

Estimation of chlorophyll-*a* concentrations in diverse water bodies using ratio-based NIR/Red indices

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Abstract

Numerous studies indicate that biological and chemical water quality parameters such as chlorophyll-*a* have distinctive spectral characteristics and can thus be measured using spectral indices. But these indices appear to be less reliable in diverse water bodies including lakes, ponds, rivers and streams in coastal regions. The purpose of this study was to develop a new ratio-based two-band spectral index to estimate chlorophyll-*a* concentrations in diverse water bodies. In this study, an Ocean Optics Spectroradiometer (300-900 nm) was used to collect hyperspectral data from ponds, lakes, streams and rivers in the coastal St. Jones River Watershed, DE from March 2006 to May 2007, while independent *in situ* water samples were collected concurrently and analyzed for chlorophyll-*a* and total suspended solids (TSS). The relationship between the reflectance value of individual bands and *in situ* chlorophyll-*a* concentration was first examined to identify bands sensitive to chlorophyll-*a* but not to TSS. The most sensitive band was then selected as the numerator to build a series of ratio-based indices and each of them was examined for its correlation with *in situ* chlorophyll-*a* concentration. The ratio showing the highest correlation coefficient was determined as the new ratio-based spectral index. Also, the performance of ratio-based spectral indices from the literature was examined to compare with this newly developed spectral index. It was found that the new spectral index

R716/R667 showed high correlation ($r = 0.82$) with *in situ* chlorophyll-*a* concentration and it is not sensitive to TSS in diverse water bodies and cross different seasons. This new spectral index could be used as an alternative of two popular indices (R700/R670 and R700/R675) in diverse water bodies with large spatial variation in concentration of chlorophyll-*a* and TSS. Findings from this study demonstrate the suitability of hyper-spectral remote sensing techniques for mapping chlorophyll-*a* concentrations in diverse water bodies.

Keywords: *spectral indices, chlorophyll-a, NIR, Red*

Capsule: The spectral index R716/R667 showed high correlation ($r = 0.82$) with chlorophyll-*a* concentration and it should be useful for estimating chlorophyll-*a* in diverse water bodies.

INTRODUCTION

There are numerous water quality studies on the retrieval of chlorophyll-*a* concentration from spectral data collected by spaceborne, airborne and ground-based remote sensing (ex. Gilerson et al 2010, Yang et al 2010, Gitelson et al 2011, Odermatt et al 2012, Olmanson et al 2013, Song et al 2013, Huang et al 2014, Moore et al 2014, Mouw et al 2015). Yet even with all this information, it is still a challenge to accurately estimate chlorophyll-*a* concentrations by remote sensing in diverse waters with high or heterogeneous concentrations of total suspended solids (TSS) and colored dissolved organic matter (CDOM) (Odermatt et al 2012, Mouw et al 2015). This is because the presence of high inorganic suspended sediments and colored dissolved organic matter can overwhelm the spectral signal of chlorophyll-*a*, and thus it is difficult to distinguish the signal of chlorophyll-*a* from those of TSS and CDOM (Yacobi et al 2011, Sun et al 2014).

A variety of spectral indices based on empirical or semi-empirical relationships have been developed for transforming spectral data into water quality parameters. These indices could involve as many as three bands (Yacobi et al 1995, Pierson and Stombeck, 2000, Yacobi, et al 2011, Song et al 2013, Sun et al 2014, Huang et al, 2014, Yang et al 2010) and four bands (Le et al 2009, Song et al 2013, Sun et al 2014). Some researchers developed specific indices by water type using a pre-classification approach to improve estimation accuracy (Shi et al 2013, Sun et al 2014). However, the majority of spectral indices from the literature are based on reflectance ratios of two spectral bands (Table 1) for operational purpose. The spectral rationing has been a proven technique in detecting variably pigmented targets such as traumatized human skin (Meyer et al., 1984). Band ratios are used to suppress illumination differences attributable to surface albedo, look angle, and topographic effects (Avery and Berlin 1992). A band ratio between the near infrared (NIR) and Red has frequently been used to estimate chlorophyll-*a* in waters due to a positive reflectivity of chlorophyll-*a* in the NIR and an inverse behavior in the red (Rundquist et al 1996, Pepe et al 2001). Note in Table 1 that near infrared (NIR) and red bands are involved in most indices, and that those bands range from 670 -780 nm, which is located at red edge region (Horler et al 1983).

Table 1. Spectral ratio-based indices used to estimate chlorophyll-*a* obtained from literature.

Spectral indices	References
R700/R670	Gitelson et al. 1986
R705/R670	Mittenzwey et al. 1992
R704/672	Gons 1999
R443/R560, R490/R560	O'Reilly et al. 2000
R560/440	George and Malthus 2001

R490/R550	Melack and Gastil 2001
R705/R675	Shafique et al. 2001
R672/R695	Gin et al. 2002
R705/678	Thiemann and Kaufmann 2002
R490/550, R550/590	Darecki et al. 2003
R490/555, R510/R555	D'Sa and Miller 2003
R680/R670	Szekielda et al. 2003
R765/670	Dall'Olmo et al. 2005
R412/R670	Cannizzaro and Carder 2006
R719/667	Jiao et al. 2006
R714/R650	Zimba and Gitelson 2006
R705/R663	Koponen et al. 2007
R709/R665	Randolph et al. 2008
R861.1/R856.7	Huang et al. 2010
R749/R703	Xiao and Guo , 2010
R708/R665	Tao et al. 2013

The reflectance ratio R700/R670 was first used as a predictor of chlorophyll-*a* concentration in the early 80s' (Gitelson et al. 1986, Gitelson et al. 1993a, b). Almost the same indices including R705/R670 and R704/R672 were identified by Mittenzwey et al. (1992) and Gons (1999) due to their ability to minimize interference of strong absorption by CDOM and inanimate particles when estimating chlorophyll-*a* in estuary and coastal waters. Later, R709/R665, R861.1/R856.7 and R749/R703 were reported by Randolph et al. (2008), Huang et al. (2010) and Xiao and Guo (2010) to correlate significantly with Chlorophyll-*a* concentration in waters. Moreover, Moses et

al. (2012a) investigated the performance of NIR-Red indices when applied to multi-temporal Airborne Imaging Spectrometer for Applications (AISA) data, and found that the spatial distribution of chlorophyll-*a* can be captured using NIR-Red indices even without atmospheric correction. Bagheri et al. (2012) concluded that two-band NIR-Red algorithms had proven highly reliable for estimating chlorophyll-*a* concentration in turbid productive waters when applied to MERIS data in different geographic locations. Tao et al. (2013) noticed that the ratio index NIR (708 nm)/Red (665 nm) estimated chlorophyll-*a* concentrations better than three or four band indices. It was also evidenced by Le et al. (2013) that a two-band NIR/Red band ratio index had the best performance for different types of data sources including *in situ* hyperspectral, simulated broad-band, or satellite-derived reflectance.

Despite a significant progress, the value of NIR/Red spectral indices mentioned above is limited when they are employed to monitor diverse water bodies including lakes, ponds, rivers and streams. There is still a need for reparameterization of spectral indices in which bands/band combinations are adjusted for different water bodies with different optical properties (Moses et al 2009, Gurlin et al. 2011, Mose et al 2012b). This is because there is a large variation in chlorophyll-*a* and TSS concentrations in diverse water bodies. But a single type of water body was usually involved in the development of one spectral index in previous remote sensing studies. Seldom was a spectral index developed from diverse water bodies in the literature. Many studies suggest that the best spectral indices for retrieving chlorophyll-*a* may be dependent on the spectral characteristics of the waters investigated, and possibly the season at which was investigated (Tilstone et al 2012). This is evident in Table 1 that there is a significant variation in band combination for spectral indices used in the literature. This variation could be due to that diverse water bodies are optically complex and their reflectance is determined by the combined

effects of absorption and scattering by phytoplankton particles, inorganic and organic particles, and CDOM.

The purpose of this study was to develop a new ratio-based index for chlorophyll-*a* estimation in diverse water bodies including lakes, ponds, rivers and streams with a large variation in chlorophyll-*a* and TSS concentrations. In this study, the relationship between the reflectance value of an individual band and *in situ* chlorophyll-*a* concentration was examined to identify bands sensitive to chlorophyll-*a* in diverse water bodies and cross different seasons. We also investigated the performance of ratio-based NIR-Red spectral indices to retrieve chlorophyll-*a* concentrations from diverse water bodies when applied to reflectance data acquired by a hyperspectral sensor. This will help determine the feasibility of measuring chlorophyll-*a* in diverse waters with high or heterogeneous concentrations of total suspended solids (TSS) using satellite-based remote sensing.

MATERIALS AND METHODS

Study area

The St. Jones River watershed (SJRW, Figure 1) is located in central Kent County, Delaware and drains a portion of the coastal plain into Delaware Bay. The total area of the St. Jones River watershed is 23,300 ha, including most of the capital city of Dover and a portion of Dover Air Force Base (DNERR 1999). The upper St. Jones River is impounded by a dam 10.5 miles upstream from the bay to form Silver Lake, a municipal recreation area. Much of the eastern portion of the watershed consists of wetlands, agricultural lands and forests, including lands and waters managed for waterfowl, wild turkey, deer, and other wildlife.



Figure 1. Location of the study area within the state of Delaware.

There were significant changes in land use in the St. Jones River watershed from 1992 to 2001 (Table 2) based on the watershed’s land use and cover data in 1992 and 2001 derived from NLCD (USGS). Agriculture was the dominant land use in the St. Jones River Watershed, with more land converted to urban and agricultural use and significant loss of wetland and open water. Thus it is important to examine chlorophyll-*a*, an indicator of eutrophication potentially induced by agricultural run-off, in the watershed’s water bodies.

Table 2. Percentage of land use in the St. Jones River watershed in 1992 and 2001*

Land Use	1992	2001
	%	%
open water	2.3	1.5
urban	13.2	17.0
forest	15.4	14.7
agriculture	53.1	55.3

wetland	15.7	10.8
barren	0.3	0.7

* Calculated based on NLCD (USGS) in 1992 and 2001

There are numerous water bodies including different sizes of rivers, streams, lakes and ponds in this watershed. The major water bodies include the St. Jones River, Silver Lake, Moores Lake and Wyoming Lake. There are a total of 8 listed water segments for nutrients, DO and bacteria with the most probable source of pollutants identified as NPS (DNREC, 2006). There are two tidal segments of the St. Jones River, three freshwater stream segments, and three freshwater lakes or ponds.

Methods

1.1 Sampling Stations

Ten sampling stations were chosen for this study based on vehicle accessibility within the watershed (Table 3 and Fig 2), five in the tidal portion of the watershed and five in the non-tidal portion of the watershed. Of the non-tidal stations, two stations were located in a lake (Silver Lake) and three stations were located in small streams. Of the tidal stations, one station was located in a lake (Moores Lake), one station was located in a pond (Derby Pond), and the other three stations were located in the St. Jones River. At all stations, sampling was conducted approximately 2 m away from the bank.

Table 3. The GPS coordinates of the sampling stations

Station #	Station Name	Water Body Type	GPS Coordinates	
	Non-Tidal Stations		Latitude	Longitude
1	DENNYS	Stream	39.1955	-75.5640
2	MACKEE	Stream	39.1988	-75.5775
3	DSU	Stream	39.1830	-75.5449
4a	SILVER HOTEL	Lake	39.1752	-75.5304
4b	SILVER HOTEL	Lake	39.1771	-75.5303
5	SILVER DAM	Lake	39.1683	-75.5212
	Tidal Stations		Latitude	Longitude
6	DERBYPOND	Pond	39.0854	-75.5590
7	MOORES LAKE	Lake	39.1266	-75.5183
8	SCOTON LANDING	River	39.0849	-75.4605
9	LEBANON LANDING	River	39.1143	-75.4992
10	LOCKERMAN ST	River	39.1604	-75.5190

4a, 4b: This station has two sampling locations.

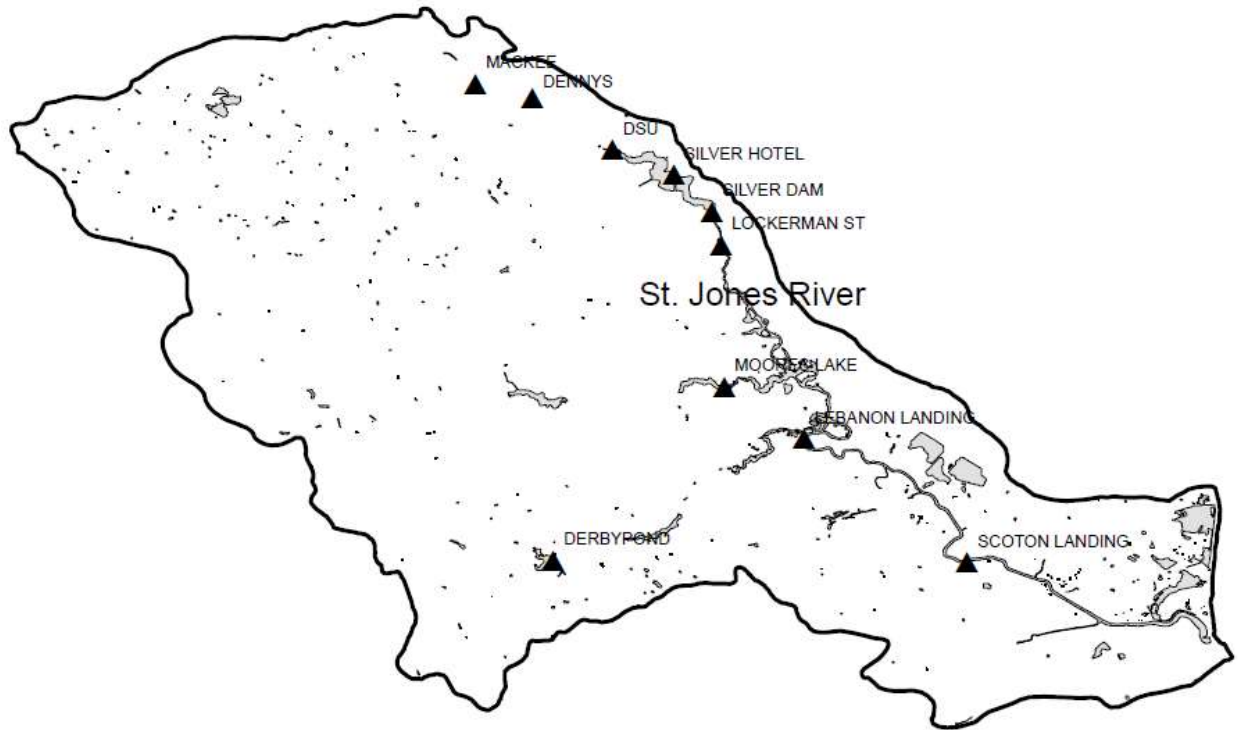


Figure 2. The locations of the sampling stations in the SJRW

1.2 Instrumentation

An Ocean Optics USB 2000 spectroradiometer (Ocean Optics Company of Florida, USA) was used to collect *in situ* spectral data between 350 nm and 1016 nm at every wavelength. The sensors were connected with a laptop using six-meter long premium SMA 200 μm fiber. Before spectral data collection, a 30 cm * 30 cm Lambertian Spectralon panel (Labsphere Inc.) was used to measure downwelling solar radiation. A laptop computer equipped with CDAP software (Center for Advanced Land Management and Information Technologies (CALMIT), University of Nebraska at Lincoln) was used to initiate spectral scanning of sensors and visualize and store the output spectral data. A model 10 AU Fluorometer (Turner Designs CA, USA) was used to measure *in situ* chlorophyll-*a* concentrations using UV fluorometric Standard Methods.

1.3 Field Data Collection

Spectral data collection was conducted around solar noon (11:00 am to 2:30 pm) at nadir angle. Data collection was stopped for dates when there was heavy cloud cover or when water was frozen and there was no access to the water surface. At each station, the downwelling radiation (L_O) was measured three times using a Spectralon panel, and water upwelling radiance (L_W) was measured six times approximately 20 cm above the water surface and six times just beneath the water surface. The instrument acquired a measurement scan in about 100 ms and a spectral curve was displayed for each scan. If any scan gave an error message such as “out of range” or had a spectral signature significantly different from the other scans of the same station, it was treated as an invalid scan. In total, fifteen valid scans were conducted for each station and each visit: three calibration scans, six scans above the water surface, and six scans below the water surface.

While conducting spectral measurements, water samples at the surface were collected using triplicate one-liter bottles. These water samples were placed on ice in the field and during trips between stations. Upon arrival at the lab, they were stored in a refrigerator at $-20\text{ }^{\circ}\text{C}$ and later filtered within four hours of testing. 241 water samples were collected during the entire sampling period from March 2006 to May 2007.

*1.4 Chlorophyll-*a* testing and data processing*

Chlorophyll-*a* concentrations in water samples were tested using the method of Strickland and Parsons (1968). Water samples were first filtered and chlorophyll was extracted using Acetone (90%). Extracts were then concentrated in a centrifuge for three minutes and the solution analyzed with a Model 10 AU Fluorometer (Turner designs CA, USA) to determine *in situ*

chlorophyll-*a* concentrations in mg l^{-3} . The trichromatic equation (Schalles et al 1998) was used to determine the average concentration values of chlorophyll-*a*

$$\text{Chl } a = V_{as} - P_{ac} * (V_{ex} / V_f)$$

where Chl *a* is chlorophyll-*a*, V_{as} is the average volume of sample filtered, P_{ac} is the average value of control filtered, V_{ex} is the volume extracted, and V_f is the volume filtered.

The calculated average of chlorophyll-*a* concentration for three sample replicates from each sampling station was subtracted by the average chlorophyll-*a* value of the three control replicates to get one chlorophyll-*a* value for each extracted sample. This value was multiplied by the volume extracted (30 ml) and divided by the volume filtered (100 ml) to get chlorophyll-*a* concentration for each sampling station for each visit.

1.5 Spectral Data Processing

1) Preprocessing

Raw data from invalid scans was first removed in pairs (both downwelling and upwelling scans) and only data from valid scans was kept. For all valid scans, each observed upwelling radiance value was normalized by dividing by the upwelling radiance from the reference panel to get a decimal reflectance value ($R = L_w / L_o$) using CDAP software at each band from 350 nm to 1016 nm. This value was then multiplied by 100 to obtain a percent reflectance value. Normalized data was arranged in a spreadsheet by sampling station and date. An average of reflectance values was calculated for six scans below the water surface for every wavelength, then sorted by sample station and date for sensitivity testing.

2) Band sensitivity testing

The data collected between March 2006 and December 2006 was used for sensitivity testing. Linear correlation was examined between chlorophyll-*a* concentration and averaged reflectance value at each individual band from 350 to 1016 nm and tested for statistical significance at a 99% confidence level (critical alpha $\alpha = 0.01$). It was found that there was a significant relationship between reflectance value and chlorophyll-*a* concentration for a band ranging from 697 to 792 nm for all water sampling stations. It is not surprising that these bands are located in Near Infrared (NIR) part of the electromagnetic spectrum. The top ten bands sensitive to chlorophyll-*a* (Table 4) range from 709 to 719 nm and fall within the red edge (680 to 730 nm).

Table 4. The top ten bands sensitive to chlorophyll-*a* and TSS

Top ten bands Sensitive To chlorophyll- <i>a</i>		Top ten bands Sensitive To TSS	
Band (nm)	Correlation Coefficient	Band (nm)	Correlation Coefficient
709	0.33427	491	0.54543
712	0.33559	487	0.54587
713	0.3358	486	0.54646
711	0.33612	480	0.54649
719	0.33628	495	0.54678
714	0.33669	494	0.54828
715	0.33744	488	0.54894
718	0.34054	490	0.54901
717	0.34324	489	0.54988
716	0.34324	482	0.55125

The linear correlation was also examined between TSS and averaged reflectance value at each individual band from 350 to 1016 nm and tested for statistical significance at a 99% confidence level (critical alpha $\alpha = 0.01$). It was found that there was a significant relationship between reflectance value and TSS concentration for a band ranging from 387 to 909 nm for all water

sampling stations, a much wider sensitive band range than was found for Chlorophyll-*a*. This may be due to the fact that TSS is a dominant factor in the surface reflectance of water. The top ten bands sensitive to TSS ranged from 482 nm to 491 nm, with the most sensitive band at 482 nm (Table 4).

1.6 Development of a new spectral index

To develop a ratio-based spectral index, two bands need to be selected: a band that would show the maximum sensitivity to changes in chlorophyll-*a* concentration and a band that would account for non-pigmented suspended matter that causes variation in reflectance taking into account the impacts of TSS or particulate matter (Gitelson et al 1986):

$$C = k * R_{sc} / R_{ait}$$

where *C* is the estimated chlorophyll-*a* concentration, *k* is a conversion factor, *R_{sc}* is the reflectance value of a band significantly correlated to chlorophyll-*a* and *R_{ait}* is the reflectance value of a band used to account for the potential impact of TSS.

Based on the sensitivity testing, the band 716 nm showed maximum sensitivity to *in situ* chlorophyll-*a* concentration and was selected as the numerator (*R_{sc}*=*R*₇₁₆) of new spectral index. Then a series of ratio-based indices: *R*₇₁₆/*R*_{tss} were calculated (*R*_{tss} is the reflectance value of a band at which there was a significant relationship between reflectance value and TSS concentration). After that each of them was examined for its correlation with *in situ* chlorophyll-*a* concentration collected in 2006. The *R*_{tss} that induced the highest correlation coefficient was identified as the denominator (*R_{ait}*) of new spectral index. Thus both numerator and denominator were identified for the new ratio-based spectral index.

1.7 Testing of literature indices

As mentioned earlier, there are many different kinds of ratio-based spectral indices. To evaluate the performance of the newly developed index, twenty-two indices from the literature (Table 1) were tested using a linear correlation. First, an index was calculated using reflectance data collected from March to May 2007 (n=80), and then *in situ* chlorophyll-*a* concentration was regressed against each index for all water sampling stations. The same approach was used to test the correlation between each index and TSS.

*1.8 Validation of a new chlorophyll-*a* index*

The validation of the new index was conducted using a separate eight-week dataset collected from March 2007 to May 2007. The differences between estimated chlorophyll-*a* values and the actual chlorophyll-*a* values (the absolute error) were first calculated using the following formula:

$$E_{abs} = chl-a_{act} - chl-a_{est}$$

where E_{abs} is the absolute error, $chl\ a_{act}$ is actual chlorophyll, and $chl\ a_{est}$ is estimated chlorophyll-*a*. Root mean square error (RMSE) was then calculated for all tidal and non-tidal stations. To determine if TSS impacted the accuracy of the chlorophyll-*a* estimation, the residuals of the chlorophyll-*a* estimates were first calculated and then regressed to measurements of TSS for all water sampling stations.

RESULTS

2.1 Status of chlorophyll-a concentration in the SJRW

The monthly average chlorophyll-*a* concentrations in the SJRW from May 2006 to December 2006 were displayed in Table 5. There were large spatial and temporal variations in the chlorophyll-*a* concentrations in the SJRW. Lower chlorophyll-*a* concentrations were observed in two tidal stations (Dennys and Mackee) while higher chlorophyll-*a* concentrations were shown in two other tidal stations (Silver Lake Dam and Hotel). Compared to non-tidal stations, smaller spatial variation in chlorophyll-*a* concentrations were found for tidal stations. Also high chlorophyll-*a* concentrations were shown for most stations in summer months, especially August.

Table 5. The average chlorophyll-*a* (mg/m³) concentrations in the SJRW from May 2006 to December 2006

Station	May	June	July	August	September	October	November	December	Grand Average
Dennys	3.22	2.48	1.38	1.15	0.73	0.67	0.85	0.48	1.52
Mackee	3.57	6.63	3.64	3.25	1.57	0.97	1.47	0.85	3.32
DSU	7.46	26.82	4.51	31.42	2.19	10.81	2.81	1.55	15.42
Silver hotel	62.15	54.34	64.50	124.46	65.68	92.01	15.77	2.46	69.82
Silver dam	31.22	56.68	52.62	123.18	117.18	101.06	29.75	5.53	69.25
Derby Pond	7.72	27.53	68.30	55.28	43.18	29.00	33.19	41.82	39.77
Moores Lake	24.79	43.10	57.68	57.06	17.46	13.28	5.70	3.09	35.01
Lebanon	13.52	38.72	51.40	40.76	17.89	26.77	18.27	14.55	32.18
Scotton	43.14	69.66	66.77	102.66	45.08	52.84	30.87	16.71	62.56
Lockerman	27.74	50.27	36.08	51.03	82.88	65.37	27.01	14.81	44.11

2.2 The Spectral Reflectance of the SJRW

The reflectance values at each band were averaged for one station at each visit and then for all sampling stations. The result is shown in Figure 3. It can be seen that there was a weak reflectance peak at around 574 nm, a trough at 673 and a reflectance peak at 705 nm. Gitelson et

al. (1992, 2000) stated that there was a trough at 670-680 nm and a distinctive peak near 700 nm for inland waters. This was confirmed by our study even though diverse water bodies including lakes, ponds, rivers and streams were monitored in this study.

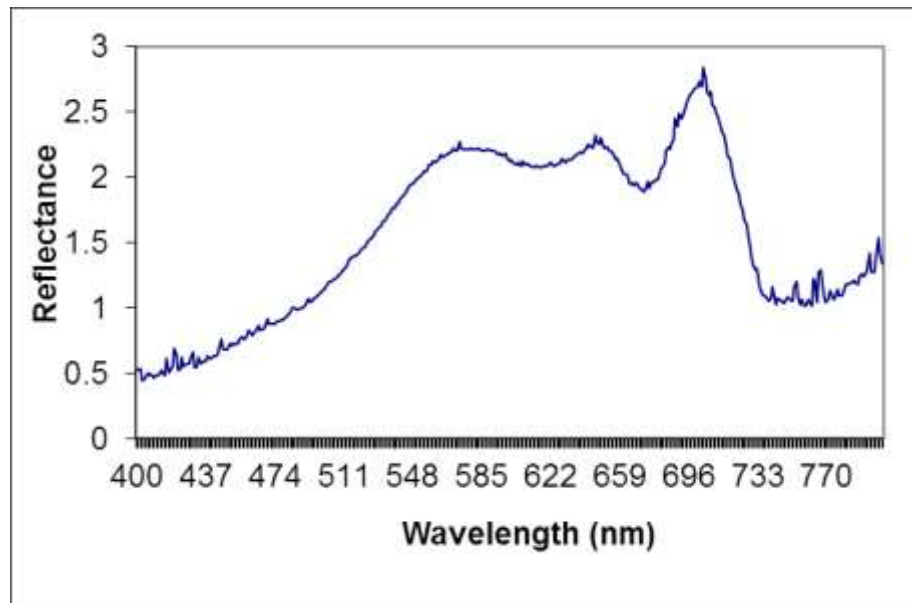


Figure 3: The averaged spectral curve for all sampling stations in the SJRW

2.3 New spectral index

Based on sensitivity testing, the band 716 nm show maximum sensitivity to chlorophyll-*a* and thus it was selected as the numerator for the new spectral index, and the band 667 nm lead to the highest correlation ($r = 0.8243$) between *in situ* chlorophyll-*a* concentration and the new spectral index and thus was selected for the denominator, giving a chlorophyll-*a* index of R_{716}/R_{667} .

Twenty four spectral indices from literature were tested using a linear correlation in order to compare their performance in retrieving chlorophyll-*a* concentration (Table 6).

Table 6. Tested literature indices and their correlation coefficients

Spectral Index	Correlation Coefficients	
	Chlorophyll- <i>a</i>	TSS
R700/R670	0.8413	-0.0784
R705/R670	0.5123	-0.1742
R704/R672	0.5377	-0.1418
R443/R560	-0.0351	0.2895
R490/R560	-0.1162	0.4802
R560/R440	0.0826	-0.3361
R490/R550	-0.5811	0.1814
R700/R675	0.8294	-0.0850
R672/R695	-0.8013	0.0311
R705/R678	0.5128	-0.1632
R550/R590	0.0378	0.1404
R550/R500	0.6839	-0.1985
R490/R555	-0.1276	0.4504
R510/R555	-0.1351	0.4317
R680/R670	0.5039	-0.1498
R765/R670	0.4731	0.5028
R412/R670	0.2429	0.0820
R719/R667	0.8216	-0.0158
R714/R650	0.2399	0.0635
R705/R662	0.4452	-0.1962
R709/R665	0.4555	-0.1321
R861.1/R856.7	0.0030	-0.1886
R749/R703	0.2394	0.8903
R708/R665	0.4612	-0.1232

Among those spectral indices, the index R700/R670 gave the highest correlation (0.84) and other indices including R700/R675, R672/R695, R719/R667 showed strong positive or negative correlations of larger than 0.8 with *in situ* chlorophyll-*a* concentration. The newly developed index R716/R667 had a very similar performance to the best of these indices.

The validation of the new index showed that the Root Mean Square Error (RMSE) is 15 mg/m³ for all sampling stations. This is likely caused by the wide variation in chlorophyll-*a* concentration, ranging from 0.46 – 189.6 mg/m³ (average 37.84 mg/m³) between March 2007

and May 2007. This result suggests that the new spectral index will not give very accurate estimation when chlorophyll-*a* concentration in water bodies is lower than 15 mg/m³.

It was found that there was no significant correlation ($R=0.16$) between the residual of chlorophyll-*a* estimate and *in situ* TSS concentration. This result indicates that TSS has no significant impact on the accuracy of the newly developed spectral index when applied to retrieve chlorophyll-*a* concentration from diverse water bodies.

Discussion and Conclusion

It is well known that it is the change in the slope of the reflectance curve from red to near infrared with increasing chlorophyll-*a* concentration that makes the ratio of NIR/Red useful for estimating chlorophyll-*a*. Based on the relationships between reflectance value of an individual band and *in situ* chlorophyll-*a* concentration, we identified the bands sensitive to *in situ* chlorophyll-*a* and TSS concentration respectively. Then we determined one band ratio (R_{716}/R_{667}) which had a highest correlation to *in situ* chlorophyll-*a*. Finally, this new spectral index was validated using an independent chlorophyll-*a* dataset and the impact of TSS on chlorophyll-*a* estimation was evaluated. These steps are reasonable and effective to develop a spectral index useful for retrieving chlorophyll-*a* in diverse water bodies.

Red edge (680 to 730 nm) bands are often used in the estimation of chlorophyll-*a* concentration. Previous research reported that chlorophyll-*a* has low absorption and higher reflectance between 690 and 715 nm (Gitelson et al. 1986, Gitelson et al. 1993 a, b) and beyond 720 nm the reflectance in the NIR range is controlled by the scattering of particulate matter (Zimba and Gitelson 2006). Thus the bands between 690 and 715 nm are more sensitive to chlorophyll-*a*

than the other red edge bands such as those between 680-690 and 720-730 nm. In this study, the top ten bands sensitive to chlorophyll-*a* ranged from 709 to 719 nm, a finding consistent with the literature. However, the band 716 nm was found to be most sensitive to chlorophyll-*a* in our study. This result is close to the result of Jiao et al (2006) who reported that a high accuracy of estimation for chlorophyll-*a* was achieved by using a peak reflectance at 719 nm.

Ratio-based indices are usually developed using the peak-trough ratio method. Many researchers report that there is a local reflectance minimum feature at approximately 670 nm due to the absorption maximum of chlorophyll-*a* (Gitelson et al. 1986, Mittenzwey et al. 1992, Gitelson et al. 1993a, b, Pepe et al. 2001, Doxaran et al. 2006), so the trough at 670 nm can be used to account for non-pigmented suspended matter that causes variation in reflectance. In our study, a trough at 673 and a peak at 705 nm were found from the averaged spectral curve for all sampling stations in the SJRW. However, 667 nm was identified as the final denominator to build our spectral index. It is the same as the denominator used by Jiao et al (2006) and deviates slightly from the 670 nm trough. Other denominator bands such as 676, 679 and 680 nm were also reported by Shu et al. (2000), Li et al. (2002) and Thiemann and Kaufmann (2002) respectively. The difference in the denominator band is likely caused by a variation in the spectral characteristics of water bodies investigated. This study involved four different water body types including lake, river, stream and pond. Since the composition of waters often varies with type of waters investigated and season, that can lead to a variation in spectral characteristic. Spectral differences in water bodies may cause a shift or change at bands/band combination most sensitive to *in situ* chlorophyll-*a* concentration.

This new spectral index could be used as an alternative of two popular indices (R700/R670 and R700/R675) in diverse water bodies. First, this new index is comparable to those two popular indices (R700/R670 and R700/R675) in terms of correlation and accuracy. The two popular indices showed good performance to estimate chlorophyll-*a* in our study, giving statistically valid chlorophyll estimates for all sampling stations in 2007. However, it was reported that the scattering peak at ~ 700 nm was also highly correlated to total suspended solids (TSS) (Koponen et al 2007, Olmanson et al 2013). Thus, the use of those two indices might lead to confusing interpretations of estimated chlorophyll-*a* in some high TSS cases. Also, the ratio R700/R670 and R700/R675 may not be appropriate for productive, turbid waters with chlorophyll-*a* concentration below 20 mg/m³ (Gitelson et al 2000). Therefore, R716/R667 could serve as an alternative spectral index for monitoring chlorophyll-*a* in diverse water bodies including lakes, rivers and streams using remote sensing techniques.

Two spectral bands (667 and 716 nm) identified in this study were not correspondent with sensor bands of some satellites such as Landsat. However, they were correspondent with two MEdium Resolution Imaging Spectrometer (MERIS) bands (band 7 centered at 665 nm and 9 centered at 708.75 nm). This is because a hyperspectral sensor (Ocean Optics) was used in this study and its bandwidth is 1 nm and bandwidth of both MERIS band 7 and 9 is 10 nm. Also, Ocean Land Color Instrument (OLCI) onboard Sentinel-3A has two spectral bands: Oa8 centered at 665 nm and Oa11 centered at 708.75 nm, which also have a 10 nm bandwidth. Thus, two identified bands (667/716) in this study match those two bands on OLCI. This result showed that both ENVISAT(MERIS) and Sentinel satellites could provide valuable spectral information on surface waters and would be effectively used in the estimation of chlorophyll-*a* in diverse water bodies.

The new spectral index should be useful for mapping chlorophyll-*a* concentrations in diverse water bodies with a large variation in concentration of chlorophyll-*a* and TSS given that concentrations ranged from 0.46 to 189.6 mg/m³ for chlorophyll-*a* and from 5 to 245 mg/m³ for TSS in waters tested in this study. Findings from this study indicate that hyperspectral imagery can be used to distinguish and separate TSS independently of chlorophyll-*a* levels, and thus demonstrate the suitability of hyper-spectral remote sensing techniques for mapping chlorophyll-*a* concentrations in diverse water bodies.

Acknowledgements

This research was supported by NOAA grant #NA17AE1624 to the Environmental Cooperative Science Center. The authors thank the Center for Advanced Land Management Information Technologies (CALMIT) at the University of Nebraska for CDAP software setup and Dr. John Schalles at Creighton University for guidance on *in situ* spectral measurements.

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