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EUTROPHICATION IN LAKES

Environmental issues of Lake Taihu, China

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Abstract Lake Taihu is characterized by its shallowness (mean depth = 1.9 m) and large surface area (2,338 km^2). Runoff sources are mostly from the mountainous west and southwest, and outflows are located throughout East Taihu. This causes shorter retention times in the south. In contrast, urban pollutants discharge into northern Taihu and result in poor water quality. Non-point pollution from rural areas and sewage wastewater is the primary pollution source. Water current velocity ranges from 10–30 cm s^{-1}, and surface currents normally follow wind direction. Bottom currents appear to be a compensation flow. Most wave heights are less than 40 cm, and underwater irradiance correlates to seston in the water column. Lacustrine sediment is distributed in littoral zones, mostly along the western shoreline, with almost no accumulation in the lake center. Intensive aquaculture in East Taihu caused eutrophication and hampered water supply in surrounding areas. In addition, development of marshiness in the eastern littoral zones and East Taihu has occurred. The function of flood discharging of East Taihu has been limited by flourishing macrophytes. The problems facing in Lake Taihu will be alleviated by improving the management of nutrient sources into the lake.

Keywords Lake Taihu · Hydrography · Water quality · Eutrophication · Aquaculture

Introduction

Lake Taihu is situated in the Changjiang (Yangtze) delta, the most industrialized area in China with high population density, urbanization, and economic development. Although Taihu Basin occupies only 0.4% of China's territory and 3% of China's population, it contributes about 10% of Gross National Product (GNP) and 15% of province revenues (NSB, 2000; SBSC, 2000; SBZP, 2000; SBJP, 2000). Lake Taihu is important for water supply, flood control, tourism and recreation, shipping and aquaculture. It is the drinking water source for several cities, such as Shanghai, Suzhou, Wuxi, and Huzhou. Since 1980's, however, economic development has resulted in pollutants being produced and discharged into rivers and the lake. With the deterioration of water quality, eutrophication and algal blooms (*Microcystis* spp.) have occurred. Recently, the algal bloom has extended its

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Eutrophication of shallow lakes with special reference to Lake Taihu, China

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coverage and persists throughout the summer, which affects the function of the lake as a drinking water supply. In 1996, the Chinese government targeted pollution and eutrophication control before 2000 and 2010. Factories within the watershed now must treat wastewater before it is discharged to rivers. Also, rivers flowing into Lake Taihu should meet grade III standards (National Surface Water Quality Standard GB3838-2002) before 2000, and lake water should be clarified before 2010. However, lake water quality has not improved to date, and, in 2001, pollution control work was reevaluated and redirected. In fact, problems facing Lake Taihu are similar to most freshwater lakes in eastern China. Based on field investigations and literature review, this paper attempts to review and address main eco-environmental issues in Lake Taihu.

General description of the lake

Lake Taihu is the third largest freshwater lake in China and is located between 30°55′40″–31°32′58″ N and 119°52′32″–120°36′10″ E. Lake length (from north to south) is 68.5 km and width (from east to west) is 56 km. Mean depth is 1.9 m, and maximum depth is 2.6 m corresponding to an elevation of 3.0 m above sea level. The lake bottom features flat terrain with an average topographic gradient of 0°0′19.66″ and elevation of 1.1 m above sea level. Shallow-water area with mean depth <1.5 m is about 452 km^2, mostly in East Taihu, accounting for 19.3% of the total surface area. Deepest areas (>2.5 m) are in the north and west occupying 197 km^2 or 8.4% of the total lake area.

Origin of the lake

Many researchers have discussed the origin and history of Lake Taihu (Wang & Ding, 1936; Wissman, 1941; Chen et al., 1959; NIGLAS, 1965; Yang et al., 1985; Yan & Xu, 1987; Sun et al., 1987; Sun & Huang, 1993; Huang, 2000; Sun, 2004). In general, Lake Taihu probably was an ancient lagoon, as suggested by its location in the Changjiang delta where solid particles have been transported and deposited in the transitional estuarine zone. Evidence of marine sediment materials found in drill cores supported this assumption (Chen et al., 1959). Continental shelf extension resulted in enclosing of the lagoon and it eventually became a freshwater lake (Chen et al., 1959; Yang et al., 1985; Yan & Xu, 1987). Recently, new evidence from stratigraphy and archaeological sites suggest that Taihu originated from extreme flooding. Flood water discharged by man-made channels was retained in the depression (Sun & Huang, 1993; Sun, 2004).

Hydrology of the lake

Lake Taihu has a complicated river and channel network. There are 172 rivers or channels connecting to the lake (Xu & Qin, 2005). The total length of rivers in Taihu basin is ca. 12,000 km, i.e., about 3.24 km km^{-2}. During flooding season (spring and summer), flooding runoff from the west or southwest goes through lake to the east and empties into the East China Sea (Fig. 1). In the dry season (autumn and winter), however, water flow can reverse, especially in rivers in the east. Generally, rivers in the west of the lake are defined as upstream and vice versa. Runoff is defined as positive or negative. Table 1 shows the runoff of main rivers flowing into or out of the lake from May 2001 to April 2002. The greatest inflow rivers are Chendonggang, Xitiaoxi, and Yincungang. Three are located in the west or southwest watershed. The main outflow rivers are Taipu, Xinyunhe, and Xijiang located in the southeast (Table 1). Table 2 shows the monthly distribution of runoff from May 2001 to April 2002. Some rivers flow into the lake year-round, some flow out all year, and some reverse flow direction in different seasons (Table 2). There is no definitive estimate of water balance yet because of the complicated hydraulic connections between rivers and the lake. Table 3 is a rough estimate of water balance based on surveys of 115 rivers from May 2001 to April 2002. Flowing water from these rivers account for 90% of total runoff input and output, but the measuring frequency was insufficient because measurements were taken once in normal months and twice in

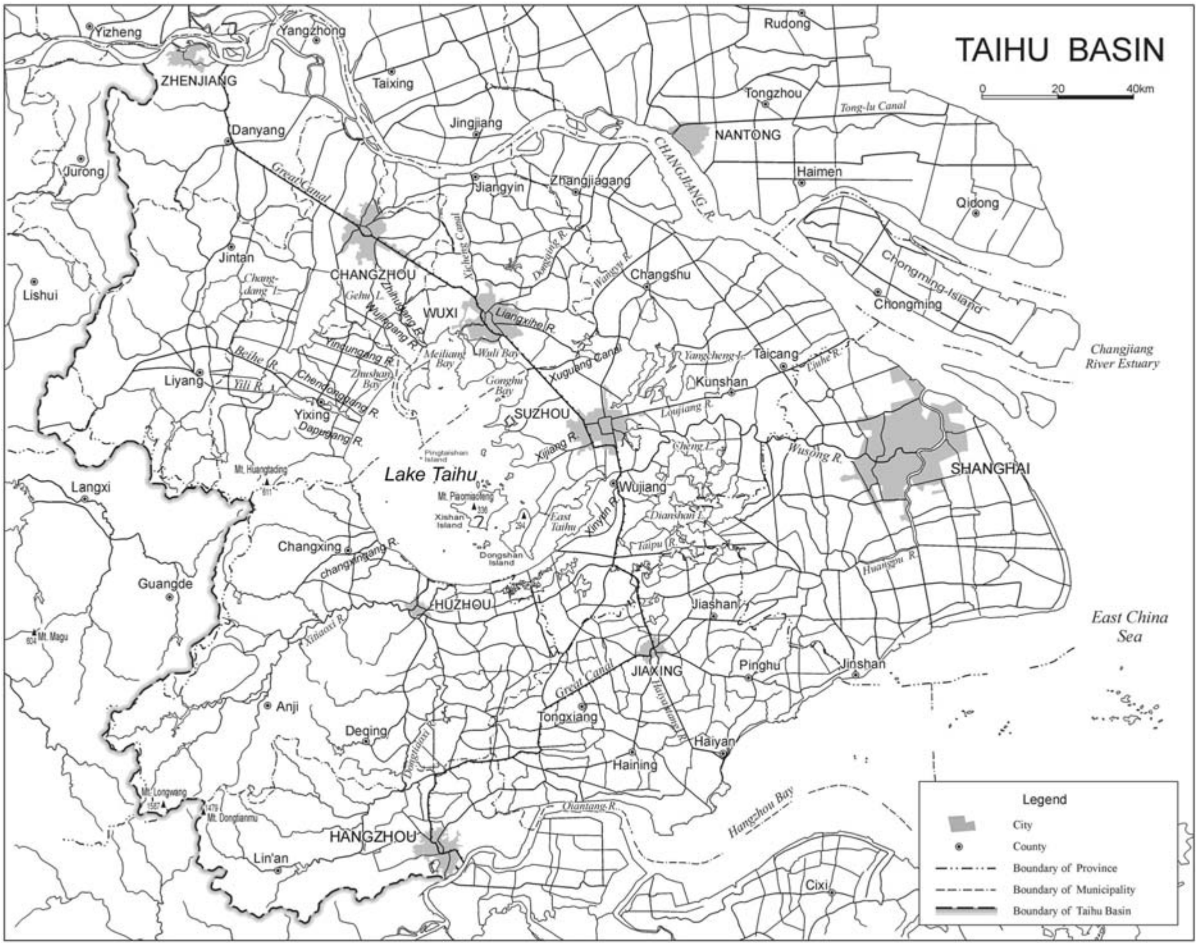

Fig. 1 Sketch map of Taihu Basin

flooding months. Annual runoff input, output, and water balance from May 2001 to April 2002 is estimated based on the measurement (Table 3). This water balance represents more flooding years versus the multi-year averaged water balance (Mao et al., 2004). Water retention time is about 5 months, but it is shorter in the south since most runoff water is discharged via the Taipu River, in the southeast. Water quality, therefore, is better in the south than in the north.

Hydrodynamics

There still is not a complete understanding of water currents in Lake Taihu. Earliest measurements were made in 1960, when two boats cruised around the lake at the same speed (NIGLAS, 1965). Other measurements were made in 1986–1987 (Sun & Huang, 1993) and summer in 1997 (Qin et al., 2000). These measurements were incomplete and incomparable since records were collected on different dates or at different sites. In summer, prevailing winds from the southeast or southwest generate a counter-clockwise water current in western Taihu centered near Pingtaishan Island (Fig. 2). Current velocity ranged from 10 cm s^{-1} to 30 cm s^{-1} (Qin et al., 2000). There was a stable southward current along the western coast and a weak and unstable current in Meiliang Bay (Fig. 2). This current pattern was reproduced by a numerical simulation under the same conditions (Luo & Qin, 2004; Hu et al., 2004). Regardless of season, there is a weak counter-clockwise current in northern Meiliang Bay (Qin et al., 2000; Luo et al., 2004a, b), which may explain

Table 1 Inflow and outflow of main rivers around Lake Taihu during May 2001 to April 2002 (if the sum of number of days of inflow and outflow less than 365, the remainder is days of no flow)

River	Inflow				Outflow				Annual runoff (10^8 m^3)
	Days	Mean daily inflow rate (m^3 s^{-1})	Mean inflow rate (m^3 s^{-1})	Total inflow (10^8 m^3)	Days	Mean daily outflow rate (m^3 s^{-1})	Mean outflow (m^3 s^{-1})	Total outflow (10^8 m^3)	
Xitiaoxi R.	234	273.0	34.9	7.05	125	–57.8	–12.79	–1.38	5.67
Dongtiaoxi R.	118	400.0	71.5	7.29	247	–122.0	–45.37	–9.68	–2.39
Changxingang R.	301	61.0	6.8	1.76	64	–10.4	–2.21	–0.12	1.64
Chendonggang R.	338	147.0	34.2	9.98	26	–38.7	–10.07	–0.23	9.76
Yincungang R.	347	72.9	18.5	5.56	18	–14.8	–5.47	–0.09	5.47
Wujingang R.	339	49.8	6.6	1.95	26	–7.1	–2.89	–0.06	1.88
Zhihugang R.	244	78.1	8.3	1.75	27	–14.1	–5.56	–0.13	1.62
Liangxihe R.	174	60.7	11.8	1.78	60	–23.3	–9.58	–0.50	1.28
Wangyu R.	116	240.0	82.8	8.30	249	–177.0	–44.10	–9.49	–1.19
Xinyun River	32	33.1	15.4	0.43	333	–183.0	–31.47	–9.05	–8.63
Dapugang R.	14	4.2	2.7	0.03	348	–14.2	–5.78	–1.74	–1.71
Xijiang R.	7	16.5	8.7	0.05	358	–44.3	–18.72	–5.79	–5.74
Xuguang Canal	38	7.7	3.3	0.11	290	–27.3	–8.03	–2.01	–1.91
Taipu River	8	73.2	27.5	0.19	357	–296.0	–119.47	–36.85	–36.66

Table 2 Monthly runoff rate of rivers around Lake Taihu during May 2001 to April 2002 (m^3 s^{-1}) (inflow is defined as positive and outflow is defined negative)

River	2001								2002				Yearly Average
	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	
Xitiaoxi R.	8.8	49.3	22.0	57.0	–9.4	–1.7	–6.3	6.8	7.9	–4.1	28.5	55.6	17.9
Dongtiaoxi R.	–2.2	80.6	–5.9	8.2	–76.7	–45.6	–54.5	–20.3	–15.1	–31.0	9.6	61.1	–7.7
Changxingang R.	3.7	10.7	6.6	10.3	1.1	0.1	1.0	3.6	3.1	1.2	9.8	11.0	5.2
Chendonggang R.	15.7	44.8	33.1	67.1	31.1	26.4	24.7	32.0	22.2	12.7	37.4	22.3	30.8
Yincungang R.	14.8	28.8	11.9	37.2	18.9	15.4	14.0	19.3	10.0	7.1	18.4	11.6	17.3
Wujingang R.	4.5	11.2	4.9	11.7	5.5	4.9	5.8	4.2	3.1	4.2	7.0	4.6	6.0
Zhihugang R.	5.7	13.4	0.1	12.9	5.4	3.9	2.9	2.1	0.9	2.9	9.0	2.4	5.1
Liangxihe R.	5.9	14.1	–5.8	2.6	3.6	10.3	5.8	10.4	1.6	0	0	0	4.0
Wangyu R.	12.0	–12.4	–87.4	–48.5	–41.6	15.0	–12.8	–18.0	–37.2	115.0	116.0	–36.5	–3.0
Xinyun R.	–23.4	–47.4	–34.3	–24.8	–22.0	–31.3	–26.6	–28.7	–30.9	–21.8	–15.8	–21.1	–27.3
Dapugang R.	–2.7	–2.0	–5.9	–5.2	–5.5	–5.3	–6.5	–8.4	–9.5	–5.5	–5.8	–2.4	–5.4
Xijiang R.	–10.7	–9.3	–27.4	–27.9	–25.2	–17.6	–17.0	–15.3	–17.4	–14.0	–18.5	–17.6	–18.2
Xuguang Canal	–1.6	0.2	–10.5	–12.4	–10.2	–4.7	–6.1	–3.9	–7.3	–2.2	–7.7	–5.6	–6.0
Taipu R.	–49.6	–84.9	–132.0	–135.0	–125.0	–85.4	–107.0	–127.0	–118.0	–116.0	–160.0	–156.0	–116.3

Table 3 The water balance of Lake Taihu during May 2001 to April 2002

Input runoff (10^8 m^3)	Output runoff (10^8 m^3)	Precipitation (10^8 m^3)	Evaporation (10^8 m^3)	Change in capacity (10^8 m^3)	Inflow from uncontrolled areas and river net (10^8 m^3)
80.11	–96.67	27.19	–17.71	–5.38	12.46

why this area is favorable for concentrating algal blooms (Qin et al., 2000).

In July 2003, an Acoustic Doppler Current Profiler was deployed at the center of Meiliang Bay, and 10-min interval current velocity and direction data from 11 layers were collected. Surface currents followed the direction of wind forcing (Fig. 3a), but current velocity attenuated

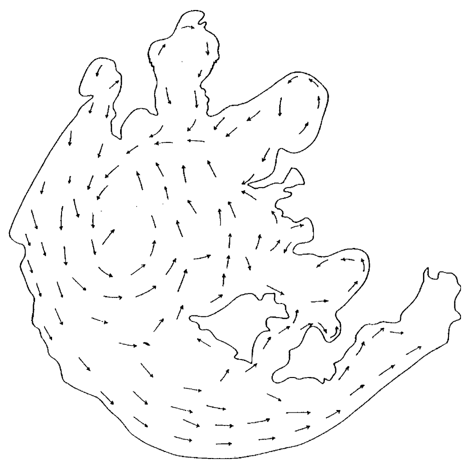

Fig. 2 The prevailing current pattern during the summer, the velocity of current ranged from 10 cm s^{-1} to 30 cm s^{-1}

with depth and reversed direction at the bottom (Fig. 3b). This indicates that there is a compensation current at the bottom opposite wind forcing on the surface (Fig. 3b).

Wave action is a key factor in interactions between the sediment and water (Qin et al., 2004).

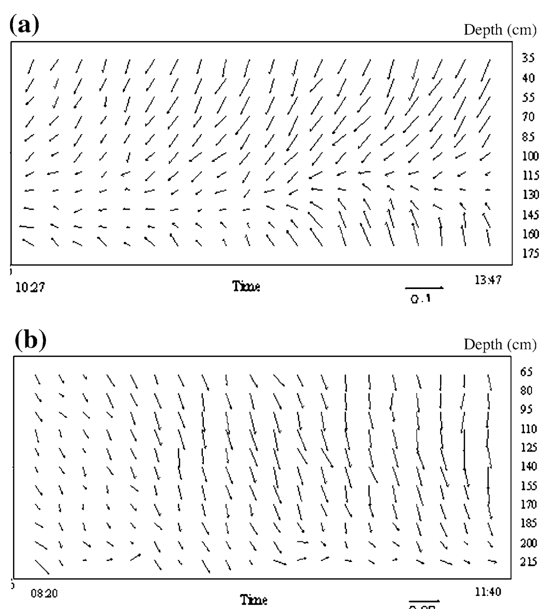

Fig. 3 (**a**) Current vectors at 35, 40, 55, 70, 85, 100, 115, 130, 145, 160, 175 cm below surface (water depth is 2.4 m) at 10-min intervals in Meiliang Bay during 10:27–13:47 on 14 July 2003. (**b**) Current vectors at 65, 80, 95, 110, 125, 140, 155, 170, 185, 200, 215 cm below surface (water depth is 2.4 m) at 10-min intervals in Meilaing Bay during 8:20–11:40 on 17 July 2003

In August 1986, a continuous observation of waves was made in the northwest (Wu et al., 1987). Statistical analyses with cumulative frequency of one-third highest wave height ($H_{1/3}$) and maximum wave height (H_{max}) showed that most waves were low in height with 80% of $H_{1/3} < 8$ cm, 98% of $H_{1/3} < 20$ cm, and 5% > 40 cm (Wu et al., 1987). From field observations, the empirical relationship among average wave height ($\overline{H}$), wind speed (W), wind fetch (F), and period (T) was derived as follows (Hu et al., 2004):

$$\frac{g\overline{H}}{W^2} = 0.00168\left(\frac{gF}{W^2}\right)^{0.46}$$

If water depth was assumed not to change, then wave height was proportional to wind speed (Hu et al., 2004):

$$\overline{H} = 5.497W^{0.5} - 4.516$$

Similarly, the relationship between maximum wave height (H_{max}) and wind speed can be expressed as (Wu et al., 1987):

$$\frac{gH_{max}}{W^2} = 0.1094\left(\frac{gD}{W^2}\right)^{0.7508}$$

$$H_{max} = 5.237 \times 10^{-2}\ W$$

Underwater light climate

Lake Taihu is a shallow and eutrophic lake, and Secchi depths are normally low, i.e., about 30–40 cm in the north and 40–50 cm in the south (Qin et al., 2004; Zhang et al., 2004a). Based on water quality monitoring conducted by Taihu Laboratory for Lake Ecosystem Research (TLLER), transparency is related to seston abundance (Fig. 4):

$$S^{1/4} = 8.103 - 5.847\ln ST$$

$$(R = 0.87,\ SD = 0.32,\ N = 135,\ P < 0.0001)$$

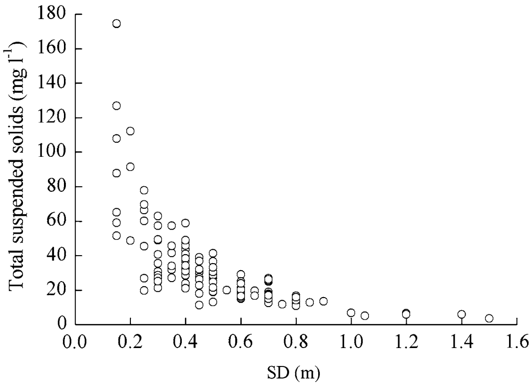

Fig. 4 The relationship between the solid suspension and secchi depth (SD) in Lake Taihu

where *S* is seston abundance (mg l^{-1}), *ST* is secchi depth (m). Correlation and regression analysis based on measurements of light attenuation and seston, including inorganic and organic seston, and chlorophyll-*a* showed that inorganic solids were important in autumn, whereas organic solids were important in summer, especially in the north (Zhang et al., 2004b). Correlation analysis also indicated that chlorophyll was not a large factor on light attenuation (Zhang et al., 2004b).

Underwater irradiance measurements show that daily light distribution at specific depth followed solar radiation, i.e., increase in the morning and decrease in the afternoon (Fig. 5) (Zhang et al., 2004b). Irradiance at 1 m was about 10% of that at the surface (Fig. 5). Ultraviolet (UV) radiation, which is harmful for phytoplankton growth, was attenuated rapidly, i.e., UV-B at 20 cm was about 1% of surface levels (Zhang et al., 2004b). Short-wave irradiance, therefore, is attenuated faster than long-wave irradiance in this lake.

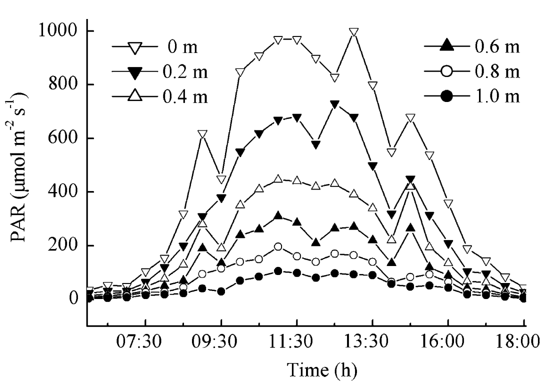

Fig. 5 Daily variations of underwater irradiance at different depth (0.0, 0.2, 0.4, 0.6, 0.8, 1.0 m under the surface) at the site nearby Taihu Laboratory for Lake Ecosystem Research (TLLER) on May 17, 1998

Sediment in Lake Taihu

Spatial and vertical distribution of lacustrine sediment was investigated at 723 sites in Lake Taihu. Successive correction schemes and geostatistical methods were used to determine sediment thickness in the 69 × 69 whole lake grids. Spatial statistical analysis revealed that sediment covers about 1,100 km^2 of lake bottom, which accounts for about 47.5% of lake area (Fig. 6) (Luo et al., 2004a, b). Total volume of lacustrine sediment is estimated to be 1.86×10^9 m^3 (Luo et al., 2004a, b), and, in most regions, lacustrine sediment depth was 0.5–2.0 m (Luo et al., 2004a, b). Most lacustrine sediments are distributed along the western shoreline from Meiliang Bay to the south. There is little lacustrine sediment in the center of the lake (Fig. 6).

Dating sediment at different depths from drill cores showed that sedimentation rates range from 0.6 mm $year^{-1}$ to 3.6 mm $year^{-1}$ with an average of 2 mm $year^{-1}$ (Fan et al., 2004). Bulk density of surface sediment is 1.2 g cm^{-3} with lowest bulk density from East Taihu and highest from the western lake (Fan et al., 2004). Organic matter content ranges from 0.13% to 16.6% with maxima from East Taihu and minima from the center and west (Fan et al., 2004). TN and TP in sediments, range from 0.01% to 0.66% and 0.01% to 0.015%, respectively (Fan et al., 2004).

Pollution and eutrophication

In 1960, Lake Taihu was categorized as oligotrophic because total inorganic nitrogen (TIN), total inorganic phosphorus (PO_4^{3-}-P), and chemical oxygen demanded (COD_{Mn}) were low (Table 4) (NIGLAS, 1965). TIN increased dramatically until 1981 to about 18 times greater than that in 1960, COD_{Mn} increased by 49%, and PO_4^{3-}-P remained stable (Table 4) (Sun & Huang,

Fig. 6 Distribution of lacustrine sediment in Lake Taihu

Table 4 Change of water quality indexes since 1960's

Year	TIN (mg l^{-1})	TN (mg l^{-1})	PO_4^{3-}-P (mg l^{-1})	TP (mg l^{-1})	COD_{Mn} (mg l^{-1})	Sources
1960	0.05		0.02		1.90	NIGLAS (1965)
1981	0.894	0.9	0.014		2.83	Sun & Huang (1993)
1988	1.115	1.84	0.012	0.032	3.3	Sun & Huang (1993)
1994	1.135	2.05	0.010	0.086	5.77	SEPA (2000)
1995	1.157	3.14	0.011	0.111	5.53	SEPA (2000)
1998[a]	1.582	2.34	0.007	0.085	5.03	TLLER
1999[a]	1.79	2.57	0.004	0.105	4.99	TLLER

[a] Data provided by TLLER

1993). From 1981 to 1998, TP and COD_{Mn} increased by 2.7 and 1.5 times, respectively (Table 4). Total nitrogen (TN), total phosphorus (TP), and chemical oxygen demand (COD_{Mn}) increased from 1.8, 0.03, and 3.3 mg l^{-1} in 1988 to 2.3, 0.085, and 5.03 mg l^{-1} in 1998, respectively (Table 4).

Table 5 shows quantities of pollutants which rivers transport into the lake. Most pollutant inflow rivers are located in the west or northwest, whereas pollutant outflow rivers are located in the south or southeast. Based on studies in 2002 and 2003, about 30–40% of nitrogen and phosphorus is retained inside the lake (Table 5).

Table 5 Nutrient flux of inflow and outflow of Lake Taihu during 2001–2002

	COD_{Mn} (ton)	NH_4^+-N (ton)	NO_2^--N (ton)	NO_3^--N (ton)	TN (ton)	TP (ton)
Inflow	37,571.06	12,431.70	1,007.86	10,469.12	28,657.97	1,029.37
Outflow	–35,431.36	–4,864.99	–379.77	–5,862.28	–14,599.90	–668.27
Inflow–outflow	2,139.70	7,566.71	628.09	4,606.83	14,058.07	361.10
Retention rate	5.7%	60.9%	62.3%	44.0%	49.1%	35.1%

Wastewater produced within the basin amounted to 2.25×10^5 t year^{-1} of COD_{Cr}, 4.13×10^4 t year^{-1} of TN and 3.8×10^3 t year^{-1} of TP in the 1980's (Sun & Huang, 1993), increasing to 2.82×10^5 t year^{-1} of COD_{Cr} and 8.0×10^4 t year^{-1} of TN and 5.66×10^3 t year^{-1} of TP in the early 1990's (SEPA, 2000), and increasing further to 7.46×10^5 t year^{-1} of COD_{Cr}, 1.09×10^5 t year^{-1} of TN and 1.56×10^4 t year^{-1} of TP in the late 1990's (Huang, 2004). However, pollutants discharged into the lake were less than the pollutants produced within the basin. About 1.06×10^5 t year^{-1} of COD_{Cr}, 2.0×10^4 t year^{-1} of TN and 1.55×10^3 t year^{-1} of TP in the 1980's were discharged into the lake (Huang et al., 2001). During the early 1990's, total pollutants discharged increased to 1.31×10^5 t year^{-1} of COD_{Cr}, 3.1×10^4 t year^{-1} of TN and 1.75×10^3 t year^{-1} of TP (SEPA, 2000). In the late 1990's, the COD_{Cr} empting into the lake increased to 1.71×10^5 t year^{-1}, but TN and TP decreased to 2.5×10^4 t year^{-1} and 1.3×10^3 t year^{-1}, respectively (Huang, 2004). During the early 2000's, inputs of COD_{Mn}, TN, and TP were 3.76×10^4 t year^{-1}, 2.87×10^4 t year^{-1} and 1.03×10^3 t year^{-1}, respectively (Table 5) (Xu & Qin, 2004), which are much lower than earlier estimates. These results varied among different investigators, but pollutants empting into the lake probably increased in the early 1990's and decreased in the late 1990's. This change may relate to increased wastewater treatment in surrounding areas.

Analysis of pollutant composition in wastewater in 1994 showed that 16% of total nitrogen (TN) was from industrial sources, 25% from domestic sewage, and 38% from non-point sources (agriculture production) (SEPA, 2000). For total phosphorus (TP), 10% was from industry, 60% from sewage, and 15% from non-point sources (SEPA, 2000). For COD, 39% was from industry, 42% from sewage, and 10% from non-point sources (SEPA, 2000) (Table 6). In 1998, industrial pollution to the lake, decreased dramatically either in total COD, or TN and TP (Table 6), whereas the contribution from agriculture to COD and TN increased significantly and sewage pollution contributed 70% of TP (Table 6). This change in pollution composition reflects rapid economic growth and land use alteration.

Based on data from 1998, pollutants produced by industry were mainly from the east or southeast of the lake basin, such as Suzhou, Wuxi, and Jiaxing (Huang, 2004). Pollutants from agriculture (cropping, rice growing, etc.) accounted for 37% of COD, 49.5% of TN and 48% of TP produced in the basin (Huang, 2004). These non-point pollutants came mostly from the west. In addition, poultry culture scattered in the rural region accounted for 5% of COD, 6% of TN, and 18% of TP (Huang, 2004). Fish culture made up 5.5% of COD, 5.2% of TN, and 4.1% of TP. With strengthening control of point sources, the contribution from non-point sources, i.e., agriculture and animal culture, likely will increase with time.

Aquaculture in the lake

The main form of aquaculture in Lake Taihu is pen-fish-culture. Aquaculture has been limited to East Taihu, a macrophyte-dominated bay in the southeast part of the lake with an area of

Table 6 Comparison of composition of different pollution sources in COD, TN, and TP in 1994 and 1998

Year	Pollution source	COD_{Cr}		TN		TP	
		Amount (ton)	Percentage (%)	Amount (ton)	Percentage (%)	Amount (ton)	Percentage (%)
1994	Industry	111,061	39	12,544	16	591	10
	Domestic	119,029	42	19,948	25	3,394	60
	Agriculture	28,138	10	29,842	38	852	15
	Aquaculture			13,195	17	533	9
1998	Industry	93,822	26	2,686	4	191	2
	Domestic	96,782	27	16,232	25	6,510	70
	Agriculture	91,582	25	17,815	28	1,362	15
	Aquaculture	49,627	14	17,750	28	733	8

126 km^2. Although the documented area of pen-fish-culture was 2,830 ha (Chen & Wu, 2004), field observations reveal that almost the entire water surface of East Taihu is occupied by net pens. Fish culture in this area has raised some environmental problems. East Taihu is a shallow bay with 95% coverage by macrophytes. In 1993, annual macrophyte production in East Taihu was 1.12×10^6 t, which accounts for 3,920 tons of nitrogen and 496 tons of phosphorus (Wu et al., 1995; Yang & Li, 1996), corresponding to 58% and 95%, respectively, of total external loading to East Taihu. About 60×10^4 t of macrophytes were harvested for fish farming resulting in removal of 1,890 t of nitrogen and 296 t of phosphorus, corresponding to 28% and 57%, respectively, of total external loading to East Taihu (Wu et al., 1995; Yang & Li, 1996). Harvesting of macrophytes now is blocked due to the proliferation of net pens. Consequently, the lake lost an important pathway for nutrient export. This loss has promoted sedimentation and eutrophication in East Taihu (Table 7). Aquaculture activities also contribute to increases in nutrient loading and eutrophication. It is estimated that producing 1 ton of fish requires 141 kg nitrogen and 14 kg phosphorus (Yang & Li, 1996; Wu et al., 1995; Li, 1998), and about 65% of each is not assimilated and is subsequently released into the overlying water (Yang & Li, 1996). In pen-fish-culture areas, increased nutrient loading leads to rapid growth of phytoplankton, zooplankton, and bacteria. After one year of fish farming, the phytoplankton abundance was three times higher than in non-culture areas, and heterotrophic bacteria abundance increased 3- to 4-fold (Wu et al., 1995). Total organic carbon, total nitrogen, and total organic nitrogen in surface sediments increased by 141, 87.5, and 86%, respectively, after 2 years of fish culturing (Li, 2004). Recently, fish culturing has been replaced by the more profitable freshwater crab culturing, which will increase the input of feed, and further increase the deposit of organic materials from the remnants of feed. Because fish culture will make use of macrophytes for fish food, the lake will output the nutrients and retard the development of marsh in this way. In turn, the recent aquaculture aggravates the deterioration of water quality and degradation of ecosystem.

Table 7 Changes in water quality parameters in East Taihu in 1990's

Year	TN (mg l^{-1})	NH_4^+-N (mg l^{-1})	NO_3^--N (mg l^{-1})	TP (ug l^{-1})	COD_{Mn} (mg l^{-1})
1991	1.01	0.14	0.32	43	5.5
1993	1.04	0.20	0.25	75	5.6
1997	1.39	0.19	0.10	31	5.5
1999	1.65	0.475	0.23	40	6.6
2000	1.08	0.26	0.30	100	6.4

Marsh development

Marsh development mainly takes place in the eastern shoreline areas, i.e., East Taihu, Xikou Bay, and Gonghu Bay. Figure 7 shows the expansion of spatial macrophyte distribution (TBA & NIGLAS, 2000). From Fig. 7, macrophytes have extended from East Taihu in the 1960's (Fig. 7a) to Xikou Bay and Gonghu Bay in the 1980's (Fig. 7b). Marsh development in East Taihu is more serious in East Taihu because it also functions as a flood discharge area and drinking water supply for Suzhou and Shanghai. These functions, however, are hampered by marsh development. Generally, marsh development in lakes results from organic or inorganic material deposition, which elevates the lake bottom, decreases water capacity, and eventually leads to elimination of the lake (Li, 2004).

According to field investigations and TM satellite image data in 1997, 95% of East Taihu is covered by aquatic vegetation. Dominant species include *Potamogeton maackianus, Vallisneria natan*s, and *Zizania latifolia*. Average macrophyte biomass in East Taihu is about 3.8 kg m^{-2} with a range of 2.0–5.6 kg m^{-2} (Li, 2004). Total standing biomass of aquatic plants in Lake Taihu is about 500,000 t, and *Potamogeton maackianus* accounted for 42%, *Zizania latifolia* 29.5% and *Vallisneria natan*s 0.2% (Li, 2004). Floating-leaf and emergent vegetation, such as *Zizania latifolia*, indicate accelerated marsh development in East Taihu (Li, 2004).

Since East Taihu is the major outlet of Taihu Lake, particles are transported and deposited in

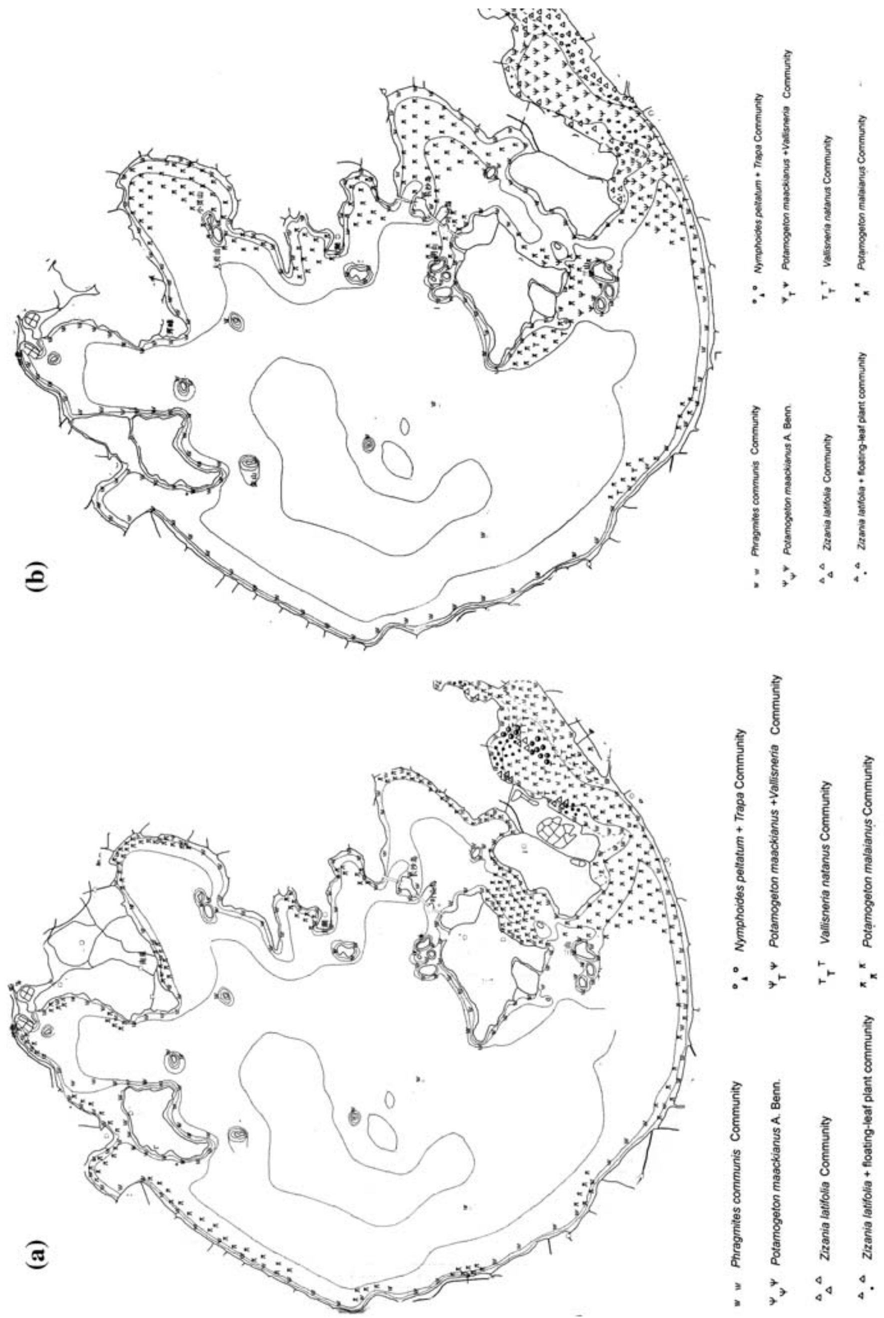

Fig. 7 Spatial distribution of macrophytes in 1960's **(a)** and in 1980's **(b)**

East Taihu. Macrophytes reduce water flow velocity and, hence, increase silting. Investigation of sediment distribution in East Taihu showed that the top 1 m of sediment was soft and composed of sand (98%) and organic materials (1.5%) (Li, 2004). Sediment composition showed that most deposit materials were allocthonous. Thus, increased sedimentation rates and marsh development may be attributed to pen-fish-culture, since it limited macrophyte harvest, promoted succession from submerged to emergent and floating-leaf vegetation, inhibited water movement, and augmented deposition of macrophyte detritus and other particles.

Management

Lake Taihu has many functions, including drinking water supply, flood water retention, fisheries, tourism and shipping. These varied functions have resulted in multi-purpose-oriented management without sufficient coordination. Over-exploration and over-utilization caused degradation of the lake ecosystem and deterioration of water quality, since some functions are contradictory, such as water supply and fish culture. Development of a centralized-management system, therefore, should be considered to decelerate eutrophication and marsh development, restore the ecosystem, and improve water quality. Regulations and administrative policies should be enacted, e.g., reclamation should be forbidden and fish-culture should be limited in spatial distribution. A long-term plan for pollution and eutrophication control should be based on accurate prediction of economic development and contaminant sources. Watershed management should be planned and implemented aiming at pollution source control. Scientific research should be emphasized and focus on internal loading from sediment, water and nutrient budgets, and ecological restoration in the littoral zone.

Conclusion

1. Lake Taihu has a complicated inflow and outflow system. Water retention time is shorter and water quality is better in the south or southeast, whereas retention time is longer and water quality is worse in the north or northwest.
2. Major pollutants are mostly from the western watershed. Most COD input is balanced by river output, and about 30–40% of nutrient input is retained in the lake. Most pollution is from non-point agriculture production and domestic sewage.
3. Light attenuation is associated with suspended solids, which is related to wave forcing. Most sediments are distributed in the littoral zone, especially along the western shoreline.
4. Aquaculture in East Taihu increases nutrient concentrations in water and sediments, which accelerates eutrophication and marsh development. Swamping in East Taihu results from macrophyte success, which increases sedimentation rate, reduces the ability of flooding water passing through the system and quickens the tempo of extinguishment of the lake.

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