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Application of Remote Sensing Techniques in Monitoring and Assessing the Water Quality of Taihu Lake

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Located in the southern part of Yangtze River Delta, which is the most populated and one of the major industrial regions of China, Taihu is one of the largest freshwater lakes in China. The Lake has an area of 2427.8 square kilometers. The average depth of the lake is about 4 meters (Jin 1995). According to a biological investigation carried out from 1987 to 1988 (Jin 1990), there were 97 kinds of phytoplankton, 79 kinds of zooplankton, 59 kinds of benthos, and 106 kinds of fish in the Lake. In recent years, however, the water quality in Taihu Lake has been getting worse. Both agriculture and sewage effluents have led to an increase of nutrients which has encouraged the growth of aquatic plants.

In recent years, especially in the last two years, the government has taken a number of steps in reducing the inflow of pollutants. Many factories near the Lake which produced serious pollution have been shut down. The use of phosphate containing washing powders has been prohibited in the whole Taihu Lake catchment since 1999. It is expected that the water quality of Taihu will be improved gradually.

Traditional water quality monitoring methods can be precise, but are usually expensive and time consuming, especially for the large area of water body like Taihu Lake. It is very difficult to report and predict the water quality situation in time, which is essential in modern water quality assessment, planning and management.

The spectrum characteristics of water and pollutants are essential for the utilization of remote sensing information in water quality monitoring and assessment. Remote sensing techniques have been widely used in estimating the pollution situation of surface water (Chen and Shi 1996; Lavery and Pattiaratchi 1993). Ekstrand (1992) estimated the content of Chlorophyll-a in coastal waters using Landsat Thematic Mapper (TM) data. Lathrop and Lillesand (1986) evaluated the water quality of Green Bay and Central Lake Michigan using the TM data of Landsat-5. Chen and Shi (1996) established a model for the estimation of the content of Chl-a using TM data. In this paper, the authors attempt to use remote sensing information and limited sampling data in water quality prediction and assessment in Taihu Lake.

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MATERIALS AND METHODS

MSS of Landsat, TM, HRV data of SPOT are popularly used remote sensing data. Among them, TM was widely used in China, which contains rich remote sensing information. In this paper, TM image data was selected as water quality remote sensing data source of Taihu area. This TM image data were produced by the Ground Satellite Station of China.

The Landsat-5 flies through the sampling area every 16 days. A Landsat TM image, taken by Landsat-5 on May 4, 1997 was available for use in this study. The Landsat TM obtains data from seven spectral bands: band 1, 0.45-0.52μm; band 2, 0.52-0.6μm; band 3, 0.63-0.69μm; band 4, 0.76-0.90μm; band 5, 1.55-1.75μm; band 6, 10.4-12.5μm; and band 7, 2.08-2.35μm.

Eighteen representative water samples were collected in the lake area from May 4 to May 7 in 1997 by Taihu Lake Environmental Monitoring Central Station. The sampling locations are shown in Figure 1. In order to carry out this study efficiently, the sampling on the Lake should be as close as possible to the flying over of the satellite. The water samples were collected for each site at 0.5m beneath the water-surface. Chemical analyses were carried out for suspended sediment (SS), Secchi Depth (SD), DO, COD_{Mn}, BOD_5, Total Nitrogen (TN) and Total Phosphorus (TP) which are considered as of high environmental concern by the Center. The sampling and chemical analysis were conducted based on the standard methodology (China Standard Press 1998). The National Environmental Monitoring Center of China was responsible for calibrating the quality of all reagents used. The quality of the reagents used for the analysis was of high standard.

Grubb's Test (at a significant level of 0.05) was applied to identify the outliers in the raw data set prior to all statistical analysis. Samples No. 9, 16 and 17 were eliminated. Table 1 shows the statistics of the sampling data.

Table 1. Statistics of sampling data (Number of samples = 15)

Statistics	SS	SD	DO	COD_{Mn}	BOD_5	TN	TP
MIN	10.0	20.0	7.1	2.3	1.0	1.92	0.07
MAX	107.0	50.0	11.4	10.0	6.0	7.33	0.56
AVG	37.53	33.33	8.83	4.05	2.07	4.39	0.13
STD	27.35	8.80	1.45	1.97	1.49	1.70	0.12

Note: SD is in centimeters; concentrations for all other parameters are in mg/l

In this study, ENVI 2.7 software (Better Solutions Consulting LLC 1997) was applied in remote sensing image processing. ArcView (ESRI 1997) was used for spatial structure analysis and kriging analysis. Statistic analysis was conducted using SAS statistical package (SAS 1996).

The original information for this study includes remote sensing data and water quality monitoring data. The image data were pretreated (through radiance adjustment, geometry adjustment and geographical positioning, and etc.).

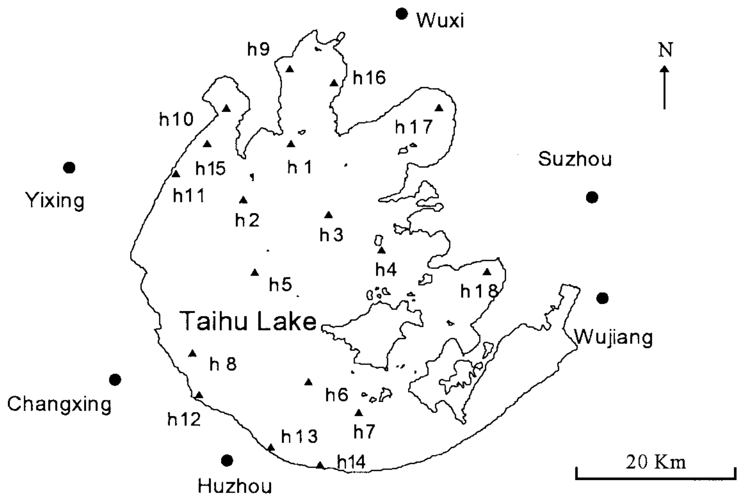

Figure 1. Sampling locations in Taihu Lake

Topographic map of 1: 50,000 was applied in the geographical positioning. Pixel digital numbers (DNs) were obtained by the sampling function of ENVI3.0. Three by three moving windows were applied in the sampling process. The average was calculated from nine adjacent pixels. Then, the averaged pixels were transferred into optical radiation value by ENVI2.7. Statistical information of the radiation data were listed in Table 2.

Table 2. Radiation data of TM satellite (10^{-1}MW.CM^{-2}.SR^{-1})

Statistics	TM_1	TM_2	TM_3	TM_4	TM_5	TM_6	TM_7
MIN	5.76	4.08	1.15	0.008	0.06	0.84	0.008
MAX	7.3	6.06	3.37	0.84	0.13	0.87	0.03
AVG	6.87	5.54	2.67	0.33	0.10	0.86	0.02
STD	0.43	0.52	0.66	0.25	0.02	0.01	0.006

RESULTS AND DISCUSSION

Pearson correlation analysis was performed for radiation data of seven bands and the synchronous sampling data. The results are presented in Table 3. It indicates that the three bands of TM_1, TM_2 and TM_3 in visible light area are closely correlated to each other, and are correlated with some water quality parameters from the Lake. The three bands of TM_5, TM_6 and TM_7, from infrared and thermal infrared area, are correlated with each other, but not correlated with most water quality parameters. TM_4 has no correlation with other bands and water quality parameters.

Among the water quality parameters, SD has close relations with most bands of the remote sensing data. Correlations can also be found between water quality

TABLE 3. Correlation of single band data

	$LnTM_1$	$LnTM_2$	$LnTM_3$	$LnTM_4$	$LnTM_5$	$LnTM_6$	$LnTM_7$	LnSS	LnSD	LnDO	LnCOD	LnBOD	LnTN
$LnTM_2$	++												
$LnTM_3$	++	++											
$LnTM_4$													
$LnTM_5$													
$LnTM_6$													
$LnTM_7$					++	-							
LnSS													
LnSD	-	-	-					-					
LnDO			-					-					
LnCOD	-	-	-										
LnBOD													
LnTN	-	-											
LnTP	-	-	-										+

Note: Logarithmic transformations were applied because all the parameters are in logarithmic normal distribution

+,-: α=0.05; ++, --: α=0.01

parameters, such as the significant negative correlations between SS and SD, SS and DO, and significant positive correlation between TN and TP.

Single band data have been widely used in water quality study. However, attempts have been made to find combinations of Landsat TM bands which would provide more information about water quality parameters than were available in single band (Chen and Shi 1996; Lavery and Pattiaratchi 1993; Li and Ji 1993). There are seven bands in TM image. It is essential to select feasible combinations of bands in the correlation analysis. In this study, 16 combinations were selected. Results are shown in Table 4.

Table 4. Correlation matrix of multi-band combinations

	LnSS	LnSD	LnDO	LnCOD	LnBOD	LnTN	LnTP
LnS_1		-		-		-	-
LnS_2	-	+	+	++			+
LnS_3		-		-		-	-
LnS_4					+		+
LnS_5					+		+
LnS_6			+				
LnS_7	+	-	-	-			
LnS_8							
LnS_9			-	-			
LnS_{10}					-		--
LnS_{11}		-		-			-
LnS_{12}		-		-			-
LnS_{13}	+	-	-	-			
LnS_{14}	+	-	-	-			
LnS_{15}	+	-	-	-			
LnS_{16}		-		-		-	-

In the table: $S_1=(TM_1+TM_2+TM_3)/3$; $S_2=TM_2/TM_3$; $S_3=(TM_3*TM_2)/TM_1$;
$S_4=(TM_1-TM_2)/TM_1$; $S_5=TM_1-TM_2$; $S_6=TM_5+TM_6+TM_7-TM_4$;
$S_7=(TM_3+TM_4)/(TM_1+TM_2)$; $S_8=(TM_3-TM_4)/TM_3$;
$S_9=(TM_3+TM_1)/TM_2$; $S_{10}=TM_2/TM_1$; $S_{11}=TM_2+TM_4+TM_5$;
$S_{12}=TM_2+TM_4+TM_7$; $S_{13}=TM_3+TM_4+TM_7$; $S_{14}=TM_3+TM_4+TM_5$;
$S_{15}=TM_3+TM_4$; $S_{16}=TM_1+TM_2$.

The results indicate that the correlations between some variances have been improved. For example, both SS and BOD correlated with none of these single bands, but correlated with certain combinations of bands.

Principle component analysis is an useful tool for obtaining more comprehensive remote sensing information, and thus was applied in this study. The loadings of the first three principle components are shown in Table 5.

The first principle component presents the characteristics of $LnTM_1$, $LnTM_2$ and

Table 5. First three principle components loading

Bands	PC_1	PC_2	PC_3
$LnTM_1$	0.5638	0.1253	0.0126
$LnTM_2$	0.5562	0.1819	0.0201
$LnTM_3$	0.5566	0.0913	-0.2069
$LnTM_5$	0.1119	-0.7494	-0.6327
$LnTM_7$	-0.2248	0.6174	-0.7459
Accumulative variances (%)	61.13	87.69	99.25

$LnTM_3$, and contributes 61.13% of the variances. As for the second principle component, $LnTM_7$ is in the positive direction, and $LnTM_5$ is in the negative direction. The third principle component tells the characteristics of $LnTM_5$ and $LnTM_7$, which are in the negative direction of the component.

Correlations of the first three principle components and water quality parameters are presented in Table 6. It can be found that LnSD and PC_1 are closely correlated. PC_1 also shows close correlations with LnSS and LnTN, while PC_2 shows close correlations with LnCOD and LnTP.

Table 6. Correlation matrix for principle components and water quality parameters

	LnSS	LnSD	LnDO	LnCOD	LnBOD	LnTN	LnTP
PC_1	+	--		-		-	-
PC_2							
PC_3				-			-

Based on the correlation analysis of single band TM data, multi-bands combined TM data and principle component analysis, the following equations were adopted to represent different water quality parameters:

$$SD = e^{(5.7099-0.6991*PC1)}$$
$$TP = e^{(-0.4081-8.659*LnS10)}$$
$$TN = e^{(8.228-2.713*LnS16)}$$
$$SS = e^{(5.6394 + 1.5493*LnS7)}$$
$$DO = e^{(2.3704-0.2107*LnTM3)}$$
$$BOD = e^{(4.2380+2.2546*LnS4)}$$
$$COD = e^{(0.3671+1.2454*LnS2)}$$

In these equations:

$$PC_1=0.5638*LnTM_1+0.5562*LnTM_2+0.5566*LnTM_3+0.1119*LnTM_5-0.2248*LnTM_7$$

Re-sampling was taken on the TM image of the study area. Totally 52 samples were obtained through regular grid sampling (three by three window moving average), and were involved in the estimation of the contents of water quality parameters in the sampling locations using the equations above. Spatial structural analysis and kriging interpolation for these water quality parameters in the Lake

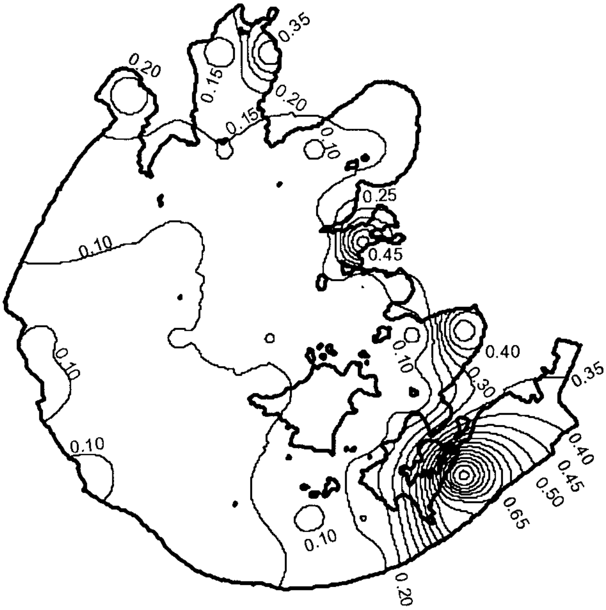

Figure 2. Concentration contour map of TP in Taihu Lake (mg/l)

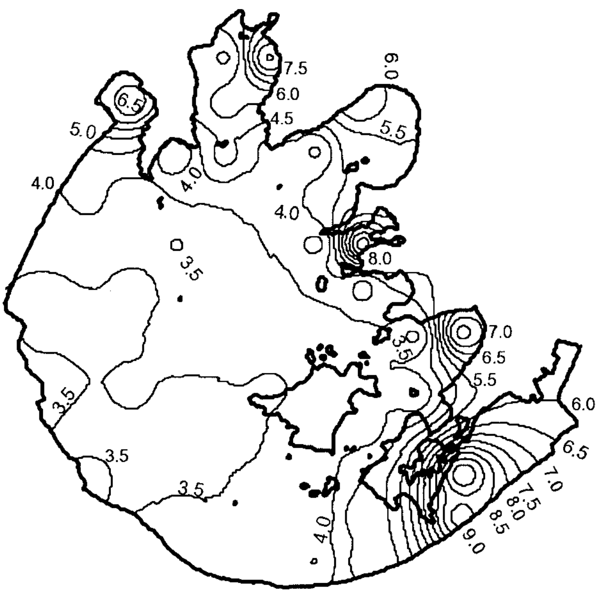

Figure 3. Concentration contour map of TN in Taihu Lake (mg/l)

area were then taken. Due to limited space, Figures 2 and 3 only show the contour maps of TP and TN drawn from the kriged data.

Figures 2 and 3 illustrate that the contents of TP and TN in Taihu area were quite high, and there were significant regional differences. The highest contents of TP and TN can be found in the Eastern Taihu area (down-right corner), and there was serious eutrophication in the area. The Eastern Taihu area is a very shallow and partly closed water body. Pollutants received from the nearby sources were accumulated in the area and producing serious pollution. The contents of TP and TN in water bodies near Wuxi and Suzhou were also quite high, which might be caused by the input of wastewater from these two largest cities in Taihu Lake area.

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