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Chapter 23

Use of a Wetland System for Treating Pb/Zn Mine Effluent: A Case Study in Southern China from 1984 to 2002

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Abstract. A constructed wetland system in Guangdong Province, South of China has been used for treating Pb/Zn mine discharge since 1984. In this chapter, the performance of this system in the purification of mine discharge, metal accumulation in different ecological compartments and ecological succession within the system during the period of 1984–2002 has been reviewed. The data show that the wetland system not only effectively remove metals (mainly Pb, Zn, Cd and Cu) and total suspended solids from the mine discharge over a long period leading to significant improvement in water quality, but also gradually increase diversity and abundance of living organisms.

23.1. Introduction

Water quality problems can be caused by water storage and by pollution due to effluent discharge to the drainage system (Finlayson & Mitchell, 1982). The deliberate use of wetlands (both natural and constructed) as biological treatment systems for effluent purification has developed rapidly over the last 30 years with the increasing scientific documentation of the role of plants in wastewater purification (Wolverton, 1987; Dunbabin & Bowmer, 1992; Sundaravadivel & Vigneswaran, 2001). The growing interest in wetland systems is in part due to the recognition that natural treatment systems offer advantages over conventional concrete-and-steel, equipment-intensive, mechanical treatment plants. When the same biochemical and physical processes occur in a more natural environment instead of reactor tanks and basins, the wetland system often consumes less energy, is more reliable, requires less operation and maintenance and, as a result, costs less (Smith, 1989). Most research on the use of wetlands for wastewater

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treatment has been directed towards using municipal wastewaters to reduce the concentrations of nitrogen and phosphorus and to lower the biological oxygen demand. The use of wetlands to treat metal-contaminated mine drainage water by removing metals has been largely ignored until the last decade (Dunbabin & Bowmer, 1992).

In comparison with organic effluents, drainage waters from mining activities and abandoned mines are frequently higher in metal loads, more poorly buffered, of more extreme pH, lower in organic compounds and fluctuate in volume. Metals present in mine discharges, such as lead, zinc, cadmium and copper can pose serious environmental threats, as they are potentially toxic to all living organisms. Metal-contaminated mine drainage waters cause widespread and serious water pollution problems as they can ruin fisheries and recreational lakes, damage structures, increase the cost of municipal water treatment, degrade the value of land and lower the potential of an area for tourism (National Rivers Authority, 1992; Sundaravadivel & Vigneswaran, 2001).

It is both a difficult and expensive task to decontaminate large volumes of wastewater polluted with heavy metals by conventional physico-chemical techniques. As Eger et al. (1994) have indicated, although this type of drainage can be chemically treated in an active treatment plant, this is an expensive and long-term commitment, particularly since drainage problems can persist for over a 100 years. In western countries some successful case studies have indicated that wetlands can effectively purify metal-contaminated mine drainage water, and can offer an economical, self-maintaining, and therefore preferred alternative to conventional treatment of different types of contaminated water (Gersberg et al., 1984; Erten et al., 1988; Hammar & Bastian, 1989; Wildeman & Laudon, 1989; National River Authority, 1992; Ye et al., 2001a,b).

In P.R. China, the drainage water from mining activities has caused some serious environmental problems, but little information is available concerning the use of wetlands to treat metal-contaminated mine drainage water. In this chapter, some experimental results are reviewed for a wetland system dominated by *Typha latifolia* (cattail) to treat the wastewater generated from the lead/zinc (Pb/Zn) mine at Shaoguan, Guangdong Province, China, during the period of 1984–2002. Full experimental details can be found in the various papers referred to.

23.2. Description of the Study Site

The Pb/Zn mine is situated at Shaoguan, Guangdong, in the subtropical region of China. The mean annual temperature is about 20°C and the extreme values are −5°C in January and 40°C in July. Average annual rainfall is 1,457 mm. The total land area of the mine is about 4 km^2, and it is situated at 100–150 m above sea

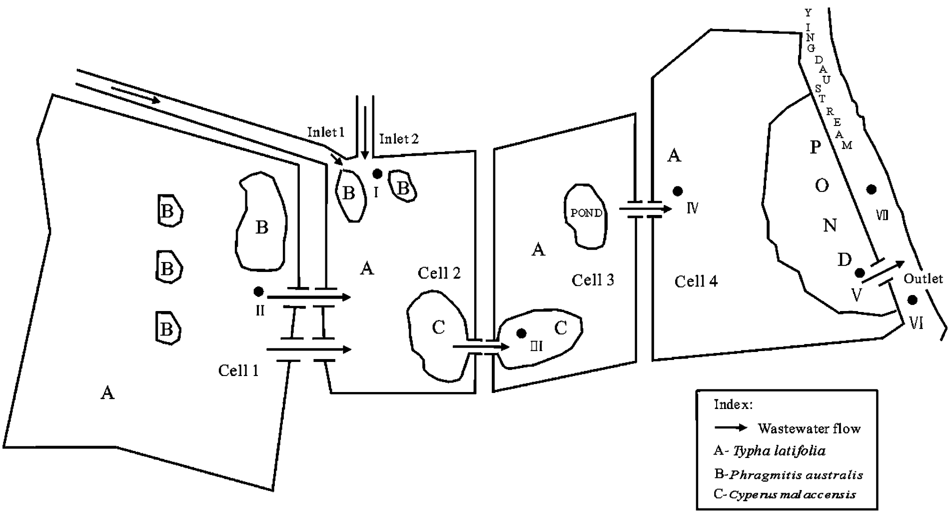

Figure 1: Sketch map of Fankou wetland system.

level. The original area of the wetland system (Cell 1) (Fig. 1) was about 87,500 m^2; it was 350 m in length and 250 m in width with an average depth of 2.5 m. The system was enclosed by dam walls constructed of rocks and mine tailings. Its capacity was about 150,000 m^3, and the treatment capacity was about 29,800 t day^{-1}, with a retention time in the range of five to seven days. This system could be divided into two parts: an upper part that was a wetland dominated by cattail, and a lower, a stabilization pond without physical separation. The mean depths of the wastewater in the wetland area and the stabilization pond were about 10 cm and 2.5 m, respectively. There were two entrances to the combined treatment system. Cattail was planted in the wetland area in 1983, and after two years it had expanded to cover about 55% of the area; after six years (1989), it had colonized about 73.6% of the area. No hydrophytes had been found on the stabilization pond. The wastewater draining from the entrances flowed into the aquatic treatment system and then into the stabilization pond, finally leaving through two exits. About 26,000 tonnes drainage per day were discharged into the system during the period of 1984–1989. Because of the high content of total suspended solids (TSS) in the drainage; an average of about 52,900 t per year of sediment were deposited in the system. This sediment gradually raised the bottom of the system thus decreasing both volume and treatment capacities, therefore, Cells 2–4 were constructed in 1988, 1995 and 1998, respectively (Fig. 1, Table 1). Cattail is the major dominant plant species in all four cells, other dominant species included *Phragmites australis* and *Cyperus malaccensis*. Cell 1 and Cell 2 ceased to be used in treating mine drainage in 1995 and October 2001, respectively.

Table 1: The time schedule of Fankou wetland cells used for treating Pb/Zn mine drainage in Shaoguan, Guangdong Province, Southern China.

	Cell 1	**Cell 2**	**Cell 3**	**Cell 4**
Year wastewater treatment started	1984	1988	1995	1998
Year wastewater treatment finished	1995	2001	–	–
Area (m^2) of cell	87,500	23,510	14,950	33,220

Although mine drainage had not been discharged into Cell 1 since 1995, metal polluted-runoff from the surrounding area still passed through Cell 1 into Cell 2. The Cell 2 served as a ditch after its use for drainage treatment was stopped in October 2001.

23.3. Efficiency of Metal Removal from the Effluent by the Wetland System

Table 2 illustrates the changes in water quality resulting from the system by comparing the properties of the influent and effluent waters. The results indicate that influent water had a rather high level of TSS (4,635.4 mg l^{-1}), high levels of Pb (1.61 mg l^{-1}) and Zn (1.96 mg l^{-1}) and a moderate level of Cd (0.022 mg l^{-1}). After treatment by the system, water quality was significantly improved: pH changed from 8.03 to 7.78, TSS in the influent water were reduced by 99% ($p < 0.001$), Pb by 90% ($p < 0.001$), Zn 84% ($p < 0.001$), Cd 86% ($p < 0.001$), Fe 97% ($p < 0.05$). Other metals: Cu, Ca, Mg, Al, Na, Co and K were reduced by between 50 and 91% of their original concentrations in the influent water. The concentrations of soluble Pb, Zn, Cd, as well as other metals and TSS in the treated effluent, were all within the upper limits set for industrial wastewater discharge in China (Ye et al., 1992a).

In 1984, the mean Pb concentration in effluent water was 0.60 ± 0.147 (mg l^{-1}), and Zn: 1.09 ± 0.222 (mg l^{-1}), and pH: 8.07 ± 0.05 ($n = 15$, mean $\pm$ se, January–July 1984). The efficiencies of Pb and Zn removal from January to July 1984 were 62.7 and 44.4% after the drainage passed the same area but only a few patches of cattail grew within in the this area. The efficiencies of metal and TSS removal were increased rapidly after 1985 and tended to improve in subsequent years with increasing plant area in the system (Ye et al., 1992a).

General properties of influent and effluent waters were monitored again in 1998 and in period of June 2001–May 2002. The data presented in Table 3 show that TSS in the influent water were reduced by 99.6%, Pb by 80.1%, Zn 97.2%,

Table 2: General properties of influent and effluent water collected at the entrance and exit of the purification system compared with the industrial discharge standard (mean values ± se) (January 1985–December 1989).

Property	**Influent**	***n***	**Effluent**	***n***	**Industrial discharge standard**
pH	8.03 ± 0.08	7	7.78 ± 0.03	174	
Total suspended solids (mg l^{-1})[a]	4635.40 ± 384.49	5	28.11 ± 10.99	5	500
Pb (mg l^{-1})[a]	1.61 ± 0.41	21	0.157 ± 0.019	177	1.00
Zn (mg l^{-1})[a]	1.96 ± 0.41	23	0.309 ± 0.026	177	5.00
Cd (mg l^{-1})[a]	0.022 ± 0.005	7	0.003 ± 0.0002	136	0.10
Cu (mg l^{-1})	0.044 ± 0.012	7	0.017 ± 0.005	7	
Fe (mg l^{-1})[a]	17.26 ± 6.26	7	0.49 ± 0.17	7	
Al (mg l^{-1})	12.43	3	0.002	3	
Ca (mg l^{-1})	195.71	3	41.25	3	
Co (mg l^{-1})	0.013	3	0.001	3	
K (mg l^{-1})	5.00	3	2.50	3	
Mg (mg l^{-1})	112.86	3	33.75	3	
Na (mg l^{-1})	8.86	3	3.88	3	

Ye et al. (1992a). *n* denotes the number of samples.
[a] *t*-test indicate a statistical difference of $p < 0.05$ between samples values of influent and effluent water.

Cd 96.5%, and Cu 96.8% after treatment by the system. The average concentration recorded in the influent water were: 99.3 mg l^{-1} Pb, 61.4 mg l^{-1} Zn (Inlet 1), 1.13 mg l^{-1} Cd, and 1.15 mg l^{-1} (Inlet 2); after treatment, however, only 0.128 mg l^{-1} Pb, 0.34 mg l^{-1} Zn, 0.003 mg l^{-1} Cd and 0.008 mg l^{-1} Cu were recorded in the effluent water (Table 3). The water quality of effluent was not only below the upper limits set for industrial wastewater discharge, but also met the Grade V quality standard for surface water: agricultural water for general landscapes (Table 4).

The data presented in Table 5 show the values for pH, TSS and metal concentrations in the surface water collected from site I (inlet of the system) to site V (outlet of the system), and from the upper and lower reaches of the receiving stream (sites VI and VII). The pH value was significantly increased from 6.48 in site I to 6.71 in site V, while concentrations of TSS, Pb, Zn, Cd and Cu in water were gradually reduced from the inlet to outlet of the system.

Table 3: General properties of influent and effluent water collected at the entrance and exit of the wetland system (mean values ± se, $n = 4$) in 1998, and June 2001–May 2002.

	Cell		pH	mS/cm	COD	TSS ($mg\ l^{-1}$)	Pb ($mg\ l^{-1}$)	Zn ($mg\ l^{-1}$)	Cd ($mg\ l^{-1}$)	Cu ($mg\ l^{-1}$)
1998	2	Inlet	7.71	1.06	75.9	8802	2.41 ± 0.51	4.28 ± 1.20	0.80 ± 0.11	0.377 ± 0.044
	3	Outlet	7.34	0.49	7.69	31.5	0.48 ± 0.03	0.12 ± 0.08	0.028 ± 0.007	0.012 ± 0.004
		Reduction (%)			89.9	99.6	80.1	97.2	96.5	96.8
2001.6 ~ 2002.5	2	Inlet 1	7.34	3.10	–	1400	99.33 ± 13.7	61.4 ± 1.33	0.382 ± 0.226	0.756 ± 0.904
	2	Inlet 2	7.52	–	–	–	44.94 ± 5.78	27.5 ± 1.36	1.133 ± 1.530	1.15 ± 1.87
	4	Outlet	7.21	0.42	–	153	0.128 ± 0.03	0.34 ± 0.06	0.0026 ± 0.001	0.0076 ± 0.002

Yang et al. (2001) and Leung (2002).

Table 4: Chinese environmental quality standard for different grades of surface water.

	I	**II**	**III**	**IV**	**V**
pH			6–9		
Pb (mg l^{-1})	0.01	0.01	0.05	0.05	0.1
Zn (mg l^{-1})	0.05	1.0	1.0	2.0	2.0
Cd (mg l^{-1})	0.001	0.005	0.005	0.005	0.01
Cu (mg l^{-1})	0.01	1.0	1.0	1.0	1.0

Only pH and relative metal contents are listed in this table. China State Bureau of Environmental Protection Bureau (2002). According to the environmental functions and protective objectives of surface waters, all surface water in Mainland China are divided five grades: Grade I, source water or within national nature conservation zones; Grade II, surface water for drinking purpose (1st grade protection area), water for aquaculture (precious species); Grade III, surface water for drinking purpose (2nd grade protection area), water for aquaculture (common species); Grade IV, agriculture water for general landscapes.

The data in Table 5 also show that the outlet water from the system did not significantly increase metal concentrations in the receiving water body.

The above monitoring data show that the wetland system, whether consisting of one, two or three cells, was able to effectively remove metals and TSS from the mine drainage over a relatively long period. Reduction of TSS in the drainage before it was discharged into the system would elongate the life span of each cell.

23.4. Metal Accumulation in Different Ecological Compartments

23.4.1. Accumulation in Sediment

The data presented in Table 6 show that the sediment of the system (Cell 1) contained very high concentrations of Pb and Zn, and medium high concentration of As. Concentrations of these three metals in sediment at entrance site were about 66, 20 and 6 times higher than those in “clean” soil collected from control site (about 40 km west of Shaoguan Pb/Zn mine), respectively. Except for As, Cd, and Na, the other metal concentrations in the sediment were similar between the entrance site and the exit site of the system. Concentrations of As, Cd and

Table 5: Physical and chemical characteristics of surface water in January 2002 (mean ± se, $n = 3$).

Sites	pH	TSS (g l^{-1})	Pb (mg l^{-1})	Zn (mg l^{-1})	Cd (mg l^{-1})	Cu (mg l^{-1})
I[a]	6.48 ± 0.01c[b]	0.22 ± 0.02a	44 ± 1.3a	17 ± 0.33a	0.02 ± 0.001a	0.03 ± 0.003a
II	6.62 ± 0.07bc	0.11 ± 0.03ab	0.02 ± 0.02e	0.27 ± 0.08c	0.006 ± 0.006b	0.04 ± 0.039a
III	6.54 ± 0.02bc	0.22 ± 0.01a	38 ± 1.8b	16 ± 0.58a	0.02 ± 0.001a	0.02 ± 0.001a
IV	6.84 ± 0.02a	0.18 ± 0.01ab	5.7 ± 0.67d	3.3 ± 1.3b	0.01 ± 0.001ab	0.01 ± 0.001a
V	6.71 ± 0.03ab	0.07 ± 0.001b	0.05 ± 0.03e	0.37 ± 0.21c	0.005 ± 0.001b	0.005 ± 0.002a
VI	6.62 ± 0.06bc	0.11 ± 0.04ab	0.07 ± 0.05e	0.06 ± 0.05c	0.0024 ± 0.0009b	0.019 ± 0.031a
VII	6.85 ± 0.04a	0.12 ± 0.03ab	0.05 ± 0.03e	0.11 ± 0.06c	0.0003 ± 0.0005b	0.018 ± 0.017a

Yu et al. (2004).

[a] I: Inlet of Cell 2, II: outlet of Cell 1, III: inlet of Cell 3, IV: inlet of Cell 4; V: outlet of Cell 4, VI: upper reach of the stream, VII: lower reach of the stream.

[b] Different letters in the same column indicate a significant difference at $p < 0.05$ according to Tukey-HSD test.

Table 6: Total concentrations of metals and N, P in the soil/sediment collected at the entrances and exits of wetland system and control site (samples collected from Cell 1 in period of December 1988–March 1990) (mg kg^{-1}, mean ± sd).

Order	**Sites**	**Total N (%) ($n = 3$)**	**Total P (%) ($n = 3$)**	**Pb ($n = 7$)**	**Zn ($n = 7$)**	**Cd ($n = 7$)**	**Cu ($n = 7$)**	**Fe ($n = 5$)**	**K ($n = 5$)**	**Na ($n = 5$)**	**Mn ($n = 5$)**	**As ($n = 5$)**	***t*-test of differences between sites**
1	Entrance	0.084	0.109	5,977 ± 2,191	3,057 ± 162	24 ± 7.0**	87 ± 16	35,974 ± 10,544	10,463 ± 4,023	1,257 ± 42**	1,549 ± 602	529 ± 162*	1–2
2	Exit	0.074	0.120	5,395 ± 2,457**	2,960 ± 420**	17 ± 9.1*	112 ± 32**	40,925 ± 6,723**	9,006 ± 3,413	943 ± 84**	1,454 ± 372	201 ± 177*	2–3
3	Control	0.174	0.047	91 ± 49**	153 ± 83**	1.52 ± 0.40**	22 ± 11**	18,008 ± 3,827*	7,419 ± 1,876	1,392 ± 77**	884 ± 582	86 ± 81**	1–3

Ye et al. (1992b). Probability values for t: $*p < 0.05$, $**p < 0.01$.

Table 7: Total concentrations of Pb, Zn, Cd and Cu in sediments of Fankou wetland system (samples collected in period of June 2001–January 2002, mg kg^{-1}, mean ± sd, $n = 9$).

	Pb	Zn	Cd	Cu
Cell 1	6,747 ± 3,228a[a]	5,697 ± 2,074a	15 ± 4.5a	145 ± 115a
Cell 2	5,124 ± 2,059a	4,117 ± 2,678a	12 ± 5.0a	70 ± 17a
Cell 3	4,538 ± 1,692a	4,960 ± 2,307a	12 ± 7.0a	84 ± 28a
Cell 4	3,992 ± 1,069a	4,611 ± 1,527a	14 ± 3.2a	69 ± 21a

Leung (2002).
[a] Different letters in a same column indicate a significant difference at $p < 0.05$ according to Tukey-HSD test.

Na in sediment were significantly higher in the entrance site than in the exit site (Ye et al., 1992b).

The data in Table 7 show the concentrations of Pb, Zn, Cd and Cu in the sediments of four wetland cells collected from June 2001 to January 2002. Although concentrations of Pb, Zn and Cu in sediment tended to decrease from Cell 1 to Cell 4, there were no significant differences between any of the cells. Compared to the data presented in Tables 6 and 7, the concentrations of Pb and Cu were similar, but Zn concentrations in the sediments were obviously higher in 2001–2002 than in 1988–1990. Concentration of total N in sediment of the wetland in Cell 1 was half that of the control soil, but the reverse was true for total P (Table 6).

23.4.2. Accumulation in Plants

The average concentrations of Pb, Zn and Cu in belowground tissues (roots, rhizome) of cattail were obviously higher than in aboveground tissues (Tables 8 and 9). Cattail grown in the system accumulated much higher concentrations of Pb and Zn than when grown in the control site (Table 8). Concentrations of Pb, Zn, Cd and Cu in both aboveground and belowground tissues of cattail grown in Cell 1 were similar to those of cattail grown in the other three cells (Table 9). The concentrations of metals in the aboveground tissues of cattail were similar in the two surveys carried out at different times. Both data suggest that cattail mainly excludes metals from its aboveground tissues and maintains low metal concentrations in its aboveground tissues, despite high metal concentrations in both sediment and its belowground tissues.

Table 8: Metal concentrations in root, rhizome and leaf of *Typha latifolia* grown in the Fankou wetland system and a control site (mg kg^{-1}, mean ± sd, $n = 7$).

Site	Organ	Pb	Zn	Cd	Cu	Mn
Fankou	Root	1,108 ± 693a[a]	946 ± 362a	1.5 ± 0.25a	29 ± 3.7a	178 ± 50b
Control	Root	90 ± 5.3b	139 ± 45b	1.3 ± 0.66a	10 ± 1.4b	531 ± 61a
Fankou	Rhizome	354 ± 182a	456 ± 175a	1.6 ± 1.6a	17 ± 6.5a	138 ± 19b
Control	Rhizome	39 ± 14b	78 ± 22b	0.81 ± 0.51a	4.8 ± 0.22b	335 ± 35a
Fankou	Leaf	99 ± 53a	155 ± 77a	0.62 ± 0.23a	9.1 ± 3.8a	586 ± 137a
Control	Leaf	15 ± 7.2b	43 ± 8.0b	0.55 ± 0.32a	3.2 ± 0.26b	664 ± 48a

Ye et al. (1992b).

[a] Different letters in a same organ and a same metal indicate a significant difference at $p < 0.05$ according to *t*-test.

23.4.3. Accumulation in Animals

Animal samples were collected in March and November 1990. Metal concentrations in muscle tissue varied greatly among the different species, for example, Pb contents ranged from 0.29 mg kg^{-1} in *Ophiocephalus maculates* to

Table 9: Concentrations of Pb, Zn, Cd and Cu in aboveground tissues and belowground tissues of *Typha latifolia* grown in the Fankou wetland system (samples were collected during the period June 2001–January 2002, mg kg^{-1}, mean ± sd, $n = 9$).

	Pb	Zn	Cd	Cu
Aboveground tissues				
Cell 1	118 ± 76a[a]	116 ± 46a	0.82 ± 0.46a	24 ± 17a
Cell 2	115 ± 96a	106 ± 41a	0.96 ± 0.84a	21 ± 10a
Cell 3	112 ± 76a	130 ± 60a	0.86 ± 0.60a	22 ± 15a
Cell 4	221 ± 124a	116 ± 70a	0.79 ± 0.91a	21 ± 21a
Belowground tissues				
Cell 1	4,108 ± 3,072a	2,641 ± 2,174a	3.4 ± 2.1a	32 ± 14a
Cell 2	1,315 ± 777a	749 ± 571a	2.8 ± 2.7a	25 ± 6.4a
Cell 3	1,456 ± 1,088a	1,125 ± 867a	6.7 ± 4.6a	23 ± 6.0a
Cell 4	1,497 ± 627a	1,271 ± 551a	8.4 ± 5.3a	21 ± 10a

[a] Different letters in a same column indicate a significant difference at $p < 0.05$ according to Tukey-HSD test.

Table 10: The concentrations of Pb, Zn, Cu and Cd in aquatic animal organism collected from the wetland system (mg kg^{-1}).

Species	Sampling parts	Pb	Zn	Cu	Cd
Cipangopaludina cathayensis	Muscle	68.5	169.2	15.3	1.48
Carassius auratus	Muscle	5.92	34.7	0.26	0.98
Ophiocephalus maculates	Muscle	0.29	8.87	1.84	0.08
	Liver	1.43	25.47	9.97	1.52
	Skeleton	27.1	107.5	4.05	0.65
	Egg	1.13	24.40	21.51	0.06
	Gill	31.4	63.1	4.14	0.26
	Scale	30.8	0.36	2.89	0.36
Maximum permitted concentration for consumption in China		1.0			0.5

Chen et al. (1990).

68.5 mg kg^{-1} in *Cipangopaludina cathayensis*, and Zn from 8.9 mg kg^{-1} in *O. maculates* to 169 mg kg^{-1} in *C. cathayensis* (Table 10). Among the three species tested, *C. cathayensis* accumulated the highest Pb, Zn, Cu and Cd in its muscle. Concentrations of Pb and Cd in muscles of *C. cathayensis* and *C. auratus* were higher than the maximum permitted concentration for consumption in China (PRC Agriculture Department, 2001), especially Pb in muscle of *C. cathayensis*, which was nearly 70 times higher than the maximum permitted concentration for this metal.

The concentrations of metals in different parts of the same animal body also varied greatly, for example, Pb ranged from 0.29 mg kg^{-1} in muscle to 31.4 mg kg^{-1} in gill tissue of *O. maculates*, and Zn from 0.36 mg kg^{-1} in scales to 107 mg kg^{-1} in skeleton of the same body. In *O. maculates*, muscle tissue accumulated the highest concentrations of Zn, scales the highest Pb (31.4 mg kg^{-1}), and egg the highest Cu (21.5 mg kg^{-1}) (Table 10).

23.5. Ecological Succession: Changes in Diversity and Abundance of Plants and Animals with Time and Space

23.5.1. Protozoa

Surveys of protozoa communities were conducted along the water flow from inlet to outlet of the wetland system in January 2002, using the polyurethane foam unit (PFU) method (China State Bureau of Technical Supervision and China EPA

Table 11: Protozoan communities in Fankou wetland system in 2002.

Sites	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**
Total number of protozoan species	0	28	0	1	28	65	62
Number species of Phytomastigophora	0	5	0	0	7	27	22
Percentage of Phytomastigophra	0	17.8	0	0	25.0	41.5	35.4

Yu et al. (2004).

1992). A total of 44 species was identified in water samples collected from the wetland system. No protozoa were observed in either sites I (inlet of the system) or III, and only one species was found in site IV. Twenty-eight species of protozoa, however, were found in site II (outlet of Cell 1) and site V (outlet of the system), respectively. There were 65 and 62 protozoan species recorded in the upper reach (site VI) and in the lower reach (site VII) of stream, respectively (Table 11).

The diversity of protozoa increased with the reduction of metals and TSS in the water (see Table 5). The higher diversity of protozoa in site II (28 species, outlet of Cell 1) may be due to the fact that Cell 1 had not been used in purifying mine drainage since 1995, so the water and the environment of this cell had improved gradually. Results of correlation analysis also indicate that both the species numbers and diversity index for protozoa were negatively correlated with concentrations of Pb, Zn, Cd and TSS in water (Table 12), which suggest that metals, especially Pb, Zn and Cd, and TSS in water play an important role in inhibiting the growth of protozoa, while the wetland system could effectively

Table 12: Relationships between biotic factors and abiotic factors in Fankou wetland system.

	Total species	**Diversity index**	**Heterotrophic index**
Pb	-0.70^{a}	-0.72^{a}	0.88^{a}
Zn	-0.74^{a}	-0.75^{a}	0.85^{a}
Cu	-0.07	-0.70	0.39
Cd	-0.70^{a}	-0.68^{a}	0.74^{a}
TSS	-0.71^{a}	-0.71^{a}	-0.73^{a}
pH	0.34	0.32	-0.77^{a}

Yu et al. (2004).

[a] Correlation coefficient, $p < 0.05$.

reduce the toxicity of the drainage and improve water quality, resulting in a higher microbial diversity.

23.5.2. Algae

Changes in Diversity with Time. The diversity of algae in the wetland system increased with time. In March 1986, only six genera belonging to three divisions were recorded in the system. Among these genera, three belonged to the Bacillariophyta, one to the Chlorophyta and two to Cyanophyta. *Nitzschia* was both highly abundant and also widely distributed in the system, including the heavy polluted sites (Table 13). Twenty-seven genera belonging to five divisions were recoded in March 1987. Among these 27 genera, 11 genera belonged to the Bacillariophyta, 8 to the Chlorophyta, 5 to the Cyanophyta, 2 to the Euglenophyta and 1 to the Cryptophyta (Table 14). The Bacillariophyta were widespread in the system with an abundance in genera, species and individuals, especially *Nitzcshia* (Table 15). A total of 40 algal species belonging to five divisions and 29 genera were observed in March 1989. Among these species, 17 belonged to 12 genera of the Bacillariophyta, 10 to 6 genera of the Chlorophyta, 9 to 9 genera of the Cynophyta, 3 to 1 genus of the Euglenophyta and 1 to 1 genus of Crytophyta. *Nitzchshia*, *Synedra* and *Oscillutouia* were dominant algae in the system, and these species were also distributed in heavily polluted areas within the system.

Changes in Diversity and Abundance with Space. The diversity and abundance of algae within the system increased from inlet to outlet (Tables 13 and 15). In March 1986, no *Nitzschia* were found in site I (inlet of the wetland), and only 48 (cells per liter water) in site II, however, numbers of this species increased rapidly along

Table 13: Algae (number of individual per liter) in wetland system (Cell 1) (samples collected in March 1986).

Site	***Nitzcshia***	***Fragilaria***	***Oscillutouia***	***Ocdogonium***
I[a]	0	0	0	0
II	48	0	0	0
III	2,676	191	96	95
IV	2,961	716	143	143
V	3,535	1,815	239	287

Chen et al. (1990).
[a] I: inlet of wetland 1, II and III: inside of Cell 1 along the water flow, IV: outlet of wetland, V: in the stream system nearby the wetland.

Table 14: Numbers of genus and individuals of algae in wetland system (samples collected in March and May 1987).

Division	No. of genera	% of total genera	Individual ($10^3\ l^{-1}$)	% of total individuals
Bacillariophyta	11	40.7	1,322.78	95.3
Chlorophyta	8	29.6	8.36	0.6
Cyanophyta	5	18.5	54.75	3.9
Cryptophyto	1	3.7	1.28	0.1
Euglenophyta	2	7.4	1.28	0.1
Total	27	100	1,388.45	100

Chen et al. (1990).

the flow, reaching 3535 in site V (outlet of the wetland). Similar trends were found in the other three alga species, *Fragilaria*, *Oscillutouia* and *Ocdogonium*. Similar results were reported in the survey conducted in 1990. The numbers of algal divisions and genera increased from 1 in site I to 5 and 15 in site IV, respectively. The number of diatoms was 50,000 (cells l^{-1}) in site I gradually increasing to 298,000 in site IV. No green algae and blue algae were found in site I, but 11,000 and 25,000 (cells l^{-1}) were recorded in site IV (Table 15). Only the diatom genus *Nitzchia* was found in site I. The above results show that the diversity and

Table 15: Algae in wetland system (Cell 1 and Cell 2) (samples collected in 1990).

Site	Number of division	Number of genera	Number of individual per liter (cells l^{-1})				Number of *Nitzschia*	Percentage of *Nitzchia* algae
			Diatom	Green algae	Blue algae	Total		
I[a]	1	1	50,000	0	0	50,000	50,000	100
II	2	6	29,000	9,000	0	38,000	24,000	63
III	4	9	24,000	3,000	2,000	248,000	200,000	
IV	5	15	298,000	11,000	25,000	339,000	250,000	

Chen et al. (1990).

[a] I: inlet of Cell 1 (inlet of wetland), II: center of the Cell 1, III: outlet of Cell 1, and IV: outlet of Cell 2 (outlet of wetland).

abundance of algae gradually increased with water quality improvement or i.e. reduction of metal and TSS concentrations in water. Compared with the other algae, *Nitzcshia* showed higher tolerance to poor water quality and metal toxicity.

23.5.3. Higher Plants

During 1984 and 1989, the area of higher plants, mainly cattail, increased from about 100 m^2 to about 64,000 m^2 in Cell 1 (73.6% of Cell 1 in area). In addition to cattail, 11 other plant species were also found in 1989, including *Phragmites australis* and *Paspapum distichum*. Except above 12 plant species, four new species were found in the wetland in 1994. In 1998, 63 plant species belonged to 34 families and 59 genera were found within the wetland system (Table 16). The data from above three surveys show that plant diversity within the wetland system increased rapidly with time.

23.5.4. Benthic Invertebrates

Like the protozoa, no benthic invertebrates were found in site I (inlet of the system), diversity and abundance of these animals rapidly increased from site II to site IV, only 4 species were recorded in site II, but 8 and 9 species were found in site III and site IV, respectively (Table 17).

23.5.5. Vertebrates (Fishes, Terrestrial Animals and Birds)

Seven fish species were recorded in the stabilization pond in Cell 1 during 1986–1989. They were *Carassius auratus*, *Ctenopharyngodon idellus*, *Ophiocephalus maculates*, *Parasilurus asotus*, *Monopterus albus*, *Misgurnus anguillicaudaudatus* and *Oryzias latipes*.

Nine terrestrial animal species were found in the system in 1998 (Table 18). In the class Amphibia, *Bufo melanostiutus* and *Rana guentheri* were frequently found, while in the class Mammalia, *Rattus rattoides* was a dominant species.

Totally 26 bird species belonged to 7 orders and 13 families were observed in wetland with different degrees of abundance. *Ixobrychus cinnamomenus*, *Phylloscopus cantator ricketti*, *Orthotomus sutorius longicaudus*, *Prinia flaviventris delacouri*, and *Prinia subflava extensicauda* were dominant bird species in the system (Chang et al., 1999).

Table 16: The changes of plant species composition within the wetland system in period of 1989–1998.

Species composition	1989	1994	1998
Marchantiaceae			
Marchantia polymorpha L.			•
Leucobryaceae			
Leucobryum sp.			•
Equisetaceae			
Equisetum ramosissimum Desf.	•	•	•
Thelypteridaceae			
Cyclosorus acuminatus (Houtt.) Nakai			•
Ampelopteris prolifera (Petz.) Cop.			•
Marsileaceae			
Marsilea quadrifolia L.	•	•	•
Saururaceae			
Houttuynia cordata Thumb.			•
Papaveraceae			
Macleaya cordata (Willd.) R.Br			•
Fumariaceae			
Corydalis edulis Maxim.			•
Moraceae			
Ficus variolosa Lindl.			•
Urticaceae			
Boehmeria nivea (L.) Gaud.			•
Chenopodiaceae			
Spinacia oleracea L.			•
Chenopodium ambrosioides L.			•
Amaranthaceae			
Achyranthes aspera L.			•
Alternanthera philoxeroides (Mart.) Griseb.	•	•	•
Alternanthera sessilis (L.) Dc.			•
Caryophyllaceae			
Stellaria media (L.) Vill.			•
Polygonaceae			
Polygonum hydropiper L.	•	•	•
Polygonum chinense L.			•
Malvaceae			
Abelmoschus moschatus Medic.			•
Abutilon theophrasti Medic.			•
Malvastrum coromandelianum (L.) Garcke			•

(*continued*)

Table 16: Continued.

Species composition	1989	1994	1998
Cruciferae			
Capsella bursa-pastoris (L.) Medic.			•
Papillionaceae			
Pueraria phasedoides Benth.		•	•
Euphorbiaceae			
Bischofia polycarpa (Levl.) Airy	•	•	•
Euphorbia thymifolia L.			•
Sapium discolor (Champ.) Muell.-Arg.			•
Oxalidaceae			
Oxalis corymbosa DC.			•
Umbelliferae			
Centella asiatica (L.) Urban			•
Oenanthus benghalensis (Roxb.) Kurz.			•
Loganiaceae			
Buddleja asiatica Lou.		•	•
Solanaceae			
Solanum photeinocarpum Nak.et Odash.			•
Verbenaceae			
Verbena officinallis L.			•
Labiatae			
Prunella vulgaris L.			•
Perilla frutescens var.*acuta* (Thb.) Kudo			•
Callitrichaceae			
Callitriche stagnalis Scop.	•	•	•
Oleaceae			
Jasminum mesnyi Hance			•
Scrophulariaceae			
Mazus japonicus (Thb.) Kuntze			•
Compositae			
Ageratum conyzoides L.			•
Ambrosia artemisiifolia L.			•
Artemisia annua L.			•
Xanthium sibiricum Patr.			•
Youngia japonica (L.) Dc.			•
Hydrocharitaceae			
Hydrilla verticillata (L.f.) Royle			•
Potamogetonaceae			
Potamogeton crispus L.			•
Commeliaceae			

(*continued*)

Table 16: Continued.

Species composition	1989	1994	1998
Floscopa scandens Lour.			•
Commelina communis L.			•
Cyperaceae			
Fimbristylis sp.			•
Scirpus triqueter L.			•
Cyperus rotundus L.	•	•	•
Rhynchospora rubra (Lour.) Mak.			•
Gramineae			
Cynodon datylon L.	•	•	•
Paspalum distichum L.	•	•	•
Pennisetum purpureum Schum.			•
Imperata cylindrical var. *major* Habb. et Vs		•	•
Phragmites communis (L.) Trin.	•	•	•
Neyrandia reynaudiana (Kunth) Keng ex Hich.		•	•
Panicum repens L.			•
Digitaria chinensis (L.) Scop.			•
Mischanthus floridulus (Labill.) Warb.		•	•
Leersia hexandra Sw.	•	•	•
Typhacaeae			
Typha angustifolia L.			•
Typha latifolia L.	•	•	•

Yang et al. (2001).

23.6. Conclusions

1. The wetland system is able to effectively remove metals (mainly Pb, Zn, Cd and Cu) and TSS from the Pb/Zn mine drainage over a long-term period.
2. The wetland system not only improves the quality of the flow through drainage water, but also ameliorates the local environment by reducing tailings dust and erosion, improving the appearance of the landscape, and providing good habitats for different kinds of algae, plants and animals.
3. Diversity and abundance of living organisms in the wetland system were gradually increases with maturation of the system and improvement of water quality.
4. The system requires only low maintenance cost and is easy to manage, but needs larger areas of land than conventional methods. Reduction of TSS in the drainage before it is discharged into the wetland would elongate life span of each cell and reduce use of land.

Table 17: The main genera and species of benthic invertebrates and their distribution in the wetland system (samples were collected in March and November 1990).

Sites[a]	**I**	**II**	**III**	**IV**
Hydra sp.			++	
Nais variabilis		++		
Branchiodrilus hortensis		+		
Cipangopaludina cathayensis			++	++
Lymnaea stagnalis			++	+
Assiminea sp.			++	
Caridina nilotica gracilipes			+	
Caridina denticulate sinensis				+
Laccotrephes japonensis			+	
Naucoris exclamationis				+
Hyphydrus sp.				+
Chaoborus sp.				+
Tendipedidae		+	+	+
Tendipes plumosus		+		++
Clinatanypus sp.			+	
Tanytarsus sp.				+

" + " means the existence of the species; "++" means that the species appeared in a relatively higher numbers.
[a] Site I: inlet of wetland (Cell 1), II: inside of Cell 1, III: outlet of Cell 1, IV: outlet of wetland (Cell 2).

Table 18: Diversity of terrestrial animals within the wetland system.

Class	**Order**	**Family**	**Species**
Amphibia	Salientia	Bufonidae	*Bufo melanostiutus*
		Ranidae	*Rana adenopleura* Boulenger
			Rana guentheri Boulenger
			Rana limnocharis Boie
	Anura	Microhylidae	*Microhyla ornate* (Dumeril et Bibron)
			Microhyla pulchra (Hallowell)
Mammalia	Serpentiformes		*Natrix subminiata* helleri Schmidt
	Insectivora		*Suncus murinus* Linnaeus
	Rodentia	Muridae	*Mus musculus* Linnaeus
			Rattus rattoides Hodgson
			Rattus norvegicus Berkenhout

Hu (1998).

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