)</td>
</tr>
<tr>
<td><strong>C. Biliproteins</strong></td>
<td></td>
</tr>
<tr>
<td>Phycoeyanin</td>
<td>Cyanophytes, cryptophytes, rhodophytes (minor pigment)</td>
</tr>
<tr>
<td>Phycoerythrin</td>
<td>Cyanophytes, cryptophytes, rhodophytes</td>
</tr>
</tbody>
</table>

*(from: Phytoplankton pigments in oceanography; Edited by S.W. Jeffrey, R.F.C. Mantoura and S.W. Wright; SCOR/UNESCO, 1997)*
Typical spectra of some pigments

(from: Phytoplankton pigments in oceanography; Edited by S.W. Jeffrey, R.F.C. Mantoura and S.W. Wright; SCOR/UNESCO, 1997)
Typical spectra of some algal groups

**BV_CYANOBACTERIA > 75%**

**BV_CHLOROPHYTE > 75%**

**BV_CRYPTOPHYTE > 75%**

**BV_DIATOMS > 75%**

**BV = Biovolume**
The objectives of the fourth stage of the project are the calibration and validation of the developed models using MERIS imagery and field data, and the set up of a web-based operational system for pigment mapping and water quality monitoring of the main Spanish reservoirs.

For that purpose, an accurate atmospheric correction of L1b imagery is needed, since the reflectance values of L2 are not yet useful for inland waters.

We are using as tool the SMAC processor of BEAM with some corrections, applying it to the whole image and masking the inland waters using radiometry.

The resulting reflectance spectra match the shape of the field measurements, but is linearly shifted * up or down depending of aerosol thickness values.
* The available MERIS tools show also some problems of under or subestimation of atmospheric transmittance, which leads to negative values of reflectance in red and infrared bands. To overcome those difficulties, several band indexes have been tested, instead of simple band ratios, in order to estimate the pigment concentrations.

Based in this approach, thematic maps of photosynthetic pigments are already in process, calculated from the reflectance-corrected L1b imagery. The models calibration and validation field campaigns are also under way this year.
Modelling the relationship between Pigments and Reflectance

Chlorophyll a (general algal biomass)

The ratio of MERIS bands 7 and 9 showed a good correlation with HPLC-measured chlorophyll-a concentration in the studied reservoirs, in three consecutive ranges of values.

\[
\frac{[\text{CHLa}]}{\text{IndCHLa}} = 23.726x + 9.9146 \\
R^2 = 0.567
\]

\[
y = 1094.7x - 108.43 \\
R^2 = 0.832
\]

\[
y = 189.55x + 43.931 \\
R^2 = 0.6062
\]
Modelling the relationship between Pigments and Reflectance

Phycocyanin (Cyanobacteria)

The normalized ratio of MERIS bands 9 and 6 showed a good correlation ($R^2 = 0.7701$) with phycocyanin in-situ fluorescence in the studied reservoirs.

\[
y = 25.376e^{0.0392x}
\]

\[
R^2 = 0.7701
\]
Modelling the relationship between Pigments and Reflectance

**Zeaxanthin** *(Cyanobacteria)*

The ratio of MERIS bands 9 and 6 showed a good correlation \( (R^2 = 0.8015) \) with HPLC-measured zeaxanthin concentration in the studied reservoirs.

* (although zeaxanthin doesn’t absorb in the 620 nm region, is highly correlated with phycocyanin)
Modelling the relationship between WQP and Reflectance

**CDOM (Cromophoric Disolved Organic Matter)**

The ratio of MERIS bands 1 and the integral of the infrared bands showed an acceptable correlation ($R^2 = 0.6711$) with fluorometrically-measured **CDOM** (fluorescence-measured with a Seapoint fluorometer at 440 nm, with an excitation wavelength of 370 nm, calibrated with quinine sulphate as a reference compound)
Modelling the relationship between WQP and Reflectance

$K_{d_{PAR}}$

The ratio of MERIS bands 5 and 14 showed a good correlation ($R^2 = 0.7435$) with the attenuation coefficient for PAR

$$y = -13.963x + 13.653$$

$$R^2 = 0.7435$$
Problems with imagery

After the ENVISAT launching, we begin to order MERIS FR images of Spain with levels 1b and 2.

We checked since the beginning an initial problem, not due to the radiometric quality of imagery, otherwise excellent, but to the poor inland water classification and flagging criteria. It determine the generation of wrong reflectance L2 bands in the inland water pixels, and consequently making impossible the application of any algorithm for the estimation and quantitative evaluation of water quality parameters, main goal of the Project.

The problem is being solved, but L2 imagery aren't yet useful in inland waters.

In the MERIS Users Workshop (Frascati, November 2003) we presented examples with comparative images and graphics.

<table>
<thead>
<tr>
<th>MERIS FR</th>
<th>Date: 21.06.2003</th>
<th>Orbit: 6833</th>
<th>Track: 266</th>
<th>Frame: 2745, 2835</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics on inland water classification</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pixels</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of pixels identified as water through radiometric analysis (CEDEX)</td>
<td>14444</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of pixels identified as water in Level 2</td>
<td>Total</td>
<td>6776</td>
<td>46.7</td>
<td></td>
</tr>
<tr>
<td>Water in L1b and CEDEX mask</td>
<td>1845</td>
<td>11.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water in L1b and no in CEDEX mask</td>
<td>4160</td>
<td>28.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>6776</td>
<td>46.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water in L2 and CEDEX mask</td>
<td>7900</td>
<td>55.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water in L2 and no in CEDEX mask</td>
<td>5592</td>
<td>38.1</td>
<td></td>
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</tr>
</tbody>
</table>

Comments:
1. We can provide you our “inland water layer” with the perimeter limits to substitute the “water” over Spanish territory.
2. It is very important to not exclude the coast pixels in the L2 reclassification process.
3. It is very important to forget the pixels classified as water (from the salinity) in L1 b in the L2 reclassification process.
4. It is very important to do a very accurate model of atmospheric correction over inland water taking into account the radiometric effects and the other L2 products (Chlorophyll concentration, etc.)
5. It is not possible to introduce flat changes in the ground segment processes, so we could do the classification, atmospheric correction, reflectance calculation and some of the products, following your proposed and corrected algorithms (i.e. incorporating these to the BEAM mask box for L2).

MOST RECENT DEVELOPMENTS
Possible ways to solve the problems

We have consulted with ESA people and our colleagues, mainly of University of Valencia, and after several test using different programs, and checking the results with field radiometric data, We concluded what the usual sensitivity of atmospheric correction tools are insufficient for inland waters, then

We decided to use the SMAC (BEAM, ESA), to produce reflectance bands from MERIS 1b bands, with some specific application criteria:

- selecting the desert option as model of atmosphere,
- setting null value for the aerosol optical thickness,
- removing water or land filters, and using our own radiometric inland water mask.

and some additional later corrections of reflectance values to fit it as possible with the radiometric ground truth data.

In this way, using the SMAC processor, we obtain, reflectance spectra very accurate in the shape, shifted upwards or downwards (increasing or decreasing the ordinates), needing only an arithmetic fitting taking de criteria of use the band 14 as reference level.

This approach provide an uncertainty about the real absolute values of each point of the continuous spectrum, and consequently the algorithms must be independent of reflectance absolute values, using transformations of bands ratios in normalised ratios between the bands.
REFLECTANCE BANDS GENERATION

STEP 1

Reflectance spectra generated by SMAC from 1b level images showing the shape and values.

STEP 2

Reflectance spectra generated by SMAC from 1b level images, corrected taking as reference the minimum reflectance value band.
As it has been described above, we have made advances in processing the images and modifying the initial algorithms to overcome the atmospheric correction limitations. We are starting to produce thematic maps of some of the main photosynthetic pigments in inland waters.

By introducing some modifications in the results of the ESA’s atmospheric correction tools, we can now obtain more reliable reflectance bands for inland waters, using MERIS 1b level images. The models derived from field radiometric data have also been modified, trying to minimize the errors in the atmospheric correction. Those modified models (normalized indexes instead of simple band ratios) are being applied and tested.

We are starting to produce thematic maps of Chlorophyll-a and Phycocyanin concentration, with an acceptable agreement between MERIS and field data. Nevertheless, we need more matching points to calibrate and validate the models. We also expect to produce maps of Zeaxanthin, CDOM and Kd (attenuation coefficient of PAR).
Chlorophyll-a concentration (mg/m$^3$). 18.06.2003
Chlorophyll-a concentration (mg/m³). 21.06.2003
Chlorophyll-a concentration (mg/m$^3$). 10.07.2003
Chlorophyll-a concentration (mg/m$^3$). 24.08.2003
Chlorophyll-a concentration (mg/m$^3$). 15.09.2003
Phycocyanin concentration (mg/m³). 18.06.2003
Phycocyanin concentration (mg/m³). 21.06.2003
Phycocyanin concentration (mg/m³). 10.07.2003
Phycocyanin concentration (mg/m$^3$). 24.08.2003
Some Comparison graphics between estimated and measured values of modelled WQP

The matching field points available are still very few. In the following months, as we get more matches and an improved atmospheric correction we expect to have a better fit.
CONCLUSIONS

The development of this Project show the real possibility of using the bands of sensor MERIS of ENVISAT, an excellent radiometric instrument, to obtain maps of Water Quality Parameters for inland waters.

We expect to achieve most of the initial goals of the Proposal, with some time delays due to the final ENVISAT launching date and to specific limitations of MERIS imagery for inland waters.

The limitations of MERIS imagery processing segment for Inland waters are derived from the main focusing of ENVISAT mission, the Ocean. We need to develop, in the frame of this project, some additional tools to process, in parallel, these water bodies, surrounded by land areas. The critical step is to achieve an adequate atmospheric correction, prior to implement any algorithm to estimate the WQP based in the reflectance values.

After completing the calibration and validation steps, the operational system will be developed to produce and transfer the maps to a water management tool.
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That’s all. Thank you very much for your attention!