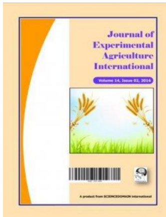

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Monitoring Water Quality in a Reservoir of the Semi-arid Region Using Remote Sensing

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Authors' contributions

This work was carried out in collaboration between all authors. Author JCM was a graduation student and this article is part of his monograph, this author conducted the study, collected the analyzes in the field and did the statistical analysis of the data, wrote the protocol and wrote the first draft of the manuscript. Authors FBL and EMA were the masters of the first author, they designed the study and monitored and supervised all of this study. Author FJOL assisted in conducting the study and collected the analyzes. Author FHOS assisted in writing in the manuscript and discussing the data. All authors read and approved the final manuscript.

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ABSTRACT

Aims: The aim of this study was to analyse the use of remote sensing as an alternative in monitoring water quality, and to analyse models that estimate the concentrations of chlorophyll-a (Chl-a) in a reservoir in the semi-arid region.
Place and Duration of Study: Field campaigns were carried out at the Pereira de Miranda reservoir, Pentecoste, in the State of Ceará (CE), at five sampling points, from December 2014 to December 2015.
Methodology: Limnological and spectral data were used, which were collected using a

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spectroradiometer. The limnological attributes of Chl-a and suspended sediments were analysed in the laboratory, and used to evaluate the spectral responses. Four three-band models were analysed for estimating the concentrations of Chl-a.
Results: The models of Lopes [11] and Gitelson et al. [15] gave the best performance, with respective satisfactory results for R^2 of 0.75 and 0.79, MAE errors of 6.74 ($\mu g.L^{-1}$) and 6.51 ($\mu g.L^{-1}$), an NSE of 0.74 for both models, and RMSE of 9.01 ($\mu g.L^{-1}$) and 8.93 ($\mu g.L^{-1}$). From these results, the models were selected and applied in the campaigns of April and September 2015.
Conclusion: The use of remote sensing is therefore viable in estimating concentrations of Chl-a, collaborating to the development of research and in water resource management at lower cost.

Keywords: Limnological attributes; Chlorophyll-a; bio-optical models.

1. INTRODUCTION

Water is the most important resource, as it is essential for the survival of all species on the planet. It is also the natural resource that most faces problems in terms of quality and quantity [1]. The adequate management of water resources, both the quantity available and the quality, can be ensured by monitoring the reservoirs. Remote-sensing data can help make this more successful [2].

The use of remote-sensing data shows great potential in the identification of water quality, allowing monitoring at different spatial and temporal scales [2]. The remote detection of inland bodies of water can be used to evaluate three main optically active components: chlorophyll-a concentrations, suspended mineral matter and dissolved organic matter [3]. According to [4], the chlorophyll-a concentration is one of the most important attributes for evaluating the state of water environments.

According to [2], with the use of remote sensing through the spectral responses of continental bodies of water, it is possible to verify the composition of the water, as well as identify and accompany problematic situations.

This relationship has been established with the development of models that try to estimate the concentrations of these attributes that have such an influence on the spectral responses of the water.

The methods of calculation are able to obtain high correlativity between the spectrum and chlorophyll-a; the only flaw is that the parametric variability is large. The correlativity data for a given body of water, or a certain period of a body of water, are difficult to apply directly to another body of water or to another period of the same body of water [5].

The particularities that these models present generally need to be reparametrised for other regions than their own region, ensuring that studies of their suitability can be made, and seeking to identify specific factors for each model.

Considering the great potential of using remote sensing combined with the study of aquatic environments, the aim of this research was to evaluate the use of remote sensing as an aid to monitoring water quality, and to analyse the application of bio-optical models that estimate concentrations of Chl-a in a reservoir of the semi-arid region.

2. MATERIALS AND METHODS

The study area was the Pereira de Miranda reservoir, also known as the Pentecoste reservoir; this is the main reservoir of the Curu Basin, with a watershed of 2,840 km² and a catchment area of 57 km² [6]. The dam was designed and built by the National Department for Anti-Drought Works – DNOCS from 1950 to 1957.

The collection campaigns took place from December 2014 to December 2015. During this period, it was possible to observe changes that occurred in the aquatic system together with climate events in the semi-arid region, covering the wet and dry seasons.

Five collections were made at five points spread along the catchment area of the reservoir (Fig. 1). Point P01 - corresponds to the point closest to the dam (water outlet), P02 - below the main inflow of the waters of the Capitão-Mor River, P03 - entrance to the Capitão-mor River, P04 - below the main inflow of the waters of the Canindé River and P05 - entrance to the Canindé River. Owing to the volume of the reservoir at the year of 2014, the collection points were defined on the superior third part of the hydraulic basin (Fig. 1).

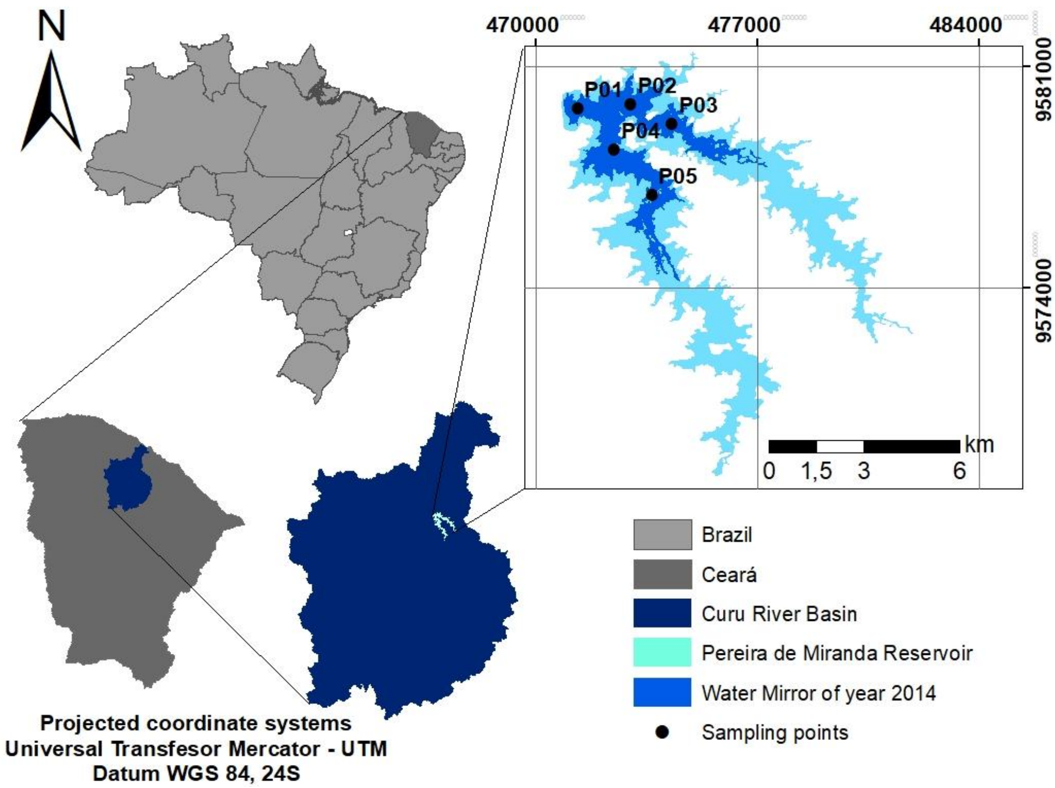

Fig. 1. Location of the collection points in the Pereira de Miranda reservoir, Pentecoste CE

At each sampling point, collections were made of spectral data, including ten radiance measurements, and water samples for later analysis of the limnological attributes. The environmental conditions were also noted in situ.

Irradiance measurements of the aquatic system were carried out using the ASD FieldSpec®3 Hi-Res Spectroradiometer with a field of view of 25º, spectral resolution of 1.4 nm covering a spectral band ranging from 350 to 2500 nm, and a Spectralon reference plate as a Lambertian surface for calibration; measurements were taken between 10:00 and 14:00, corresponding to the period with the lowest angle of solar inclination and therefore with greater energy flow in the field of irradiance.

The water samples were collected at a depth of 30 cm from the surface of the water, in properly sterilised 1L plastic bottles, for later laboratory analysis of the limnological attributes. The attribute analysed in the laboratory was Chl-a, as per the methodology of [7]. The total suspended solids (TSS), fixed suspended solids (FSS) and volatile suspended solids (SSV) were analysed following the methodology of [8].

It is worth highlighting the climate characteristics of the Curu River Basin, which has a rainfall regime with irregular spatial and temporal distribution. This is a characteristic phenomenon of the region, not only due to the irregularity of the rainfall, but also due to a rainfall period considered below average over consecutive years.

The collection dates corresponded to the dry and wet periods in the region, and took place on 3 December 2014, and on 7 April, 13 July, 26 September and 4 December 2015. (Fig. 2) shows the daily rainfall in mm and the stored volume as a percentage for the Pereira de Miranda reservoir during 2014 and 2015, as well as the specific dates of each collection, represented by vertical dotted lines.

The three-band models tested take into account that the first wavelength ($\lambda 1$) should be located in the region of greatest sensitivity to Chl-a. According to [11], the second wavelength ($\lambda 2$) should be around 700 nm, where the absorption of chlorophyll is minimal and the effects caused by the absorption of Tripton and CDOM can be minimised.

For three-band models, [12] stipulated wavelengths around 665, 709 and 754 nm, i.e. for the second wavelength (λ2), according to [5], the spectral reflectance ranges from 690-760 nm.

However, backscattering is found in λ1 and λ2, and in order to remove the effect, a third region (λ3) is defined, which should cover a range where there is a minimum effect from absorption by Tripton, CDOM and Chl-a. The spectral region where such conditions occur is in the near infrared (λ3), around 730 nm [11].

The wavelengths for the models used, which cover distinct regions, are described in (Table 1), together with the values for the coefficient of determination (R^2).

The model by [13] was developed in Nebraska. [14] developed a three-band model in a study area of the Pearl River Estuary in China. Chl-*a* concentrations in the estuarine waters of Chesapeake Bay in the USA were estimated using the three-band models of [15]. [4], developed one-, two- and three-band hybrid algorithms to evaluate Chl-*a* concentrations in five lakes in Asia. Other studies have been developed for the semi-arid region of Brazil [2,16].

In the statistical evaluation of model performance for the attribute Chl-*a*, statistical indicators were calculated by comparing the values estimated by the models (Table 1) with those determined in the laboratory.

The statistical indicators used in this evaluation were the correlation coefficient (*r*), the coefficient of determination (R^2), the Willmott index (*d*), Nash-Sutcliffe coefficient (*NSE*), mean absolute error (*MAE*) and root mean square error (*RMSE*).

The Pearson correlation coefficient is a measurement of the degree of linear relationship between two quantitative variables. The precision is given by the correlation coefficient that indicates the degree of dispersion of the data in relation to the mean, i.e. the random error [2].

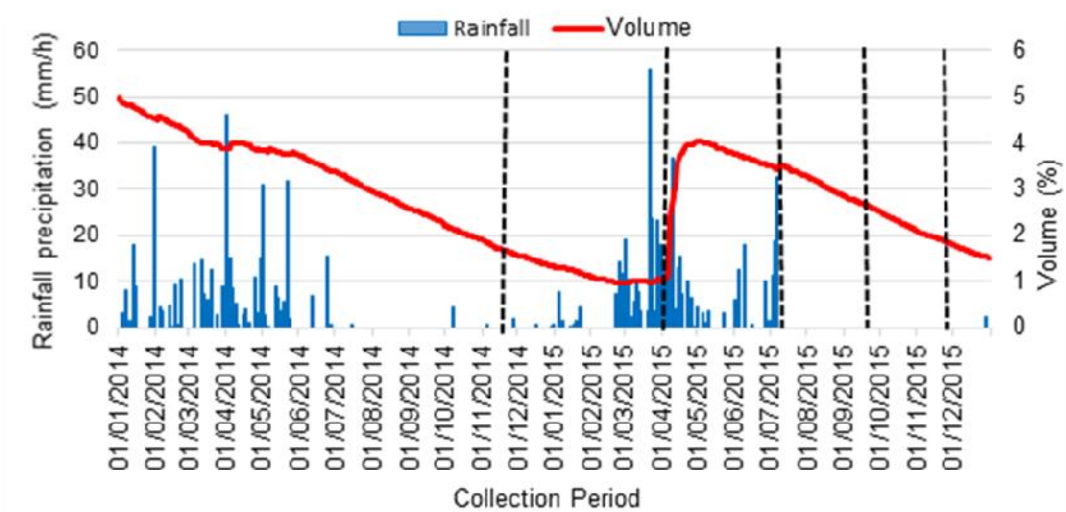

Fig. 2. Rainfall for the Pentecost station from January 2014 to December 2015 and collection dates

Source: Portal Hidrológico de Ceará [9,10].

Table 1. Three-band models tested for estimating chlorophyll-*a* concentrations using only remote sensing data

Author	Band (nm)	R^2
(Dall'Olmo and Gitelson, 2005) [13]	(λ1) = 671; (λ2) = 710; (λ_3) = 740	0.94
(Gitelson et al. 2007) [15]	(λ 1) = 675; (λ 2) = 695; (λ 3) = 730	0.81
(Chen et al. 2011) [14]	(λ 1) = 684; (λ 2) = 690; (λ 3) = 718	0.81
(Lopes, 2013) [11]	(λ 1) = 660; (λ 2) = 690; (λ 3) = 717	0.88

The coefficient of determination, R^2, is the percentage variation of the dependent variable explained by the independent variable(s), equation 1.

where the coefficient of determination is interpreted as the ratio of total variation of the dependent variable Y that is explained by the variation of the independent variable X [11].

$$R^2 = \left[\frac{\sum_{i=1}^{n} \left(X_i - \overline{X}\right) \cdot \left(Y_i - \overline{Y}\right)}{\sqrt{\left(\sum_{i=1}^{n} \left(X_i - \overline{X}\right)\right)} \cdot \sqrt{\left(\sum_{i=1}^{n} \left(Y_i - \overline{Y}\right)\right)}} \right] \quad (1)$$

The Willmott index (d) was calculated from equation 3, [17], whose values range from zero for no agreement, to 1 for perfect agreement. Values greater than 0.75 are considered satisfactory.

$$d = 1 - \frac{\sum (Pi - Oi)^2}{\sum \left(\left|Pi - Oi\right| + \left|Oi - O\right|\right)^2} \quad (2)$$

Where: d is the Willmott index of agreement; Pi expresses the estimated value of the variable; Oi represents the observed value; and O defines the mean of the observed values.

The coefficient defined by [18] translates the similarity in variability between two variables, and is an indicator of similarity quantification and an important statistical criterion for evaluating model precision [19]. It was determined with equation 3.

$$NSE = 1 - \left[\frac{\sum (Y_m - Y_c)^2}{\sum \left(Y_m - \overline{Y_m}\right)^2} \right] \quad (3)$$

Where: NSE - Nash & Sutcliffe coefficient, ($-\infty <$ NS ≤ 1); Ym - measured value; Yc - calculated value; and $\overline{Y}$ - mean of the measured values.

The mean absolute error (MAE) is defined as the difference between prediction and observation, divided by the number of observations - equation 4.

$$MAE = \frac{1}{N} \sum_{i=1}^{N} \left| X_i^{'} - X_i \right| \quad (4)$$

Where: Xi - measured data; Xi'- estimated data; N - even number of points used.

The root mean square error ($RMSE$) indicates the degree of similarity between the measured and estimated data using the models, with the ideal value being equal to zero. The RMSE was obtained with equation 5.

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{n} \left[X_i^{'} - X_i\right]^2} \quad (5)$$

Where: Xi - measured data; Xi'- estimated data; and N - even number of points used.

3. RESULTS AND DISCUSSION

The dynamics seen in the aquatic system of a reservoir are closely related to terrestrial systems. It should be noted that all the results show a direct relation to seasonality and climate factors in the region. The concentrations showed high values in all the collection campaigns (Fig. 3). This fact reveals impacts on the reservoir, since Chl-*a* concentrations are related its trophic state as well as to water quality.

The concentrations of chlorophyll-*a* ($\mu g.L^{-1}$) in the Pereira de Miranda reservoir are all classified as eutrophic to hypereutrophic according to the [20] limits of classification.

It can be seen that the smallest concentrations of Chl-*a* are at points P04 and P05, except for the fifth collection, where the concentration at P05 is the highest, approximately 100 $ug.L^{-1}$. This result is associated with the lack of anthropogenic management processes along the banks of the reservoir.

These processes also directly influence the concentration of suspended sediments. Fig. 4 shows the dynamics for the concentrations of total, fixed and volatile suspended solids.

The collection showing the highest concentration included a rainy period in the region, which consequently led to an increase in stored volume during the second collection (Fig. 2), and which explains the above result, since the rainfall that occurs prior to a collection is responsible for transporting soil sediment, organic matter and pasture residue into the reservoir by means of runoff.

Concentrations in the Pereira de Miranda reservoir are within the limit established by CONAMA Resolution 357/05 for total suspended solids for Freshwater Classes 1 and 2, which is

500 mg L^{-1}. At most sampling points, much lower values are seen. This resolution is original from the National Council of Environment, agency subordinated to the Ministry of the Environment (Portuguese acronym for the Conselho Nacional do Meio Ambiente - CONAMA).

The range between 400 and 900 nm was used for spectral analysis, as this presents less noise and corresponds to the range of interest for identifying the optically active components of the water. The data shown demonstrate the spectral behaviour of the waters of the Pereira de Miranda reservoir during the rainy and dry seasons of 2014 and 2015.

The behaviour of the spectral curves when in the presence of Chl-*a* follow a certain pattern, with peaks of absorption as well as reflectance depending on the concentrations found. The collection carried out April, which is representative of the rainy season in the state, was chosen for analysis of the spectral data, with September representing the dry period.

In (Fig. 5), which corresponds to the rainy season, high reflectance can be seen with the increase in wavelength in the visible region (500 to 700 nm), this behaviour being related to elevated concentrations of inorganic particles suspended in the water column.

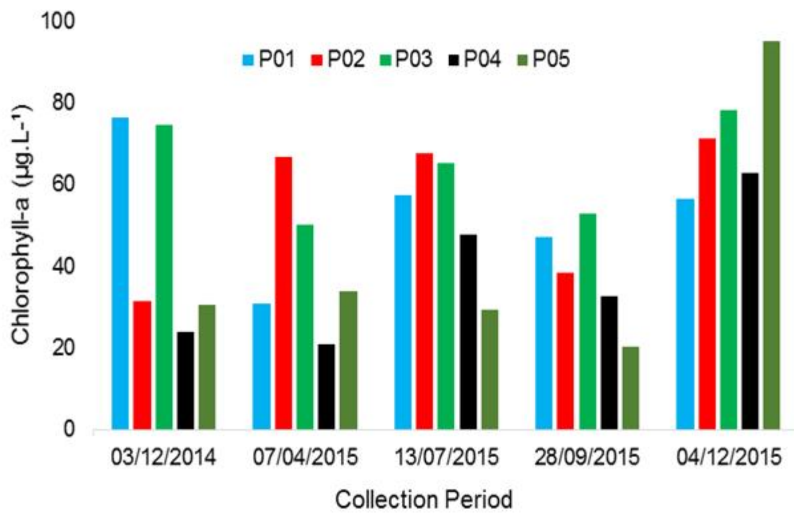

Fig. 3. Chlorophyll-*a* concentrations (µg.L-1) in the Pereira de Miranda reservoir CE, from December 2014 to December 2015

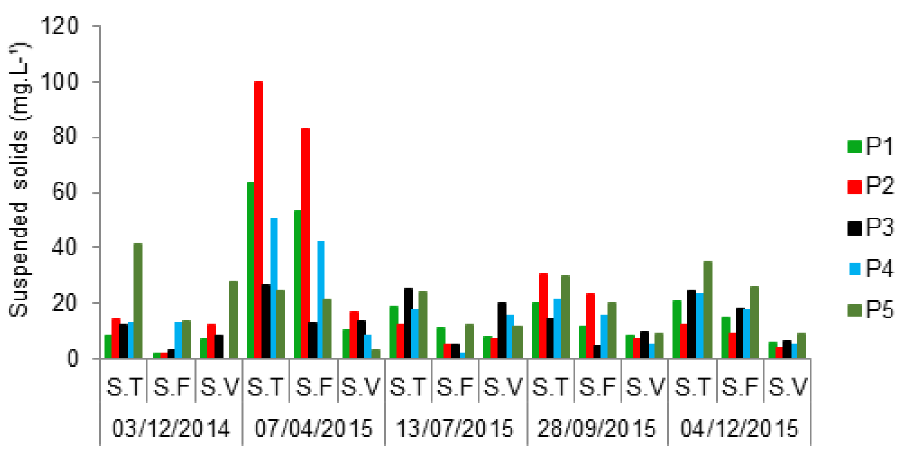

Fig. 4. Suspended-solid concentrations (mg.L^{-1}) in the Pereira de Miranda reservoir

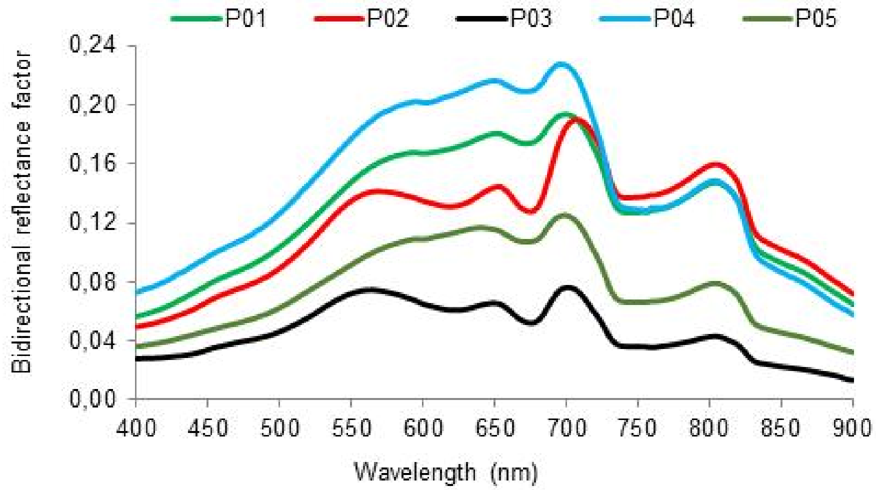

Fig. 5. Spectral response of the aquatic system of the Pereira de Miranda reservoir CE. 7 April 2015

According to [11], such behaviour may be a function of the backscattering coefficient, which in turn is highly correlated with the concentration of suspended solids. The increase in sediment concentration is due to the increase in substances that can be carried into the reservoir due to the rains that occurred during the rainy season, together with an increase in the volume of the reservoir on nearby dates (Table 1).

Points P04 and P01 show the greatest reflectance, since even though they do not have the highest concentration of suspended solids, they have lower concentrations of Chl-*a*.

This behaviour of high reflectance dispersion is explained in studies developed by [21], where he points out that the main factor for dispersion are the dissolved substances and suspended particles of different size and optical activity in the liquid medium.

A different result is seen in (Fig. 6), which shows lower reflectance and more-uniform curves, a result of the FSS concentrations. The lower reflectance at P03, also seen in (Fig. 4), can be explained by the low concentration of fixed solids and higher concentrations of Chl-*a*.

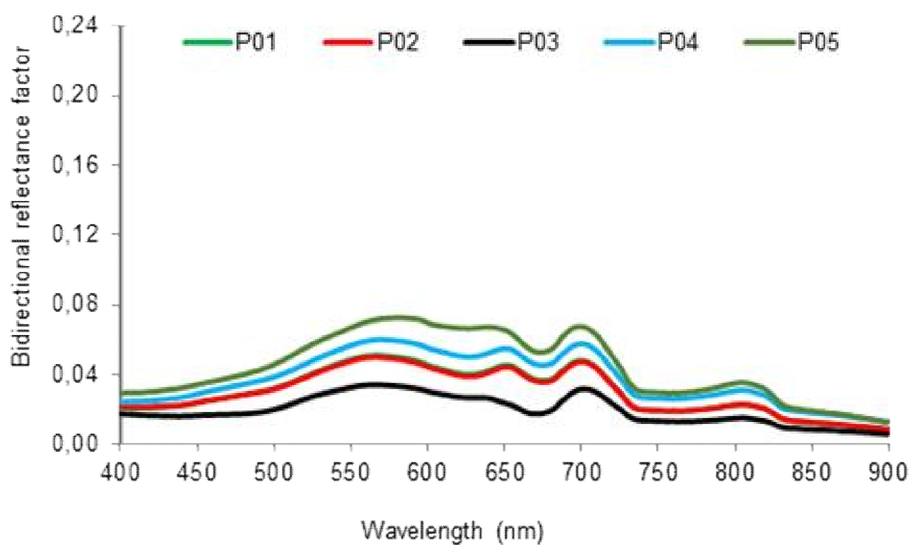

Fig. 6. Spectral response of the aquatic system of the Pereira de Miranda reservoir CE. 28 September 2015

To identify the spectral positions having the highest correlation with the chlorophyll-*a* concentrations, the correlation was determined, as shown in the correlogram (Fig. 7).

There is a low correlation between the spectral data and concentrations of chlorophyll-*a*, it is therefore not possible to estimate chlorophyll-*a* concentrations using a one-band spectral model only; this justifies the use of two- and three-band models in the study, as with the single band model there is a weak and inverse linear correlation between variables.

According to [5], it is possible to obtain high correlation between the spectrum and Chl-*a* data for a given body of water, but there are limitations due to high parametric variability; this makes it difficult to apply the models directly to another body of water.

The models tested (Table 1) demonstrate significant results by means of the complex correlation coefficient, which ranges from r = 0.87 to 0.89 (Fig. 8), and may be evaluated for estimation of the Chl-*a* concentration. However, all the parameters under study should be taken into account when validating the models, the root mean square error (RMSE) and the mean absolute error (MAE) being determining factors in model application.

In their research, [13] obtained a value for R^2 of 0,94; in this study, the model presented a value for R^2 of 0.75 and RMSE of 14.18 μg L^{-1} (Fig. 8A). With the model of [15], an R^2 of 0,81 was found, giving a satisfactory value as this was higher than the value observed by the authors of the model (0.79). However, the Mean Square Error (8.93 μg L^{-1}) was lower than that found with the [13].

For the models of [14], the R^2 was 0.80, similar to that seen by the authors (0.81), but with a value for RMSE of 12.14 μg L^{-1}. [11] obtained an R^2 of 0.88, showing inferior performance in application, since the resulting coefficient has a value of 0.75 (Fig. 8D).

Model performance was also evaluated taking into account the values of the NSE coefficient, which is considered adequate and good if the value exceeds 0.75, and acceptable for values between 0.36 and 0.75. The models of [15] and [11] had the highest values, both with an NSE of 0.74.

Considering the results, the models that presented the best performance with the smallest error were those of [15] and [11]. They were used to estimate chlorophyll-*a* concentrations at the five collection points in April and September of 2015.

For the collection made in April (Fig. 9), the rainy season, it can be seen that the concentrations estimated by the models are close to those measured in the laboratory, with the exception of point P04 using the model by [11], where the Chl-*a* concentration was overestimated.

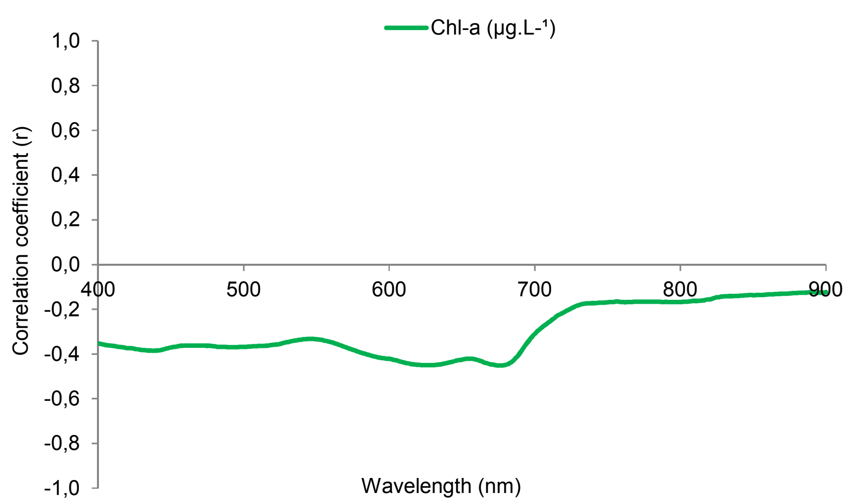

Fig. 7. Correlogram for reflectance factor and concentrations of chlorophyll-*a*

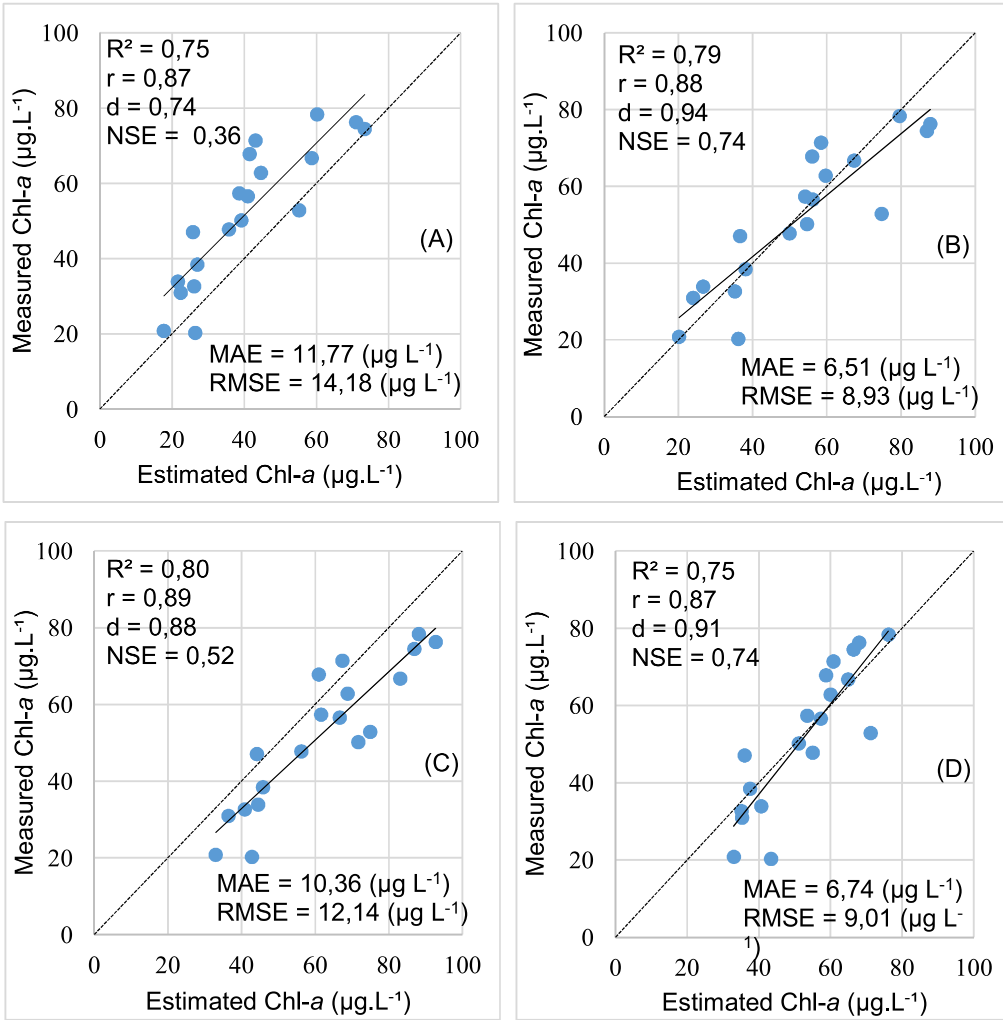

Fig. 8. Model validation: (A) Dall'Olmo and Gitelson [13]. (B) Gitelson et al. [15]. (C) Chen et al. [14] and (D) Lopes [11]

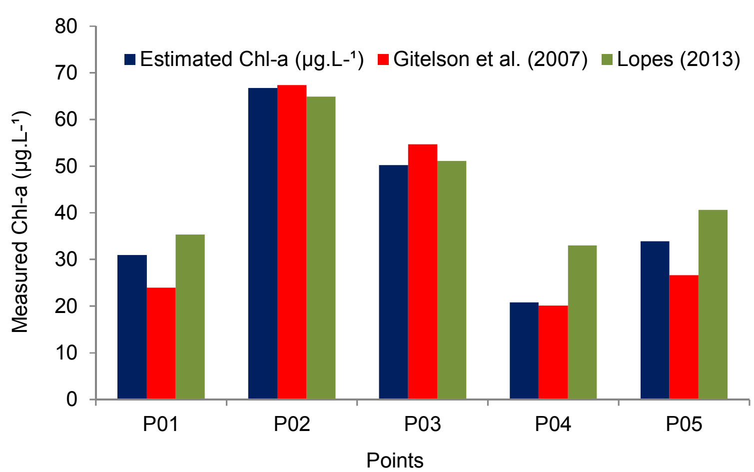

Fig. 9. Estimations of chlorophyll-*a* concentrations using the models of Gitelson et al. [15] and Lopes [11]. April 2015

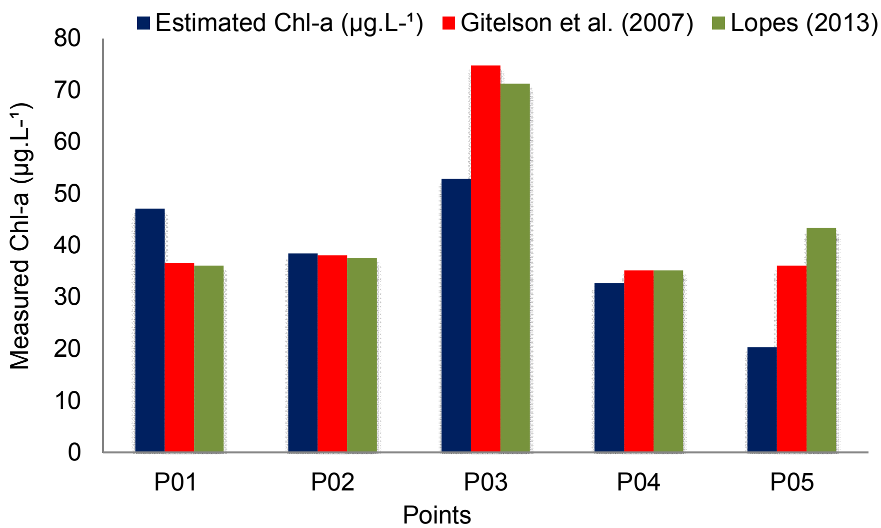

Fig. 10. Estimates of chlorophyll-*a* concentrations using the models of Gitelson et al. [15] and Lopes [11]. September 2015

For the collection made in September (Fig. 10), note that points P01, P03 and P05 show values that are more dispersed. For P01, the striking behaviour is that both models underestimate the concentrations, whereas for P03 and P05, the values are overestimated.

The results for both models indicate that this behaviour may be related to a greater complexity of the aquatic system, i.e. other attributes and factors influence the dynamics of water quality and consequently the spectral response. Due to the characteristics of the region, such behaviour may also be related to factors such as wind speed at the time of collection.

4. CONCLUSION

A remarkable point concerns the concentrations of chlorophyll-*a* in which the greatest values are observed at the last campaign, such fact related to the big sequence of dry days, what contributed to the phytoplankton proliferation in virtue of the favorable conditions to the development of such organisms, straightly related to the pigment of chlorophyll-*a*.

The fractions of suspended solids varied according to the response of the pluviometric regimen, in which is observed the increment of the fractions of total and fixed solids during the period of collection, when it is observed the greater pluviometric heights, illustrating the impact of sediments of mineral origin leaching to the hydraulic basin of the reservoir Pereira de Miranda.

The use of remote sensing to quantify the concentrations of chlorophyll-*a* in the waters of artificial reservoirs through the analysis of optically active factors is a necessary and viable alternative for monitoring water quality. Therefore, the spectral responses collected *in situ* have revealed great performance in the difference between the collected points and the evaluated periods, being able to differ according to the concentrations of the active optical components.

The bio-optical models, both analysed and applied, presented parameters with satisfactory values, with an R^2 of 0.75 and 0.79, MAE of 6.74 ($\mu g.L^{-1}$) and 6.51 ($\mu g.L^{-1}$), NSE of 0.74 for both models, and RMSE of 9.01 ($\mu g.L^{-1}$) and 8.93 ($\mu g.L^{-1}$). Although it can be seen that for some points the values that were found either overestimated or underestimated the actual concentrations of Chl-*a* due to the aquatic dynamics of the system, the models proved to be a viable alternative to be explored in monitoring water quality in the reservoirs of the semi-arid region.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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