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Nutrient budgets and biogeochemistry in an experimental agricultural watershed in Southeastern China

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Abstract. During a two-year field study, an annual nutrient budget and cycles were developed for a small agricultural watershed. The study emphasized the integrated unit of the watershed in understanding the biogeochemistry. It was found that the total nutrient input was 39.1 $\times$ 10^4 kg nitrogen and 3.91 $\times$ 10^4 kg phosphorus in the year 1995, of which the greatest input of nutrients to the watershed was chemical fertilizer application, reaching 34.7 $\times$ 10^4 kg (676 kg/ha) nitrogen and 3.88 $\times$ 10^4 kg (76 kg/ha) phosphorus. The total nutrient output from the watershed was 13.55 $\times$ 10^4 kg nitrogen and 0.40 $\times$ 10^4 kg phosphorus, while the largest output of nitrogen was denitrification, accounting for 44.1% of N output; the largest output of phosphorus was sale of crops, accounting for 99.4% of P output. The results show that the nutrient input is larger than output, demonstrating that there is nutrient surplus within the watershed, a surplus which may become a potential source of nonpoint pollution to area waters. The research showed that both denitrification and volatilization of nitrogen are key ways of nitrogen loss from the watershed. This suggests that careful management of fertilizer application will be important for the sustainable development of agriculture.

The research demonstrated that a multipond system within the watershed had high retention rate for both water and nutrients, benefiting the water, nutrient and sediment recycling in the terrestrial ecosystem and helping to reduce agricultural nonpoint pollution at its source. Therefore, this unique watershed system should be recommended due to its great potential relevance for sustainable agricultural development.

Introduction

In recent years, several studies have investigated the global changes in cycling of nutrients (nitrogen and phosphorus), Nitrogen (N) and Phosphorus (P) are considered resources, and at the same time, problems. As resources, N and P are critical agricultural components, permitting significant increases in productivity. Therefore, N and P must be carefully managed: too little fertilizer results in poor production; while too much or improper application can result in costly and potentially damaging losses to the aquatic environment. Many studies have reported nutrient losses from agricultural watersheds, especially watersheds in which chemical fertilizers have been used heavily (Bolton et al. 1970; Coote et al. 1982; McDowell et al. 1989; Jin et al. 1990, Ng et al. 1993; Gaynor & Findlay 1995; Krovang et al. 1996). Other studies show that excessive nutrient loading from agricultural watersheds can have a significant impact on receiving water bodies (Edmonson 1972; Peterjohn & Correll 1984; US EPA 1989; Tu et al. 1990; Tonderski 1996). In addition, N emissions to the atmosphere as N_2O, NH_3 and NO can have physical and chemical impact on the atmosphere (e.g., greenhouse effect) (Wayne 1991; Ismermann 1994)

China is the largest producer of nitrogen fertilizers and the largest consumer of mineral fertilizers in the world, but there is little data concerning the pollution problems caused by fertilizers. For this purpose, we selected the Liuchahe watershed of Chaohu Lake in southeastern China for our 1994–95 study of nutrient cycling. Chaohu Lake is located on a tributary of the Yangtze River, with a surface area of 760 km^2. In recent decades, nutrient-rich water has drained increasingly into the lake, causing unprecedented eutrophication (Tu et al. 1990). Research showed that nonpoint sources of nutrients accounted for 60% of total N and 63% of total P input in 1988 (Wei et al. 1992). Thus, it is very important to control nonpoint source inputs in order to minimize further impact on the water quality of Chaohu Lake. The land use of this watershed is representative of this area. This paper reports nutrient inputs, outputs, storage and internal transfers in the watershed with multipond systems.

Study site

Located on the northern bank of the lake, the Liuchahe watershed covers an area of 732 ha and a resident population of approximately 3000 inhabitants, living in some 16 small villages (Figure 1). In the Liuchahe watershed, the land pattern is composed of five types of land use (Table 1). The structure of land use is strongly influenced by geomorphological and hydrological conditions. The forestry area is on a low mountain; the nonirrigated farmland is situated on mounds; the villages are normally around the top of mounds; the rice fields and ponds are located on the plain or in the saddle between mounds. Paddy soil, yellow brown soil and purple sand stone are the main soil types (Table 2).

The 40-year (1956–1995) records from the local meteorological station for the watershed give the following annual mean values: precipitation

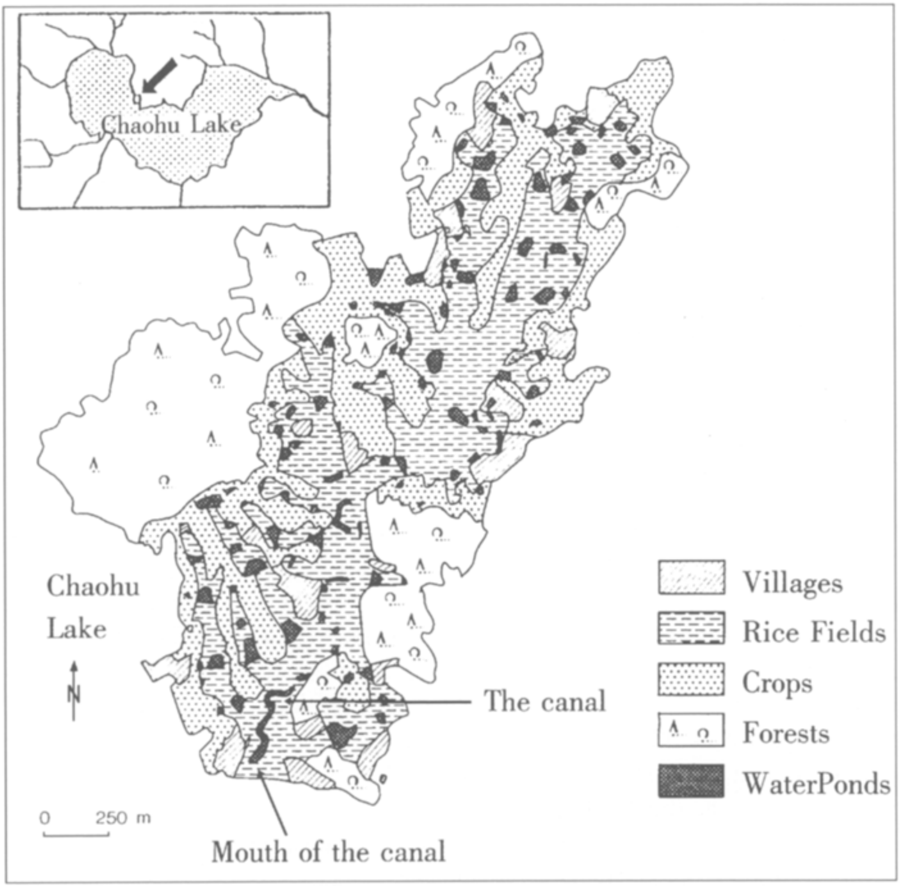

Figure 1. Location of the experimental agricultural watershed and distribution of land uses.

Table 1. Land use composition in Liuchahe watershed.

Type	Area, ha	Percentage, %
Rice fields	284.0	38.8
Nonirrigated farmlands	229.0	31.3
Forests	131.0	17.9
Villages	52.0	7.1
Ponds	36.0	4.9
Total	732.0	100.0

Table 2. Characteristics of main soils in the watershed.

Type of soil	Paddy soil	Yellow brown soil	Purple sand stone
Area (ha)	284	229	131
Texture of soil	Clay loam	Clay	Silty loam
PH value of soil	6.4	6.0	7.2
TN of soil (g/kg)	1.09	0.51–0.68	2.5
TP of soil (g/kg)	0.32	0.15	1.5
OM of soil (g/kg)	21.3	9.3	29.3
Density (g/cm^3)	1.92	1.57	
CEC (me/100 g soil)	16.6	18.5	26.6

940 mm/yr, evaporation 1484.3 mm/yr, air temperature = 15.5 °C, relative humidity = 77%, and sunshine = 2181 hr/yr.

The social and economic situation of the watershed is typical of that of a small-scale subsistence farming community. Like most of the area around the lake, a triple cropping system consisting of early rice, late rice, and rape (or wheat) is set up in the irrigated rice fields. Nonirrigated farmlands are normally cultivated with wheat, cotton, peanut, soybean, sweet potato and other vegetables all year round, year after year without fallow. Chemical fertilizers such as NH_4HCO_3, $CO(NH_2)_2$, and $Ca(H_2PO_4)_2$ are increasingly being used in this area. Figure 2 shows a long-term application of chemical fertilizers to the land in the watershed; this is typical of other areas around Chaohu Lake. The increase in the amount of chemical fertilizers has resulted in a significant increase of nutrient concentrations in Chaohu Lake. In addition, farmyard manure and other domestic waste are also applied to the croplands. There is no industry in the watershed. Thus, the watershed is typical of the agriculture areas.

In the watershed, there are approximately 150 artificial ponds, with a total surface area of 36.0 ha. Ponds, small ditches and a canal constitute an irrigation network system, called a multipond system (Yin et al. 1993). The rice fields are rainfed and irrigated by water from the multipond system in cascade alone the terrace. The multipond system is the dominant factor influencing the water, nutrients and sediment transfers and cycling in the watershed.

Materials and methods

Fifteen ponds in the watershed were chosen for the study, of which three were in the mountainous areas, four in the nonirrigated farmland, three in the

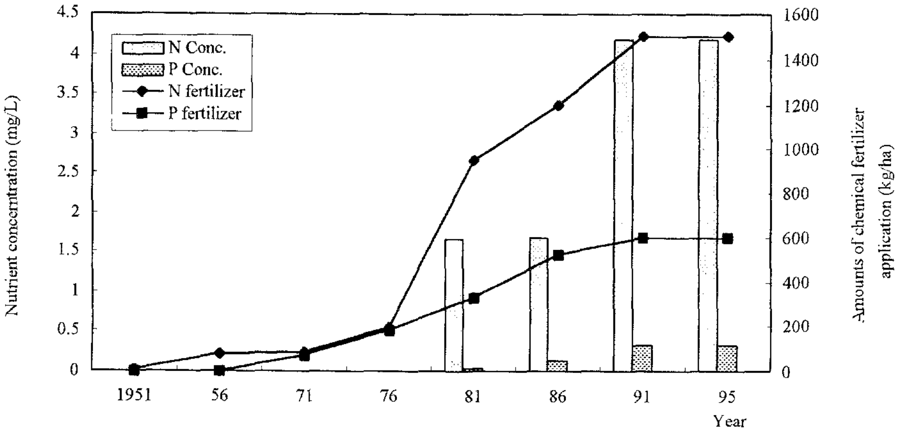

Figure 2. Long-term overview of land application of chemical fertilizers in the Liuchahe watershed, and concentration of nutrients in Chaohu Lake.

rice fields, two near villages, and three along the canal, with one in the canal mouth. In addition, three sections of rice fields, four plots in wooded tracts, and two villages were selected to determine surface runoff and nutrient load.

During the experiment, water samples from the rice fields, ponds and the canal were taken every 15 days, from April 1 to October 31 of each year. The rainfall and surface runoff water samples were taken only after each rainfall and when surface runoff existed. In each plot, surface runoff was measured using precalibrated flumes equipped with water-level recorders, with 5 to 15 samples being collected during each runoff event. Each of the water samples taken was 500 mL. After sampling, 200-mL aliquots of each water sample were filtered on 0.45 μm pore-size glassfiber filters. Within two hours, all the filtered and unfiltered water samples were digested with $K_2S_2O_4$ solution in a nearby field laboratory. They were stored at 4 °C until analysis. The digested unfiltered water samples were analyzed for total nitrogen (TN) and total phosphorus (TP); the filtered samples were analyzed for dissolved nitrogen (DN) and dissolved phosphorus (DP). Both the nitrogen and phosphorus were simultaneously determined by using the method of peroxodisulfate oxidation (Ebina et al. 1983).

Surface soils from three sections of rice fields, three sections of nonirrigated farmlands and sediments of fifteen ponds were collected. About 1-kg of the upper 200 mm of each soil (sediment) profile was sampled, placed in plastic bags, and transported to the laboratory. The samples were air-dried and passed through a 2-mm sieve. Organic matter was determined by the dichromate-wet combustion method (Raveh & Avnimelech 1972), total nitrogen by Kjeldahl digestion (Nelson & Sommers 1972), and total phosphorus by perchloric acid digestion (Sommers & Nelson 1972). Additionally, sediment thickness was directly measured from sediment profiles in the event that ponds were dried to the bottom. Sediment accumulation in each pond was calculated by the product of sediment bulk density and bottom area of each pond. Sedimentation rates are expressed in terms of deposition thickness (mm/yr) and mass accumulation (g/m^3 yr). Both the water and soil (sediment) results presented are mean values of duplicate analyses performed on each sample.

Nutrient removal by uptake of macrophytes was calculated by the product of biomass and nutrient content. This dominance, frequency, and size of distribution of macrophytes in ponds and ditches were measured in order to calculate the area of macrophytes. After that, three 1-m^2 of macrophytes were collected to measure the density of macrophytes (wet weight, g/m^2) in each pond or ditch. The samples of macrophytes per unit wet weight were transported to the laboratory and air-dried to calculate the ratio of dry to wet weight. Then each species of the air-dried macrophytes was cut into pieces and ground down to analyze the contents of TN and TP (Chapman & Pratt 1978). All the treatments were duplicated. Results were calculated by the following formula

$$\text{Nutrient content (mg/g d.w.)} \times \text{ratio (d.w./w.w.)} \times \text{biomass}$$
$$(\text{g/m}^2 \text{ w.w}) \times \text{area } (\text{m}^2)$$

Denitrification rates were studied by laboratory incubation (Zhu & Wen 1990), and expressed as N removal capacity (mg N/g soil). Approximately 20-g of dry soil (or sediment), of 40 μm in diameter, was placed in a 100 mL glass bottle. Following that, 5 mg N as KNO_3, dissolved in 5-mL of water, was added. In all cases, 20-mL of distilled water was added to bring the total addition of liquid to 25 mL. All the bottles were tightly sealed and incubated under the temperatures of 25 °C, for fourteen days. A 25-mL of KCl solution (2N) was used to extract nitrate from each bottle. Initial nitrate concentration of each soil (sediment) was similarly determined before each incubation, and all treatments were duplicated.

Rainfall intensity was recorded in mm per hour for more than ten rainfall events. Since light rain did not produce runoff, only the data of six medium and heavy rainfall was used. Water flow rate for discharge at the canal mouth to the lake was determined with a flowmeter. Also, the cross-section area was measured. For each of the six rainfall, surface runoff in different land use areas was determined by directly measuring the runoff volume at the above selected sites at unit time.

In our research, nutrient budget and cycling in the watershed can be calculated by the following formula.

Nutrient inputs

Annual nutrient inputs refer to the sum of: (1) Rainfall, (2) Chemical fertilizer application, (3) N fixation by cultivation of legumes and microorganisms. Therefore, the inputs of N and P were calculated as follows:

$$\text{kg } N_{in}/\text{yr} = \text{Rainfall N} + \text{Fertilizer N} + \text{Fixation N}$$

$$\text{kg } P_{in}/\text{yr} = \text{Rainfall P} + \text{Fertilizer P}$$

1. Rainfall: Nutrient input by rainfalls was calculated as:

$$Q_{Rin} = A \, \Sigma \, C_{Ri} \times V_{Ri}$$

where, Q_{Rin} : nutrient input per unit area by rainfall in the year 1995, kg/ha/yr.

A : unit area, $A = 1$ ha $= 1.0 \times 10^4$ m^2

C_{Ri} : average nutrient concentration in rainfall i, mg/l

V_{Ri} : volume of rainfall i, mm

2. Chemical fertilizer application: In order to estimate of nutrient input, the total amounts and types of fertilizer applied to croplands in the watershed were investigated using statistical data from the farmers and local government. Most of the fertilizer data were reported as "mixed fertilizer" and "fertilizer materials". To convert these data into elemental N and P, we multiplied by the percentages of the elements in each type of fertilizer used.

3. N fixation: The amounts of N fixation were included in the soybean and peanut calculations (105 kg N/ha/yr and 112 kg N/ha/yr respectively) (Kuenzler & Craig 1986). The areas of soybean and peanut were investigated. In addition, the non-symbiotic N fixation by microorganisms is about 50 kg/ha in soil-plant system (Moore 1966).

Nutrient outputs

Annual N and P outputs from the watershed include the following: (1) Discharges of nutrients, (2) Sales of crops, (3) Denitrification loss of N, (4) Volatilization of N, (5) Leaching to ground water. The outputs of N and P were calculated in the following manner:

$$\text{kg } N_{out}/\text{yr} = \text{Discharge N} + \text{Sale of crop N} + \text{Denitrification N}$$
$$\text{Volatilization N} + \text{Leaching N}$$

$$\text{kg } P_{out}/\text{yr} = \text{Discharge P} + \text{Sale of crop P} + \text{Leaching P}$$

1. Canal discharge of nutrients: Both the nutrient concentration at the canal mouth to the lake and volume of canal flow rate were measured to determine the nutrient output via discharges.

2. Sale of crops: The amounts of all types of crop harvest were investigated by direct inquiry of farmers as well as local government statistical data. Quantities of N and P in the harvest were determined by multiplying annual yields by the nutrient content per unit of harvest. Harvest of crop = Sale of crop + Consumption of crop, where sale of crop refers to nutrient output from the watershed, and consumption of crop refers to nutrient cycling in the watershed.

3. Denitrification of N includes soils from croplands and pond sediments. The denitrification rate is measured by the method of nitrate disappearance. The amount of denitrification is calculated by this formula: Denitrification rate (mg N/g soil) × soil quantity in 20 cm depth (g).

4. Volatilization of N is calculated by using a linear regression equation from literature (Duan et al. 1988).

5. Leaching to ground water: Nutrient loss with leaching is the product of leaching volume and nutrient concentrations.

Internal transfers

Nutrient internal transfers in the watershed include the following 5 factors:

1. Nutrient flow with surface runoff: Nutrient concentration and surface runoff for different land use including villages were measured to determine the nutrient transfer in surface runoff.

2. Nutrient flow with water irrigation from ponds to rice fields.

3. Crop consumption is calculated using this formula: crop consumption = crop harvest − crop sale.

4. Manure application was estimated by inquiry of farmers. The N and P contained in manure application was estimated to be 25% of nutrient production in the wastes. Nutrient production in the excretion of livestock in the watershed is the product of animal numbers and the individual waste production rate (Table 3).

5. Soil mineralization: The amounts of N and P contained in soil can be calculated as follows:

$$W_{ij} = \Sigma S_{ij} \times H_{ij} \times d_i$$
$$W_{SNi} = \Sigma W_{ij} \times N_u$$

where, W_{ij} : total amount of soil type i for depth j, kg

W_{ij} : area of soil type i, m^2

H_{ij} : depth of soil layer j in soil type i, m

W_{SNi} : nutrient amount in soil type i, kg

N_u : nutrient content in soil type i, %

Table 3. The content of nutrients in the excretion of livestock in the watershed.

	Number	Amount of excrement* (kg/ind./yr)	Total amount of excrement (10^4 kg)	Amount of manure converted into nutrients (kg)	
				Nitrogen	Phosphorus
Human	3000	45	13.5	554	257
Cattle	190	9000	171.0	7011	3249
Pig	800	2200	176.0	7216	3344
Chicken	10000	5	5.0	206	96
Duck	2000	10	2.0	82	38
Goose	1000	14	1.4	57	27
Total			368.9	15125	7011

* From Liu et al. 1994.

The mineralization rates are assumed to be 3% for nitrogen and 0.1% for phosphorus (Brady 1974).

Nutrient storage

Nutrient storage includes:

1. Uptake of macrophytes. The dominance, density, and distribution size of macrophytes were measured to estimate nutrient storage in biomass of macrophytes.

2. Nutrient storage in sediments of ponds and ditches. The density, area, and nutrient content of sediments were measured to calculate nutrient storage in sediments.

3. Manure storage in villages.

Results and discussion

The overall nutrient budget and internal cycling are shown in Figure 3. Calculation details pertaining to the values of nutrient fluxes and storage will be discussed below.

Nutrient inputs

Nutrient inputs to the watershed include the following three parts:

1. Rainfall: There were 747 mm of rainfall in 1995, of which 5 medium and heavy rainfalls of 231 mm caused surface runoff. The average nutrient concentration is approximately 0.31 and 0.06 mg/l for N and P respectively.

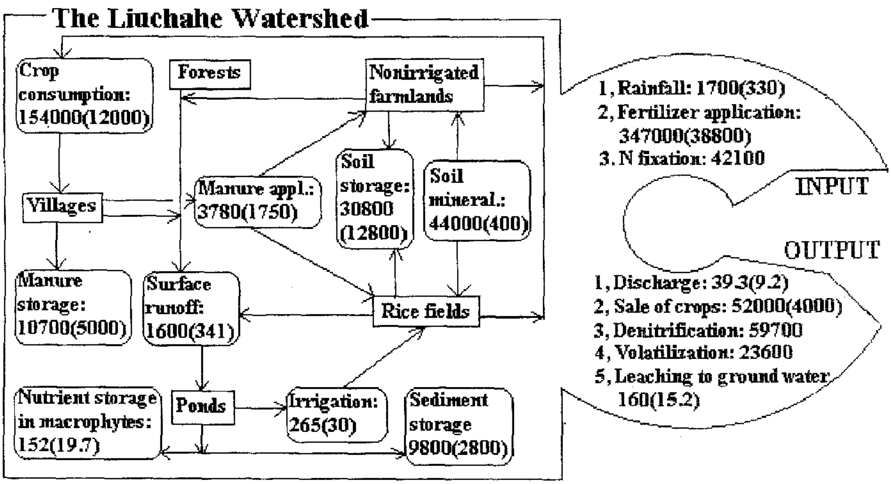

Figure 3. Nutrient budget and internal cycling in Liuchahe watershed.

This resulted in a rainfall input of 2.32 and 0.45 kg/ha/yr for N and P. Therefore, the total inputs of nutrients in the watershed were 1.70×10^3 kg of N and 0.33×10^3 kg of P. The average precipitation per year is 940 mm, so the nutrient input by rainfall in 1995 was lower than that in a normal hydrological year.

2. Chemical fertilizer application: Fertilizer applications were 1200 kg/ha of NH_4 HCO_3 (17.7% of N), 300 kg/ha of $CO(NH_2)_2$ (46.7% of N), and 600 kg/ha of $Ca(H_2PO_4)_2$ (14.0% of P_2O_5) for rice production. This resulted in a chemical fertilizer input of 353 kg/ha of N and 36.7 kg/ha of P. Therefore, total fertilizer inputs for rice fields of 284 ha for early and late rice were 20.0×10^4 kg of N, and 2.10×10^4 kg of P. In addition, there were 600 kg/ha of NH_4HCO_3, 200 kg/ha of $CO(NH_2)_2$, and 400 kg/ha of $Ca(H_2PO_4)_2$ for wheat, oilseed, and other crop production, making a total area of 734 ha. Thus, fertilizer inputs were 14.7×10^4 kg of N, and 1.80×10^4 kg of P. On the average, the total nutrient inputs to the watershed by chemical fertilizer application were 34.7×10^4 kg or 676 kg/ha N, and 3.88×10^4 kg or 76 kg/ha P in the year 1995.

3. N fixation: N input to the watershed due to N fixation was calculated as follows:

$$\begin{aligned} \text{N fixation} &= 105 \text{ kg/ha} \times 27 \text{ ha soybean} + 112 \text{ kg/ha} \times 63 \text{ ha peanut} \\ &\quad + 50 \text{ kg/ha} \times 644 \text{ ha} \\ &= 4.21 \times 10^4 \text{ kg} \end{aligned}$$

The nutrient inputs to the watershed were summarized in Table 4. The total nutrient inputs were 39.1×10^4 kg N and 3.91×10^4 kg P, of which the

Table 4. Nutrient input summary.

Nutrient inputs	Amounts (kg) N	Amounts (kg) P	Percentage (%) N	Percentage (%) P
Rainfall	0.17×10^4	330	0.40	0.80
Chemical fertilizer	34.7×10^4	3.88×10^4	88.8	99.2
N fixation	4.21×10^4		10.8	
Total	39.1×10^4	3.91×10^4	100	100

Table 5. Nutrient outputs by discharge.

Rainfall (mm)	Discharge volume (m^3)	Nutrient concentration (mg/l) N	Nutrient concentration (mg/l) P	Nutrient output (kg) N	Nutrient output (kg) P
114	56100	0.54	0.11	30.3	6.20
30.0	11100	0.43	0.13	4.80	1.44
35.0	154000	0.27	0.10	4.20	1.54
24.0	0	0	0	0	0
28.0	0	0	0	0	0
Total	82600			39.3	9.20

largest input was chemical fertilizer application, reaching 88.8% of total N input and 99.2% of total P input. N fixation also plays an important role in N input; however, P input depends on chemical fertilizer application.

Nutrient outputs

Annual N and P outputs referred to the following five parts:

1. Discharges: For the five rainfall events in 1995, the volume and nutrient concentrations of discharges are listed in Table 5. The nutrient outputs by discharge were 39.3 kg N and 9.2 kg P.

2. Sale of the crops: The amounts of crop production are listed in Table 6. The amounts of nutrient output by crop production are 20.6×10^4 Kg N and 1.6×10^4 kg P. Normally, one quarter of the total crop production left the watershed and three quarters was consumed on the watershed, so output by crop removal was 5.2×10^4 N and 0.4×10^4 kg P.

3. Denitrification of N: Nitrate denitrification is an important pathway of N loss from the watershed. Since denitrification of applied fertilizer depends

Table 6. Amounts of harvested crop materials in the watershed.

Type of crop	Area of crop (ha)	Production of crop (ha)		Content of N** (%)		Content of P*** (%)	N amount (10^4 kg)	P amount (10^4 kg)
		Grain	Stem & leaf	Grain	Stem & leaf			
Rice	284	12600*	12600	1.09	1.887	0.159	10.7	1.14
Wheat	253	3750	3750	2.665	1.07	0.096	3.55	0.18
Oilseed	260	2250	2250	3.98	3.98	0.073	4.66	0.09
Maiz	13	3600	3600	1.226	1.742	0.156	0.14	0.02
Soybean	27	3000	3000	3.378	2.30	0.174	0.46	0.03
Peanut	63	3000	3000	1.322	2.236	0.202	0.67	0.08
Cotton	110	600	1200	2.218	1.166	0.147	0.30	0.03
Potato	8	11250	2250	0.962	2.45	0.175	0.13	0.02
Total							20.61	1.59

* Rice production includes early rice and late rice
** From Huang et al. 1994
*** From Jiang et al. 1993

Table 7. Denitrification in the watershed

	Denitrification rate (mg N/g soil)	Soil quantity* ($\times 10^{10}$ g)	Denitrification amounts ($\times 10^4$ kg N)
Rice fields	0.031	109	3.38
Nonirrigated farmlands	0.029	72.0	2.09
Sediment in ponds	0.094	5.30	0.50
Total			5.97

* Soil (sediment) depth is 20 cm.

on the season of application, subsequent temperature, and rainfall regime, an accurate measurement is difficult. In our study, the denitrification rate was expressed as N removal capacity (mg N/g soil) by laboratory incubation. The results are shown in Table 7. For croplands in the watershed, denitrification is 5.47×10^4 kg N, that is, approximately 15.8% of the total chemical fertilizers applied (Table 4). This agrees with reports by other researchers (Shi et al. 1989; Cai et al. 1985; Thomas & Gilliam 1978). In addition, denitrification in ponds and ditch sediments was measured as 5000 kg N. Therefore, the total amounts of N denitrification could reach 5.97×10^4 kg.

4. Volatilization of N: Ammonium volatilization is another important pathway of N loss. Although other factors control N volatilization, the following single linear regression equation was used to determine the amount of ammonium volatilization:

$$\log y = -2.2084 + 0.27533X_1 - 0.03796X_2$$

Table 8. Ammonium volatilization in croplands.

	Rice fields	Nonirrigated farmlands
PH value	6.4	6.0
CEC (me/100 g soil)	16.6	18.5
y* (me/100 g soil)	0.074	0.07
Area (10^4 m^2)	284	229
Soil depth (m)	0.2	0.2
Soil density (g/cm^3)	1.92	1.57
Ammonia volatilization (kg)	1.45×10^4	0.91×10^4

* y: amount of ammonium volatilization

Table 9. N and P output in leaching to ground water.

	Villages	Rice fields	Nonirrigated farmlands	Forests
Area (10^4 m^2)	52	284	229	131
Leaching rate (mm/day)	0.8	0.5	1.07	0.83
Leaching time (day)	20	60	20	20
Leaching volume (10^4 m^3)	0.8	8.5	4.9	2.2
Average conc. of TN (mg/l)	0.82	1.32	0.83	0
Average conc. of TP (mg/l)	0.092	0.119	0.09	0
Leaching amount of TN (kg)	6.6	112.2	40.7	0
Leaching amount of TP (kg)	0.7	10.1	4.4	0

where y : amount of ammonium volatilization,
X_1 : PH value of soil,
X_2 : CEC (me/100g soil).

Table 8 shows the ammonium volatilization in rice fields and nonirrigated farmlands. The result of N output by ammonium volatilization is 2.36×10^4 kg/yr.

5. Leaching to ground water: The amount of N and P output through leaching in different land use areas is listed in Table 9. The total leaching amount to ground water was 156 kg N and 15.2 kg P.

The nutrient outputs from the watershed are summarized in Table 10. The total nutrient outputs were 13.55×10^4 kg N and 0.40×10^4 kg P, of which the largest output of N was denitrification, reaching 44.1% of total N output. The largest output of P was sale of crops, accounting for 99.4% of total P

Table 10. Nutrient output summary.

Nutrient outputs	Amounts (kg) N	Amounts (kg) P	Percentage (%) N	Percentage (%) P
Discharges	39.3	9.2	0.03	0.22
Sale of crops	5.2×10^4	0.4×10^4	38.4	99.4
Denitrification	5.97×10^4		44.1	
Volatilization	2.36×10^4		17.4	
Leaching	160	15.2	0.12	0.38
Total	13.55×10^4	0.40×10^4	100	100

output. In addition, sale of crops and volatilization accounted for 38.4% and 17.4% of total N output, respectively.

Internal transfer and cycling

Nutrient internal transfer and cycling in the watershed include the following five parts:

1. Nutrient flux with surface runoff: Nutrient flux due to surface runoff was measured for five rainfalls in 1995 (Table 11). Total nutrient fluxes were approximately 1600 kg N and 341 kg P. Thus, N flux in surface runoff is about 10 times of that in leaching, while P flux in surface is 20 times of that in leaching. This means that 90% of N flows through surface runoff, and 10% of N flows by leaching. 95% of P flows through surface runoff; only 5% of P flows by leaching in the watershed. The reason for high flux of N in surface runoff is that N flux from villages is the main flux (Table 11), although villages occupy a small portion of land use. Manure in the villages is generally stored in very shallow holes, and is thus easily washed out into multiponds with the surface runoff.

2. Nutrient flux by irrigation into rice fields: Normally, the average irrigation for early and late rice occurs six times each year, and the irrigation depth for the rice fields is about 0.05 m. thus, irrigation amounts for the rice fields of 284 ha are 142000 m^3. The average concentration of nutrients in the irrigation water is 1.87 mg/l N and 0.21 mg/l P. The total nutrient fluxes by irrigation are 265 kg N and 30 kg P.

3. Crop consumption: Normally, three quarters of the crop harvest is consumed in the watershed, so total crop consumption is 15.4×10^4 kg N and 0.4×10^4 kg P.

4. Nutrient flux by manure application in the watershed: Manure is one kind of fertilizer application in the watershed. The results in Table 3 show

Table 11. Nutrient load in different land uses in surface runoff.

Rainfall (mm)	Nutrient load in different land uses (kg/ha)									
	Forests		Villages		Rice fields		Nonirrigated farmlands		The entire watershed	
	TN	TP	TN	TP	TN	TP	TN	TP	TN	TP
114	0.598	0.098	8.33	3.03	1.07	0.099	1.51	0.141	1.586	0.315
30	0.072	0.016	1.14	0.457	0.172	0.011	0.152	0.023	0.208	0.046
35	0.063	0.017	0.863	0.410	0.119	0.010	0.43	0.042	0.253	0.049
24	0.031	0.010	0.540	0.282			0.06	0.007	0.063	0.024
28	0.033	0.014	0.675	0.356			0.036	0.005	0.065	0.029
Total	0.794	0.155	11.55	4.54	1.36	0.111	2.193	0.223	2.179	0.466

that the total amounts of manure converted into nutrients were 1.15×10^4 kg N and 0.70×10^4 kg P. Nutrient flux with manure application into croplands is assumed to be 25% of the total manure, so nutrient flux is 3.78×10^3 kg N and 1.75×10^3 kg P. In addition, nutrient flux with surface runoff is 601 kg N and 236 kg P (Table 11), while manure storage is 1.07×10^4 kg N and 0.50×10^4 kg P.

5. Soil mineralization: The average nutrient content and soil density for paddy soil and yellow brown soil are listed in Table 2. Supposed soil depth is 20 cm. Paddy soil of 284 ha and yellow brown soil of 229 ha contain 14.7×10^5 kg N and 4.13×10^5 kg P. The average mineralization rates are 3.0% for N and 0.1% for P, so soil mineralization contributes 4.40×10^4 kg N and 0.04×10^4 kg P.

Nutrient internal cycling is summarized in the following manner:

$$N = 1.60 \times 10^3 + 265 + 15.4 \times 10^4 + 3.78 \times 10^3 + 4.4 \times 10^4$$
$$= 20.4 \times 10^4 \text{ kg}$$
$$P = 341 + 30 + 12 \times 10^3 + 1.75 \times 10^3 + 400 = 1.45 \times 10^4 \text{ kg}$$

Nutrient storage

Nutrient storage in the watershed includes biomass storage of macrophytes, sediment storage in ponds and ditches, and manure storage in villages.

1. Nutrient storage in biomass of macrophytes: The dominance, density, distribution size of macrophytes are listed in Table 12. The results (Table 12) show that total amounts of nutrient storage in biomass of the macrophytes were 152 kg N and 19.7 kg P.

Table 12. The species and biomass of dominant vegetation in the watershed.

Species	*P. Crispus*	*M. Vertillata*	*Phragmites C. Trin*
Biomass (g/m^2.w.w.)	1780	1600	600
Area (m^2)	13400	11300	2150
Content of N (mg/g/w.w.)	4.04	2.77	4.2
Content of P (mg/g.w.w.)	0.54	0.32	0.75
Amounts of N (kg)	96.4	50.1	5.4
Amounts of P (kg)	12.9	5.8	1.0

Table 13. Nutrient contents and annual mass accumulation in sediments.

Sample pond location*	Thickness accretion (cm/yr)	Nutrient content (g/kg)		Mass accumulation (g/m^3/yr)		
		N	P	Sediment (10^4)	N	P
1	1.2	1.25	0.46	42.3	529	195
2	5.8	1.94	0.53	52.6	1020	279
3	1.6	2.14	0.57	53.7	1149	306
4	4.0	1.8	0.53	57.8	1040	306
5	2.5	1.93	0.49	48.5	936	238
Average	3.0	1.81	0.52	51.0	935	265

* sample 1 refers to sediment in ponds around mountain area, 2: ponds among nonirrigated farmland, 3: ponds by rice field, 4: ponds near villages, 5: ponds along the canal.

2. Nutrient storage in sediments of ponds and ditches: Nutrient contents and amounts in sediments of ponds and ditches are presented in Table 13. Nutrient storage in sediments is 0.98×10^4 kg N and 0.28×10^4 kg P per year.

3. Manure storage in villages: Nutrient amounts by manure storage in villages are 1.07×10^4 kg N and 0.50×10^4 kg P.

The nutrient budget and internal cycling are summarized in Table 14.

Conclusions

An analysis of nutrient budget and cycling in the watershed yields following:

1. Nutrient input is larger than output, showing that nutrients are being accumulated within the watershed. Accumulation percentage of P (89.8%)

Table 14. Annual nutrient input, output and internal cycling summary.

Nutrient	N	P
Input, kg	39.1×10^4	3.91×10^4
Output, kg	13.55×10^4	0.40×10^4
Net (I − O), kg	25.55×10^4	3.51×10^4
(I − O)/I, %	65.4	89.8
Storage, kg	2.07×10^4	0.78×10^4
Cycling, kg	20.4×10^4	1.45×10^4
Others, kg	3.08×10^4	1.28×10^4

is higher than that of N (65.4%). The annual soil accumulation of nutrients (3.08×10^4 kg N and 1.28×10^4 kg P) may become a potential source of nonpoint pollution to Chaohu Lake.

2. The main input is chemical fertilizer application; for P, fertilizer accounts for more than 99% of inputs.

3. Nutrient output from the watershed is different for N and P. For P, sale of crops is the main pathway of P output from the watershed, accounting for more than 99% of the total P output. However, for N, both denitrification and sale of crops are the main pathways, reaching 44.1 and 38.4%, respectively. Additionally, ammonium volatilization is an important pathway of N loss from the watershed.

4. For nutrient runoff within the watershed, 90% N and 95% P flow through the surface, and only 10% N and 5% P flow through leaching; but, nutrient output through discharges is very low, even lower than that through leaching, which is typical of watersheds with multipond systems. Therefore, the multipond systems within the watershed can minimize nonpoint source nutrient pollution by control at its sources.

The study also suggests that input-output budgets and internal cycling for a diverse series of watersheds throughout the world have many patterns in common with the Liuchahe Watershed, although the magnitude of precipitation, geologic substrate, vegetation type, and proximity to anthropogenic emissions may vary greatly for these widespread and diverse watersheds. The study of the Liuchahe watershed provides quantitative answers for important ecological questions about the biogeochemistry of nutrients. Yet, many of the biogeochemical relationships within the watershed such as nitrogen fixation, denitrification, phosphorus absorption in soil process, oxidation and reduction remain to be quantified.

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