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Developing algorithm for estimating chlorophyll-a concentration in the Thac Ba Reservoir surface water using Landsat 8 Imagery

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ABSTRACT

This study aims at developing a regional algorithm to quantify chlorophyll-a concentration (Chla) in the Thac Ba Reservoir surface-water using Landsat 8 imagery basing on *in-situ* data of Chla and above-water reflectance taken in both dry and rainy seasons 2018. *In situ* datasets obtained from 30 water sampling sites show a strong correlation (R^2=0.73) with the reflectance ratio of two Landsat 8 (L8) bands, the green band (band 3: B3) versus the red band (band 4: B4), B3/B4, by an exponential equation. The algorithm for estimating Chla using this ratio was well-matched up the validation using multiple-dates *in-situ* datasets (R^2 = 0.82; RMSE ~ 5 %) and was then applied to L8 images level 2 acquired in both dry and rainy seasons to understand the spatiotemporal distribution of Chla over the reservoir. Obtained maps of Chla present clearly two trends: (1) Chla in the reservoir water in the dry season (averaged at 15.3 mg/m^3) is relatively lower than those in the rainy season (averaged at 17.0 mg/m^3); (2) In both seasons, Chla increased from water area in front of the Chay River mouth to the center of the reservoir. The algorithm and method outlined in this study could be applied to monitoring Chl in other inland waters having similar features as the Thac Ba Reservoir water.

Keywords: Water quality; remote sensing; trophic state; Yen Bai; monitoring.

1. Introduction

Chlorophyll-a concentration (Chla) is considered as an indicator of phytoplankton abundance and biomass of lake waters. Therefore, Chla is commonly used to assess the trophic level of lakes (Carlson, 1977; Michelutti et al., 2010), further measure the water quality (Padisák et al., 2006; US EPA, 2009; UNEP, 2014). In many countries and territories, Chla was selected as a primary indicator to assess the lake water quality, particularly the lake trophic state because of its direct relationship to the live organisms in aquatic environment (Padisák et al., 2006; US EPA, 2009). Additionally, Chla in lake waters can be quantified properly using passive remote sensing (Kutser, 2009) with the saving cost and time. Therefore, application of remote sensing for quantifying and monitoring Chla becomes an encouraged

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technique towards the effective management of inland waters worldwide.

According to the statistics of Directorate of Water Resource (DWR, 2017), Vietnam has total 6,648 reservoirs with the total designed capacity of 12,000 million m^3 water of which hundreds of reservoirs have been exploited for multi-purpose utilization, particularly for hydroelectric produce, local drinking water supply, tourism and aquaculture, therefore monitoring the water quality of these reservoirs is indispensable task of not only local governments but also inter-sectoral managers. Most of reservoirs are located in inaccessible areas and cover a large land area, making challenges for collecting essential field-data for the environmental management. Remote sensing with the advantages in collecting data on a large region even where people cannot access, providing a synoptic view of the study area and updating data frequently basing on a fix designed schedule can help ones come over-mentioned challenges, therefore, serves effectively many tasks in the environmental management framework, particularly monitoring purpose. The Thac Ba Reservoir has the largest area among reservoirs in Vietnam (~23,400 hectares) and is serving as a water supply source for local communities and a tourist attraction site. Therefore, frequently monitoring water quality is a critical work towards protecting the value of the reservoir.

Estimating and monitoring Chla using satellite data are a traditional approach of remote sensing. However, the use of satellite data for inland waters has been facing many challenges due to both the complexity of inland water physical and biogeochemical properties the specifications of current sensors (Palmer et al., 2015). Among numerous available sensors, Landsat program provides a promising tool for monitoring the quality of inland waters (Olmanson et al., 2008; Kutser, 2012; Tebbs et al., 2013) with free of charge and long historical data. The medium spatial resolution of Landsat imagery can support effectively for local studies, particularly for objects with medium size area such as the Thac Ba Reservoir in this study. The new Landsat, Landsat 8 (L8), has been used as a promising tool for monitoring lake water quality, particularly for estimating Chla over the world (Yang & Anderson, 2016; Watanabe et al., 2018; Boucher et al., 2018).

In Vietnam, L8 data has been exploited for measuring several water-quality parameters such as Chla in hypertrophic lakes in Hanoi urban areas (Bac et al., 2017), total suspended solids concentration (TSS) in estuarine waters (Nhung et al., 2016), water turbidity in Ha Long and Thuy Trieu Bays (Thuy et al., 2016; Quang et al., 2017). The use of L8 for monitoring water quality in a large reservoir where water is typically clear and is mostly ranked at mesotrophic level (Son et al., 2000) such as the Thac Ba Reservoir has not been carried out, creating a gap in the use of free satellite data for environmental study and management in the country.

This study aims at investigating the water optical feature and developing a regional algorithm for estimating Chla using the L8 imagery basing on statistical and regressive analyses of *in-situ* datasets of multi-date 30-point data of Chla and reflectance measured in the Thac Ba Reservoir. The algorithm then was experimented using L8 level 2 images to conduct the maps of Chla spatial distribution over the reservoir in rainy and dry seasons.

2. Materials and Methods

2.1. Study area

The Thac Ba Reservoir is located within two districts, Yen Binh and Luc Yen, of Yen Bai Province and is created by the construction of the Thac Ba hydroelectric plant in the 1960s. The total water coverage area of the Thac Ba Reservoir is approximately 20 thousands hectares, extends following the direction of Northwest-

Southeast (Fig. 1). The length of the reservoir is 80 km with the maximum width is 10 km and the average depth is 15–25 m creating an appropriate condition for water monitoring using medium resolution satellite data such as Landsat with 30 m pixel-size. The total capacity of the reservoir ranges from 3 to 3.9 billion m^3 water which is feed by the Chay River and local streams. Currently, addition to provide water for the Thac Ba Hydroelectric Plant, the reservoir is also a source of drinking water supply for thousands of households in Yen Bai city and Yen Binh district (Yen Bai Province) and is a tourist attraction in Northern Vietnam, therefore water quality is one of the critical issues attracting the attention of both managers, tourist agencies and local community. Besides, floating fish farming has been blooming recently, causing serious environmental consequence for the reservoir's water quality. However, studies and projects associated with the water quality of the Thac Ba Reservoir are limited and unavailable that challenges local managers and communities to understand the water environmental state thoroughly and effectively manage the human activities in the reservoir.

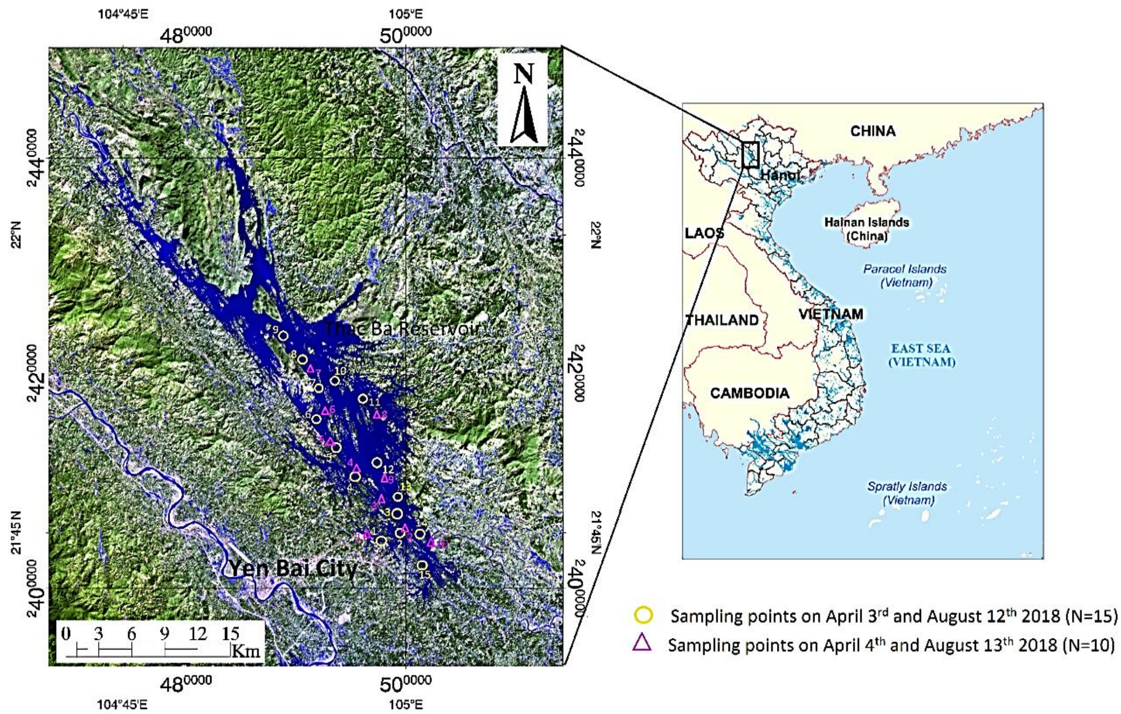

Figure 1. Locations of the Thac Ba Reservoir in Vietnam and 50 sampling points in two field trips in April and August 2018 overlaid the L8 image of the reservoir (false color 7:6:4)

2.2. Water sampling and measurement

The *in-situ* Chla and above-water radiometric data were collected concurrently during the two field campaigns on April 3rd–4th 2018 and August 12th–13th 2018. Water samples and reflectance measurement were collected/recorded at total 50 sites (Fig. 1) within an hour before and two hours after the L8 overpass at ~ 10:30 AM local time by a speedboat. Water samples were taken at a depth of 0–50 cm using a Van Dorn water sampler, preserved in 1-liter cleaned, dark-color bottles and then refrigerated and transported to the laboratory.

In the laboratory, Chla of the water samples were determined, following the standard method coding SMEWW 10200H: 2012 of the American Public Health Association (APHA, 1998). Accordingly, the water samples were filtered using a pre-washed 47 mm glass fiber filter and then extracted into 90% acetone. The Chla of the extracts was determined spectrophotometrically using a Labomed UV–VIS RS model UV-2502 spectrometer (Labomed Inc., Los Angeles, CA, USA). Chla was calculated accordingly, using the following equation:

$$\text{Chla } (\mu g/L) = (Ca \times V_1)/V_0 \qquad (1)$$

where V_1 is the extract volume in liters (L), V_0 is the sample volume in cubic meter (m^3), and C_a is Chla pigment in the extract. The Chla pigmented, C_a, is calculated as:

$$C_a = 11.85 \times D_{664} - 1.54 \times D_{647} - 0.08 \times D_{630} \qquad (2)$$

where D_{664}, D_{647}, and D_{630} are optical density at 664, 647, and 630 nm, respectively.

The above-water reflectance measurements were made at all the sites using the SVC (Spectra Vista Corporation) GER1500 spectroradiometer. The reflectance at each measured point, $\mathbf{R_w}(\lambda)$, was corrected for surface Fresnel reflection using the following equation:

$$R_w(\lambda) = R_p * \{[L_w(\lambda) - \rho * L_{sky}(\lambda)]/\pi * L_p\} \qquad (3)$$

where R_p is the reflectance of our standard reference panel, $L_w(\lambda)$ is the water-leaving radiance, $L_{sky}(\lambda)$ is the sky radiance measured sequentially at 40-45 degrees from nadir and zenith, respectively, and 135 degrees from the Sun in azimuth (Mobley, 1999), ρ is the air-water interface Fresnel reflectance with a value of 0.022, and L_p is the radiance for the reference panel.

Along with water sampling, water clarity was measured concurrently in the field using a standard 20 cm plastic Secchi disk. The Secchi depth measurements were used in the field as a reference to select the sampling points avoiding the effects of the reservoir bottom on water reflectance data.

2.3. L8 images used

Two free-cloud L8 images acquired in different seasons (dry and rainy seasons) were used and analyzed in this study. The image characteristics, including acquisition time, cloud coverage, path/row, and spatial resolution are tabulated in Table 1.

Table 1. The Landsat 8 (L8) scenes used in the study

No.	Image ID	Path/row	Time of acquiring	Cloud coverage	Level/ module	Spatial resolution
1.	LC81270452014019LGN01	127/45	January 19th 2014	< 10%	2/LaSRD	30 m
2.	LC81270452014243LGN02	127/45	August 31st 2014	< 40 %	2/LaSRD	30 m

The standard Landsat 8 surface reflectance products (L8SR), obtained from the Landsat Surface Reflectance Code (LaSRC) was directly ordered and downloaded from USGS Earth Explorer data portal (https://earthexplorer.usgs.gov/) whereas R_w(L8SR) was retrieved at a 30-meter spatial resolution generated from L8 data through using the Landsat Surface Reflectance Code (LaSRD) which uses the Moderate Resolution Imaging Spectroradiometer-Climate Modeling Grid-Aerosol Information as input data to correct the effect of the atmosphere (Vermote et al., 2016). Although the primary target of L8SR is for land surface change studies, it has been proven to be most suitable for monitoring water constituents in inland lake waters (Bernardo et al., 2017), therefore is selected for demonstrating the proposed algorithm performance in this study.

3. Results and Discussions

3.1. Features of the Thac Ba reservoir water

The measured reflectance spectra ($R_w(\lambda)$) within the range of 400–900 nm of the 50 water sampling points over the Thac Ba

Reservoir are shown in Figures 2A, 2B and 2C, 2D for data obtained on April 3rd–4th 2018 and August 12th–13th 2018, respectively. The hyperspectral reflectance of the reservoir water measured on August 10th 2018 is slightly larger in magnitude than those measured in April 2018, corresponding to higher levels of Chla in water in the rainy season 2018 (August). The $R_w(\lambda)$ are similar in shape and magnitude to previously reported spectra of clear lake waters (Tiwari et al., 2012) with a distinct peak of water-leaving radiance within the green region, i.e., 550 to 570 nm. A small reflectance peak appeared weakly within 800 to 850 nm indicating the presence of photosynthesis bacteria, (Gitelson et al., 1997) in the reservoir water.

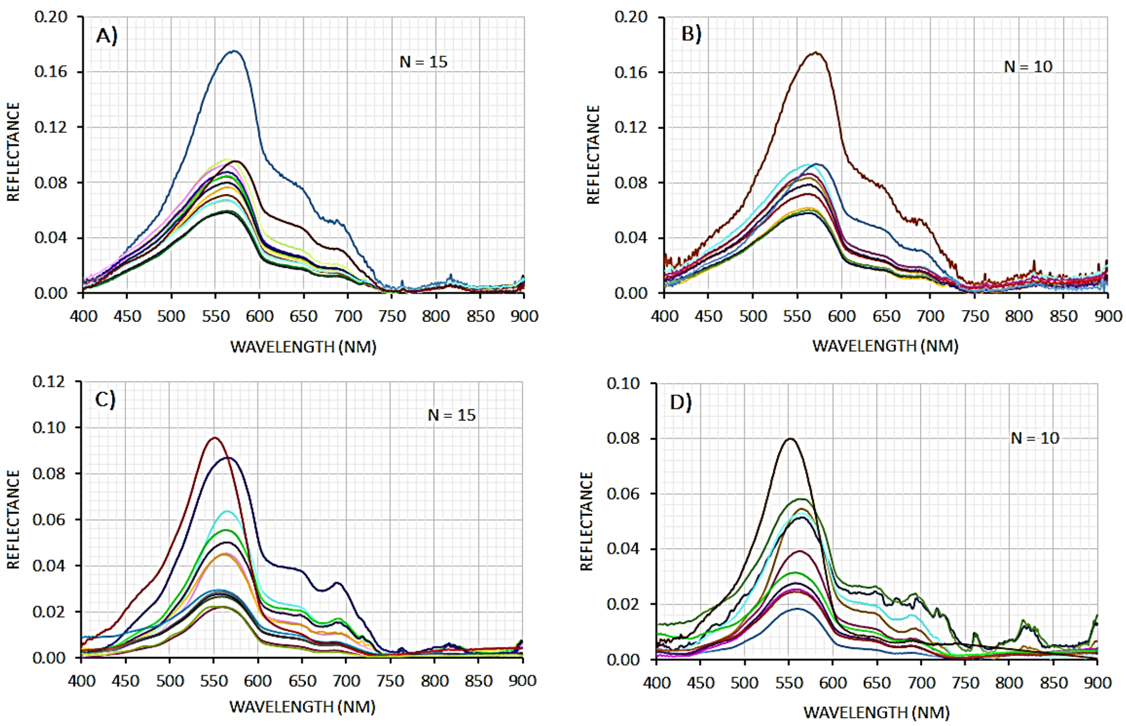

Figure 2. Reflectance spectra curves of water 50 sampling points over the Thac Ba Reservoir measured on April 3rd and 4th 2018 (A and B, respectively), and August 12th and 13th 2018 (C and D, respectively). Each curve line is corresponding for a sampling point water reflectance feature

Table 2 shows the descriptive statistics parameters of *in-situ* Chla obtained from two surveyed dates and its correlations (R_{Cha}) to *in-situ* SD and L8 band-response reflectance mean values. Accordingly, Chla in the reservoir water ranged widely, from 14 to 19.5 mg/m^3 (average value of 17.5 mg/m^3) in April 2014 and from 15 to 40 mg/m^3 in January 2018 (average value of 21.0 mg/m^3), correlated highly to SD (R_{Cha} = 0.73 and 0.74). According to Carlson and Simpson's (1996) scale, the Thac Ba Reservoir can be classified as a eutrophic water with Chla ranged within the Eutrophy level (Chla: from 7.3 to 56 mg/m^3; SD: from 0.5 to 2 m).

Also, in table 2, Chla correlates poorly and unstably to reflectance values those are corresponding to L8 band data. For example, in dataset obtained in April 2018, Chla does not correlate to any L8 band-response reflectance means values (Pearson correlation coefficient, R_{Chla}, are 0 to –0.21). With the highest correlation observed between Chla and the L8 blue band (B1 and B2, R_{Chla} = 0.54 and 0.52) from the dataset in August 2018, the L8 single band algorithm is proven inappropriate for estimating Chla in the Thac Ba Reservoir water. As consequence, the band-ratio algorithms should be employed and evaluated for Chla estimation purpose.

Table 2. Descriptive statistics result of *in-situ* Chla and its correlations to *in-situ* SD and L8 band-response reflectance mean values (band 1 to band 5: B1 to B5)

Date	Parameter	N	Range	Minimum	Maximum	Mean	Median	Std. Deviation	R_{Chla}
April 3rd – 4th 2018	Chla (mg/m^3)	25	5.50	14.00	19.50	17.50	17.50	1.40	
	SD (m)	25	1.27	1.53	2.80	1.85	1.7	0.17	0.74
	B1: R_w(435-451)	25	0.021	0.013	0.035	0.021	0.021	0.005	0.18
	B2: R_w(452-512)	25	0.036	0.027	0.063	0.039	0.038	0.009	0.18
	B3: R_w(533-590)	25	0.109	0.055	0.163	0.080	0.070	0.027	0.00
	B4: R_w(636-673)	25	0.054	0.014	0.068	0.026	0.021	0.014	-0.21
	B5: R_w(851-879)	25	0.011	0.001	0.012	0.005	0.004	0.003	0.15
August 12th –13th 2018	Chla (mg/m^3)	25	25.00	15.00	40.00	21.10	20.50	6.10	
	SD (m)	25	0.90	1.40	2.30	1.80	1.85	0.15	0.73
	B1: R_w(435-451)	25	0.015	0.002	0.017	0.005	0.005	0.003	0.54
	B2: R_w(452-512)	25	0.032	0.005	0.037	0.013	0.104	0.007	0.52
	B3: R_w(533-590)	25	0.065	0.017	0.082	0.038	0.029	0.019	0.32
	B4: R_w(636-673)	25	0.032	0.003	0.035	0.011	0.008	0.007	0.38
	B5: R_w(851-879)	25	0.004	0.001	0.005	0.002	0.002	0.001	0.16

3.2. L8 band based algorithm for estimating Chla in Thac Ba Reservoir water

Commonly used band ratios to estimate Chla such as green-to-red, NIR-to-red and blue-to-green (Gholizadeh et al., 2016) were also examined using the *in-situ* dataset of 30 points obtained in April 3rd 2018 and August 12th 2018. The L8 data has two bands in the blue region (band 1 and 2: B1 and B2) therefore cross-correlation analysis was conducted for four ratios: green-to-red (B3/B4), NIR-to-red (B5/B4), blue-to-green (B3/B2 and B3/B1). Table 3 shows the linear regression analysis result of Chla and these band ratios with computed parameters of the correlation coefficient (R), determination coefficient (R^2), root mean square error (RMSE), slope and *y*-intercept. Accordingly, the reflectance ratio corresponding L8 green-to-red bands (B3/B4) is highly correlated to the *in-situ* Chla (R^2 = 0.79) and can be used to estimate Chla in the reservoir water with the average error is corresponding approximately 10 % (the standard error of the estimates = 2.13) of the mean of *in-situ* Chla dataset (19.2 mg/m^3).

Table 3. Linear regression result of *in-situ* Chla and L8 band ratios

Ratio	R	R^2	RMSE	Slope	*y*-intercept
B3/B4	*0.89*	*0.79*	*2.13*	0.24	-1.09
B5/B4	0.69	0.48	3.35	0.02	-0.10
B3/B2	0.07	0.05	4.62	0.10	2.29
B3/B1	0.09	0.01	4.62	0.05	4.65

Figure 3 presents the result of curve-fit regression analysis of Chla and B3/B4 with the computed model, R-squared (R^2: determination coefficient) and RMSE of the estimates. As result, the linear function has the highest value of R^2 (R^2 = 0.79, Fig. 3A), but the exponential has the lowest value of error (the standard error of the estimate is 1.00 corresponding approximately 0.5 % of the Chla dataset, Fig. 3B). Logarithm and Power functions (Fig 3C and 3D) are getting the lower values of R^2 than 0.70, therefore, are not the fit models to estimate Chla in this case. The result again confirms the suitable of exponential function for estimating water constituents from remote sensing data which was proven in the preceding study (Ha and Koike, 2011).

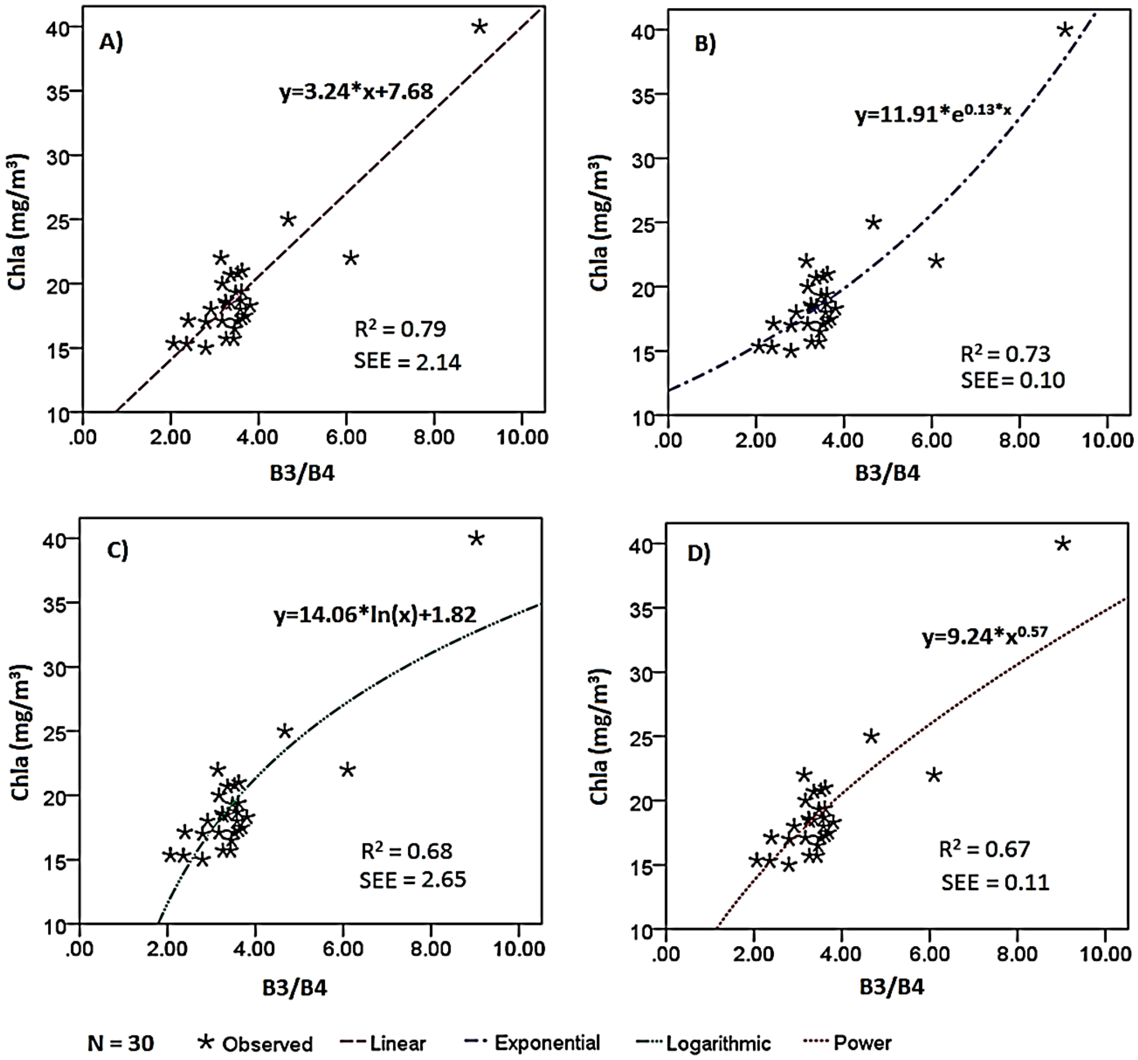

Figure 3. Results of the curve-fit regression analysis between Chla and reflectance ratio corresponding L8 green-to-red bands (B3/B4) using 30 points *in-situ* data over the Thac Ba Reservoir measured on April 3rd 2018 August 12th 2018. Acceptable R^2 value and low error (through the standard error of the estimates: SEE) of the exponential curve (B) confirm the suitability of exponential function for estimating Chla

The exponential function for estimating Chla in the Thac Ba Reservoir water presented in Figure 3B then was validated using the 20 points *in-situ* datasets of Chla and reflectance obtained on April 4th 2018 and August 13th 2018. Figure 4 shows the validated result where estimated Chla is highly correlated to *in-situ* Chla (R^2 = 0.82) with low error value (RMSE = 0.91, corresponding to approximately 5 % of *in-situ* Chla). The well matched-up of estimated Chla to *in-situ* Chla confirms the appropriateness of the function for estimating Chla. In the other words, Chla in the Thac Ba Reservoir surface-water can be estimated using the following equation:

$$Chla = 11.91*e^{0.18*B3/B4} \quad (4)$$

where Chla is united in mg/m^3, B3/B4 is the ratio of reflectances retrieved from the L8 green and red bands which is unit-less.

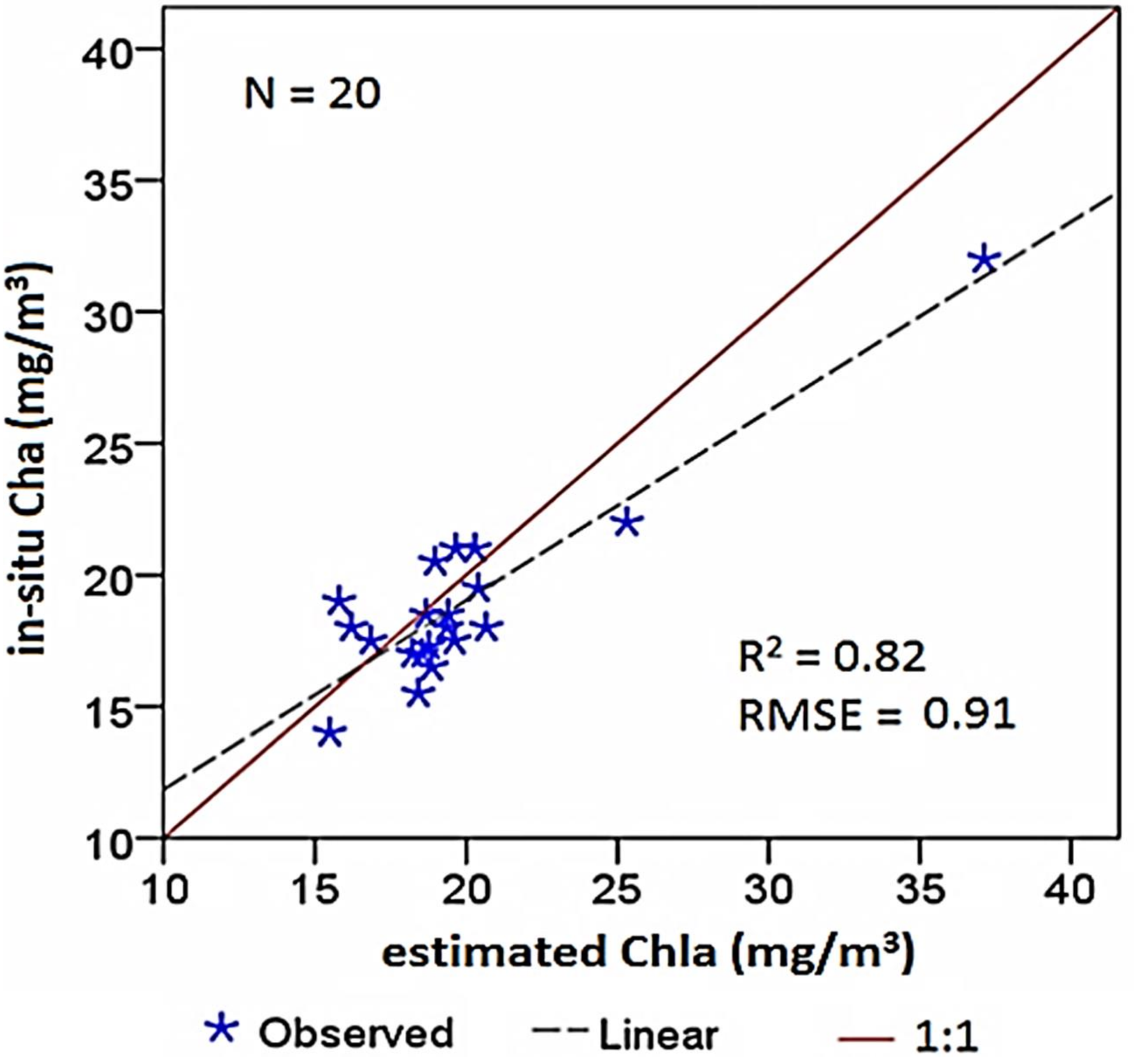

Figure 4. Validation the exponential function for estimating Chla in the Thac Ba Reservoir water in Figure 3B using *in-situ* dataset of total 20 points obtained on April 4th 2018 (N = 10) and August 13th 2018 (N = 10)

3.3. Experiment on mapping spatial distribution of Chla using L8 imagery

With the assumption that L8 level 2 data is well atmospheric corrected for retrieving the $R_W(\lambda)$ as mentioned in the preceding study (Bernardo et al., 2017), two free-cloud L8 level 2 scenes acquired dry season (January) and rainy season (August) of the year 2014 were used in combined with Eq. 4 to map the spatial distribution of Chla in the Thac Ba Reservoir. Figure 5 presents the spatial and seasonal change of estimated Chla over the reservoir. Accordingly, Chla in the reservoir water in January 2014 (dry season), ranged from 14.2 to 16.0 mg/m^3, averaged at 15.3 mg/m^3 (Fig. 5A), is relatively lower than one estimated in August (rainy season) which ranged from 13.5 to 20 mg/m^3 and averaged at 17.0 mg/m^3 (Fig. 5B). In space, Chla presents at the lowest levels at area in front of the Chay River mouth and tends to the highest level at the center area of the reservoir. In dry season, Chla at high level presents along the water area along the tourist route from Huong Ly Port to Thuy Tien Cave in Mong Son Mountain, while in the rainy season Chla tends to accumulate at high level in the center of the reservoir and in the water area in front of the Thac Ba hydropower dam.

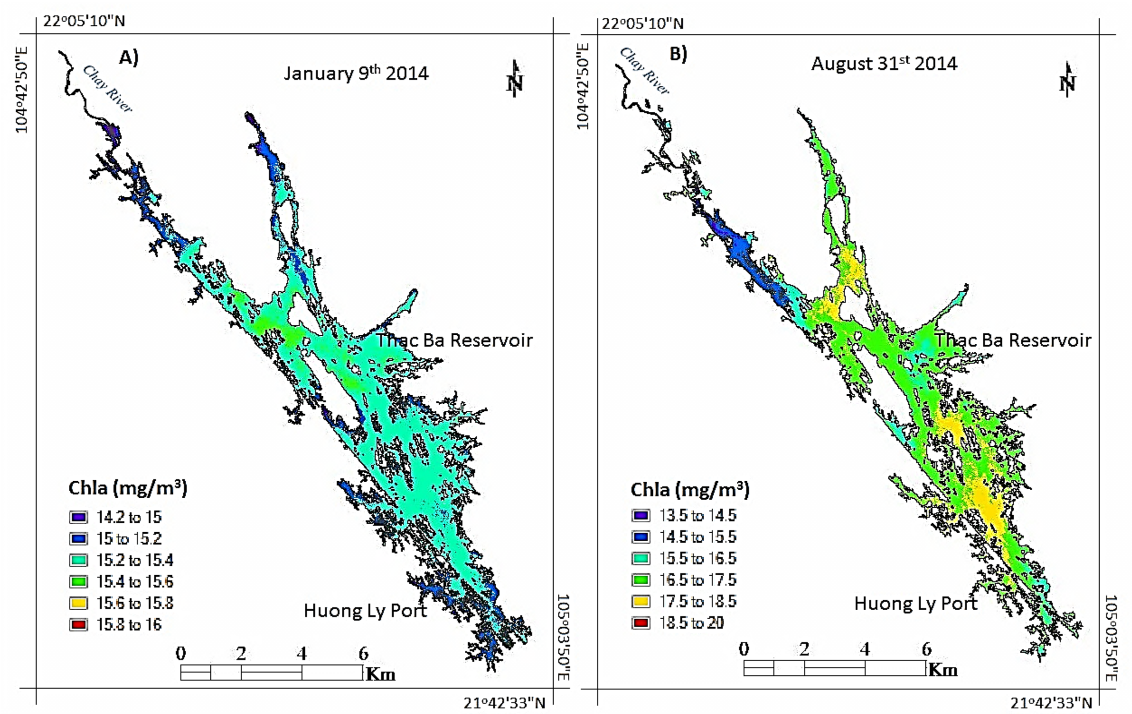

Figure 4. Maps of Chla spatial distribution over the Thac Ba Reservoir estimated from the L8 level 2 images acquired in January 2014 (A) and August 2014 (B) and Eq. (4)

Because the high coverage of cloud in L8 scenes acquired in April and August 2018, the estimated Chla from L8 at that time is absent, therefore, is unable to use to validate the Eq. (4) by satellite data directly. However, the obtained results from the L8 images acquired in both dry and rainy seasons in 2014 demonstrated the real applicability of the proposed method and indicated the appropriateness of the Eq. (4) for monitoring Chla through the estimates at different times of the year. Estimated Chla in the reservoir water presenting in these two maps (Fig. 5) showed clearly the seasonal trend and spatial pattern that conforming to the field monitored data which presented in the preceding study (Son et al., 2000).

It should be noticed that the method for estimating Chla using L8 data described in this work is based mainly on the *in-situ* data of reflectance and Chla measured concurrently. As the concept of optical remote sensing, Chla in this study is the concentration in the surface water only (0-50 cm depth, just below the air-water interaction layer). Furthermore, remote sensing for aquatic environment is much depended on the atmospheric correction procedure due to the large effect of the atmosphere on water reflectance. This work used the L8 level 2 data which is processed by the USGS with the main purpose for land studies that needs be further evaluated for water quality monitoring task, particularly for inland waters in the tropical region such as Vietnam.

The regional algorithm for estimating Chla in the Thac Ba Reservoir water proposed in this study can be used to quantify and monitor this parameter in the reservoir using L8 data after appropriate atmospheric correction procedure and opened widely to measure Chla in water-bodies having similar water optical feature and geographic condition such as the reservoir.

4. Conclusions

The algorithm for estimating Chla in the Thac Ba Reservoir water presented in this study was developed basing on the analysis of cross-relationship between Chla and the L8 band featured data which measured concurrently over the reservoir in both dry and rainy seasons. Results from this work can be summarized as the followings: (1) Chla in the Thac Ba Reservoir water can be estimated by an exponential function of the L8 band-ratio of the green-to-red bands with a high accurate estimated result (R^2 = 0.82, RMSE = 0.91); (2) Estimated Chla from the L8 images acquired in both dry and rainy seasons shows clearly the seasonal trend and spatial pattern of Chla in the reservoir water, i.e.: Chla in the dry season (mean value of 15.3 mg/m^3) is relative lower than those in the rainy season (mean value of 17 mg/m^3) and distributes at low-to-high levels following the direction from water area in front of the Chay River mouth to the center of the reservoir; (3) The resultant spatial distribution maps of Chla over the reservoir using L8 level 2 images demonstrated the high applicability of the proposed method for monitoring Chl in the reservoir water and other waters having similar geographic feature such as the Thac Ba Reservoir.

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