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Control of agricultural non-point source pollution in Fuxian lake with riparian wetlands

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ABSTRACT

To control eutrophication caused by agricultural non-point sources, integrated riparian wetlands were constructed and operated to intercept and treat the polluted water flowing into the Fuxian Lake. The influent and effluent mass loadings of total nitrogen (TN), total phosphorus (TP), suspended solid (SS), and chemical oxygen demand (COD) of riparian wetland systems were monitored for nearly one year. In addition, influent and effluent samples of each riparian wetland treatment unit were collected and analyzed for nitrogen (nitrate, nitrite, ammonia, and organic nitrogen) and phosphorus (organic phosphorus and phosphate). Results showed that the wetland systems removed various pollutants. There was a little seasonal change on the COD, SS, TN, and TP removal efficiency. There was no flow in the wetland during the winter. Therefore, the pollutant removal efficiency could not be determined. The nitrogen analysis results showed that ammonia nitrogen and nitrate nitrogen were the main nitrogen species present in the influent and effluent of each wetland functioning unit. Information obtained from this study is helpful in providing a design basis for similar wetland systems to control agricultural non-point source pollution.

Keywords: Phosphorus; Nitrogen; Removal efficiency; Yuxi City

1. Introduction

Agricultural run-off, if not properly managed, can result in serious non-point source pollution [1–3]. Agricultural activities that cause non-point source pollution include poorly located or managed animal feeding operations, overgrazing, and excessive or poorly timed application of fertilizer and pesticides. Nutrients contained in the fertilizer or animal waste can wash into aquatic ecosystems resulting in pollution of these water bodies [4]. The occurrence and transmission of non-point source pollution are closely related to hydrogeological, meteorological conditions, soil fertilizer, pesticide use, and farming practices [5,6]. It is challenging to manage and control agricultural non-point sources because the sources are dispersed.

Using riparian wetland is an effective way to control agricultural non-point source pollution. A riparian wetland is an ecological system that combines biological, physical, and chemical mechanisms for treating wastewater [7]. The wetland components that are responsible for treating wastewater contaminants

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include the sediments (sand, gravel, etc.), the vegetation (Phragmites australis, Iris, Glyceria, Scripus, etc.), and the rhizonsphere (root zone) organisms [8].

Applying wetland systems to treat polluted water has become a research focus in recent years. Horizontal subsurface flow wetland and vertical flow constructed wetland have been used to treat various types of wastewater [9,10] including municipal wastewater [11,12] and wastewater from tannery industries [13], grazed dairy pasture [14,15], landfill leachate [16], agricultural wastewaters [17], and stormwater run-off [18–20]. Seven constructed surface flow-through wetlands were used to improve the water quality of irrigation return flows prior to discharge into surface waters of the Sacramento-San Joaquin River [21]. Floating treatment wetlands planted with emergent macrophytes (FTWs) provided an innovative option for treating urban storm waters [22]. Using the field experiment method and an isotope tracing technique, the agricultural non-point source pollution control function of different vegetation type in riparian wetland was also studied [23].

To date, most studies have focused on the wetlands purification capacity and mechanism [24–29]; the semi-natural riparian wetlands used for non-point source pollution control have received relatively little attention. The focus of this paper was on non-point source pollutants retention and removal by semi-natural riparian wetlands. Monthly mass loading rates of chemical oxygen demand (COD), suspended solid (SS), total nitrogen (TN), and total phosphorus (TP) to the wetland system from the East River and Doudisi Ditch were monitored. Nitrogen and phosphorus speciation of wetland influent (East River and Doudisi Ditch) and effluent, as well as effluents from the sedimentation tank and oxidation pond were also analyzed in order to value the purification capacity of wetland.

2. Material and methods

2.1. Site description

Fuxian Lake is located in Yuxi City, Yunnan Province, China. The lake area is 216.6 km^2 and its watershed area is 674.69 km^2. As a static water resource, it is difficult for continuous development and utilization. Due to rapid economic growth, tourism, and industrialization, water quality in the lake has rapidly deteriorated. The pollution sources are domestic sewage from farms, agricultural run-off, and soil erosion. Among these, agricultural non-point source pollution is most significant, accounting for 69.7% of nitrogen, 56.1% of phosphorus, 92.6% of SS, and 67.4% of COD loadings to the Fuxian Lake.

East River, located in Chengjiang Country, Yuxi City, is the second largest natural river on the north shore of Fuxian Lake. The watershed area is 31.5 km^2, and its length is 19.9 km. During the dry season, there is almost no water in the river. In the rainy season (May–October), there is a large amount of water in the river; the average flow into the Fuxian Lake is 17.8 million cubic meters per year. The average depth of the river is 2.3 m. The river bottom is relatively flat and consists of sand and gravel. The river originates from northern mountains. Pollution in the river is mainly caused by soil erosion, and carries an amount of floating debris and sediment.

Doudisi Ditch, an agricultural irrigation ditch, is a small artificial river. Its watershed area is 0.75 km^2. Annual water input to the Fuxian Lake is 250,000 m^3. The average width of the ditch bed is 1.2 m, and the average river depth is 1.1 m. The river water comes mainly from agricultural run-off. The peak flow rate is less than 1 $m^3\ s^{-1}$.

East River and Doudisi Ditch are the two most important pollution sources on the north shore of Fuxian Lake. Pollutants entering the lake are as follows: TN 123,320 kg y^{-1}, TP 31,280 kg y^{-1}, COD 157,370 kg y^{-1}, BOD 77,520 kg y^{-1}, and SS 110,810 kg y^{-1}. These pollutants cause accelerated eutrophication in the Fuxian Lake.

2.2. The riparian wetland

A typical riparian wetland was selected to control the non-point source pollution from the East River and Doudisi Ditch. The riparian wetland was built in 2006 and has an area of 3.73 hectares. It is located on the north shore of the Fuxian Lake (Fig. 1).

The riparian wetland was situated in the East River and Doudisi Ditch estuary. Pictures of the wetlands before and after construction are presented in Fig. 2. The process flow diagram of the wetland treatment system is shown in Fig. 3. The trash rack and grit chamber were built in the entrance to the wetland to intercept floating material and garbage. The polluted water then entered into a biological oxidation pond, followed by surface flow wetland and natural gravel bed wetlands for deep purification. In the biological treatment unit, various kinds of floating plants, emergent plants, and submerged aquatic plants were used to remove inorganic suspended matter and organic detritus through enhanced precipitation, adsorption, and decomposition.

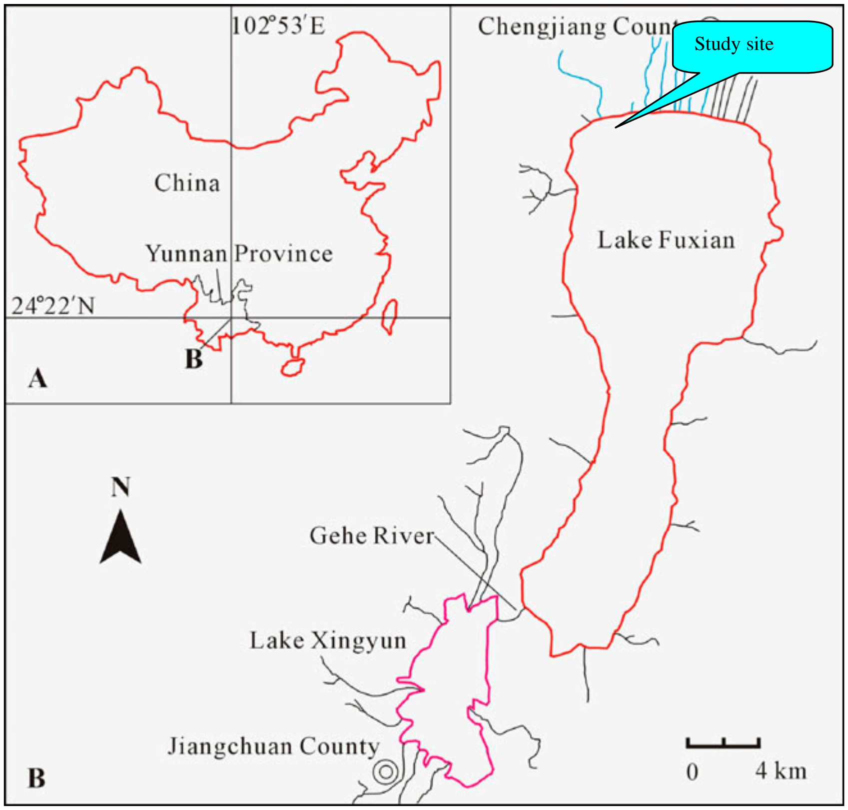

Fig. 1. Map of Fuxian Lake showing the riparian wetland site.

The design parameters of each function unit of the wetland treatment system are summarized in Table 1. The effective purification area of the wetland is 26,235 m^2, and the total volume is 25,541 m^3. The volume of various function units are shown in Table 1. The sewage treatment capacity of the wetland system is 15,000 $m^3\ d^{-1}$ in dry period and 25,000 $m^3\ d^{-1}$ in wet period, respectively. The average hydraulic loading of total area is 0.488 $m^3\ m^{-2}\ d^{-1}$ in dry period and 0.81 $m^3\ m^{-2}\ d^{-1}$ in wet period. The plants selected for different wetland function units, cultivation methods, planting density, and pattern are summarized in Table 2.

2.3. Sampling

Between April 2009 and January 2010, water samples were collected once a month, at 8:00 am, from each wetland function unit and analyzed immediately in the laboratory for COD, SS, TN, TP, NH_4^+-N (ammonium nitrogen), NO_3^--N (nitrate nitrogen), NO_2^--N (nitrite nitrogen), and PO_4-P (phosphate), et al.

During the dry season, there was no water at the sampling point, and therefore no samples were collected. COD was measured using the potassium dichromate method. SS, nitrogen (ammonia nitrogen, nitrate nitrogen, and nitrite nitrogen) and phosphorus (TP and phosphate) were analyzed using ultraviolet-visible spectrophotometry. All water quality parameters were analyzed using conventional methods described in APHA-AWWAWPCF [30].

3. Results and discussion

3.1. Flow

The monthly flow rates of the East River and Doudisi Ditch are summarized in Table 3. The annual run-off of Doudisi Ditch was 1,591,500 $m^3\ y^{-1}$, far below its historical annual average run-off of 4,023,400 $m^3\ y^{-1}$. The annual run-off of East River was 6,556,900 $m^3\ y^{-1}$, also far below its historical annual average run-off of 20,654,000 $m^3\ y^{-1}$. The average and peak flow rates of Doudisi Ditch were 4,360 $m^3\ d^{-1}$ and >120,000 $m^3\ d^{-1}$, respectively in 2009. There was less flow in 2010; the peak flow was >80,000 $m^3\ d^{-1}$. As for the East River, the average daily flow was 17,964 $m^3\ d^{-1}$, and the peak flow was >350,000 $m^3\ d^{-1}$ in 2009. During the dry season, from 21 December 2009 to 30 April 2010, there was either no run-off or very little flow into the wetland treatment system.

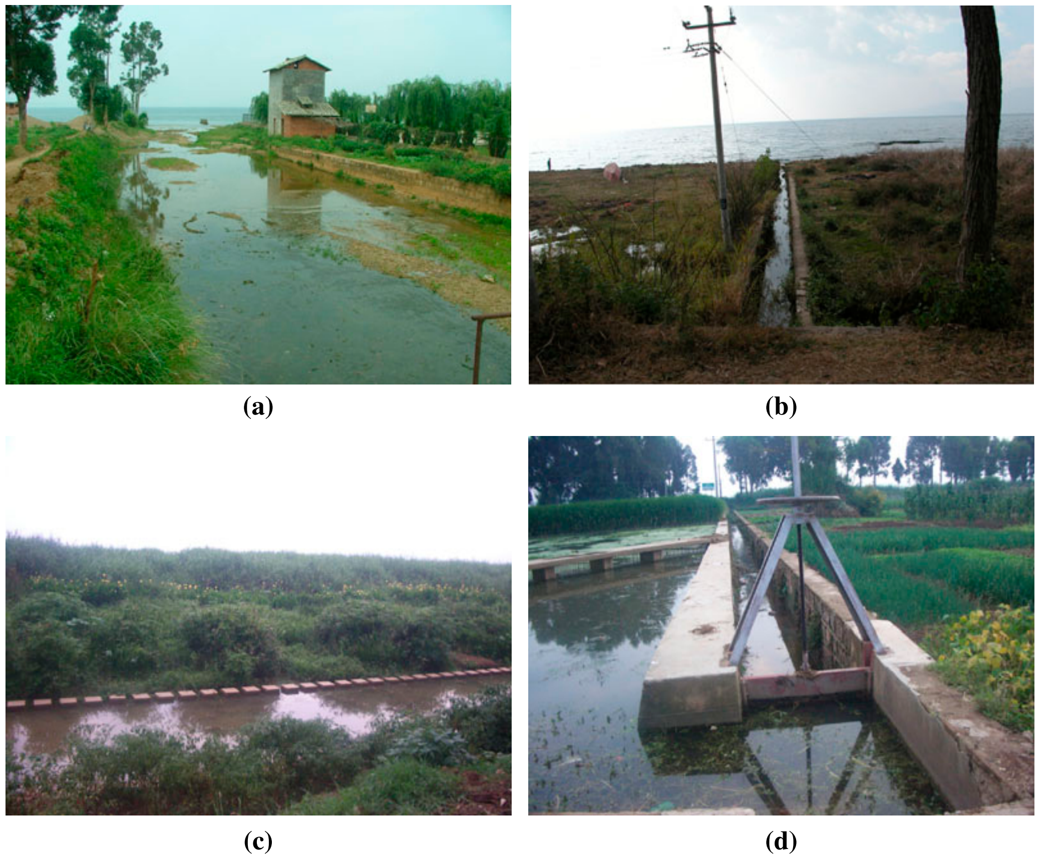

Fig. 2. Comparisons before and after construction of riparian wetlands: (a) the estuary of East River (before construction), (b) the estuary of Doudisi Ditch (before construction), (c) the estuary of East River (after construction), and (d) the estuary of Doudisi Ditch (after construction).

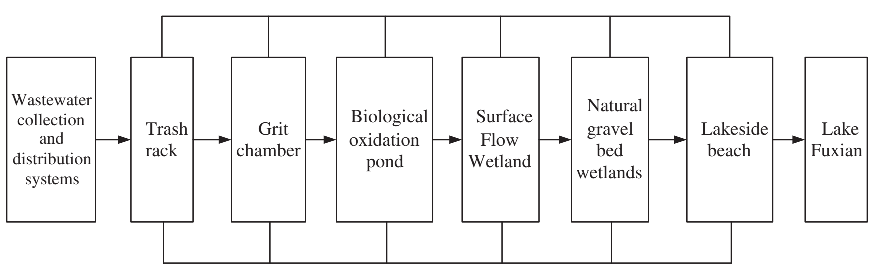

Fig. 3. The process flow diagram of the riparian wetland.

3.2. *Pollution loadings*

Monthly mass loading rates of COD, SS, TN, and TP to the wetland system from the East River and Doudisi Ditch are plotted in Figs. 4–7, respectively. Also shown in these figures are the mass flow rates in the wetland effluent. The differences between the influent and effluent mass flow rates represent the amounts of pollutants removed by the wetland system.

The north shore of Fuxian Lake is located in Chengjiang County, Yuxi City, where tobacco, vegetable, and rice are planted by local villagers. Sowing was carried out in April which was part of the dry season. As a result, the total COD loading into the wetland was relatively low (Fig. 4). During the period from late spring to summer, it was hot and microbial activity was strong. These factors accelerated the oxidation and decomposition of organic matter. Beginning in June,

Table 1
Design parameters of function units of the wetlands

No.	Function units	Surface area (m^2)	Volume (m^3)	Average hydraulic retention time (h)	
				Dry period	Wet period
1	Grit chamber	3,094	4,088	7.1	4.22
2	Biological oxidation pond	7,780	15,560	21.7	13
3	Surface flow wetland	10,641	3,192	8.2	2.6
4	Natural gravel bed wetlands	4,720	1,510	2.42	1.4
5	Lakeside beach	–	1,191	1.91	1.1
Total		26,235	25,541	41.33	22.32

Table 2
Plant parameters of function units of the wetlands

No.	Function units	Area (m^2)	Water depth (m)	Plants selected	Cultivation	Density (Plant m^{-2})	Planting pattern
1	Biological oxidation pond	3,767	1.8–2.0	Cress (*Oenanthe. javanica* (*Blume*). *DC*)	Seedlings transplanting	4	Young stems
		1,273	1.8–2.0	Waterlily (*Nymphaea tetragona*)	Seedlings transplanting	1	Tubers
		4,020	1.8–2.0	Water chessuspended solid (SS)ut (*T. natans*)		2	Seedling
2	Surface flow wetland	3,353	0.2–0.4	Squash (*Cucurbita pepo L.*)	Seedlings transplanting	6	Seedling age 1
		2,867	0.2–0.4	Arrowhead (*Sagittaria trifolia L.*)		6	Tubers
		1,107	0.2–0.4	Calla Lily (*Calla palustris*)		6	Tubers
		1,360	0.2–0.4	Lotusflower (*Nelumbo* nucifera)		2	Tubers
		2,127	0.2–0.4	Chufa (*Eleocharis dulcis*)		6	Tubers
3	Natural gravel bed wetlands	2,793		Unbrella plant (*Cyperus alternifolius*)	Seedlings transplanting	3	Seedling age 2
		1,107		Calamus (*Acorus calamus Linn*)		4	
		860		Canna (*Canna indica*)		4	
		840		Daylily (*Hemerocallis citrina Baroni*)		6	
		767		Unbrella plant (*Cyperus alternifolius*)		4	
4	Lakeside beach			Willow trees	Cuttings	One plant/ 5 m, 72 plants	Caliber greater than 0.08 m

precipitation began to pick up and sand, gravel, and soil from the mountains were washed into the river during the rainy season resulting in increased COD and SS loadings to the wetland system. In August, crops harvesting began. In September, with precipitation decreasing, COD loading into the wetland decreased correspondingly. From November 2009 to January 2010, there was no water in the wetland.

SS removal by the wetland is shown in Fig. 5. SS loading was low in April and May. After wetland treatment, the effluent was almost free of SS. However, in June and July, heavy rain storms stirred up river sediments and eroded farmland topsoil resulting in high SS loading into the wetland. Following treatment, the SS concentration decreased to 10 mg L^{-1} in the wetland effluent.

The peak TN loading to the wetland occurred in June. The TN loading from Doudisi Ditch was 111.71 kg d^{-1}, and was 71.19 kg d^{-1} from East River. The peak TN loading was caused by fertilizer being

Table 3
Monthly flow rates of East River and Doudisi Ditch

	Doudisi Ditch			East river		
Months	Average daily flow ($m^3\ d^{-1}$)	Standard error	N	Average daily flow ($m^3\ d^{-1}$)	Standard error	N
2009–04	6,075.67	2,385.17	10	8,264.64	1,872.36	10
2009–05	4,386.56	2,010.33	10	24,891.36	2,881.57	10
2009–06	20,493.24	9,349.09	14	72,108.73	24,214.25	14
2009–07	9,984.67	2,501.42	29	54,794.94	11,332.79	29
2009–08	5,232.20	1,636.45	23	23,804.63	11,393.24	23
2009–09	518.86	249.07	18	2,128.78	1,201.61	18
2009–10	10,063.60	2,540.08	15	29,956.70	12,041.44	15
2009–11	914.42	381.13	19	2,300.53	564.83	19
2009–12	452.49	238.95	18	3,146.43	663.86	18
2010–01	0.00	0.00	18	642.84	467.35	18

Note: The numbers of times the flow was sampled.

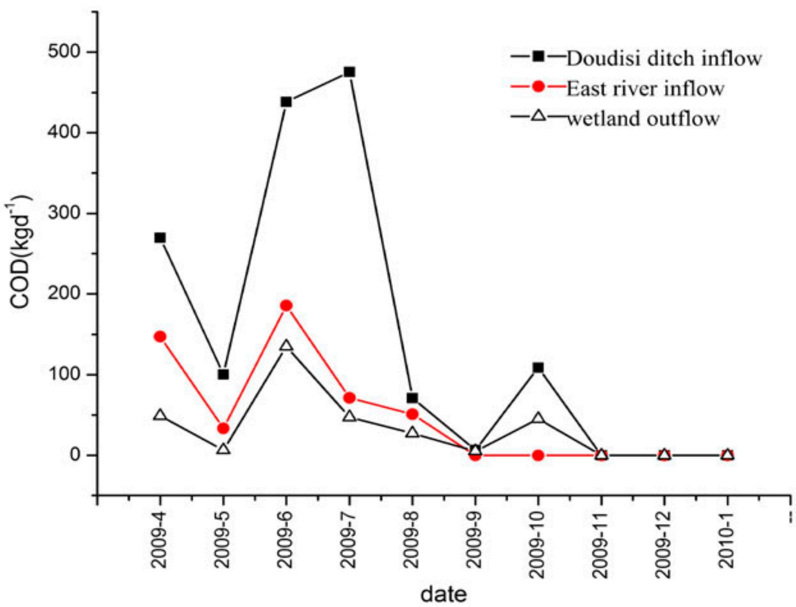

Fig. 4. COD loading of the riparian wetland.

washed away by the run-off. The wetland system apparently removed TN, as shown in Fig. 6. Following harvest, TN loading to the wetland treatment system decreased significantly. Influent TN loading to the wetland system was 3–160 kg d^{-1}. TN removal by the wetland system was >50%. The effluent TN loading was low throughout the years except during the rainy season. Note that there was no water in the wetland during winter.

The phosphorus loading was very low in April and May (Fig. 7). There was almost no phosphorus in effluent. For the same reason as nitrogen, phosphorus loading increased in June and July; then gradually decreased. TP loading was very low, between 0 and 8 kg d^{-1}. The effluent TP loading was always low, and therefore was not a major pollution factor. From November 2009 to January 2010, there was no water in the wetland. Phosphorus removal depended mainly on precipitation and adsorption by sediments.

3.3. Nitrogen and phosphorus speciation

Nitrogen speciation results of wetland influent (East River and Doudisi Ditch) and effluent, as well as effluents from the sedimentation tank and oxidation pond are shown in Fig. 8. Ammonia and nitrate nitrogen were usually the most dominant nitrogen species in the wetland influent; nitrite nitrogen was

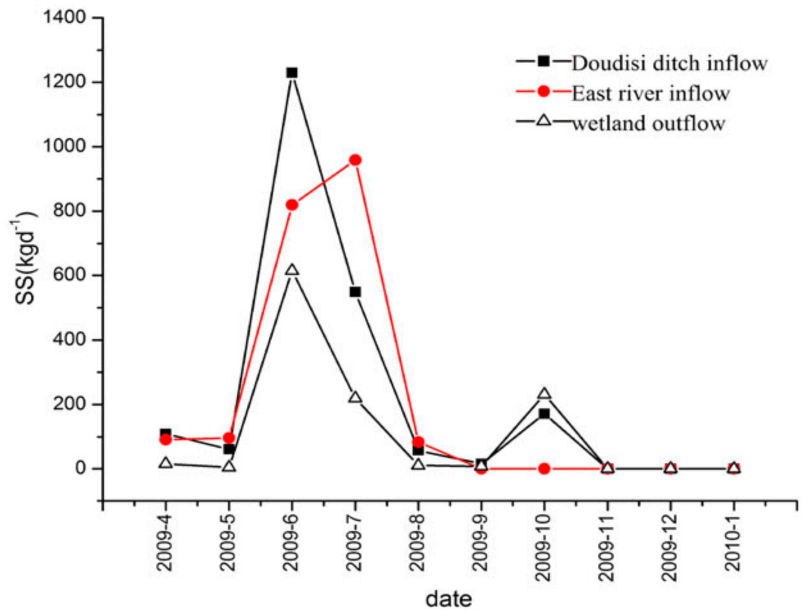

Fig. 5. SS loading of the riparian wetland.

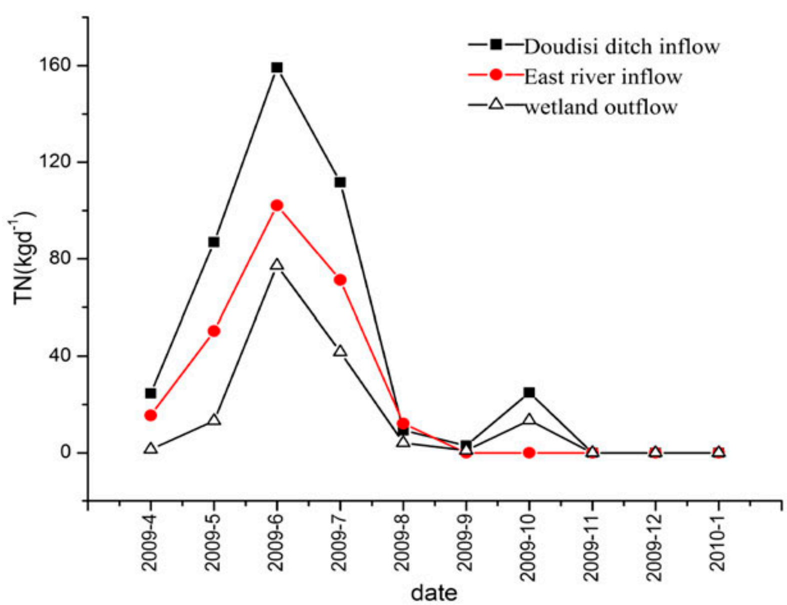

Fig. 6. TN loading of the riparian wetland.

insignificant. The Doudisi Ditch TN loading was lower than that of East River, which was 7 mg L^{-1}. The effluent TN concentration was 3 mg L^{-1}.

Nitrogen transformation processes in wetlands mainly depended on plants uptake, sediment absorption, and microbial nitrification and denitrification. Ammonia and nitrate were major nitrogen sources for plants uptake. After plants and microbes died and decomposed, the nitrogen contained in them were released. Ammonium-nitrogen was removed through plant uptake and microbial nitrification/denitrification processes since temperature and pH were within the range that could support both nitrification and denitrification processes [31]. Nitrogen removal occurred in sedimentation tank. But the removal efficiency in the surface flow wetland was significantly higher than in

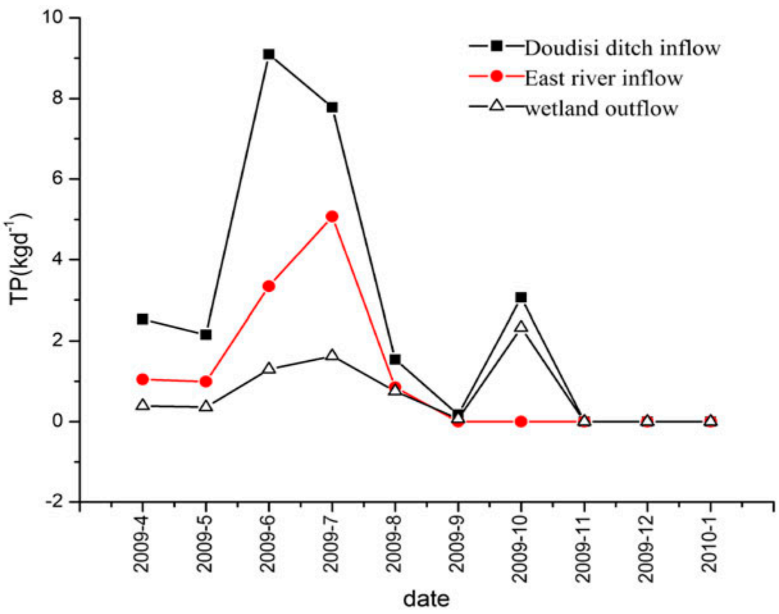

Fig. 7. TP loading of the riparian wetland.

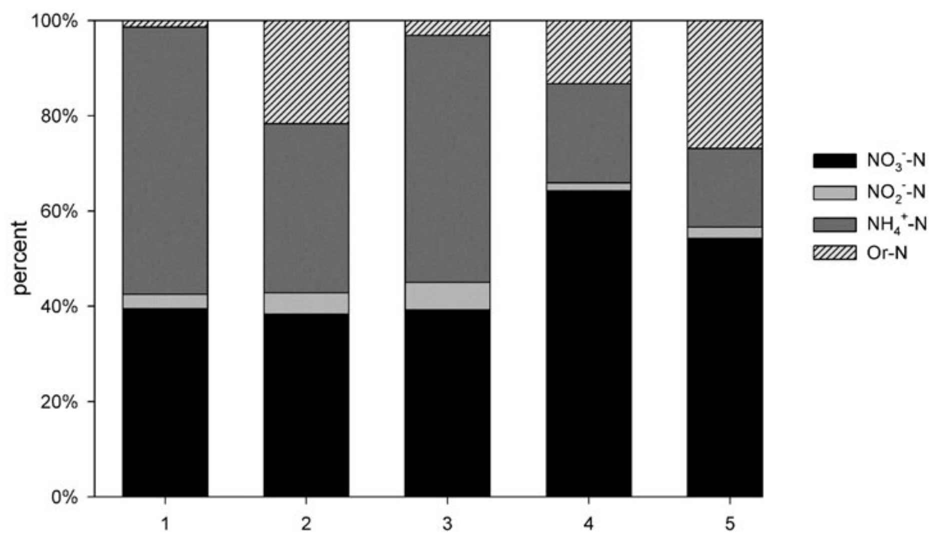

Fig. 8. Fractionation of the different N-forms of function units of the riparian wetland.
Notes: (1) Doudisi Ditch inflow, (2) Sedimentation tank outflow, (3) Oxidation pond outlow, (4) East River inflow, (5) Wetland outflow.

sedimentation tank. Nitrogen was also removed in the oxidation pond.

The organic nitrogen concentration in the Doudisi Ditch inflow was low, but it increased after the settling tank. Organic nitrogen was almost removed completely in the oxidation pond. Aquatic plants in the oxidation pond accelerated its roots to secrete oxygen. Therefore, organic nitrogen was biodegraded and removed through microbial nitrification and denitrification.

Phosphorus speciation results are shown in Fig. 9. Phosphorus removal in oxidation pond and surface flow wetland was better than in sedimentation tank. Part of the phosphorus was absorbed by micro-organism. Upon death and cell decay, phosphorus is released to the water. Phosphorus removal depended

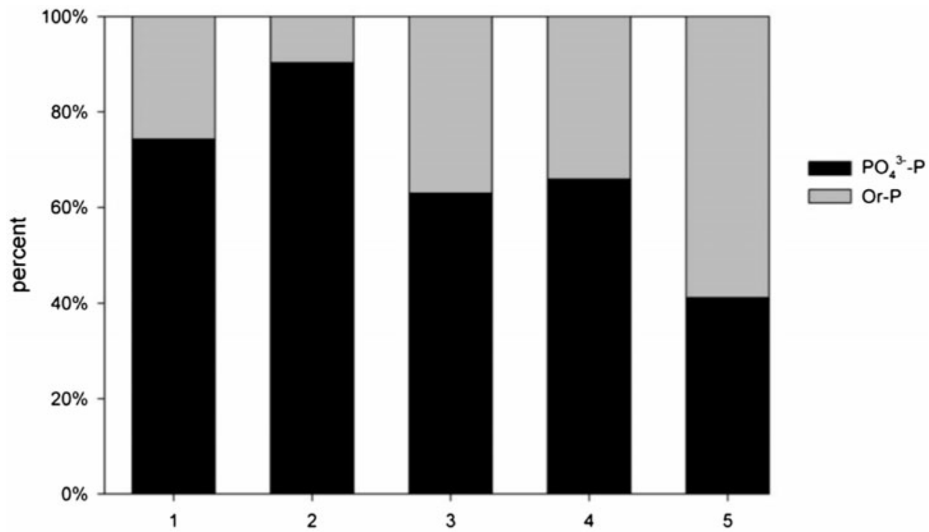

Fig. 9. Fractionation of the different phosphorus-forms of function units of the riparian wetland.
Notes: (1) Doudisi Ditch inflow, (2) Sedimentation tank outflow, (3) Oxidation pond outflow, (4) East River inflow, (5) Wetland outflow.

mainly on plant uptake and sediment adsorption, and was less affected by microbial activity and DOES concentration [32]. Even though plant uptake was not quantified, it could not account for the differences observed in the treatment systems since they were all exposed to similar conditions. The possibility of phosphorus precipitation, adsorption of soluble phosphorus to the roots systems, and SSs settling at the bottom of treatment CWs could not be ruled out [33–35]. The influent phosphorus concentration of wetlands was less than 0.4 mg L^{-1}. Surface flow wetland contributed the greatest to phosphorus removal, especially the soluble phosphate.

The influent soluble phosphate concentrations were low (between 0.08 and 1.1 mg L^{-1}). Phosphorus removal partly depended on influent phosphorus concentration. Effluent soluble phosphate concentrations stabilized at below 0.4 mg L^{-1}.

The results indicated that the wetland had adsorption capacity for treating agricultural run-off containing low phosphorus concentration.

4. Conclusions

Wetlands are a viable alternative for wastewater treatment for non-point source pollution, especially when organic matter and nutrients is the treatment target. The integrated riparian wetland consisting of grit chamber, biological oxidation pond, surface flow wetland, natural gravel bed wetland, proved to be very effective in reducing organic matter, SS and nutrients from agricultural wastewater and municipal sewage. Removal of organic matter and nutrients (nitrogen and phosphorus) was high and steady over the years of operation (the study period was only one year). Removal of TN exceeded 50% for wastewater. Ammonia and nitrate nitrogen were much more than nitrite nitrogen. Nitrogen removal mainly occurred in the surface flow wetland.

Phosphorus removal occurred mainly in oxidation pond and surface flow wetland functioning units. Surface flow wetland contributed the greatest to phosphorus removal, especially the soluble phosphate. The results indicated that the wetland had adsorption capacity for treating agricultural run-off containing low phosphorus concentration.

Our results also suggested that there was a little seasonal variation in water quality parameter concentrations of agricultural wastewater and municipal sewage. Mass loads of COD, SS, ammonia, nitrite, nitrate, TN, and TP on a yearly basis suggest that agricultural wastewater contains considerable amounts of nutrients and contaminants, thus the management of those pollutants are important on the north shore of Fuxian Lake, of which wetlands may be a suitable component.

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