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PERFORMANCE STUDY ON THE CONSTRUCTED WETLAND FOR CLARIFICATION OF POLLUTED WU-LUO RIVER WATER

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ABSTRACT

The Wu-Luo River located in the Ping-Tong County of southern Taiwan has long been polluted by untreated domestic and partially treated swinery wastewaters and is among the most polluted rivers in Taiwan. Since January 2005, a full-scale constructed wetland system (CWS) has been in operation for cleaning a portion of the polluted river water. The purpose of this study was to investigate the performance of the CWS for removing both organic and inorganic pollutants from the influent water. Results indicate that during the investigation period (April to December of 2006) the CWS had a total water volume of about 9,930 m^3 and 10,000-20,000 m^3 d^{-1} (CMD) (average 10,800 CMD) of the polluted water was introduced to the CWS with a hydraulic retention time (HRT) of 0.92 d. Water analysis indicate that the influent water had the following qualities (unit in mg L^{-1} except pH): COD (total chemical oxygen demand) 52±31, BOD (biochemical oxygen demand) 21±10, SS (suspended solids). Water sampled from near the midpoint of the CWS got better clarification results than those from the effluent end. Pollutant removal efficiencies were 60, 60, and 67%, respectively, for COD, BOD, and SS at the midpoint.

INTRODUCTION

Constructed wetland systems (CWS) have long been used as natural means for the clarification of polluted water. CWS are usually shallow ponds in which microorganisms in the bottom soils and attached to bottom rocks and roots of the water plants are responsible for the removal of soluble and particular pollutants from the inflow water. Parts of nitrogen and phosphorus nutrients can also be biodegraded and/or absorbed by the plants. Some soluble and particle-borne heavy metals are physically or chemically combined with soils and slimes in the systems as well [1,2].

CWS are usually constructed for sewage clarification. Field data show that, with a hydraulic residence time (HRT) of less than 5 d, removal efficiencies of chemical oxygen demand (COD) from raw sewage are below 50% and achieve close to 90% with influent COD of less than 50 and in the range of 51-270 mg L^{-1}. Biochemical oxygen demand (BOD) removals are around 50% with both influent BOD and nutrients of less than 10 and 1 mg L^{-1}, respectively. However, an average of 80% BOD removal was reported with influent BOD and nutrients of less than 10-40 and > 1 mg L^{-1}, respectively. Removals of other pollutants are 30-90% (average 60%) for suspended solids (SS), 60-90% (average 80%) for nitrogen, and 30-90% (average 50%) for phosphorus [1,2].

In Taiwan, most CWS are planted with reed (*Phragmites australis*), water spinach (*Ipomoea aquatica*), water lettuce (*Pistia stratiotes*), vetiver grass (*Vetiveria zizanioides*), water hyacinth (*Eichhornia crassipes*), para grass (*Urochloa mutica* (Forssk.) Stapf), and giant duckweed (*Spirodela polyrrhiza*). Figure 1 shows some appearance of these plants. Among these, *E. crassipes* and reed have better pollutant removing abilities than others [1,4].

CWS have been found to be useful in improving river water qualities [5-7]. Especially, it has been shown that they are especially suitable for the clarifycation of polluted waters in subtropic regions [8].

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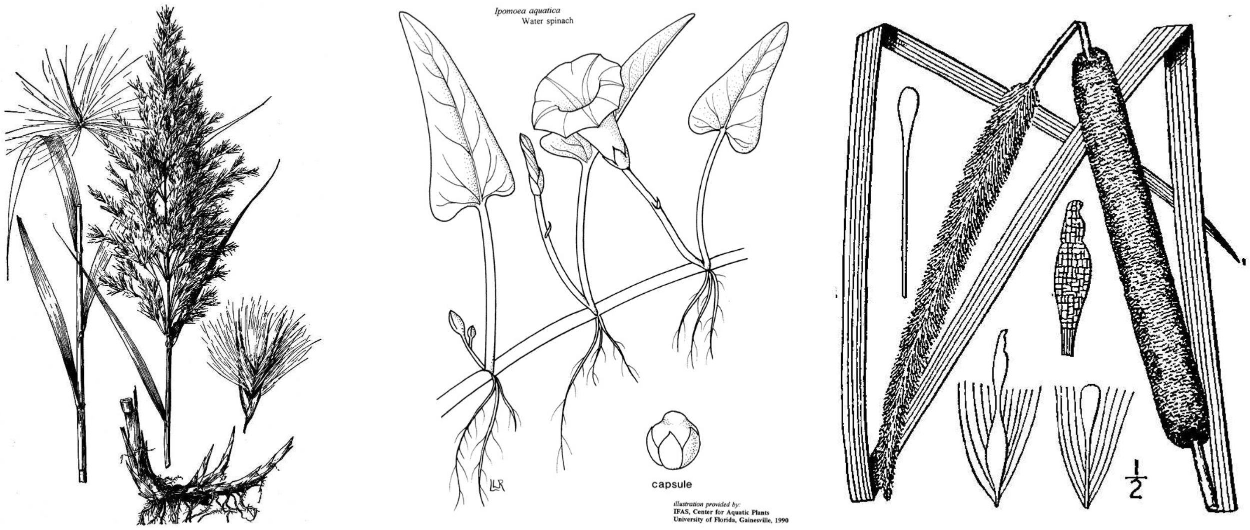


Reed
(*Phragmites australis*) [3]

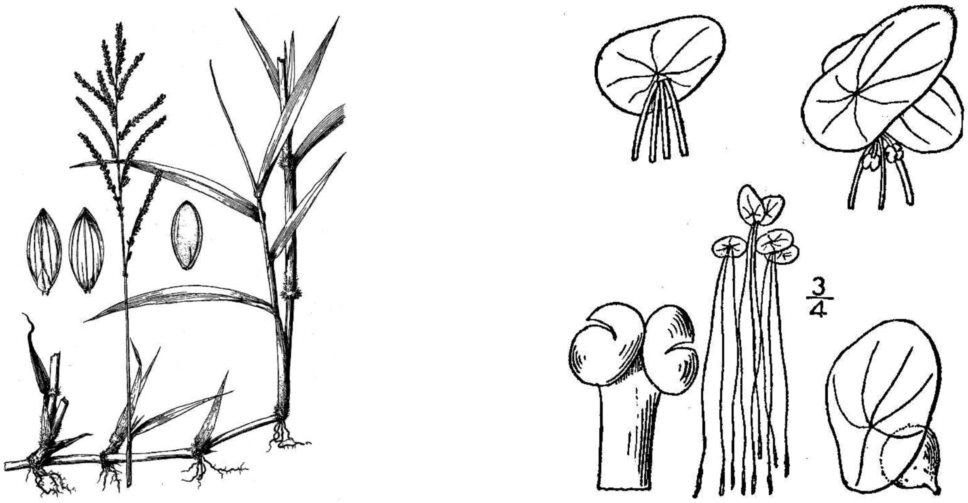
Swamp morning-glory or
water spinach (*Ipomoea aquatica*) [4]

Narrowleaf cattail
(*Typha angustifolia*) [5]

Water lettuce
(*Pistia stratiotes*) [4]

Vetiver grass
(*Vetiveria zizanioides*) [3]

Water hyacinth
(*Eichhornia crassipes*) [4]



Para grass
(*Urochloa mutica* (Forssk.) Stapf) [3]

Giant duckweed
(*Spirodela polyrrhiza*) [3]

Fig. 1. Some aquatic vegetation commonly used in Taiwan's CWS.

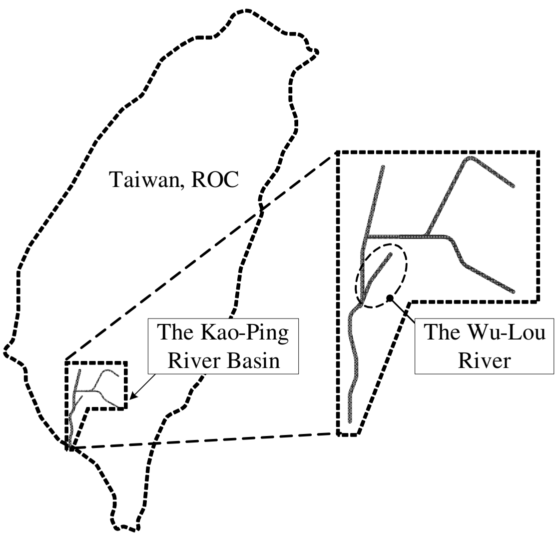


Fig. 2. Location of the Kao-Ping River Basin and the Wu-Luo River in Taiwan.

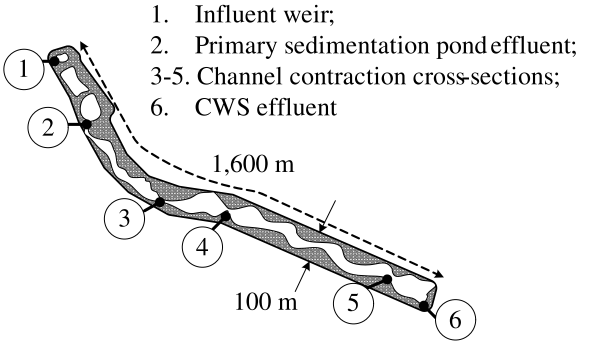


Fig. 3. Sampling points for the performance study of the Wu-Lou CWS.

Field-scale CWS are still developing in Taiwan. An example is a multiple pond CWS located in the north bed of the Kao-Ping River in southern Taiwan. The CWS has a net pond area of around 5 ha (50,000 m^2) and is being used for the clarification of sewage mixed with a treated effluent wastewater from a paper mill. The CWS has total BOD and hydraulic loadings of 112 kg ha^{-1} d^{-1} and 200 m^3 ha^{-1} d^{-1} (20 L m^{-2} d^{-1}) respectively [9]. It has been shown that influent COD, BOD, SS and ammonia-N could be removed from 190, 103, 50 and 6 mg L^{-1}, respectively, to 58, 12, 12 and 1.2 mg L^{-1} [10].

The Kao-Ping River (Fig. 2) has long been polluted by domestic, industrial, and swinery wastewaters. Among the branches, the Wu-Luo River is the most contaminated one and contributes the largest component of the influent pollutants to the main stream. According to the 2006 river water quality data provided by the Taiwan Environmental Protection Administration (Taiwan EPA), the annual average BOD, COD, SS, and ammonia-N were 17, 49, 43 and 5.5 mg L^{-1}, respectively. Accordingly, Taiwan EPA commenced a project to clarify the river water by establishing a primary facility for sedimentation of a part of SS and pre-aeration of the introduced water in the middle of 2004. In December 2004, a CWS (the Wu-Luo CWS) was completed for improving the effluent qualities from the primary facility.

The Wu-Luo CWS (Fig. 3) has the following design parameters: total area 18 ha, pond area 9 ha, and influent 50,000 CMD with average BOD and SS of 21 and 50 mg L^{-1}, respectively. The CWS has widths of 86-112 m (average 100 m) with a total length of about 1,600 m. It was expected that the CWS has the capabilities of removing 60 and 70%, respectively, of the influent BOD and SS, or could achieve the effluent BOD and SS, respectively, to less than 10 and 20 mg L^{-1}.

This paper reports the performances of the Wu-Luo CWS regarding the clarification of the influent river water. Studies were conducted from April to December of 2006. Items investigated included aquatic vegetation in the CWS as well as the removing characteristics of COD, BOD, SS, nutrients (N and P), and heavy metals (Zn and Cu) from the influent river water.

MATERIALS AND METHODS

The investigated parameters and their methods are listed as follows:

1. Measurement of water qualities: pH, BOD, COD, SS, DO (dissolved oxygen), TN (total nitrogen), ammonia-N, TP (total phosphorus), phosphate-P, Zn and Cu were measured from water samples collected bimonthly from sampling points as shown in Fig. 3. Table 1 shows the related analytical methods and apparatus.
2. Measurement of system parameters: Influent flow rate, channel length and cross-sectional area, status of the vegetations, and HRT for the water flow through the CWS were measured monthly at the points as shown in Fig. 3. Monthly water precipitation as well as evaporation rates were also measured to estimate the water infiltration rate to the CWS bottom. Table 2 shows the related measuring methods.

RESULTS AND DISCUSSION

1. Point Variations of Pollutants in Water, Bottom Sludge, and Plant Body

Mean concentrations and standard deviations for the influent water qualities (unit in mg L^{-1}) to the CWS were measured to be total COD 52±31, BOD 21±10, SS 59±29, ammonia-N 12.8±5.5, nitrate-N 3.4±2.6, nitrite-N 0.4±0.4, TN 23.5±9.6, phosphate-P 1.34±0.78, TP 5.8±9.1, Cu 0.07±0.14 and Zn 0.15±0.09.

Table 1. Analytical methods and apparatus

Items	Methods	Apparatus
pH	Standard methods- NIEA W424.51A	pH meter (Suntex, TS-100, Taiwan)
DO	Electrode method	Portable DO meter (WTW, Oxi 315i/Set, Taiwan)
Temperature	Standard methods- NIEA W217.51A	
COD	Standard methods- NIEA W517.50B	
BOD	Standard methods for BOD_5- NIEA W510.54B; Standard methods for DO- NIEA W421.54C	
SS	Standard methods- NIEA W210.57A	
TKN	Standard methods- NIEA W451.51A	UV/VIS spectrophotometer (Thermo Spectroinc, 4001/4, USA)
NH_3	Standard methods- NIEA W448.51B	
TP	Standard methods- NIEA W427.52B	
NO_3^-	Standard methods- NIEA W415.52B	Ionic chromatrography (DIONEX, DX-100, USA)
NO_2^-	Standard methods- NIEA W415.52B	
PO_4^{3-}	Standard methods- NIEA W415.52B	
Cu, Zn (water)	Standard methods- NIEA W303.51A	Atomic absorption spectrophotometer (Thermo S2 AA System, GE711232, USA)
Cu, Zn (plants and bottom soils)	According to Martion, 1993 [13].	

NIEA: Standard analytical methods developed by the Environmental Analysis Laboratory of EPA of Taiwan, ROC. The methods were developed by referring related ones as cited in the Standard Methods for the Examination of Water and Wastewater, APHA (1998) [14].

Table 2. Methods and apparatus for system parameter measurements

Items	Methods	Apparatus
Flow rate	Standard methods- NIEA W023.51C for stream velocity Flow rate = average stream velocity over the channel cross-section × channel cross-sectional area (measured by a calibrated rod ruler)	Paddle-type liquid velocity meter (GRT-400-20N, KENEK, Japan)
Depth of water or bottom sludge	Measured by a calibrated rod ruler	Portable DO meter (WTW, Oxi 315i/Set, Taiwan)
Vegetation area	Scales of boundaries measured by a measuring tape and a GPS	GPS (eTrex Vista C, Garmin, Taiwan)
Plant size and weight	Select a representative plant and measure its height and weight	
Water precipitation	Measured by a standard ombrometer (20 cm dia)	
Evaporation rate	Measured by a standard evaporation rate meter (20 cm dia)	
Water evaporation loss from plant leaves	Measuring water amount difference after a definite time between two 100 L-tanks, one planted with water lettuce and one without.	
HRT	HRT = Total CWS water volume/flow rate	
Total channel length	Aided by a GPS, a map of the CWS prepared and the total channel length measured from the map.	

Table 3 shows mean water qualities at all sampling points. Figure 4 indicate that water qualities at sampling point 3 were the best among all points with approximately 62, 63, 73, and 20%, respectively, of COD, BOD, SS, and TN of the influent possibly being removed. However, water qualities at point 4 deteriorated conceivably due to the rapid growth of the water lettuce between points 3 and 5 and decaying roots. Water qualities at the effluent end with approximately 56, 54 and 45%, respectively, for COD, BOD, and SS of the influent possibly being removed. As vegetation dies in the CWS, the dead tissue acts as COD to consume oxygen and therefore causes COD removal decreasing. Plant uptake is a N-removal pathway and harvesting of the wetland plants at the optimum interval should be able to maximize N removal efficiency [11,12]. Koottatep and Polprasert [11] suggested that the plant harvesting interval of once in 8 wk resulted in the maximum N plant uptake and maximum TN removal in free water surface constructed wetland units [11].

Table 3. Mean water qualities at all sampling points (unit: mg L^{-1})

	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6
COD	52±31	36±18	20±8	47±45	21±12	23±17
BOD	21±10	20±13	8±3	25±23	11±7	10±5
SS	59±29	33±30	16±11	54±46	56±39	41±28
TN	24±10	23±16	19±9	21±16	19±17	29±45

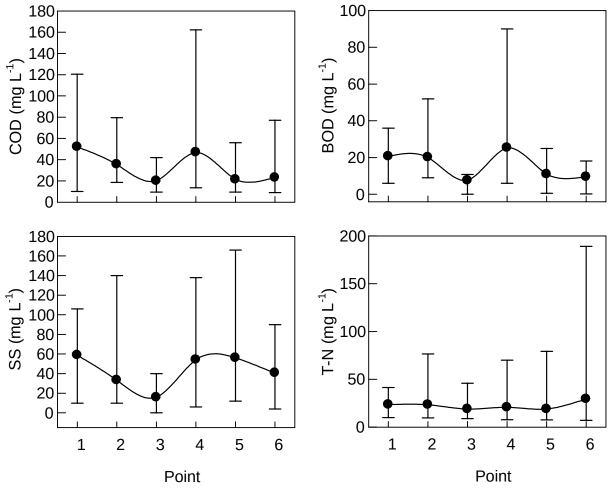


Fig. 4. Variations of water COD, BOD, SS and TN with the sampling point, respectively.

Table 4 shows the mean metal concentrations at all sampling points. Figure 5a indicates that mean concentrations and standard deviations of Cu in water varied from 0.07±0.14 mg L^{-1} at point 1 to 0.02±0.01 mg L^{-1} at point 3 and the average removal was estimated to be 69%, while at point 6, Cu was raised to 0.15±0.16 mg L^{-1}. Figure 5b indicates that mean concentrations and standard deviations of Cu in the bottom sludge reduced from 1859±138 at point 1 to 43±22 mg kg^{-1} (dry base) at point 6 with an average decrease of 77%. Figure 5c shows variations of Cu in plant body with the sampling points and the mean concentrations and standard deviations reduced from 43±59 at point 1 to 13±8 mg kg^{-1} (dry base) at point 6 with an average reduction of 70%.

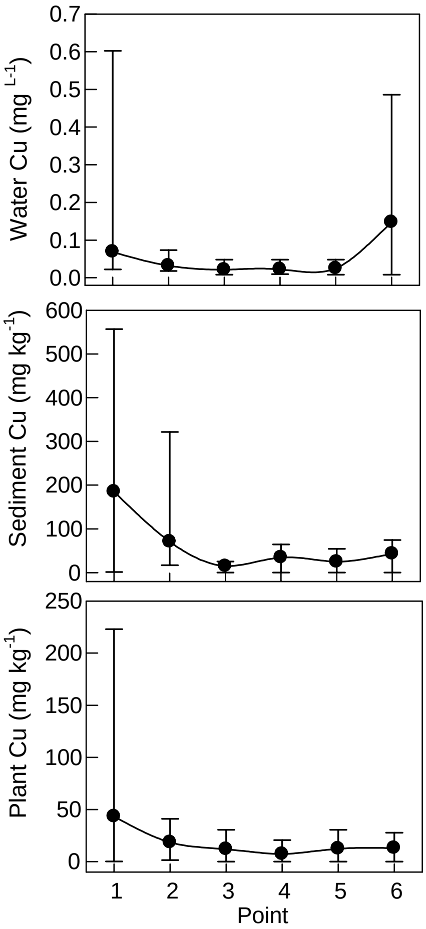


Fig. 5. Variation of Cu at the sampling points in water, sediment and plant.

Figure 6a indicates that mean concentrations and standard deviations of Zn in water varied from 0.15±0.09 at point 1 to 0.16±0.15 mg L^{-1} at point 6, with an average increase of 13%. Figure 6b indicates that mean concentrations and standard deviations of Zn in the bottom sludge reduced from 306±168 at point 1 to 115±44 mg kg^{-1} (dry base) at point 3 with an average decrease of 62%. Figure 6c shows variations of Zn in plant body and the mean concentrations and standard deviations reduced from 95±74 at point 1 to 49±22 mg kg^{-1} (dry base) at point 6 with an average reduction of 55%.

Table 4. Mean metal concentrations at all sampling points (unit: mg L^{-1})

	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6
Water Cu	0.07±0.14	0.03±0.02	0.02±0.01	0.02±0.01	0.02±0.01	0.15±0.16
Sediment Cu	185±138	71±99	15±7	35±18	25±14	43±22
Plant Cu	433±59	19±11	12±8	7±5	124±7	13±8
Water Zn	0.15±0.09	0.17±0.16	0.25±0.37	0.23±0.29	0.15±0.14	0.16±0.15
Sediment Zn	306±168	175±163	79±31	104±41	89±35	115±44
Plant Zn	95±74	87±45	56±29	43±25	48±25	49±22

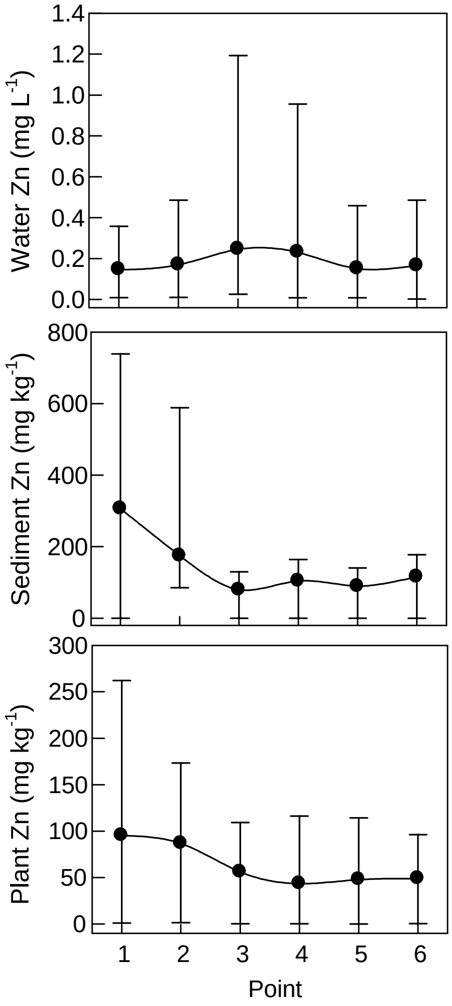


Fig. 6. Variation of Zn at the sampling points in water, sediment and plant.

2. Time Variations of System Parameters

Field water evaporation rate, water precipitation, water evaporation rate from water lettuce leaves, area of water bodies, and influent and effluent water flow rates are presented in Table 5. Water lettuce was selected for evaporation rate measurement as the plant grew profusely in the CWS. Table 5 indicates that ranges and averages (in parentheses) of water flow rates varied from 0.012-0.247 (0.125) at point 2 (influent to the planted area) to 0.016-0.181 (0.072) m^3 s^{-1} at point 6 (effluent of the CWS). From the data, it could be estimated that the average daily flows to point 2 and from 6 were 10,760 and 6,240 CMD, respectively. The range of inflow was 10,000-20,000 CMD; an imbalance between the in and out flow rate was due to the variable on/off times of the six (one as a spare) inflow pumps for the CWS.

Data shown in Table 5 indicate that from May to Oct 2006, approximately 23-72% (average 40%) of the influent water infiltrated through the bottom of the CWS to the ground. The high percentages indicate that the prevention of infiltration of partially clarified water to the ground should be an important issue when designing and constructing a CWS. Table 5 also shows that evaporation of water from free water surface and plant leaves accounted for only 1.2 and 0.2%, respectively, of the total inflow. Evaporation could thus be ignored when assessing the performance of the CWS.

Table 6 lists data on the area of vegetations and water bodies as measured from June 14 to 16, 2006. Figure 7 shows a plane plot of the data which indicates that the total wet land area was 46,700 m^2 during that time period. The wetted area could increase or

Table 5. Water evaporation and precipitation rates at the CWS site and the system parameters (unit: mm month^{-1})

	May	June	July	Aug.	Sep.	Oct.	Nov.	Note
Evaporation	111	122	139	115	121	115	110	1 (A)
	105	100	179	85	88	77	74	2
Precipitation	162	752	1,513	182	376	2	17	1 (B)
	197	675	1330	294	417	6	17	3
	107	569	902	159	161	2	36	4
Evaporation from water lettuce leaves	–	–	25	20	22	34	26	1 (C)
Area of water bodies (m^2)	36,530	30,600	26,940	43,410	33,120	32,920	–	5
Influent	4,990	3,350	12,730	7,900	14,590	14,640	–	6 (D)
Effluent	5,870	1,570	6,630	3,600	11,540	7,530	–	6 (E)
Infiltration	-830	2,410	7,450	4,350	3,290	6,970	–	7
Infiltration/Influent (%)		72	59	55	23	48		

1. Data of 2006 measured in the present study.
2. Data of 2005 from Kaohsiung District Agricultural Research and Extension Station, the Council of Agricultural, Taiwan, ROC [15].
3. Data of 2006 from Kaohsiung District Agricultural Research and Extension Station, the Council of Agricultural, Taiwan, ROC [16].
4. Data of 2006 from Kaohsiung Weather Station [16].
5. Data of 2006 measured in the present study.
6. Data of 2006 measured in the present study, mm month^{-1}= [flow rate (m^3 month^{-1}) ÷ (area of water bodies (m^2)) × 1000. Influent flow rates were obtained by the monthly-average values measured at point 1.
7. Infiltration (mm month^{-1}) = B + D - (A + C + E)

Table 6. Wetted and vegetation area of the CWS

Measurement date (2006)	Wetted area (m^2)	Vegetation area (m^2)				
		Paragrass	Water lettuce	Reed mace	*Ipomoea aquatica*	Total
02-05, May	45,780	–	5,830	7,690	2,320	15,840
14-16, June	53,060	2,510	18,100	8,070	1,070	29,740
04-06, July	44,860	750	790	6,870	2,230	10,630
11-12, July	53,110	2,560	18,100	8,070	1,070	29,790
02-03, Aug.	56,310	690	3,080	4,960	670	9,400
09-11, Aug.	44,190	–	4,600	7,770	2,310	14,680
26-27, Sep.	47,000	–	10,460	7,210	2,520	20,200
11-12, Oct.	46,040	1,850	9,990	7,670	2,400	21,910
Average	46,650	1,670	8,870	7,290	1,830	19,020

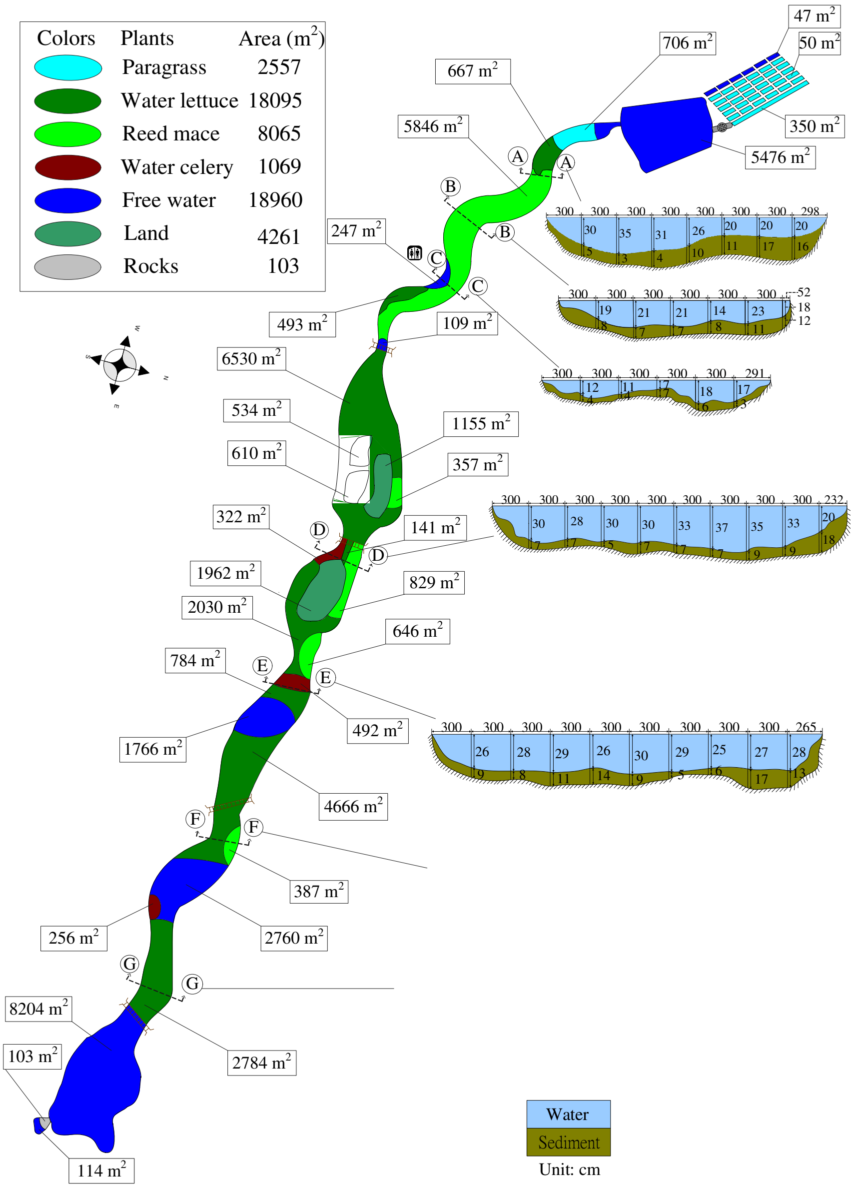


Fig. 7. A plane plot of the Wu-Luo CWS (Measured from June 14 to 16, 2006).

decrease depending on an inflow of surface storm water or influent pumping rates.

Table 7 lists mass distributions of the four main plants in the CWS. A total vegetation area of 19,000 m^2 was estimated in which water lettuce, reed mace, *Ipomoea aquatica*, and paragrass occupied 47, 38, 10 and 9%, respectively, of the total area. Multiplied by the average mass area density of each plant, it could

Table 7. Mass of the four main plants in the CWS (2006)

	Paragrass	Water lettuce	Reed mace	*Ipomoea aquatica*	Total
Date of measurement (kg, wet)					
02-05, May	–	10,980	105,290	18,490	134,760
14-16, June	11,590	34,110	110,480	8,510	164,690
04-06, July	4,200	720	65,100	7,170	77,090
11-12, July	11,820	34,120	110,470	8,510	164,930
02-03, Aug.	3,170	5,810	67,930	5,350	82,270
09-11, Aug.	–	8,670	106,350	18,420	133,440
26-27, Sep.	–	19,720	98,790	20,090	138,600
11-12, Oct.	8,540	18,830	105,080	19,110	151,560
Average	7870	16,620	96,170	13,210	130,920
Mass percentage (%)	6	13	73	10	100
Area density (kg m^{-2})	4.6	1.9	13.7	8.0	–

Table 8. Performance characteristics of some selected surface-flow CWS in USA and the present study[*]

Cases[**]	Q (m^3 d^{-1})	A (10^3 m^2)	Q/A (L m^{-2} d^{-1})	BOD			SS			TN			TP		
				In	Out	%R	In	Out	%R	In	Out	%R	In	Out	%R
1	2,500	100	2.5	27	6	77	51	11	78	–	–	–	–	–	–
2	226	46	4.9	–	4	–	–	4	–	–	0.9	–	–	0.24	–
3	30,000	5700	5.3	4	3	20	6	5	16	10.4	2.0	81	9.1	4.2	53
4	5,400	812	6.7	–	–	–	–	–	–	40	4	90	7	<1	>86
5	450	61	7.5	28	7	77	93	12	87	16.2	1.1	93	–	–	–
6	10,800	180	60	21	10	54	59	32	45	23.5	19.3	18	5.8	5.8	0

[*] Q: average influent flow rate; A: total wetland area; Q/A: surface hydraulic loading; In: influent to the wetland; Out: effluent from the wetland; %R: % removal efficiency; TN: total nitrogen, except noted; TP: total phosphorus. All values are averaged ones and BOD, SS, TN, and TP are in the unit of mg L^{-1}.

[**]

Cases	Location	Influent	Period of data	Note
1	Cannon Beach, Oregon	Raw sewage	1985-1989	
2	Vermontville, Michigan	Effluent from lagoons for sewage treatment	1990	N: NH_3-N
3	Lakeland City, Florida.	Effluent from the secondary treatment unit of sewage of the city	1987-1990	
4	Show Low City, Arizona	Effluent from the secondary treatment unit of sewage of the city	1981	
5	Fort Deposit, Alabama	Effluent from the sewage stabilization lagoon of the city	1990-1992	In: TKN Out: NH_3-N
6	Ping-Dong, Taiwan	Sewage- and swinery-polluted river water	2006	The present study

be discerned that water lettuce, reed mace, *Ipomoea aquatica*, and paragrass accounted for 13, 74, 10 and 6%, respectively, of the plant mass in the CWS. This could be used as a basis for estimating how much plant mass should be removed in a certain period.

From the data, it was estimated that in 2006 the average total wetted area of the CWS was roughly 47,000 m^2 with a holding water volume of 9,930 m^3. Based on the average inflow rate of 10,800 CMD, HRT of the water in the CWS was close to 0.92 d. The HRT is far shorter than 4-5 d for other CWS and could be not enough for water clarification as discussed as follows [1,2].

3. Comparisons with Other CWS

Table 8 lists performance characteristics of some selected surface-flow CWS in the USA and the present study. Data indicate that for most of the listed CWL in the USA, influent water to the wetland were low strength in pollutants and the surface hydraulic loadings were all less than 10 L m^{-2} d^{-1}. Pollutant strengths in the influent water to the present CWS were low too (average BOD 21, SS 59, TN 23.5 and TP 5.82 mg L^{-1}), however, the average surface hydraulic loading was 60 L m^{-2} d^{-1} which was more than 6 times of those for the CWS in the USA. The relatively poor performances of the present CWL might be attributed to the high loading and the decayed plants. It is advised that the performances could be improved by firstly harvesting the plants in proper periods, and secondly planting long-lived plants such as water celery and reed mace instead of water lettuce. Reducing the hydraulic loadings by cutting down the influent flow rates should only be tried after the above-cited improvements have been taken.

CONCLUSIONS

Several conclusions can be drawn from the intensive investigations on the Wu-Luo CWS for nine months are listed as follows.

The influent water had the following average qualities (unit in mg L^{-1}): COD 52, BOD 21, SS 59, TN 23.5 and TP 5.8. Water sampled from near the midpoint of the CWS got better clarification results than those from the effluent end. Pollutant removal efficiencies were 60, 60 and 67%, respectively, for COD, BOD and SS at the midpoint, and 56, 54 and 45%, respectively, for COD, BOD, and SS at the effluent end. Organics, N and P released from decayed plants were responsible for the poor water qualities at the end. The CWS had only a TN removal efficacy of approximately 18% with no TP removal effect.

A total water volume of about 9,930 m^3 was estimated for the CWS to which 10,000-20,000 CMD (average 10,800 CMD) of the polluted river water was introduced and an average HRT of 0.92 d was estimated for the influent water flow through the CWS. However, an average of 40% of the influent water infiltrated through the bottom of the CWS to the ground. The high percentages indicate that the prevention of infiltration of partially clarified water to the ground should be an important issue when designing and constructing a CWS. Evaporation of water from free water surface and plant leaves accounted for 1.4% of the total inflow and could thus be ignored when assessing the performance of the CWS.

The relatively poor performances of the present CWS could be attributed to the high loading and the decayed plants. The performances could be improved by harvesting the plants in proper periods and planting long-lived plants such as water celery and reed mace.

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