

Remote sensing of urban lake water quality: a preliminary result from spectral angle based approach

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Abstract. This study aimed to develop a quick methodology of spectral angle (SA) to evaluate overall water quality status and spatial variance in urban lakes using in-situ water quality parameters of lakes or reservoirs and synchronous SPOT 5 remote sensing image, 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 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, $R^2 = 0.929569$, $p < 0.01$; COD, $R^2 = 0.9767916$, $p < 0.01$; TN, $R^2 = 0.58767495$, $p < 0.05$; TP, $R^2 = 0.8705$, $p < 0.05$) or TSI ($R^2 = 0.9066$, $p < 0.001$) 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 variances, 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)

1.1 Introduction

Guangzhou, located in southern China, is one of the most rapidly industrializing cities in the world. With economic development and urban population increasing, the discharge of waste water and sewage are also constantly increasing.

36 Because of the sewage from urban roads, populated areas, and industry drainage, large
37 quantities of nutrients enter the urban lakes, stimulating excessive algal growth. Eutrophication
38 is a big concern in lakes during the dry season, particularly in the urban lakes and the
39 Guangzhou reach of Pearl River, the largest river in southern China. Water samples were
40 taken on a seasonal schedule for water quality analysis for minority lakes within Guangzhou,
41 which was part of a long-term water quality monitoring project on the Guangzhou river way
42 and urban lakes. According to statistic report [1], there are more than 1300 reservoirs and 20
43 urban lakes within Guangzhou. Except for 16 large-middle sized reservoirs, it is difficult to
44 spatially map the water quality of all other reservoirs and urban lakes using 20-30 m
45 resolution remote sensing sensors like Landsat TM/ETM+ due to small area coverage, not to
46 speak of field sampling monitoring for so many quantities.

47 Urban lakes play an important role in maintaining the region's wetland and are an important
48 water source and leisure place for urban populations. Mapping the urban lake water quality
49 over time can provide urban lake managers with their temporal change information to assess
50 lake health, but in Guangzhou this information is limited at several lakes or one sample
51 location of lakes in more than 1300 reservoirs and 20 urban lakes within Guangzhou, partly
52 due to restricted human and material resources and lack of suitable methodology.
53 Historically, urban lake water quality variance assessment has been undertaken via laboratory
54 analysis [2], which is labor intensive and costly. Most important, the analysis cannot provide
55 the factual spatial overview needed for quick assessment of spatial water quality or changes
56 within lakes and reservoirs. There were studies trying to find such association between
57 disease and water quality based on ontology and data mining [3, 35].

58 The optical properties of a water body depend on the concentration and characteristics of the
59 total suspended sediments (TSS), phytoplankton, and colored dissolved organic matter
60 (CDOM, "yellow substance"). The empirically-based statistical remote sensing model has
61 been applied to estimate water transparency and quality in lakes and inland waters for years.
62 This is accomplished by applying the correlation method on remote sensing spectra and water
63 quality characteristics [4,5]. The value of Landsat Thematic Mapper (TM) data was
64 demonstrated to estimate variations in suspended sediment in conjunction with a major flood
65 event [6]. Remote sensing of large-middle sized reservoir water quality studies by
66 Landsat/TM imagery has also been conducted in Shenzhen, China [7]. A remote sensing
67 model of assigning the ecological status was created to support regional lake quality
68 assessment using Landsat 8 imagery data, and it was found there exists a combination of OLI
69 bands (OLI2/OLI4 was used) which correlates well with the trophic state of the lakes [31].
70 Chang et al. [32] developed a remote sensing-based multiscale modeling system in support of
71 feature extraction with machine learning leading to automate continuous water quality
72 monitoring. The SA mapping matching technique has been widely used in the geological
73 application (mineral mapping), however, the application of this kind of techniques is limited
74 in water quality studies due to non-availability of reference spectral libraries [33]. However,
75 the application of Landsat/TM imagery in water quality mapping will be difficult for small
76 lakes and reservoirs (< 30m in diameter) due to coarse spatial resolution (30 m).

77 The Spectral Angle (SA) mapping is a physically-based spectral classification that uses
78 an n-dimensional angle to match pixels to reference spectra. The algorithm determines the
79 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 [8]. 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 [9]. 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 capability. However, the use of satellite imagery in water quality studies by SPOT 5 has not yet been reported for the central urban area of Guangzhou, even south China. 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. Usually, we can acquire 2-4 archived cloud-free scenes of SPOT 5 throughout the year, such as 2007-2010. Beyond all doubt, the SPOT 5 imagery-based monitoring program is more useful for so many small reservoirs and lakes of Guangzhou than Landsat TM. And in any case, there is not a field monitoring program covering all the reservoirs and lakes within Guangzhou due to huge cost and workload. This study presents a fast method of SA-based monitoring for evaluating the grades of urban lake water quality and eutrophication by correlating higher resolution satellite image (SPOT 5) and reference spectrum-based SA with ground observation of water quality parameters.

1.2 Materials and methods

1.2.1 Study site and data collection

There is lake area of 5123 ha within Guangzhou City. Four urban lakes of 89 ha were concerned in the study with pH range of 7.7~9.2. Their areas are: Liwan: 10.4 ha, Liuhua: 32.7 ha, Lu: 25 ha, and Dongshan: 20.9ha, respectively. They are located in the downtown district of Guangzhou, southern China (Fig. 1 and 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.

There are 9 sites data used in the study. 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 [10]. The parameters used included the chemical oxygen demand (COD); total nitrogen (TN); total phosphorus (TP); chlorophyll a (Chl-a) (Table 1). According to China's surface water standard [11], 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. 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) [10]. 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 all of them were in the eutrophic state grade V. The water samples were taken during the last 10 days of September and first 10 days of October 2002 [10]. The water quality parameters were compared to their optical characteristics on SPOT 5 satellite image.



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



Figure 2.-Location of four lakes featuring on SPOT 5

Table 1. Physicochemical parameters and image spectrum features for 4 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 (5 levels in total, 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- <i>a</i> (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)	30.7 7 (II)	26 (I)
Mean reflectance (XS1)	0.047191	0.053415	0.055305	0.050450	0.07704	0.03 7025	0.070 778
Mean reflectance (XS2)	0.030906	0.034286	0.038204	0.031716	0.05554	0.018 525	0.032 436
Spectral Angle	0.263925	0.259694	0.252011	0.25017	0.169756	0.048239	0.02

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142 In addition, the Chl-*a*, COD, TP and TN concentrations of the fourth lake-Dongshan on
 143 20 December 2006 were collected for the study in similar season with Chen et al.' collection
 144 [10]. The water quality parameters of all 4 urban lakes were analyzed.

145 We also collected the corresponding Chl-*a*, COD, TN and TSI values from another lake
 146 as the TSI of Jiulongtan Reservoir on November 7 of 2002 since they are close to one another
 147 in distance and have similar montane environment. Then, the reservoir's spectrum was
 148 retrieved from the Landsat 7 ETM+ image. Besides, the Chl-*a*, TP, TN and TSI values of
 149 Furongzhang and Sankeng Reservoirs in dry season of 2010 were collected together with
 150 reservoirs' Landsat 7 ETM+ spectra on March 18 of 2010 [12,13] (Table 1).

151 There are 5 samples of COD, 7 samples of Chl-*a*, 7 samples of TN, 6 samples of TP and
 152 7 samples of TSI for model calibration, and 2 sites (1 sample of COD, 2 samples of TN, 1
 153 sample of Chl-*a* and 1 sample of TSI) for model validation in total. The water quality
 154 parameters and image or in-situ spectra data pairs used were listed in Table 2 while the
 155 validation data were listed in Table 3.

156 The water temperatures of all lakes and reservoir at 0.5m under surface are about between 27
 157 ~33.6°C in summer and 16.4~24°C in winter.

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Table2 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

1.2.2 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 [10]. SPOT 5 is the first satellite that can balance large scene sizes (60×60 or 60×120 km²) 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 sized urban lakes (usually under about 30 ha). The corresponding Landsat 7 ETM+ image bands are b2, green: 0.525–0.605 μm ; b3, red: 0.63–0.69 μm ; b4, near infrared: 0.75–0.90 μm ; b5, short wave infrared (SWIR): 1.55–1.75 μm). The two sensors have similar spectral resolution (8 bits).

Landsat 7 is the most accurately calibrated Earth-observing satellite compared to the same measurements made on the ground. The consistent global archiving scheme, large coverage (185*185 km²) and reduced pricing of Landsat 7 image led to a large increase of Landsat data users. In October 2008 USGS made all new Landsat 7 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 acquires 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 included two dates: November 1, 2000 for Qiyashi Reservoir (22°48'N, 114°12'E) and March 18, 2010 for Furongzhang (23~29°N, 113°13' E) and Sankeng (23°27' N, 113°03' E) Reservoirs.

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

For this assumes that the water quality did not change significantly over a one month period, the variation of lake water quality grade was analyzed between SPOT 5 imaging and lake water sampling in 2002. Although the precipitation reached 122.5 mm during the period (mean annual precipitation for the period is 70 mm), the quantity of precipitation should be insufficient to change the lake water quality grade. The previous studies showed that the rainfall runoff in dry season only brought one portion of pollutant [14]. In recent years, the limiting factor of water quality in Guangzhou in dry season was minor dissolved oxygen [15]. For example, with 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). For another example, one automated water quality 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 [10](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 a set of approximate analyzing data for the study.

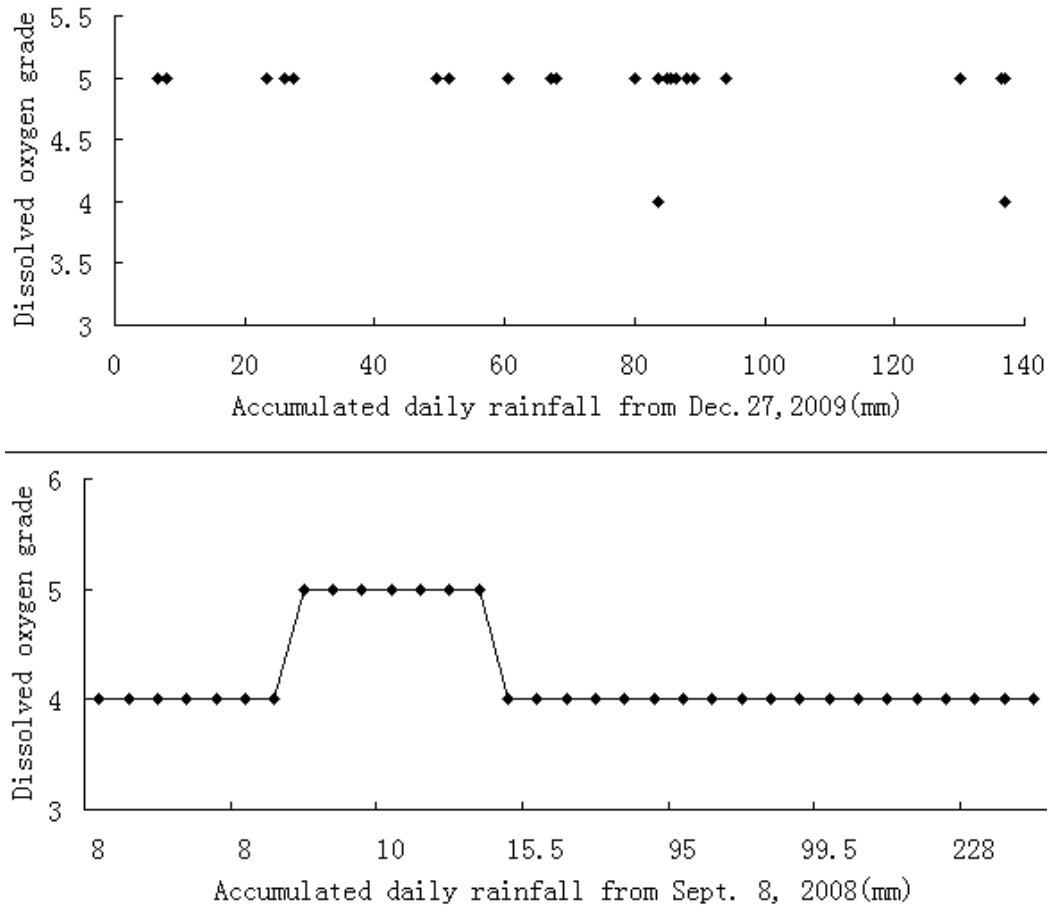


Figure 3.-Upper panel: Comparison of Observations of dissolved oxygen (mostly at grade V) and accumulated rainfall (136 mm) at Changzhou National Water Quality Station, Guangzhou (dissolved oxygen) and Guangzhou meteorological station (rainfall) from December 27 of 2009 to February 19 of 2010; Lower 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	IV
Sep 15~21	2	10	V
Sep 22~28	3	85	IV
Sep 29~ Oct 5	4	133	IV
Oct 5~11	5	0	IV

Actually, the TSI values with little season change (<2.2% at percent of averaged relative error) were found from six small and middle sized reservoirs between March-April (dry season) and July-August (high water period) 2010 in Guangzhou (Jiang et al. 2010), and from eighteen middle and large sized reservoirs between November-December (dry season) and June-July (high water period) 2000 in whole Guangdong Province, southern China [16].

1.2.4 Methodology

The eutrophication of a water body depend on many parameters of water quality, such as the concentration of the total suspended sediments (TSS), phytoplankton, TN, TP and COD. Data for solar radiation at various wavelengths was obtained from satellite sensors aboard SPOT 5 or Landsat 7 ETM+. The data can be calibrated to reflectance and transformed to SA, then correlated to water quality parameters mentioned above. This constitutes an alternative means of evaluating the eutrophication grade of lakes and reservoirs by remotely sensing technologies, which have proved to have many significant advantages over routine laboratory analysis and ground sampling (e.g., nearly-continuous spatial coverage, periodic observation, and relatively long record of archived satellite imagery).

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 lake 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, the accurate and 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 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 [17]:

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

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 $\text{mW cm}^{-2} \text{ster}^{-1} \text{m}^{-1}$; and θ_s is solar zenith angle in degrees.

Removal of atmospheric effects due to absorption and scattering was completed using dark pixel subtraction method [18], 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 , is 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 study lakes only, while eliminating reflectance data for not target area.

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 rests on 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 together in feature space, regardless of the shape of the pattern, will be classified into one class based on the distribution pattern [9]. 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 $\theta_{i,r}$ is the SA between pixel i and a reference spectrum r ; 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 .

Because the water source of Reservoir Jiulongtan is mostly from mountain spring water, the Jiulongtan reservoir's water is of good quality. In fact, the survey of hygienic condition of source water in Huadu District of Guangzhou showed that Jiulongtan Reservoir's water complied with the standard of China's drinking water [19]. So, we took the Jiulongtan's water as a category with best water quality to be compared with other lake water using a supervised procedure of image classification. Taking the procedure, we were predicting the relative water quality grade based on the broad and integrated water quality condition we described earlier. At the same time, we were also trying to map the water quality change of urban lakes spatially 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 image data, the analyst is required to relate field information to spectral shape patterns of water body pixels of different 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.

Regression analysis & evaluation between water quality parameters and SA

It is essential to think of some predictive analysis for analyzing data and to get meaningful information [34]. 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 also 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, including the water quality parameters: Chl-a, COD, TN and TP [20]. The grading standards of reservoir trophic state of China are: TSI of 0-30 representing oligotrophic; TSI of 30-50 representing mesotrophic, and TSI of larger than 50 representing eutrophic.

Results

Water quality parameters and the reflectance of urban lakes and clear reservoir

First, the urban lakes (monitored objectives) and the montane reservoir's reflectance (reference objective) were analyzed according to their spatial reflectance transects (Fig. 4 and 5). The transections were selected randomly. Spatial reflectance transects of lakes and reservoir in SPOT 5 XSi band (Fig. 5) showed that their reflectances are below 0.02 and 0.03 for the montane reservoir and urban lake water studied, respectively. 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.

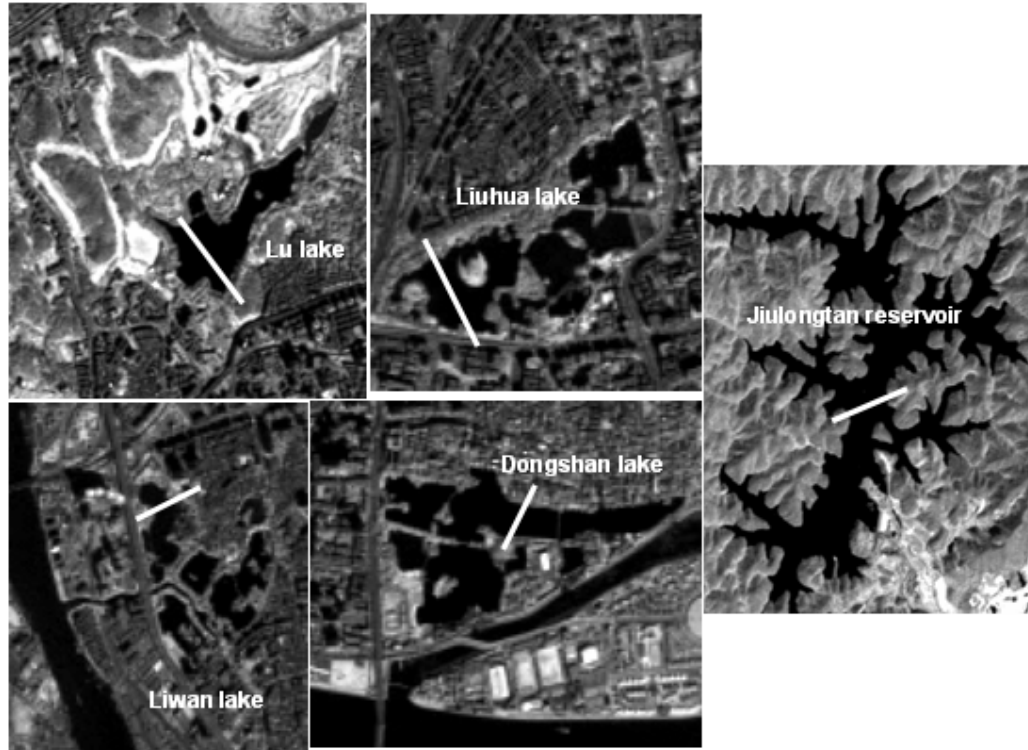


Figure 4. Location of spectral profile of four lakes and a montane reservoir for retrieval of urban lake or reservoir area.

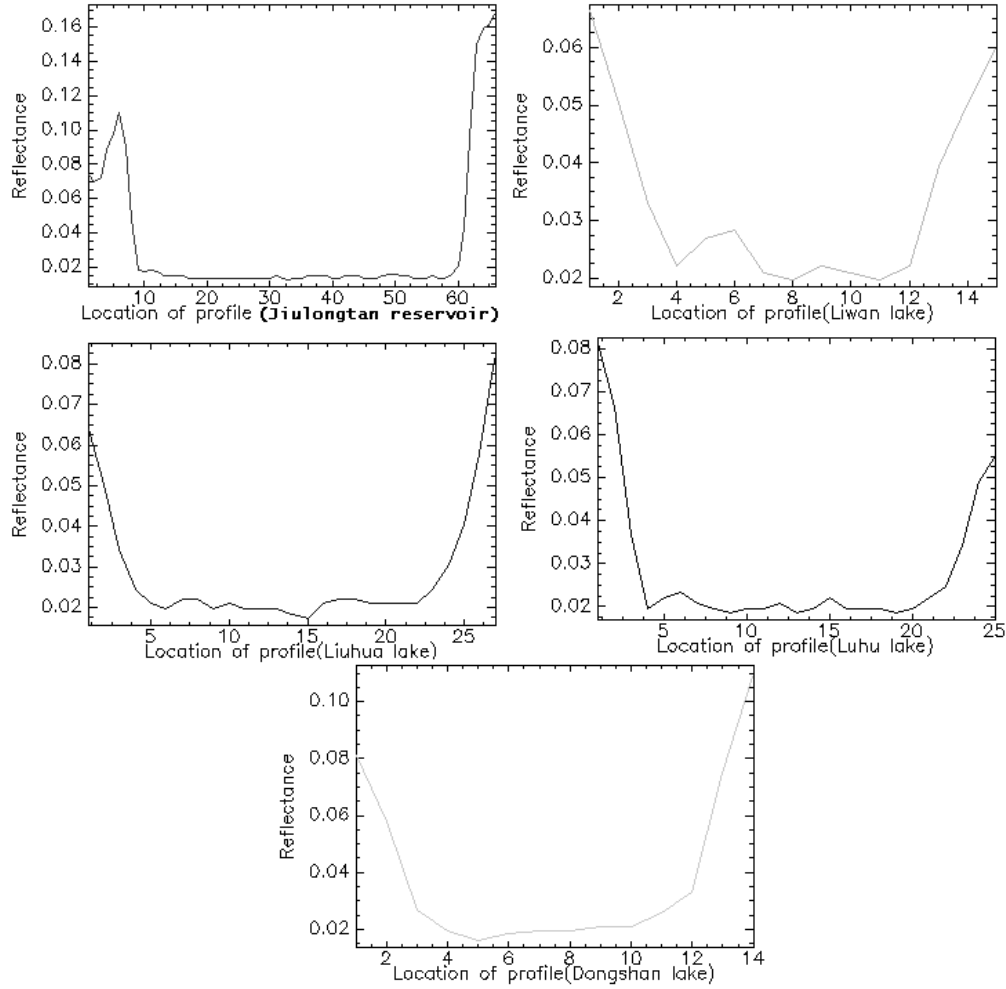
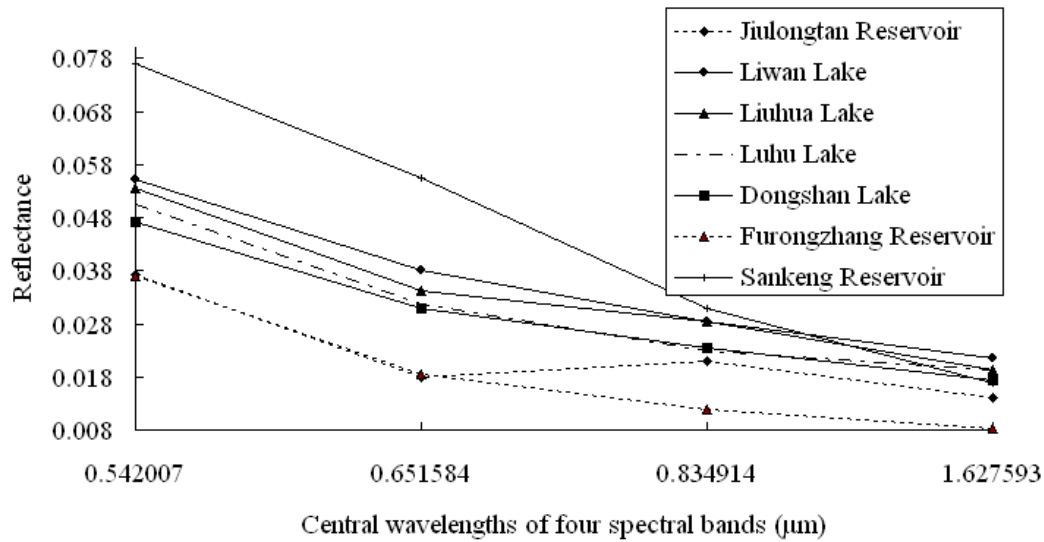


Figure 5. Variance range of lakes and reservoir reflectance profiles in figure 5 from XS3 at near infrared range (0.78–0.89 μm) of SPOT 5. The location of profile indicates the pixel number.

Using the training area data (reflectance transect) from the 4 urban lakes and the clear reservoir in the montane area of northern Guangzhou, the averaged reflectance values for four urban lakes and a montane reservoir can be easily recorded (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

338 Lake. Note that this is not completely consistent with our previous knowledge of water
 339 quality grades of these water bodies or with the response of SPOT 5 image to water quality.
 340 For example, the water quality of Liwan Lake is better than Liuhua Lake, and the water
 341 quality of Liuhua Lake is better than Dongshan Lake. In other words, the reflectance is not
 342 always consistent with the water quality grades of lakes or reservoirs. Obviously, the order is
 343 completely different for XS3 and XS4 bands of SPOT 5.



344
 345 Figure 6. Difference of mean reflectance of four urban lakes and three reservoirs. The
 346 four central wavelengths from small to large correspond to blue, green, red, near-infrared bands,
 347 respectively
 348

349 Many experiments and *in-situ* studies showed that reflectance increases with increasing
 350 TSS concentration in visible and near-infrared bands [21,22]; however, a negative
 351 correlation between reflectance and TSS was found in the Pearl River Estuary under
 352 condition of suspended solid adsorbing organic matter (Chen et al. 2009). TSS concentration
 353 also has a strong correlation to Chl-*a* concentration [23,24]. Dongshan Lake has lower
 354 reflectance than other three urban lakes at the blue and green bands of SPOT 5 (Luhu,
 355 Liuhua, and Liwan, Fig. 6). However, whether the lake water quality grade could be

identified by optical information (reflectance or SA) of remote sensing image remains unknown.

All reflectance variance of the four urban lakes and the montane reservoir in SPOT 5 XSi bands was also demonstrated (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). The SA statistic for four lakes and the montane reservoir was also listed (Table 6). The result of correlation analysis between SA and water quality parameters (Chl-*a*, COD, and TN) was presented (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 remarkably 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, $R^2 = 0.9066$, $p < 0.001$).

Table 5. Variation range of reflectance of different lakes and reservoir

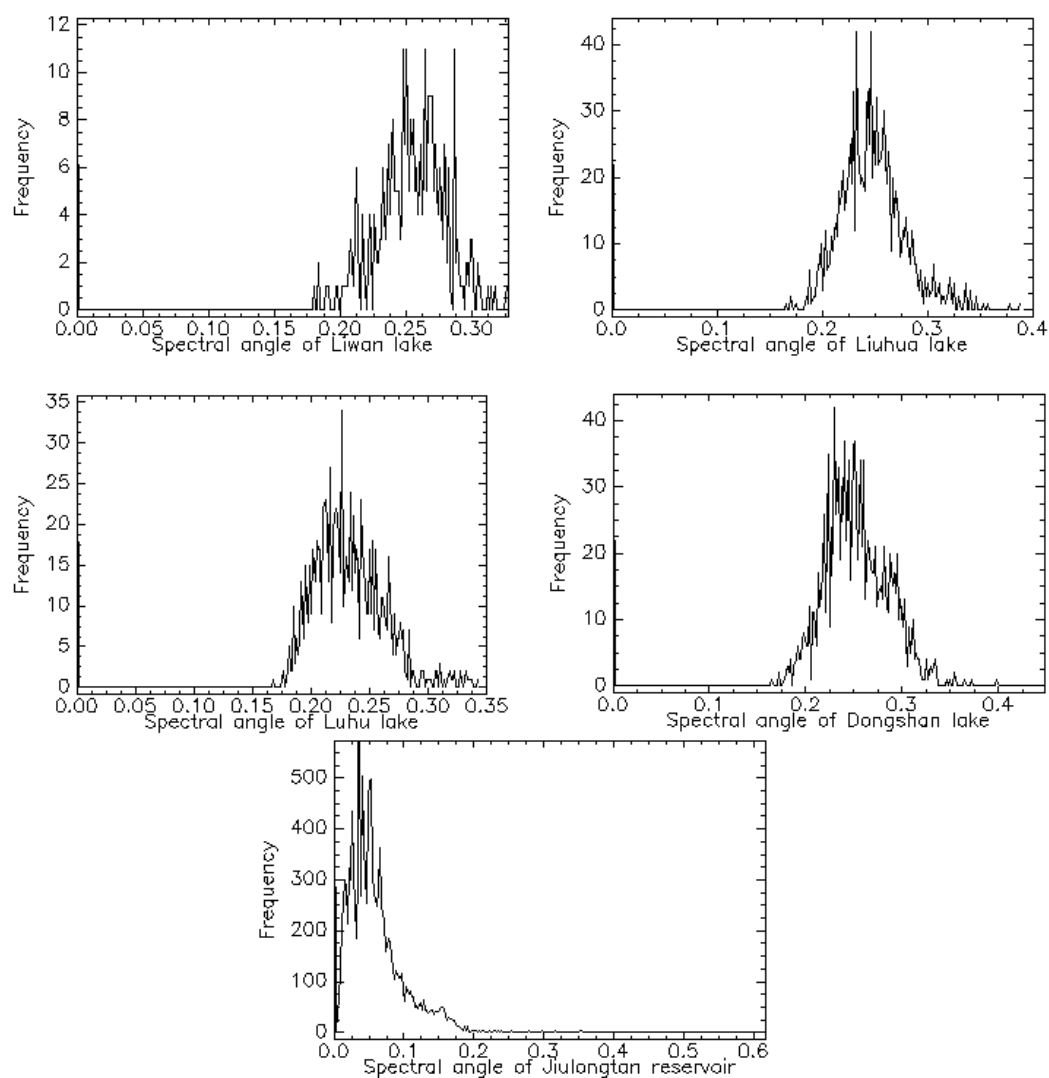
Water body	Min.	Max.	scope of most pixels
Jiulongtan reservoir	0.0061	0.0246	0.0061~0.0246 (97%)
Liuhua Lake	0.0135	0.0258	0.014~0.024 (94.7%)
Liwan Lake	0.0147	0.0270	0.015~0.026 (93.8%)
Luhu Lake	0.014735	0.024535	0.015~0.024(96.7%)
Dongshan Lake	0.0123	0.0233	0.014~0.021 (93.9%)

Table 6. Variation range of spectral angles between urban lakes or clear Jiulongtan reservoir water and reference spectrum.

Water body	Spectral angle
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types	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

375



376

377 Figure 7. Spectral angle between different water bodies reflectance of urban lakes and
378 reference endmember of Jiulongtan reservoir.

379

380 Performance of regression models

381 Statistical analysis between SA and water quality parameters (or eutrophication grade)
382 shows that the significance value of the F statistic is very small (less than 0.01 for COD and
383 Chl-a, less than 0.05 for TN and TP, and less than 0.001 for TSI), while the determination
384 coefficient and correlation coefficient of the five models are all very high (R^2 : 0.8705~0.9767,
385 Fig.8) except for TN. This indicates that the relationships between the water quality variables
386 and SA did not occur by chance, showing that regression analysis was a valid method of
387 predicting Chl-a, COD, TN and TP concentrations and evaluating the trophic state of the
388 lakes or reservoirs studied.

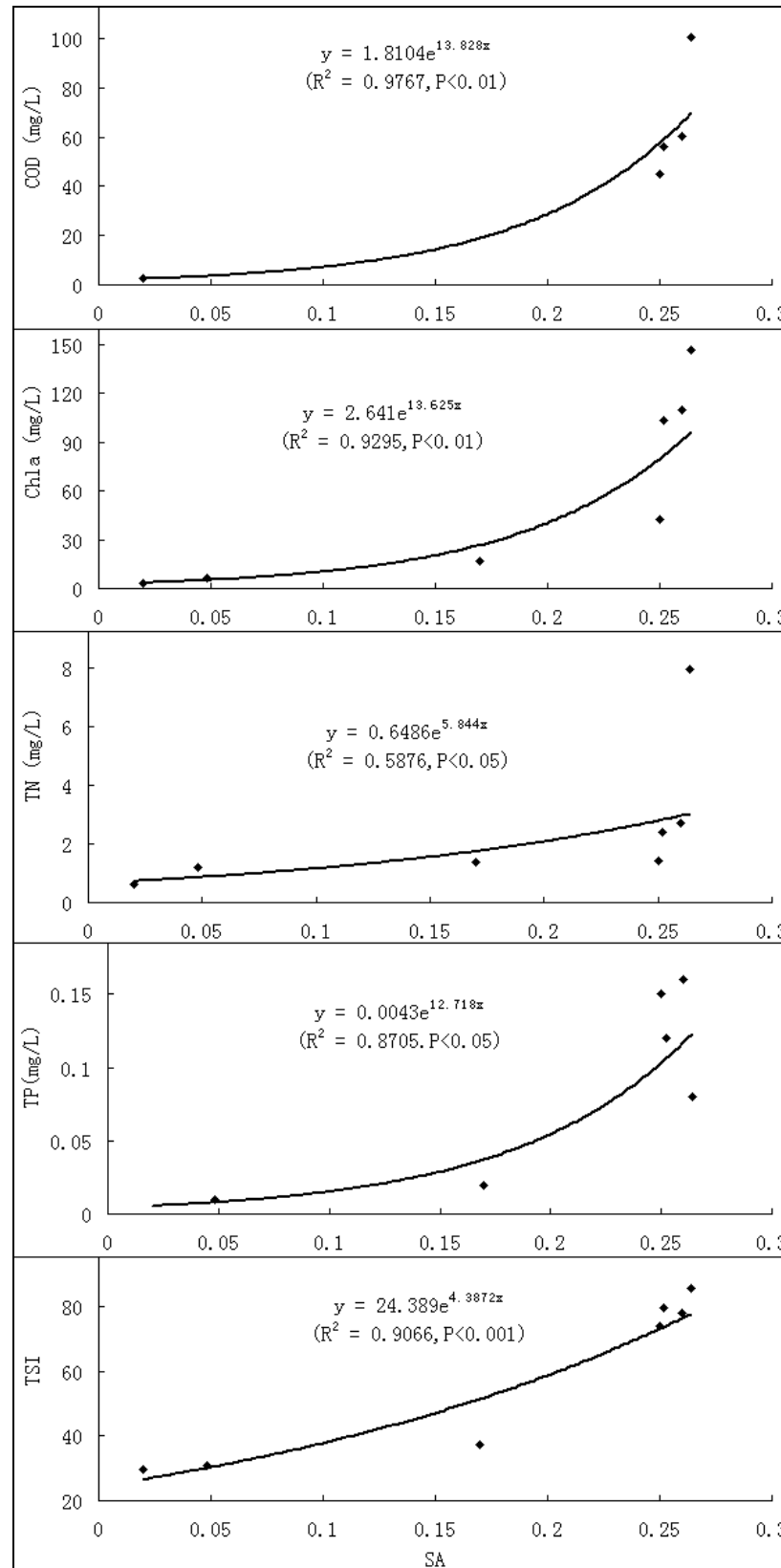


Fig. 8 The regression model between lake-averaged spectral angles and parameters (Chl a, COD TN, TP and TSI) of water quality in urban lakes.

392

393 Although the collection of synchronous *in-situ* data with satellite imaging is really
394 difficulty, there is *in-situ* data of five sites collected for validation of four statistical regression
395 models. The regression models of Chl-*a* and TSI are proven more effective than model of TN,
396 especially the model of COD. Specially, the Chl-*a* concentration can be a key indicator of
397 over standard TN and TP concentrations [25].

398 **Discussion**

399 **Reflectance, SA, water quality parameters and eutrophication grade**

400 By comparing the 4 urban lakes with the clear water of the Jiulongtan Reservoir (Fig. 7;
401 Table 6) using SA analysis, we found that the mean SA of Dongshan Lake is the highest of
402 four urban lakes, followed by Liuhua, Liwan, and Luhu lakes, sequentially. From this we can
403 deduce that the lake or reservoir water quality can be ordered as Jiulongtan Reservoir, Luhu
404 Lake, Liwan Lake, Liuhua Lake, and Dongshan Lake, from most desirable to least desirable
405 in terms of used aims for urban landscape and residential living surroundings,. The results of
406 water quality for Luhu, Liwan, and Liuhua Lake by SPOT 5 image mapping are basically
407 consistent with the laboratory analysis of most water quality parameters (COD, TN, Chl-*a*,
408 NO₃-N, TP, and TSI; Table 1). Moreover, the results of SA predict the water quality grade of
409 Dongshan Lake in Chl-*a*, COD, and TN, yet many other parameters of water quality need to
410 be further researched (Table 1). [Yu et al.\[26\]](#) used water quality data from April and May
411 2006 and found that the Guangzhou section of the Pearl River (connected to Dongshan Lake)
412 had higher TN and TP contents than other urban lakes in Guangzhou, which implies that
413 Dongshan Lake among urban lakes of Guangzhou was probably the worst lake in terms of

water quality.

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 [10,27]. The PFU method could more accurately show the water quality grade of urban lakes (Table 1).

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 $\text{NO}_3\text{-N}$ in eutrophication water is transformed into $\text{NO}_2\text{-N}$ 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 [28]. 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), higher even than the CDOM values (0.22–1.88 at 440 nm) of Taihu Lake, another severely eutrophication lake in China, in 2006–2007 [29].

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 also exponentially correlated with SA. The other parameters such as TN are exponentially

correlated with SA. However, the correlative degree 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 ($R^2 > 0.87$) while SA have a slightly lower correlation with TN ($R^2 = 0.5876$).

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

The SA is closely correlated with main water quality parameters, TP, COD and Chl-a concentrations in the urban lake freshwater systems, compared with other parameters such as TN. Chl-a concentration is also an important parameter for monitoring water TSI by applying remote sensing techniques because it produce visible changes in the surface of waters [25]. According to the correlative relations between SA and these parameters, by applying remote sensing images to map the TSI we can analyze its size and distribution, and know about the grade and distribution of reservoir or lake eutrophication. Moreover, it can also provide powerful support for further detailed investigation, field analysis and management action on specific lake.

Although error of the COD prediction for only one site are large at about 8 mg/L, there is acceptable error of TN prediction at one of two sites at 1.34 mg/L. By contrast, the errors of Chl-a and TSI prediction are small. Reasons for this might result from 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 may have potential to quickly map the TSI by

SPOT 5 or similar other satellite sensors due to the spectral shape including all band information of an image.

SA & TSI mapping of 4 urban lakes

The spatial variance of urban lake water quality can be easily obtained from maps of the SA between pixel spectrum of lakes and reference endmember of reservoir (Note: smaller numbers of SA indicate better lake water quality; Fig. 9). For example, 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; Luhua 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. At the white area of urban lakes, the better water quality (white color area) can be expected usually as first choice of recreation area for city residents. Further, we can find that there was better water quality at south of the four urban lakes than at north, which should be contributed to the monsoon southerly. So, the more reinforced water quality management can be planned at north of the urban lake parks.

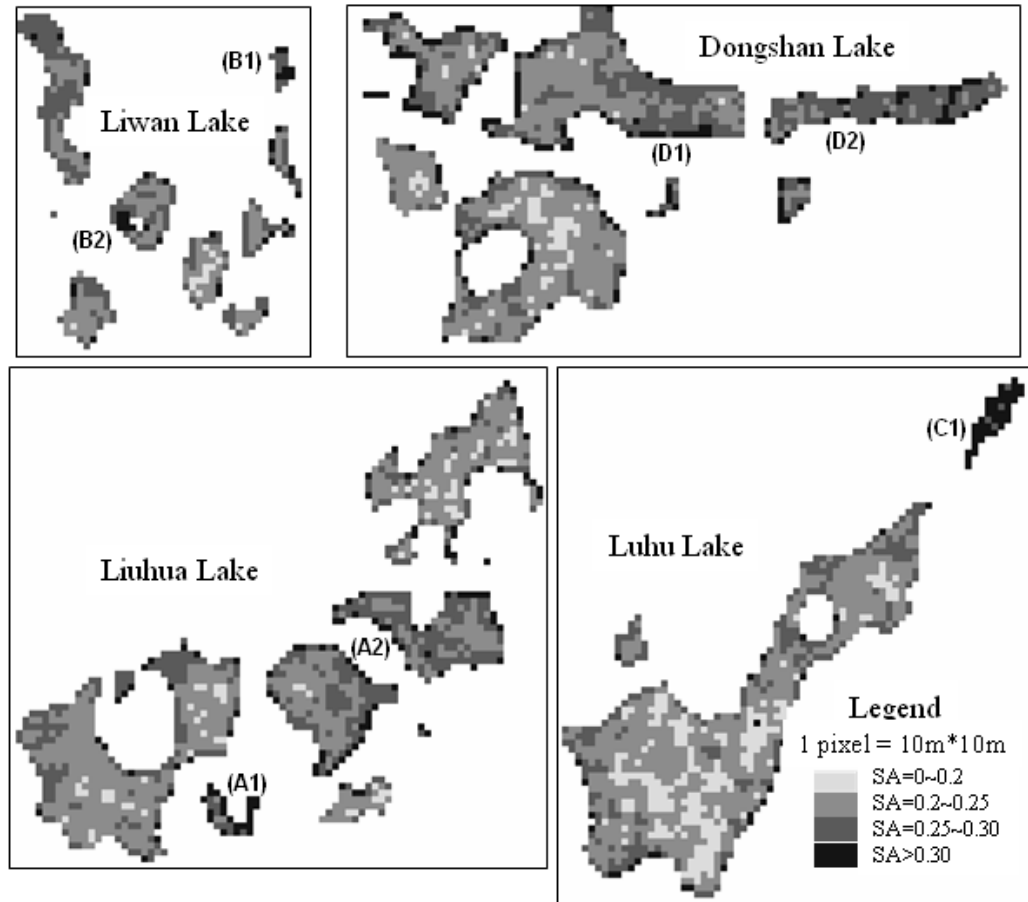


Figure 9. Spatial distribution of spectral angle (SA) of four lakes in Guangzhou urban area (small number represents better lake water quality because of close to montane reservoir in water quality). (Characters indicate the relatively more severe pollution area in each urban lake (Liuhua Lake: A1, A2; Liwan Lake: B1, B2; Luhu Lake: C1; Dongshan Lake: D1, D2))

In using remote sensing to monitor TSI of urban lake or reservoir water bodies, its accuracy and reliability are often affected or restricted by suspended matter including silt [30]. When developing the relationship between spectrum value (SA here) from remote sensing images and TSI, it is necessary to select a relatively clear water body with relatively high transparency and low suspended matter for the acquirement of reference spectrum. Water in the Jiulongtan Reservoir meets these conditions, making it suitable for the retrieval of

reference spectrum.

Conclusions

1) 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), 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. Specially, the SPOT 5 multi-band images are probably the best choice of urban lake water quality grade from the balance of cost effect and large coverage.

2) 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 or SPOT 5 multi-band (or Landsat ETM+) satellite remote sensing image. The mapping of SA from SPOT 5 multi-band image of 10m resolution of 30m resolution provide the detailed spatial variance of urban lake water quality grade that is complicated and difficult to obtain with field investigation at large scale, or Landsat 7 ETM+ image sometimes. Meanwhile, the average SA of all image pixels represented the water quality grade of urban lakes as a whole. The grade of urban lake water quality can be sorted from most desirable to least desirable, related to urban landscape and residential living surroundings probably here, as Jiulongtan Reservoir (the clear montanic reservoir), Luhu Lake, Liwan Lake, Liuhua Lake, and Dongshan Lake (a seriously polluted urban lake connected to the Guangzhou section of the Pearl River).

The area of relatively more severe pollution in each urban lake of Guangzhou can

actually be identified by presented method 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 urban lakes or reservoirs 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 helpfully used to predict the partial water quality parameters or the eutrophication grade of urban lake water bodies.

3) 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, and it most likely only reflects the suspended material status on the lake or reservoir surface. By contrast, the SA of all image pixels of a lake or reservoir with the clear reservoir water as reference endmember (spectrum), are able to substantially depict the difference of lake water quality grade through the comparison of spectral shapes of different lakes or reservoir in 4-band space. In the future, the *in-situ* investigation and actions within urban lakes or reservoirs can be scheduled effectively based on the spatial SA mapping and analysis of water quality grades.

4) The spatial variance mapping 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 due to its large coverage ($60 \times 60 \text{ km}^2$) and fine spatial resolution (10 m) for small urban lakes. Due to its highly detailed resolution (10 m), SPOT 5 technologies 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.

532 5) Although suffering from the loss (about 2-14 pixel width) of its scan line corrector (SLC)
533 depending on the distance from scene center and impacting the imagery of Landsat 7 ETM+
534 since May 31, 2003, the ETM+ image can still acquire approximately 75 percent of the data
535 for any given scene, which is still appropriate for monitoring the water quality grade or
536 eutrophication of middle to large-sized lakes and reservoirs (larger than 30 ha) due to
537 appropriate 30 m resolution.

538 6) This approach of SA comparison could potentially be used globally to quantify the grade
539 of surface water quality or TSI if a relatively clear water body can be referred (such as ocean
540 water). In the future, the regression models of all five water quality parameters (Chl-1, COD,
541 TP, TN and TSI) could be expected to be improved with the further validation of more *in-situ*
542 data and in-situ (or remote sensing) image SA pairs.

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