Asian Journal of Environment & Ecology

6(2): 1-18, 2018; Article no.AJEE.40840
ISSN: 2456-690X

Remote Sensing of Urban Lake Water Quality: A Preliminary Result from Spectral Angle Based Approach

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Authors' contributions

This work was carried out in collaboration between all authors. Authors WC, XM and SC co-designed the study. Author WC also performed and managed the statistical analysis, wrote the protocol, and first draft of the manuscript. Author JL managed the literature edit. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/AJEE/2018/40840
Editor(s):
(1) Wen-Cheng Liu, Professor, Department of Civil and Disaster Prevention Engineering, Taiwan Typhoon and Flood Research Institute, National United University, Taiwan.
Reviewers:
(1) Fábio Henrique Portella Corrêa de Oliveira, Universidade Federal Rural de Pernambuco, Brazil.
(2) Işın Onur, Akdeniz University, Turkey.
(3) Clement Kwang, Earth and Space Sciences Institute, Anadolu University, Turkey.
Complete Peer review History: http://www.sciencedomain.org/review-history/24236

Original Research Article

Received 1st February 2018
Accepted 12th April 2018
Published 20th April 2018

ABSTRACT

This study aims to develop a quick method based on spectral angle (SA) to evaluate overall water quality and spatial variation in urban lakes using in-situ water quality parameters of lakes or reservoirs and synchronous SPOT 5 remote sensing imagery, referring to the spectrum of a clear montanic Jiulongtan Reservoir in satellite image. The regression models between SA and water quality parameters were built for analysis, including chlorophyll a (Chl-a), chemical oxygen demand (COD), total phosphorous (TP), total nitrogen (TN) and integrated trophic state index (TSI). The

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results show that the grades of lake water quality in Guangzhou could be ordered by SA values from most desirable to least desirable as Jiulongtan Reservoir, Luhu Lake, Liwan Lake, Liuhua Lake, and Dongshan Lake. Further, the results also show that the SA of urban lakes correlates potentially with the parameters of water quality (Chl-a, R2 = 0.929569, $p < 0.01$; COD, R2 = 0.9767916, $p < 0.01$; TN, R2 = 0.58767495, $p < 0.05$; TP, R2 = 0.8705, $p < 0.05$) or TSI (R2 = 0.9066, $p < 0.001$) in spite of limited data samples collected in the study. The SA classification results by SPOT 5 multi-spectral images roughly reflect the grade difference of water quality as a whole and their spatial variations, i.e. consistent with concurrent result of lake water sampling analysis. The validation shows this approach can be helpfully used to quickly monitor the water quality status of lakes or reservoirs for broad region, to effectively identify the sampling locations for water sample taking and water quality analysis, and provide information for the management of urban lakes (by SPOT 5 or higher resolution satellite image) or large-middle sized reservoir (by Landsat ETM+).

Keywords: Remote sensing; spectral angle; urban lake; reservoir; water quality; trophic state index (TSI).

1. INTRODUCTION

Guangzhou, located in southern China, is one of the most rapidly industrialized cities in the world. The economic development and increase of urban population further drive the discharge of sewage and waste water.

The urban lakes were in quick eutrophication for past several decades year due to the sewage from urban roads, human settlements, and industry drainage, stimulating excessive algal growth. Eutrophication is a big concern in lakes during the dry season, particularly in the urban lakes and the Guangzhou reach of Pearl Rivers, the largest river in southern China. Water samples were taken on a seasonal schedule for to monitor water quality of minority lakes within Guangzhou, which was part of a long-term water quality monitoring project of rivers and urban lakes in Guangzhou. According to statistic reports [1], there are more than 1300 reservoirs and twenty urban lakes within Guangzhou. Monitoring water quality of the sixteen middle to large sized reservoirs may be feasible using the remote sensing imagery with a 20-30 m resolution such as Landsat but challenging for smaller water bodies due to their small sizes in relative to the spatial resolutions.

Urban lakes play an important role in maintaining the region's wetland and are an important water source and leisure place for urban populations. Mapping water quality of urban lakes over time can provide temporal change information to assess lake health for environment management. Yet, these information are limited to several selected lakes among 20 urban lakes and more than 1300 reservoirs in Guangzhou, partly due to restricted human and material resources and lack of suitable methodology. Historically, urban lake water quality variation assessment has been undertaken via laboratory samples [2], which is labor intensive and costly. Furthermore, the analysis cannot provide the factual spatial overview needed for quick assessment of spatial water quality or changes within lakes and reservoirs although there were studies trying to find such association between disease and water quality based on ontology and data mining [3,4].

The optical properties of a water body obtained by remote sensors vary with the concentration and characteristics of the total suspended sediments (TSS), phytoplankton, and colored dissolved organic matter (CDOM, "yellow substance"). The empirical statistical models have been applied to estimate water transparency and quality in water bodies for years by establishing correlations between remote sensing spectral bands and field measurements of water quality characteristics [5,6]. The value of Landsat Thematic Mapper (TM) data was demonstrated to estimate variations in suspended sediment in conjunction with a major flood event [7] as well as middle to large sized reservoirs in Shenzhen, China [8]. Recent studies based on Landsat 8 imagery further proved valid correlation between the trophic state of the lakes and OLI bands (OLI2/OLI4) [9]. Chang et al. [10] developed a multiscale modeling system to automate continuous water quality monitoring based on feature extraction and machine learning. The Spectral Angle (SA) mapping matching technique has been widely used in the geological application (mineral mapping), however, their applications have a limitation due to a lack of reference spectral libraries [11]. The coarse resolution of Landsat imagery further prohibits their usage in small lakes and reservoirs (< 30 m in diameter).

The SA mapping is a physically-based spectral classification that uses an n-dimensional angle to match pixels to reference spectra. The algorithm determines the spectral similarity between two spectra by calculating the angle between the spectra, treating them as vectors in a space with dimensionality equal to the number of bands [12]. This technique, when used on calibrated reflectance data, is relatively insensitive to illumination and albedo effects. A vector is plotted in n-dimensional space for an unknown pixel from the origin. The angle this vector forms is compared with that of the vectors of reference endmember, and the pixel is assigned to the reference class that has the smallest angle with the unknown pixel vector [13]. So, the SA better matches similar substances by spectral shape than traditional classifiers using statistical distribution pattern.

Satellite Pour l'Observation de la Terre (SPOT) was a high-resolution remote sensing system. SPOT 5 was launched on 4 May 2002 with 2.5, 5, and 10 m resolutions. However, the use of satellite imagery in water quality studies based on SPOT 5 were less reported for the central urban area of Guangzhou. There is a need to take advantage of the 10 m spatial resolution and 4 multi-spectral characteristics of SPOT 5 data (corresponding to Landsat TM 1- 4 bands with 30 m spatial resolution) to monitor lake water quality and eutrophication grades in fast-growing urbanizing areas, where the application of Landsat images is difficult. This study presents a fast SA-based method to monitor and evaluate water quality and eutrophication by correlating higher resolution satellite imagery (SPOT 5) and reference spectrum-based SA with ground observation of water quality parameters.

2. MATERIALS AND METHODS

2.1 Study Site and Data Collection

The study site includes four representative urban lakes of Liwan (10.4 ha), Liuhua (32.7 ha), Lu (25 ha), and Dongshan (20.9 ha) located in downtown area of Guangzhou, southern China (Fig. 1 and 2) with a pH range of 7.7~9.2. The referential montane reservoir, Jiulongtan, had an area of about 180 ha according to the SPOT 5 image in 2002 and is located about 50 km north (Huadu District) of the Guangzhou urban center.

Water quality of the three urban lakes was assessed using the Polyurethane Foam Unit (PFU) method for aquatic microbial communities as well as for water chemistry [14]. The parameters used included the chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), and chlorophyll a (Chl-a) (Table 1). According to China's surface water standard [15], the dissolved oxygen content of Luhu Lake was at grade II (6.0–7.5 mg/L), and Liwan and Liuhua lakes were at grade V (2.0–3.0 mg/L) at that time of data collection. TN of Luhu Lake was at grade IV (1.0–1.5 mg/L), and those of Liwan and Liuhua Lakes were at grade V (1.5–2.0 mg/L). The TP concentrations for Luhu, Liwan, and Liuhua Lakes were at grade V (0.1-0.2 mg/L), while the COD concentrations for these lakes exceeded even the grade V (30-40 mg/L) [14]. However, the corresponding water quality data were not available for Dongshan Lake. The trophic status index (TSI) values for lakes Luhu, Liwan, and Liuhua are 77.7, 79.3, and 73.9, respectively, indicating the eutrophic state grade V. The water samples were taken during the last 10 days of September and first 10 days of October in 2002 [14]. The water quality parameters were compared to their optical characteristics in the SPOT 5 satellite image. In addition, the Chl-a, COD, TP and TN concentrations of the fourth lake Dongshan on 20 December 2006 were collected for the study in similar season with Chen et al. collection [14]. The water quality parameters of all 4 urban lakes were analyzed.

The corresponding Chl-a, COD, TN and TSI values were collected from another lake as the TSI of Jiulongtan Reservoir on November 7 of 2002 since they are close to one another in distance and have similar montane environment. Then, the reservoir's spectrum was retrieved from the Landsat 7 ETM+ image. Additional Chl-a, TP, TN and TSI values of Furongzhang and Sankeng Reservoirs in dry season of 2010 were collected together with the Landsat 7 ETM+ spectra on March 18 of 2010 [16,17] (Table 1).

There are a total of five samples of COD, seven samples of Chl-a, seven samples of TN, six samples of TP, seven samples of TSI for model calibration, and two sites (one sample of COD, two samples of TN, one sample of Chl-a, and one sample of TSI) for model validation. Table 2 lists the water quality parameters and image or in-situ spectra data pairs while table 3 lists the validation data.

The water temperatures of all lakes and reservoir at 0.5 m depth were between 27～33.6°Cin summer and 16.4～24°Cin winter.

2.1.1 SPOT 5 and Landsat 7 ETM+ satellite images

Acquired on November 7, 2002 (path 284, row 304), the SPOT 5 image is the only quasisynchronous 10 m resolution image archived for reference and comparison of SA mapping results with field water quality parameters [14]. SPOT 5 is the first satellite that can balance large scene sizes (60 × 60 or 60 × 120 km^2) with highly detailed imagery. SPOT 5 imagery has 4 spectral bands of 10 m with a 8-bit depth (XS1, green: 0.50–0.59 μm; XS2, red: 0.61–0.68 μm; XS3, near infrared: 0.78–0.89 μm; XS4, short wave infrared (SWIR): 1.58–1.75 μm), which is most cost effective for water quality investigation of small urban lakes (usually under 30 ha). The corresponding bands in Landsat 7 ETM+ image are green (0.525–0.605 μm), red (0.63–0.69 μm), near infrared (0.75–0.90 μm), and short wave infrared (SWIR 1.55–1.75 μm). The SPOT 5 and Landsat 7 ETM+ sensors have similar radiometric resolution (8 bits).

Fig. 1. Location of study area, Guangzhou, Guangdong Province, South of China

Fig. 2. Location of four lakes featuring in the SPOT 5 Image

Table 1. Physicochemical parameters and image spectrum features for four urban lakes and a montanic reservoir. The number in parenthesis indicates the water quality level according to the Chinese national environmental quality standards for surface water (five levels in total with level I I and V show the most desirable and least desirable water quality, respectively). The trophic state index was evaluated based on Chinese eutrophication standard for evaluation of lake water quality (Chen et al. 2004)

Water quality parameters	Dongshan lake (2006)	Liuhua lake (2002)	Liwan lake (2002)	Luhu lake (2002)	Furongzhang reservoir (2010)	Sankeng reservoir (2010)	Jiulongtan reservoir (2002)
DO (mg/L)		4.0 (IV)	3.92 (IV)	6.95 (II)			
COD (mg/L)	100.4(V-)	60.1 (V-)	56.1 (V-)	45.1 (V-)			2.43
TN (mg/L)	7.94(V-)	2.72 (V-)	2.42 (V-)	1.43 (Ⅳ)	1.4	1.2	0.62
NO_3-N (mg/L)		0.68	0.53	0.26	17.2	6.8	3.25
TP(mg/L)	0.08 (Ⅳ)	0.16 (V)	0.12 (V)	0.15 (V)	0.02 (II)	0.01 (I)	
Chl-*a*(mg/m^3)	146.5	109.5	103.5	42.7	17.2	6.8	3.25
Trophic State index (TSI)	85.6 (V)	77.7 (V)	79.3 (V)	73.9 (V)	37.11 (II)	30.77 (II)	26 (I)
Mean reflectance (XS1)	0.047191	0.053415	0.055305	0.050450	0.07704	0.037025	0.070778
Mean reflectance (XS2)	0.030906	0.034286	0.038204	0.031716	0.05554	0.018525	0.032436
Spectral Angle	0.263925	0.259694	0.252011	0.25017	0.169756	0.048239	0.02

Table 2. Data for calibration of regression models between SA and water quality parameters or trophic state index (TSI)

Calibration samples	Year	SA	COD	TN	TP	Chl-a	TSI
Luhu, Liuhua, Liwan and Dongshan Lake	2006	Yes	Yes	Yes	Yes	Yes	Yes
A lake near Jiulongtan Reservoir	2002	Yes	Yes	Yes		Yes	Yes
Furongzhang reservoir	2010	Yes		Yes	Yes	Yes	Yes
Sankeng reservoir	2010	Yes		Yes	Yes	Yes	Yes

Table 3. Comparison of In-situ and prediction data of water quality for validation of models

Validation samples	SA		COD	TN	Chl-a	TSI
From Guangzhou in 2006 (By authors)	0.16157	measurement	9	3	--	--
		prediction	16.91	1.67	--	--
Qieyashi reservoir by Lin et al., 2003	0.190698	measurement	--	7.15	32.4	55.1
		prediction	--	1.98	35.5	56.3

Landsat 7 is one of the most accurately calibrated Earth-observing satellites compared to the same measurements made on the ground. The consistent global archiving scheme, large coverage (185*185 km2) and free pricing of Landsat 7 image led to a large increase of Landsat data users. In October 2008 USGS made all Landsat data free to the public. Although suffering the loss (about 2-14 pixel width) of its scan line corrector (SLC) depending on the distance from scene center and impacting the imagery of Landsat 7 since May 31, 2003, the ETM+ image still acquired approximately 75 percent of the data for any given scene. The Landsat 7 ETM+ image of 30 m resolution is still an effective means to monitor the water quality of middle to large sized lakes and reservoirs. The Landsat 7 ETM+ satellite images used in this study included two dates: November 1, 2000 for Qiyashi Reservoir (22°48’N, 114°12’E) and March 18, 2010 for Furongzhang (23~29°N，1 13°13’ E) and Sankeng (23°27’ N, 113°03’ E) Reservoirs.

2.1.2 Invariability of water quality grade between satellite imaging and field sampling

The variation of lake water quality grade was analyzed between the lake water sampling in 2002 and the closest SPOT 5 image assuming that the water quality grades did not change significantly over a one month period. Although the precipitation reached 122.5 mm during the period (the mean annual precipitation for the period was 70 mm), the quantity of precipitation should be insufficient to change the lake water quality grade in a short period in dry season. The previous studies showed small level of dissolved oxygen in the dry season of water bodies in Guangzhou regardless of the kinds of rainfall levels [18,19]. For example, the concentrations of dissolved oxygen mostly were at grade V (2–3 mg/L) from December 29, 2009 to February 19 of 2010 (except on January 20 and February 12, 2010), although there was the precipitation of 136 mm (Fig. 3, Table 4). In another example, one automated water quality measurement station in Guangzhou showed little change of dissolved oxygen from 8 September to 11 October 2008 in dry season (almost consistently stayed on grade IV of water quality) when accumulated rainfall attained almost 236 mm. Therefore, the contemporaneous physicochemical parameters (COD, TN, TP) based TSI (water quality grade) from the previous study in the 3 lakes (Luhu, Liwan, and Liuhua) could be referenced for comparison [14] (Table 1).

The ground measurement data, together with the averaged SA of lakes with different water quality grades from SPOT 5 satellite image mapping, provide the set of quasi-synchronous analyzing data for the study. Furthermore, the TSI values with little seasonal change (<2.2% at percent of averaged relative error) were found in six small and middle sized reservoirs between March-April (dry season) and July-August (high water period) 2010 in Guangzhou [17] and from eighteen middle and large sized reservoirs between November-December (dry season) and June-July (high water period) 2000 in Guangdong Province, southern China [20].

2.1.3 Methodology

The eutrophication of a water body varies with many parameters of water quality, such as the concentration of TSS, phytoplankton, TN, TP and COD. Data for solar radiation at various wavelengths was obtained from satellite sensors

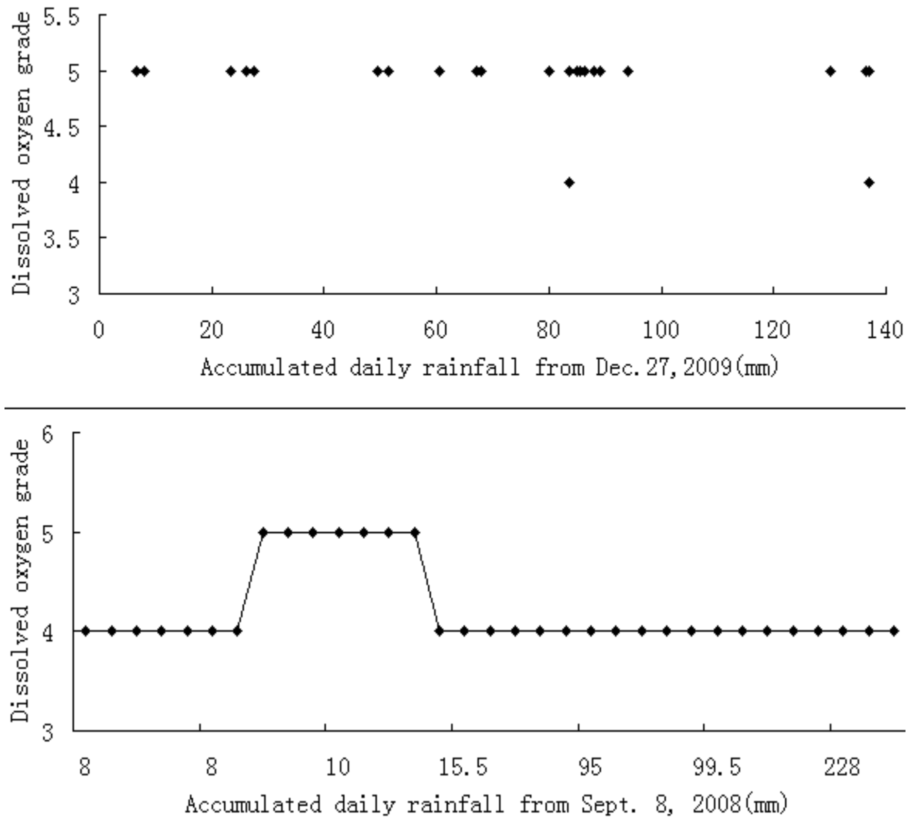

Fig. 3. Upper panel: Comparison of Observations of dissolved oxygen (mostly at grade V) and accumulated rainfall (136 mm) at Changzhou National Water Quality Station, Guangzhou (dissolved oxygen) and Guangzhou meteorological station (rainfall) from December 27 of 2009 to February 19 of 2010; Lower panel: Comparison of Observations of dissolved oxygen (mostly at grade Ⅳ) and accumulated rainfall (236 mm) at Changzhou National Water Quality Station, Guangzhou (dissolved oxygen) and Guangzhou meteorological station (rainfall) from September 8 to October 11 of 2008

Table 4. An example between the relation of rainfall and water quality during autumn season showing no obvious change of lake water quality grade with heavy rainfall of 133 mm

Dates of year 2008	weeks	Accumulated rainfall (mm)	Water quality grade
Sep 8~14	1	8	?
Sep 15~21	2	10	?
Sep 22~28	3	85	?
Sep 29~ Oct 5	4	133	?
Oct 5~11	5	0	?

aboard SPOT 5 or Landsat 7 ETM+. The data can be calibrated to reflectance and transformed to SA and correlated to water quality parameters mentioned above. This creates an alternative approach to evaluate the eutrophication grade of lakes and reservoirs through remotely sensed imagery, which have proven to have many significant advantages over routine laboratory analysis and ground sampling considering nearly-continuous spatial coverage, periodic observation, and relatively long record of archived satellite imagery.

2.1.3.1 Image calibration to reflectance

Absolute radiometric sensor calibration is a complicated procedure that imposes the greatest limitations on the quantitative applications of remote sensing. The objective of absolute radiometric sensor calibration is to produce accurately calibrated data for consistent image quality, meaning that the digital data on the delivered medium must be convertible to spectral radiance or a well-defined physical unit. Since the fraction of light reflected from water is very small and the desired radiance leaving the water has only a small portion of the signal recorded by the satellite due to atmospheric disturbance, accurate absolute radiometric correction of the sensor is critical [3].

The calibration coefficient A(i) for SPOT 5 cameras is specified in the metadata file of image as:

$$DN(\lambda) = A(\lambda) * L(\lambda). \quad (1)$$

For each spectral channel, DN(λ) and L(λ) are the digital number value of a pixel and at-sensor radiance, respectively. The calibration coefficient A(i) for Landsat 7 ETM+ image is 1.

The conversion from spectral radiance to exoatmospheric reflectance uses the following equation [21]:

$$\rho_p = \frac{\pi \bullet L_\lambda \bullet d^2}{ESUN_\lambda \bullet \cos\theta_s}, \quad (2)$$

where ρ_p is unit-less planetary reflectance; L_λ is spectral radiance at the sensor's aperture in mW cm^{-2} $ster^{-1}$ m^{-1}; d is Earth-Sun distance in astronomical units; $ESUN_\lambda$ is mean solar exoatmospheric irradiances in mW cm^{-2} $ster^{-1}$ m^{-1}; and θs is solar zenith angle in degrees.

Removal of atmospheric effects due to absorption and scattering was completed using dark pixel subtraction method [22], which means that every visible band (SPOT 5 XS1, XS2, XS3, XS4; Landsat 7 ETM+ b1, b2, b3, b4) subtracts a minimal value. The reflectance of SPOT 5 or Landsat 7 ETM+ images at the Earth's surface, ρ, was produced for further analysis after atmospheric correction by dark pixel subtraction and then for spectral angle calculation here. The empirical reflectance range cross transects of lakes and reservoirs was used to extract reflectance data for each of the lakes only, while eliminating the reflectance data for no area of interest.

2.1.3.2 Spectral angle calculation

The comparison of two spectra had developed into a new image classification method. A major difference between the SA classifier and conventional classifiers (e.g., Iterative Self-Organizing Data Analysis Techniques [ISODATA], maximum likelihood, decision trees, and neural networks) is that the SA classifier utilizes the spectral shape pattern (all bands concerned) while conventional classifiers rely on the statistical distribution pattern. When "angular distances" are used, image pixels that have similar shape patterns will be classified into one cluster class. When the "distance" concept is used, pixels close in feature spaces will be classified into one class based on the distribution pattern regardless of the shape of the pattern [13]. The SA is defined as follows:

$$\theta_{i,r} = \cos^{-1}\left[\frac{\sum_{k=1}^{m} x_{i,k}\,\mu_{r,k}}{\sqrt{\sum_{k=1}^{m} x_{i,k}^2 \sum_{k=1}^{m} \mu_{r,k}^2}}\right] \quad (3)$$

where $\theta_{i,r}$ are the SA between pixel *i* and a reference spectrum *r*; and *m* is the number of bands; $X_{i,k}$ is the pixel value in band *k*; and $\mu_{r,k}$ is the mean pixel value of reference class *r* in band *k*.

The water quality of Jiulongtan reservoir is usually high as spring water is the main water source. In fact, the survey of hygienic condition of source water in Huadu District of Guangzhou showed that the water complied with the standard of China's drinking water [23]. Therefore, this study treated water from Jiulongtan as a category with the best water quality to be compared with other lakes using a supervised procedure of image classification and predicted the relative water quality grade of other water bodies based on the broad and integrated water quality condition described earlier. Meanwhile, the water quality change of urban lakes was spatially mapped by SPOT 5 remote sensing in spite of limited experimental data performed for this statistical test. The pixel area near the center of Jiulongtan Reservoir was averaged and retrieved as the reference spectrum from calibrated SPOT 5 image, which was representative of a relatively clear water body. Because the SA calculation utilizes the shape of the pattern for clustering and classification of multi-spectral data, the analyst is required to relate field measurements to spectral shape patterns of water body pixels of different trophic types to simulate the accurate water quality grades. The low or high of SA values reflect the good or bad of water quality grades, such as oligotrophic, mesotrophic or eutrophic reservoirs.

2.1.3.3 Regression analysis & evaluation between water quality parameters and SA

Predicting water quality based on historical data is critical for environmental management [24]. The statistical regression analysis between water quality parameters and SA was performed with t-test. The parameters of water quality include COD, Chl-a, TN and TP. Besides, the regression equation was produced between TSI and SA. In order to assess the trophic state of lakes or reservoirs, the weighted average of integrated trophic state index was calculated as TSI using the water quality parameters of Chl-a, COD, TN and TP [25]. The grading standards of reservoir trophic state of TSI include oligotrophic (0-30), mesotrophic (30-50), and eutrophic (more than 50).

3. RESULTS

3.1 Water Quality Parameters and the Reflectance of Urban Lakes and Clear Reservoirs

First, the urban lakes (monitored objectives) and the montane reservoir's reflectance (reference objective) were analyzed according to their randomly selected spatial reflectance transects (Figs. 4 and 5). The transects of lakes and reservoir in the SPOT 5 XS bands (Fig. 5) showed that their reflectance were below 0.02 for the montane reservoir and below 0.03 for the urban lakes based on the selected water bodies. Because the analysis in this study was limited to 4 urban lakes and one montane reservoir, it was not necessary to extract the information of all lakes or reservoirs within the SPOT 5 image.

Using the training data (reflectance transects), the averaged reflectance values for the four urban lakes and the montane reservoir can be calculated (Fig.6). The reflectance of Furongzhang and Sankeng Reservoirs corresponding to the wavelengths of SPOT 5 was retrieved from Landsat 7 ETM+ image for comparison. In XS1 (0.50–0.59 μm) and XS2 (0.61–0.68 μm) bands of SPOT 5, the mean reflectance of water bodies increases in the following order: Jiulongtan Reservoir, Dongshan Lake, Luhu Lake, Liuhua Lake, and Liwan Lake. Note that this is not completely consistent with the fact of water quality grades of these water bodies or with the response of SPOT 5 image to water quality. For example, the water quality of Liwan Lake is better than Liuhua Lake, and the water quality of Liuhua Lake is better than Dongshan Lake. In other words, the reflectance is not always consistent with the water quality grades of lakes or reservoirs. Obviously, the order is completely different for XS3 and XS4 bands of SPOT 5.

Many experiments and *in-situ* studies showed that reflectance increases with increasing TSS concentration in visible and near-infrared bands [26,27]. However, a negative correlation between reflectance and TSS was found in the Pearl River Estuary under condition of suspended solid adsorbing organic matter [28]. TSS concentration has a strong correlation to Chl-*a* concentration [29,28]. Dongshan Lake has lower reflectance than other three urban lakes at the blue and green bands of SPOT 5 (Luhu, Liuhua, and Liwan in Fig. 6). However, whether the lake water quality grade could be identified by other optical information (such as SA) from remote sensing imagery remains unknown.

All reflectance variation of the four urban lakes and the montane reservoir in SPOT 5 XS bands was demonstrated in Table 5. The lake area was automatically extracted by reflectance range from SPOT 5 image for SA analysis of the lake region. The frequency distribution of spectral angles for four urban lakes was different (Fig. 7). Table 6 shows the SA statistic for four lakes and the montane reservoir. The result of correlation analysis between SA and water quality parameters (Chl-*a*, COD, and TN) is in Fig.8. The regression result between SA and water quality parameters (Chl-*a*, COD, TN, TP and TSI) shows that the SA of urban lakes correlates significantly with the parameters or eutrophication grade of water quality (Chl-*a*, $R^2 = 0.9295$, $p < 0.01$; COD, $R^2 = 0.9767$, $p < 0.01$; TN, $R^2 = 0.5876$, $p < 0.05$; TP, $R^2 = 0.8705$, $p < 0.05$; TSI, $R^2 = 0.9066$, $p < 0.001$).

3.2 Performance of Regression Models

Statistical analysis between SA and water quality parameters (or eutrophication grade) shows that the significance value of the F statistic is very small (less than 0.01 for COD and Chl-a, less than 0.05 for TN and TP, and less than 0.001 for TSI), while the determination coefficient and correlation coefficient of the five models are all very high (R^2: 0.8705~0.9767, Fig. 8) except for TN. This indicates that regression analysis was a valid method for predicting Chl-a, COD, TN and TP concentrations and evaluating the trophic state of the lakes or reservoirs.

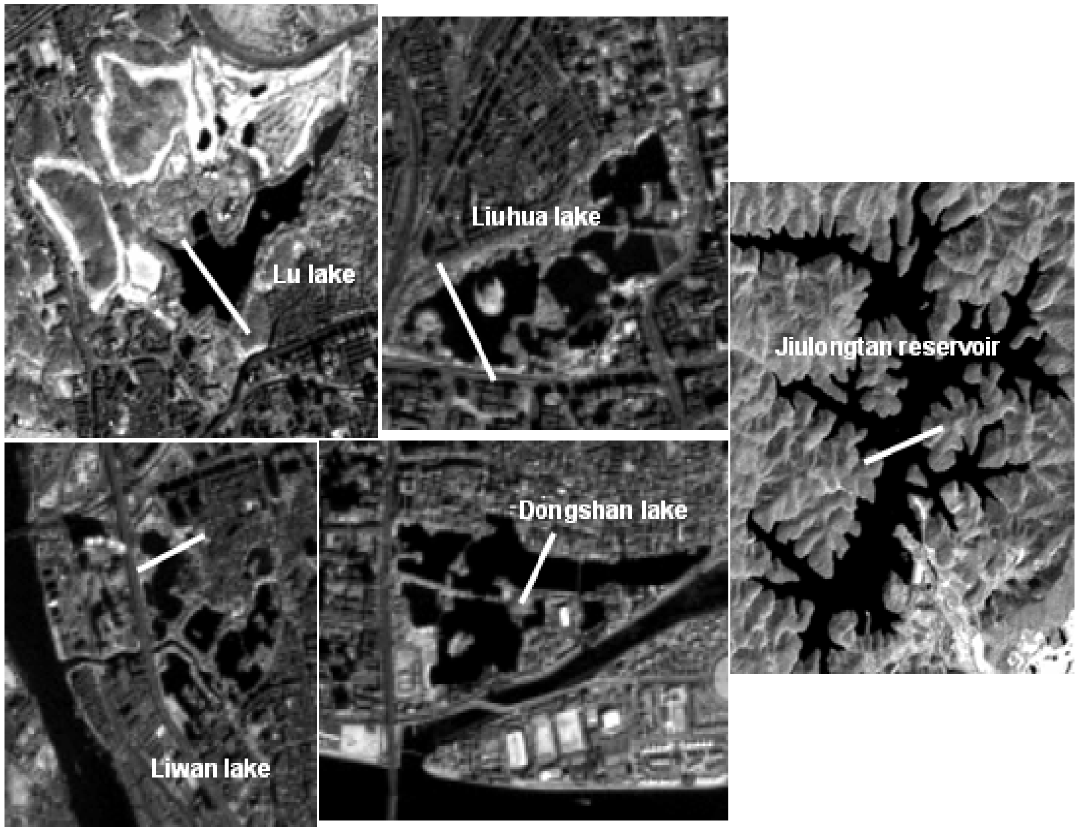

Fig. 4. Location of spectral profiles for producing the typical variation range of reflectance in four lakes and a montane reservoir

Table 5. Variation of reflectance ranges in different water bodies

Water body	Min.	Max.	scope of most pixels
Jiulongtan reservoir	0.0061	0.0246	0.0061~0.0246 (97%)
Liuhua Lake	0.0135	0.0258	0.014~0.024 (94.7%)
Liwan Lake	0.0147	0.0270	0.015~0.026 (93.8%)
Luhu Lake	0.014735	0.024535	0.015~0.024(96.7%)
Dongshan Lake	0.0123	0.0233	0.014~0.021 (93.9%)

Table 6. Variation range of spectral angles between water bodies and reference

Water body types	Spectral angle		
	Min.	Max.	Mean
Jiulongtan reservoir	0.0048	0.6167	0.204713
Liuhua lake	0.1658	0.3878	0.259694
Liwan lake	0.1797	0.3273	0.252011
Luhu lake	0.1676	0.3419	0.25017
Dongshan lake	0.1651	0.448	0.263925

Although the collection of synchronous *in-situ* data with satellite imaging is really difficulty, there is *in-situ* data of five sites collected for validation of four statistical regression models. The regression models of Chl-a and TSI are proven more effective than model of TN and COD. Specially, the Chl-a concentration can be a key indicator of over standard TN and TP concentrations [30].

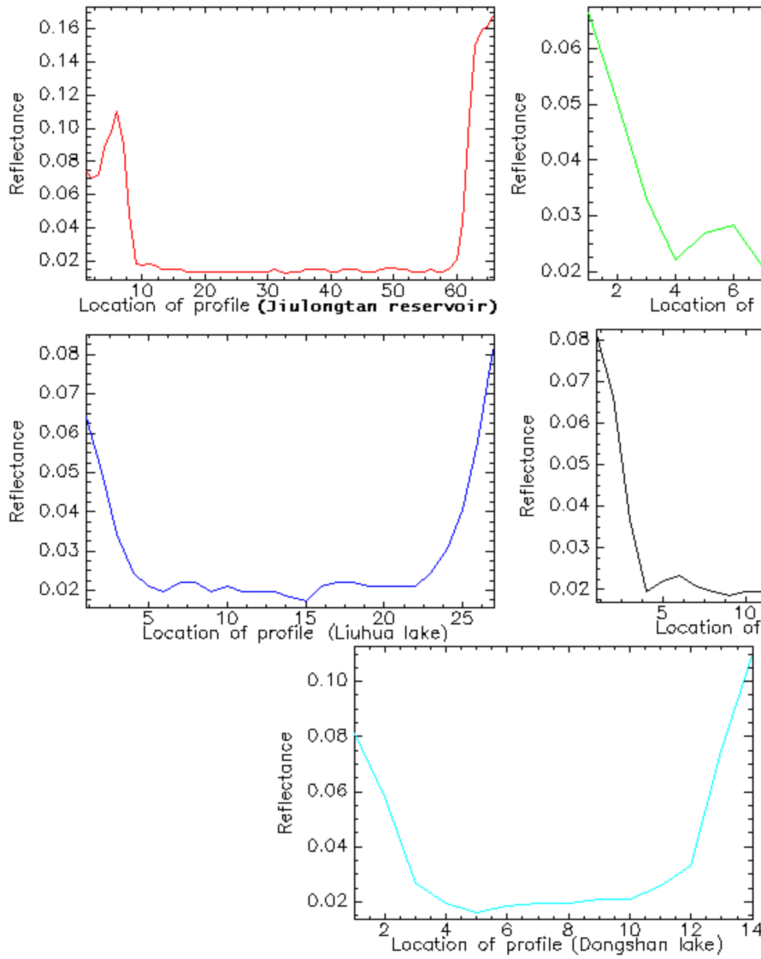

Fig. 5. Variation range of reflectance profiles in figure 4 from XS3 at near infrared range (0.78–0.89 µm) of SPOT 5. The location of profile indicates the pixel number in relative to the starting pixel of the profile

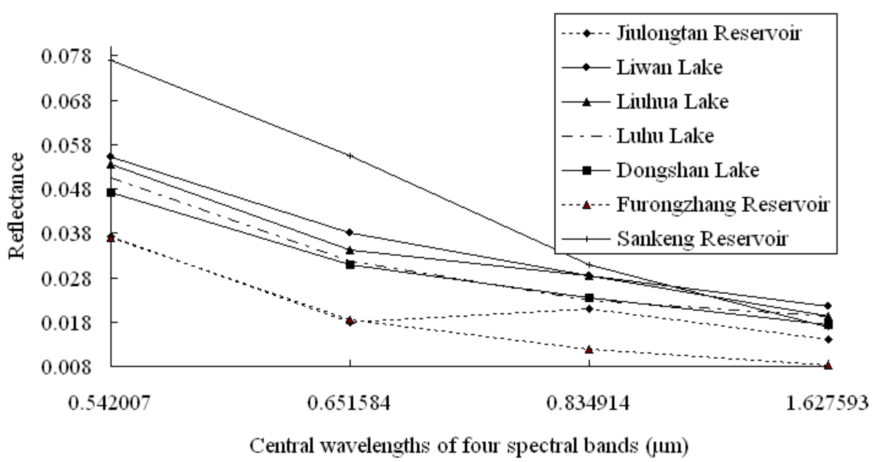

Fig. 6. Mean reflectance of four urban lakes and three reservoirs. The four wavelengths from small to large correspond to blue, green, red, and near-infrared bands, respectively

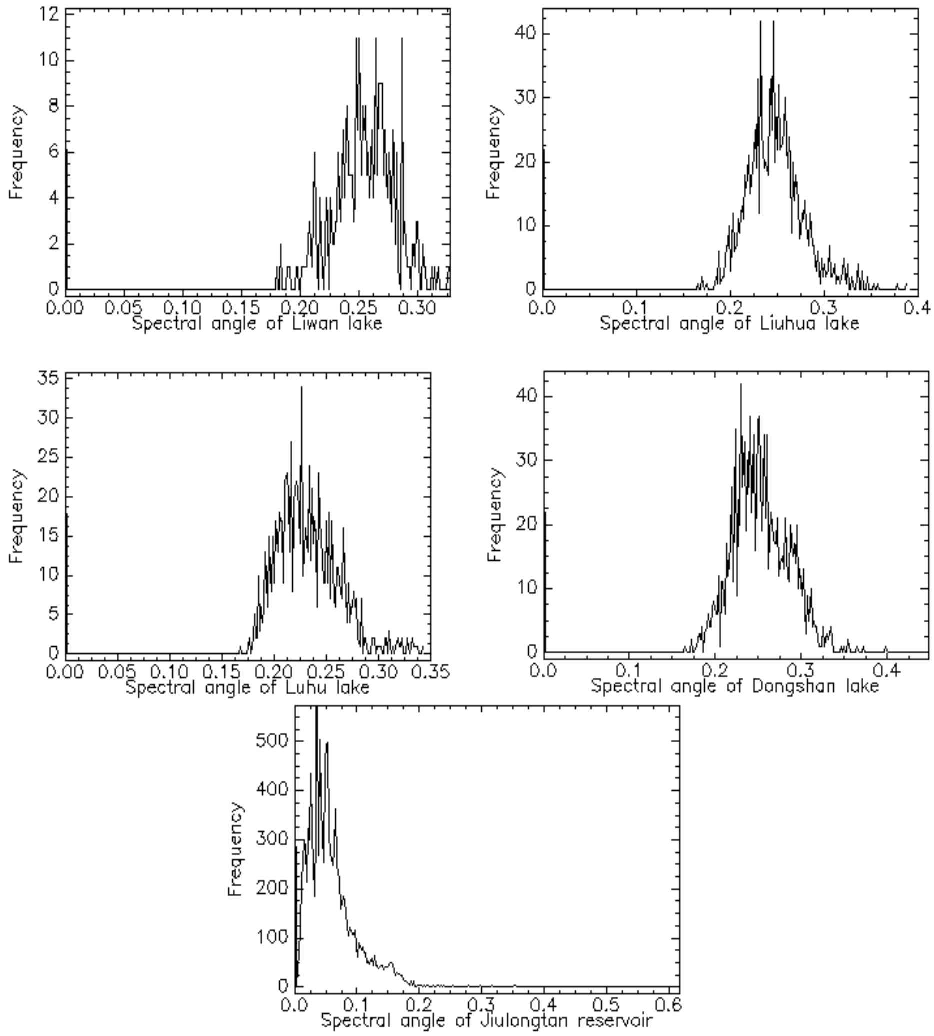

Fig. 7. Spectral angle between reflectance of urban lakes and reference endmember of Jiulongtan reservoir

4. DISCUSSION

4.1 Reflectance, SA, Water Quality Parameters and Eutrophication Grade

By comparing the 4 urban lakes with the clear water of the Jiulongtan Reservoir (Fig. 7, Table 6) using SA analysis, we found that the mean SA of Dongshan Lake was the highest of four urban lakes, followed by Liuhua, Liwan, and Luhu lakes, sequentially. This indicates that the lake or reservoir water quality can be ordered as Jiulongtan Reservoir, Luhu Lake, Liwan Lake, Liuhua Lake, and Dongshan Lake, from the most desirable to the least desirable for urban landscapes and settlements. The results of water quality for Luhu, Liwan, and Liuhua Lakes estimated through the SPOT 5 image generally agree with the laboratory analysis of most water quality parameters (COD, TN, Chl-*a*, NO_3-N, TP, and TSI; Table 1). Moreover, the results of SA predict the water quality grade of Dongshan Lake in Chl-*a*, COD, and TN, yet many other parameters of water quality need to be further researched (Table 1). Yu et al. [31] used water quality data from April and May 2006 and found that the Guangzhou section of the Pearl River (connected to Dongshan Lake) had higher TN and TP contents than other urban lakes in Guangzhou, which implies that Dongshan Lake among urban lakes of Guangzhou was probably the worst lake in terms of water quality.

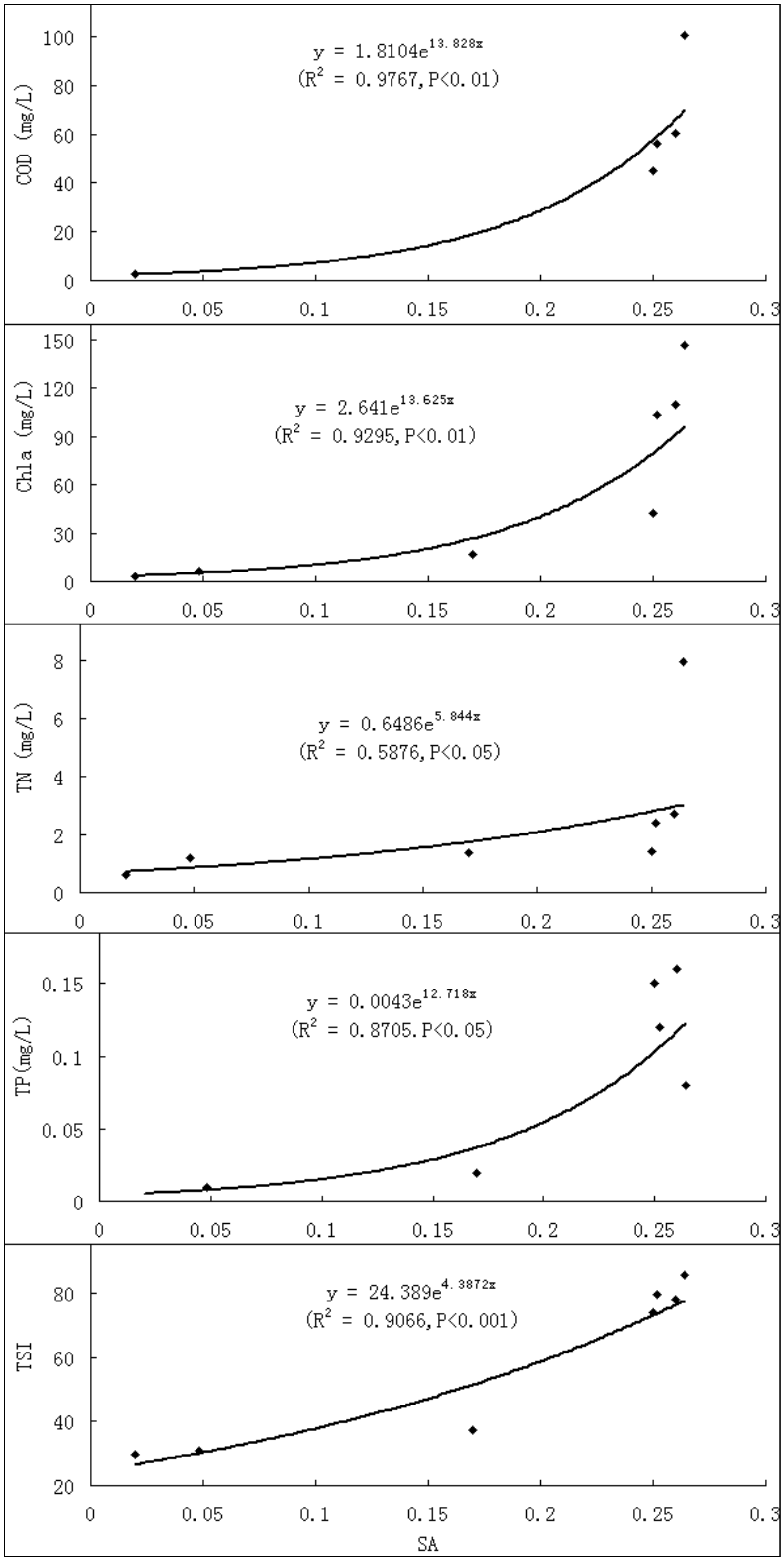

Fig. 8. The regression model between lake-averaged spectral angles and parameters (Chla, COD TN, TP and TSI) of water quality in urban lakes

The PFU method is a biological water quality monitoring method with more comprehensive community grades. Many of its parameters (e.g., community colonization parameters, heterotrophic index, and diversity index) are remarkably related to a comprehensive chemistry index and TSI. Therefore, the status of lake water quality grade can be represented by PFU community parameters [14,32]. The PFU method could more accurately show the water quality grade of urban lakes (Table 1).

4.2 Water Quality Analysis and Regression Model between Water Quality Parameters and SA

The change tendency of most water quality parameters in lakes of Guangzhou is in accordance with that of SA. However, the relatively low determination coefficient on TN was probably because the NO_3-N in eutrophication water is transformed into NO_2-N in anoxic conditions. However, the SA method for ordering of water quality is more accurate than the reflectance method when applied to urban lake water with high organic matter concentration [33]. As a matter of fact, the absorption coefficient of colored dissolved organic matter (CDOM) of the 4 urban lakes in Guangzhou on 20 December 2006 was between 1.17 and 2.77 (440 nm; collected by authors), even higher than the CDOM values (0.22–1.88 at 440 nm) of Taihu Lake, another severe eutrophication lake in China, in 2006–2007 [34].

Basic statistics on Chl-a and the other water parameters (COD, TP & TN) were summarized and their regression correlation analysis with SA was constructed (Table 1 & Fig.8). The results show that Chl-a concentration is exponentially correlated well with SA. Just like the Chl-a concentration, COD is another important indicator of water quality and is exponentially correlated with SA. The other parameters such as TN are exponentially correlated with SA. However, the degree of correlation is different between these four parameters (Chl-a, COD, TP & TN) and SA. SA have a high correlation with Chl-a, COD, TP and TSI (R^2>0.87) but a slightly lower correlation with TN (R^2=0.5876).

The Chl-a concentrations from surface layers of urban lake water bodies are large in this study. High concentration of N and P benefits the growth of algae. COD at grade of "V-"(>40 mg/L) for studied urban lakes indicate large organic matter content that is in accordance with the grade of urban lake eutrophication (TSI > 50).

The SA is closely correlated with the main water quality parameters of TP, COD and Chl-a concentrations in the urban lake freshwater systems, compared with other parameters such as TN. Chl-a concentration is an important parameter for monitoring water TSI through remote sensing techniques because it produces visible changes in the surface of waters [30]. According to the correlations between SA and these parameters, we can detect its size and distribution and assess the grade and distribution eutrophication of water bodies through remote sensing imagery. Moreover, it can also provide effective support for further detailed investigation, field analysis and management recommendation on specific lake.

Although error of the COD prediction for one site is large at about 8 mg/L, error of TN prediction at one of two sites is acceptable at 1.34 mg/L. In contrast, the errors of Chl-a and TSI prediction are small. Reasons for this might result from a lack of direct optical effect for COD and TN constituents in Lakes or reservoirs water. Besides, the Chl-a concentration mainly regulates the grade of lake or reservoir trophic state in study area.

The results suggest that the SA method has potential to quickly map the TSI by SPOT 5 or other similar satellite sensors based on the spectral shape.

4.3 SA & TSI Mapping of 4 Urban Lakes

The spatial variation of urban lake water quality can be easily obtained from maps of the SA between pixel spectrum of lakes and reference endmember of reservoir. The variant characteristic of SA can indicate the areas with relatively more severe pollution within the 4 urban lakes (Liuhua Lake labeled as A1, A2; Liwan Lake labeled as B1, B2; Luhu Lake labeled as C1; Dongshan Lake labeled as D1, D2). For an area with a large SA value, a ground investigation can be considered for the purpose of water quality sampling, analysis and further management of urban lakes or reservoirs. The area with better water quality (light color area) can be the choice of recreation areas for city residents. Further, there was better water quality at south of the four urban lakes than at north, which is like an effect of the monsoon southerly. Therefore, more reinforced water quality management can be planned at north of the urban lakes.

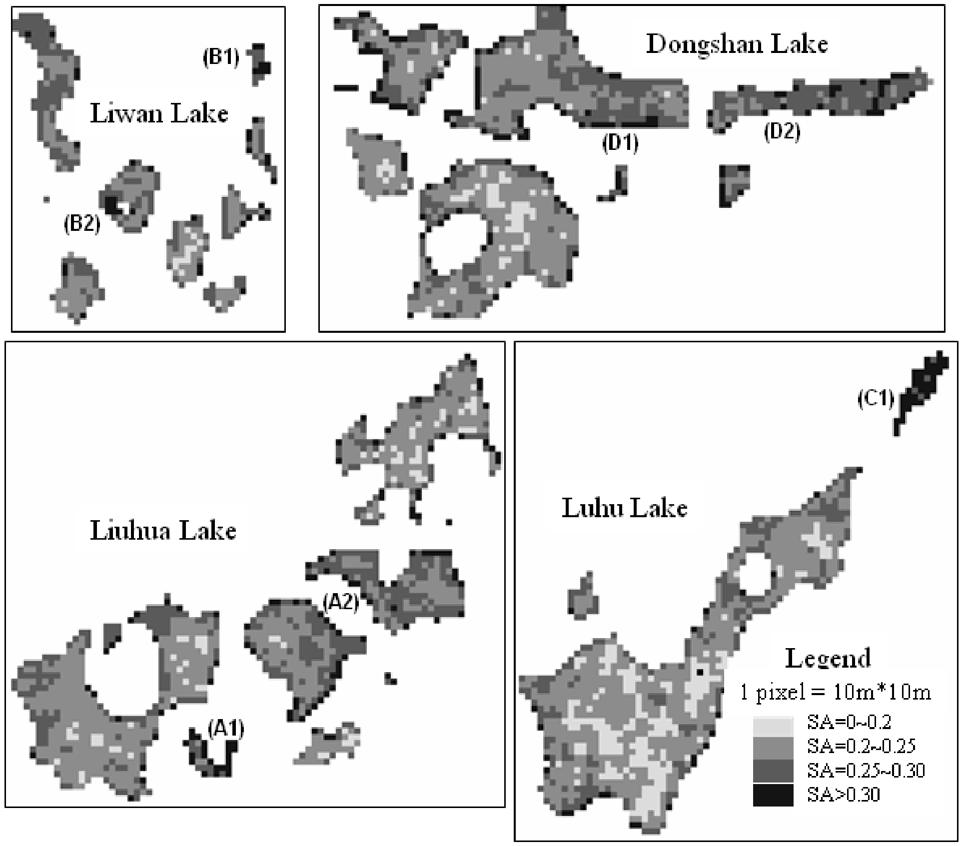

Fig. 9. Spectral angle (SA) of four lakes in Guangzhou urban area. Small number (Chracter) represents better lake water quality for each lake

The reliability of remotely sensed approach to monitor TSI of urban lake or reservoir water bodies is often affected by suspended matter including silt [35]. When developing the relationship between the spectral value from remote sensing images and TSI, it is necessary to select a relatively clear water body with relatively high transparency and low suspended matter as the spectral reference for relative water quality assessment.

5. CONCLUSIONS

Quasi-synchronous *in-situ* water quality data at a seasonal or year scale can be used to analyze the lake water quality status by the image spectra of SPOT 5 or Landsat 7 ETM+ in dry season because the grade of lake water quality is a relatively invariable parameter within a certain period (such as in dry season, even in one year in south China). Specially, the high-resolution multi-band images (such as SPOT 5) are probably the best choice of urban lake water quality grade from the balance of cost effect and large coverage.

The concentrations of water quality parameters (e.g., Chl-*a*, COD, TP and TN) from the *in-situ* lake sampling analysis are generally consistent with the spectral angles derived from *in-situ* spectra and remote sensing images. The SA maps from SPOT 5 multi-band image provide the detailed spatial variation of urban lake water quality grade that is infeasible for field investigation at large scale or Landsat imagery for small water bodies. In addition, the average SA of all image pixels represents the overall water quality grade of an urban lakes.

The grade of urban lake water quality can be sorted from most desirable to least desirable in relation to urban landscape and residential living quality. The area with relatively more severe pollution can be identified for the managers of urban lakes. Based on regression analysis on the water quality parameters of urban lakes and reservoirs, the mean SA of different water bodies correlates potentially with the parameters or grade (TSI) of water quality (Chl-a, R^2 = 0.929569, $p < 0.01$; COD, R^2 = 0.9767916, $p < 0.01$; TP, R^2=0.8705, $p < 0.05$; TN, R^2 = 0.58767495, $p < 0.05$; TSI, R^2 = 0.9066, $p < 0.001$), which means that the SA can be used to predict the partial water quality parameters or the eutrophication grade of urban lake water bodies.

The spectral reflectance and angle both correspond to lake water quality, but the single reflectance of SPOT 5 XS1-2 bands could limit the exploration of water quality grades as the band mainly reflects the suspended material on the water surface. In contrast, the mean SA provides more reliable and stable assessment of lake water quality grades. SA mapping results can be used to effectively schedule *in-situ* investigation and remedies within urban lakes or reservoirs based on their spatial distribution.

Estimating the spatial variation of lake water quality grade based on SA mapping attained from SPOT 5 satellite image is more time- and cost-effective than traditional water sampling analysis considering its large coverage (60 × 60 km^2) and fine spatial resolution (10 m) for small urban lakes. SPOT 5 images are useful and promising for instructing the location of *in-situ* water quality sampling for managers of urban lakes in routine monitoring, as well as in the practice of lake pollution management.

Although suffering from the missing scan lines in the imagery of Landsat 7 ETM+ since May 31, 2003, the Landsat 7 imagery can still acquire approximately 75 percent of the data for any given scene, which is still applicable for monitoring the water quality grade or eutrophication of middle- to large-sized lakes and reservoirs (larger than 30 ha).

This SA approach has a potential for global estimation of surface water quality or TSI if a relatively clear water body can be referred (such as ocean water). Future regression models of all five water quality parameters (Chl-1, COD, TP, TN and TSI) could be beneficiary from further validation with more *in-situ* field data and simultaneous imagery.

ACKNOWLEDGEMENTS

This research was partly funded by GDAS' Special Project of Science and Technology Development (2017GDASCX-0101), Technology transformation project of Zhongshan City-Guangdong Academy of Sciences (2016G1FC0017) and Natural Science Fund (10151007003000008) of Guangdong Province, China.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Available:http://gd.southcn.com/
2. Luo, Jiahai. 2002. On water pollution of Shijin River in Guangzhou and its influence on the drinking water source. Chongqing Environ Sci. 24(5):70–72. Chinese.
3. Brivio, Pietro Alessandro, Claudia Giardino, Eugenio Zilioli. 2001. Validation of satellite data for quality assurance in lake monitoring applications. Sci Total Environ. 268(1-3):3–18.
4. Alkhammash Eman, Mohamed S. Waleed, Ashour S. Amira, Nilanjan Dey, , Aarti Singh, Balas Valentina. Designing ontology for association between water quality and kidney diseases for medical decision support system. Conference: VI International Conference Industrial Engineering and Environmental Protection 2016 (IIZS 2016), At Zrenjanin, Serbia; 2016.
5. Kutser T, Arst H, Mäekivi S, Kallaste K. Estimation of the water quality of the Baltic Sea and lakes in Estonia and Finland by passive optical remote sensing measurements on board vessel. Lakes Reserv Res Manage. 2006;3(1):53–66.
6. Gons Herman J, Martin T. Auer, Steven W. Effler. MERIS satellite chlorophyll mapping of oligotrophic and eutrophic waters in the Laurentian Great Lakes. Remote Sens Environ. 2008;112(11):4098–4106.
7. Nellis, M. Duane, John A. Harrington Jr., Jaiping Wu. Remote sensing of temporal and spatial variations in pool size, suspended sediment, turbidity, and Secchi depth in Tuttle Creek Reservoir, Kansas: 1993. Geomorphology. 1998;21(3-4):281–293.
8. Wang, Yunpeng, Hao Xia, Jiamo Fu, Guoying Sheng. Water quality change in reservoirs of Shenzhen, China: detection using LANDSAT/TM data. Sci Total Environ. 2004;328(1–3):195–206.

9. Urbanski, Jacek Andrzej, Agnieszka Wochna, Iwona Bubak, Waldemar Grzybowski, Marek Zajączkowski. Application of Landsat 8 imagery to regional-scale assessment of lake water quality. International Journal of Applied Earth Observation and Geoinformation. 2016;51:28-36.
10. Chang, Ni-Bin, Kaixu Bai, Chi-Farn Chen. Integrating multisensor satellite data merging and image reconstruction in support of machine learning for better water quality management. Journal of Environmental Management. 2017;201: 227-240.
11. Garg Vaibhav, A Senthil Kumar, Aggarwal SP, Vinay Kumar, Gurdeep Rastogi. Spectral similarity approach for mapping turbidity of an inland waterbody. Journal of Hydrology. 2017;550:527-537.
12. Kruse FA, Lefkoff AB, Boardman JW, Heidebrecht KB, Shapiro AT, Barloon PJ, Goetz AFH. The spectral image processing system (SIPS) - Interactive visualization and analysis of imaging spectrometer data. Remote Sens Environ. 1993;44:145-163.
13. Sohn YoungsInn, Sanjay Rebello N. Supervised and unsupervised spectral angle classifiers. Photogramm Eng Remote Sens. 2002;68(12):1271–1280.
14. Chen Ting, Huang Jianrong, Chen Shengping, Qiu Wenzhi, Lin Tiehao, Zheng Zejun, Wen Shaoming, Xu Runlin. PFU Progtozoan community colonization process and its indication of water quality in Guangzhou urban artificial lake. Chin J Appl Environ Biol. 2004;10(3):310-314. Chinese.
15. State Environmental Protection Administration of China and General Administration of Quality Supervision, Inspection and Quarantine of China. Surface Water Quality Standards of the People's Republic of China (GB3838-2002). Beijing: China Environmental Science Press; 2002.
16. Luo Weilin. Performance investigation and development suggestion on reservoir fishery production in Guangzhou. Fisheries Science & Technology. 2005;27(1):34-35.
17. Jiang Qiming, Hou Wei, Gu Jiguang, Peng Liang，Lei Lamei. Nutritional status and population characteristics of Cyanobacteria in small and medium-sized reservoirs in Guangzhou, southern China. Ecology and Environmental Sciences. 2010;19(10): 2461-2467.
18. Li, Liqing, Yin Chengqing, He Qingci, Kong Ling. Contribution of pollution load of storm runoff in urban areas of Hanyang, Wuhan City on the receiving water. China Environ Sci. 2007;27(3):312–316.
19. (http://58.68.130.147/).
20. Lin, Qiuqi, Hu Ren, Duan Shunshan, Han Boping. Reservoir trphic states and the response of plankton in Guangdong Province. Acta Ecologica Sinica. 2003;23(6):1101-1108. Chinese.
21. Chander, Gyanesh, Brian L. Markham, Dennis L. Helder. Summary of Current Radiometric Calibration Coefficients for Landsat MSS, TM, ETM+, and EO-1 ALI Sensors. Remote Sens Environ. 2009;113: 893–903.
22. Pickup G, Chewings VH, Nelson DJ. Estimating changes in vegetation cover over time in arid rangelands using landsat MSS data. Remote Sens Environ. 1993; 43(3):243–263.
23. Xiao, Lin, Yuan Xiaoling, Lu Wenyan. Survey of hygienic condition of source water in Huadu District of Guangzhou. China Tropical Medicine. 2010;10(9):1166.
24. Acharjya, Debi and A. Anitha. A Comparative study of statistical and rough computing models in predictive data analysis. International Journal of Ambient Computing and Intelligence. 2017;8(2):20.
25. Jin, Xiangcan, Tu Qingying. The standard methods in lake eutrophication investigation. Beijing: China Environmental Science Press. 1990;286-302.
26. Li, Suju, Wang Xuejun. The spectral features analysis and quantitative remote sensing advances of inland water quality Parameters. Geogr Territorial Res. 2002;18(2):26–30.
27. Binding CE, Bowers DG, Mitchelson-Jacob EG. Estimating suspended sediment concentrations from ocean colour measurements in moderately turbid waters; the impact of variable particle scattering properties. Remote Sens Environ 2005;94(3):373−383.
28. Chen, Shuisen, Ligang Fang, Lixin Zhang, Wenrui Huang. Remote sensing of turbidity in seawater intrusion reaches of Pearl River estuary- A case study in Modaomen waterway of Pearl River Estuary, China. Estuar Coas Shelf Sci. 2009;82(1):119–127.

29. Pulliainen Jouni, Kari Kallio, Karri Eloheimo, Sampsa Koponen, Henri Servomaa, Tuula Hannonen, Simo Tauriainen, Martti Hallikainen. A semi-operative approach to lake water quality retrieval from remote sensing data. Sci Total Environ. 2001;268(1-3):79–93.
30. Tian, Guoliang, Ni Xiaodong, Song Fu and Zhao Weiling. Estimating chlorophyll concentration using spectral data. Remote Sensing of Environment China. 1988;3:71-79. (in Chinese).
31. Yu, Jiang, Yang Yufeng, Yang Cuichan. Study on the eutrophic status and genetic toxicity of the water bodies in Guangzhou section of Pearl River and several urban lakes in southern China. Journal of Chongqing University (Natural Science Edition). 2007;30(9):139–43.
32. Wang, Rongchang, Wen Xianghua, Li Cuizhen, Qian Yi. Study on the corelation between aqualic microbial community Parameters and the indicators of water quality. Res Environ Sci. 2002;15(4):43–49. Chinese.
33. Li, Xing, Li, Changyou, Li, Weiping, Shi, Xiaohong, Dai, Wenjie & Gou Mangmang. 2009. Temporal and spatial distribution of different species of nitrogen in Lake Wuliangsuhai, Inner Mongolia. J Lake Sci. 21(6):885–890. Chinese.
34. Liu, Mingliang, Zhang Yunlin, Wang Xin, Li Yunliang. 2009, Comparison Between Four Models in Modeling Spectral Absorption of Chromophoric Dissolved Organic Matter in Lake Taihu. J Ecol Rural Environ. 25(1):42–46. Chinese.
35. Volpe V, Silvestri S, Marani M. Remote sensing retrieval of suspended sediment concentration in shallow waters. Remote Sensing of Environment. 2011;115(1): 44-54.
36.

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