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An Enhanced Three-Band Index for Estimating Chlorophyll-a in Turbid Case-II Waters: Case Studies of Lake Kasumigaura, Japan, and Lake Dianchi, China

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Abstract—A three-band index was previously proposed and successfully utilized to estimate the chlorophyll-a concentration (Chl-a) in case-II waters. However, this index shows uncertainties in highly turbid situations. In this study, an enhanced three-band index is proposed to solve this problem. Since the new index employs bands that are identical to those of the original three-band index, it can be applied to Medium Resolution Imaging Spectrometer (MERIS) data. The performance of the index was evaluated using the data collected from two turbid Asian lakes: Lake Kasumigaura, Japan, and Lake Dianchi, China. The results showed that the Chl-a predicted by the enhanced three-band index was strongly correlated with the measured Chl-a ($R^2 > 0.83$), and the root-mean-square error (rmse) and the normalized root-mean-square error (NRMS) were both reduced for the two lakes (for Lake Kasumigaura, rmse from 13.97 to 8.68 $\text{mg} \cdot \text{m}^{-3}$ and NRMS from 19.01% to 12.30%; for Lake Dianchi, rmse from 41.29 to 15.28 $\text{mg} \cdot \text{m}^{-3}$ and NRMS from 35.83% to 21.34%). These findings imply that, if accurately atmospheric-corrected MERIS data are available, the enhanced three-band index could be used for mapping Chl-a even in highly turbid case-II waters.

Index Terms—Chlorophyll-a, four-band index, highly turbid case-II waters, Medium Resolution Imaging Spectrometer (MERIS) data, three-band index.

I. INTRODUCTION

CHLOROPHYLL-A is an important optically active substance (OAS) existing in water bodies; its concentration is strongly related to the total primary production of water bodies and also acts as an index of eutrophication with respect to water quality. However, the accurate estimation of chlorophyll-a con-

centration (Chl-a) from remotely sensed data is particularly challenging in case-II waters (waters containing not only phytoplankton but also suspended sediments, dissolved organic matter, and anthropogenic substances whose concentrations are not correlated with Chl-a). Therefore, substantial efforts have been made to improve the estimation accuracy in case-II waters [1].

Recently, a conceptual three-band model has been proposed for determining Chl-a in case-II waters [2]. This model requires reflectance in three spectral bands ($\lambda_1 = 660\text{--}670$ nm, $\lambda_2 = 700\text{--}730$ nm, and $\lambda_3 = 740\text{--}760$ nm) as input to calculate a three-band index. The selection of these bands is based on the following three requirements [2]: 1) The first band λ_1 should be maximally sensitive to phytoplankton absorption; 2) the second band λ_2 should be minimally sensitive to phytoplankton absorption, but tripton and colored dissolved organic matter (CDOM) absorption should be similar to those in the first band; and 3) the third band λ_3 should be minimally affected by the absorption of phytoplankton, tripton, and CDOM but should have similar backscattering to those of the first and second bands. Given these requirements, the three-band index can be expressed as follows:

$$\begin{aligned} & [1/R_{\text{rs}}(\lambda_1) - 1/R_{\text{rs}}(\lambda_2)] \times R_{\text{rs}}(\lambda_3) \\ & = [a_{\text{ph}}(\lambda_1) + a_w(\lambda_1) - a_w(\lambda_2)] / a_w(\lambda_3) \end{aligned} \quad (1)$$

where R_{rs} is the above-water remote-sensing reflectance and a_{ph} and a_w are the absorption coefficients for phytoplankton and pure water, respectively. The three optimal bands are available on the Medium Resolution Imaging Spectrometer (MERIS) sensor, allowing the application of the three-band model to real MERIS data.

However, *Le et al.* [3] pointed out that one of the assumptions of the original three-band model that the absorption and backscattering of suspended solids can be neglected at λ_3 is not reasonable in some highly turbid case-II waters such as those of Lake Taihu, China. Therefore, the original three-band index for highly turbid case-II waters should be expressed as follows:

$$\begin{aligned} & [1/R_{\text{rs}}(\lambda_1) - 1/R_{\text{rs}}(\lambda_2)] \times R_{\text{rs}}(\lambda_3) \\ & = [a_{\text{ph}}(\lambda_1) + a_w(\lambda_1) - a_w(\lambda_2)] / [a_w(\lambda_3) + b_b(\lambda_3) + a_d(\lambda_3)] \end{aligned} \quad (2)$$

where a_d is the absorption coefficient of the water constituents excluding pure water and b_b is the total backscattering coefficient. To further remove (or minimize) the absorption and backscattering effects of suspended solids and also to partially

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suppress the absorption of pure water at the denominator of (2), *Le et al.* [3] developed a four-band index instead of the original three-band index suggested in [2]. The four-band index can be expressed as follows:

$$\begin{aligned} & [1/R_{rs}(\lambda_1) - 1/R_{rs}(\lambda_2)] / [1/R_{rs}(\lambda_4) - 1/R_{rs}(\lambda_3)] \\ & = [a_{ph}(\lambda_1) + a_w(\lambda_1) - a_w(\lambda_2)] / [a_w(\lambda_4) - a_w(\lambda_3)]. \quad (3) \end{aligned}$$

The four-band index was found to provide a better estimation of Chl-a than the original three-band index in the case of Lake Taihu, China [3]. As a crucial prerequisite, successful application of the four-band model depends on the availability of reflectance data at four narrow bands within the wavelength range of 660–760 nm. However, in practice, it is difficult to satisfy this prerequisite from existing satellite sensors.

The objectives of the present study are the following: 1) to enhance the original three-band index by adapting the principle of a four-band index and 2) to evaluate the performance of the enhanced three-band index using the data collected from two turbid Asian lakes, namely, Lake Kasumigaura, Japan, and Lake Dianchi, China.

II. DATA AND METHODS

A. In Situ and Laboratory Data Collection

Water samples and corresponding reflectance spectra were collected from two lakes in Japan and China. Lake Kasumigaura is located in the eastern part of Japan's Kanto Plain and has a surface area of 171 km², an average depth of 4 m, and a maximum depth of 7.3 m; Lake Dianchi is located in a plateau area of southwestern China and has a surface area of 300 km², an average depth of 4.3 m, and a maximum depth of 11.3 m. Four data collection campaigns were carried out in February 2006 (10 sites), in September 2007 (11 sites), in August 2008 (14 sites), and in September 2009 (21 sites) in Lake Kasumigaura. Another four campaigns were carried out in October 2007 (3 sites), in July 2008 (5 sites), and in March and July 2009 (4 and 41 sites, respectively) in Lake Dianchi. Reflectance measurements were performed between 10:00 and 14:00 h local time. All measurements were taken over optically deep water, and floating scum was not found at these sampling sites. The water-leaving radiance ($L_u(\lambda)$), the downward irradiance ($E_d(\lambda)$), and the downward radiance of skylight ($L_{sky}(\lambda)$) were measured at each site using a FieldSpec HandHeld spectroradiometer (Analytical Spectral Devices, Inc., Boulder, CO) in the range of 325–1075 nm at 1-nm intervals. The above-water remote-sensing reflectance ($R_{rs}(\lambda)$) was calculated approximately using the following equation [4]:

$$R_{rs} \approx \left(\frac{L_u(\lambda)}{E_d(\lambda)} - \frac{F(\theta)L_{sky}(\lambda)}{E_d(\lambda)} \right) \times Cal(\lambda) \times 100 \quad (4)$$

where $Cal(\lambda)$ is the spectral reflectance calibration factor for the Spectralon reflectance panel (SRT-99-100). $F(\theta)$ represents the reflectance of the skylight at the air–water interface ranging from 0.022 to 0.025, and θ is the measurement view angle [5]. In this study, a constant value of 0.024 was used for $F(\theta)$.

Chlorophyll-a was extracted using methanol (100%) at 4 °C for 24 h under dark conditions. The absorbances of the extracted

chlorophyll-a were measured at four wavelengths (750, 663, 645, and 630 nm), and the concentrations were calculated according to Scientific Committee on Oceanic Research–United Nations Educational, Scientific and Cultural Organization equations [6]. CDOM absorption was measured using a Shimadzu UV-1700 spectrophotometer after water was filtered. The concentrations of the total suspended solids (TSSs), organic suspended solids (OSSs), and inorganic suspended solids (ISSs) were determined gravimetrically. Samples were filtered through precombusted Whatman GF/F filters at 500 °C for 4 h to remove dissolved organic matter in suspension, which was then dried at 105 °C for 4 h and weighed to obtain TSS. The filters were recombusted at 500 °C for 4 h and then weighed again to obtain ISS. OSS was derived by subtracting ISS from TSS.

B. Development of an Enhanced Three-Band Index and Accuracy Assessment

For the original three-band index, the following assumptions were presented by Gitelson *et al.* [2]:

- Assumption 1) $a_{ph}(\lambda_1) \gg a_{ph}(\lambda_2)$, $a_{tr}(\lambda_1) \approx a_{tr}(\lambda_2)$, and $a_{cdom}(\lambda_1) \approx a_{cdom}(\lambda_2)$;
- Assumption 2) $a_w(\lambda_3) \gg a_{ph}(\lambda_3) + a_{tr}(\lambda_3) + a_{cdom}(\lambda_3)$;
- Assumption 3) $b_b(\lambda_1) \approx b_b(\lambda_2) \approx b_b(\lambda_3)$.

Here, a_{tr} and a_{cdom} are the absorption coefficients for tripton and CDOM, respectively. Accordingly, the original three-band index written as (1) can remove the effects of tripton and CDOM. However, in highly turbid case-II waters, assumption 2 is violated, and the original three-band index should be rewritten as (2). The remaining effects of tripton and CDOM in (2) resulted in uncertainty in estimating Chl-a [3]. On the other hand, comparing the characteristics of the absorption coefficients of phytoplankton, tripton, and CDOM between the second and third bands suggested by Gitelson *et al.* [2], it is found that their absorptions in the second band are similar to those in the third band (i.e., $a_{ph}(\lambda_2) \approx a_{ph}(\lambda_3)$, $a_{tr}(\lambda_2) \approx a_{tr}(\lambda_3)$, and $a_{cdom}(\lambda_2) \approx a_{cdom}(\lambda_3)$), even for the highly turbid case-II waters. Therefore, if we adapt the format of the four-band index by using the second band twice, the original three-band index can be modified as

$$\begin{aligned} & [1/R_{rs}(\lambda_1) - 1/R_{rs}(\lambda_2)] / [1/R_{rs}(\lambda_3) - 1/R_{rs}(\lambda_2)] \\ & = [a_{ph}(\lambda_1) + a_w(\lambda_1) - a_w(\lambda_2)] / [a_w(\lambda_3) - a_w(\lambda_2)]. \quad (5) \end{aligned}$$

It is clear that this modified three-band index (which we designated the enhanced three-band index) has the same physical meaning as the four-band index while holding bands that are identical to those used in the original three-band index. Consequently, the enhanced three-band index overcomes the limitations of the original three-band index (2), particularly in its applications over highly turbid case-II waters.

To evaluate the enhanced three-band index, its performance was compared with that of the original three-band index. For Lake Kasumigaura, the data collected in February 2006, September 2007, and August 2008 (35 sites) were used to establish and calibrate the relationships between Chl-a and the enhanced/original three-band index, while the data collected in September 2009 (21 sites) were used to test the validity of the algorithms. For Lake Dianchi, the data collected in July 2009 (41 sites) were used for algorithm calibration, and the

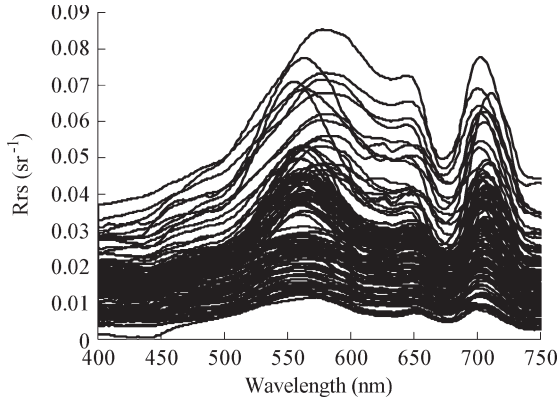


Fig. 1. Remote-sensing reflectance spectra collected in this study.

data collected in October 2007, July 2008, and March 2009 (12 sites in total) were used for algorithm validation. The field-collected reflectance spectra were resampled to MERIS bands 7 (660–670 nm), 9 (703.75–713.75 nm), and 10 (750–757.5 nm) through MERIS spectral response functions to calculate the enhanced and original three-band indexes.

The root-mean-square error (rmse), the mean normalized bias (MNB), and the normalized root-mean-square error (NRMS) were employed to assess the performances of the original and enhanced three-band indexes, which were defined as

$$rmse = \sqrt{\frac{\sum_{i=1}^N (Chla_{pred,i} - Chla_{meas,i})^2}{N}} \quad (6)$$

$$MNB = \text{mean}(\varepsilon_i)\% \quad (7)$$

$$NRMS = \text{stdev}(\varepsilon_i)\% \quad (8)$$

$$\varepsilon_i = 100 \times (Chla_{pred,i} - Chla_{meas,i}) / Chla_{meas,i} \quad (9)$$

where N is the number of samples. $Chla_{pred,i}$ and $Chla_{meas,i}$ are the predicted and measured Chl-a values for the sample i , respectively.

III. RESULTS

A. Spectral Properties and Constituent Concentrations

The magnitude and shape of the reflectance spectra collected in the two lakes, shown in Fig. 1, were quite similar to those for typical case-II waters [2], [3], [7]. Remote-sensing reflectance showed high variability over the visible and near-infrared (NIR) spectral regions. Reflectance in the blue range (400–500 nm) was very low due to the high absorption of water constituents but was much higher in the green range (500–600 nm). There was a reflectance trough at around 620 nm in the spectra because of cyanobacteria that are dominant in the water [8]; a second minimum around 675 nm corresponded to the red chlorophyll-a absorption maximum. In addition to chlorophyll-a, the reflectance near 675 nm was also affected by absorption and scattering by other constituents. A distinct peak located between 690 and 715 nm appeared in almost all spectra. This peak was from the result of both high backscattering and a minimum in the absorption of all OASs, including pure water [9], [10]. The magnitude of the peak varied widely and was comparable to the magnitude of the green peak for moderate-to-high Chl-a. Finally, reflectance in the NIR range (700–750 nm)

varied widely and was consistently higher than that in the blue range. In the NIR region of the spectrum, reflectance is mostly controlled by the scattering of all particulate matters.

The data collected in Lake Kasumigaura and Lake Dianchi encompassed varying constituent concentrations. The TSS concentration in Lake Dianchi was very high, averaging $37.11 \text{ g} \cdot \text{m}^{-3}$, and hence, its water was extremely turbid. The TSS concentration of Lake Kasumigaura was somewhat lower, averaging $24.77 \text{ g} \cdot \text{m}^{-3}$. The overall Chl-a of the two lakes was in the range of $22.98\text{--}318.6 \text{ mg} \cdot \text{m}^{-3}$. The low correlation between TSS and Chl-a clearly indicated that chlorophyll-a was not the only contributor to the optical properties of the waters ($R^2 = 0.062$ and $p < 0.001$ for Lake Kasumigaura and $R^2 = 0.096$ and $p < 0.001$ for Lake Dianchi). A low correlation between Chl-a and CDOM was also found in Lakes Kasumigaura ($R^2 = 0.053$ and $p < 0.001$) and Dianchi ($R^2 = 0.079$ and $p < 0.001$). Thus, these two lakes can be classified as case-II waters.

B. Comparison Between the Enhanced and Original Three-Band Indexes

Fig. 2(a) and (b) shows the calibration results for estimating Chl-a in Lake Kasumigaura. There is a clear and significant linear relationship between the two indexes and Chl-a, while the enhanced three-band index yielded a higher determination coefficient and a smaller rmse ($R^2 = 0.90$ with an rmse of $5.59 \text{ mg} \cdot \text{m}^{-3}$) than the original one ($R^2 = 0.84$ with an rmse of $9.26 \text{ mg} \cdot \text{m}^{-3}$). For Lake Dianchi, the determination coefficient and rmse of the Chl-a estimation model were also increased and reduced, from 0.84 to 0.91 and from 11.99 to $9.14 \text{ mg} \cdot \text{m}^{-3}$, respectively, by using the enhanced three-band index instead of the original one [Fig. 3(a) and (b)]. The slope and intercept of both three-band algorithms were different between Lakes Kasumigaura and Dianchi and also significantly different from the previous study performed in five American lakes and reservoirs (117.4 and 23.1 for slope and intercept, respectively) [11].

For the validation data set, the use of an enhanced three-band index increased the determination coefficient from 0.48 to 0.83 in Lake Kasumigaura. The rmse and random error (NRMS) were also reduced, from 13.97 to $8.68 \text{ mg} \cdot \text{m}^{-3}$ and from 19.01% to 12.30% [Fig. 2(c) and (d)], respectively. In the case of Lake Dianchi, the rmse and NRMS of the Chl-a estimation were substantially reduced, from 41.29 to $15.82 \text{ mg} \cdot \text{m}^{-3}$ and from 35.83% to 21.43%, respectively, by the use of the enhanced three-band index. The determination coefficient was also increased, from 0.74 to 0.96 [Fig. 3(c) and (d)]. The systematic errors (MNB) were slightly increased for both lakes due to the offset of relative errors [ε_i in (9)]. Additionally, Gons *et al.* [12] proposed a Chl-a estimation algorithm using the reflectance ratio of two MERIS bands (7 and 9) and absorption and backscattering coefficients at these wavelengths. This algorithm was also investigated in the present study using the same data sets for purposes of comparison. The results showed lower accuracy in both lakes compared with the three-band algorithms (the rmse, MNB, and NRMS were $24.97 \text{ mg} \cdot \text{m}^{-3}$, -25.47% , and 12.06% for Lake Kasumigaura and $50.19 \text{ mg} \cdot \text{m}^{-3}$, -20.06% , and 28.36% for Lake Dianchi, respectively).

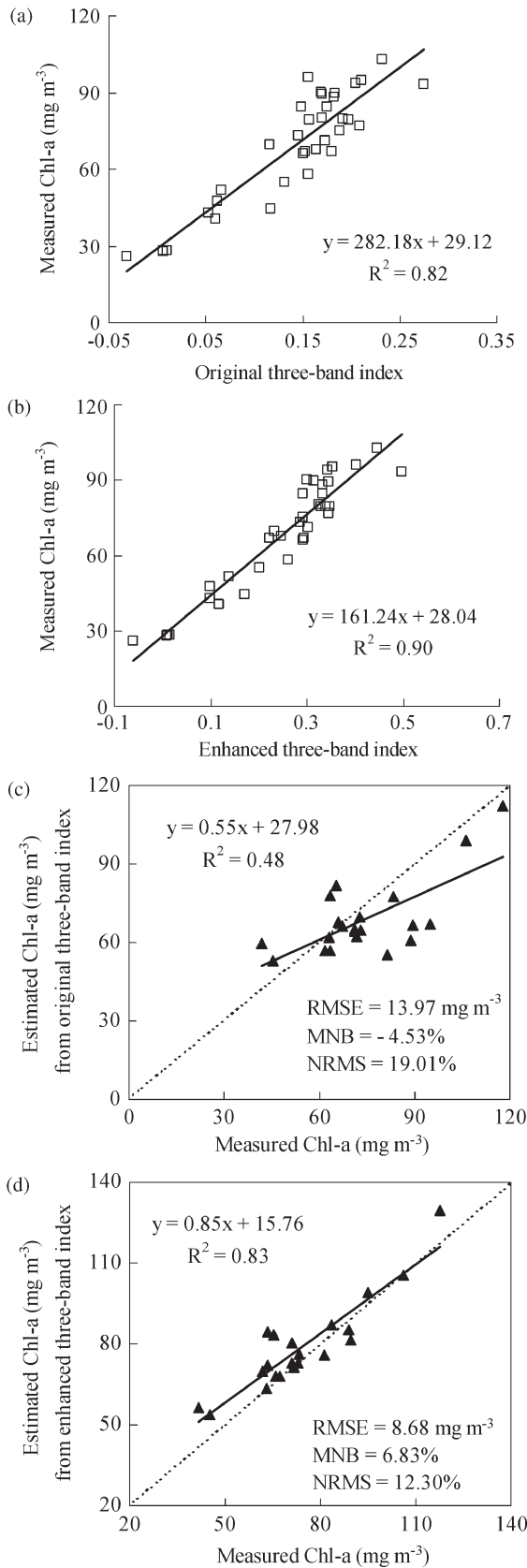


Fig. 2. Calibration and validation of the original/enhanced three-band algorithm for Lake Kasumigaura, Japan. (a) Calibration of the original three-band algorithm. (b) Calibration of the enhanced three-band algorithm. (c) Comparison of the measured and estimated Chl-a using the original three-band algorithm. (d) Comparison of the measured and estimated Chl-a using the enhanced three-band algorithm.

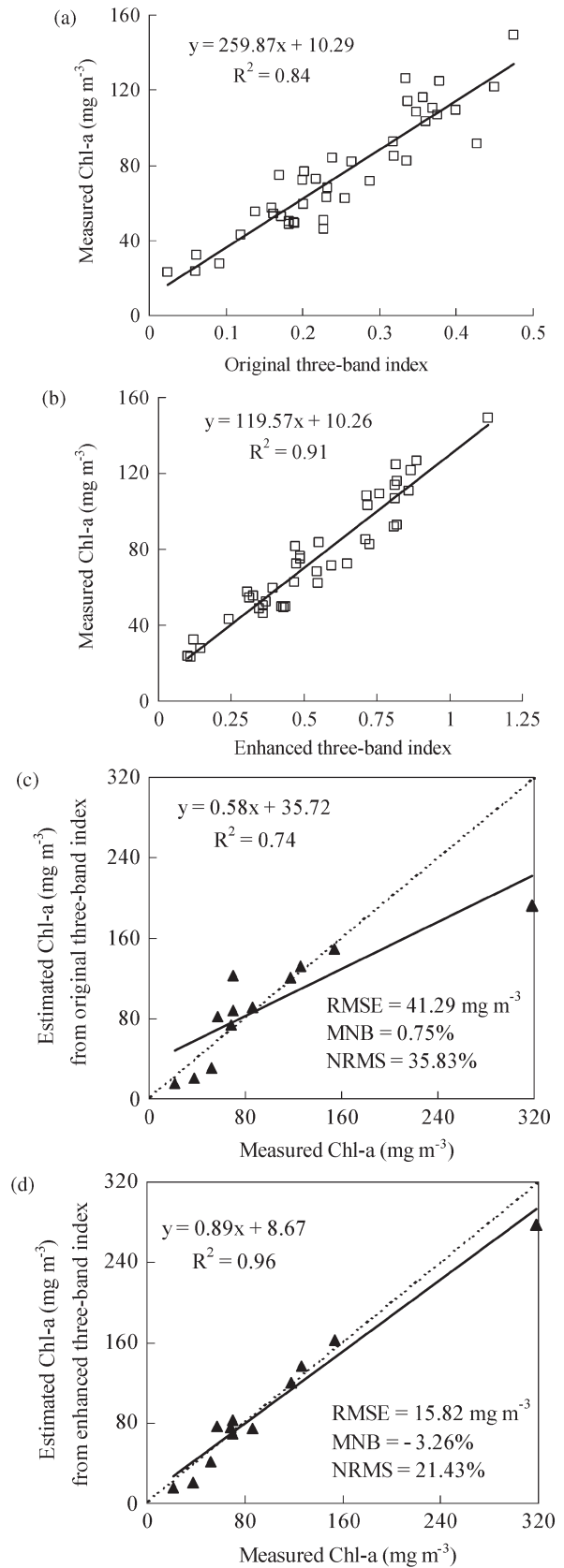


Fig. 3. Calibration and validation of the original/enhanced three-band algorithm for Lake Dianchi, China. (a) Calibration of the original three-band algorithm. (b) Calibration of the enhanced three-band algorithm. (c) Comparison of the measured and estimated Chl-a using the original three-band algorithm. (d) Comparison of the measured and estimated Chl-a using the enhanced three-band algorithm.

IV. DISCUSSION AND CONCLUSION

A new three-band index (i.e., the enhanced three-band index) has been proposed to estimate Chl-a in case-II waters. Like the original three-band index, it requires only three bands within the wavelength range of 660–760 nm, which can be provided by the MERIS sensor (bands 7, 9, and 10). Its performance was also improved compared with the original index, particularly in the case of highly turbid case-II waters (e.g., Lake Kasumigaura and Lake Dianchi). One of the assumptions for the original three-band index, that the absorption and backscattering of suspended solids can be neglected at the third band (750–757.5 nm), was violated in Lake Kasumigaura and Lake Dianchi. However, the enhanced three-band index successfully overcomes this problem by adapting the principle of the four-band index.

Although the four-band index can also be successfully applied to highly turbid case-II waters, the fact that it requires four narrow bands within the wavelength range of 660–760 nm limits its practical use to the existing satellite sensors. Hyperion is the only satellite hyperspectral sensor that can meet this criterion, but this is still an experimental sensor with a small swath (7.6×185 km) and a long revisit time and thus cannot be used in routine monitoring. Airborne hyperspectral sensors, such as the Airborne Imaging Spectroradiometer for Applications or the Compact Airborne Visible Spectrographic Imager, can also meet the prerequisite of the four-band index, but the high cost of the data per unit of study area limits their extensive use. In contrast, the MERIS provides the widest capabilities in water monitoring from space, with a spatial resolution of 300 m and a data acquisition period of three days.

The chlorophyll-a fluorescence emission peak at 685 nm may impact MERIS bands 7 and 9 used in the three-band index. Nevertheless, Dall'Olmo and Gitelson [13] have shown that the fluorescence has a negligible effect on the formation of the red peak in the reflectance spectra of productive waters. The results of the present study also showed that the enhanced three-band index could estimate Chl-a satisfactorily.

It should be noted that both the slope and intercept of the enhanced three-band algorithm (based on the enhanced three-band index) were clearly different between Lake Kasumigaura and Lake Dianchi [Figs. 2(b) and 3(b)]. This was probably attributable to the different specific inherent optical properties (SIOPs) between these two lakes [14]. These results demonstrated that the mechanism of the enhanced three-band index can remove or minimize the adverse effects of tripton and CDOM for estimating Chl-a, but the index still suffered from effects resulting from phytoplankton itself, such as the variation of SIOPs for chlorophyll-a between the lakes. Challenges still remain in calibrating the algorithm for universal application to different study areas.

The biggest challenge in the application of the enhanced three-band index to real MERIS data is how to remove the atmospheric effects included in the satellite data. The atmosphere usually contributes more than 90% of the signals measured at the top of the atmosphere. Accurate and reliable atmospheric correction for coastal and inland water imagery is still an unsolvable problem [15]. Dall'Olmo *et al.* [16] showed that models using red and NIR bands are reasonably resistant to systematic errors due to the atmospheric correction. Nevertheless, Moses *et al.* [11] demonstrated that the original three-band

index was more sensitive to uncertainties in the atmospheric correction procedure than a two-band index, particularly for waters with low reflectance in the NIR region. The enhanced three-band index utilizes the same bands as the original one, and thus, it may still be sensitive to the error due to the atmospheric correction. Further studies will be needed to explore the performance of the enhanced three-band index for retrieving Chl-a from accurately atmospheric-corrected MERIS imagery.

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