Bio-Optical Modeling of Laguna de Bay Waters and Applications to Lake Monitoring Using ASTER Data

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Abstract: A bio-optical model was developed specific for turbid and shallow waters. Special studies were carried out to estimate absorption and scattering properties as well as backscattering probability of suspended matter. The inversion of bio-optical model allows for direct retrieval of turbidity and chlorophyll-a from the visible-near infrared (VNIR) range sensor. Time-series satellite imagery from ASTER AM-1 sensor, were used to monitor the Laguna de Bay water quality condition. Spatial distribution of temperature for the lake was extracted from the thermal infrared (TIR) sensor. Corresponding field surveys were conducted to parameterize the bio-optical model. *In-situ* measurements include suspended particle and chlorophyll-*a* concentrations profiles from nephelometric devices and processing of water samples. Hyperspectral measurements were used to validate results of the bio-optical model and satellite-based estimation. This study provides a theoretical basis and a practical illustration of applying space-based measurements on an operational basis.

Keywords: Laguna De Bay, water quality, remote sensing, bio-optical modeling, radiative transfer.

1. Introduction

Laguna De Bay (N14° 21, E 121°14') ranks as one of the largest freshwater inland in Asia at over 900 km^2 surface area. Known for In the face of massive environmental stresses imposed by adjacent land area and within the lake itself demands constant and dedicated monitoring system for the sustainable management of its resources [1, 2]. Natural conditions (topography, presence of tributaries, wind forcing, circulation etc.) coupled with anthropogenic forcing such as aquaculture, power generation, irrigation in and around the lake contribute to the significant variability, both at temporal and spatial scales, in the lake water quality conditions. While previous studies established distinctive seasonal variations in water quality [3, 4], critical data to deduct further information on the state of shallow lake, which is often turbid, are still piecemeal and intermittent since the primary mode of data collection are still point-specific, costly and labor-intensive. Although remote sensing techniques possess considerable potential for limnological monitoring on an operational basis due to synoptic data acquisition mode and periodic onsite revisit capability, its application to assess water quality conditions particularly for Laguna de Bay remains scarce or untapped. For instance, only the work by Mancebo *et al.* [5] to determine the correlation between the total suspended solids (TSS) in-situ and the reflectance in the Landsat TM of Laguna de Bay, exist. Nonetheless, methods such as these are based mainly on statistical analysis of remotely-sensed and field data, leading to algorithms with limited applicability and accuracy.

Our objective therefore in this study is to demonstrate the capability of time-series satellite image analysis, particularly that from ASTER sensor to generate seasonal patterns of spatially distributed water quality parameters through the use of physically-based bio-optical model.

2. Methods and Materials

2.1 Theory

Bio-optical modeling in natural waters exploits the fact that various optically active constituents such as suspended sediments and chlorophyll-a respond differently to visible portions of the electromagnetic spectrum. A basic remote sensing equation relating the inherent optical properties (IOPs) of natural waters with measured reflectance is

$$R(l)_{0-} = \frac{k\left(b_{bw} + b_S B C_S\right)}{a_w + a_S C_S + a_{CHL} C_{CHL} + a_{CDOM} + b_{bw} + b_S C_S} \quad (1)$$

where $R(l)_{0-}$ is irradiance reflectance just below the water surface at wavelength l . k is a constant factor (unitless) $= 0.544(0.629\cos q_s + 0.975)$ considering the q_s sun angle. Optical parameters include absorption coefficient for pure water a_w, the absorption coefficient for suspended sediment, a_S ; absorption coefficient for colored dissolved organic matter (CDOM; unitless), a_{CDOM} . b_w is scattering coefficient for pure water $\left(m^{-1}\right)$ b_S : backscatter coefficient for suspended particles $\left(m^{-1}\right)$ B : backscattering ratio (unitless) C_S : concentration of suspended sediments (mg/L) and C_{CHL} : concentration of chlorophyll-*a* (mg/L) while the concentration of total suspended matter for the same volume is $C_T = C_S + C_{CHL}$. Eq. (1) holds when the vertical distribution of water constituents is uniform over the water column and that optical thickness through depth z on a portion of the lake is large enough making bottom influence on reflectance negligible. Use of an auxiliary variable, $x = 1 - k / R(l)_{0-1}$ casts Eq. (1) as

$$
\begin{aligned}
&-\left(a_w + a_{CDOM} + b_{bw} x\right) = \\
&\left[a_{CHL} + \left(a_S - b_S\right) x\right] C_{CHL} + b_S BC_S
\end{aligned}
\tag{2}
$$

For m number of wavelength bands, Eq. (2) can be rewritten in matrix form as $\mathbf{z} = \mathbf{AC} + \mathbf{n}$. $\mathbf{z}$ is $(m \times 1)$ matrix containing $-0.5\left(a_w + a_{CDOM} + b_{bw} x\right)$ for all m wavelength ranges available. $\hat{\mathbf{C}}$ is (2×1) the water constituents $\left[C_{CHL} \quad BC_S\right]^T$ to be estimate while $\mathbf{n}$: variations in $\mathbf{z}$ not explained by the model. $\mathbf{A}$ is an $m \times 2$ matrix

$$
\mathbf{A} = \begin{bmatrix} a_{CHL} + \left(a_S - b_S\right) x \\ b_S \end{bmatrix} \tag{3}
$$

An ordinary least squares solution to simultaneously estimate the water constituents, $\hat{\mathbf{C}}$ is

$$
\hat{\mathbf{C}} = \left(\mathbf{A}^T \mathbf{A}\right)^{-1} \mathbf{A}^T \mathbf{z} \tag{4}
$$

By setting the partial derivatives $\partial\left(\mathbf{n}^T \mathbf{n}\right) / \partial \mathbf{C} = 0$ and $\partial F / \partial l = 0$, we can invert Eq. (2)

$$
\hat{\mathbf{C}} = a\,\mathbf{Uj} + \left(\mathbf{U} - a\,\mathbf{UJU}\right) \mathbf{A}^T\, \mathbf{N}^{-1} \mathbf{z} \tag{5}
$$

where $\mathbf{U}$: $(m \times m)$ $\mathbf{U}^{-1} = \mathbf{A}^T \mathbf{N}^1 \mathbf{A}$; $\mathbf{N}$: $(m \times m)$ the dispersion or covariance matrix of the residuals. $\mathbf{j}$ is $(2 \times 1) = [1,1]^T$ is integrated over the instrument response function $S(l)$ to calculate the radiance that corresponds to a brightness temperature for a particular instrument channel or band i within the $\left[x_1, x_2\right]$ range.

$$
L(b) = \frac{\int_{l_1}^{l_2} S(l)\, L(b)_{BB}\, d\, l}{\int_{l_1}^{l_2} S(l)_{BB}\, d\, l} \tag{6}
$$

where $L(b)_s$ is the radiance measured by the sensor.

2.2 ASTER Datasets

ASTER is composed of three instruments to detect 14 wavelength ranges in the visible infrared (VNIR), shortwave infrared (SWIR) and thermal infrared (TIR) spectrum. As it is, images over water-laden areas produced by ASTER will be sensitive to shorter wavelengths but the extended wavelength ranges are useful for determining the thermal properties of surface waters. The application of optical imagery on surface with high absorption requires precise spectral calibration. This is of particular concern for ASTER since it is reported that the detectors undergo continuous serious deterioration. Radiance calculation from DN_{L1B} based on the results for the trend analysis of the on-board calibrator and/or the vicarious calibration

$$
L(b)_{\mathrm{L1B}} = \frac{C(b,m)\left[DN_{\mathrm{L1B}}(b,m,v) - 1\right] K(b,v)}{K_{trend}(b,d)} \tag{7}
$$

where $C(b,m)$: Unit conversion coefficients in band b and gain mode m. R(b, v) is an optical calibration coefficients for sensor degradation in band b and calibration version v while $K_{trend}(b,d)$: Degradation function in band b and the *days* since launch estimated from the sensor trend analysis due sensor degradation in band b and calibration version v.

For this study, ASTER datasets (level 1b and 2) acquired at seven different dates in a period of two years (2001/01/03; 2001/04/25; 2001/11/03; 2002/03/27; 2002/09/03; 2002/12/08; 2003/01/16) have been compiled. All images were acquired approximately 10:35 AM at –8.59° viewing angle.

2.3 Field Data and Processing Techniques

Field surveys were conducted on October 2001, February 2002, March 2003 and August covering the west, central and south bay portions of Laguna de Bay. Chlorophyll-a, temperature, turbidity and salinity values were obtained using three modes of measurement. The first is by deployment of data-logging sensors, designed to capture the temporal variability of the water quality parameters at diurnal to monthly time scales at a fixed point in the lake. The second method is done through lowering an STD (Alec Instruments Inc.) instrument at desired locations to obtain profile of the water quality, and third, by direct water sampling, particularly for precise determination of chlorophyll-*a* and suspended particle concentrations and sizes, and identification of dominant algal species through laboratory processing. To characterize the optical properties of Laguna Lake waters, particularly absorption and scattering, an Ocean Optics S2000 underwater spectroradiometer was used to acquire spectral vertical profiles in the 350-1015 nm range to obtain downwelling and upwelling radiances.

3. Results and Discussion

A visual inspection of the time series images of Laguna de Bay as depicted by visible band 1 sensor (0.52-0.60 μm) the varying intensity of water reflectance that significant changes in water composition take place through time. The shorter wavelength range of the VNIR sensor detects the scattering of the suspended matter present in the lake waters, thus giving rise to the appearance of brighter reflectance returns from the water body in contrast to the darker hues of the land area. These bright scatter returns however are not uniform throughout the bay implying that it is not horizontally-well mixed. *In-situ* hyperspectral profiles follow the Beer's law of light attenuation but the rate of extinction is seen to vary from one sampling point to the other. Profiles of water quality parameters portray slight stratification (Fig. 1).

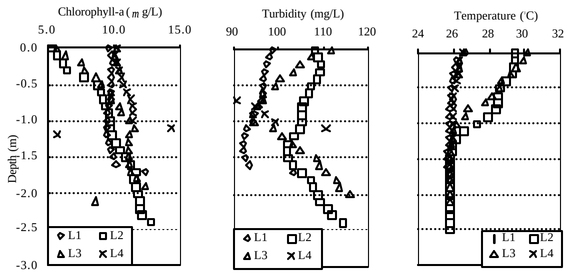

Fig. 1. Vertical profile of a) chlorophyll; b) turbidity concentrations and c) temperature in the west bay portion of Laguna de Bay observed March 2003 by STD measurements.

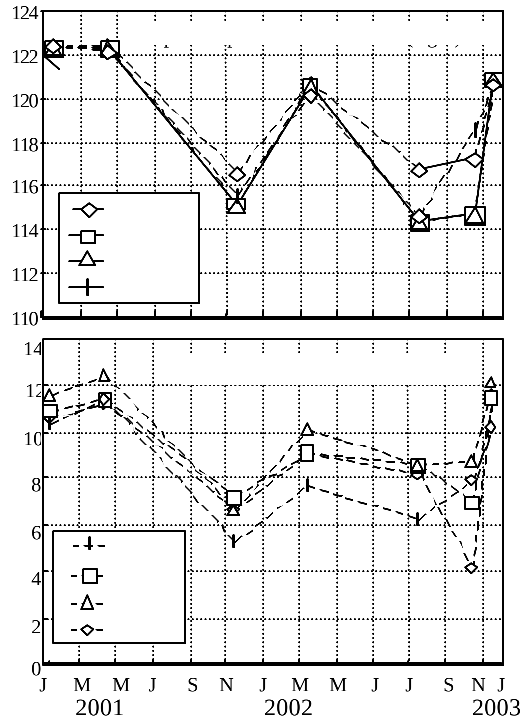

Fig. 2. Results of the chlorophyll-a, suspended particle and temperature estimations based on ASTER data.

Temporal patterns deducted from Fig. 2 indicate higher suspended particle levels during the dry season (November to May: 122 mg/L) than during the wet season (June to October: 114 mg/L). Trends in cholorophyll-a results closely follow this trend. Based on the computations, the east bay turbidity levels almost remained constant all throughout the year. Productivity is seen to be much lower in the west bay than in the central bay while chlorophyll-*a* values remain consistently lower in the south bay portion all throughout the period of study. Although the bay is shallow, influence of bottom cover reflectance is considered practically negligible. Derived lake surface temperatures follow general climate patterns. The resulting temperature estimates from the satellite data is comparable to the field data within limits of standard deviation (Fig. 3). Thermal plumes are apparent near a refinery plant.

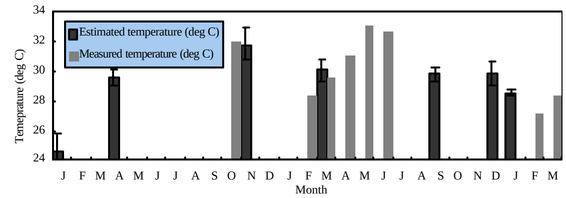

Fig. 3. Lake surface temperature at the west bay.

2.4 Discussion

A physics-based method has been outlined for extracting water quality parameters from optical (visible and thermal) remote sensing age data. This exercise demonstrates the capability of time series ASTER imagery to assess water quality, consistent with known conditions but providing more spatial detail at broader time scales. Results of the chlorophyll-a estimation can be used for providing input or validation data to number of physical nutrient and plankton growth models and for correlation with tributary runoffs and suspended solid loads. Another benefit of satellite-based processing is that assessment of surrounding watershed regions can be carried out with the same dat aset covering these areas. This feature allows cost-effective and synchronized monitoring of the Laguna de Bay ecological system as a whole because the same set of hardware and software resources can be utilized.

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