Water quality and sediment geochemistry in lakes of Yunnan Province, southern China

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Abstract Yungui Plateau lakes in southwestern China are economically important, although few have been studied previously. Water and sediments of 24 lakes throughout Yunnan Province were sampled in October 1994. We describe the chemical and physical characteristics of Yunnan lakes, and address effects of regional geology and human influences on water quality and sediment type. Water quality differs between deep Yunnan lakes of tectonic origin and shallow solution basins. Shallow lakes generally have higher nutrient concentrations and appear to be more susceptible to riparian disturbance than deeper lakes. Shallow lakes with high macrophyte standing crops, nevertheless, exhibit nutrient-poor waters. Principal ions Ca^{2+}, Mg^{2+}, and HCO_3^- reflect regional carbonate geology, except in Cheng Hai, which is a sodium bicarbonate lake. Specific conductance and $\delta^{18}O$ are positively correlated, indicating that evaporation concentrates both solutes and ^{18}O. Large, shallow lakes in southeastern Yunnan exhibit ^{18}O-enriched waters because of substantial evaporation, whereas small, deep lakes are ^{18}O-depleted. Lake waters are ^{18}O-depleted in small, shallow basins that receive substantial rainwater input relative to their small volumes. ^{18}O enrichment in Cheng Hai suggests that a recent 5-m water-level decline in this lake was caused by increased evaporation or diversion of freshwater inflow. Yunnan watersheds have undergone substantial deforestation, agricultural cultivation, soil erosion, and industrialization. Limnetic nutrient concentrations indicate that human activities have affected water quality. Organic matter content is low in sediments because of increased non-carbonate, clastic sediment yield from watersheds. Environmental policies are needed to balance ecological contraints with economic activities that impact water quality.

Key words China · Sediment · Water quality · Yunnan · Lakes · Isotopes

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Introduction

The Yungui Plateau lies within Yunnan, Sichuan, and Guizhou Provinces in southwestern China. Although the Plateau is located just north of the tropic, its climate is moderated by elevation ($\approx$2000 m above MSL). Mean annual temperature ranges between 14 °C and 18 °C (Jin and others 1990). Kunming, the capital of Yunnan Province, is known as the "City of Eternal Spring" because of its equable climate. Winter temperatures in Kunming are further moderated by Dianchi (Fig. 1), a large nearby lake (Zhang 1989). The Yungui Plateau experiences distinct wet and dry seasons. Central Yunnan receives 800–1100 mm of precipitation annually (Jin and others 1990), 85–90% of which falls between May and October under the influence of a strong southwesterly monsoon that emanates from the Bay of Bengal (Walker 1986). Evaporation approximates or slightly exceeds rainfall in an average year on the plateau (Jin and others 1990).

The majority of the Yungui Plateau lakes are concentrated in Yunnan Province, which is bounded on the west by Myanmar (Burma), on the south by Vietnam and Laos, to the northeast by Sichuan and Guizhou Provinces, and to the northwest by the Tibet (Qingzang) Plateau. Thirty-seven lakes in Yunnan Province have an area $>1\ km^2$ (Liang and Cuo 1989) and lie between 1280 m and 3370 m above MSL.

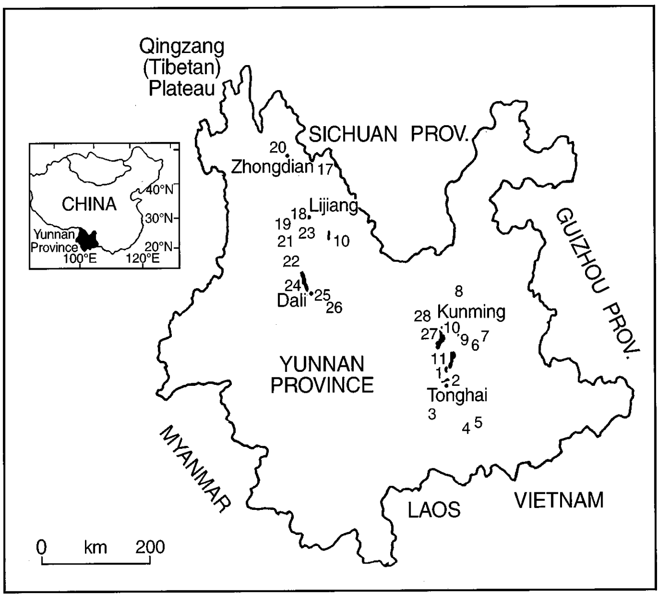

Fig. 1
Map of Yunnan Province showing location of study lakes. See Table 1 for lake names

Lakes in Yunnan Province fall within three recognized geographical clusters. Dianzhong lakes are located in east-central Yunnan Province, principally between Kunming and Tonghai, and include Yilong Hu and Qing Shui Hai (Fig. 1; 3 and 8, respectively). Diannan lakes lie in southeastern Yunnan near Viet Nam, and include Datun Hai (4) and Chang Qiao Hai (5). Dianxi lakes are located in northwestern Yunnan Province in the cluster that includes Qing Hai (26) to the south and Na Pa Hai (20) to the north. Lugu Hu (17) lies at 2691 m above MSL on the border between Yunnan and Sichuan Provinces. Na Pa Hai (20) is located at 3366 m above MSL on the southern part of the Tibet Plateau.

Several Yunnan lakes have shallow basins ($z_{mean} < 10$ m). Qilu Hu, for example, was formed by solution in carbonate bedrock, whereas Dianchi and Xingyun Hu were formed by faulting but are shallow because of sediment inwash (Jin and others 1990). Other Yunnan lakes, formed by tectonic faulting and folding, are comparatively deep ($z_{mean} > 20$ m). Fuxian Hu, for example, is the second deepest lake in China ($z_{max} = 155$ m, $z_{mean} = 89.6$ m; Ley and others 1963). Lugu Hu, located in mountainous northwestern Yunnan, has a mean depth of 40 m. Diannan lakes, in the southeast, are shallow lakes that are situated in unconsolidated Quaternary sands, pebbles, and clays.

The majority of Yunnan lakes have numerous inflows that consist of short rivers with local origins in adjacent steep-sloped areas, and most lakes lack overland outflows. Interannual variations in precipitation often induce water level fluctuations of 1–2 m (Jin and others 1990). Much has been done to alter the hydrology of Yunnan lakes during recent centuries. For instance, Dianchi's only outflow, the 3-m deep Tanglang River, was constructed as a flood control measure in the Systematic Conservancy Project of 1273 A.D. The lake level in Dianchi consequently dropped 4 m in the last 700 years (Wu 1989). The Gehe River, the only outflow from Xingyun Hu, has been channelized for flood control twice since 1923, which lowered the lake level by 3 m (Water Conservancy and Electric Power Bureau of Jiangchuan County, Yunnan Province, unpublished data). In 1939, a channel was dug from Qilu Hu to a nearby sinkhole and a sluice gate was installed that permitted water-level regulation for flood control (Brenner and others 1991; Song and others 1994). Human activities, such as removal of water for irrigation, continue to affect lake hydrology. Cheng Hai lacks outflows, and evaporative loss and hydraulic removal exceed inputs. The lake level in Cheng Hai fell 5 m between 1960 and 1990, and pumping stations were sequentially relocated down slope as lake level dropped (Wang 1989, personal communication 1994).

Ninety-five percent of the Yungui Plateau area is mountainous, and population and agriculture are thus centered around valley lakes that are closely tied to the regional economy. Yungui lakes have been described as "The pearls on the plateau" because of their importance as water resources (Jin and others 1990). Virtually all lakes in the counties surrounding Kunming are exploited for fishing, water supply, waste disposal, lake bottom reclamation, agriculture and industry. Lake catchments in Yunnan Province have been subjected to deforestation, intensive agricultural cultivation, soil erosion, urbanization, and industrialization, and are among the most disturbed ecosystems in the world. Forest cover in Yunnan declined from 50% to 25% between 1950 and 1977 (Delfs 1982), and natural vegetation is now restricted to a few alpine and subalpine areas (Li and Walker 1986).

Riparian disturbance influences water quality in many Yunnan lakes, especially those that lack outflows and have long residence times. Yunnan lakes have changed dramatically in recent decades, but many of these limnological changes are poorly documented. Dianchi, for example, which is Kunming's principal fishery (Lu 1989b), sustained species losses and fish deaths that are attributed to nutrient enrichment and industrial pollution (Li 1989; Hu, personal communication). Yunnan scientists express concern about the decline of fisheries and rapid infilling of the region's shallow lakes.

Despite the economic importance of the region's lakes (He 1988; Shen 1989), few have been studied. Hsiao (1946, 1949) examined physical, chemical, and biological features of Er Hai. In 1957, Ley and others (1963) studied Er Hai and eight lakes surrounding Kunming. General studies of Yunnan lakes were begun in the late 1980s by students at Yunnan University, but these investigations were concerned mostly with Er Hai and with large lakes in the vicinity of Kunming. To date, there has been no comprehensive characterization of water quality and sediments of Yunnan lakes.

We present results of water and sediment analyses from a limnologically diverse group of lakes throughout Yunnan Province, many of which were previously unstudied. We characterize the physical and chemical limnology of these lakes and address effects of regional geology and human influences on water quality. In addition to examining the current status of water quality in Yunnan lakes, this study provides baseline information for future studies to evaluate subsequent changes in water quality.

Methods

Water samples were collected from 24 Yunnan lakes in October 1994. Samples were obtained at three sites in each lake. At each sampling site, water depth was measured by lowering a 20-cm-diameter Secchi disk on a metered rope to the sediment surface. The Secchi disk transparency was also recorded at each sampling location. Epilimnetic water samples for water chemistry were obtained at each location by filling bottles about 0.5 m below the water surface. A 125-ml dark Nalgene bottle was used to collect water for conductivity, and chemical analysis (Ca^{2+}, Mg^{2+}, Fe^{3+}, Na^{+}, K^{+}, Cl^{-}, HCO_3^{-}, SO_4^{2-}, SiO_2). A second sample was taken in a 20-ml scintillation vial and preserved with HCl for total N and total P analyses. A water sample was collected in glass Qorpak bottles for stable oxygen isotope analysis ($\delta^{18}O$) from each lake, from the spring Hu Die Quang, and from the well Jin Kuai Shi. Rainwater was collected in Kunming on 12 October 1994. Surface sediment samples were collected at each lake sampling site using a small dredge or Hongve gravity corer, and sediments were stored in labelled scintillation vials prior to chemical analysis.

Conductivity in waters was measured with a YSI Model 33 S-C-T meter. Cations and chloride in waters were measured by inductively coupled plasma spectroscopy on a Jarrell-Ash ICP 9000 and sulfates were measured on a Dionex DX 500 ion chromatograph. Total phosphorus in water was measured by ascorbic acid-ammonium molybdate flow analysis on a Technicon Auto-Analyzer, following acidic persulfate digestion in an autoclave (APHA 1989). Total nitrogen in water was measured on the Auto-Analyzer by cadmium reduction, after basic persulfate digestion (APHA 1989). Soluble SiO_2 in lake waters was measured by the automated method for molybdate-reactive silica (APHA 1989) using the Technicon Auto-Analyzer, after centrifuging and decanting unfiltered water samples. Water samples for isotopic analysis were equilibrated with pure CO_2 gas in Vacutainer^{Tm} tubes (Socki and others 1992), and equilibrated CO_2 gas was distilled off-line from H_2O and non-condensable gases. Purified CO_2 was sealed in 6-mm breakseal tubes and transferred to a VG Isogas Prism II Mass Spectrometer to measure oxygen isotopes. $\delta^{18}O$ values are expressed using standard delta notation relative to standard mean ocean water (SMOW).

Sediment samples were dried at 70 °C in a Blue M Stabil-Therm Gravity Oven and ground to a fine powder using a mortar and pestle. Organic matter content in sediments was estimated by weight loss on ignition at 550 °C (Håkanson and Jansson 1983) in a Sybron Thermolyne muffle furnace. Remaining ash was digested in 50 ml of boiling 1N HCl (Andersen 1976), and samples were brought to 100 ml volume with deionized water. Elemental concentrations (Ca, Mg, K, Fe, Na, Mn, P, Zn, Pb, and Cd) in digestate were determined on the Jarrell-Ash ICP 9000. Carbonate content in sediments was measured by coulometric titration using a UIC/Coulometrics Model 5011 coulometer (Engleman and others 1985). All chemical concentrations are expressed as amount per unit dry mass sediment.

Statistical analyses, including means, correlations, and cluster analyses, were performed using Statistical Analysis System (SAS Institute, Inc. 1985) procedures. Cluster analyses were performed using Euclidean distances and the average clustering method.

Results

Thirteen lakes were sampled from the Dianzhong and Diannan regions in the east-central portion of the province (Fig. 1). Eleven lakes were sampled from the Dianxi region in the northwestern portion of Yunnan, and two of these, Lugu Hu (17) and Na Pa Hai (20), were montane lakes in the Hengduan Shan range. Although Na Pa Hai is reported to have an area of 31 km^2 (Table 1), we found that the lake was reduced to a small, shallow pool (diameter = 20 m, $z_{max} = 0.1$ m). A plaque near Na Pa Hai described the lake as a “seasonal, high-plateau lake.”

Yunnan lakes fall into two categories with respect to mean depth. Sixteen lakes have z_{mean} or “study mean depths” < 10 m (Table 1), and most of these lakes exhibit $z_{mean} < 5$ m. These include several shallow lakes probably formed by solution processes in the karst terrain. Eight lakes have z_{mean} or study mean depth values > 13 m, and z_{mean} in the majority of these lakes is > 20 m. These include deeper Yunnan lakes probably formed by faulting and folding. Most of them have their maximum-length axis aligned in a north-south direction, parallel to the main orientation of tectonic folding that occurred on the plateau during the Yanshanian and Himalayan orogenies (Ley and others 1963).

Yunnan lakes typically range between 150 and 600 μS cm^{-1} specific conductance (mean = 272 μS cm^{-1}, $n = 23$). Principal ions in these lakes are Ca^{2+}, Mg^{2+}, and HCO_3^{-} (Table 2). Cheng Hai’s specific conductance (1043 μS cm^{-1}) is highest among the study lakes, and its salinity is dominated by sodium and bicarbonate, which makes Cheng Hai unique among these lakes.

Yunnan lakes span a broad range of limnetic nutrient concentrations. Total P values (Table 2) indicate that Dianchi and Cui Hu (Green Lake), which are shallow lakes near Kunming, are hypereutrophic (> 100 μg l^{-1} total P; Wetzel 1975). Qilu Hu and Yilong Hu, in the Dianzhong region, are algal-dominated, eutrophic lakes (30–100 μg l^{-1} total P; Wetzel 1975) that support fish farming. Qilu Hu has emergent weedbeds and floating is-

Table 1
Geographic and morphometric data for Yunnan study lakes. Survey mean depth is the mean of water depths at three mid-lake stations where water samples were collected during this study. A single station was sampled at Na Pa Hai because the lake was seasonally reduced to a small, shallow pool

Survey lave	Lake	County	Elevation (m asl)	Area (km^2)	z_{mean} (m)	z_{max} (m)	Survey mean depth (m)
1	Xingyun Hu	Jiangchuan	1723[a]	39[a]	2.9[d]	9.8[d]	5.6
2	Qilu Hu	Tonghai	1797[g]	42[g]	4.0[e]	6.8[e]	4.7
3	Yilong Hu	Shiping	1412[a]	44[e]	2.8[e]	6.2[e]	4.1
4	Datun Hai	Geiju	1281[a]	18[a]	2.6[d]	3.0[d]	3.3
5	Chang Qiao Hai	Mengzi	1281[a]	14[a]	1.6[a]	2.5[a]	2.7
6	Chang Hu	Lunan	1900[c]	1[f]	15.9[f]	–	9.1
7	Yue Hu	Lunan	1850[i]	3[g]	–	–	4.0
8	Qing Shui Hai	Xundian	2173[a]	7[g]	20.2[a]	30.0[a]	21.3
9	Cao Dian Hai	Yiliang	1850[i]	1[g]	–	5.0[g]	5.4
10	Yangzong Hai	Chengjiang	1770[a]	31[a]	20.3[d]	28.0[d]	20.3
11	Fuxian Hu	Chengjiang	1720[a]	212[e]	89.6[e]	155.0[e]	32.0
16	Cheng Hai	Yong Sheng	1503[a]	79[a]	15.0a	36.9[a]	21.7
17	Lugu Hu	Ning Lang	2691[a]	48[a]	40.3[a]	93.5[a]	22.3
18	Wen Bi Hai	Lijiang	2350[i]	2[h]	–	–	3.6
19	Bei Han Chang Hai	Lijiang	2500[i]	<1[h]	–	–	5.2
20	Na Pa Hai	Zhong Dian	3366[b]	31[b]	–	–	0.1
21	Jian Hu	Jian Chuan	2150[i]	6[h]	–	–	4.4
22	Zhi Bi Hu	Er Yuan	1900[h]	8[h]	–	–	15.8
23	Cao Hai	He Qing	2150[i]	<1[h]	–	–	1.0
24	Er Hai	Da Li	1974[a]	248[a]	10.5[a]	21.5[a]	13.1
25	San Shou Shuiku	Da Li	1700[i]	<1[h]	–	–	15.4
26	Qing Hai	Xiang Yun	1950[i]	<1[h]	–	–	1.4
27	Dianchi	Kunming	1885[a]	305[a]	4.2[a]	10.2[a]	5.7
28	Cui Hu	Kunming	1850[i]	<1[h]	–	–	1.6

[a] Liang and Cuo 1989
[b] From marker at Na Pa Hai
[c] Peng 1989
[d] Ley and others 1963
[e] Jin and others 1990
[f] Li 1989
[g] Moore and others 1988
[h] Estimated in field during this study
[i] determined from Army Map Service (1944–1956) topographic relief maps

lands of *Eichhornia*. Xingyun Hu and Cao Dian Hai are algal-dominated lakes that are subject to extensive shoreline erosion. Along with Qing Hai, a shallow, macrophyte-dominated lake, Xingyun Hu and Cao Dian Hai exhibit total P values in the mesotrophic range see attached comments (10–30 $\times 10^5$ kg of harvested fish per year. Cheng Hai and Er Hai are large, deep, oligotrophic lakes (5–10 $\mu g\ l^{-1}$ total P). Wen Bi Hai, Cao Hai, Datun Hai, and Jian Hu are shallow lakes that are dominated by macrophytes and exhibit limnetic total P concentrations of 5–10 $\mu g\ l^{-1}$. Six deep lakes, Chang Hu, Qing Shui Hai, Yangzong Hai, Fuxian Hu, Lugu Hu, and Zhi Bi Hu, show ultraoligotrophic waters ($<5\ \mu g\ l^{-1}$ total P). Lugu Hu has exceptionally clear waters (Secchi depth = 13.9 m; Table 2). Other lakes that show $<5\ \mu g\ l^{-1}$ total P include Yue Hu, which is macrophyte dominated, Bei Han Chang Hai, a small impoundment 6 km west of Lijiang, and Chang Qiao Hai.

Chemical content of groundwater from Hu Die Quang ("Butterfly Spring"), an artesian source at the base of the Dian Cang mountains near Dali, was ionically similar to the majority of study lakes, and was dominated by Ca^{2+}, Mg^{2+}, and HCO_3^- (Table 2).

$\delta^{18}O$ values from Hu Die Quang (–15.6‰), Jin Kuai Shi, a well in Xi Zhou on Er Hai's western shore (–13.3‰), and rainwater collected on 12 October 1994 from Kunming (–13.1‰) are ^{18}O-depleted relative to most Yunnan lake waters (Table 2). Hu Die Quang is the most ^{18}O-depleted, whereas Jin Kuai Shi's $\delta^{18}O$ value closely approximates the value for rainwater (Table 2).

A significant positive correlation exists between specific conductance and $\delta^{18}O$ values (Table 5, Fig. 2). $\delta^{18}O$ values are relatively enriched in several large, shallow lakes including Xingyun Hu, Qilu Hu, Yilong Hu, and Dianchi (Table 2). $\delta^{18}O$ is most enriched in Cheng Hai which, despite its great depth and large size, has undergone a rapid water-level decline for more than 30 years (Wang 1989, personal communication 1994). In contrast, $\delta^{18}O$ values were relatively depleted in two deep lakes, San Shou Shuiku and Zhi Bi Hu (Table 2). Depleted $\delta^{18}O$ values were also observed in several shallow lakes including Jian Hu, Cao Hai, and Wen Bi Hai.

Differences in water chemistry were found between shallow lakes and deeper lakes with larger volumes. Total P and total N concentrations are significantly higher in lakes that have mean depths <10 m (Table 3). Mean lim-

Table 2
Water quality data for Yunnan study lakes and sites. SO_4 was assayed on one mid-lake water sample per lake. Values shown for Hu Die Quang (Butterfly Spring, Dali Co.), Jin Kuai Shi (well near Er Hai), and Kunming rain were obtained from one water sample at each location. All other reported values are means of three mid-lake samples obtained from each lake, except at Na Pa Hai where one sample was collected because of low water levels. HCO_3 was calculated as the difference between the sum of cation concentrations and the sum of remaining anion concentrations. Secchi depth at Datun Hai and Qing Hai exceeded maximum depth. $\delta^{18}O$ values are relative to SMOW. Spec. cond. is specific conductance

Lake or site	Secchi depth (m)	Spec. cond. ($\mu S\ cm^{-1}$)	Total P ($\mu g\ l^{-1}$)	Total N	SiO_2	Ca	Mg	K	Fe	Na	Cl	SO_4	HCO_3	$\delta^{18}O$ (‰)
				($mg\ l^{-1}$)										
Xingyun Hu	2.4	344	18	0.50	0.5	25.4	29.5	5.3	0.01	15.0	9.4	17.7	235.0	−5.7
Qilu Hu	0.6	470	54	1.69	5.5	28.6	40.5	10.0	0.03	21.0	28.6	63.4	231.8	−5.9
Yilong Hu	0.2	507	66	5.05	16.8	34.6	43.0	15.7	0.02	19.6	22.6	15.6	338.8	−4.3
Datun Hai	–	375	5	1.76	1.1	55.4	12.3	4.0	0.01	8.5	19.5	122.1	70.5	−9.1
Chang Qiao Hai	1.0	270	4	0.37	5.0	44.3	13.6	2.1	0.01	2.4	1.8	17.5	187.4	−10.0
Chang Hu	3.7	261	2	0.28	0.7	36.3	20.3	1.2	0.02	0.6	0.0	6.8	207.2	−5.4
Yue Hu	1.4	202	4	0.20	0.1	41.6	3.8	2.5	0.01	0.5	0.8	6.0	141.9	−10.0
Qing Shui Hai	4.1	150	1	0.12	0.6	25.0	7.7	1.3	0.01	0.4	0.6	2.0	114.2	−9.0
Cao Dian Hai	1.0	261	22	0.40	2.9	33.6	17.1	4.3	0.01	4.1	4.9	26.7	163.3	−10.2
Yangzong Hai	4.7	353	2	0.25	0.8	39.0	31.5	3.3	0.02	4.4	2.9	55.4	218.2	−5.3
Fuxian Hu	8.6	270	1	0.11	0.1	26.5	24.2	2.5	0.01	7.0	2.1	10.7	207.3	−3.6
Cheng Hai	5.6	1043	7	0.46	0.4	6.5	73.8	11.0	0.04	193.3	15.9	4.7	886.7	−2.9
Lugu Hu	13.9	210	1	0.14	0.2	29.3	8.5	1.1	0.01	10.2	8.2	5.0	140.1	−6.5
Wen Bi Hai	1.3	181	5	0.19	1.6	17.0	17.4	0.4	0.01	3.8	0.7	1.5	146.6	−12.5
Bei Han Chang Hai	1.7	236	1	0.13	0.8	37.2	11.9	1.7	0.01	3.0	1.3	20.2	155.6	−10.9
Na Pa Hai	–	202	69	1.48	0.0	32.2	7.8	1.8	0.02	5.8	2.4	9.3	139.4	–
Jian Hu	1.0	216	7	0.16	5.8	34.1	10.6	1.0	0.01	4.3	0.5	6.4	161.0	−13.3
Zhi Bi Hu	3.8	280	3	0.11	7.9	52.2	9.6	1.5	0.01	5.4	1.03	3.7	217.3	−12.7
Cao Hai	1.1	190	5	0.11	0.7	28.9	11.9	0.5	0.01	1.2	0.6	1.0	149.3	−14.2
Er Hai	6.1	216	7	0.21	0.2	27.3	13.0	2.3	0.01	8.0	1.8	6.2	162.2	−9.0
San Shou Shuiku	0.8	187	24	0.20	2.8	28.6	10.5	1.6	0.01	1.6	0.0	4.9	140.2	−12.7
Qing Hai	–	296	16	0.54	6.0	16.2	27.3	3.9	0.02	16.7	16.7	15.6	188.1	−9.5
Dianchi	0.4	350	144	1.59	0.2	34.5	20.5	7.8	0.02	32.9	42.4	21.3	206.5	−6.4
Cui Hu	0.3	233	242	2.63	0.7	25.2	10.8	4.1	0.02	8.4	9.5	24.6	112.0	–
Hu Die Quang	–	–	–	0.35	7.1	38.6	20.2	0.6	0.02	1.0	0.0	3.3	217.8	−15.6
Kunming rain	–	–	–	–	–	–	–	–	–	–	–	–	–	−13.1
Jin Kuai Shi	–	–	–	–	–	–	–	–	–	–	–	–	–	−13.3

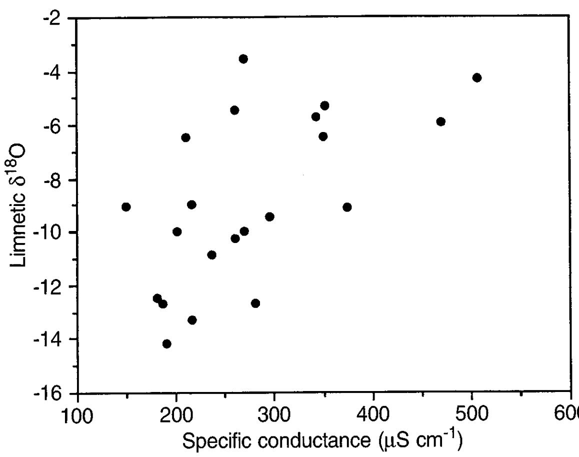

Fig. 2
Limnetic $\delta^{18}O$ versus specific conductance in Yunnan study lakes. Cheng Hai was excluded

netic total P concentration among deep lakes (5 $\mu g\ l^{-1}$) is at the oligotrophic to mesotrophic boundary, whereas mean limnetic total P among shallow lakes (43 $\mu g\ l^{-1}$) falls in the middle of the eutrophic range (Wetzel 1975). Secchi depth in deep lakes averages 5.7 m and in shallow lakes averages 1.0 m (Table 3), which corresponds approximately to ultraoligotrophic and eutrophic conditions, respectively (Huber and others 1982). Lakes that exhibit greater Secchi depths are deep lakes that possess lower limnetic nutrient concentrations, whereas lakes with lesser Secchi depths are shallow lakes that exhibit high limnetic total P concentrations (Fig. 3). Na, K, and Cl concentrations are higher in shallow lakes than in deep lakes (Table 3).

Organic matter content in surface sediments of Yunnan lakes (Table 4) is relatively low considering that many Yunnan lakes are highly productive. Organic matter content averages 15.2% of dry sediment weight among the lakes studied. In contrast, organic matter content in a set of 97 shallow, karst Florida lakes averaged 39.7% (Brenner and Binford 1988). Sediment organic matter content is positively correlated with limnetic total P and total N

Table 3
t-tests comparing characteristics of shallow versus deep study lakes. Shallow lakes are defined as those with $z_{mean} < 10$ m. For lakes with unknown z_{mean}, study mean depth values (Table 1) were used to approximate z_{mean}

Depth category	Sample size (No. of lakes)	Mean	Standard deviation	Prob. $>F$ under H_0: $\mu_1 = \mu_2$
		Total P (μg l^{-1})		
Deep	9	5	8	
Shallow	15	43	67	$\ll 0.001$
		Total N (mg l^{-1})		
Deep	9	0.21	0.11	
Shallow	15	1.12	1.34	$\ll 0.001$
		Na (mg l^{-1})		
Deep[a]	8	4.7	3.6	
Shallow	15	9.8	9.3	0.018
		K (mg l^{-1})		
Deep[a]	8	1.8	0.8	
Shallow	15	4.3	4.1	< 0.001
		Cl (mg l^{-1})		
Deep	9	3.6	5.2	
Shallow	15	10.8	12.7	0.017
		Secchi depth (m)		
Deep	9	5.7	3.7	
Shallow	12	1.0	0.7	$\ll 0.001$

[a] Cheng Hai was removed from the set of deep lakes because its high Na and K values were outliers

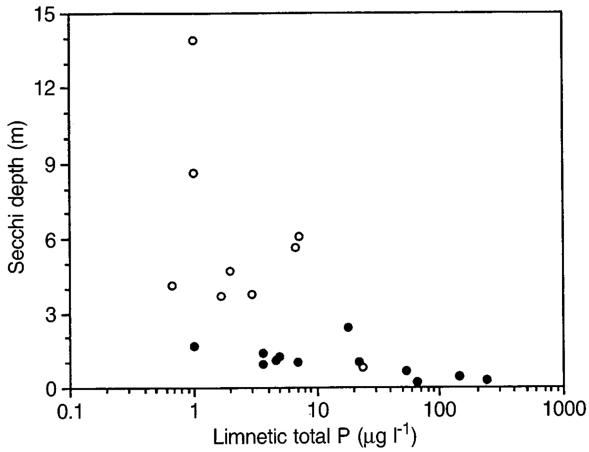

Fig. 3
Secchi depth versus log limnetic total P concentration. Deep lakes ($z_{mean} > 10$ m) are denoted by *open circles*, and shallow lakes ($z_{mean} < 10$ m) are denoted by *shaded circles*. Three lakes with missing Secchi depth values are not included in this figure

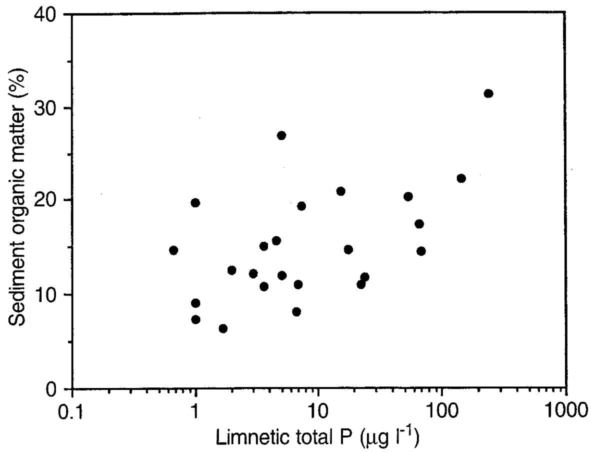

Fig. 4
Sediment organic matter content versus limnetic total P concentration in Yunnan study lakes

(Table 3, Fig. 4), perhaps indicating that greater deposition of organic sediments occurs in lakes with higher productivity.

Calcium carbonate content in Yunnan lakes (mean = 10% of dry sediment weight) is two times higher than total carbonate content in the Florida karst district (5.5%; Brenner and Binford 1988). Non-carbonate, inorganic content was estimated as the remainder of sediment after organic matter content and carbonates (as $CaCO_3$) were subtracted from total sediment mass. Non-carbonate, inorganic content (silt and clay) in Yunnan lake sediments is high (mean ≈ 75%).

Sediment Pb concentrations are fairly low and consistent among Yunnan lakes (Table 4), providing evidence for little anthropogenic enrichment. One possible exception is Cui Hu, an urban lake in Kunming that shows distinctly higher concentrations of Pb and Zn in its sediments. Lead in sediments is positively correlated with organic matter content (Table 5, Fig. 5), which suggests that Pb may be bound to the organic sediment fraction. Cadmium values are also low but, in contrast to Pb, are correlated with sediment Fe rather than organic matter (Table 5). Cadmium may be associated with inorganic clays derived from weathered catchment soils. Previous studies of fluvial deposits show that these heavy metals may be variably associated with carbonates, hydroxides, sulfides, or organic solids (Salomons and De Groot 1978).

A cluster analysis of Yunnan lakes using water quality variables produced six clusters (Fig. 6). All water quality variables were used in this analysis, except $\delta^{18}O$ and Secchi depth, which had missing values for some lakes, and specific conductance and HCO_3^-, which are strongly correlated with cation concentrations. Cheng Hai, the only lake in cluster A, is strongly differentiated from the other study lakes because of its high Na^+, Mg^{2+}, and Fe^{3+} concentration, and its low Ca^{2+} value. Cluster B is comprised of Datun Hai, which is differentiated from other lakes by its high Ca^{2+} and SO_4^{2-} concentrations. Cluster C consists of lakes with the second highest SO_4^{2-} range and the second highest ionic concentrations. Cluster D1

Table 4
Constituent concentrations in study lake sediments. One sediment sample was collected at Na Pa Hai because of seasonally low water levels. Values reported for Lugu Hu and Fuxian Hu, in which organic sediments were scarce, are means of two samples. All other reported values are means from three mid-lake sites. Organic matter content was assessed by loss on ignition

Lake	Ca	Mg	K	Fe	Na	Mn	Total P	Zn	Pb	Cd	$CaCO_3$ (%)	Organic matter content (%)
	(mg g^{-1})											
Xingyun Hu	40.0	8.3	9.8	45.9	0.4	0.77	2.15	0.09	0.25	0.02	9.8	14.7
Qilu Hu	51.5	11.1	9.7	51.6	0.5	0.73	1.35	0.11	0.22	0.02	13.3	20.2
Yilong Hu	49.0	7.2	10.7	35.2	0.4	0.44	0.79	0.06	0.19	0.02	12.5	17.5
Datun Hai	74.6	4.2	6.3	40.3	0.3	0.46	0.90	0.14	0.32	0.02	16.8	26.8
Chang Qiao Hai	27.9	7.7	8.6	42.0	0.3	0.73	0.83	0.09	0.20	0.01	7.0	10.8
Chang Hu	37.6	4.7	7.0	65.8	0.1	1.08	1.07	0.33	0.33	0.03	9.9	16.3
Yue Hu	26.0	2.6	7.9	47.7	0.2	0.33	0.88	0.15	0.28	0.02	6.3	15.1
Qing Shui Hai	3.3	4.6	5.9	94.4	0.1	0.93	1.60	0.12	0.31	0.03	1.0	14.7
Cao Dian Hai	3.9	6.5	10.0	57.8	0.3	0.69	1.30	0.09	0.22	0.02	0.5	11.1
Yangzong Hai	4.0	11.5	8.0	42.1	0.3	0.50	1.34	0.16	0.21	0.02	11.5	12.5
Fuxian Hu	6.1	7.8	6.2	33.4	0.6	0.59	0.82	0.23	0.15	0.02	1.8	7.4
Cheng Hai	3.0	11.3	6.3	33.0	0.8	0.75	0.91	0.07	0.13	0.01	3.0	8.2
Lugu Hu	47.2	14.0	3.8	56.1	0.3	1.19	1.63	0.09	0.15	0.02	9.6	19.7
Wen Bi Hai	62.5	46.9	4.2	49.6	0.4	1.29	1.25	0.07	0.19	0.02	13.9	11.9
Bei Han Chang Hai	27.9	5.4	8.2	49.9	1.2	1.22	1.21	0.09	0.17	0.02	7.1	9.1
Na Pa Hai	62.8	6.4	8.5	35.8	1.0	0.52	0.68	0.13	0.14	0.01	14.0	14.5
Jian Hu	11.8	12.8	8.3	46.3	0.5	1.32	1.25	0.10	0.19	0.02	2.6	11.0
Zhi Bi Hu	77.8	10.7	6.5	42.2	0.5	0.77	1.09	0.11	0.23	0.01	19.4	12.3
Cao Hai	64.5	8.1	4.1	51.1	0.2	0.83	0.88	0.11	0.23	0.02	16.2	15.7
Er Hai	14.2	12.4	6.8	53.1	0.5	1.78	1.46	0.12	0.21	0.02	3.7	19.4
San Shou Shuiku	8.8	6.5	9.3	32.6	0.6	0.81	1.19	0.11	0.22	0.01	2.9	11.7
Qing Hai	86.2	9.5	9.0	37.9	0.8	0.50	0.85	0.07	0.20	0.02	21.6	20.9
Dianchi	65.2	7.7	8.2	55.1	0.5	0.79	2.01	0.21	0.24	0.02	14.6	22.2
Cui Hu	95.0	4.6	5.8	30.5	0.2	0.36	1.98	1.06	0.40	0.02	20.7	31.3

Table 5
Correlations between water and sediment constituents (*OMC*, sediment organic matter content)

Relationship	Correlation coefficient	Prob $>\|r\|$ under H_0: rho = 0	Sample size (no. of lakes)
Water variables with water variables			
Spec. cond. with $\delta^{18}O$	0.606	0.003	22
Total P with total N	0.604	0.002	24
Water (w.) variables with sediment variables			
W. total P with OMC	0.644	< 0.001	24
W. total N with OMC	0.511	0.011	24
Sediment variables with sediment variables			
Ca with OMC	0.657	0.001	24
Pb with OMC	0.627	0.001	24
Cd with OMC	0.169	0.431	24
Cd with Pb	0.509	0.011	24
Cd with Fe	0.741	< 0.001	24

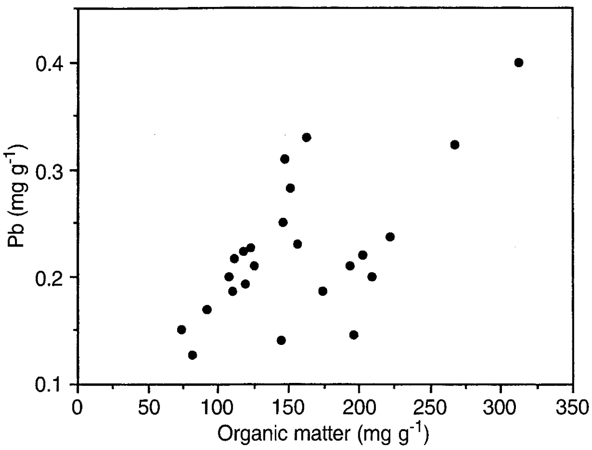

Fig. 5
Pb concentration versus organic matter content in sediments

consists of three shallow lakes with the third highest ionic concentrations, but a wide range in most other variables. Cluster D2 consists of 12 lakes with a wide range of mean depths that together exhibit the lowest ionic and nutrient concentrations. Cluster D3 consists of four shallow lakes with the second lowest ionic concentrations. Organic matter content is the strongest determinant of

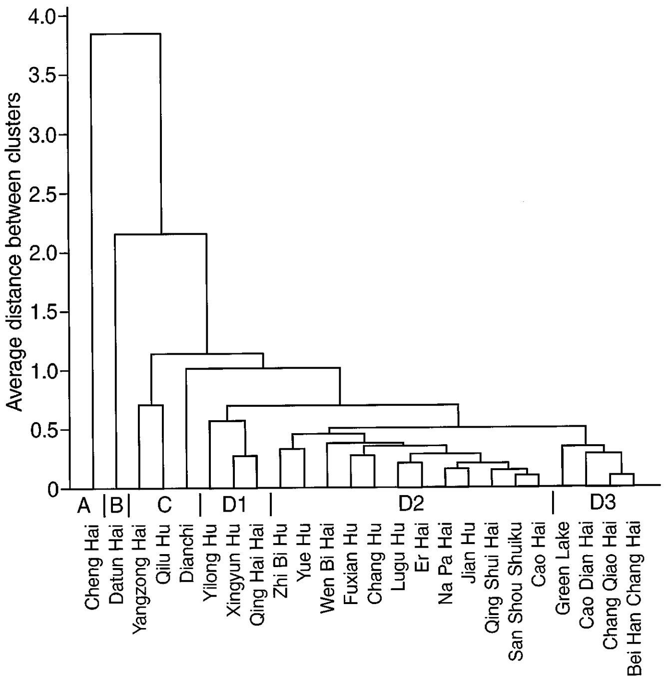

Fig. 6
Cluster analysis of Yunnan study lakes based on selected water quality variables

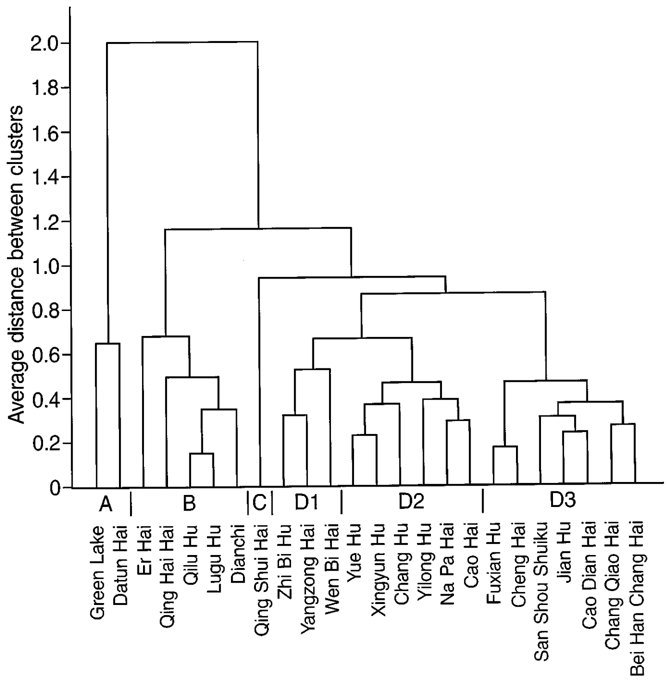

Fig. 7
Cluster analysis of Yunnan study lakes based on selected sediment variables

cluster composition of lakes based on sediment constituents. Cluster A (Fig. 7), which consisted of Cui Hu and Datun Hai, showed the highest organic matter and Ca content, and the lowest Fe and Mn content. Lakes in cluster B showed the second highest organic matter content and are shallow, with the exception of Lugu Hu, which is deep. Analyzed sediments from Lugu Hu may not represent the entire lake very well because lacustrine deposits are absent throughout most of the basin. Cluster C consists of Qing Shui Hai, which exhibits the highest Fe and Cd values and the lowest Ca and Na values. Sediments from shallow lakes in cluster D2 contain the third highest organic matter content among the study lakes, and they vary widely in other constituents. Cluster D3 contains lakes with the lowest amount of sediment organic matter content, and low concentrations of Ca and total P.

Discussion

Yunnan lakes are diverse with respect to water quality. This diversity reflects differences in basin origins, morphometry, and human influences. Principal ions in most Yunnan lakes are Ca^{2+}, Mg^{2+}, and HCO_3^-, which is consistent with the predominant carbonate geology of the region.

Water quality is generally different between deep Yunnan lakes with large volumes that were formed by tectonic processes and shallow lakes that formed by solution or have been subject to infilling. Deep lakes exhibit comparatively low nutrient concentrations and high water clarity. Low productivity and large volumes allow deep lakes, such as Qing Shui Hai, to sustain oxygenated hypolimnetic waters during summer stratification (Moore and others 1987). Shallow Yunnan lakes tend to display significantly higher nutrient concentrations than deeper lakes. Summertime oxygen profiles from three shallow lakes suggest that water columns are mixed on a frequent basis and remain oxygenated during summer months (Moore and others 1988). Oxygenated water in shallow lakes and in the hypolimnion of deep, oligotrophic lakes precludes internal nutrient loading caused by remobilization of phosphorus from sediments. High limnetic nutrient concentrations in shallow Yunnan lakes are sustained by external loading rather than by release from sediments.

Several factors affect limnetic nutrient concentrations, including the nutrient loading rate, lake mean depth, flushing and nutrient sedimentation rates. Human disturbance in watersheds can greatly increase nutrient loading. Dianchi and Er Hai have comparable surface areas (305 and 248 km^2, respectively) and comparable watershed areas (2920 and 2565 km^2, Jin and others 1990). However, Dianchi's water volume (1.3×10^9 m^3) – see attached comments – and there are three times as many inhabitants (1.8×10^6) in Dianchi's watershed as in Er Hai's (6.5×10^5; Jin and others 1990). Consequently, Dianchi sustains higher limnetic nutrient concentrations than Er Hai.

Fuxian Hu's surface area (212 km^2) is similar to that of Er Hai. Although Fuxian Hu's watershed area (1053 km^2)

is about one half that of Er Hai's, the human population in Fuxian Hu's watershed (5.2×10^5) is comparable to that of Er Hai. Fuxian Hu's water volume (1.9×10^{10} m^3), however, is approximately 7 times greater than Er Hai's volume and 15 times greater than Dianchi's volume. Nutrient inputs to Fuxian Hu, therefore, tend to be diluted by the greater volume of water in this lake. Nutrient inputs of a given magnitude have a greater effect on small waterbodies than on large, deep lakes (Cole 1983). Shallow Yunnan lakes, therefore, are generally more susceptible to disturbance and show greater effects of increased nutrient loading than do deeper lakes in the region (Jin and others 1990).

Although many shallow lakes possess high limnetic nutrient concentrations, several shallow lakes have high macrophyte standing crops and exhibit low concentrations of nutrients in the water column. By reducing current velocity and wave action, macrophytes promote phytoplankton settling and minimize sediment resuspension (Carpenter and Lodge 1986). Non-rooted macrophytes such as *Eichhornia* also remove nutrients from the water column. Limnetic nutrients may be low in the vicinity of macrophytes, but nevertheless primary production in macrophyte-dominated lakes is probably high. Lakes such as Qilu Hu, Qing Hai, Wen Bi Hai, Cao Hai, Datun Hai and Jian Hu, which support high macrophyte standing crops, are probably more subject to infilling because of the accretion of organic material and sediment trapping in the littoral zone (Carpenter and Lodge 1986).

The oxygen isotopic composition of lake water is determined by temperature, by the isotopic composition of precipitation, and by preferential evaporation of the light isotope ($H_2{}^{16}O$) from the lake. Isotopic composition of precipitation is controlled by several factors including the distance from the water-vapor source area and the elevation where the rainfall occurs. Isotopically heavier $H_2{}^{18}O$ precipitates preferentially over $H_2{}^{16}O$, leading to more ^{18}O-depleted precipitation at higher elevations. $\delta^{18}O$ values were not significantly correlated with elevation ($r = 0.338$, $P = 0.631$, $n = 24$) in this study; however, $\delta^{18}O$ of Yunnan lake waters may be more influenced by surface-water evaporation and flushing rate than by elevation. $\delta^{18}O$ of Kunming rain was more ^{18}O-depleted than the weighted mean value previously reported for Kunming rain (–10.6‰; Rozanski and others 1993).

Hu Die Quang, the artesian spring, is ^{18}O-depleted compared with lake waters because surface-water evaporation from lakes leads to ^{18}O enrichment relative to groundwater sources. Despite Jin Kuai Shi's close proximity to Er Hai, its $\delta^{18}O$ value is more depleted than the lake. The similarity of Jin Kuai Shi's $\delta^{18}O$ value to rainwater is consistent with the observation that Jin Kuai Shi is a cistern that appears to be filled from a local, shallow aquifer.

The positive correlation between specific conductance and $\delta^{18}O$ values suggests that evaporation concentrates both solutes and ^{18}O in Yunnan lakes. Enriched $\delta^{18}O$ values in Qilu Hu, Xingyun Hu, and Yilong Hu, which are large, shallow lakes in the southeastern part of the province, indicate that evaporative effects are significant in these basins. In contrast, ^{18}O-depleted waters in San Shou Shuiku and Zhi Bi Hu suggest that solutes are not concentrated by evaporation in these small, deep lakes. Rapid surface water flow through the San Shou Shuiku impoundment may also preclude ^{18}O enrichment by evaporation. Depleted $\delta^{18}O$ values observed in Jian Hu, Cao Hai, and Wen Bi Hai suggest that these small, shallow lakes receive substantial rainwater inputs relative to their small volumes during the monsoonal season when they were sampled.

Cheng Hai is distinctive from other Yunnan lakes in several ways. The principal cation in Cheng Hai is Na^+ rather than Ca^{2+} or Mg^{2+}, and the lake has a significantly higher concentration of HCO_3^- than other Yunnan lakes. $\delta^{18}O$ in Cheng Hai surface waters is more positive than in all other study lakes. Heavy isotopic values and high ionic content suggest that much of the recent 5-m water-level decline in Cheng Hai (Wang 1989, personal communication 1994) is related to evaporation, rather than a change in surface or subsurface outflows. Cheng Hai's shift in water balance in recent decades, however, does not reflect a regional trend. Cheng Hai may have been subject to recent diversion of surface inflows that reduced the input of ^{18}O-depleted fresh water. Water that is hydraulically removed from Cheng Hai for irrigation may become salt-enriched by evaporation in rice paddies and contribute to increased water-column salinity when it is flushed back to the lake.

Higher nutrient concentrations in shallow lakes provide evidence that deforestation, agricultural cultivation, and soil erosion have had considerable impact on water quality. Sediment and nutrient accumulation rates show that delivery of non-carbonate, clastic sediments and phosphorus eroded from watersheds increased 15–20 fold in shallow Yunnan lakes during recent centuries (Whitmore and others 1994). High inorganic sediment deposition may account for the low organic matter content observed among Yunnan lakes. In some shallow lakes, light penetration may be restricted in part by suspended silt and clay particles. Historical impacts on some large lakes, such as Er Hai, have been less profound (Whitmore and others 1994), although recent studies document some change in water quality (Jin and others 1990). Despite Dianchi's large size, limnetic nutrient concentrations and cyanobacterial blooms indicate considerable disturbance. Preliminary evidence suggests that accelerated sediment loading to Dianchi, because of its proximity to Kunming, exceeds that of smaller, disturbed lakes in the region (Whitmore and others 1994). This study shows little evidence for heavy metal contamination in Yunnan lakes with the possible exceptions of Dianchi and Cui Hu, which are both subject to the industrial influence of Kunming.

Yunnan lakes have been subjected to considerable anthropogenic influence because their watersheds have a long history of human occupation. Rice agriculture was widespread by 4000 B.P. (Li and Walker 1986), and terracing was practiced beginning circa 1740 B.P. (Sun and others 1986). Yunnan's current population exceeds 31 million, and many lakes in the region are severely affected. Qilu Hu, for instance, receives untreated wastewater from 39 factories, including fertilizer, electroplating, textile, dyeing and food-processing plants. It also receives 1.5×10^6 tons of domestic sewage each year (Jin and others 1990). Between 1957 and 1984, forest cover in Qilu Hu's watershed declined from 30% to 12%. Farmlands in the watershed currently receive 15 000 tons of fertilizer and 160 tons of pesticides per year. Increased runoff to Qilu Hu from this deforestation is likely to have increased the deposition of silts that carry these applied nutrients and pesticides (Golterman and others 1983). Limnologists in China indicate that environmental problems result from contradictions between ecological and economic interests (Sandbach 1980; Yu 1989). Lakes such as Dianchi, near Kunming, are seen as vital for social and economic development (Lu 1989a). Good water quality in Lugu Hu is considered favorable for development of industry, agriculture, and fisheries (Pan and others 1989). Environmental protection in China is viewed as a means of conserving resources that can be exploited and utilized for economic development. Poor management of lakes and watersheds is considered to be a hindrance to social advancement (Yu 1989). Yunnan scientists blame excessive emphasis on economic development for water pollution, infilling of lakes, and disruption of water balance caused by hydroelectric production (Lu 1989a; Jin and others 1990). Environmental protection of Yunnan lakes will require the formulation of environmental policies that balance ecological considerations with economic interests.

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