USE OF CHRIS FOR MONITORING WATER QUALITY IN ROSARITO RESERVOIR

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ABSTRACT

CHRIS/Proba imagery has been acquired, in the period from May to November 2004, in Rosarito reservoir (Spain). This eutrophic water body was chosen as a test site for analyzing the possibilities offered by CHRIS/Proba for water quality monitoring, applying models for estimating chlorophyll-a and phycocyanin concentrations from water reflectances.

An atmospheric correction algorithm developed in Valencia University has been tested and validated with field data. Its application has allowed to assess the accuracy of previously developed models for MERIS, as well as new empirical models based on CHRIS bands. Although further research is needed, the results confirm the usefulness of CHRIS imagery for pigment retrieval and thus for the estimation of phytoplankton and cyanobacterial biomass in inland waters.

1. INTRODUCTION AND OBJECTIVES

One of the main indicators of water quality in inland waters is the biomass and composition of phytoplankton. This group of pelagic organisms are the main primary producers of the water bodies, using the sun energy for the process of photosynthesis. The impact of human activities can lead to an important increase of phytoplankton biomass, through the increase of nitrogen and phosphorous loads in waters, which act as nutrients for these organisms. This process, known as *eutrophication*, has undesirable consequences for most human uses of water, especially for drinking water supply and recreational uses. The phytoplankton growth often occurs in the form of *blooms*, massive growths that usually are produced by a specific algal group. In many cases those blooms are produced by cyanobacteria, which can produce toxins that affect aquatic organisms and humans.

Phytoplankton can be studied by remote sensing since it modifies the optical properties of pure water through two basic processes: backscattering and absorption of incident light [1]. The light absorption is produced mainly by the photosynthetic pigments of these organisms, of which chlorophyll-a is the most ubiquitous. In the last ten years, several sensors have been launched with narrow bands designed to detect the absorption and fluorescence features of chlorophyll-a in the reflectance spectra. Of them, the sensor MERIS is the best suited for studying phytoplankton biomass in relatively small inland water bodies, thanks to its spatial resolution and the presence of a band centred at 620 nm, around the absorption maximum of phycocyanin.

The ratio of MERIS bands 9 and 7 has been successfully used for chlorophyll-a estimation in coastal and inland waters [2] whereas the ratio of bands 9 and 6 has been proposed for phycocyanin [3]. We have used these band ratios for the development of empirical models based on a database of reflectance spectra and pigment and biomass data [4]. The database was generated during the years 2001-2002 in the framework of a project for monitoring water quality in the biggest Spanish reservoirs using MERIS imagery. The launch of the CHRIS/Proba instrument gave us the opportunity for calibrating those empirical models in a test site, since its water bands (mode 2) are very similar to the MERIS band set.

Rosarito reservoir (40º06'06"N; 05º16'47"W) was proposed as a site for CHRIS/Proba because of its specific characteristics: It's a eutrophic reservoir, dominated by cyanobacteria and located in an area with more than 3000 sunny hours per year. Also, its size allows its study with MERIS imagery, at least when is full. For those reasons, it seemed an adequate place to test algorithms for photosynthetic pigment estimation, especially for phycocyanin.

Thus, the main objectives for the 2004 activities with CHRIS/Proba in Rosarito were:

- Proving the usefulness of CHRIS Water Bands for the monitoring of phytoplankton in inland waters, especially cyanobacteria
- Using Rosarito as a test site for applying empirical models for pigment detection, previously developed for MERIS, in CHRIS imagery

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– Analysing the effects of different observation angles on water reflectance

For reaching those objectives, the first and essential step is to obtain reliable reflectance bands from the CHRIS imagery. Therefore, an accurate method for the atmospheric correction of CHRIS Water Bands over inland waters was required. This method has been developed at University of Valencia [5], and tested and improved in Rosarito during 2004.

2. MATERIALS AND METHODS

2.1 Sampling campaigns

The sample campaigns were planned in possible acquisition dates, according with the Nominal Acquisition Plan. In the period April – November 2004, a total of 14 campaigns were made in Rosarito reservoir. In the same period, 9 CHRIS image sets were successfully obtained (cloud free or almost free). Taking into account the acquisition uncertainties, in only 5 dates there was a coincidence between imagery and field data. In the other four acquisitions, sample data was acquired with a difference of 1 to 3 days. Although all the dates have been processed, the dates considered in this work have been the 5 *match-up* days:

– May 20th
– June 15th
– August 27th
– September 22nd
– November 26th

In all dates, at least four fixed points were sampled for all the measured variables (Fig. 1), to allow a continuous monitoring. Besides those points, transects were made at most dates for reflectance validation. A total of 45 complete sampling points and more than 300 georeferenced spectra have been collected and processed.

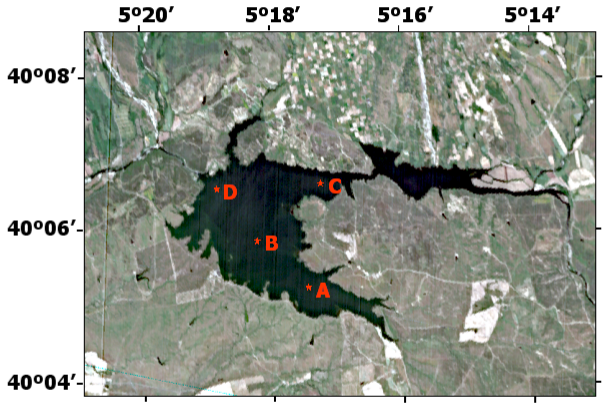

Fig. 1. Fixed sampling points overlaid to the CHRIS image of May 20th

2.2 Field measurements

The radiometric measurements were made with an ASD-FR spectroradiometer, in the 350-1050 wavelength range (nm) and with an 8º FOV. The end of the radiometer optic fibre was mounted at the bow of the boat, in a device that allows controlling the azimuth and zenith observation angles. The reflectance was calculated following the protocols from Fargion and Mueller [6], and applying the corrections for specular reflections proposed by Mobley [7].

For water sampling, the first optical depth was estimated from the Secchi disk depth, using an empirical equation calculated for Spanish reservoirs [4]. An integrated water sample was taken up to that depth, from where 90% of the remote sensed signal comes from [8]. A fraction of the sampled water was vacuum filtered (150 mm Hg) through Whatman GF/F filters, and then used for the calculation of chlorophyll and carotenoids concentration using HPLC [9]. The phytoplankton composition and the suspended solids concentration were determined in the other fraction.

Additionally, vertical profiles were made at each sampling point, using a CTD (Sea-Bird Electronics), equipped with four fluorometers (Chelsea and SeaPoint) designed for the measurement of chlorophyll-a, phycocyanin, phycoerytrin and CDOM. Independent measurements for nutrient concentration were taken each 15 days throughout the period May-October, as well as toxicity tests for cyanobacterial toxins.

2.3 Image processing

All the images have been acquired in the Mode 2 spectral configuration (*Water Bands*) with full swath and a nominal ground spatial resolution of 17 m. Most of the images had to be reprocessed (at SIRA) to the last format (version 4.1) and the calculated observation angles were extracted and applied in the atmospheric correction algorithm. The method proposed by Guanter *et alli.* [5] was applied for the atmospheric correction of imagery. The images were georreferenced using ground control points and standard image processing software (ENVI and PCI/Geomatica). Once georreferenced, a vector layer with the field sampling points was overlaid to extract the reflectance spectra of imagery.

3. RESULTS AND DISCUSSION

3.1 Atmospheric correction and angular effects

The atmospheric correction algorithm has been subject to a preliminary validation with the five processed images. Although a more detailed error analysis has to be performed, the algorithm yields good results in the bands ranging form 500 to 750 nm. The average errors for bands 9, 11, 12 and 14 are between 5-25% in sun glint free images, depending on the dates and on the observation angles. These errors are partially compensated when applying the band ratios used for pigment modelling, and thus allowing the application of those models.

Regarding the angular dependence on image reflectances, the main observed effect is the sun glint induced reflectance increase. The sun glint can be predicted from the satellite observation angles relative to the sun and is clearly observed in the reflectances extracted from the images. As it can be noted in Fig. 2, the reflectance can be two or three times higher than the water leaving reflectance and this increase is not spectrally flat. The correction of this effect is a difficult task, as its magnitude is highly variable throughout the water surface (Fig. 4). Apparently, minor roughness differences of the water surface, that appear under light breeze conditions, are responsible of this variability. Without an effective sun glint correction, the affected images must not be used for water quality modelling.

In the sun glint free imagery it has not been possible to detect any significant angular dependence on observed reflectance. Taking into account the anisotropic nature of the water leaving radiance [10] some differences could be expected, but it appears that its magnitude lies within the limits of experimental errors. An experimental set up for measuring water leaving radiances at different angles would be desirable for analysing this effect.

The atmospheric correction model, although useful for water quality modelling in inland waters, must be improved to achieve a better agreement with field data, especially in the blue and infrared regions. Using dynamic thresholds for the surface reflectance in band 2, dependent on the illumination/observation geometries, would increase the model accuracy, as it tends to underestimate the reflectance in the visible bands (Fig. 3). The current model has yield good results in all dates except in the November image set, in which there is a combination of a very low sun elevation angle and water reflectances. This causes a very low radiance arriving at the sensor. As a result, small inaccuracies in radiative transfer computations, such as the model selected for the extraterrestrial solar irradiance, or the assumption of a plane-parallel atmosphere, may lead to large errors in the final surface reflectance. Therefore, further investigation on the radiative transfer code used for the simulation of the atmospheric functions is needed.

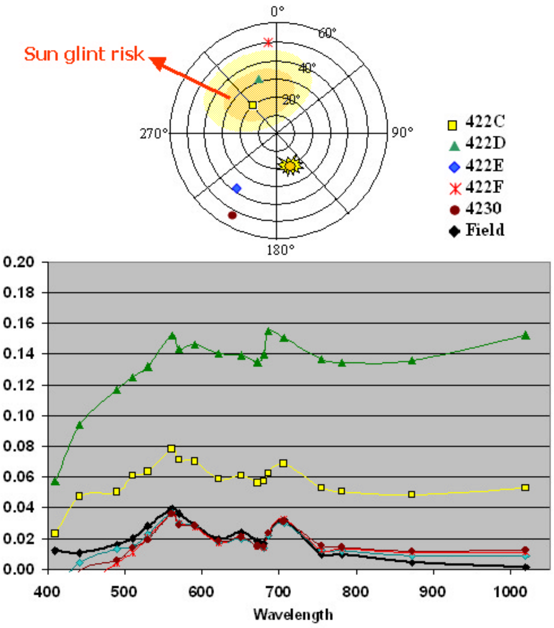

Fig. 2. Polar diagram (above) showing the sun and imagery azimuth and zenith angles on June 15th. The reflectance spectra measured in the field at one sampling point (black line) and derived from corrected images, are shown below.

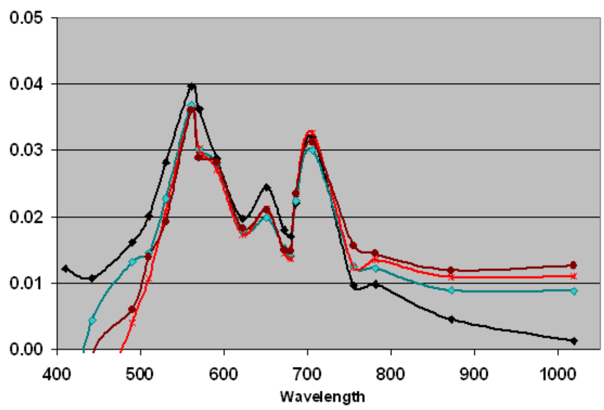

Fig. 3. Reflectance spectra of Fig. 2, but showing only the sun glint free images

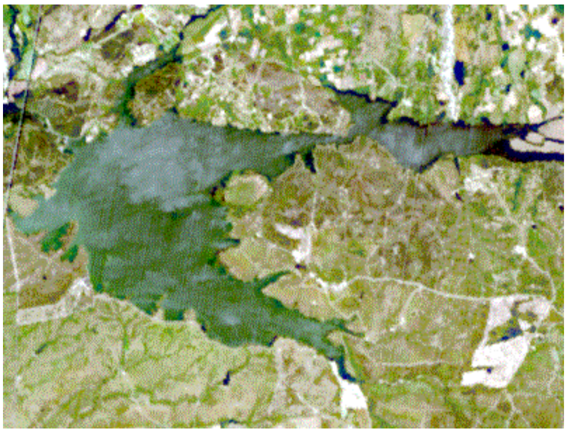

Fig. 4. Example of an image with moderate sun glint (May 20th), showing its variability on the water surface

3.2 Application of algorithms for chlorophyll-a

As it has been commented above, the main objective of this work was to demonstrate the usefulness of CHRIS water bands for water quality monitoring, through phytoplankton pigment modelling, and as a test site for applying algorithms developed for MERIS bands.

For MERIS, a simple empirical model, based on the ratio of bands 9 (708,4 ±10) and 7 (664,6 ±7) was developed from a database of field data collected in 36 reservoirs during 2001-2002 [11]. For applying this model to CHRIS, the most similar bands must be used. CHRIS bands 14 (706 ±12) and 11 (672 ±11), being the best option. But the actual centres and bandwidths differ notably from nominal and vary slightly between dates, as shown in Table 1.

Date	Centre band 14	Bandwidth band 14	Centre band 11	Bandwidth band 11
20/05/04	706.1	18.2	669.1	10.7
15/06/04	706.5	18.3	669.2	10.8
27/08/04	707.1	18.3	669.8	10.8
22/09/04	707.4	18.4	669.9	10.8
26/11/04	709.3	18.5	671.7	10.9
CHRIS nominal	706	12	672	11
MERIS nominal	708.4	10	664.6	10

Table 1. Actual centres and bandwidths (nm) of CHRIS Water Bands 14 and 11 (Mode 2), extracted from the image header information

To assess the effect of shifting band settings in the chlorophyll estimation, MERIS and actual CHRIS bands were calculated from the field reflectance spectra, and the empirical model was applied. The predicted chlorophyll-a concentrations were compared (Fig.5).

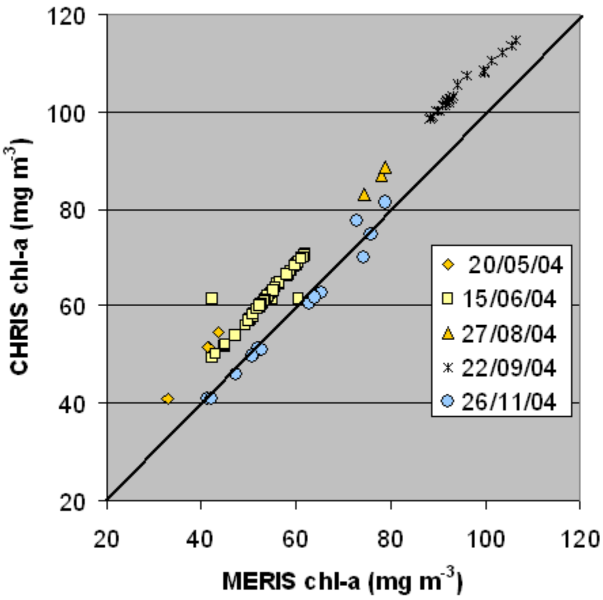

Fig. 5. Effect of the band limits of CHRIS on the chlorophyll-a estimations. Results are from field reflectance data, using the same empirical model for the calculated CHRIS (14/11) and MERIS (9/7) bands.

It can be expected, from Fig. 5, that the different band limits of CHRIS could have a significant effect on predicted chlorophyll-a concentrations, when applying a fixed model developed for MERIS bands. This effect is date-specific and can be corrected when field data are available, but it is not clear whether the correction applied at Rosarito could be extrapolated to other water bodies with different phytoplankton composition. In the analysed images, chlorophyll-a tends to be overestimated (10-25% higher) except on the November image.

When the empirical MERIS model is applied to the CHRIS data and compared with field measurements of chlorophyll-a concentration (by HPLC) an overestimation is observed (Fig. 6), which can be explained in part by the shifting band limits of CHRIS.

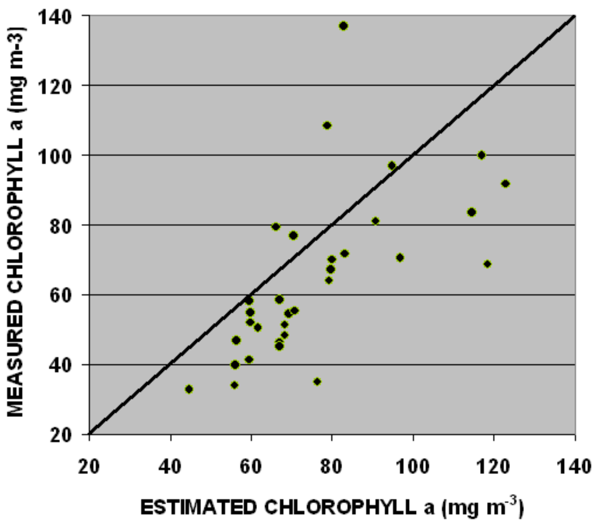

Fig. 6. Comparison of measured and estimated chlorophyll-a concentrations, applying an empirical model developed for MERIS bands

Another source of error comes from the empirical model itself. The inclusion of Rosarito data could improve the model accuracy, especially for high concentrations (50-100 mg m^{-3}) for which there was a lack of data in the previously formulated model (Fig. 7).

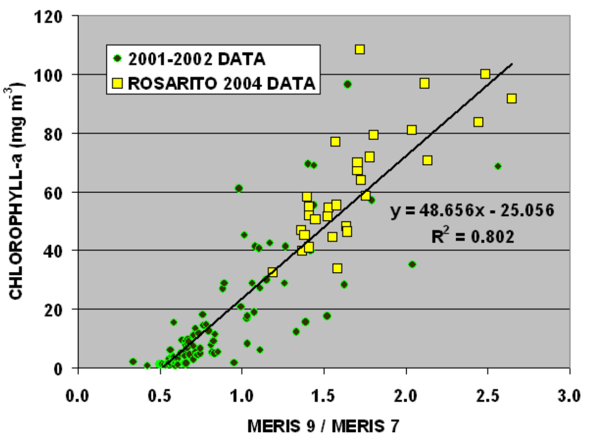

Fig. 7. New empirical model for chlorophyll-a estimation from MERIS, including the field reflectance data of Rosarito

To analyse the usefulness of CHRIS for chlorophyll-a concentration estimation, empirical regression models have been obtained for the ratio of Water Bands 14/11, and 14/12. Using band 12 (centred at 680 nm) as the chlorophyll-a absorption band of the model makes sense in Rosarito, an eutrophic water body. It has been noted that the red absorption feature of chlorophyll-a in reflectance spectra shifts to longer wavelengths as the concentration of this pigment increases [12]. That explains that the correlation coefficient of chlorophyll-a concentration is higher with the 14/12 ratio (R^2=0.80, Fig. 8) than with the 14/11 ratio (R^2=0.62). In both cases the error could be reduced if a correction for the effect of shifted bands is introduced.

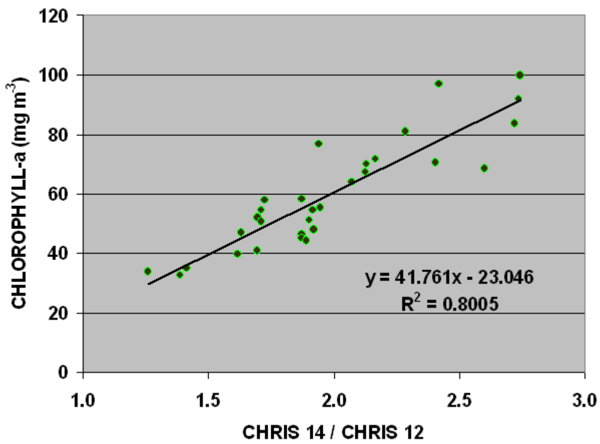

Fig. 8. Empirical regression model for chlorophyll-a estimation from CHRIS water bands, developed from Rosarito 2004 field data.

3.3 Application of algorithms for phycocyanin

The band 9 of CHRIS (Mode 2), centred at 622 nm, is especially useful for phycocyanin quantification, since this pigment has an absorption maximum around this wavelength. MERIS has a band centred at 620 that has been used for this purpose, by means of an empirical model based on our database of spectral and pigment data [4]. This model, formulated with the ratio of MERIS bands 9 and 6, has been applied in CHRIS data using Water Bands 14 and 9.

Date	Centre band 14	Bandwidth band 14	Centre band 9	Bandwidth band 9
20/05/04	706.1	18.2	622.3	13.5
15/06/04	706.5	18.3	622.2	13.6
27/08/04	707.1	18.3	622.7	13.6
22/09/04	707.4	18.4	622.9	13.6
26/11/04	709.3	18.5	624.3	13.7
CHRIS nominal	706	12	622	9
MERIS nominal	708.4	10	619.6	10

Table 2. Actual centres and bandwidths (nm) of CHRIS Water Bands 14 and 9 (Mode 2), extracted from the image header information

The actual centres and bandwidths of CHRIS band 9 (Table 2) are close to MERIS band 6 and, as Fig. 9 shows, they don't have a noticeable effect on the phycocyanin prediction with respect to MERIS, when the empirical model is applied to the field reflectance data.

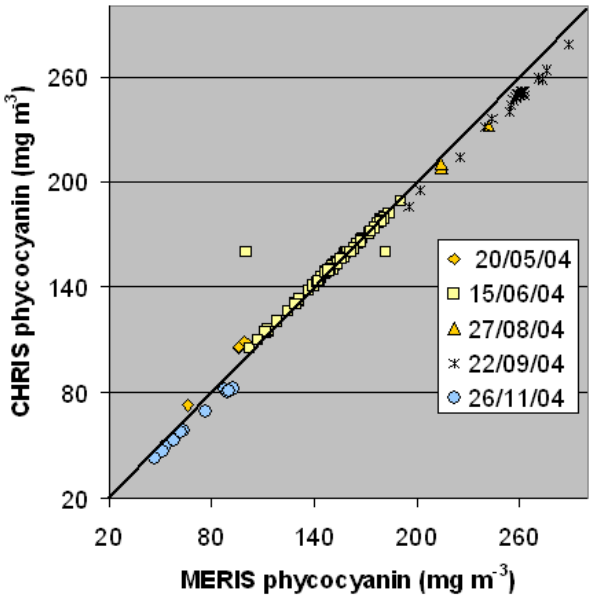

Fig. 9. Effect of the band limits of CHRIS on the phycocyanin estimations. Results are from field reflectance data, using the same empirical model for the calculated CHRIS (14/9) and MERIS (9/6) bands.

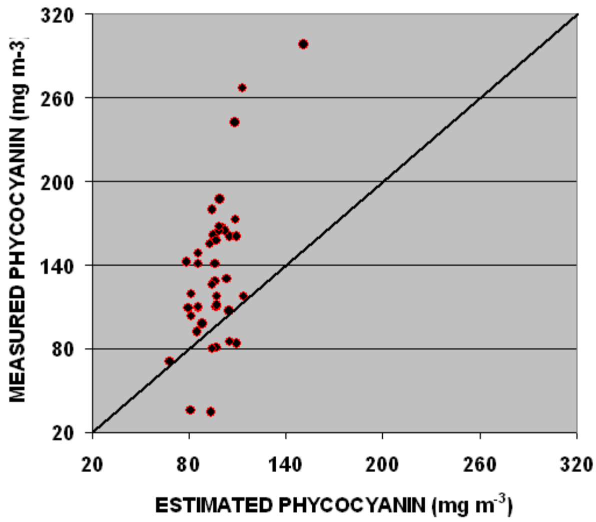

Fig. 10. Comparison of measured and estimated phycocyanin concentrations, applying an empirical model developed for MERIS bands

Despite this agreement of MERIS and CHRIS band ratios, the result of the application of the MERIS model to Rosarito data has been very poor (Fig. 10). This result shows the limitations of our current phycocyanin model. The data used for its formulation was in a range of relatively low phycocyanin concentrations, below the concentrations observed in Rosarito. As with the chlorophyll model, the data from Rosarito could serve to improve the phycocyanin model, although a simple linear model would not fit the whole dataset. A potential equation developed from Rosarito data fits with the old dataset (Fig. 11), but this relationship requires a physical explanation which is not evident. This fact deserves further research, with a possible solution being the application or adaptation of existing semi empirical models [3], that require information on Inherent Optical Properties of the water body (absorption and backscattering coefficients).

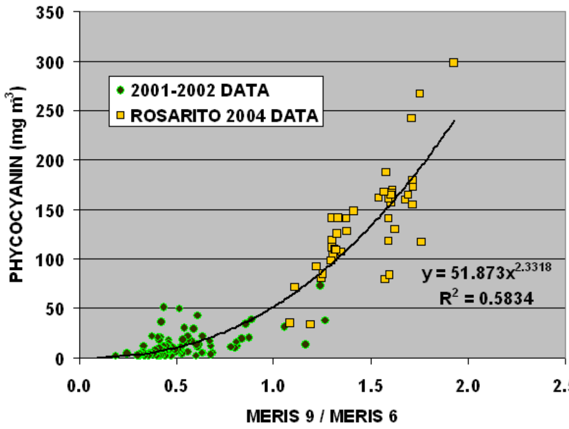

Fig. 11. New empirical model for chlorophyll-a estimation from MERIS, including the field reflectance data of Rosarito

As with chlorophyll-a, the analysis of the correlation of CHRIS band ratios and phycocyanin measured concentrations (by fluorescence) yields good results. The ratio of bands 14 and 9 presents a high correlation (R^2=0.79) with measured phycocyanin concentrations (Fig. 12), allowing the application of the resulting regression equation for phycocyanin mapping in Rosarito CHRIS imagery.

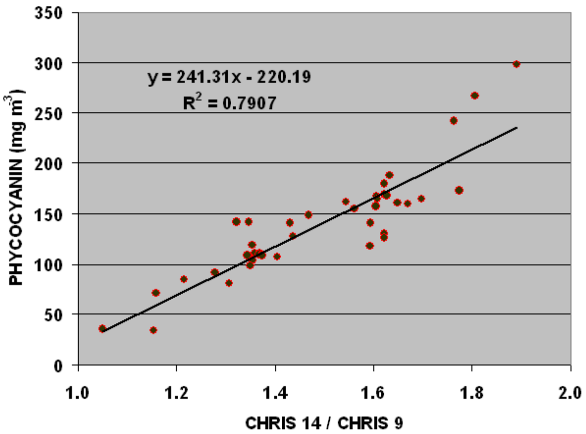

Fig. 12. Empirical regression model for phycocyanin estimation from CHRIS water bands, developed from Rosarito 2004 field data.

3.4 Pigment concentration mapping

The empirical models developed from Rosarito field data (Fig. 8 and Fig. 12), have been applied to the CHRIS imagery, obtaining thematic maps for chlorophyll-a (Fig. 13) and phycocyanin concentration (Fig. 14). This maps have served for the monitoring of the spatial distribution of phytoplankton and cyanobacteria on the water surface. The temporal evolution of these variables can be tracked at any point of the reservoir. Looking at the sampling points has allowed a preliminary assessment of the model performance. An example could be seen in Fig. 15

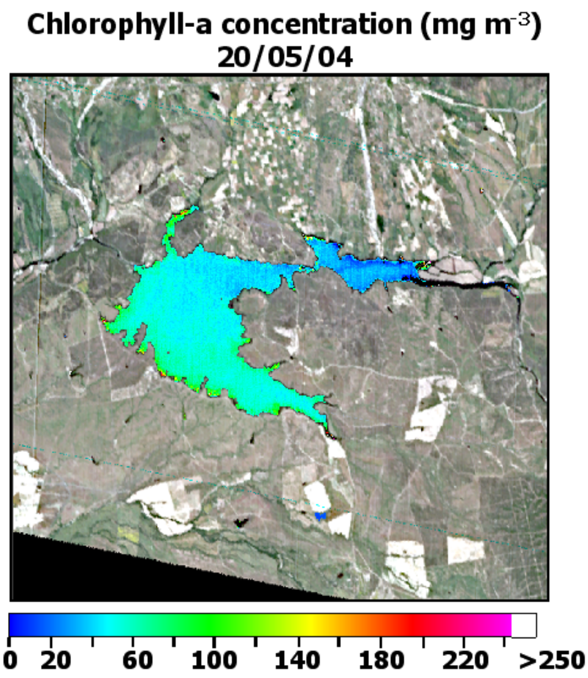

Fig. 13. Example of thematic map for chlorophyll-a concentration

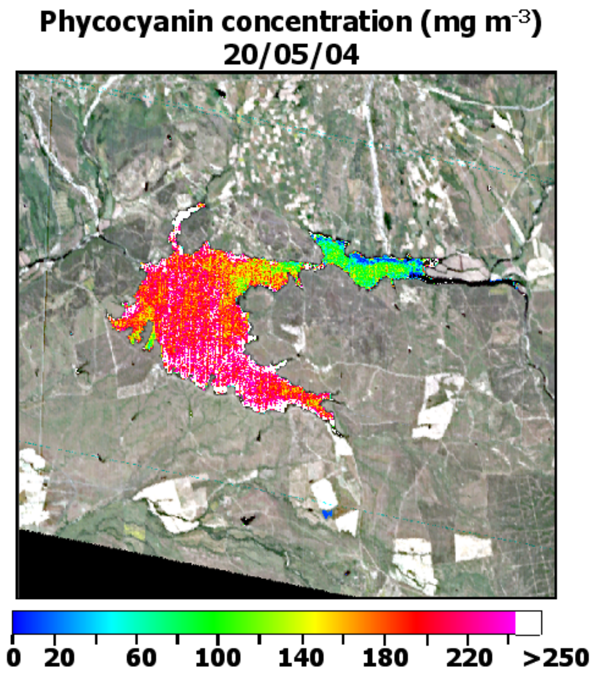

Fig 14 Example of thematic map for phycocyanin concentration

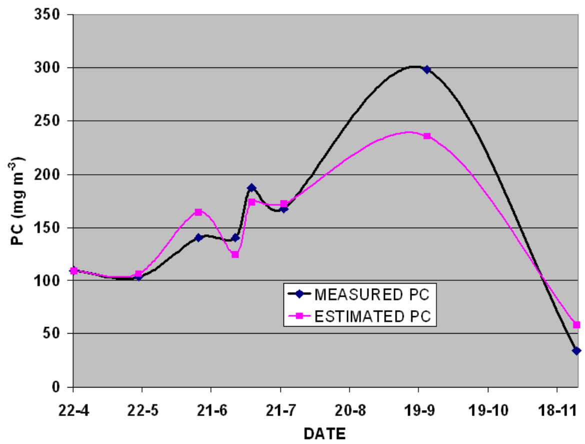

Fig 15 Example of temporal evolution of measured and predicted phycocyanin concentration at one sampling point

4. CONCLUSIONS

The first year of CHRIS/Proba acquisitions over Rosarito has been very successful in terms of the number of acquired images (a total of 9) and the field data collected (14 sampling dates). This high amount of information has allowed the testing and preliminary validation of an algorithm for the atmospheric correction of CHRIS imagery over inland waters. The lowest errors of the algorithm occur in the green - near infrared bands, which are those used for mapping photosynthetic pigments. This fact has allowed the application of models previously developed for MERIS bands, as well as the development of new models based on the Rosarito dataset.

The sun glint increase in reflectance is the main angular effect observed in the corrected images. It has not been possible to detect significant variations in reflectance that could depend on the water leaving radiance.

The MERIS models for chlorophyll-a can be applied to CHRIS data, although the effect of the different band limits in CHRIS must be taken into account and evaluated. Our own empirical model yield acceptable results, although a new parameter fit with Rosarito data is advisable. More fieldwork in 2005 will be necessary for validating this modified model. Anyway, a regression equation has been obtained for Rosarito, that allows the estimation of Chlorophyll-a concentration from CHRIS bands.

Our MERIS empirical model for phycocyanin has failed in Rosarito, when applied to CHRIS data. The model accuracy can be improved with the Rosarito field data and validated in 2005. Also, more physically sound semi-empirical models will be applied. As with Chlorophyll-a, a regression model has been obtained for phycocyanin, with an acceptable accuracy, and applied to CHRIS imagery to generate phycocyanin thematic maps.

As a general conclusion, the work in Rosarito has proved the usefulness of CHRIS/Proba for water quality monitoring in inland waters, through phytoplankton and cyanobacterial biomass mapping, The results are promising, although the algorithms for atmospheric correction and pigment quantification should be improved.

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