Hydrobiologia (2007) 581:63–70
DOI 10.1007/s10750-006-0515-3

EUTROPHICATION IN LAKES

Total inputs of phosphorus and nitrogen by wet deposition into Lake Taihu, China

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Abstract Lake Taihu suffers from eutrophication caused by riverine nutrient inputs and air deposition. To characterize wet deposition of phosphorus (P) and nitrogen (N) to the lake, precipitation collection and measurements of total phosphorus (TP) and total nitrogen (TN) and other components at five cities around Lake Taihu were made from July 2002 to June 2003. TP and TN concentrations and deposition rates exhibited strong spatial variation in the whole catchment. An inverse correlation between station-averaged TP and TN concentrations and precipitation amount was found. Maximal TP concentration in rainfall was found in Suzhou, and maximal TN in Wuxi. However, highest wet deposition rates of TP and TN were found in Suzhou, which suggests that atmospheric nutrients are mostly from the east and northwest area of Lake Taihu. Mean TP and TN deposition rates were 0.03 and 2.0 t km^{-2} year^{-1} respectively in Lake Taihu, which are greater than reported values in other areas by comparision. Total N and P contributed to the lake by wet deposition were 75 and 4720 t per year, respectively, which represent about 7.3% and 16.5% of total annual N and P inputs via inflow rivers. Wet deposition, especially N, could have significant effects on eutrophication in the lake, which shows that air deposition should be taken into account while reducing the external nutrients in the lake.

Keywords Nitrogen · Phosphorus · Wet deposition · Eutrophication · Riverine inputs · Lake Taihu

Guest editors: B. Qin, Z. Liu & K. Havens
Eutrophication of shallow lakes with special reference to Lake Taihu, China

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Introduction

Wet deposition may impact freshwater ecosystems, terrestrial environments (Buijsman & Erisman, 1988; Likens, 1989; Khemani et al., 1989; Lovett & Kinsman, 1990; Owens et al., 1992; Spokes et al., 1993; Helmers & Schrems, 1995; Raper & Lee, 1996) and coastal seas (De Leeuw et al., 2003). Input of nutrients by rainfall (e.g. P and N) and acidic rain characterized by low pH (<5.6) can affect the chemistry of lakes, soils, forests and wetlands (Gorham, 1998) and make ecosystems nutrient-limited or susceptible to acid deposition. For instance, it was noted (Gordon & Gorham, 1963) that acid deposition close to the iron-sintering plant at Lakes Wawa and Ontario was causing substantial leaching of calcium from local soils into adjacent ponds and lakes. It then was observed that acid deposition led to dissolution of aluminum in soil minerals and strong enrichment of aluminum ions in lake water (Wright et al., 1976). Many other researchers have addressed acidic rain in different areas (Cowling & Nilsson, 1995; Lin et al., 1998; Okochi et al., 2000; Peart, 2000; Vasjari et al., 2000).

Polluted rain also may deposit nutrients and trace elements, resulting in eutrophication and iron-concentration changes. Input of nutrients by wet deposition can contribute to total nutrients in water, especially in seepage lakes, regulate primary productivity and affect algal community structure (Pollman et al., 2002). Atmospheric N can be available for algae growth, which makes this contribution more significant because only a fraction of river runoff contributes N that is incorporated into biological material (De Leeuw et al., 2003). Heavy metals from rainfall (e.g. Zn, Cu, Fe, Ca and Mg) can affect surface water production (Morel et al., 1991) and influence biological activity in marine waters (Coale & Bruland, 1990; Sunda & Huntsman, 1992).

Lake Taihu is located in the lower Changjiang (Yangtze) River delta and is important for water quantity regulation, water supply, cultivation, irrigation, navigation, culture fisheries and tourism. In the 1950s, lake water was oligotrophic (Chang, 1995). With rapid industrial and agricultural development and population growth, increasing amounts of nutrients, heavy metals (Shen et al., 2001) and other pollutants (Feng et al., 2003) have been delivered to the lake via river runoff (Zhou & Zhu, 2003; Chen et al., 2003; Qu et al., 2001) or bulk deposition (Qu et al., 2002; Pu et al., 1998). Pollutants can be absorbed onto or associated with fine-grained sediment particles, resulting in limnic ecosystem recovery prevention and long-term eutrophication problems by sediment-water exchange. The lake is hypertrophic in three northern bays, with seasonal algae blooms increasing the cost of water purification. Consequently, reasons for deterioration and improvement of lake water-quality have received much attention in recent years (Wang et al., 1998; Qin, 1998; Yang et al., 2001; Chen, 2002; Yang et al., 2003; Qin et al., 2004). The largest project, ''Zero-point Action'', initiated by the State Environmental Protection Administration (SEPA) in 1998, required ''Standard Discharge'' of all industrial units. However, water quality has not improved remarkably despite reduction of external loading from rivers, which raises the possibility that net air-deposition and sediment resuspension may have considerable impacts.

Many reports have focused on effects of sediment and river inputs (Zheng et al., 2001) on water quality degradation in Lake Taihu, including acid rain impacts (Chen et al., 2000, 2001; Yang et al., 2001; Yang, 2001). Little is known about amounts of N & P contributed by wet deposition. The aim of this study is to estimate wet-deposition of P and N into the lake based on data from samples collected from July 2002 to June 2003.

Methodology

Site description

Fifteen sampling sites, located in five cities (Wuxi, Suzhou, Huzhou, Jintan and Changzhou; Fig. 1) around Lake Taihu, were selected for rain collection. Four were at Changzhou situated northwest of the lake, four in Suzhou in the east, three in Huzhou in the south, two in Wuxi in the north and two in Jintan in the northwest (Table 1). Several sites in each city were sampled

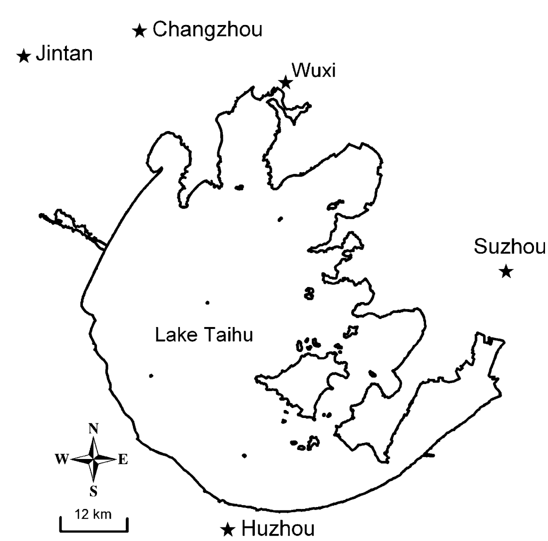

Fig. 1 Map of the study area

Table 1 Sample stations and their locations in Taihu Basin

Station	Longitude (°E)	Latitude (°N)	Site number	Location
Wuxi	120.25	31.58	2	North
Suzhou	120.61	31.30	4	East
Changzhou	119.97	31.77	4	Northwest
Jintan	119.58	31.73	2	Northwest
Huzhou	120.10	30.89	3	South

to evaluate different land-use types (e.g. rural, urban, industrial, forest, etc.).

Sample collection and analysis

Precipitation samples were collected automatically by a tipping-bucket rain gauge at all sites from July 2002–June 2003. Analytical parameters included pH, conductivity, K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, NO_3^-, NH_4^+, TP and TN (no TP & TN in Huzhou due to technical limits). All chemical components were analyzed monthly in the local Environmental Monitoring Center (EMC). pH was measured immediately without stirring by a digital pH meter, and conductivity was measured using an ion chromatography detector. All ions were determined using suppressed ion chromatography (Chen et al., 2001). All data from different EMCs were assumed to have similar accuracy since ion concentration measurements were done using standard SEPA methods.

Calculation of annual amount of deposited nutrients

Annual amounts (in: t year^{-1}) of TP and TN can be calculated from the following equation,

$$AA = \frac{1}{m}\sum_{j=1}^{m}\sum_{i=1}^{n} S \times RR_{ij} \times C_{ij} \times 10^{-3} \qquad (1)$$

where S is the lake surface area (km^2), RR_{ij} (i = 1,2,...12; j = 1,2,3,4) is the precipitation rate (mm month^{-1}) at station j and month i, C_{ij} is the concentration of a substance in precipitation (mg l^{-1}) with the same subscript as RR_{ij}, m is the number of stations (4 in this case due to lack of data in Huzhou). The wet deposition rate (in: t km^{-2} year^{-1}) of chemical components can be derived from Eq. 1 without consideration of S.

Results

Seasonality

Monthly precipitation (RR) and TN and TP concentrations are shown in Fig. 2. RR ranged from 24–130 mm per month. Minimum RR was in January, with a value of 24.3 mm, and November, with a value of 50.7 mm. There was more rainfall in summer (128 mm in August and 117 mm in July). RR exhibited a summer (June–August) maximum and a fall (September–November) minimum, demonstrating strong seasonality.

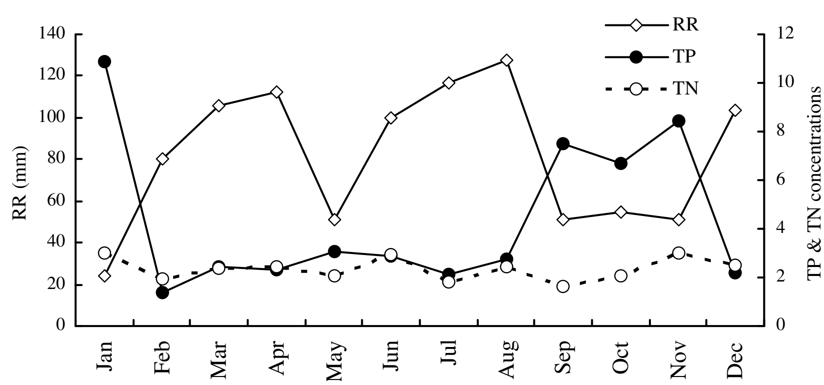

Fig. 2 Monthly station-averaged precipitation amount (RR, in mm), precipitation-weighted concentrations of TP (in: 100 mg l^{-1}) and TN (in: mg l^{-1})

TP concentration varied from 0.01 to 0.11 mg l^{-1} with the peak value in January, which is, in magnitude, similar with those reported by Brown et al. (1984, 0.015–0.15 mg l^{-1}) and Migon and Sandroni (1999, 0.002–0.14 mg l^{-1},), but significantly greater than those reported by Chen et al. (1985) and Filoso et al. (1999). Although no significant seasonal variation in TN was found (Fig. 2), there was a seasonality of TP and TN despite slight differences among the 12 months. TN and TP followed an inverse pattern to RR.

TN contributed by rain followed a similar seasonal pattern to RR and peaked in summer and fall, with minima in winter and spring. However, TP had a maximum in fall and winter and minimum in spring and summer (Fig. 3). These seasonal differences varied from those of TP and TN concentrations throughout the year due to differences in precipitation amounts.

Total annual TP and TN deposition rates

Deposition rates of NO_3^-, NH_4^+, TP and TN were estimated from Eq. (1) with lake surface area excluded. In each city, monthly precipitation amounts were used to calculate average precipitation rates. Table 2 shows month-averaged wet deposition rates of the five cities. There was no data on TN and TP in Huzhou, but concentrations of NO_3^- and NH_4^+ suggest a moderate contribution. Spatial differences suggest that the east region of Lake Taihu (Suzhou), and then the northwest (Changzhou and Jintan) have the largest N and P contribution from rainfall. Wuxi and Huzhou have moderate influences. Wet deposition of TP within the lake catchment was 0.03 t km^{-2} $year^{-1}$, TN was 2.0 t km^{-2} $year^{-1}$, NO_3^- was 3.70 t km^{-2} $year^{-1}$, and NH_4^+ was 1.56 t km^{-2} $year^{-1}$. Based on individual deposition rates, total annual contribution from precipitation was 75 and 4720 t per year for TP and TN, respectively.

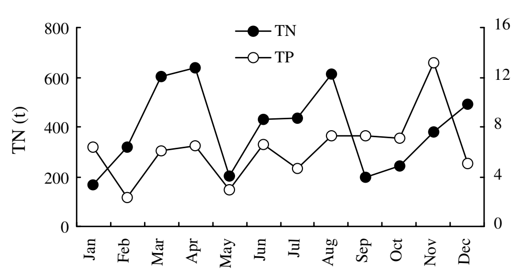

Fig. 3 Monthly station-averaged amounts of TP & TN (in: t)

Discussion

The simple model based on Eq.1 may overestimate total input of N & P into Lake Taihu because precipitation chemistry over the lake may differ from cities. Raindrops are formed when small water droplets adhere to particles, including chemical components in air, and, consequently, depend on local air movement and concentrations of vapor and particles in the atmosphere. Due to low nutrient concentrations in air over the lake, especially the center, precipitation inputs of P and N in these regions may be lower than those in the shore areas. However, this uncertainty for regional differences is difficult to quantify unless many observation sites are established over the water surface of Lake Taihu.

Despite the spatial variability of nutrient concentrations in precipitation, results obtained from observation data and calculations should indicate

Table 2 Wet-deposition rates (t km^{-2} $year^{-1}$) and concentrations (mg l^{-1}) of TP and TN at different stations

City	Wet deposition rate (t km^{-2} $year^{-1}$)				Averaged concentration (mg l^{-1})	
	TP	TN	NO_3^-	NH_4^+	TP	TN
Wuxi	0.016	2.25	2.76	1.44	0.022	3.28
Suzhou	0.06	2.81	4.36	2.26	0.075	2.58
Changzhou	0.018	1.81	0.82	1.52	0.023	2.22
Jintan	0.033	1.20	6.70	0.95	0.057	1.33
Huzhou			3.87	1.65		
Average	0.03	2.0	3.70	1.56	0.044	2.35

effects of wet deposition on lake eutrophication. In Lake Taihu, the primary source of N and P is from Suzhou, where the highest TP concentration and deposition rates were found. Changzhou and Jintan had the second greatest contribution of TN and TP. Thus, the main N and P inputs via rainfall are from the east and northwest. The smallest TP deposition rate and the greatest TN concentration were found in Wuxi. Therefore, Wuxi, with a greater annual precipitation, may make the greatest contribution to total N input into the lake.

Deposition rates of NO_3^- and NH_4^+ are high relative to TN inputs, with values of 3.70 and 1.56 t km^{-2} year^{-1}, respectively, which are 2 and 5 times higher than those for Barnegat Bay (1.81 and 0.34 t km^{-2} year^{-1} for NO_3^- and NH_4^+; Gao, 2002). Estimated TP deposition rate (0.03 t km^{-2} year^{-1}) near Lake Taihu also is high compared to that in the Amazon (0.004 t km^{-2} year^{-1}; Swap et al., 1992), Connecticut (0.004 t km^{-2} year^{-1}; Yang et al., 1996), New Zealand (0.01 t km^{-2} year^{-1}; Chen et al., 1985), Corsica (0.01–0.02 t km^{-2} year^{-1}; Bergametti et al., 1992), Apalachicola, FL (0.012 t km^{-2} year^{-1}; Fu & Winchester, 1994) and Ireland (0.021 t km^{-2} year^{-1}; Gibson et al., 1995). Also, TN deposition rate is about 10 times that in Colorado and southern Wyoming (<0.2 t km^{-2} year^{-1}; Burn, 2003). High N and P deposition rates result from livestock and fertilization of croplands (Vitousek et al., 1997), crop senescence, fossil fuel combustion, automobile emissions and factories. In Taihu Basin, agriculture and coal combustion are the main contributors to high rates of N and P deposition.

Wet deposition is greater than dry deposition, especially in ocean areas (Owens et al., 1992; Hertel et al., 2002), the Mississippi River Basin (Lawrence et al., 2000), and Barnegat Bay (Gao, 2002). With this hypothesis, annual net atmospheric inputs of TP and TN into Lake Taihu should be slightly higher than estimated values. However, deposition effects on lake eutrophication are significant even excluding dry deposition. Based on nutrient concentrations observed at inflow rivers connected to Lake Taihu, annual riverine input of TP was estimated to be 1,030 t and TN about 28,650 t (Xu & Qin, 2005). Therefore, atmospheric inputs of TP and TN represent about 7.3% and 16.5% of annual total inputs of P and N via inflow rivers, which suggests that air deposition should be considered in the evaluation nutrient inputs to Lake Taihu. Nitrogen from air deposition may promote primary productivity. For example, 5.3 mmol C m^{-2} day^{-1} could result from average deposition of 0.8 mmol N m^{-2} day^{-1} (De Leeuw et al., 2003). Also, atmospheric deposition can affect nitrogen-saturated forests and acidic freshwater lakes and streams (Stoddard, 1994; Aber et al., 1995; Fenn et al., 1998). However, Lake Taihu generally is P-limited and inherently vulnerable to N deposition (Yin et al., 1996). As a result, deposited P could promote primary productivity. Moreover, some deposited N and P may be absorbed onto or associated with sediment particles, which could make bottom sediment a source of nutrients. In shallow lakes, perturbation has substantial effects on sediment-water interactions (Sheng & Lick, 1979; Furumai et al., 1989; Shrestha, 1996; James et al., 1997; Bailey and Hamilton, 1997; Blom & Winkels, 1998; Poelma & Ooms, 2002), and therefore, waves may resuspend sediment and release nutrients resulting in increased N & P. For example, 1.64×10^4 t P can be suspended from sediment into water of Lake Taihu with a 15.0 m s^{-1} SE wind event, resulting in an average TP increase of 4.70 mg l^{-1} (Luo, 2004). Some suspended P may be available for aquatic plants, and some may be redeposited.

Atmospheric N originates mainly from ammonium nitrate aerosol (NH_4NO_3), ammonia gas (NH_3) and nitric acid gas (HNO_3) (Lindberg et al., 1990). NO_x exists primarily as NH_4NO_3 and HNO_3, and can be transformed to HNO_3 after photochemical processes. HNO_3 and NH_3 (primary pollutant) can form an equilibrium with NH_4NO_3 (Tarnay et al., 2001). These compounds are mainly derived from fossil fuel combustion and agricultural production (e.g. fertilizer and animal waste). The origin of atmospheric deposition can reflect nutrient-source patterns of riverine inputs. Consequently, external N loading control in Lake Taihu Basin should include production of agricultural and fuel-combustion emissions. The ''Zero-point Action'' initiated by SEPA in 1998 has resulted in significant reduction of TP and TN inputs in Lake Taihu, but agricultural inputs of TP and TN still constitute a large proportion. Thus, control of only industrial discharge is not an effective method to control eutrophication. Municipal policy should include control of agricultural emission and coal combustion inputs in Lake Taihu Basin.

Conclusion

A study of wet deposition in Lake Taihu Basin examined the effects of N and P contributed by rainfall on lake eutrophication. Fifteen sites were selected in five cities around the lake. Results lead to the following conclusions:

(1) Deposition rates and concentrations of TP and TN in precipitation over Lake Taihu exhibited strong spatial variation. N and P in precipitation come mainly from the east (Suzhou) and northwest (Changzhou and Jintan). Wuxi and Huzhou make only moderate contributions to atmospheric inputs into Lake Taihu.

(2) Precipitation had a summer maximum and a fall minimum and followed an inverse seasonal cycle compared to TP and TN concentrations.

(3) Deposition rates of NO_3^- and NH_4^+ were 3.70 and 1.56 t km^{-2} year^{-1}, respectively. TP and TN deposition rates were 0.03 and 2.0 t km^{-2} year^{-1}, respectively.

(4) Total amounts of N and P contributed to the lake by wet deposition were 75 and 4720 t per year, respectively, which may contribute to lake eutrophication.

Acknowledgements We would like to gratefully acknowledge financial support from Chinese Academy of Sciences (No. KZCX1–SW–12), National Natural Science Foundation of China (No. 40501078, 40131160734), Ministry of Science and Technology of China (No. 2002AA601011) and Director Foundation of Nanjing Institute of Geography & Limnology, Chinese Academy of Sciences. Thanks to the Environmental Monitoring Centers of Wuxi, Suzhou, Changzhou, Jintan and Huzhou for their sample collection and analysis. The authors are indebted to Professor Guang Gao, Dr. Guangwei Zhu, Dr. Xiaoli Shi and Dr. Lu Zhang for their help with mathematical analysis on chemical data. This manuscript benefited from the comments of two anonymous reviewers.

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