BIO-OPTICAL CHARACTERIZATION OF TWO BRAZILIAN HYDROELECTRIC RESERVOIRS AS SUPPORT TO UNDERSTAND THE CARBON BUDGET IN HYDROELECTRIC RESERVOIRS

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ABSTRACT

This study aims at carrying out a bio-optical characterization of two Brazilian hydroelectric reservoirs as a support to current investigation regarding their net carbon budget. This characterization is a key step for both (1) developing bio-optical models to retrieve water constituents by remote sensing and (2) describing the availability of light for photosynthesis, whose information is essential to understand biogeochemical processes related to emissions of methane and carbon dioxide in aquatic systems. Twenty-two sampling stations were profiled at each reservoir, using an attenuation-absorption meter (ACS-WET Labs) and a set of six Ramses radiometers (TriOS). Water samples were acquired at each sampling station for determining concentrations of optically active constituents. The results showed spatial heterogeneity in the concentration of constituents which ranged from 1.17-40.45μgL^{-1} for chlorophyll-a, 0.26-20.41 mgL^{-1} for total suspended sediments, 0.93-9.48 mgL^{-1} for dissolved total carbon and 0.93-3.87 m^{-1} for CDOM absorption. The diffuse attenuation coefficient ($K_{d(PAR)}$), ranged from 0.35 to 4.03 m^{-1} while euphotic depth ($Z_{eu\ (1\%)}$) ranged from 1.14 to 13.06 m.

***Keywords* —** Inland water, Dissolved organic matter, Lakes, Inherent optical properties, Apparent optical properties

1. INTRODUCTION

In a scenario of global changes and finite energy sources, the use of renewable energy becomes essential for all countries. Brazil has an outstanding position regarding renewable energy with ≈75% of its energy matrix based on renewable sources, against an average of 13% in the world and only 6% in developed countries. The Brazilian electric power matrix is predominantly hydroelectric. The area flooded by the largest 150 hydropower reservoirs is nearly 45 10^3 km^2. The net carbon budget in these aquatic environments, however, is not well known and needs to be determined and monitored, because besides renewable energy, clean energy sources are also important. Biogeochemical properties of the aquatic systems, however, affect the carbon budget, since they affect the sources and sinks of greenhouse gases [9]. Water optical properties are important surrogates of biogeochemical properties such as concentration of optically active substances. Therefore, the objective of this study is to carry out a bio-optical characterization of two Brazilian hydroelectric reservoirs as a support to current investigation on the net carbon budget of Brazilian hydroelectric reservoirs.

2. MATERIALS AND METHODS

2.1. Study area

The study area comprises two Brazilian hydroelectric reservoirs: Tucuruí and Três Marias. The Tucuruí reservoir is located in the northern of Brazil, in the Amazon region. It was flooded by damming the Tocantins River in Pará state (-3.833º; -49.651º- Figure 1-a). Tucurui dam was built between 1976 and 1984, when the water filled a surface of around 2850 km^2. The Três Marias reservoir is located in the southeastern region of Brazil and dammed the upper course of the São Francisco River, in Minas Gerais state (-18.215º; -45.258º- Figure 1-b). Três Marias dam was built between 1957 and 1962, and flooded an area of 1040 km^2. Três Maria reservoir is characterized by a dendritic shape, reaching a maximum depth of 56 meters [3]. Those two reservoir have distinct factors controlling their bio-optical properties: 1) Tucurui reservoir belongs to the Amazon Biome and flooded 2850 km^2 of the Terra Firme Forest whereas Três Marias reservoir is in the transition between the Atlantic Forest Biome and Cerrado Biome; 2) Tucurui reservoir was set up in a region poorly populates whereas Três Marias was built in area of old human occupation

2.2. In situ data collection

Due to the reservoir dimensions, the geographical location of the sampling stations were defined according to the methodology described in [1], based on an analyses of a TM/Landsat-5 time series. In each reservoir, 22 sampling stations were profiled, on a six day campaign, using a 25cm pathlength AC-S attenuation-absorption meter (WET Labs) along with six inter-calibrated RAMSES-TRIOS spectroradiometers, concurrently to water sample acquisition.

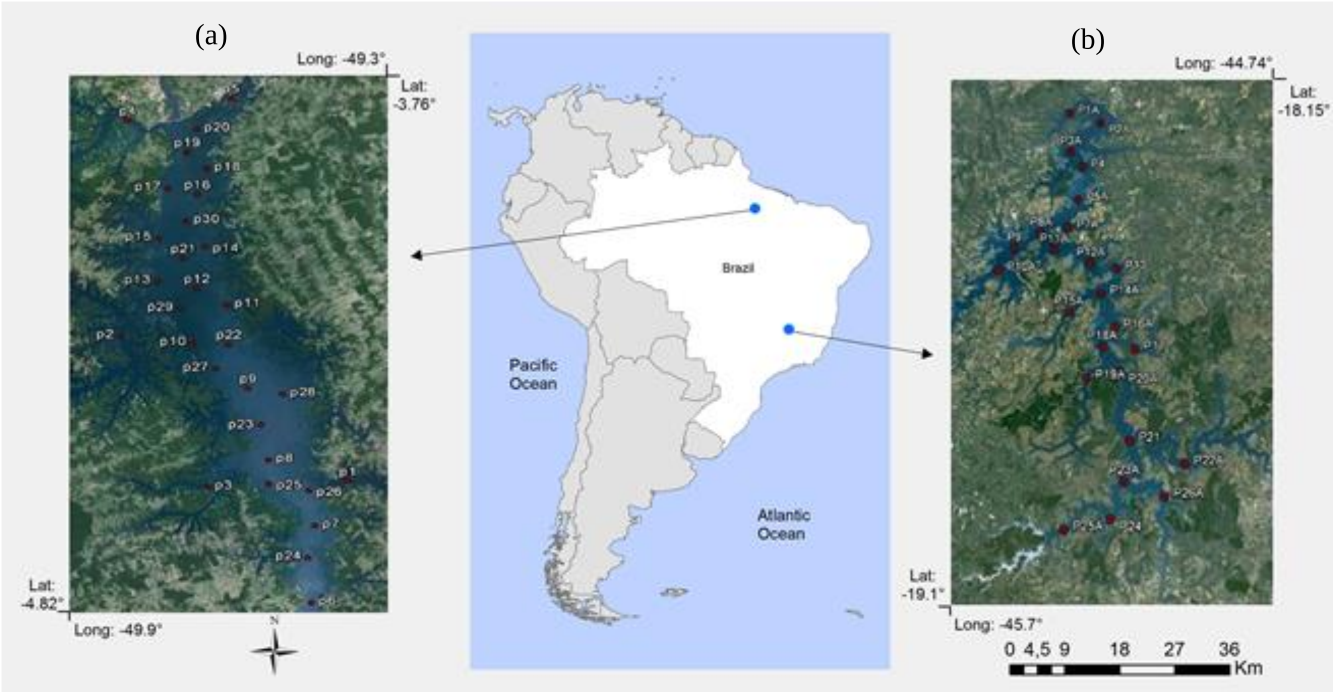


Figure 1: Landsat images with sampling stations locations: (a) Tucuruí reservoir (b) Três Marias Reservoir.

Water samples were collected at subsurface (0.3 m depth), stored at cool temperatures and filtered on the same day. Whatman GF/F 0.7 μm pore size filters were used to determine chlorophyll-a concentration according to [2]. Water samples were also filtered through pre-weighed and pre-ignited Whatman GF/F 0.7 μm pore size filters for analyses of suspended matter (total, inorganic, and organic fractions) based on [8]. In situ absorption/attenuation measurements were carried out in the spectral range of 400 to 750 nm at a sample rate of 4 Hz.

Above and in-water radiance/irradiance measurements were acquired following Ocean Optical Protocols [4]. Three spectroradiometers were mounted in an underwater open cage for profiling downwelling irradiance $E_d(z,\lambda)$, upwelling irradiance $E_u(z,\lambda)$ and upwelling radiance $L_u(z,\lambda)$. The cage was lowered from subsurface up to the depth in which the $E_d(z,550)$ reached ≈1% of its subsurface value, stopping every meter, to take 10 measurements. The three remaining sensors were set for measuring above water radiance $L_w(\lambda)$, sky radiance $L_{sky}(\lambda)$, and surface incident irradiance $E_s(\lambda)$ concurrently with each in-water measurement.

Water temperature, pH, turbidity, dissolved oxygen, conductivity, and Secchi depth were taken at each sampling station.

2.3. Data processing

To account for illumination changes during measurements, $E_d(z,\lambda)$ values were normalized by the first $E_s(\lambda)$ measurement [4], before computing the diffuse attenuation coefficient for the downward Photosynthetically Available Radiation ($K_{d\,(PAR)}$).

The AC-S data were corrected for temperature dependency along the wavelengths [7]. Salinity correction was disregarded, considering that its effect is negligible in freshwaters [5].

Overestimation of the absorption coefficient [8];[11] was corrected using the proportional method [11].

The diffuse attenuation coefficient $K_d(\lambda)$ for the wavelengths 450, 550, 670 nm and PAR was calculated according to Kirk [5]

3. DATA ANALYSIS AND PRELEMINARY RESULTS

3.1. Limnological Data

A synthesis of the bio-optical properties of Tucuruí (TI) and Três Marias (T.M) reservoirs is presented in Table 1. An exploratory analysis of limnological and optical data revealed that Tucuruí and Três Marias reservoirs are not bio-optically homogeneous. Both displayed spatial variability in terms of constituent's concentrations. On average the concentrations of Chlorophyll-a (Chl-*a*), Total Suspended Matter (TSM), Dissolved Organic Carbon (DOC) for Tucuruí/Três Marias reservoirs were, respectively, 7.19/5.47 $\mu g/L^{-1}$, 3.43/4.34 mgL^{-1}, 2.59/1.95 mgL^{-1}.

Although there are no significant differences in terms of average values, Tucurui displayed higher amplitude of concentration for all three parameters. The organic to inorganic matter ratio (not shown in Table 1) in the Tucuruí reservoir (3.1) was five times higher than that one of Três Marias reservoir (0.62). This difference is explained by the fact that the watershed of Tucurui reservoir, located in the Amazon region, drains a vast area of forest exporting a large amount of organic matter to the reservoir.

Table 1: Descriptive statistics of some bio-optical properties of two Brazilian hydroelectric reservoirs: **TI** = **Tucuruí** reservoir, **T.M** = **Três Marias** reservoir, $\mathbf{Z_{eu\ (1\%)}}$ = lower limit of the euphotic zone, $\mathbf{K_{d\ (PAR)}}$ = vertical attenuation coefficient for downwards irradiance of PAR (Photosynthetically Available Radiation), $\mathbf{c_{(450)}}$ = beam attenuation coefficient in 450 nm, $\mathbf{a_{(550)}}$ = absorption coefficient in 450 nm, Chl-*a* = chlorophyll-a, **TSM** = Total Suspended Matter, **DOC** = Dissolved Organic Carbon.

Statistic	Reservoir	Mean	Median	Minimum	Maximum	Amplitude
$Z_{eu\ (1\%)}$	TI	6.17	6.85	1.14	9.42	8.28
[m^{-1}]	T.M	7.76	7.50	2.19	13.06	10.87
$K_{d\ (PAR)}$	TI	0.99	0.67	0.49	4.03	3.54
[m^{-1}]	T.M	0.70	0.61	0.35	2.10	1.74
$c_{(450)}$	TI	4.42	2.32	1.53	13.62	12.09
[m^{-1}]	T.M	2.52	2.46	1.17	4.92	3.76
$a_{(450)}$	TI	1.61	0.88	0.68	4.63	3.95
[m^{-1}]	T.M	0.84	0.60	0.36	4.36	4.00
Temp	TI	30.56	30.09	29.95	32.20	2.25
(°C)	T.M	24.54	24.61	21.03	25.75	4.72
Chl-*a*	TI	7.19	5.08	2.66	40.45	37.78
(µg/L)	T.M	5.47	4.67	1.17	13.22	12.05
TSM	TI	3.43	1.92	0.26	20.41	20.15
(mg/L)	T.M	4.34	3.33	1.33	11.93	10.60
DOC	TI	2.59	2.59	1.45	9.48	8.03
(mg/L)	T.M	1.95	1.90	0.93	2.71	1.78

3.2. Optical properties

The attenuation ($c_{(450)}$) and the absorption ($a_{(450)}$) coefficients of light in the water column, in 450 nm, were twice higher in Tucurui than Três Maris reservoir (Table 1). The higher attenuation in Tucurui was expected since the organic to inorganic ratio was 3.1 in Tucurui against 0.62 in Três Marias. These values of attenuation directly reflect in the availability of light for photosynthesis in the water column.

In Tucurui reservoir, about 50% of incident PAR were attenuated (absorbed or scattered) in the upper two meter of the water column (Fig. 2-a) while in Três Marias reservoir, these same percentage of attenuated were reached in the upper three meters (Fig. 2-b). In both reservoirs, downwelling irradiance (E_d) decreased to less than 10%, of their subsurface values, between four and six meters depth, for all sampling stations. Beyond this range of depth, Ed decay became subtle until light vanished.

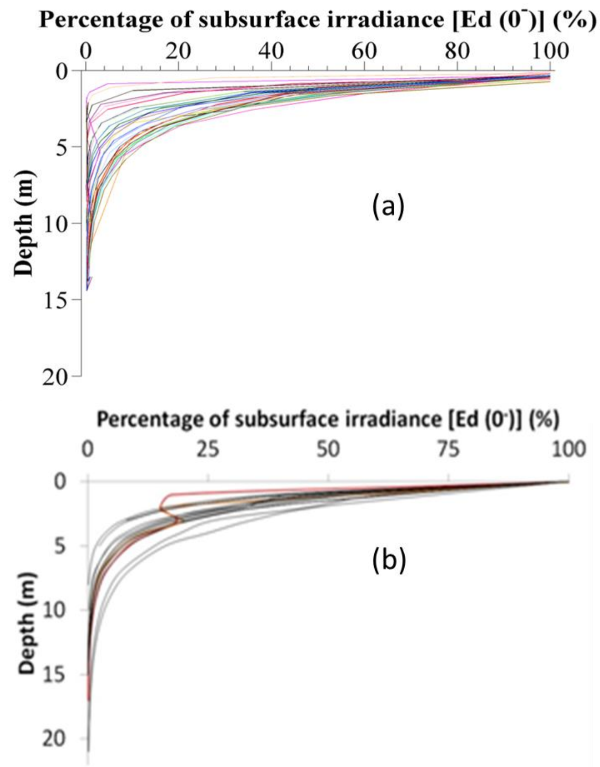
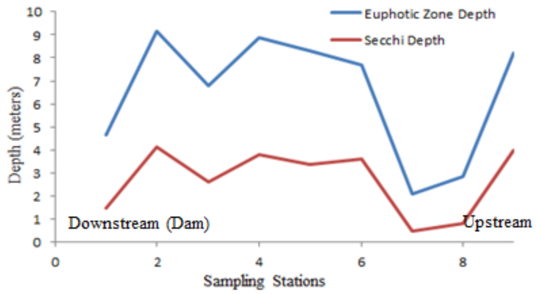


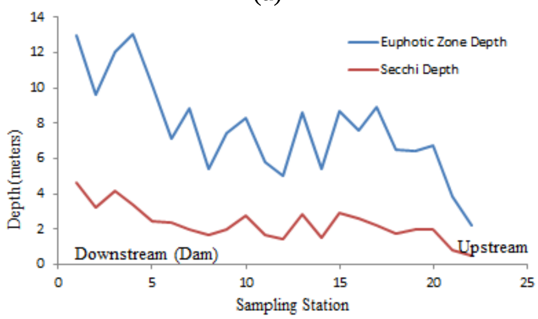
Fig. 2 Downwelling irradiance decay with depth: (a) in Tucurui and (b) Três Marias reservoir.

The diffuse attenuation coefficient Kd(PAR) varied from 0.50 to 2.19 in Tucurui, with mean value 0.91 and from 0.35 to 2.10, with mean value 0.70 in Três Marias. Values of Kd(λ) at three wavelengths (450, 550 and 670nm) in both reservoirs (not presented here) indicated that light penetrates more in green region, followed by red and blue, respectively. According to Kirk [6] this results can be related to higher productive environment due to phytoplankton and dissolved organic matter.

Figure 3 shows horizontal profiles of euphotic depth zone from downstream to upstream in each reservoir. While Tucurui reservoir displayed a low depth of euphotic zone near the dam, Três Marias showed a much higher euphotic depth (≈13.8 meters-Figure 3-b) with a systematical decrease towards upstream. At Tucurui reservoir, the highest euphotic depth (≈7.5 meters-Figure 3-a) occurred at the central and downstream sectors.



(a)



(b)

Figure 3 Horizontal profiles of the depth of euphotic zone from downstream to upstream in Tucuruí reservoir (a) and Três Marias reservoir (b).

4. CONCLUSION

As part of a larger project whose goal was to estimate carbon budget in Brazilian hydroelectric reservoirs, this study represented the first effort to provide a comprehensive bio-optical characterization, using a set equipment to determine IOPs and AOPs, in two of these reservoirs.

Profiling measurements provided information to understand the vertical structure of the water column as well as to relate it to changes in limnological variables, e.g., TSM, Chl-a, DOC.

The results of this preliminary study show the potential of hyperspectral profilers as support bio-optical characterization of aquatic environments. The possibility of determining the spectral composition and the decline of the light field along the water column, as well the accurate spatial determination of depth of the euphotic zone are high-value information as input to models to estimate primary productivity and carbon budget models in aquatic environments.

5. ACKNOWLEDGMENTS

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