Bull. Environ. Contam. Toxicol. (2006) 76:90–97
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DOI: 10.1007/s00128-005-0893-7

Bulletin of Environmental Contamination and Toxicology

Treatment of Polluted River Water Using Pilot-Scale Constructed Wetlands

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Received: 20 February 2005/Accepted: 12 October 2005

From 1970s to 1980s, the Constructed Wetland (CW) technique has already been rapidly developed and widely applied in more than 10 countries, such as USA, Australia and countries in Europe (Amelia, 2000; Brown, et al., 1994; Haberl, et al., 1995). Nowadays, there have been about 5000 CWs built in Europe, and 1000 CWs used in USA. In recent years, some CWs technics have substituted for the traditional secondary or advanced treatment technics (Chris, 1994; Wu, 1994; Jos et al., 1999; Du et al., 2002). In China, however, the CW was started to be studied and applied only from 1990s. Although many studies have been published on the treatment of urban sewage and industrial wastewater using CWs technology, little-attention has been given to the polluted river water treated by CWs.

There are three types of CW, Surface Flow Constructed Wetland (SFW), Integrated Vertical-Flow Constructed Wetland (IVFW) and Subsurface Flow Constructed Wetland (SSFW). In contrast to the SSFW and IVFW systems, the SFW system is closer to natural wetland and its investment and operation cost are lower, but this type occupies larger structural areas and the unit treatment efficiency is lower. In this paper, the IVFW and SSFW systems are choosed to be studied.

Xinyi River is situated in Jiangsu Province. It originates from the Zhangshan Sluice of Luoma Lake, and flows into the Yellow Sea. The total length is 144 km. The width of river bed ranges from 2500 m to 2800 m. This river is a typical floodway with design flood discharge of 6000 m^3/s. However, the flow is quite low in most time of the year. Discharge from upstream is normally 1.75 m^3/s, and the flow at downstream is about 4.45~20.00 m^3/s.

The water quality along Xinyi River is worse than Grade V (Chinese EPA, 2002). The main pollutant factors are NH_3-N and COD_{Mn}, and heavy metal content is normal. The main pollution sources include treated and untreated sewage and industrial wastewaters. The water quality has large spatial differences and it becomes better from upstream to downstream. For example, the annual mean concentrations of NH_3-N and COD_{Mn} are 370.7 mg/L and 31.3 mg/L respectively at the Xinmo River Section (upstream), and 16.1 mg/L and 3.15 mg/L at the Xiaocha River Sluice section (downstream) respectively. The measured water quality is listed in Table 1.

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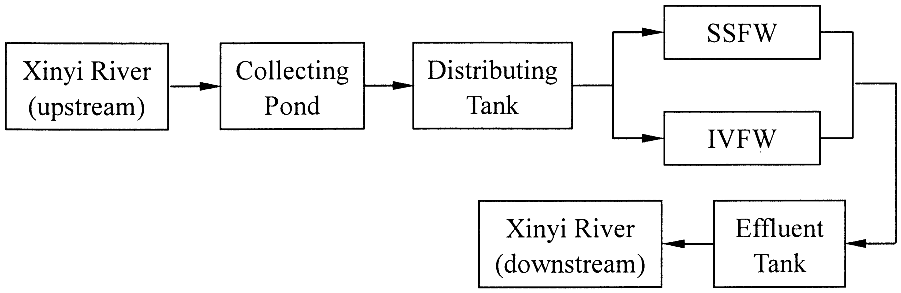

Figure 1. Flow chart of testing wetland system.

Table 1. Measured values of water quality of studied polluted river water

Pollution Index	COD_{Mn}	COD_{Cr}	NH_3-N	BOD_5	DO	SS
Range (mg/L)	5.1~58.0	19.8~182	0.16~12.8	1.8~38.7	0.5~12.7	45.8~902
Mean value (mg/L)	22.9	65.3	4.63	12.9	7.6	223

The objective of this paper was to study the removal efficiencies of polluted Xinyi River water using choosed pilot-scale CWs (IVFW and SSFW) built on the bottomland of upstream of Xinyi River (Shuyang Section).

MATERIALS AND METHODS

Based on field investigation, the construction site of CWs was chosen to be within the Baomaizi Weir, which is at the east of Shuyang Culvert and west of Yi River Bridge in Shuyang County. The mean gradient of the bottomland is 1/17000 and the width is about 1.2 km.

The treatment process is shown in Fig.1. And the target effluent quality of the pilot-scale CWs is required to reach Grade V (Chinese EPA, 2002).

In both systems, the substrate is stratified sand stones. The sizes (Length*Width*Depth) of SSFW and IVFW are 45m*10m*0.75m and 30m*10m*0.85m, respectively. The structures are shown in Fig.2 and Fig.3. In order to improve the homogeneity of water distribution, the water distribution part of IVFW was renovated by surface water distribution method at the first 1/3 part of the influent section.

The selection of aquatic plants has significant effects on the treatment efficiency and longevity of the wetland system. The main factors to be considered for the selection of plants include the purification capacity, anti pest ability, frost resistance, environment adaptability, economic value, scenery etc. At present, the generally accepted plants can be used in wetland systems include *Phragmites communis*, *Typha latifolia*, *Scirpus locustris*, *Canna indica* etc. According to the

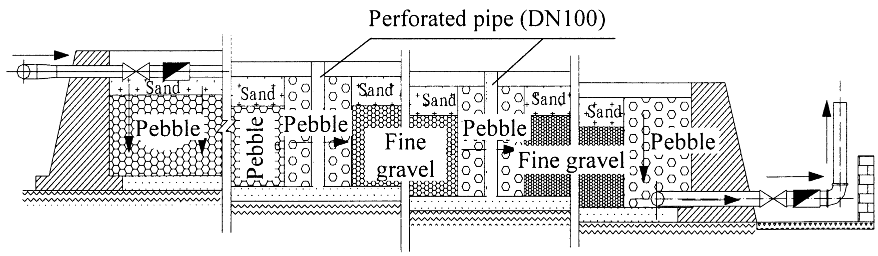

Figure 2. The structure of SSFW

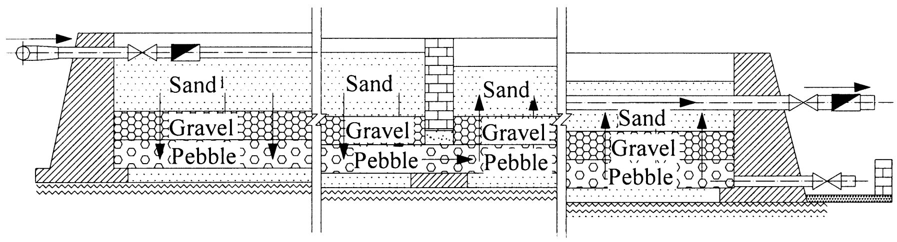

Figure 3. The structure of IVFW

experimental results, *Typha latifolia* and *Scirpus locustris* were selected as the plants in the CWs and the hydraulic loads of 0.23 $m^3/m^2 \cdot d$ of IVFW and 0.16 $m^3/m^2 \cdot d$ of SSFW were selected in this study. During the study period, the whole systems were operated under natural conditions. Since CW will be at anaerobic status after long-time operation and the redox potential is negative (Zhang et al., 1999), there will not have good conditions for nitrification. Therefore, the systems were operated in intermittent way, i.e., the wetlands were fed ten hours during the day in the 24 hours. In this way, the anoxic problem after long-time operation can be alleviated.

RESULTS AND DISSCUTION

The pilot-scale experiment was started from January 2003, and it was lasted for more than one year. The results are shown in Figure 4 and Figure 5. Figure 4 shows that when COD_{Mn} of influent is 3.11~117.28 mg/L, both SSFW and IVFW systems are efficient for its removal, and the mean removal rate is 61.1% and 77.8% respectively. In comparison, IVFW is more efficient than SSFWIt is because that in IVFW system, water flows from surface into bottom and then from bottom into surface again. In this way, the medium in the system has more connection with air than in SSFW system, which is benefit for the aerobic decomposition of organic matter by microorganisms. Thus, the removal rate of COD_{Mn} increased.

Fig. 5 indicates that the influent COD_{Mn} concentration has only small effect on the removal rate of IVFW system For SSFW system, when the influent COD_{Mn} is higher than 90 mg/L, the effluent COD_{Mn} increases rapidly and the water quality deteriorates. This indicates that when COD_{Mn} of influent is 3.11~117.28 mg/L, the

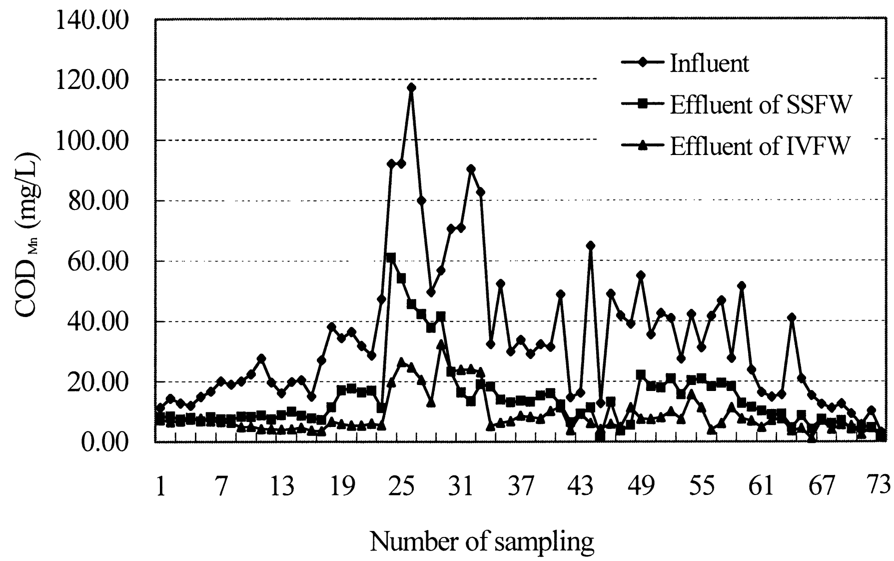

Figure 4. COD_{Mn} Changes of influent and effluent of SFW and IVFW systems.

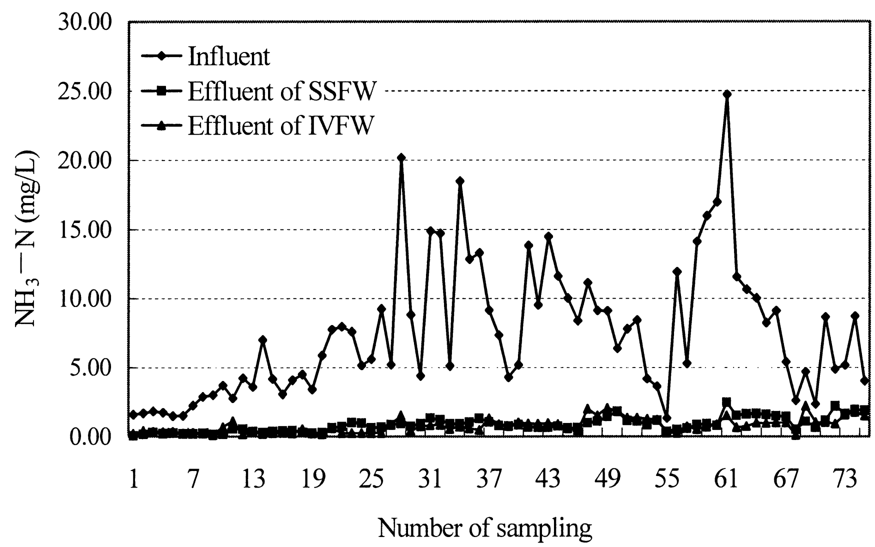

Figure 5. NH_3-N Changes of influent and effluent of SSFW and IVFW systems.

efficiency of IVFW is more stable. This system has better resistance to pollutant impact load than SSFW system.

Normally, nitrogen in wastewater exists in the forms of organic nitrogen and ammonium nitrogen. The removal of nitrogen from wastewater is mainly done by

Table 2. Comparison of water quality in over time in the SSFW system.

Item	Time period	Influent concentration		Effluent concentration		Mean removal rate (%)
		Range	Mean value	Range	Mean value	
COD_{Mn} (mg/L)	Jan.~Mar.	12.00~47.36	23.01	6.85~17.72	9.48	58.80
	Apr.~Jun.	12.74~117.28	50.19	1.86~61.06	14.30	71.51
	Jul.~Sep.	—	—	—	—	—
	Oct.~Dec.	3.11~12.53	9.2	2.33~7.46	5.26	42.83
NH_3-N (mg/L)	Jan.~Mar.	1.47~20.17	4.86	0.05~1.01	0.45	90.74
	Apr.~Jun.	1.30~24.71	9.31	0.37~2.46	1.11	88.08
	Jul.~Sep.	—	—	—	—	—
	Oct.~Dec.	2.52~4.14	3.09	0.20~1.01	0.64	79.29

nitrification and denitrification of microorganisms. In wetland systems, ammonium is also necessary for the growth of plants. Ammonium can be taken by plants directly and be used to synthesize protein. Ammonium is then removed by the harvesting of plants (Wu, 1994; Zhang et al., 1999). Because of the transportation and transfer of oxygen by plants, there is continuous aerobic-anoxic-anaerobic status, which is similar to the serial or parallel connection of many A/A/O processes. It is propitious to the simultaneous nitrification and denitrification in wetland systems (Du et al., 2002).

Figure 5 shows that when NH_3-N of influent is 1.30~24.71 mg/L, both SSFW and IVFW are efficient for its removal, and the mean removal rate can reach 85.5% and 86.9% respectively. It is the result of both plant assimilation and bacterial nitrification. In comparison, IVFW is more efficient than SSFW (see Fig.5). It's also because of the better reoxygenization in IVFW system as mentioned above, which is beneficial for nitrification. Fig.5 shows that in both systems, the change of influent ammonium concentration has small effects on the effluent ammonium concentration. It also indicates that both systems have stable and good removal efficiency of ammonium in the studied range of influent ammonium.

During the study period of more than one year, it is found that there were different concentrations removal efficiencies of pollutants in different times of the year. From Table 2 and Table 3, the concentrations of COD_{Mn} and NH_3-N are relatively higher from April to June, while relatively lower from October to December. Because of flooding, there was no data from July to September.

The removal rates of COD_{Mn} of SSFW and IVFW systems are the highest from April to June (71.51% and 80.27% respectively) and the lowest from October to December (42.83% and 52.17%). In general, the plants grow well from April to June and the root systems spread widely to the substrates in CW systems. This not only increases the amount of pollutants assimilated directly by plants, but also accelerates the aerobic decomposition of organic pollutants because of the better

Table 3. Comparison of water quality in over time in the IVFW system.

Item	Time period	Influent concentration		Effluent concentration		Mean removal rate (%)
		Range	Mean value	Range	Mean value	
COD_{Mn} (mg/L)	Jan.~Mar.	12.00~47.36	23.01	3.44~7.67	6.33	72.49
	Apr.~Jun.	12.74~117.28	50.19	1.11~32.40	9.90	80.27
	Jul.~Sep.	—	—	—	—	—
	Oct.~Dec.	3.11~12.53	9.2	1.54~7.07	4.40	52.17
NH_3-N (mg/L)	Jan.~Mar.	1.47~20.17	4.86	0.10~1.52	0.39	91.98
	Apr.~Jun.	1.30~24.71	9.31	0.10~2.21	1.01	89.15
	Jul.~Sep.	—	—	—	—	—
	Oct.~Dec.	2.52~4.14	3.09	0.17~1.26	0.46	85.11

transportation of oxygen. Besides, the temperature from April to June is relatively higher, so the microorganisms are more active and propagate more rapidly in this period. With the oxygen being transferred by plants, the decomposition of organic pollutants by aerobic microorganisms is accelerated. Therefore, the removal rate of organic pollutants is relatively higher. But from October to December, temperature goes down and plants wilt and the withered leaves and shoots fall to the wetland system. The activity of microorganisms slows down. Therefore, the COD_{Mn} concentration of effluent increases and the removal rate decreases.

From January to March, the temperature is the lowest. The number of microorganisms is the fewest. And the activity is the lowest. The degradation ability in this period should be weaker than in the period from October to December. But seen from both tables, the removal rates of COD_{Mn} and NH_3-N in this period are higher. It is because both systems were just built and started in this period, and there were strong interception and exchange functions. The changes of removal rate of NH_3-N in different time period are similar to those of COD_{Mn}.

The removal efficiencies of COD_{Mn} of SSFW and IVFW under different pollutant loads are shown in Table 4. It indicates that pollutant loads have significant effects on the removal rates of COD_{Mn} of both systems. In both systems, when the pollutant load is less than 3 $g/m^2 \cdot d$, the removal rates are all lower. The efficiency increases with the increment of pollutant load till it reaches 12 $g/m^2 \cdot d$. When the load is more than 12 $g/m^2 \cdot d$, the removal rate decreases.From Table 4, the removal rate of COD_{Mn} of IVFW is higher than that of SSFW. When the pollutant load is within the range of 8~12 $g/m^2 \cdot d$, the highest removal rate occurs. This range is called the "optimal pollutant load of COD_{Mn}". When exceeding this range, the removal rate decreases. Table 4 also shows that although the removal rate of IVFW decreases after the pollutant load reaches 12 $g/m^2 \cdot d$, it still remains high. However, the removal rate of SSFW decreases rapidly. This indicates that pollutant loads have less influence on IVFW system than on SSFW system and IVFW has better resistance to pollutant impact load.

The removal efficiencies of NH_3-N of SSFW and IVFW under different pollutant

Table 4. Removal efficiencies of COD_{Mn} of SSFW and IVFW under different pollutant loads.

System	Pollutant load ($g/m^2 \cdot d$)				
	Less than 3	3~5	5~8	8~12	More than 12
Removal rate of SSFW (%)	49.16	49.52	67.80	74.68	39.35
Removal rate of IVFW (%)	55.67	70.16	76.02	82.17	72.71

Table 5. Removal efficiencies of NH_3-N of SSFW and IVFW under different pollutant loads.

System	Pollutant load ($g/m^2 \cdot d$)				
	Less than 0.2	0.2~0.5	0.5~0.8	0.8~1.3	More than 1.3
Removal rate of SSFW (%)	85.33	85.58	85.12	89.95	90.92
Removal rate of IVFW (%)	82.27	86.59	86.91	87.78	92.10

loads are shown in Table 5. It shows that the removal rates of NH_3-N of both systems remain high within the studied range of pollutant load. And it increases slightly with the increment of pollutant load. When the pollutant load of NH_3-N is more than 1.3 $g/m^2 \cdot d$, the removal rates of both systems are more than 90%, which indicates they can resist more pollutant loads than 1.3 $g/m^2 \cdot d$. Results show that the proper ranges of pollutant load of NH_3-N for SSFW and IVFW are 0.075~1.45 $g/m^2 \cdot d$ and 0.11~1.60 $g/m^2 \cdot d$ respectively.

In conclusion, the polluted Xinyi River water could be treated efficiently by pilot-scale SSFW and IVFW systems. The mean concentrations of pollutants of effluent reach Grade V (Chinese EPA, 2002). Under the hydraulic loads taken in these experiments, when the influent concentrations of COD_{Mn} and NH_3-N are 3.11~117.28 mg/L and 1.30~24.71 mg/L, the mean removal rates of COD_{Mn} and NH_3-N are 61.1% and 85.5% of SSFW system, and the mean removal rates of COD_{Mn} and NH_3-N of IVFW are 77.8% and 86.9%. The efficiency of pollutant removal of IVFW is better than that of SSFW. And the IVFW system has better resistance to pollutant load impact than SSFW system. The optimal pollutant load of COD_{Mn} for both systems is 8~12 $g/m^2 \cdot d$. Except the effects of instability in start up period, the removal efficiencies of COD_{Mn} and NH_3-N are best in the period from April to June and are worst in the period from October to December in both systems.It indicated that the CW system can be used successfully to the treatment of polluted river water.

Acknowledgments. This work was supported by the project *Study on the Control Plan and Treatment of Polluted River Water from Xinyi River*. This project was sponsored by the Environmental Protection Bureau of Jiangsu Province.

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