FEASIBILITY STUDY ON AUTOMATIC EXTRACTION OF WATER QUALITY IN STORAGE RESERVOIR USING ALOS AVNIR-2 DATA

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KEY WORDS: ALOS/AVNIR-2, spectral reflectance, storage reservoirs, chlorophyll-a

Abstract: The objectives of this study were to develop the chlorophyll-a (Chl.a) estimation algorithm in storage reservoirs and to develop an automatic processing technique for the Chl.a extraction system using ALOS AVNIR-2 data. The reservoirs in Akashi, Hyogo Prefecture was chosen as the test site. First, we simulated the reflectance of AVNIR-2 using the acquired data set, and several Chl.a estimation models were applied. Second, this model was validated using another data set. For the validation data, we used AVNIR-2 data of October 19, 2006 and the Ch.a data at 31 points surveyed by the National Institute for Environmental Studies from October 23 to 26, 2006. Conversely, Matlab software (Mathworks Ltd.) was used to automate the pre-processing technology. The results obtained are as follows: 1) The Chl.a estimation model of the reservoir obtained using AVNIR-2 was created using the survey spectral reflectance/Chl.a data set. As a result, the model using the green index of "AV2/(AV1 + AV2 + AV4)" was optimum (r^2 = 0.83, N = 26, RMSE = 36.3 μg/L, $p < 0.001$). 2) We validated the Chl.a estimation model obtained by using the AVNIR-2/Chl.a data set, and with the exception of an aquatic plant and turbid water that were removed, the model and insitu Chl.a were mostly in agreement. 3) To separate the vegetation/non-vegetation judgment, the normalized difference vegetation index (NDVI) was effective, and the threshold was approximately 0.1. 4) We developed a program that can verify the automatic processing using Matlab software; thereby, enabling quick and intelligible Chl.a data mapping.

INTRODUCTION

In recent years, the roles of storage reservoirs have increased from being just a base for storing water for agricultural use to biodiversity applications. However, the actual condition of the biodiversity in the storage reservoir is seldom known when compared with coastal regions or lakes. In recent years, the National Institute for Environmental Studies has performed general research on the biodiversity of reservoirs in Japan as a whole from such a viewpoint (Takamura, 2004). In one of these studies (Kadoya et al., 2011), the integrated biodiversity indicator in the reservoir was modeled as a weighted mean of pressures. The most influential factors in the pressure category are selected chlorophyll a (Chl.a), the proportion of bank protection, and bluegill density. In particular, Chl.a is an important primary factor. However, since it is labor intensive and costly, it is difficult to perform the Chl.a survey of over 200,000 reservoirs in Japan. In addition, many Japanese reservoirs are located on private land, and in many cases, the field survey itself is difficult. As a result, the use of Chl.a monitoring in reservoirs using remote sensing technology, which can simultaneously measure wide areas, is expected to become more widespread. Chl.a estimation from satellites is well known for its use as an ocean color sensor, e.g., MODIS and SeaWiFS. However, the surface imagery of a common ocean color sensor has a scale of approximately 1 km, and it cannot be used to monitor multiple reservoirs scales of the order of tens of meters. Therefore, in such small-scale water areas, the use of land observation satellites such as LANDSAT/TM with spatial resolutions of several meters has been substituted (Lathrop et al., 1986; Chacon-Torres et al., 1992). Although there are disadvantages regarding the use of land observation satellites in Chl.a estimation, such as the wide band width (approximately 100 nm), quantization (usually 8 bits), and repeat cycle (usually several weeks or more), the ability to obtain high spatial resolution compensates for those weak points. For example, we have to remove the aquatic plant area before Chl.a estimation can be realized using satellite imagery in reservoirs. Such aquatic plant detection can efficiently employ the advantage of high resolution satellite. However, in such reservoirs, there are no examples in which chlorophyll quantitative evaluation was carried out. Moreover, in future, there is a desire to map the biodiversity of reservoirs in all of Japan using the integrated biodiversity index. For this, technology which carries out automated mapping of Chl.a satellite data obtained at the center of each pond is also required.

In this study, we used data obtained from the high resolution satellite ALOS AVNIR-2 to perform chlorophyll estimation in the reservoir around Akashi, Hyogo Prefecture, Japan, which has the largest domestic reservoir. The objectives of this study were to develop the chlorophyll-a (Chl.a) estimation algorithm in storage reservoirs and to develop an automatic processing technique for the Chl.a extraction system using ALOS AVNIR-2 data. AVNIR-2 is the "Advanced Visible and Near-Infrared Radiometer 2 model" sensor used by the earth observation satellite "Advanced Land Observing Satellite (ALOS)," which was launched by the Japan Aerospace Exploration Agency (JAXA), Japan in January, 2006. However, the mission was completed in May, 2011.

METHOD

Chlorophyll estimation algorithm

In general, the empirical Chl.a estimation model obtained using satellites employs the following two-band model on the basis of blue–green bands such as 443 nm/555 nm, 490 nm/555nm, and 510 nm/555 nm (Martin, 2002). However, the model is often not suitable for eutrophic waters. The model using the above sets of wavelengths is tried, and a Chl.a estimation equation suitable for each water area is obtained in many cases.

$$Chl.a \propto R_i / R_j \tag{1}$$

$$Chl.a \propto (R_i - R_j) / (R_i + R_j) \tag{2}$$

$$Chl.a \propto R_i / (R_i + R_j + R_k) \tag{3}$$

where R is the reflectance, and i, j, and k represent wavelengths. The insitu spectral reflectance data was calculated by applying it to the model using formulae (1)–(3), and the optimal Chl.a estimation model and band by AVNIR-2 were determined.

Field Survey

We conducted field surveys in storage reservoirs, which are located in the northwestern area along the shore of Nishi-Akashi, as shown in Fig. 1 (area A and B of Fig. 1, 5 km × 5 km area), on July 30 and 31, 2010 from 9:00 AM to 5:00 PM. We acquired field data for spectral reflectance, Chl.a, and SS. There were 26 survey points (A-1–A-16 and B-1–B-10). We measured the Chl.a and SS after sampling the water from reservoir in the laboratory. We measured the Chl.a in the water using the spectrophotometer (U-2800A, Hitachi High-Technologies Co.) after filtrating it with the Whatman GF/F filter paper. The ranges of values obtained for Chl.a and SS are shown in Table 1. With regards to the spectral reflectance measurement in reservoirs, the water (approximately 10 L) sampled from the shore was measured using the simple spectral reflectance method in a black bucket (NINJYA IKASHI MIZUKUMI 21 and POINT BAY) made from rubber material of size "22 cm × 22 cm × 23 cm". A portable spectral radiometer (MS72, Eko) was used from a position approximately 20 cm below the water surface, and the spectrum radiance of the water surface immediately above that position was measured. The measurement wavelength range of the spectral radiometer is 350–1050 nm, and has a wavelength interval of 3.3 nm and half breadth 10 nm. The data was changed into 1-nm data using the software "SpectroManager Ver.1.6" (Eko) of this machine attachment. Moreover, the spectral reflectance was computed as a ratio of the spectral irradiance observed just under 20 cm right above with the 99% standard 5-inch white board (Labsphere) to the irradiance of the water surface right above, as mentioned above. In addition, to reduce the noises (time gap of measurement of the water surface and white board, etc.) due to the measurement environment, the spectral reflectance was measured every 1.3 s, and the average value was subsequently adopted as the central value. Moreover, in this research, the response function, r, of AVNIR-2 (Murakami et al., 2007) is used for the spectral reflectance R obtained by the field survey, and it is AVNIR-2 from the following formulas. It was then changed into the considerable reflectance R.

$$R_{AVN\lambda} = \int R_\lambda r_\lambda d\lambda \Big/ \int r_\lambda d\lambda \tag{4}$$

Table 1: Summary of water quality data.

	Chl.a(µg/L)		SS(mg/L)		N
	Min	Max	Min	Max	
10/23−26/2006	1.4	616.8	0.87	94.75	31
7/29−30/2010	1.0	394.8	2.0	38.4	26

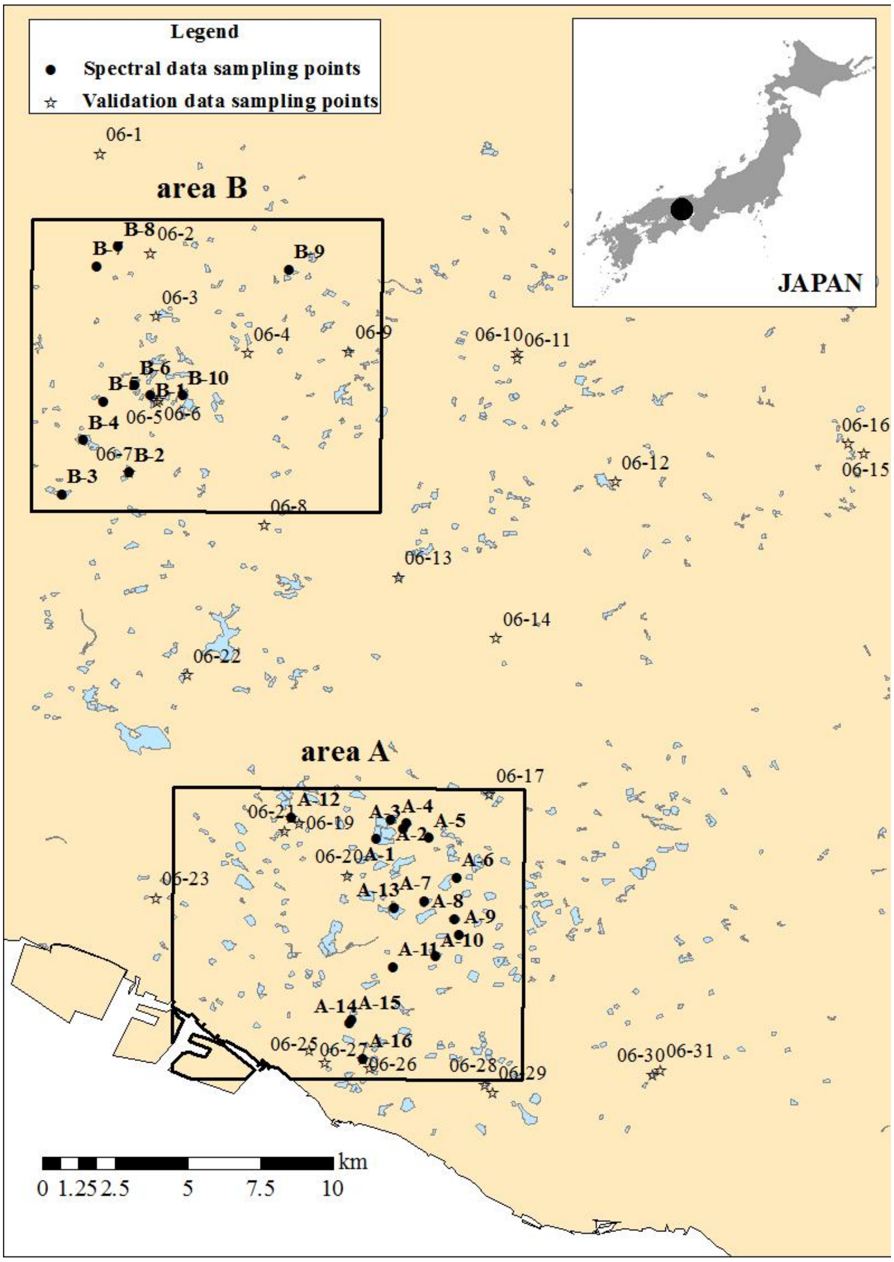

Figure 1: Sampling points of spectral and validation data.

Validation data set

The satellite/insitu data set was used to verify the created Chl.a estimation model. Chl.a data in the field survey (refer to Fig. 1) comprised 31 points of AVNIR-2 data on October 19, 2006 (L1B2 ortho image) and the data from National Institute for Environmental Studies conducted at the same place for a duration of five days, i. e, October 23–27, 2006. The specifications of this sensor are as follows: observation bands are blue (AV1: 420–500 nm), green (AV2: 520–600 nm), red (610–690 nm), and near-infrared (760–890 nm), the spatial resolution is 10 m, the swath is 70 km, and the quantization is 8 bits. Moreover, AVNIR-2 data was changed into reflectance using the following equation and response function (CEOS, Cal/Val Portal, http://calvalportal.ceos.org/cvp/web/guest/alos-avnir-2)

$$R'_{AVi} = \frac{(L_{si} - L_{pi})\pi d^2}{F_{0i} \cos\theta_0}, \tag{5}$$

where, L_s is the radiance at the top of the atmosphere, L_p is the path-radiance, d is the sun-earth distance, F_0 is the exoatmospheric irradiance, θ_0 is the solar zenith angle, and i is the AVNIR-2 band. L_s is changed from the digital value DN using the following equation:

$$L_{si} = gain_i DN_i + offset_i, \tag{6}$$

where *gain* and *offset* represent the radiance conversion coefficient of AVNIR-2, and are written in the header file. Furthermore, the dark pixel method, which assumes a setup of L_p in Equation (5), where the aerosol is uniform in an image in the case of high resolution satellites, such as Landsat TM, is often used (MacFarlane and Robinson, 1984). However, in many cases, suitable dark pixels, such as the adjoining sea, are not found. The following equation with the major variables, such as "satellite observation angle," the "solar zenith angle," and the "wavelength," which are used in the path radiance analysis of land (Aoi et al., 2007), was used to overcome such a problem, so that it be applied to the reservoirs throughout the country in future.

$$L_{pi} = \frac{1}{4\pi}\left(\frac{\mu_0}{\mu+\mu_0}\right)\left[1 - e^{-t_i\left(\frac{1}{\mu}+\frac{1}{\mu_0}\right)}\right]P(\varphi)\frac{F_{0i}}{d^2}, \tag{7}$$

$$\mu_0 = \cos\theta_0, \tag{8}$$

$$\mu = \cos\theta_n, \tag{9}$$

$$t = 0.00879\,\lambda^{-4.09}, \tag{10}$$

$$P(\varphi) = \frac{3}{4}(1+\cos^2\varphi), \tag{11}$$

$$\varphi = 180 - \theta_0, \tag{12}$$

where, θ_n is the satellite observation angle and d is the sun–earth distance (Astronomical Unit). As mentioned above, the values of F_0, gain, and offset, which were actually used in this study in Equations (5)–(12), i.e., θ_0, θ_n, and d, are shown in Table 2.

Table 2: Input parameters for reflectance conversion.

	Band1	Band2	Band3	Band4
F_0(Wm^{-2}μm^{-1})	1943.3	1813.7	1562.3	1076.5
gain	0.588	0.573	0.502	0.557
offset	0	0	0	0
θ_0(°)	47.43			
θ_n(°)	11.4			
d	0.99			

Extraction of storage reservoir shape and aquatic plant mask

The extraction of the reservoir shape from AVNIR-2 data representing 1 km^2 is done beforehand based on topographical maps and aerial photographs. It was extracted from the polygon data of the reservoir which has the above area. Moreover, when we estimate Chl.a from AVNIR-2 data, the cover of aquatic plants is considered as noise. Therefore, the NDVI was used for to evaluate the activity of plants on land, and we tried to obtain the plant cover mask using the NDVI threshold.

$$NDVI = \frac{R_{AV4} - R_{AV3}}{R_{AV4} + R_{AV3}} \tag{13}$$

RESULTS AND DISCUSSION

Correlation between the simulated AVNIR-2 Chl.a model and insitu Chl.a

The characteristics of the insitu spectral reflectance in storage reservoirs obtained by the position of AVNIR-2 bands are shown in Fig. 2. Table 3 shows the slopes (m) and intercepts (n) of the relationship between the model and Chl.a with the corresponding root mean square error of the Chl.a estimation (RMSE, in µg/L) and the coefficient of determination (r^2). From this table, a significant correlation ($p < 0.001$) was acquired for the following models: "AV2/AV3" ($r^2 = 0.61$, RMSE = 55.6 µg/L), "(AV2 – AV3)/(AV2 + AV3)" ($r^2 = 0.57$, RMSE = 58.0 µg/L), and "AV2/(AV1 + AV2 + AV3)" ($r^2 = 0.83$, RMSE = 36.3 µg/L). The relationship between "AV2/(AV1 + AV2 + AV3)" (the most suitable model) and Chl.a is shown in Fig. 3. This shows that it is more effective to use dispersion by the phytoplankton itself rather than the method of using the absorption band of Chl.a at blue (AV1) or red (AV2) wavelength, for which the open sea and coast might be sufficient, as is actually done. Therefore, the following equation is used in subsequent analyses.

$$Chl.a = 7028.1[R_{AV2}/(R_{AV1} + R_{AV2} + R_{AV3})] - 2283.6 \tag{14}$$

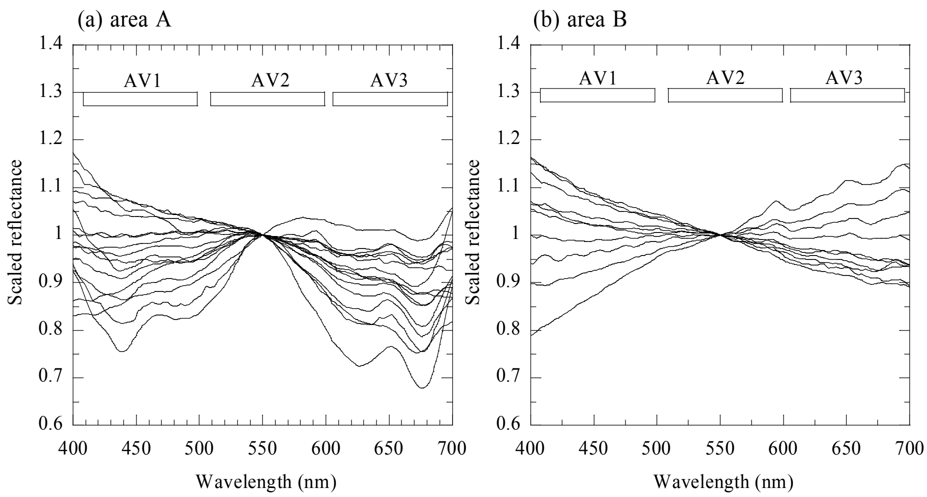

Figure 2: Characteristic of spectral reflectance in storage reservoirs.

Table 3: Slopes (m) and intercepts (n) of the relationship between the model and Chl.a with corresponding root mean square error of Chl.a estimation (RMSE, in µg/L) and coefficient of determination (r^2).

Models	*m*	*n*	r^2	RMSE
AV1/AV2	−608.7	693.5	0.25	76.6
AV1/AV3	139.4	81.4	0.03	87.4
AV2/AV3	883.8	853.2	0.61*	55.6
(AV1 − AV2)/(AV1 + AV2)	−1248.5	836.4	0.26	76.3
(AV1 − AV3)/(AV1 + AV3)	307.2	58.2	0.03	87.2
(AV2 − AV3)/(AV2 + AV3)	1820.8	32.6	0.57*	58.0
AV1/(AV1 + AV2 + AV3)	−612.9	278.4	0.02	88.0
AV2/(AV1 + AV2 + AV3)	7028.1	2283.6	0.83*	36.3
AV3/(AV1 + AV2 + AV3)	−2151.8	761.1	0.20	79.4

*Statically significant ($p < 0.001$) N = 26

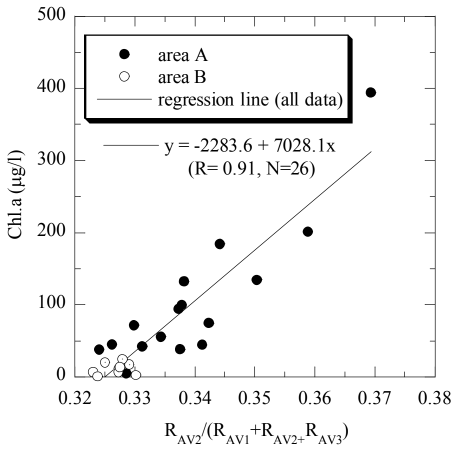

Figure 3: Correlation between simulated AVNIR-2 Chl.a model and measured Chl.a.

Validation of the Chl.a algorithm using AVNIR-2 data

To apply the AVNIR-2 data to the Chl.a estimation models, such as in Equation (14), the removal of the covered aquatic plant is first required. Figure 4 shows NIR color images and contour maps of NDVI obtained from AVNIR-2 at St.A-3 and St.A-8, which are typical reservoirs with aquatic plants. From this, we observed that the NDVI of the line of 0.1 corresponded with the boundary of the aquatic plant and non-aquatic plant regions. That is, when the NDVI is 0.1 or more, it is regarded as a covering of aquatic plants. From similar observations made in other reservoirs, it was determined that 0.1 was the approximate threshold of NDVI. On the basis of these results, Fig. 5 shows the correlation between AVNIR-2 Chl.a, which was estimated using Equation (14), before and after the aquatic plants mask and insitu Chl.a. Except for four points (the round mark part of Fig. 6 (b)), the presumed Chl.a error in the survey where Chl.a is below 25μg/L, having been very large before compensation, corresponds to the straight line of about 1:1 after the vegetation mask. Because these four points had high ratios of SS to Chl-a (five or more times), it was believed that this was due to the influence of inorganic SS.

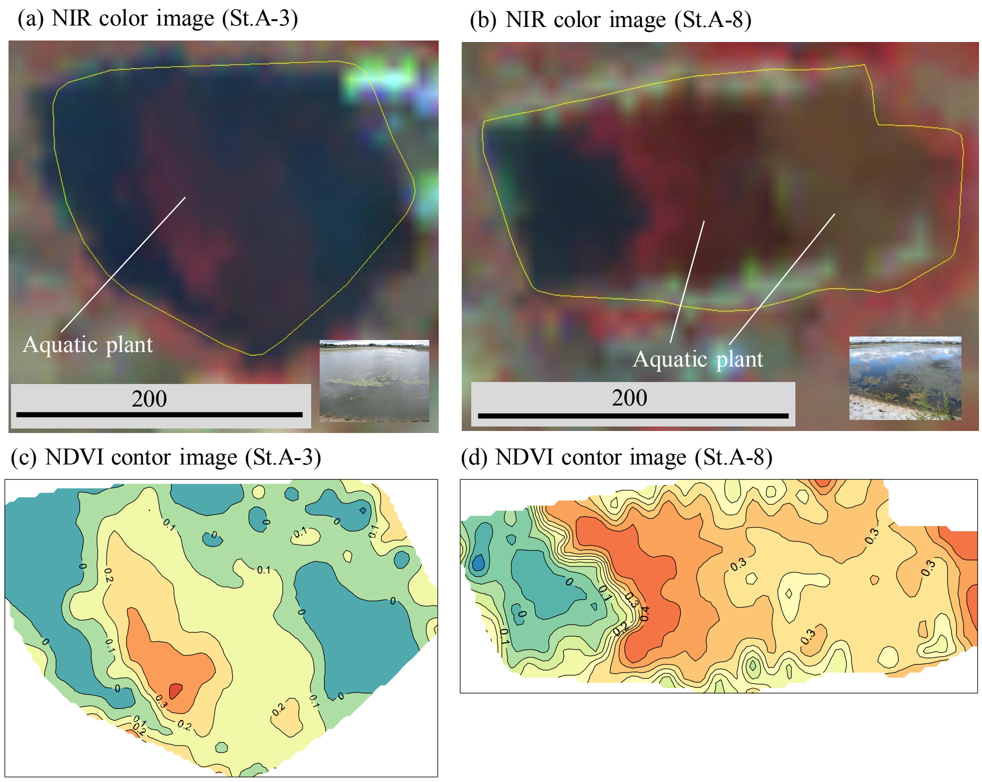

Figure 4: NIR color images and contour maps of NDVI from AVNIR-2 at St.A-3 and St.A-8.

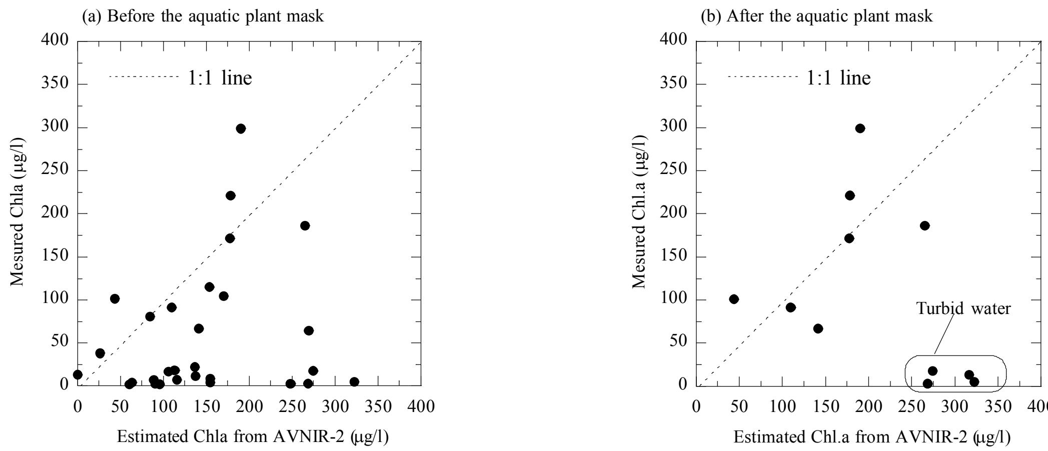

Figure 5: Relationship between AVNIR-2 Chl.a and insitu Chl.a before and after the aquatic plant mask when validating the sampling points.

Automatic processing using MATLAB software

The final objective of this study is the automatic mapping of Chl.a using satellite imagery at the reservoir centers all over Japan. For this, it is required that we program the Chl.a estimation process confirmed in the preceding chapter. In this study, we used the Image Processing Toolbox of the Matlab 2012 software package (Mathworks Ltd.), which can easily calculate the digital data of Chl.a from an image. Figure 6 shows a schematic of the automatic pre-processing for the Chl.a extraction system at the center of reservoirs using Matlab software with AVNIR-2. The inputs for the Matlab program were the digital value (DN) of the AVNIR-2 data and the discretized image of the reservoirs shape. The Chl.a data of the center of each reservoir, which had masked aquatic plants, the data extraction of the center position, etc., was performed on the program, and finally the Equation (14) for these pictures is outputted. When this program is used, the pre-processing for the masked aquatic plants, data extraction of the center position, etc., are first performed by the program. Finally, the Chl.a data at the center of each reservoir is outputted using Equation (14). Thus, the mapping of the calculated Chl.a data proved that the local characteristic shown in Fig. 7 is suitable.

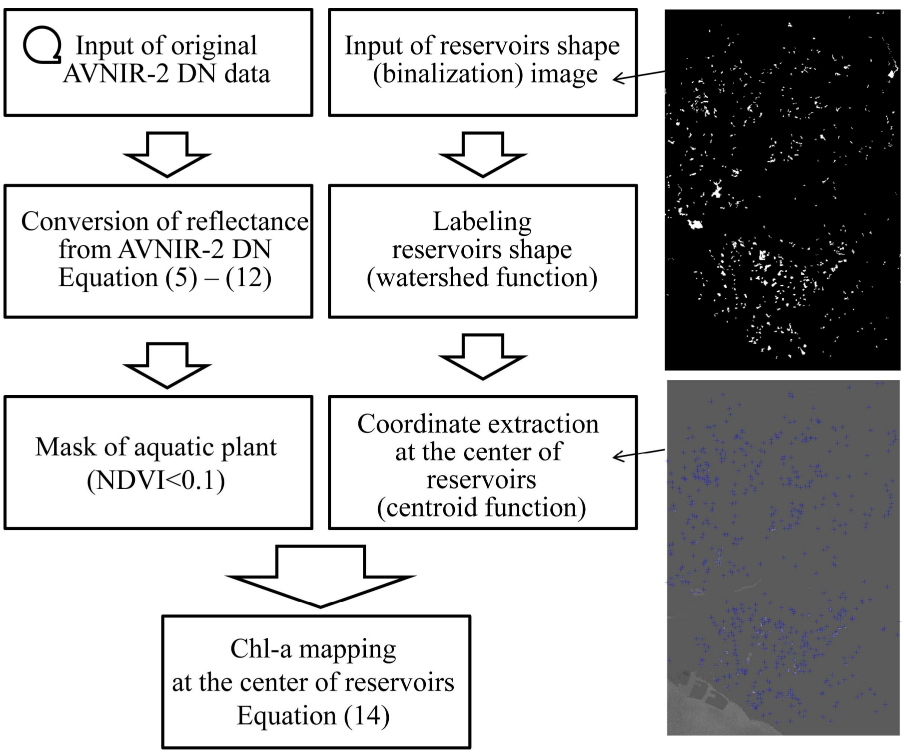

Figure 6: Schematic of automatic pre-processing for Chl.a estimation at the center of reservoirs from AVNIR-2 using Matlab software.

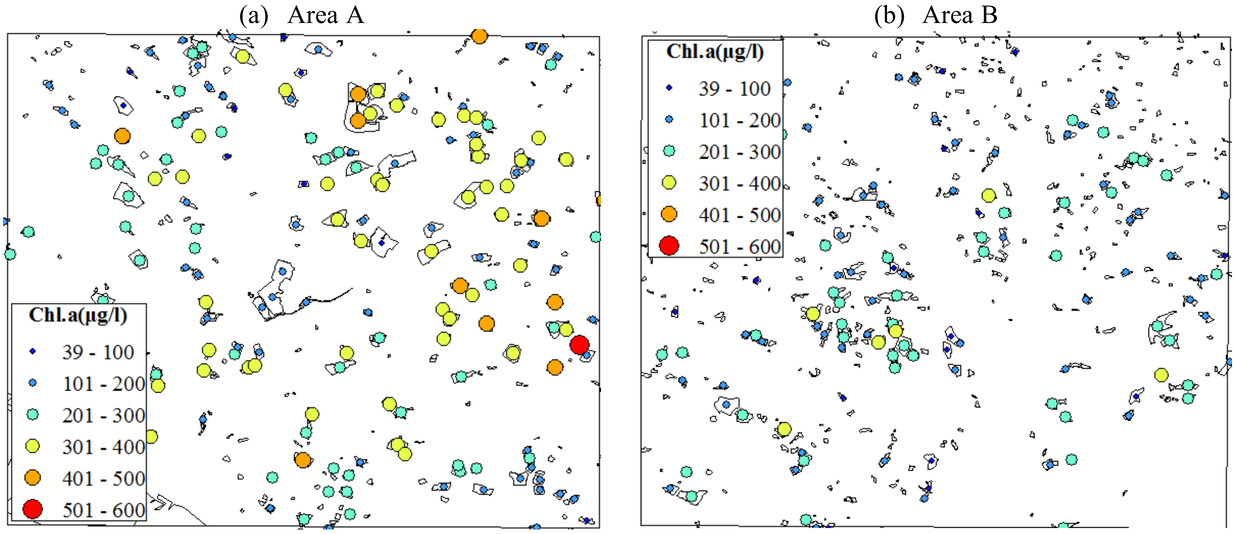

Figure 7: Automatic Chl.a mapping from AVNIR-2 in areas A and B using Matlab software.

CONCLUSION AND FUTURE WORK

The following was found in this research.

1) We created a Chl.a estimation model for the AVNIR-2 reservoir using the survey spectral reflectance/Chl.a data set. As a result, the model using the green index of "AV2/(AV1 + AV2 + AV4)" was optimum ($r^2 = 0.83$, N = 26, RMSE = 36.3 microg/L, $p < 0.001$).
2) We validated the Chl.a estimation model obtained by the AVNIR-2/Chl.a data set from which aquatic plants and turbid water were eliminated, and the model and insitu Chl.a data were found to be in agreement with each other.
3) The NDVI allowed us to effectively distinguish between vegetation/non-vegetation results, and the threshold was approximately 0.1.
4) We developed a Matlab program, which allows us to perform automatic processing.
   We were therefore able to realize quick and intelligible Chl.a data mapping.

This Chl.a estimation model is based only on data obtained for one area. In future, we intend to apply the same method in other areas. Moreover, we would like to examine the Chl.a estimation method using an aerial photo in a small-scale reservoir, which cannot be imaged by AVNIR-2 (area is less than 10 m × 10 m).

ACKNOWLEDGEMENTS:

This study was supported by the Environment Research and Technology Development Fund (S9) of the Ministry of the Environment, Japan, and JSPS KAKENHI (24560623, 23404001, and 24404006). The authors would like to thank Ms. Yasuko Oikawa, Center for Environmental Biology and Ecosystem Studies, National Institute for Environmental Studies, for the water quality analysis data.

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