Chapter 4
Sediment–Water Exchange and Its Significance

4.1 Sedimentation Rate and Distribution of Sediment

Guangwei Zhu

Throughout the history of lakes, inorganic and organic matter, nutrients, and pollutants from within the lake, from rivers, and from the air in the watershed deposit new layers of sediments through physical, chemical, and biological processes such as flocculation and deposition. At the same time, sediments release nutrients to the water; this is the internal source of nutrients in lakes. The distribution and properties of sediments are closely related to the distribution, growth, and population sizes of hydrophytes and benthos.

Therefore, study of the distribution and properties of lake sediments helps us to understand the hydrological characteristics, ecosystem, and pollution status of lakes and their catchments. Such studies play an important role in quantifying the development of lake ecosystems, through understanding lake sediments, the laws governing exchange of materials across the sediment–water interface, and the effects of environmental factors, such as hydrodynamic processes, on this exchange of materials.

The role of sediments in oceans, lakes, and rivers as reservoirs of nutrients and pollutants is one of the most important topics of aquatic environmental studies. However, most studies have been focused on seasonal variation of the conversion between "sources" and "sinks" of sediments, the effects of sediments on adsorption and deposition of pollutants, and measurement of fluxes of nutrients and pollutants across the sediment–water interface using geochemical balance techniques. Few studies have considered the effects of hydrodynamic processes on the exchange of materials across the sediment–water interface and on the development of aquatic environments. In large and shallow Lake Taihu, hydrodynamic processes could strongly influence the release and/or adsorption of nutrients to sediments. Sediment resuspension driven by wind waves and lake currents has important effects on the

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exchange of materials across the sediment–water interface, on nutrient cycles, and on algae blooming in the lake. In recent years, the exchange of materials across the sediment–water interface in Lake Taihu has been studied from a hydrodynamic perspective because of the effects of hydrodynamic processes on both deterioration and restoration of lake ecosystems. Some important achievements have been made.

Lake Taihu has numerous bays and can be divided into many ecosystem types. Areas differ from each other in deposition conditions for suspended particulates, environmental conditions, and exchange of materials across the sediment–water interface. Therefore, the distribution, sedimentation rates, and deposition situation of sediments in different areas of the lake must be understood to study the exchange of materials across the sediment–water interface in the whole lake.

Since the 1970s, Nanjing's Institute of Geography and Limnology (Chinese Academy of Sciences) has made numerous investigations on the bottom sediment properties of Lake Taihu and has surveyed the sedimentation history of the lake using deep-boring, shallow-boring, and sub-bottom profilers. Previous investigations showed that sediments could be divided into two categories: (1) primeval sediments, which could be further divided into two types [(1a) loess-like silt clay, which is wind-deposited in the middle and lower reaches of the Yangtze River, transported by rivers, and redeposited in the Lake Taihu basin, and is common in the bottoms of Lake Taihu, the Yellow Sea, and the East China Sea; (1b) silt-like deposits in rivers and lakes, distributed along river courses or in shallow depressions on loess-deposition lands]; and (2) modern sediment, mainly including silt and clay, that is distributed in most of the lake areas, participates in material exchange across the sediment–water interface and other activities, and has an important effect on eutrophication in the lake (Sun & Wu, 1987). In recent years, the studies on sediments in Lake Taihu have focused on sedimentation rate and the distribution of sediment in relation to managing the lake environment.

4.1.1 Sedimentation Rate

Since the 1980s, the deposition rates of surface sediment in different areas of Lake Taihu have been measured many times using dating methods such as ^{210}Pb, ^{137}Cs, and ^{14}C dating (Sun & Wu, 1987; Chang & Liu, 1996; Qu et al., 1997; Xue et al., 1998). There have been great differences in deposition rates of sediment in different areas, especially in sediments formed in the past 100 years, because Taihu is a shallow lake with a large area, numerous bays, and complex ecosystem types. It must be pointed out that parts of the lake bottom might be erosion areas, while other parts may be depositing areas because of the shallowness and spatial heterogeneity of the lake.

4.1.1.1 Sedimentation Rate in the Past 15,000 Years

Qu et al. (1997) used ^{14}C to date sediment layers formed in the past 15,000 years using scintillation at the WT1 core in the south area of Mashan Hill in western Lake Taihu. The relationship between date and depth could be obtained from the four ^{14}C dates, specifically, $5,936 \pm 44$ years B.P. (50–60 cm) (B.P., before present), $7,899 \pm$

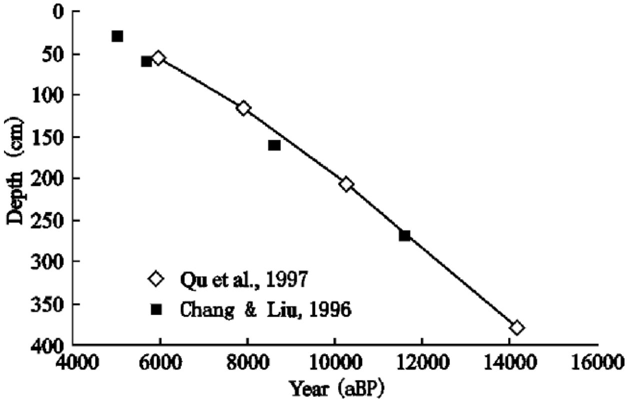

Fig. 4.1 Dates of sediment in a core from western Lake Taihu by the ^{14}C method

110 years B.P. (108–124 cm), 10, 299 ± 123 years B.P. (202–212 cm), and 14, 188 ± 865 years B.P. (374–384 cm) (Fig. 4.1). "Soft sediment" (which is easy to penetrate with a bamboo pole) at a depth of 50 cm was deposited 5,000 years ago, whereas at 100 cm it was deposited about 7,000 years ago, and at 2 m in western Lake Taihu, it was deposited about 10,000 years ago; this means that there was lowland with water-logged depressions 14,000 years B.P. (Xue et al., 1998). Chang & Liu (1996) showed that the age of surface sediments in Eastern Taihu Bay was 15,885 ± 170 years B.P. Other dating work showed that the history of loess sediments might be up to 11,240 years B.P. This sediment was not rock, but Quaternary loess, formed 14,000 years ago.

4.1.1.2 Sedimentation Rate in the Past 100 Years

The sedimentation rate in the past 100 years has been obtained using ^{210}Pb and ^{137}Cs dating methods at more than ten sampling locations (Table 4.1).

Sedimentation rates measured in 2002 were higher than in most previous years (Table 4.1) because sampling locations in 2002 were closer to the lakeshore than in previous years and were affected by human activities. For example, the sampling location in Wuli Bay was less than 200 m from the lakeshore. In contrast, the locations in northeastern Meiliang Bay, at Jiapu in southwestern Lake Taihu (with a large amount of sand input), and in Xukon Bay between Dongshan and Xishan Island, were 2.5 km, 3 km, and 4 km from the lakeshore, respectively. The data from the four locations in 2002 were all higher than those from the same locations in 1982, showing a recent trend towards increasing sedimentation in Lake Taihu. Moreover, it was estimated that the amount of sedimentation was about 2.35×10^6 t based on the sedimentation rates collected before 1990 (Sun & Huang, 1993). This value was much higher than that measured in 1954.

Table 4.1 Sedimentation rates of modern sediments in Lake (L.) Taihu

Locations	Year	Date range	Mean sedimentation rate (mm/yr)	Mean sedimentation fluxes (g/(cm^2 · yr))
Southeastern L. Taihu	1982	1927–1982	1.83	0.13
Northwestern L. Taihu	1982	1901–1982	1.11	0.08
Northeastern L. Taihu	1986	1920–1986	2.99	0.23
Dapu River mouth	1986	1885–1986	1.66	0.14
Meiliang Bay	1988	1931–1988	1.80	0.13
Gonghu Bay	1989	—	0.76	0.06
Northwestern L. Taihu	1992	—	0.60	0.05
Southern Meiliang Bay	2001	—	1.90	0.16
Wuli Bay	2002	—	3.1	/
Northeastern Meiliang Bay	2002	1922–2000	3.6	0.25
Jiapu, southwestern L. Taihu	2002	1911–2000	2.8	0.40
Xukou Bay	2002	1887–2000	2.5	0.34

Altogether, sedimentation rates ranged from 0.6 to 3.6 mm/yr, with a mean value of 2.1 mm/yr (Table 4.2), within the range for other large lakes in China and elsewhere (Table 4.2).

Previous dating data showed that silt deposition was extremely unstable. Sediments were disturbed violently, leading to coarsened sediments, decreased clay content, and decreased element content. For example, the quantity of sediments on the bottom of Gonghu Bay was recorded daily using sediment traps (Table 4.3). The maximum sedimentation during the survey was 9.23 kg/(m^2 · yr) on September 1, with another exceptionally high rate of 8.17 kg/(m^2·yr) recorded on September 29. The annual sedimentation rate at the same location was 0.76 mm/yr, with a mean value of 0.6 kg/yr or 0.0016 kg/(m^2·d). This value was ten times that obtained from sediment traps, which means that sedimentation rates can be extremely variable in shallow lakes, depending on weather conditions; bottom particles can be repeatedly disturbed, resuspended, transported, and redeposited in different places during strong wind-wave events.

There is a significant increasing trend of sedimentation in recent years in Eastern Taihu Bay. The sediment was from river and marsh deposits before 6,000 years

Table 4.2 Sedimentation rates in large lakes in the world (Sun & Huang, 1993)

Name of the lake	Depth (m)	Sedimentation rates (mm/yr)
Lake Taihu, China	2.6	0.6–3.6
Lake Poyang, China	16	2.0–2.5
Lake Dongting, China	5	25–35
Lake Chaohu, China	5	2.4
Lake Biwa, Japan	104	1.3–1.6
Lake Michigan, U.S.A.	400	1.8
Lake Constantine, Germany	300	1.2–1.4
Lake Tanganyika, Africa	1000	1.0–1.4
Lake Van, Turkey	450	0.4–0.9

Table 4.3 Daily sedimentation rates from traps in Gonghu Bay in September 1989

Date	Weight of sediments (g)	Mean deposition rate (kg/(m^2 · yr))	Date	Weight of sediments (g)	Mean sedimentation rate (kg/(m^2 · yr))
Sept. 1	9.34843	9.23	Sept. 16	0.29778	0.3
Sept. 2	5.09176	5.09	Sept. 17	0.35435	0.36
Sept. 3	0.65154	0.65	Sept. 18	0.65292	0.65
Sept. 4	0.14414	0.14	Sept. 19	0.30980	0.31
Sept. 5	0.08597	0.09	Sept. 20	0.17408	0.17
Sept. 6	0.13475	0.13	Sept. 21	0.09509	0.10
Sept. 7	0.09204	0.29	Sept. 22	0.11430	0.11
Sept. 8	0.08305	0.08	Sept. 23	0.02320	0.02
Sept. 9	0.08758	0.09	Sept. 24	0.13640	0.14
Sept. 10	0.09077	0.09	Sept. 25	0.03588	0.04
Sept. 11	0.09960	0.10	Sept. 26	0.01509	0.01
Sept. 12	0.06373	0.06	Sept. 27	0.00809	0.01
Sept. 13	0.06967	0.07	Sept. 28	0.02646	0.03
Sept. 14	0.09035	0.09	Sept. 29	8.16604	8.17
Sept. 15	0.09726	0.10	Sept. 30	0.86514	0.87

B.P. (Chang & Liu, 1996). Before the 1980s, the mean sedimentation rate in southeastern Taihu Bay was 0.11 g/(cm^2·yr), which is slightly lower than that in the northeastern bay, 0.299 g/(cm^2·a) (Sun & Huang, 1993) (Table 4.4).

In 1992, the mean sedimentation rate ranged from 0.17 to 0.45 cm/yr (Table 4.5). The annual mean quantity of sediment deposited on the bottom of Eastern Taihu Bay since 1920 showed that the sedimentation rate was increasing in Eastern Taihu Bay (Table 4.6).

Table 4.4 The deposition fluxes in Eastern Taihu Bay measured in 1982 and 1986 (Sun & Huang, 1993)

Location	Period	Sedimentation rates g/(cm^2 · a)	Mean sedimentation rates g/(cm^2 · a)
Southeastern Taihu Bay	1955–1982	0.145	0.11
	1945–1955	0.083	
	1977–1986	0.214	
Northeastern Taihu Bay	1970–1977	0.649	0.299
	1945–1970	0.140	
	1920–1945	0.192	

Table 4.5 Sedimentation rates measured at five sites in Eastern Taihu Bay in 1992

Locations	Entrance	Dongjiaozui	Mouth of Taipu River	Western shore	Eastern shore
Mean sedimentation rate (cm/yr)	0.17	0.23	0.10	0.19	0.16

Table 4.6 Mean annual sedimentation in Eastern Taihu Bay since 1920

Periods	1920–1940	1940–1970	1970–1991
Sedimentation rates (t/(km^2 · a))	1065.36	1357.62	7549.80
Annual sedimentation quality (10^4 t)	13.85	17.65	20.15

Moreover, according to data for 1999 obtained from the Taihu Basin Administration, Ministry of Water Resources, P.R. China, the average thickness of siltation in Eastern Taihu Bay was greater than 1 m, of which 98% was silt. From 1991 to 1998, the depth of new silt was about 0.2–0.3 m and the mean sedimentation rate was 0.25–0.38 cm/yr in the area from Dongjiaozui (the mouth of Eastern Taihu Bay) to the mouth of the Taihu River. The great amount of silt on the bottom of Eastern Taihu Bay showed that there was a trend towards bogginess, which requires attention for environmental protection and preservation of water resources.

4.1.2 Soft Sediment Distribution

With deterioration of the water environment and frequent algal blooms occurring, treatment of eutrophication has been undertaken gradually in recent years. Numerous investigations on sediment have been made because the distribution and physicochemical properties of sediments are closely related to the internal sources of nutrients. The fundamental purposes of such investigations are to understand the depth and properties of sediment and its nutrient content, to determine the potential release of nutrients from internal sources, and to discuss the environmental effects of ecological dredging and its practicability. The Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, has investigated the distribution of sediment at 108 sites in Lake Taihu.

Based on these data, the distribution of "soft" sediment, specifically, the sediment that was easy to penetrate by a hard bamboo pole, was mapped out for the whole lake (Fig. 4.2) (Zhu et al., 2006). A hard bottom was hypothesized as a sediment thicknesses of less than 0.1 m depth.

The investigations showed that the area where soft sediment thickness exceeded 0.1 m was 1,692 km^2, occupying 72.4% of the total area of the lake. The general distribution of sediment shows that there is more sediment in the western lake than in Eastern Taihu Bay, and more sediment is present in the littoral regions than in the centre (Fig. 4.2). The mean thickness of sediment in regions with more than 0.1 m sediment was 0.87 m in the area of 1,692 km^2; the mean depth of sediment was 0.65 m in the whole lake area (2,338.1 km^2). Moreover, the greater sediment thickness in the western and northern parts of the lake was significantly different than in the east, with a maximum sediment thickness of more than 5 m in the deepest region.

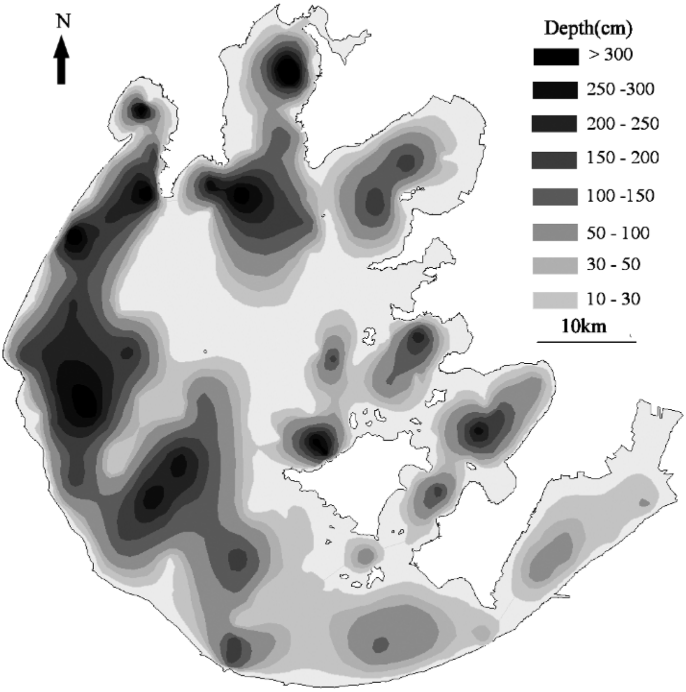

Fig. 4.2 Distribution of soft sediment in Lake Taihu (Zhu et al., 2006)

In the sediment investigations, sediment thickness was measured using a hard bamboo pole penetrated by hand into the sediment by a strong worker. Thus, sediment thickness in this investigation refers to the "soft" sediment layer, which includes the soft soil formed in the Quaternary period (Quaternary silt clay, under the modern sediments of Lake Taihu). Our results showed that the mean thickness of sediment was 0.87 m in the regions covered with sediment, and the sediments were formed 6,500 years ago, based on data obtained using ^{14}C dating.

Although Taihu is large and shallow and its sediment is frequently disturbed by wind waves, generally only the surface 30 cm of sediment has strong effects on the quality of the overlying water. Nevertheless, the thicker sediments must be considered if dredging is carried out, because such sediment would then be exposed to the sediment–water interface after the surface mud (generally 30–50 cm deep) was removed. Moreover, the resuspension potential, the nutrient content and chemical form, and the hardness of the deeper sediment must be considered if the surface sediment were removed, because these factors would have potential effects on water quality improvement and restoration of macrophytes. Therefore, understanding the distribution of sediment has important environmental significance in terms of treatment of lake environments.

The factors affecting sediment distribution are complex. The principal determinants are the activity of rivers entering the lake (most rivers entering Taihu are located in the west), the effects of the ancient river channel, and hydrodynamic factors, such as wind waves and lake currents. According to the investigation on changes in suspended matter in 139 rivers delivered to Lake Taihu during 1986–1990, the maximum content of suspended matter in rivers was 645 mg/L and the minimum was 13 mg/L. Of the 139 rivers, the drainage networks of the Tiaoxi River and the Yili River contributed the most sand to the lake (Sun & Huang, 1993). These rivers are located in southwest and western Lake Taihu, respectively, locations that roughly overlap with the distribution area of sediment in the western lake (this is the biggest region in terms of the sediment stock in Lake Taihu). Thus, particulates carried by rivers into the lake, to some extent, affect the distribution of surface sediments.

The sediment core study (Sun & Huang, 1993) showed a series of ancient riverbeds and depressions that were silted up and covered by the loess layer on the bottom. The riverbeds passed through Lake Taihu, extending from west to east, and are now merged with the output courses in Eastern Taihu. The distribution of the three main sediment zones is shown in Fig. 4.2. The first zone, from Dapukou, the main input mouth of the drainage networks of the Yili River, extends to the northeast, reaches the region south of Mashan Hill, and then divides into two branches; the first branch passes through western Meiliang Bay, extends to the north, and goes into the Liangxi River in the northern lake; the second branch extends to the east, goes into Gonghu Bay, and connects to the Wangyu River). The second zone extends from Zhushan Bay to the east, passes through Mashan reclaimed land, goes into Meiliang Bay, joins with the first zone, and then goes into the Liangxi River. The third zone is formed by extensions of the Yili and Tiaoxi Rivers (which join in the east of Daleishan Island), extends to the east along the north edge of Xishan Island, goes into Xukou Bay, and then joins with the old Xujiang River. The sediment region that joins Xiaomeikou north of Xishan, Ducun, and the paleochannel of the Wusongjiang River overlaps extensively with the sediment zone in the north of Xishan Island in Fig. 4.2. It also is possible that the merged sediment region was waterlogged lowland in ancient times.

The centre of Lake Taihu is almost all covered by hard earth, which may be the result of erosion by lake currents. Lake Taihu is significantly affected by the southeast monsoon in summer. Being a large shallow lake with a long wind fetch, it is characterized by strong wind waves and lake currents. According to long-term studies conducted by the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, current velocity in the centre of Taihu increased with increased wind velocity (Ma & Cai, 2000). It is difficult for suspended matter to deposit and accumulate in the centre of the lake, and hard bottom areas are created there (Sun & Huang, 1993). Although many rivers of different sizes enter the lake, no deltas are formed at the mouths of these rivers. This observation implies that the hydrodynamic effects of lake currents are strong, because alluvial deposits were washed away and transported by the currents.

4.2 Physicochemical Properties of Sediments

Guangwei Zhu

4.2.1 Particle Size Distribution of Surface Sediments

The particle size distribution of lake sediment may reflect inputs into the basins, the lake ecosystems, and the sediment resuspension potential. Since the 1980s, studies have been undertaken on particle size distribution of the sediments, using techniques such as surface sampling, shallow boring, and deep boring.

The results showed that most surface sediment was silt clay, 60–80% of which was silt sand (0.01–0.1 mm diameter) and 20–40% of which was clay (<0.01 mm diameter). The size composition of sediment is shown in Table 4.7.

In June 2001, investigations on particle size distribution of sediments in some major regions were conducted by the Nanjing Institute of Geography and Limnology. Sediment cores were sampled at four sites: site 1, Dapukou (31°18′25″ E, 119°56′37″ N); site 2, Xiaomeikou (31°05′05″ E, 120°06′04″ N) in the southwestern lake; site 3, Eastern Taihu Bay (31°01′18″ E, 120°27′14″ N); and site 4, central Meiliang Bay

Table 4.7 Particle size composition of sediment in Lake Taihu measured in 1980 (Sun & Huang, 1993)

Regions	Properties	Particle size distribution (% per region)				
		Fine sand (> 1 mm)	Coarse silt (1–0.1 mm)	Fine silt (0.1–0.01 mm)	Clay (< 0.01 mm)	Median diameter (mm)
Northern Meiliang Bay	Silt clay	4.57	4.35	48.33	42.78	0.012
Southern Meiliang Bay	Silt clay	—	6.59	56.54	36.87	0.012
Northwestern L. Taihu	Silt clay	—	11.59	54.35	34.8	0.015
Centre of L. Taihu	Silt clay	6.44	4.93	46.19	32.06	0.016
Southern L. Taihu	Silt clay	8.04	8.31	41.59	32.0	0.165
Western L. Taihu	Silt sand	5.88	5.94	72.65	15.59	0.031
Southwestern L. Taihu	Silt sand	7.31	10.69	63.72	16.28	0.023
Eastern Taihu Bay	Silt sand	10.14	48.55	31.53	9.78	0.027

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Table 4.8 Particle size composition of sediments in Lake Taihu measured in 2001

Location	Properties	Particle size distribution (% per site)				Median diameter (mm)
		Fine sand (> 1 mm)	Coarse silt (1–0.1 mm)	Fine silt (0.1–0.01 mm)	Clay (< 0.01 mm)	
Dapukou	Silt clay	—	0.88	70.95	28.17	0.015
Xiaomeikou	Silt clay	—	0.45	62.21	37.35	0.013
Eastern Taihu Bay	Silt clay	—	0.85	64.36	34.79	0.015
Meiliang Bay	Silt clay	—	1.06	55.17	43.77	0.011

(31°29′00″ E, 120°10′03″ N). The sediment cores were stratified 2 cm by 2 cm, and then the size composition of sediments was measured using a particle size analyzer.

The surface sediments (10 cm thick), composed of silt clay, were mainly made up of silt sand and clay, which together constituted more than 98% of the total (Table 4.8).

There was no significant difference in the median size of sediment particles among the four sites in Lake Taihu in 2001, similar to a result obtained in the early 1980s (Sun & Huang, 1993). The surface sediment in Xiaomeikou was much sandier than that in Dapukou in the 1980s investigation; however, the 2001 investigation did not find a significant difference between the two sites, which may be because the sampling sites were nearer to the centre of the lake and were slightly affected by the Tiaoxi River in 2001. The median size of sediment particles was 0.015 mm in the upper 10 cm of sediments in Eastern Taihu Bay (site 3), mainly because rivers with high sand contents entered the eastern bay through the southern lakeshore, which shortened the water residence time significantly. The sand content of the sediments of Eastern Taihu Bay was significantly greater than in northern Lake Taihu. Thus, the minimum median particle size was found in Meiliang Bay, with the longest water residence time there.

The particle size distribution curves for sediments at the four sites were similar (Fig. 4.3). Sediments in Meiliang Bay were fine. Sediments in Dapukou and Eastern Taihu Bay were slightly smaller, whereas sediment in Xiaomeikou was intermediate size.

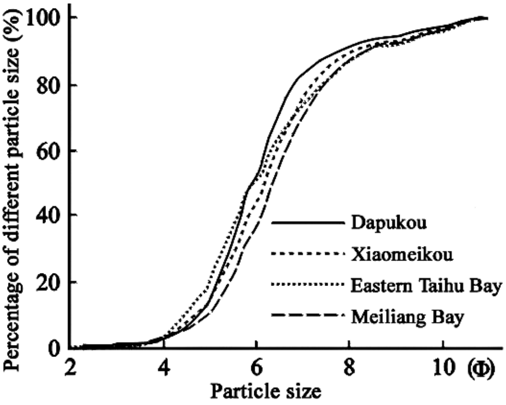
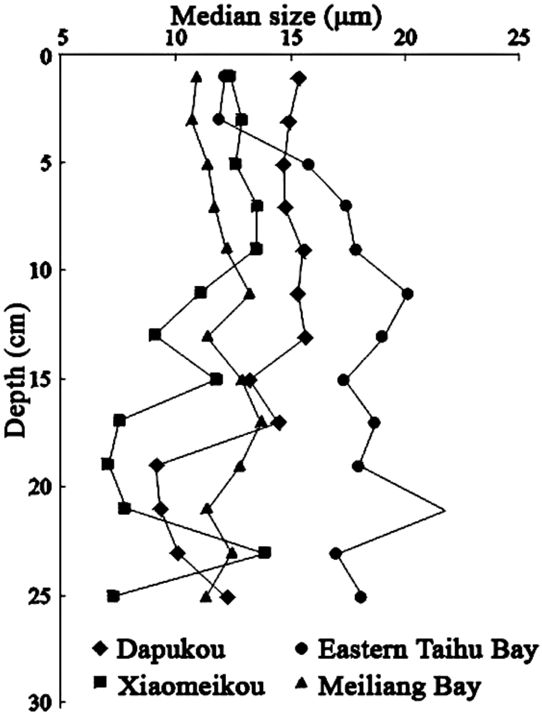


Fig. 4.3 Particle size distribution of surface 10 cm sediments in Lake Taihu. $\Phi = -\log_2 D$; D is grain size (mm). The larger the value of Φ, the smaller the particle size

Fig. 4.4 Vertical profiles of median sediment size



The lake regions were significantly different in terms of the vertical distribution of sediment size (Fig. 4.4). In Eastern Taihu Bay, the median size of sediments below the surface 4 cm layer at all four sites reached the maxima at relatively shallow depths, which shows great changes have occurred in the lake sediments recently. The vertical change in median sediment size was slight in Meiliang Bay, because there has been no significant change in hydrological characteristics at this location in the past 50 years. The median size of the surface sediment was larger than that of the underlayer in Dapukou and Xiaomeikou, which might be related to increasing human activities and the increasing intensity of soil erosion in the catchments.

The size curve of sediments in the surface 2 cm layer was compared with that in the 18–20 cm layer (Fig. 4.5). In Dapukou and Xiaomeikou, sediments in the surface 2 cm were significantly larger than those in the 18–20 cm layer; in Eastern Taihu Bay, the reverse was true. In Meiliang Bay, the size curve of the surface 2 cm layer was not significantly different from that of the deeper layer.

4.2.2 Water Content and Porosity of Sediments

Water content and porosity of sediments are important parameters that reflect sediment resuspension potential. The higher water content, the smaller porosity, and the more easily sediment is resuspended by wind waves. During April and May 2002,

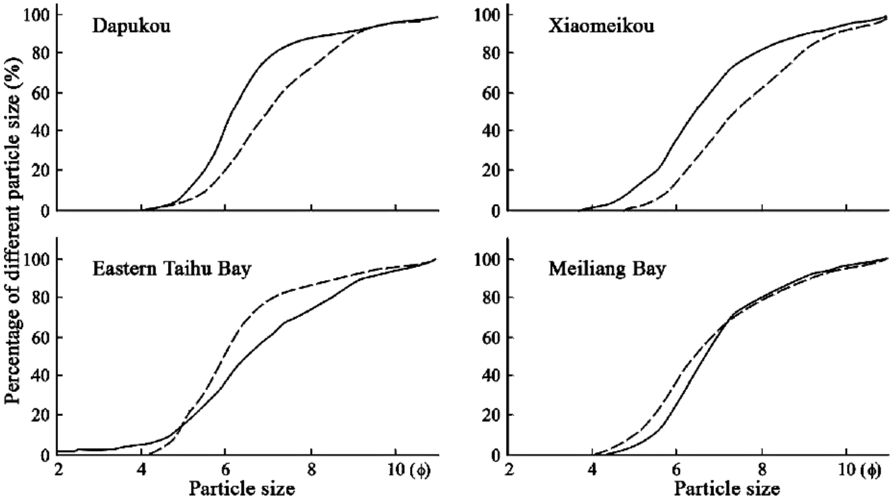


Fig. 4.5 Particle size distribution of surface 2 cm (*solid lines*) and deeper 18–20 cm (*dotted lines*) sediments. $\Phi = -\log 2D$, D is grain size (mm)

investigations were made at more than 100 sampling sites in the main regions of Lake Taihu to further understand the water content and porosity of the sediments. Soft sediment was collected from nearly 50 sites (Fig. 4.6). Hard bottom was found in central Lake Taihu, a section of the littoral belt, and southeastern Meiliang Bay.

Vertical profiles of water content and porosity of sediments in the seven lake regions are shown in Figs 4.7 and 4.8 (in the latter, porosity is the ratio of wet

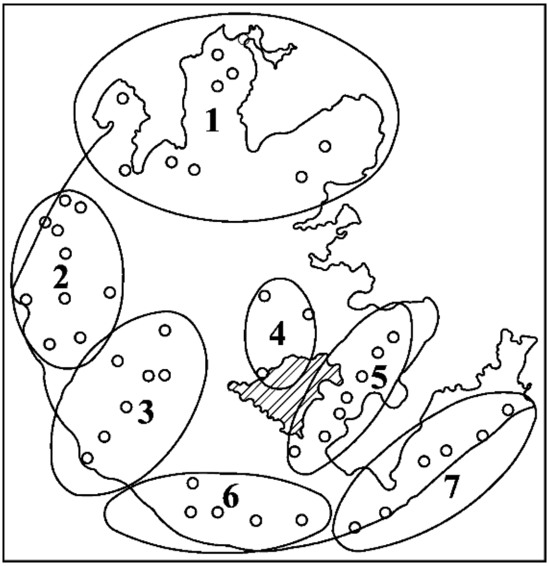


Fig. 4.6 Sampling sites for water content of sediments in Lake Taihu. *1*, Northern Lake Taihu; *2*, Western Lake Taihu; *3*, Southwestern Lake Taihu; *4*, lake centre; *5*, Xukou Bay; *6*, Southern Lake Taihu; *7*, Eastern Taihu Bay

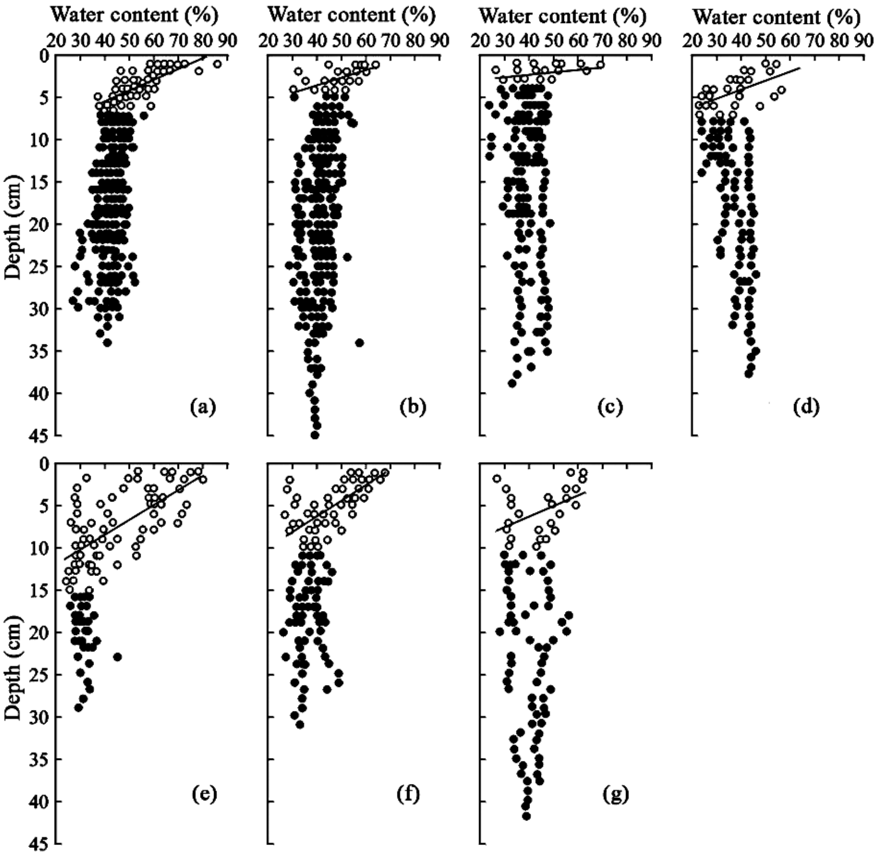


Fig. 4.7 Vertical profiles of water content in sediment of seven regions of Lake Taihu. (**a**) Northern Lake Taihu; (**b**) Western Lake Taihu; (**c**) Southwestern Lake Taihu; (**d**) Southern Lake Taihu; (**e**) Eastern Taihu Bay; (**f**) Xukou Bay; (**g**) Lake centre

sediment mass to its volume, in g/cm^3). Water content decreased significantly with increasing depth from sediment surface to bottom; water content decreased from more than 60% to less than 50%. Porosity increased from about 1.2 to about 1.6 g/cm^3. Although a transition in water content with depth was seen in all seven regions, the depth at which it occurred differed among sites, ranging from 4 cm to 15 cm (Fig. 4.7).

The greatest change in water content and porosity with sediment depth was in Eastern Taihu Bay, where the transition zone was the deepest (at 12 cm for water content, and 13 cm for porosity). This condition was related to both the abundance of organic matter and high water content in the sediments.

In general, the water content of the sediment determined its porosity, which is an important parameter reflecting compaction and resuspension potential of sediments. Not only water content, but also porosity, has decisive effects on the critical shearing stress for sediment resuspension.

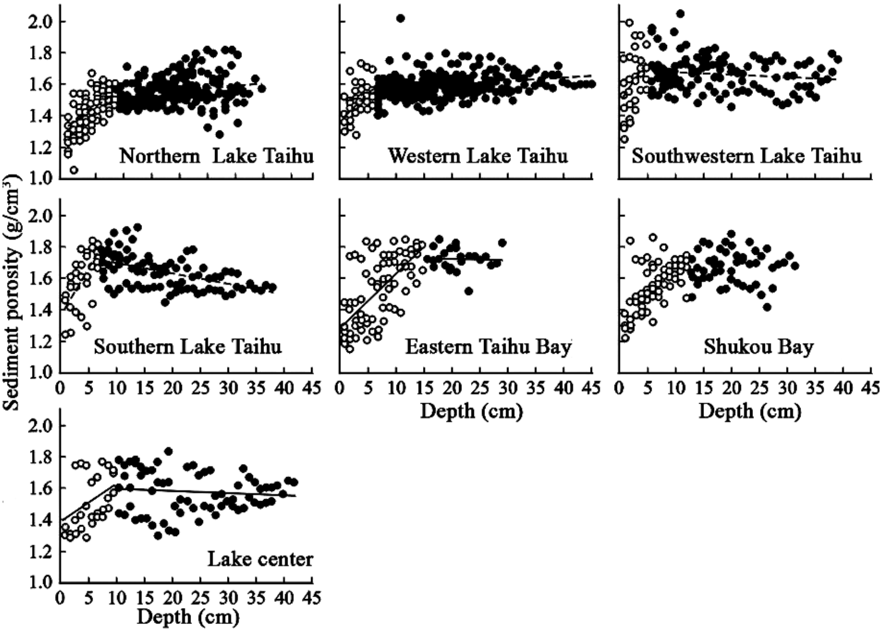


Fig. 4.8 Depth profiles of sediment porosity of seven regions of Lake Taihu

Therefore, identification of the transition depth of sediment water content is important in understanding the exchange between sediments and the overlying water and the nutrient cycling in shallow lakes. The transition depth of the water content of surface sediments (about 4–15 cm) should be given more attention in studies on the release of chemicals from the sediments, because the sediment above the transition depth may be the most active layer contributing to nutrient and pollutant exchange between sediments and the overlying water. Moreover, the different water content in sediments could affect microorganism communities in surface sediments and the conservation of living things such as plankton (for example, *Microcystis*), and then proceed to affect the biogeochemical cycles of nutrients.

4.2.3 The pH and Eh of Sediments

The pH and *Eh* (oxidation-reduction potential) of sediments have important effects on the formation and decomposition of minerals, and on the release, transportation, adsorption, and accumulation of elements. Moreover, the pH and *Eh* of sediment are also related to the growth and species distribution of aquatic vascular plants and benthic animals.

Analyses of sediment cores from eight sites with relatively deep mud showed that pH varied from 6.70 to 8.35 (Fan et al., 1998). In general, pH of the sediments decreased with increasing depth of sediment.

Pore water is defined as the water stored in the spaces between sediment particulates in contact with each other at the bottom of a lake. Pore water is affected by factors such as the ion exchange between solid- and liquid-phase sediments, the dissolution of solid-phase components in sediments, the dispersion of solid-phase components into liquid because of chemical decomposition, and the separation of some minerals or salts that do not readily dissolve in the pore water. Thus, the chemical properties of pore water are different from those of the overlying water and sediments.

The pH and *Eh* values of the surface overlying water and pore water sampled in Meiliang Bay and Eastern Taihu Bay using Peeper pore water samplers in July, September, and November 2002 are shown in Figs. 4.9 and 4.10.

The pH of the pore water varied with the seasons. The pH values of the lower water layer in pore water were less than or similar to those at the sediment–water interface and increased with increasing depth during July to November, with a trend of increasing rate. The acidity of sediments was reduced gradually, and the alkalinity increased with time; the transition from H_2CO_3 to $CO_3{}^{2-}$ in the pore water carbonate system was controlled by the dissolution and removal of $CaCO_3$ and $MgCO_3$ from the sediments. The spatial and temporal trends of pore water pH were similar in Meiliang Bay, a typical algae-dominated lake, and in Eastern Taihu Bay, a typical submerged macrophyte-dominated lake. Comparison of the pH of the overlying water showed that the pH increased gradually within the 10 cm of overlying water in Meiliang Bay, yet there was almost no change in Eastern Taihu Bay. However, pH decreased when the season changed from summer to winter, in both Meiliang Bay and Eastern Taihu Bay, which was related to the abrupt decrease in production of

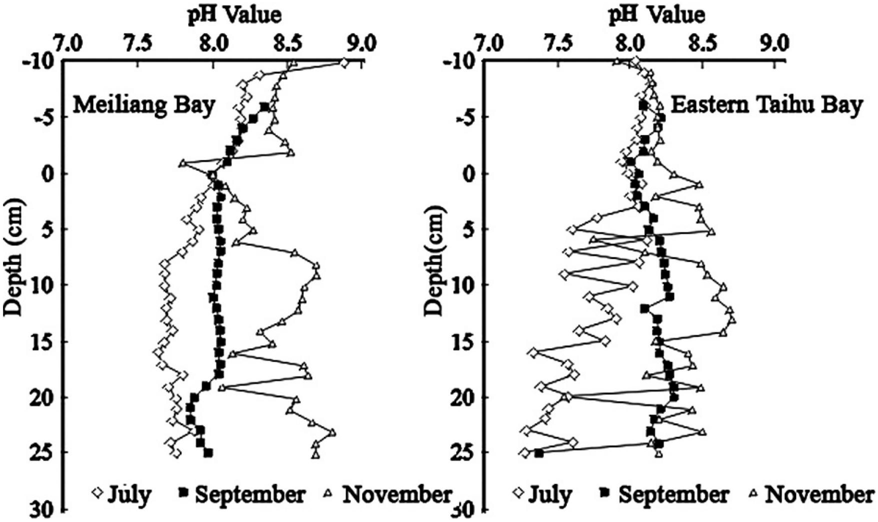


Fig. 4.9 pH of overlying water and pore water in Meiliang Bay and Eastern Taihu Bay in 2002. (Negative depth means overlying water; positive depth means pore water in sediment core) (Zhang Lu, unpublished data)

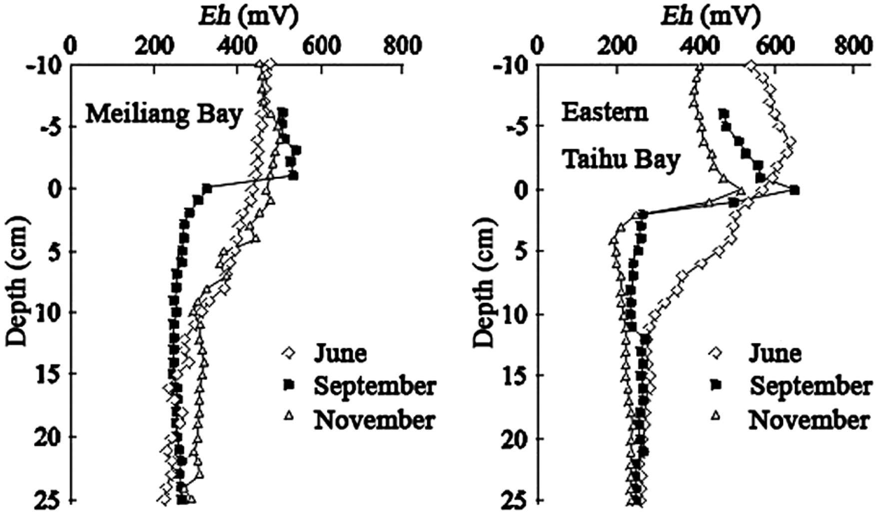


Fig. 4.10 *Eh* of overlying water and pore water in Meiliang Bay and Eastern Taihu Bay in 2002 (negative depth means overlying water, positive depth means pore water in sediment core) (Zhang Lu, unpublished data)

aquatic plants and algae in the overlying water and to the decrease in photosynthetic capacity.

The *Eh* values of overlying water and pore water decreased sharply in the interface between sediments and water, reaching a steady state (about 200 mV) at a depth of 3–10 cm (see Fig. 4.10). That result was significantly different from the change in the vertical distribution of *Eh* values in sediment, which showed that no lowest redox value occurred at the 10 cm depth. The differences between *Eh* values in pore water in Meiliang Bay and Eastern Taihu Bay showed that the redox states in sediments and pore water of Lake Taihu might be controlled by different systems (Fig. 4.10). The most important difference between the two bays is the difference of organic matter content in the sediment.

4.2.4 The Spatial and Temporal Distribution of Nutrients in Sediments and Pore Water

4.2.4.1 Contents of Nutrients in Sediments

Numerous investigations on the nutrient contents of sediments in Lake Taihu have been made since the 1960s, with several large-scale studies undertaken in the 1990s. An overview of the results is given in Table 4.9.

During the five decades since 1960, there have been sustained increases in the mean content of total nitrogen (TN) and total phosphorus (TP) in the sediment (Table 4.10). For example, TN in the surface sediment increased by 44.6% during

Table 4.9 The nutrient contents of sediment in Lake Taihu from 1960 to 1999 (%) (Fan et al., 2000a)

Year	Organic matter		Total nitrogen		Total phosphorus	
	Range	Mean value	Range	Mean value	Range	Mean value
1960	0.54–6.23	0.68	—	0.067	—	0.044
1980	0.24–2.78	1.04	0.022–0.147	0.065	0.037–0.067	0.052
1990–1991	0.57–15.10	1.90	0.049–0.558	0.080	0.040–0.107	0.056
1995–1996	0.31–9.04	1.70	0.022–0.45	0.094	0.039–0.237	0.058
1997–1999	0.31–15.73	1.83	0.022–0.618	0.092	0.028–0.280	0.060

Table 4.10 Phosphorus content of sediment samples from Meiliang Bay and Wuli Bay, showing difference in content of seven forms of phosphorus (μg/g) (Zhang et al., 2001)

Sample	Ex-P	Al-P	Fe-P	Ca-P	Oc-Fe-P	Oc-Al-P	Or-P
Meiliang Bay (I)	1.91	0.65	204.79	180.13	2,263.46	2.11	2,589.9
Wuli Bay (II)	2.63	0.64	300.74	181.58	2,042.44	5.98	1,652.1

Ex-P, exchangeable phosphorus; Al-P, aluminum-binding phosphorus; Fe-P, iron-binding phosphorus; Ca-P, calcium-binding phosphorus; Oc-Fe-P, occluded Fe-binding phosphorus; Oc-Al-P, occluded aluminum-binding phosphorus; Or-P, organic phosphorus.

the 15 years between 1980 and 1995–1996, and TP increased by 31.8% during the 35 years between 1960 and 1995. The results indicate that serious man-made pollution has affected the sediments in local areas of Lake Taihu.

In January 2003, a core of sediment was sampled from central Meiliang Bay, Lake Taihu. After stratifying the cores (each layer was 2 cm thick), TN and TP contents in each layer were analyzed. The results are shown in Fig. 4.11 (Zhu et al., 2006). The contents of nutrients in the top 5 cm layer was significantly higher than in the underlayers.

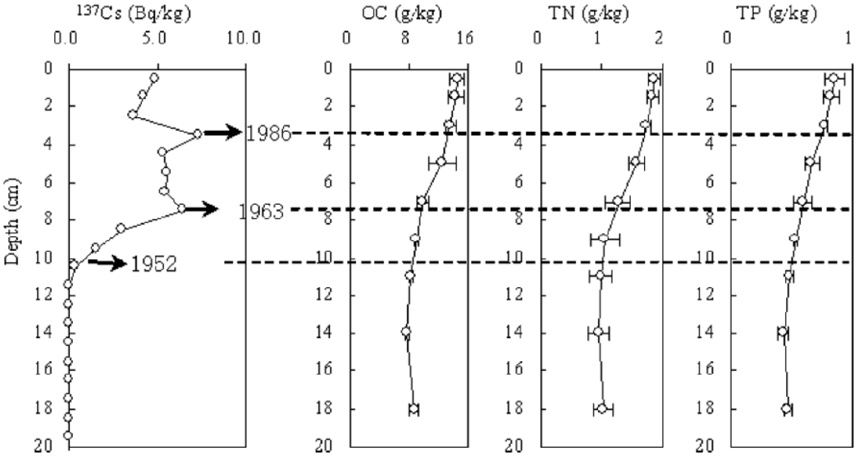


Fig. 4.11 Vertical profiles of organic carbon (OC), total nitrogen (TN), and total phosphorus (TP) in central Meiliang Bay, Lake Taihu

4.2.4.2 Vertical Distribution of Nutrient Content in Pore Water

In 2002, the P content in pore water in northern Meiliang Bay, Dapukou, southeast central lake, and Eastern Taihu Bay was investigated again (Fig. 4.12). In Meiling Bay, the P content in pore water in the surface 12 cm layer was significantly higher than that in the other three areas (Fig. 4.12). In Dapukou, the P content in pore water in the surface 10 cm also was rather high and then decreased between 10 and 18 cm. In the southeast central lake, the P content in pore water in the surface 12 cm layer was less than those in deeper layers. In Eastern Taihu Bay, the P content in sediment pore water was low.

These results for 2002 were similar to those obtained from the analyses of the distribution of N and P in pore water in some lake areas in 1998 (Fan et al., 2000b). This phenomenon might be related to the depth of P exchange between pore water and overlying water. In large shallow lakes, resuspension often happens because of frequent disturbance by wind waves, and the depth of pore water exchange with the overlying water (or infiltration exchanging) is greater than that in deep lakes or in small lakes disturbed slightly by wind waves. However, for Lake Taihu, the specific depth of frequent exchange between overlying water and pore water is unknown. In the southwest central area, with the most violent disturbance driven by wind waves, there was no significant difference in the P content in pore water in the surface 12 cm layer (see Fig. 4.12), indicating that there might be active exchange between the surface 5–15 cm sediment layer and the overlying water.

4.2.5 Forms of Phosphorus in Sediments

In June 2001, 30-cm-deep sediment cores were taken in northern Meiliang Bay (A), Dapukou (B), southwest of central Lake Taihu (C), and Eastern Taihu Bay (D), and then air dried, ground, and passed through a 200-mesh sieve for analyses. The P forms were analyzed using the sequential extraction method to fractionate P in sediments (Ruttenberg, 1992), which was improved by Li et al. (1998a).

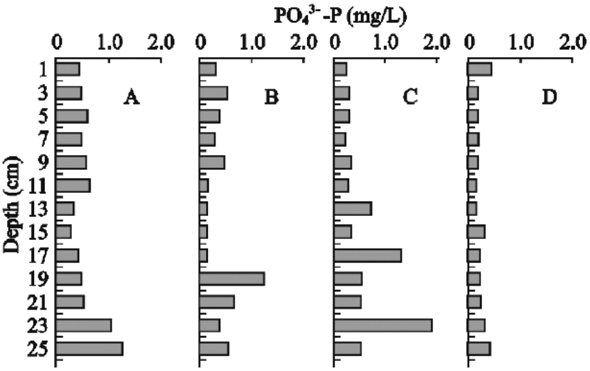


Fig. 4.12 Vertical profiles of PO_4^{3-}-P in sediment pore water of different lake regions (2002). (**A**) Northern Meiliang Bay; (**B**) Dapukou; (**C**) southeast of the central lake; (**D**) Eastern Taihu Bay

4.2.5.1 The Phosphorus Forms in Sediments

There were significant differences in the distribution of the seven P forms in the sediment cores from the four areas of Lake Taihu (Fig. 4.13). Concentrations of exchangeable P were commonly ranked as Eastern Taihu Bay <Meiliang Bay < Dapukou ≈ the southwestern central lake. The P content in sediments in Eastern Taihu Bay was significantly lower than those in the other three lake areas. At different sediment depths in Eastern Taihu Bay, there was little difference in the exchangeable P content, whereas in Meiliang Bay, the exchangeable P content in the upper sediment layers exceeded that in lower layers. These results contrasted with those in Dapukou and the southwest central lake, where the exchangeable P content decreased with depth within the surface 10 cm and then increased gradually at greater depths. The significant differences in P distribution characteristics in different lake areas were related to differences in biological conditions and hydrodynamics. In Eastern Taihu Bay, a grassy region of the lake with abundant plant roots, the macrophytes have a high demand for P in the sediments and water in the fast-growing season. Thus, much of the active P is adsorbed by the plants.

Previous studies in soil science, plant nutrition, and sediment geochemistry showed that both exchangeable P, and P fixed with Al and Fe in the sequential extraction method, were phosphorus with releasing potential, whereas other forms of P do not have such releasing potential. Based on the extraction (see Fig. 4.13), the content of P fixed with Al in sediments was low in different areas (all <1 mg/kg, and less than the content of exchangeable P). Therefore, the content of P fixed with Al in sediments could not contribute much to eutrophication. The distribution of P fixed with Fe was similar to that of exchangeable P; specifically, in Eastern Taihu Bay, the P content was significantly lower than that in the other three lake areas, and its vertical distribution was similar to that of exchangeable P. This result showed that aquatic plants could effectively inhibit the activity of P, and that it is unlikely that there would be a surge of P release from sediments in the grassy lake areas, even if there were large wind waves. The fact that P content occluded in sediments had irregular vertical distribution in the four sampling cores, combined with the fact that P content in the upper 10 cm layer exceeded that in deeper layers (Fig. 4.13), showed that occluded P was transformed into relatively stable calcium-P and organic-P during the early diagenesis of sediments.

The P in biogenic debris derives mainly from organism residues in the sediments. The P content in biogenic debris was similar to that of calcium-P, and the content in Eastern Taihu Bay was significantly higher than those in any other lake areas (see Fig. 4.13), which might be related to blooming macrophytes and the long-established pen culture of fish. In the other lake areas, the P contents in biogenic debris were not significantly different from each other and changed little vertically. Most calcium-P comes from calcium phosphate minerals such as hydroxyapatite and superphosphate, which are difficult to dissolve; these minerals, as the end products formed during the early diagenesis of sediments, are relatively stable. The extraction results showed that calcium-P content increased with increasing sediment depth in all lake areas except Meiliang Bay. In B, C, and D sampling cores (Fig. 4.13), the

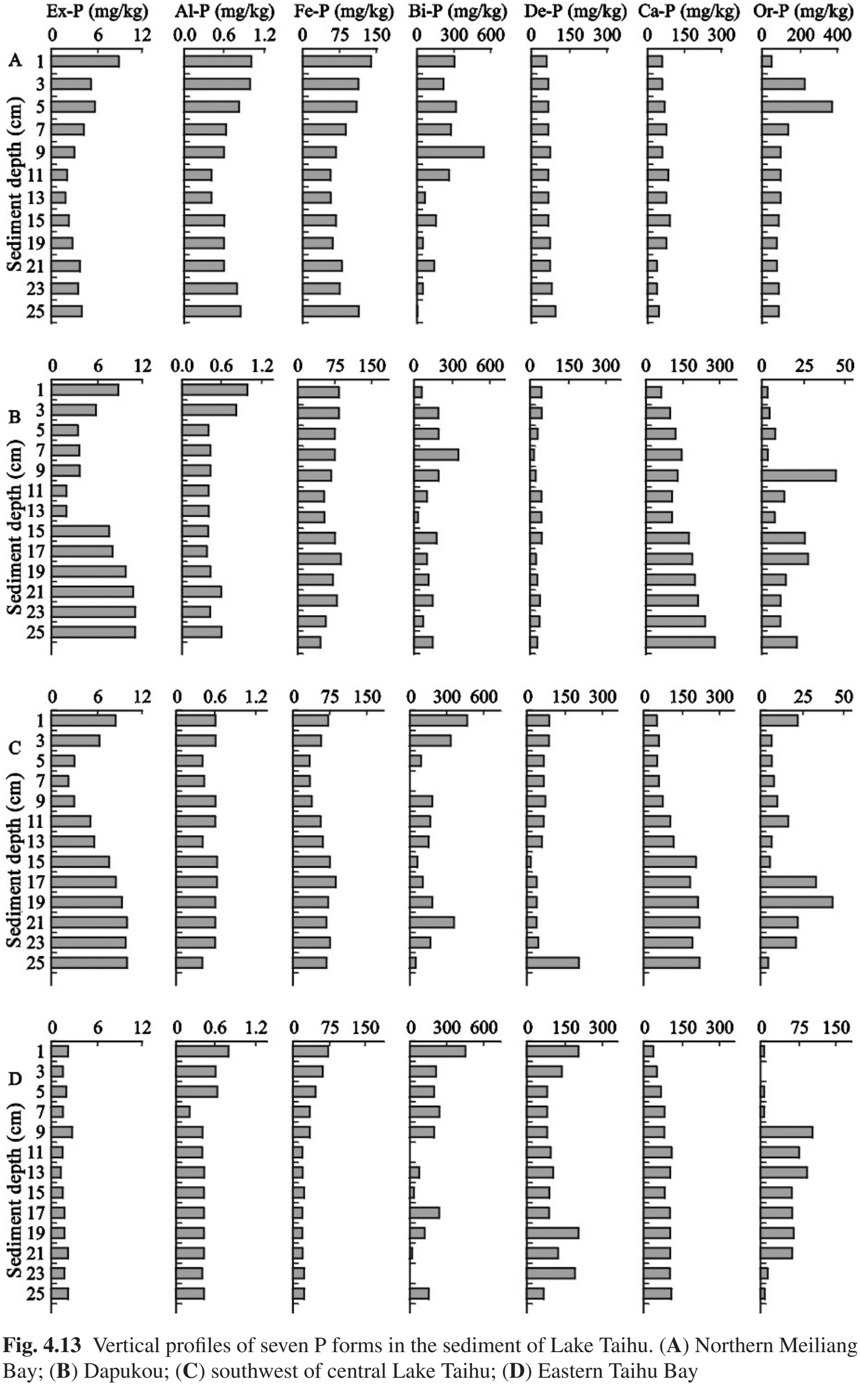


Fig. 4.13 Vertical profiles of seven P forms in the sediment of Lake Taihu. (**A**) Northern Meiliang Bay; (**B**) Dapukou; (**C**) southwest of central Lake Taihu; (**D**) Eastern Taihu Bay

correlation coefficients between the contents of calcium-P and the depth of sediments were 0.927, 0.929, and 0.865, respectively ($P < 0.001$). In the core of north Meiliang Bay, there was no correlation between calcium-P content and sediment depth, but these values were significantly positively correlated within the upper 16 cm layer ($R = 0.800$, $P = 0.017$, $n = 8$). The lack of correlation below 16 cm might be attributed to the significant differences in characteristics of the water environment in Meiliang Bay recently compared to the past. The results showed that calcium-P is the main P form in Lake Taihu.

The vertical distribution of organic P was irregular in three of the four lake areas (Fig. 4.13). The exception was in northern Meiliang Bay (core A in Fig. 4.13), where organic P content initially increased with depth (within the 5–6 cm layer, it reached 371.7 mg/kg, about 40% of the total), and then decreased at 8 cm, and remained rather stable below this depth.

In general the content of organic P in sediments was low in Dapukou, the southwest central lake, and in Eastern Taihu Bay. Especially, the organic-P content in the surface 8 cm was low, and peaked below 8 cm depth. In Eastern Taihu Bay, the low organic-P content in the surface layer contrasted markedly with the high organic matter content in the surface layer.

4.2.5.2 The Factors Controlling P Activity in Sediments

The main sedimentation mechanisms of phosphorus are adsorption with $CaCO_3$ or adsorption on ferric oxide colloids (Hartley et al., 1997; Hongve, 1997). The P generally passes though the process of release-deposition many times before being permanently deposited on the lake bottom (Hupfer et al., 1995).

Numerous factors affect P release in sediments, including biological (such as bacterial activity, the mineralization of organic matter, biological disturbances), chemical (such as *Eh*, pH, the percent of P fixed with Fe, nitrate content), and physical factors (such as resuspension of sediments) (Boers et al., 1998). The factors controlling P activity in sediments become more complex in shallow lakes than in deep lakes because of frequent wind-wave disturbance, numerous human activities, and complicated aquatic ecological factors.

Typically, P in sediment pore water passes into the overlying water through molecular diffusion and resuspension of surface sediments and is used by living organisms. Of the different P forms, P as PO_4^{3-}-P was the most active form in sediments. Exchangeable P primarily is deposited in the surface layer through physical adsorption, and is easily dissolved into water when P concentrations in the water change, maintaining a concentration balance between adsorption and dissolution with a relatively high activity. The P that is fixed with Al and Fe primarily is physically and chemically adsorbed on the surface of ferric oxide (or aluminum oxide) colloids; its amount can vary greatly because ferric oxide is easily affected by the redox potential, which is easily disturbed by the environment, and is the major source of potentially active phosphorus.

The foregoing analyses of the four sample cores (see Fig. 4.13) showed that the relationships between P concentrations in pore water, exchangeable P, P fixed with

Fe, other forms of P, and physical and chemical indexes were complex. In Meiliang Bay, P in sediment pore water only was positively correlated with P in biogenic debris and was negatively correlated with calcium-P. In Dapukou, P in sediment pore water was only positively correlated with loss on ignition (LOI) of the sediments. In the southwest of the central lake, P in sediment pore water was positively correlated with P fixed with Fe. In Eastern Taihu Bay, there were no significant correlations between P in sediment pore water and any of the other parameters investigated. These results agree with those obtained in 1998 (Fan et al., 2000b). In particular, redox potential, which can significantly affect P release in deep lakes, was not related to P in sediment pore water in the four sample cores in shallow Lake Taihu. Thus, redox potential had no decisive effects on the P distribution in sediment pore water in Lake Taihu.

In Meiliang Bay, the concentrations of exchangeable P in sediment cores were all significantly correlated with P fixed with Fe, P fixed with Al, LOI, and water content, showing that P fixed with Fe, P fixed with Al, and P adsorbed by organic colloids were the major active forms of P. However, in Dapukou, the concentrations of exchangeable P in sediment cores were not significantly correlated with P fixed with Fe or Al, which might be attributed to the polluted water from the Yili River. In the southwest of the central lake, exchangeable P in sediment cores was significantly correlated with P fixed with Fe and LOI. In Eastern Taihu Bay, concentrations of exchangeable P were not significantly correlated with any indexes listed, which also showed the individuality of this grassy bay relative to other kinds of bays.

The correlations showed that both biological and hydrodynamic factors play key roles in P geochemistry in Lake Taihu, which is a typical large shallow lake.

4.3 Experimental Studies on Nutrient Exchange at the Sediment–Water Interface

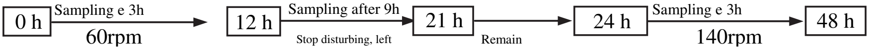
Lu Zhang and Wenchao Li

4.3.1 Phosphorus Release and Sorption Under Dynamic Disturbance Conditions

In shallow lakes, sediment–water interfaces are not stable. The shear forces caused by wind and wave disturbance directly influence the sediment–water interface, resulting in resuspension of the sediment. Disturbance of the water also significantly influences nutrient release from the sediment. Static release simulations (as described above in Part 1 of this section) can only reflect the biological and chemical changes in the release, as shown by the phosphorus release simulation experiments of Wu et al. (1998) and Yin et al. (1994) on the sediments of West Lake and Wuli Bay, Lake Taihu. To develop more realistic simulations, Zhang et al. (2001) have conducted preliminary studies on nutrient release in dynamic disturbance simulations.

4.3.1.1 Phosphorus Release

Zhang et al. (2001) selected two sampling sites: (I), at Meiliang Bay (31°28′31″ N; 120°11′39″ E), and (II), at eastern Wuli Bay (31°30′55″ N; 120°15′04″ E).



About 1 kg sediment was taken from the surface, and 2 L overlying water was collected and filtered through a Whatman GF/C membrane; 5 g fresh sediment was put into a 250-mL conical flask, to which 100 mL filtered overlying water was added. Then, the flasks were put into a constant temperature shaker incubator at 25°C in the dark and open to the air. During the 48-h experiment, the water was disturbed intermittently; the disturbance and sampling process are shown in Fig. 4.14.

The results indicate that under natural conditions of dynamic disturbance, sediments have both sorption and desorption effects on phosphate, and these two actions happen simultaneously (Fig. 4.14). Whenever the release of phosphate under dynamic disturbance conditions exceeds sorption by the sediments, the apparent release of the phosphate by the sediments is actually the difference between release and sorption.

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For the surface sediments in central Meiliang Bay and Wuli Bay with the 60 rpm disturbance, the nutrient release was not obvious; instead, some sorption was observed. During the static period, between 12 h and 24 h, the release curve was almost level. When the disturbance strength was increased to 140 rpm after 24 h, there was marked release from sediment of both sites, with maximum release concentration reaching three times that seen at 60 rpm.

Although we cannot define the exact relationship between the simulated disturbance under experimental conditions and the actual disturbance caused by wind, waves, and biological events under natural conditions, this does not hamper our research on the behavior of phosphorus in the sediment under disturbance conditions. The resuspension release curves of the surface sediments in the two samples begin to drop after reaching peak values, which is similar to the situation in Lake Ge (Fan, 1995). The reason for this result may be that phosphorus release from resuspended sediments enters into an "exhausted" state after a certain degree of release to the water under dynamic disturbance conditions, when a dynamic balance of phosphorus release and sorption is reached.

The time taken to reach maximum release (T_{max}) was different for sample I (Meilieng Bay) and sample II (east Wuli Bay). Thus, T_{max} (I) $>$ T_{max} (II), which may relate to the forms of phosphorus in the sediment (see Table 4.10). Exchangeable phosphorus can enter the overlying water more easily than organic phosphorus, so it has less influence on the time for release balance than organic phosphorus. Aluminum-binding phosphorus and iron-binding phosphorus can transform into dissolved phosphorus through chemical hydrolysis, with high reaction speeds and low content in sediment samples, so these are not the main factors affecting the phosphate release balance. The organic form of phosphorus can be transformed biologically, but this is a slow process. However, organic phosphorus is significant in this experiment and may be one of the main factors affecting the phosphate balance.

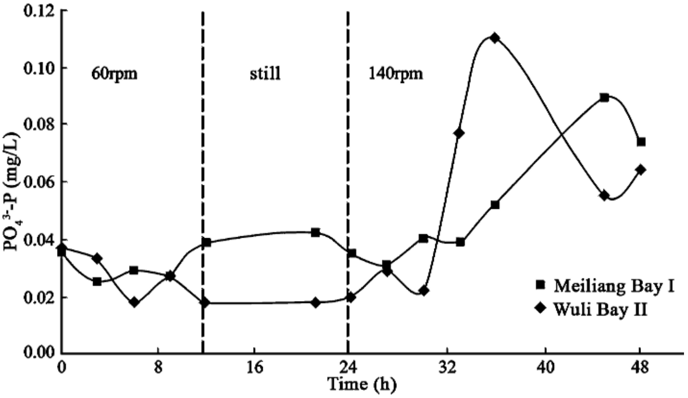

Fig. 4.14 PO_4^{3-}-P release from Meiliang Bay (■) and Wuli Bay (◆) sediments in simulated disturbance conditions (Zhang et al., 2001)

Phosphorus in other forms, such as occluded phosphate, is unlikely to enter the overlying water through hydrolysis under disturbance conditions. Because organic phosphorus content in Meiliang Bay sediment was higher than in Wuli Bay sediment, the time taken to reach release balance in the Meiliang Bay sample (I) was longer than that in the Wuli Bay sample (II), which was reflected in the lag in reaching maximum release.

4.3.1.2 Phosphorus Sorption Experiment

Zhang et al. (2001) conducted phosphorus sorption experiments on sediments under dynamic disturbance conditions, using the above-mentioned samples. Because the monthly mean phosphate concentration of Lake Taihu is 0.001–0.146 mg/L over a year [1], and the maximum was 0.29 mg/L (in Meiliang Bay), a value of 0.2 mg/L was adopted as the mean peak value for phosphate concentration. To simulate this in the experiments, lake water was mixed with a solution of 50 mg/L sodium dihydrogen phosphate ($NaH_2PO_42 \cdot H_2O$) to get a solution of 0.2 mg P/L as the overlying water in the incubation system. First, 5 g wet sediment was put into 250-mL conical flasks, then 100 mL filtered overlying water was added, and the preparation was incubated at 25°C, open, in the dark, at 100 rpm. The concentration of $PO_4{}^{3-}$-P was measured ten times during the 24-h incubation.

The sorption experiment under dynamic disturbance conditions indicated that the phosphate concentration drops quickly within the first 30 min of the experiment (Fig. 4.15). The concentration in the Meiliang Bay sample decreased from 0.215 to 0.013 mg/L (94%), and the concentration in the Wuli Bay sample decreased from 0.229 to 0.050 mg/L (78%). Thereafter, the decrease in phosphate concentration slowed down, and approached a stable concentration after 4 h, which indicates the sampling sites at Meiliang Bay and Wuli Bay have strong sorption activities under simulated disturbance conditions. The balanced concentrations during the 24-h incubation in systems with sediment from both the sampling sites approached 0.020 mg/L under the same disturbance conditions.

The sediments demonstrate marked adsorption under simulated disturbance conditions. The main reason for this may be the destruction and recreation of biological and chemical balances at the sediment–water surface, indicating significant changes to the adsorption behavior of the phosphorus in the sediment when disturbed. In large shallow lakes such as Lake Taihu, disturbance to the sediment–water interface is fairly frequent. In such circumstances, the release, sorption, and fate of sediment transformation is much more complex than in deep lakes that are less vulnerable to disturbance.

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[1] *Data source: Taihu Laboratory for Lake Ecosystem Research, Chinese Academy of Sciences, 1998, Annual Report.*

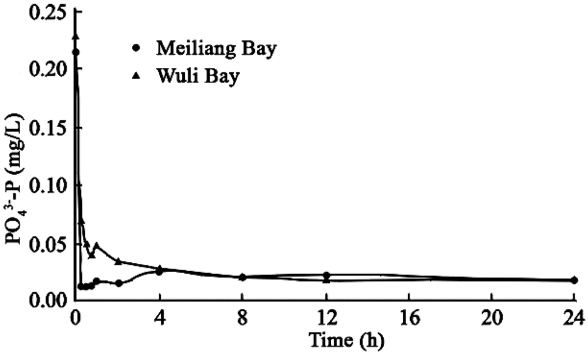

Fig. 4.15 Adsorption of P by sediments from Meiliang Bay and Wuli Bay under simulated conditions of dynamic disturbance (Zhang et al., 2001)

4.3.1.3 Phosphorus Adsorption Capacity of Sediment

The discharge of sewage may cause sudden increases in phosphate concentration in some areas. Capacity measurement experiments enable us to better understand how the sediments can reduce the peak phosphate concentrations. Experiments on the phosphorus adsorption capacity (PAC) of sediment were conducted on the aforementioned sediment samples (Zhang et al., 2001). Four phosphorus concentration gradients in the overlying water were chosen: 0.1, 0.2, 0.5, and 1.0 mg/L. The samples were placed in a constant temperature (25°C) shaker incubator at 100 rpm, to shake the sediment–water mixture to obtain the adsorption balance. The samples then were incubated for 24 h. The phosphorus adsorption capacity of resuspended sediments was calculated through comparison of the concentrations of phosphate before and after the incubation.

During the PAC experiments, there was no significant difference of phosphate concentration in the overlying water with sediment from Meiliang Bay and from Wuli Bay, which proves the sorption capability of the two samples were similar (Fig. 4.16). The phosphorus adsorption capacity (PAC, mg/g dry sediment) of surface sediment under simulated disturbance conditions can be obtained by the following formula:

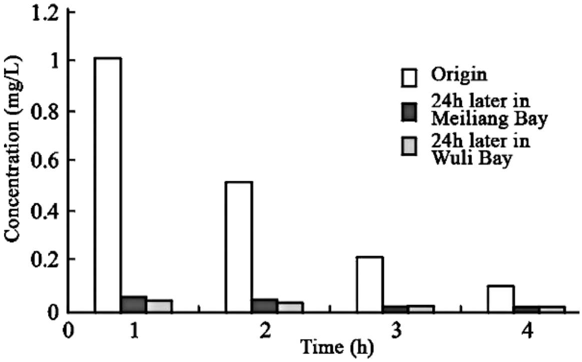

Fig. 4.16 Phosphate concentration in phosphorus adsorption capacity (PAC) experiments with sediments from Meiliang Bay and Wuli Bay (Zhang et al., 2001)

$$PAC = \frac{(C_0 - C_t) \times V}{\mathrm{W} \times (1 - \mu)}$$

In the formula, C_0 refers to the initial concentration of phosphate of the overlying water sample (mg/L), C_t refers to the concentration of phosphate after 24 h disturbance (mg/L), V refers to volume of water samples (L), W refers to wet weight of the sediments (g), and μ refers to the water content of the sediments (%).

The results of the PAC experiment are shown in Table 4.11.

Research on nutrient release and adsorption capacity of sediments in Lake Taihu indicates that the effects on phosphate release from surface sediments are significant. Under conditions of minor disturbance, release of nutrients from sediment is difficult to observe. However, when the disturbance strength is increased, marked release of nutrients from sediment is evident. The maximum release concentrations at 140 rpm are 0.110 and 0.089 mg/L for sediments from Wuli Bay and Meiliang Bay, respectively. These values are almost three times higher than those at 60 rpm conditions. The results indicate disturbances in natural conditions, such as winds, waves, and biological processes, have a significant effect on release of phosphate.

The effect of disturbance on phosphate adsorption by sediment also is marked. Based on these results, release and adsorption of phosphorus by sediments under dynamic disturbance conditions exist simultaneously. Adsorption of phosphorus by sediment (or suspended sediment) may be higher than release of phosphorus from sediment when the disturbance of the water–sediments system is strong enough. Which process dominates depends on the joint effects of factors such as phosphate concentration and disturbance intensity. Release will be the main activity if the disturbance is strong and the concentration of phosphate in the overlying water is low enough. However, sorption will be the main activity if the disturbance is strong and external phosphate concentration is higher than the balance concentration. The surface sediment acts as a natural buffer system for phosphate; whenever the phosphate concentration in the water is low, the sediment will release phosphorus and the release strength will increase with disturbance strength; in contrast, if the phosphate concentration in the water is high, the sediment will act as an adsorbent. The release process of phosphorus is comparatively slow, so the peak release value in summer usually lags behind wind activity, but the sorption process is more rapid.

Table 4.11 Initial and final phosphorus concentration in overlying water and the calculated phosphorus adsorption capacity (PAC) of sediments (Zhang et al., 2001)

	Meiliang Bay sediment				Wuli Bay sediment			
C_0 (mg/L)	1.01	0.514	0.213	0.104	1.01	0.514	0.213	0.104
C_t (mg/L)	0.048	0.046	0.021	0.017	0.041	0.032	0.019	0.016
PAC (10^{-3} mg/g)	42.2 ±0.4	20.9 ±0.3	8.4 ±0.2	3.8±0.1	50.0±0.5	25.3 ±0.3	10.3 ±0.2	4.7 ±0.1

4.3.2 Phosphorus Adsorption Saturation of Sediment from Eastern Taihu Bay

In the lake ecosystem, the sediment has a great capacity for phosphorus storage, yet this capacity is finite. With eutrophication of lakes, the amounts of phosphorus in the sediment approach saturation. The buffering capacity for phosphorus of the ecosystem decreases with increasing phosphorus pollution, as evidenced by a steep rise in phosphorus content and algae blooms. The relationship between phosphorus adsorption saturation and eutrophication, as well as the buffering capacity of sediment to external phosphorus pollution, can provide important data for controlling eutrophication.

Li et al. (1998b) have conducted research on the phosphorus adsorption saturation (PAS) of the sediments of Eastern Taihu Bay. They collected sediment samples at ten sites in Eastern Taihu Bay (Fig. 4.17). Sites 9 and 10 were located in the Eastern Taihu Bay section of the Taihu Laboratory for Lake Ecosystem Research, Chinese Ecosystem Research Network. Site 9 was located in an enclosure for the pen-culture fishery, and site 10 was located in a separate fishery pond near the lake.

Surface sediment was collected with a core sampler, with an inner diameter of 90 mm and a length of 1,000 mm. The surface 100 mm layer of sediment was separated for the experiment. Subsequently, 60 L clean lake water was filtered with a plankton net (no. 25) into a 90-L white plastic barrel, placed in a dark room (a total of ten barrels were used for the experiment). Approximately 2 kg sediment was collected from the surface layers (100 mm) from the above-mentioned 10 sites, then washed and filtered with a 100 − μm nylon sieve, separated into the ten barrels, and then more filtered water was added to bring each barrel to 65 L. The barrels were kept in the dark to minimize algal growth and their use of phosphate. Aeration was held at levels that maintained oxidation of the system, promoted aerobic degradation of organic matter, and facilitated phosphorus release and the phosphorus balance in the system. The sediments were disturbed each day by strong aeration to thoroughly suspend them. Water was regularly sampled and centrifuged, and then the phosphate content was

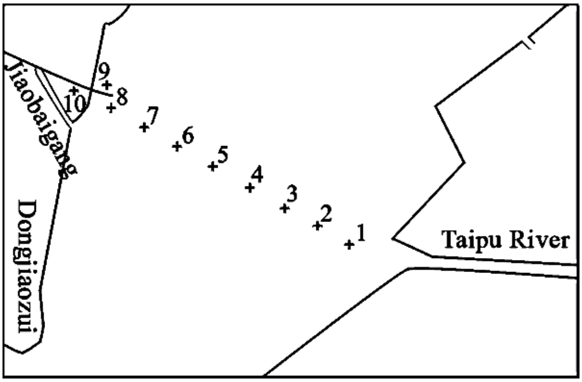

Fig. 4.17 Locations of sampling sites for phosphorus adsorption saturation experiment

determined. The ten experimental systems of water and sediments were incubated at 25°–30°C in darkness, with continuous aeration, and intermittently oxygenated to create disturbance.

The experiment ran from June 20 to September 3, 1997. After 20 days, the systems were stable (Fig. 4.18). On July 13, 6.5 mL phosphorus standard solution (buffer made with KH_2PO_4 and Na_2HPO_4, pH = 7.0; P content, 1 mg/mL) was added to each of the barrels. Additional phosphorus standard solution was added to each barrel on July 13 (20 mL), July 25 (6.5 mL), and July 30 (20 mL). After adding phosphorus, the balance of the system was determined. At the end of the experiment, the sediment was air dried and weighed, and the total phosphorus content and Olsen-P content were determined.

In the first 5 days, the phosphate concentration rose rapidly from the initial 7 μg/L to 18–43 μg/L, and then continually decreased to 1–23 μg/L at day 20, a typical sediment P release curve. Phosphorus release from the sediment occurs mainly because the original biological and chemical balances are disturbed, particularly the microbial system at the sediment–water interface, which breaks the phosphorus cycle. Thereafter, a new balance is created because oxidation of the sediment, increase in adsorption of phosphorus, and phosphorus release into water and readsorption by sediment result in decreased phosphorus concentrations in the water. On day 20, the addition of 6.5 mg phosphorus caused slight fluctuations of the phosphate concentrations. On day 23, the addition of 20 mg phosphorus caused

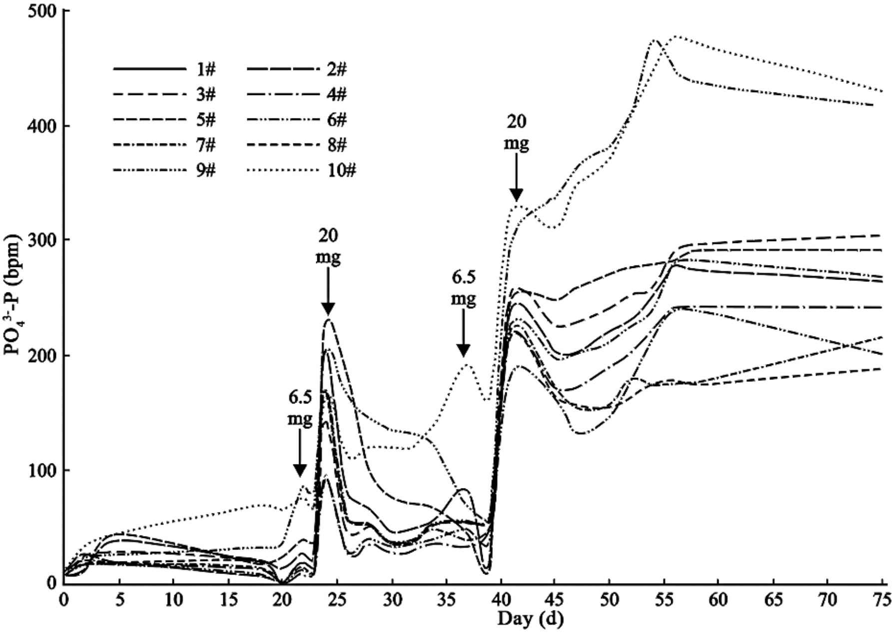

Fig. 4.18 Temporal changes in water phosphate concentration in ten systems in the phosphorus addition experiment (Li et al., 1998b)

rapid increases in phosphate concentrations to 92–225 μg/L. Thereafter, the concentrations dropped quickly to 30–60 μg/L. On day 40, the addition of 20 mg phosphorus again resulted in a rapid rise in phosphate concentration, this time reaching a new maximum of 184–253 μg/L. The concentrations did not return to their previous levels, but reached new levels of 200–300 μg/L 35 days after the second addition of 20 mg phosphorus.

Although the reactions of sediment samples 9 (from the fish pen enclosure) and 10 (from the fishery pond) were somewhat similar to those of other samples, they differed in their reaction to additions of external phosphorus. At day 20, the PO_4^{3-}-P concentrations in the water had reached 35 and 60 μg/L for samples 9 and 10, respectively (see Fig. 4.18). The stable concentrations after phosphorus additions were markedly higher than those of the other systems, with final PO_4^{3-}-P concentrations of 417 and 431 μg/L for samples 9 and 10, respectively. This result indicates that the phosphorus saturation is greatly decreased by the addition of fish foods where these sediment samples were taken. The initial and final amounts of phosphorus in the sediment and phosphate adsorption saturation (PAS) for each of the ten experimental systems are given in Table 4.12.

In general, the content of exchangeable phosphorus in the sediment of Lake Taihu is lower than 10 mg/kg (Zhang et al., 2001; Zhu et al., 2006). Table 4.12 shows that the addition of phosphorus was 53 mg. The dose was equal to 52–172 mg P per kilogram sediment, which is several times higher than the exchangeable phosphorus content of Lake Taihu sediment. With the large load of active phosphorus, the sediment still adsorbs more than half of the additional phosphorus, which indicates that its adsorption potential is fairly high. The main adsorption action can be attributed to oxidation of the sediment and to products such as active ferric oxide that adsorb the active phosphorus in the water. However, with such a large load of external phosphorus, although the sediment is thoroughly oxidized, it cannot completely overcome the effects of external phosphorus, and reaches maximal phosphorus adsorption capacity.

Table 4.12 Initial and final phosphorus contents and PAS in ten sediment samples (Li et al., 1998b)

Sediment sample	Dry weight (g)	Initial P content (mg)	Final P content (mg)	P addition (mg)	P adsorption (mg)	Adsorption (%)	PAS (mg/kg)
1	556	458	489	53	31	58	56
2	611	557	593	53	36	68	59
3	435	385	419	53	34	64	78
4	455	418	456	53	38	72	84
5	512	427	463	53	36	68	70
6	316	331	371	53	40	75	127
7	308	283	322	53	39	74	127
8	536	486	527	53	41	77	76
9	732	558	585	53	27	51	37
10	1021	1248	1274	53	26	49	25

Initial concentration of phosphate was 7 mg/m^3.

Sediments used in the experiment were collected from the lake bottom with the area of about 0.02 m^2. The addition of 53 mg phosphorus was equal to a phosphorus pollution load of 2.65 g/m^2, which was similar to the actual external phosphorus pollution load on Eastern Taihu Bay during 7 months. The experiment demonstrates that the PAS of sediment in Lake Taihu is finite, so additional methods of phosphorus export from the lake ecosystem are necessary. The phosphorus content in Eastern Taihu Bay is consistent with conditions of eutrophication. In addition, the phosphorus carried by the water from western Lake Taihu cannot be well controlled, so in addition to water exchange, proper biological export should be considered; also, phosphorus pollution in Dongshan Peninsula should be reduced to control and prevent further eutrophic deterioration. In addition, the research shows that fish pen-culture causes significant phosphorus pollution. The phosphorus content of the sediment and the PAS of the sediment in the fish pen-culture zone in the northwest of Eastern Taihu Bay are higher than those in other areas of the lake.

4.4 Conceptual Model of Internal Nutrient Loading

Boqiang Qin, Guangwei Zhu, and Lu Zhang

4.4.1 Effects of Wind-Wave Disturbance on Nutrient Concentrations in the Water

4.4.1.1 Field Investigations

Field investigations were conducted on five occasions in February–March and July 1998, June and September 2001, and May 2003.

The two investigations in 1998 were conducted inside Meiliang Bay (sampling site no. 1) and at the mouth of the bay (sampling site no. 4) (Fig. 4.19); both sites were in pelagic areas, but with a greater depth of soft sediment at site 4 than at site 1. These studies focused on the vertical profiles of nutrient and total suspended solid (SS) concentrations under different wind conditions. Wind speed, wind direction, water temperature, transparency, and lake current were measured in situ. Samples from different water depths were taken to analyze total organic matter (TOM) content, different N and P forms, and SS concentration. In February–March, three different wind intensities were observed: 2 m/s (February 26), 5 m/s (February 24), and 6.5 m/s (March 11), which represented light, moderate, and strong wind conditions, and water samples were collected from three depths: 0.25, 1.25, and 2.25 m (water depth was 2.50 m). On July 23, 25, and 30, wind speeds were all 2–4 m/s (light–moderate), and water samples were collected from five depths: 0.25, 0.63, 1.25, 1.88, and 2.25 m.

In June 2001, a total of four sediment cores, each 26 cm long, were collected from site 2 at central Meiliang Bay, site 5 at Dapukou in the northwest, site 6 in the southwest, and site 7 in the east part of the lake (see Fig. 4.19). Each core was sliced at 2-cm intervals, and measurements made of the oxidation-reduction potential (*Eh*), porosity, specific gravity, size, moisture content, organic matter content, total nitrogen (TN), and total phosphorus (TP). Pore water from each core was obtained by centrifugation, and interstitial TN and TP concentrations were measured by a spectrophotometer after alkaline potassium persulfate digestion.

From September 8 to 11, 2001, an observation platform was built at site 1 in Meiliang Bay, and a capacitive wave recorder and a SonTek Doppler current meter were deployed to obtain time-series measurements of waves and currents. In situ wind speed, water temperature, transparency, and water depth were also measured. Meanwhile, water samples from seven different depths (0, 1.0, 1.5, 2.0, 2.25, 2.50, and 2.7 m; bottom depth was 2.75 m), were taken three times a day (at 13:00, 17:00,

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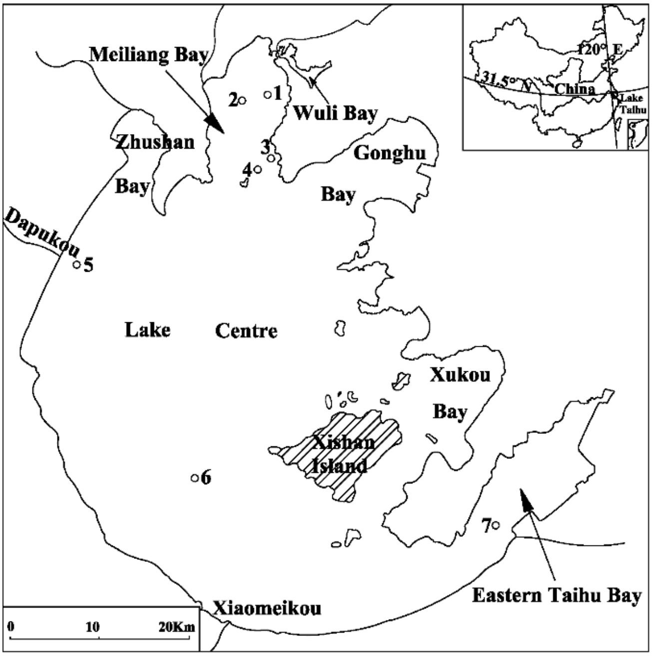

Fig. 4.19 Location of field sampling sites in Lake Taihu

and 21:00 on September 8 and at 9:00, 13:00, and 17:00 on September 9 to 11) to monitor changes in SS and nutrient concentrations.

In May 2003, samples were taken at site 3 in southern Meiliang Bay, approximately 100 m from the bank, where the sediment was about 20 cm thick. For 3 days until the afternoon of May 6, there had been light winds and rain. From the evening of May 6, the wind speed increased, and on May 7, speeds exceeded 8 m/s from 9:00 to 17:00 and 12 m/s at 13:00. The prevailing west wind and longer wind fetch created strong dynamic disturbance in the lake. On May 8, the wind speed decreased to 4–6 m/s and subsequently dropped below 3 m/s. On May 10, the east wind prevailed and the waves subsided in the observed area. Water samples were taken at 1300–1400 on May 7 and 10 from 0.2, 0.9, 1.4, and 1.9 m (bottom depth was 1.95 m). Measurements were made of SS, loss of ignition (LOI), TP, total dissolved phosphorus (DTP), and soluble reactive phosphorus (SRP).

4.4.1.2 Vertical Profiles of Nutrient Concentrations in the Sediment and Overlying Water

The vertical profiles of the mean nutrient concentrations in the sediment pore water and the water column in Meiliang Bay on September 8–11, 2001, are shown in Fig. 4.20. The data show that the total dissolved nitrogen (DTN) concentration was ten times higher in the sediment pore water than in the overlying water, and that

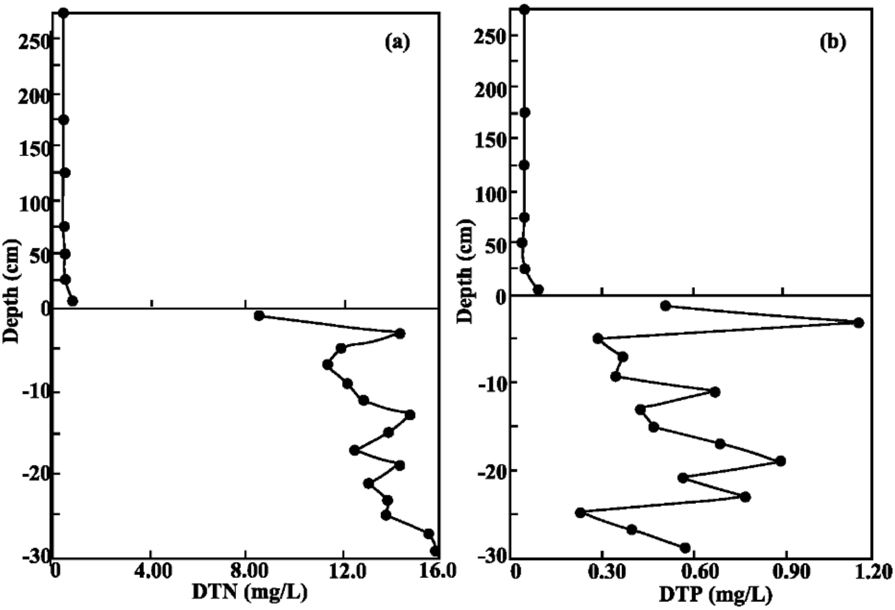

Fig. 4.20 Vertical concentration profile of (**a**) of total dissolved nitrogen (DTN) and (**b**) total dissolved phosphorus (DTP) in the water column and sediment pore water at site 2 in September 2001. Data are means for September 8 to 11 (4 days, 3 measurements/day)

the DTP concentration was seven to eight times higher; this concentration gradient caused the release of nutrients from the sediment pore water into the water column. In the sediments, concentrations of DTN varied and generally increased with depth, whereas concentrations of DTP varied without any apparent trend with depth.

The vertical profiles of six water quality parameters in the water column at sites 1 and 4 in Meiliang Bay on July 23, 25, and 30, 1998 are shown in Fig. 4.21. Total dissolved nitrogen (DTN) concentration in lake water increased with increasing water depth. SS concentration and its organic matter content (SS-OM) were typically higher near the lake bottom than near the surface of the water column. In contrast, TN, TP, and Chl a concentrations were higher in the upper layer than near the bottom of the water column. These vertical distributions showed that the dissolved nitrogen and phosphorus will be affected by nutrient release from the sediments, but that TN, TP, and Chl a will be influenced by the phytoplankton and suspended organic detritus. Thus, nutrient concentrations vary greatly by water depth in this shallow lake.

4.4.1.3 Relationship Between Nutrient Concentration in the Overlying Water and Wind Speed

The column mean values of eight water quality variables from seven depths in September 2001, at site 2, were used to determine correlations of the variables

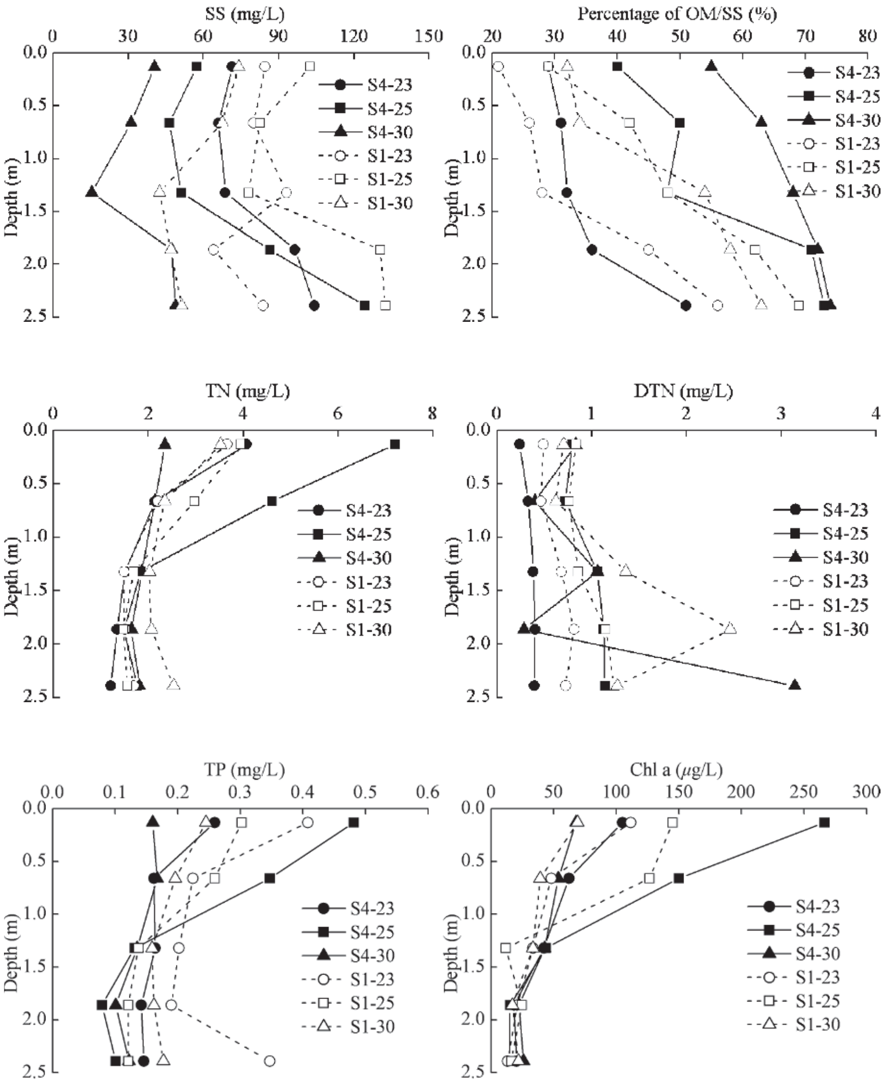

Fig. 4.21 Vertical profiles of suspended solids (SS) and organic matter content (SS-OM), total nitrogen (TN), total dissolved nitrogen (DTN), total phosphorus (TP), and chlorophyll *a* (Chl a) content in the water column at sites 1 and 4 in Meiliang Bay on July 23, 25, and 30, 1998

with wind speeds (Fig. 4.22). Data for the lowest depth of the water column was excluded from calculation of the mean concentration, since SS concentration was much higher near the sediment-water interface than that in upper layers, and was affected by sampling. The excluded data should not affect the qualitative analysis of the release of nutrient under dynamic disturbances.

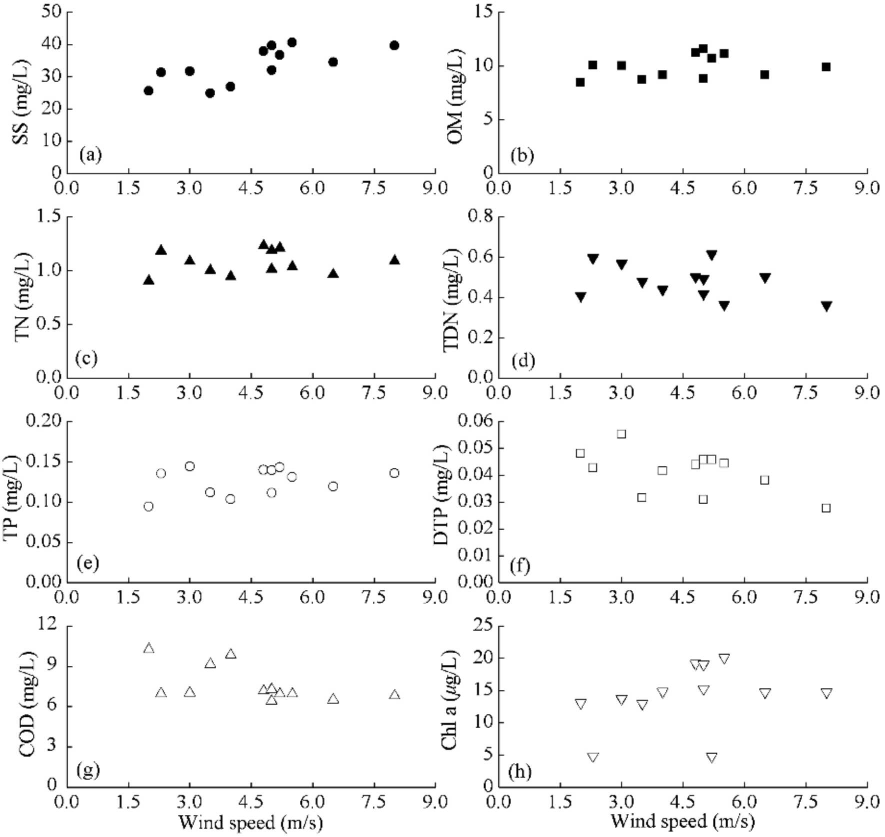

Fig. 4.22 Relationships between column mean values of SS (**a**), OM (**b**), TN (**c**), DTN (**d**), TP (**e**), DTP (**f**), chemical oxygen demand (COD) (**g**), and Chl a (**h**) with wind speed in Meiliang Bay (site 2) in September 2001

The concentrations of SS, TP, and Chl a increased with wind speed (Fig. 4.22a,e,h, respectively). In contrast, DTP and COD decreased with wind speed (Fig. 4.22f,g, respectively). The increased dynamic disturbances associated with increasing wind speed brought more SS and SS-OM into the water column by means of resuspension, and as a result, the TN and TP content of the water would also greatly increase. However, soluble nutrients such as DTN and DTP did not show a marked increase with increasing of wind speed, probably because of sorption of particles.

From May 6 to 11, 2003, at site 3 in Meiliang Bay, data were collected on concentrations of SS, LOI of organic matter (which denotes the organic matter content of the suspended solids in lake water), TP, and DTP under different wind conditions (Fig. 4.23). Concentrations of SS and TP were high at high wind speeds (7–8 m/s) and low at low wind speeds (<3 m/s), which was the direct result of increased suspension of sediments under strong wind stresses (Fig. 4.23). However, LOI of the suspended solids was low at high wind speed and high at low wind speed. No

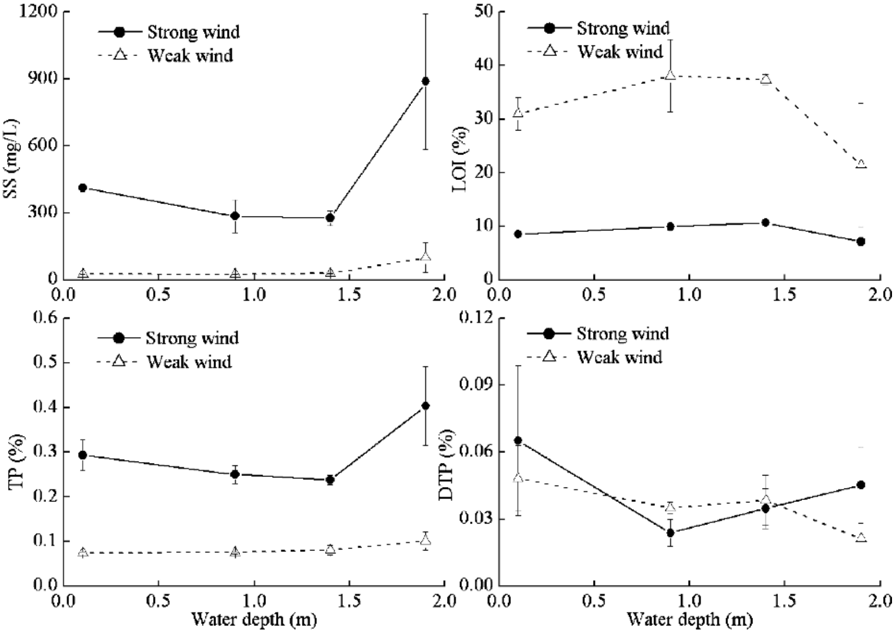

Fig. 4.23 Relationship between concentration of suspended solids (SS), loss on ignition of SS (LOI), total phosphorus (TP), and dissolved total phosphorus (DTP) in lake water with wind strength (strong wind >8 m/s; weak wind <3 m/s) and depth at site 3 in Meiliang Bay in May, 2003

marked changes in DTP contents in lake water were noted at different wind stresses, similar to the situations at another site, site 2, in Meiliang Bay in September 2001, as noted earlier.

4.4.2 Internal Loading of Nutrients

A variety of mechanisms can transport nutrients from the sediment to the overlying water; for example, diffusion, wind-induced water turbulence, bioturbation, release of sediment gases, and removal by algae and rooted aquatic plant harvest (Wetzel, 2001). In Lake Taihu, the first two mechanisms are the main types of nutrient release. Diffusion of nutrients from the sediment to the overlying water occurs in calm conditions, and is temperature dependent, with faster diffusion occurring at higher temperatures. In calm conditions, the sediment–water interface becomes more reducible than in strong mixing conditions. Nutrient release following sediment resuspension takes place during wind-induced water turbulence. This latter mechanism of nutrient release, which can involve significant amounts of nutrients, is more efficient than the former diffusive release. Under field conditions, these two mechanisms of nutrient release alternate.

Nutrient concentrations in pore water increase with sediment depth in shallow lakes (Qin et al., 2004). The constant weak oxidized conditions across the sediment–water interface favor decomposition of organic matter in the sediment. At the same time, dynamic disturbance erodes the surface sediment particles and releases dissolved nutrients to the water column. Some dissolved interstitial nutrients, especially SRP, may be adsorbed by ferric iron and other oxides. In calm conditions, the suspended sediment particles and the adsorbed nutrients may settle to the bottom of the lake and be subjected to another suspension during the next wind disturbance (Qin et al., 2004). During calm periods, nutrient release from the sediment is controlled by diffusion associated with nutrient gradients from the dissolved interstitial regions to the overlying water. During strong wind-wave activity, there is not only a great increase in TP and TN concentrations in the water column, but also a possible decrease of soluble nutrients in the water. Thus, in a shallow lake such as Lake Taihu, there is a totally mixed mode of nutrient release; this is distinct from the situation in a deep lake, where nutrient release is only from diffusion.

4.4.2.1 Nutrient Exchange Flux Across the Sediment–Water Interface Under Static Conditions

The daily exchange rates and annual released amounts of nutrients at three different temperatures in static conditions are given in Table 4.13 (NH_4^+-N) and Table 4.14 (PO_4^{3-}-P). Generally, in the lower water temperatures, some areas of the lake, such as southern Mashan, the west littoral area, and the southwest centre, serve as a “sink” rather than a “source” for nutrient exchange, meaning that relatively low temperatures reduce the production of ammonium in the sediments. In contrast, release of PO_4^{3-}-P did not increase with temperature. The annual amount of nutrient release in static conditions was considerable, equal to some 10,000 t NH_4^+-N and 900 t PO_4^{3-}-P, or 20–30% and 30–35% of the annual external load of nitrogen and phosphorus, respectively.

4.4.2.2 Estimates of the Total Nutrient Release Under Dynamic Conditions

Estimates for soluble nutrient release are complicated, because sediment suspension was usually accompanied by soluble nutrient release and adsorption, and the adsorption and suspension processes for SS in sediments are related to the oxygen and Fe concentrations in the water.

Here we describe an estimate for release of DTN and DTP from pore water, and of TN and TP from sediments under one distinct dynamic process. It was assumed that dissolved nutrients released from pore water were not adsorbed by suspended solids, and that there was no sedimentation. In the wind-wave disturbance process, the dissolved nutrients in sediment pore water were mixed in the overlying water column and were bioavailable without any inactivation reaction. Therefore, the internal loading of soluble nutrients comprises the total dissolved nutrients in pore water in all the eroded sediments. Similarly, the internal loading of TN and TP comprises the total nitrogen and phosphorus in all eroded sediments. Based on the

Table 4.13 Flux of NH_4^+-N at the sediment–water interface of Lake Taihu, at three different temperatures under static conditions (Fan et al., 2004)

District of the lake	Area of soft sediment (km^2)	Flux of NH_4^+-N exchange at different temperatures (mg/(m$^2 \cdot$ d))			Loading of ammonium (t/yr)
		5°C (75 d)	15°C (120 d)	25°C (170 d)	
Eastern Wuli Bay	3.4	78.8 ± 27.6	−113.9 ± 52.4	13.1 ± 7.5	−18.8 ± 10.0
Western Wuli Bay	1.1	33.7 ± 11.8	66.2 ± 30.5	187.0 ± 106.6	46.5 ± 24.9
Xiaowanli	19.2	23.1 ± 8.1	17.1 ± 7.9	40.7 ± 23.2	205.7 ± 105.6
Central Meiliang Bay	21.5	17.3 ± 6.1	131.7 ± 60.6	−11.2 ± 6.4	326.5 ± 142.6
Mashan Bay	21.2	94.9 ± 117.7	−44.8 ± 42.1	−77.2 ± 49.4	−241.3 ± 98.1
Gonghu Bay	74.8	13.2 ± 16.4	−92.0 ± 86.4	63.1 ± 40.4	51.6 ± 170.2
Zhushan Bay	24.9	−19.3 ± 23.9	−15.1 ± 14.2	56.9 ± 36.4	159.6 ± 66.9
West littoral area	247.6	−48.6 ± 17.0	−22.2 ± 10.2	62.4 ± 35.6	1, 067.0 ± 879.2
Southwest centrr	214.0	−27.1 ± 33.6	1.0 ± 1.0	39.6 ± 25.3	1, 030.8 ± 406.8
Southwest littoral	203.6	−3.9 ± 4.8	4.2 ± 4.0	45.6 ± 29.2	1, 621.7 ± 1, 033.2
Southern Mashan	101.8	−75.3 ± 93.4	79.3 ± 74.5	30.6 ± 19.6	923.3 ± 536.6
Central Lake Taihu	119.8	−13.6 ± 4.8	0.1 ± 0.1	20.7 ± 11.8	301.8 ± 198.7
Littoral of Xishan	162.2	−18.3 ± 22.7	55.2 ± 51.9	23.5 ± 15.0	1, 500.7 ± 1, 149.5
Xukou Bay	118.0	6.4 ± 7.9	−51.3 ± 48.2	19.7 ± 12.6	−274.4 ± 359.6
Eastern Taihu Bay	289.7	28.7 ± 10.0	64.5 ± 29.7	18.0 ± 10.3	3, 868.9 ± 1, 809.5
Mean value	–	−16.0 ± 17.6	12.6 ± 6.9	34.1 ± 20.8	—
Sum	1631.8	—	—	—	10, 569.6 ± 6, 991.4

Note: Minus means the contents of ammonium decrease when exchanged with sediments.

Table 4.14 Flux and loading of phosphate at the sediment–water interface of Lake Taihu at three different temperatures under static conditions (Fan et al., 2006)

District of the lake	Area of soft sediment (km^2)	Exchange flux of phosphate at different temperatures (mg/(m^2·d))			Loading of phosphate (t/yr)
		5°C (75 d)	15°C (120 d)	25°C (170 d)	
Eastern Wuli Bay	3.4	2.95 ± 1.99	−0.40 ± 0.34	0.50 ± 0.50	0.9 ± 0.7
Western Wuli Bay	1.1	5.20 ± 3.51	3.13 ± 2.61	2.11 ± 2.10	1.2 ± 1.0
XiaoWanli	19.2	2.87 ± 1.94	−3.25 ± 2.72	−3.72 ± 3.70	−15.5 ± 15.6
Central Meiliang Bay	21.5	1.20 ± 0.81	−0.13 ± 0.11	−0.57 ± 0.57	−0.5 ± 1.0
Mashan Bay	21.2	2.57 ± 0.84	0.29 ± 0.10	−0.80 ± 0.28	1.9 ± 0.6
Gonghu Bay	74.8	−0.08 ± 0.03	4.02 ± 1.35	0.63 ± 0.22	43.6 ± 14.8
Zhushan Bay	24.9	−2.08 ± 0.68	2.42 ± 0.82	2.54 ± 0.88	14.1 ± 4.9
West littoral area	247.6	3.93 ± 2.65	1.60 ± 1.34	0.60 ± 0.60	145.9 ± 114.2
Southwest centre	214.0	1.33 ± 0.43	−2.83 ± 0.95	−0.66 ± 0.23	−75.2 ± 25.8
Southwest littoral	203.6	2.19 ± 0.71	5.67 ± 1.91	1.37 ± 0.47	219.4 ± 74.0
Southern Mashan	101.8	−3.88 ± 1.26	2.49 ± 0.84	0.29 ± 0.10	5.7 ± 2.3
Central Lake Taihu	119.8	1.44 ± 0.97	−1.76 ± 1.47	0.78 ± 0.78	3.7 ± 3.5
Littoral of Xishan	162.2	2.65 ± 0.87	3.13 ± 1.05	1.44 ± 0.50	133.1 ± 44.9
Xukou Bay	118.0	3.37 ± 1.1	0.22 ± 0.08	1.49 ± 0.52	63.0 ± 21.2
Eastern Taihu Bay	289.7	0.24 ± 0.16	3.59 ± 3.00	4.41 ± 4.39	358.1 ± 334.0
Mean value	—	1.52 ± 0.78	1.78 ± 0.96	1.32 ± 1.05	—
Sum	1631.8	—	—	—	899.4 ± 573.6

Note: Minus means the contents of ammonium decrease when exchanged with sediments.

wave flume experiments, the strong waves in Lake Taihu may erode the upper 10 cm of the sediment (Qin et al., 2004). Therefore, the hypothesis is that the upper 10 cm of sediment could be suspended in a strong enough hydrodynamic process.

Estimates for nutrient release from pore water were derived from calculations of sediment porosity, dissolved total nitrogen (TN), and dissolved total phosphorus (TP) concentrations in pore water (Table 4.15). The physicochemical characteristics (gross weight, organic matter content, and porosity) of four sediment cores taken in June 2001 revealed that the upper 5–10 cm of the sediment had been actively involved in exchange of sediment with the overlying water (Qin et al., 2004). As a result, estimates of nutrient release from sediments in one strong dynamic process were calculated assuming that suspension occurred in the upper 10 cm of the sediment. Spatial distribution of surface sediments was not uniform in Lake Taihu, and a detailed distribution of the depth of the loose sediment was presented by Luo et al. (2004).

Lake Taihu consists of three regions: Meiliang Bay, Eastern Taihu Bay, and the remainder of the lake (main Lake Taihu). The vertical distribution of the physicochemical characteristics of the sediments was calculated according to the four sediment cores. As a result, if the upper 10 cm of the sediments was taken in lake water and thoroughly mixed, the total release of nutrients from the sediment to lake water was calculated to be 23,059 kg DTN and 1,236 kg DTP in Meiliang Bay, 29,618 kg DTN and 1,514 kg DTP in Eastern Taihu Bay, and 477,668 kg DTN and 20,606 kg DTP in the main Lake Taihu (see Table 4.15); this was equivalent to an increase in TN of 0.12 mg/L and in TP of 0.005 mg/L in all of Lake Taihu when the upper 10 cm sediments were eroded into the overlying water column. Compared with the mean concentrations of TN of 2–4 mg/L and TP of 0.01–0.1 mg/L in the water column in Lake Taihu, strong sediment suspension (upper 10 cm sediments moved into the lake water) would result in an increase of DTN and DTP of 3–6% and 5–50%, respectively.

The actual release of nutrients from the sediments would be lower than these estimates, which are based on only physical factors, because the abundant aquatic plants in Eastern Taihu Bay will decrease the suspension and release of sediments. Moreover, adsorption and flocculation by particles may also decrease the concentration of dissolved nutrients, because the high SS concentration in the overlying water column has sufficient organic and inorganic material to adsorb the dissolved

Table 4.15 Estimates of internal loading of dissolved total nitrogen (DTN) and dissolved total phosphorus (DTP) from pore water of the upper 10 cm of sediments in three regions of Lake Taihu

	Meiliang Bay	Eastern Taihu Bay	Main Lake Taihu
Porosity (%)	45.3	45.2	40.2
DTN content (mg/L)	8.21	4.89	8.37
DTP content (mg/L)	0.44	0.25	0.36
Areas included (km^2)	62	134	1,431
N release from pore water (kg)	23,059	29,618	477,668
P release from pore water (kg)	1,236	1,514	20,606

nitrogen and phosphorus and resediment it to the lake bottom. Sometimes, some soluble nutrients, especially SRP, decreased in dynamic suspension conditions.

4.4.2.3 Estimate of Annual Nutrient Loading in This Large Shallow Lake

Estimates of nutrient release in the foregoing two release scenarios provide an opportunity to calculate the annual nutrient release. Observations of wind speed made by the Taihu Laboratory for Lake Ecosystem Research showed that Lake Taihu is located in the monsoon climate zone with prevailing northwest winds in winter and southeast winds in summer. In addition, observations of wave height versus wind speeds show that the strong wind could cause significant wave heights frequently. When wind speed is less than or equal to 2 m/s, significant wave height is just 3.5 cm and conditions are defined as "calm" because there is only rippling on the lake (Luo & Qin, 2003). When wind speed is >2 m/s and <6 m/s, the significant wave height is 15 cm (1/10 of the time wave height is 60–70 cm), which is defined as "gentle" because this wind force aerates the overlying water well but does not cause significant sediment resuspension. When the wind speed is >6 m/s, defined as "gusty," there is significant sediment resuspension. In the 2001 wind speed study, 45 days were "calm" (12% of the year), 298 days were "gentle" (82%), and 22 days were "gusty" (6%). Because instantaneous gusts happen frequently in some areas of Lake Taihu, the actual frequency of "gusty" is probably underestimated.

By use of the percentage of "calm" weather (12% of a year) and the internal loading obtained in the laboratory calculated in Table 4.15, the total releases of nitrogen ($NH_4{}^+$-N) and phosphate ($PO_4{}^{3-}$-P) are 1,272 t and 108 t in a year, respectively. For the "gentle" weather, no laboratory experiment was conducted to determine the release rate, so we used results from flume experiments (Luo et al., 2006; Sun et al., 2006). In "gentle" wind conditions, the sediment will not be markedly resuspended, but the water will be well aerated, and the shear stress between the water and sediment is about 0.019 N/m^2. In "gusty" conditions, the sediment will be eroded and resuspended significantly, with a shear stress of about 0.217 N/m^2. Correspondingly, during "gentle" conditions, the release rates of TN and TP are 1.92×10^{-3} mg/($m^2 \cdot$ s) and 5.69×10^{-4} mg/($m^2 \cdot$ s), respectively, whereas during gusty conditions, the release rate of TN and TP are 1.16×10^{-2} mg/($m^2 \cdot$ s) and 2.14×10^{-3} mg/($m^2 \cdot$ s) (Luo et al., 2006). Therefore, under "gentle" wind conditions, the daily internal loading of TN and TP should be 186 t and 55 t, respectively (Qin et al., 2006). Accordingly, with 298 days of "gentle" wind conditions in a year, the annual contributions from "gentle" wind conditions to TN and TP should be 55,430 t and 6,390 t, respectively (Qin et al., 2006). Calculated in the same way, the annual contributions of TN and TP from "gusty" wind conditions (22 days) would be 81,000 t and 21,000 t, respectively (Qin et al., 2006).

Investigations of external loading in Lake Taihu have given values ranging from 39,000 to 41,000 t for nitrogen and from 2,900 to 3,800 t for phosphorus (Sun & Huang, 1993). The amounts of nutrients released from the sediment are two to six times those from external loading, and the internal release during turbulence is much higher than during "calm" conditions, during which diffusion provides the main release of nutrients. For TN and TP release following sediment resuspension, even one “gust” on the lake causes sediment resuspension, resulting in massive nutrient release. Therefore, wind-wave hydrodynamic disturbance must play a key role on the internal release of nutrients in large and shallow lakes such as Lake Taihu.

Only a small percentage of the released nutrients will contribute to eutrophication, because most nutrient fractions are not easily utilized by the phytoplankton. Moreover, under dynamic conditions, nutrient release occurs near the sediment–water interface, and most of the particulate nutrients will resediment quickly. Additionally, as a result of flocculation and adsorption by suspended particles and ferric iron, a considerable proportion of the dissolved nutrients will precipitate again and be buried in the sediments. Thus, most of the nutrients released from the sediment to the overlying water do not participate in biogeochemical cycling in the water ecosystem during strong wind events. In spite of that, such significant internal nutrient sources as 137,702 t TN and 27,498 t TP should not be neglected in the view of eutrophication control in Lake Taihu

4.4.3 Conceptual Model of Internal Loading of Nutrients in Large Shallow Lakes Such as Lake Taihu

The nutrient (TN and TP) concentrations in the overlying water will greatly increase under wind-stressed disturbances. Laboratory experiments have shown that winds cause suspension and diffusion-induced nutrient increases in the overlying water that may be dozens of times greater than those occurring under calm conditions, when diffusion alone operates (Reddy et al., 1996). In Lake Arresø, Denmark, with a surface area of 41 km^2 and a mean depth of 2.9 m, wind-induced resuspension could increase nutrient concentrations in the water column by up to 20–30 times those in “calm” condition simulated in the laboratory (Sǿndergaard et al., 1992). Statistics indicate that SS and TP concentrations are strongly correlated with wind speed (Kristensen et al., 1992; Sǿndergaard et al., 1992). Similar phenomena also were noted during laboratory simulations using samples from Lakes Taihu, Gehu, and Xuanwu (Wang et al., 1994; Fan 1995; Zhang et al., 2001). Investigation in Meiliang Bay in Lake Taihu during 1998 revealed that SS would double in winds of 6 m/s over those in “calm” conditions, and would increase with depth.

The upper 5–10 cm of the sediments of Lake Taihu was not only actively involved in nutrient exchange across the sediment–water interface but also provided nutrient transport into the overlying water under dynamic disturbance and resuspension. Below a sediment depth of 5–10 cm, nutrients could be carried into the upper water through gradient-induced diffusion (Qin et al., 2004). A similar finding has been reported for Lake Apopka, a large shallow lake in Florida, United States (Reddy et al., 1996).

Nutrient exchange across the sediment–water interface is not only controlled by dynamic disturbances, but also by the oxidation and reduction potential (*Eh*); this is especially true for soluble nutrients such as SRP (Mortimer, 1971; Moore & Reddy, 1994). Oxidizing conditions favor formation of Fe- or Mn oxides in surface sediments, which can enhance the adsorption ability of soluble nutrients and inhibit nutrient release to the overlying water. Reducing conditions enhance release of dissolved nutrients to the overlying water (Gächter et al., 1988; Hohener & Gächter, 1994). For this reason, variations in dissolved oxygen at the sediment–water interface in a given site are good indicators of rates of nutrient release.

Wind-stressed sediment resuspension is common in shallow lakes, such as Lake Taihu, leading to an unstable sediment–water interface. In contrast, deep lakes have a stable sediment–water interface that is much less affected by wind stress. The constant dynamic disturbance in shallow Lake Taihu frequently transports additional oxygen to the sediment–water interface. Field observations revealed small spatial variations in dissolved oxygen (DO) concentrations in Lake Taihu, ranging from 9.0 to 9.5 mg/L (Sun & Huang, 1993; Yu, 1994). As a result, the *Eh* potentials across the sediment–water interface differed slightly, from -100 to -200 mV, indicating a weak reducing environment (Qin et al., 2004). The static release from sediments in shallow lakes is likely lower than that in deep lakes, which typically possess a more reduced sediment–water interface.

In shallow lakes such as Lake Taihu, accurate estimates for internal nutrient loading, especially for SRP, require further understanding of the behavior of metallic elements such as iron and manganese in water and in sediments. Dynamic disturbances could release nutrients from the sediments through suspension, leading to increased concentrations of SS, TN, and TP in the overlying water. At the same time, the release of soluble nutrients, especially SRP, will decrease because of reoxygenation in the water. The Fe content of sediments could have a great impact on the internal nutrient release (Jensen et al., 1992). Investigations on sediments from more than 100 lakes in Denmark found that total Fe and TP in sediments were positively correlated, whereas the TP in the overlying water was negatively correlated with Fe:P in the sediments (the higher the Fe:P ratio in the sediments, the lower the TP concentration in the overlying water) (Jensen et al., 1992). A Fe:P ratio of 15:1 in sediments could be a criterion for defining marked P release from the sediments. In Lake Taihu, the Fe:P ratio was between 20 and 40 (Zhu, 2003), indicating that under intensive dynamic disturbance there is a trend towards higher TP content with lower SRP content in the lake water. In such a case, most nutrients released following resuspension would not affect the ecosystem and eutrophication. However, in Lake Taihu, wind gusts and resuspension are so frequent, and the calculated annual nutrient release is so high, that the cumulative effects of nutrient release exert profound influences on the lake ecosystem, and these effects should be addressed in subsequent studies.

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