Journal of Environmental Sciences Vol.16, No.3, pp.476—481, 2004

ISSN 1001—0742
CN11—2629/X

Article ID: 1001-0742(2004)03-0476-06 **CLC number**: X703 **Document code**: A

Performance of a subsurface-flow constructed wetland in Southern China

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Abstract: The operational performance of a full-scale subsurface-flow constructed wetland, which treated the mixed industrial and domestic wastewater with BOD_5/COD mean ratio of 0.33 at Shatian, Shenzhen City was studied. The constructed wetland system consists of screens, sump, pumping station, and primary settling basin, facultative pond, first stage wetland and secondary stage wetland. The designed treatment capacity is 5000 m^3/d, and the actual influent flow is in the range of < 2000 to > 10000 m^3/d. Under normal operational conditions, the final effluent quality well met the National Integrated Wastewater Discharge Standard (GB 8978—1996), with the following parameters (mean values): COD 33.90 mg/L, BOD_5 7.65 mg/L, TSS 7.92 mg/L, TN 9.11 mg/L and TP 0.56 mg/L.

Seven species of plants were selected to grow in the wetland: Reed, Sweetcane flower Silvergrass, Great Bulrush, Powdery Thalia and Canna of three colours. The growing season is a whole year-round. The seasonal discrepancy could be observed and the plants growing in the wetland are vulnerable to lower temperature in winter.

The recycling of the effluent in the first stage of the wetland system is an effective measure to improve the performance of the wetland system. The insufficient DO value in the wetland system not only had significant effect on pollutants removal in the wetland, but also was unfavourable to plant growth. The recycling of effluent to the inlet of wetland system and artificial pond to increase DO value of influent to the wetland is key to operate the subsurface constructed wetland steadily and effectively.

Keywords: subsurface-flow constructed wetland; operational performance; marsh plants; pre-treatment; facultative pond

Introduction

The constructed wetlands have become a global technology for water pollution control both in developed and developing countries (Seidal, 1966, 1976; Kickuth, 1977; Cooper, 1995; IWA, 2000). Recent inventories indicated that there are more than 6000 and more than 1000 constructed wetlands in Europe, North America respectively, for treating municipal, industrial wastewaters or both (Knight, 2000). The constructed wetland has attracted more and more attention in the field of water pollution control because of so many advantages, such as low capital and operational costs, high removal efficiencies for organic substances, nutrients like N, P and heavy metals, stability to shock load, easy maintenance and management as well as its aesthetic values and other advantages.

In China, the research on constructed wetland has been launched as early as in the period of "Seventh Five-Year Plan" (Li, 1993; Wang, 1991). Recently great research progress has been made at laboratory-scale constructed wetland, but the study on the performance of the full-scale constructed wetlands is limited. Of the existing three full-scale constructed wetland systems in Shenzhen City, the Shatian constructed wetland is the most successful demonstration project. The study on the operational performance of Shatian constructed wetland has been conducted since it was put into operation with the following main topics: the start-up of the wetland system, plant selection, plantation and management, effects of various factors on the performance of the wetland, and the effective measures to improve and promote the operational performance of the subsurface constructed wetland.

1 Materials and method

1.1 Quality and quantity of raw wastewater

The quality and quantity of raw wastewater of Shatian constructed wetland vary with the season and weather significantly. Less than 2000 m^3/d at its minimum and over 10000 m^3/d at its maximum. In a day's morning the inflow, which is mainly composed of industrial, commercial and domestic wastewater, is relatively large, with poor quality of grey-black color and high turbidity. The foams often appear on the water surface, which is mainly caused by domestic wastewater.

The detected values of water quality parameters are:

Foundation item: The Key Program of Heilongjiang Province (No. JLJ-GA02C201-01)

COD_{Cr} 110—250 mg/L, BOD_5 40—80 mg/L, SS 45—110 mg/L, TN 12—20.5 mg/L, TP 2.0—5.0 mg/L, and average BOD_5/COD_{Cr} ratio of 0.33.

1.2 Flowchart of the constructed wetland

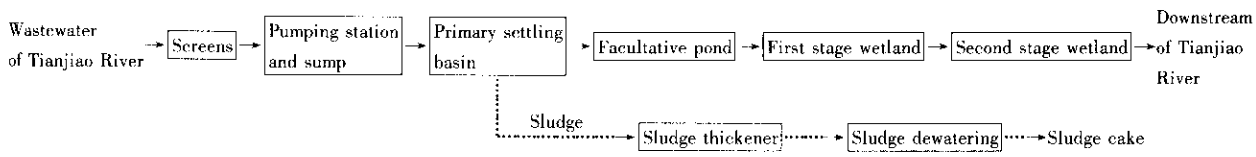

Fig.1 Schematic flow chart of Shatian Constructed Wetland

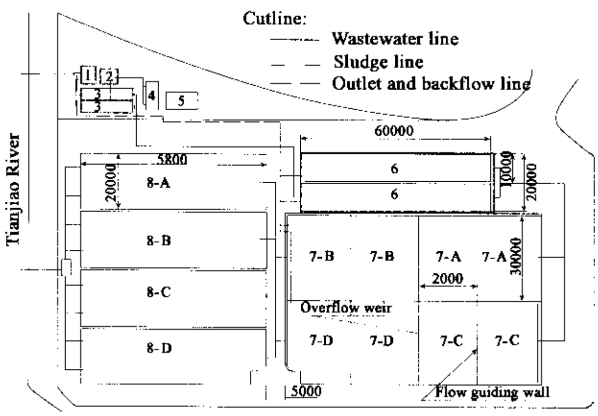

Fig.2 Plan layout of Shatian Constructed Wetland

1. sump; 2. sludge thickener; 3. primary sedimentation basins; 4. sludge dewatering; 5. duty room; 6. facultative ponds; 7. first stage wetland; 8. second stage wetland

The main treatment units in this project are two stages subsurface-flow constructed wetland. The preliminary treatment units consist of screens, primary settling basin, facultative pond. The sludge treatment units include sludge thickener and sludge dewatering.

First stage wetland designed in horizontal flow pattern, is composed of 2 series in parallel, and each series consists of upper and lower parts. The overflow weirs that can generate water falls for aeration are installed between the upper and lower part. In the middle of each part, a water guide wall was built transversely, with deep plant root at its bottom. The influent is distributed by triangle weirs and the effluent is discharged by overflow weirs. The total area of the first stage wetland is 4800 m^2, with the dimensions of each series of $L \times B \times H = 80\ m \times 30\ m \times 1.50\ m$, bed depth of 1 m and HRT of 11.5 h. The packed medium is weathering stone, whose particle diameter is 30—55 mm.

The second stage wetland takes the form of vertical-downwards flow, a total of 4 series in parallel. The perforated distribution and collection pipelines are installed on the upper and lower surface of wetland respectively. The total surface area of the 2nd stage wetland is 4640 m^2, with the dimensions of each series of $L \times B \times H = 58\ m \times 20\ m \times 1.65\ m$, bed depth of 0.75 m, and HRT of 8 h.

1.3 Operation of the wetland

The constructed wetland system is composed of pretreatment units, wetland units and sludge treatment units. The flowchart is shown in Fig.1, and the layout in Fig.2.

1.3.1 Transplantation of plants

When choosing wetland plants for transplantation, we should pay more attention to their diversity and stability. After being transplantated, the plants had an adoptive process. Those species with high death rate when growing in the wetland were eliminated through selection. A total of 7 species of plants have been chosen for this wetland system, including Canna(*Canna indica*) of 3 colors(yellow, orange and red), Reed(*Ph. australis Trin*), Sweetcaneflower Silvergrass(*M. sacchariflorus*), Great Bulrush(*S. tabernaemotani Gmel*), and Powdery Thalia(*Thalia dealbata*). The plants cultivated in various wetland blocks are distributed as follows: in block 7-A, Powdery Thalia was planted; in 7-B Sweetcaneflower Silvergrass (later the second half part changed to Sedge (*Cyperus papyrus*)); in 7-C, reed; in 7-D, Great Bulrush; in 8-A, red flower canna, orange flower canna; in 8-B, yellow flower canna; 8-C, Red flower canna; 8-D, Great Bulrush (later change to yellow flower canna).

Terrane factor should be paid enough attention to since it has significant effect on the cultivated plants in their infancy. For instance, in crushed stone bed, the separate planting was first chosen for transplantation, cuttage not being suggested. In the wetland system, survival rate of reed with separate planting and that of Sweetcaneflower Silvergrass was over 95%, while that of cuttage less than 20%.

It was found whether the plants adapted to new enviroment or not, it took half a year or longer to observe and research. After a year-round operation of this wetland, the red flower canna was eliminated due to its poor growth; and the growth of Great Bulrush was comparatively inferior; the reed, Sweetcaneflower Silvergrass, Powdery Thalia and orange flower canna grew quite well. Sedge was planted in first stage wetland in March 2002, which grew quite well.

1.3.2 Plant growth

The growth of wetland plant is affected significantly by climate factors, which are divided into two types: season and sharp change of climate.

The most suitable growth temperature for wetland plants is 20—40℃ in tropical or semi-tropical zone. Located in Southern China at the edge of equator, Shatian Wetland is close to ocean and enjoys warm climate with average daily temperature about 20℃ or higher in spring, summer and autumn. The temperature is relatively low only in December and January. The days with minimum temperature below 5℃ is few around 10 d. Such climate is extremely favorable to the growth of wetland vegetation of which growth season can be as long as one whole year-round. Based on the feature of local temperature, the year can be divided into two seasons in terms of wetland vegetation, i.e. fast growing season, from the last 10 d of February to mid November; and the other is slow growing season, from last 10 d of November to the mid of February of next year.

The effect of sudden change in climate mainly shows the effect on vegetation by low temperature. In December of 2002, sharp weather change and temperature drop occurred twice. Especially at the end of December of 2002, the daily minimum temperature was as low as around 4℃, during which growth of vegetation apparently slowed down or stopped. In 2 or 3 d after the passage of cold wave, some wetland vegetation showed injured phenomenon caused by freezing: in the windward side of leaf edge of Sedge, 10—15 cm of the leaves to the edge withered; most part of cannas leaves became yellow and withered. The situation of block 8-D was better than that of block 8-B. Reed, Sweetcaneflower Silvergrass, Powdery Thalia, Great Bulrush were much less affected. In judging from the scope and extent of freezing, the leeward plants are affected less severely than the windward plants. The plants in fast growing seasons are apparently affected less severely than those in seedling and in later stage of growth. The vegetation has little ability to resist coldness since it was used to growing at rather favorable temperature. The freezing happens when sudden drop of temperature accompanied by gale. In certain sense, the coldness resistant capability of a plant has close relationship with the water content of its cells. The process of wintriness calamity is also the process that protoplasm becomes dehydrated and bodying. The more plant can resist coldness, the more cell can resist dehydration. In the tissue of plant with strong cold resistance contains numerous hydrophilic compounds, which enable protoplasm to keep high stability in the environment of low temperature.

1.3.3 Operation management

The plant reaping is a necessary process of constructed wetland management. It can not only remove part of the pollutant in wetland, but also benefit plant growth. Its vital motion is active while photosynthetic area is small in its growth infancy. Root system grows slowly, synthetic organic substance is relatively less and the growth speed is quite slow. In growth metaphase, due to the enlargement of photosynthetic area and the expansion of root system, the vital motion is strengthened, the synthetic organic substance increases, each organ grows fast. In growth anaphase, plant tends to age. Some organs' vital motion has declined, root system ceases to grow, and photosynthetic area again tends to diminish. No other organs are growing except generative one, and growth turns to slow down. Correspondingly, the capacity of plant to get involved in water purification of wetland also shows the tendency cycle of weak-strong-weak. Therefore, the practice of reasonable plant reaping cycle is also favorable to the improvement of performance of constructed wetland systems. It was found from the operation of Shatian Wetland that in Southern China Great Bulrush, Canna, Sedge, Powdery Thalia can generally be reapped 2 to 3 times each year; Sweetcaneflower Silvergrass, 1 time each year; the reaping cycle of reed which is the most convenient to manage is estimated to be 1 time a years.

The wetland after plant reaping should be maintained and operated by adequately lower application loads, in consideration of the fact that root and stalk of wetland vegetation possess close relationship: the nutrients, water and mineral elements demanded by aerial parts of a plant rely on root system to take up from the soil medium, while the oxygen demanded by root system growth relies on leaves to produce. At this stage, if load is excessive the uptake capacity of root system to pollutants is lowered, and anaerobic conditions take place, which is easy to cause the root rotting.

In winter when temperature is low, plant growth slows down and DO value of river is low, by recycling a part of effluent of first stage wetland to its inlet, the quality of water outlet can be improved remarkably.

2 Results and discussion

The monitoring of influent and effluent was made by samplings and analysis since May and June 2002. The monitoring regulations of water quality has been confirmed since July to ensure that sampling and analysis time should be no less than 3 times a week (sample of inflow water comes from collecting well in December). Measurement of each parameter of water quality is carried out based on "monitoring analysis method of water and wastewater" enacted by Chinese National Environmental Protection Bureau, and the monthly average analysed values of some major parameters are shown in Table 1.

2.1 Removal of organic pollutants

It was found from Fig.3 that the removal of COD_{Cr} in May and June was quite low. Except the considerably low of influent COD_{Cr} value, the most important reason was that the growth of plants in first and second stage wetland systems was poor at that period. In August, wetland vegetation had reached its fast growth season, and the treatment efficiency reached the highest phase of the whole year. The removal of COD_{Cr} and BOD_5 was over 81.87% and 85.41% respectively in August, September, October and November. In December when plant growth slowed down, a part of effluent from the outlet of the first stage wetland was pumped back or recycled to the inlet of the first stage wetland for the improvement of the final effluent of the wetland system, which made COD_{Cr} value of the influent much lower. Moreover, since the plants in the wetland had been weakened, the applied COD_{Cr} load of the system should not be high. Otherwise, the final effluent could not meet the discharge standard because of the poor purification capacity of plants in winter season.

Table 1 Monitoring results(mean values) of water quality of Shatian Constructed Wetland

Month			May	June	July	August	September	October	November	December	Average value
Times of sampling			3	1	11	24	22	31	30	13	
COD_{Cr}	Influent	mg/L	66.66	64.30	149.44	204.03	182.94	189.57	187.29	20.30	145.57
	Effluent	mg/L	24.23	56.22	32.05	30.33	33.17	32.80	31.76	30.60	33.90
	Removal	%	63.65	12.57	78.55	85.13	81.87	82.70	83.04	74.56	76.72
BOD_5	Influent	mg/L	—	—	—	61.50	54.77	53.12	—	—	56.46
	Effluent	mg/L	—	—	—	7.51	7.99	7.54	—	—	7.68
	Removal	%	—	—	—	87.79	85.41	85.81	—	—	86.40
SS	Influent	mg/L	—	—	57.29	60.39	72.11	59.99	55.59	53.90	59.88
	Effluent	mg/L	—	—	7.20	7.81	8.26	8.80	7.87	7.56	7.92
	Removal	%	—	—	87.43	87.07	88.55	85.33	85.84	85.97	86.78
TN	Influent	mg/L	18.08	18.60	15.60	16.29	15.88	16.17	16.14	15.50	16.53
	Effluent	mg/L	10.05	11.84	8.15	8.95	8.32	8.34	8.55	8.64	9.11
	Removal	%	44.41	36.34	47.76	45.06	47.61	48.42	47.03	44.26	44.93
TP	Influent	mg/L	1.30	1.59	3.79	3.43	3.83	3.62	3.69	3.29	3.07
	Effluent	mg/L	0.26	0.28	0.59	0.59	0.69	0.68	0.64	0.56	0.56
	Removal	%	80.00	82.39	84.43	82.80	81.98	81.22	82.66	82.98	81.70

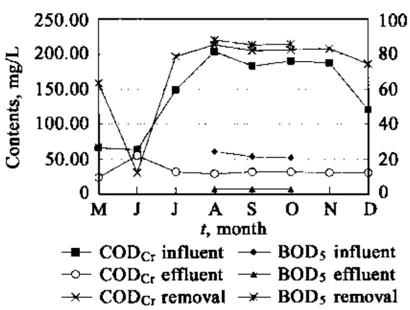

Fig.3 Removal of organic pollutants

It is evident that the plants play key role in the wastewater treatment in the wetland system. According to traditional theory, if the BOD_5/COD_{Cr} ratio of raw wastewater is less than 0.3, it is difficult to be degraded by biological method. But the system still shows rather high removal efficiency for organic pollutants under such conditions. This is because the bed media(both physico-chemical and biological processes taking place in soil) and vegetation work together to use their own purification capability to better extent.

2.2 Removal of TN

The removal mechanism for pollutants in wetland systems is very complex. Nitrogenous compounds of 7 valence states is removed through a combination of two or more processes like ammonification, nitrification and de-nitrification, volatilization, and plant uptake. Of many kinds of removal mechanisms, the main two ones are plants uptake and biological de-nitrification comprising two key processes: nitrification and de-nitrification. So the alternate aerobic and anoxic environment is the prerequisite of high efficient denitrification. In the plant root system, there exists a large amount of nitrobacteria whose oxidation-reduction potential (ORP) and nitrification rate are both higher than the area without plant(Cooper, 1998; Adcock, 1999). Each plant root system in wetland is a mini aerobic/anoxic biological treatment system, which is effective and efficient in total nitrogen removal in the subsurface-flow wetland.

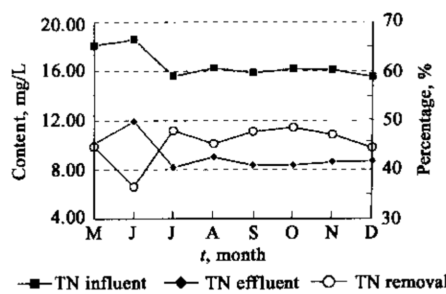

Fig.4 Removal of TN

It was found that the growth of wetland vegetation was an important factor for denitrification, which was proved by the operational results as shown in Fig. 4. It was also found from Fig. 4 that the plant growth had apparent correlation with nitrogen removal efficiency. In May and June when the vegetation area had not formed, the removal efficiency of TN was only 44.41% and 36.34%, respectively. Then with the formation of vegetation area, the TN removal efficiency raised, reaching 48.42% in October. In December, due to the impact of low temperature, plant grew slowly and the removal of TN also decreased to 44.26%.

The plant's capacity of oxygen transportation is limited (Cao, 2000). Under the conditions of high organic load and low DO value of influent of the wetland system, low ORP in its later part usually exists. In this case, the nitrification is hard to take place. Then nitrification process becomes the limited process of the system. The observation of the performance of the wetland shows if DO value of influent is rather low, the TN removal is also low. To increase the DO to an adequate value of influent in the wetland is an effective measure to increase TN removal efficiency. The aeration by water fall and surface water distribution of vertical flow increased TN average removal to 45%, which is higher than those reported in other documents with TN removal of 30%—40%.

2.3 Removal of TP

There are two main ways of phosphorus removal in wetland system, which is biological degradation and assimilation, and chemical processes taking place between the phosphorus compounds and calcium, aluminum and iron contained in bed medium(Wang, 1991).

Fig.5 shows that the total phosphorus removal of system was considerably high, exceeding 80% in each month and reached maximum, 84.43%, in July. However, it tended to descend gradually later. In May, June and July when plant growth was not so good, TP removal was also considerably high, which proved that the phosphorus removal of the wetland did not mainly depend on plant uptake and biological process, instead mainly by chemical reactions of bed medium (weathering stone). It was found from the observation of bed package material in January 2003 that the growth of bio-film on its surface was uneven and incomplete with scattered distribution. As a result, the wastewater could contact with the bed material, so the chemical reactions between them could take place, which resulted in high and stable removal of total phosphorus in the wetland system in the first year-round operation.

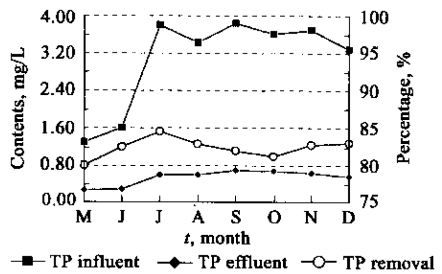

Fig.5 Removal of TP

2.4 Removal of SS

The wetland system was very stable in reducing SS, less than 10 mg/L in effluent as shown in Fig.6. The removal efficiency is 86%, which was less than 90% reported by others. It was due to some debris from withering stone in effluent. The sedimentation and filtration of suspended solids of influent mainly took place in the scope of the first 10 meters of first stage wetland and in the layer of about 20—30 cm below surface.

2.5 Dissolved oxygen

The operational performance of the wetland system has proved that the dissolved oxygen in water imposes key effect on both treatment efficiency of wetland and growth of wetland vegetation. When DO value was too low, physiological activity of plant rhizome declined, which affected the performance of wetland in pollutants removal and hindered the plant from growth. The dissolved oxygen in the influent of the wetland system came mainly from the natural aeration of raw wastewater. Generally, under the conditions of higher atmosphere pressure, and windy weather, DO value of influent was rather high, and water quality of effluent was also good. When windless and in low atmospheric pressure, DO value of influent was rather low and water quality of effluent bad. Especially in autumn and winter when temperature was low and physiological activity of organism was inactive, such phenomenon was more evident.

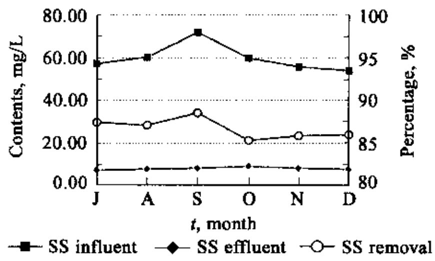

Fig.6 Removal of SS

At high organic load, dissolved oxygen was consumed greatly, causing anaerobic state in the later part of the wetland system. If such conditions were kept too long, a great deal of H_2S and NH_3 is generated and accumulated inside the wetland bed medium emitting offensive odor of H_2S and NH_3. The plants like Great Bulrush, Sedge and Cannas are weak in transporting oxygen to roots, which results in the accumulation of alcohol and CO_2 because of anaerobic respiration for a long period. As a result, root rotting takes place, which severely affects plant growth. And the rotten debris of plant or the metallic sulfides caused by anaerobic state would cause poor effluent in quality. Therefore, it is necessary to take efficient measures to increase dissolved oxygen in the wetland, such as recycling a part of effluent from the outlet of the first stage wetland to its inlet; so organic load is properly decreased. Then remarkably improvement of the wetland system performance could be acquired. Besides, some aeration devices are suggested to install in facultative ponds for the increase of DO in their effluent or influent of the wetland system, as well as for more abatement of organic load in the facultative ponds.

3 Conclusions

Seven species of plants were selected to grow in the wetland: Reed, Sweetcaneflower Silvergrass, Great Bulrush, Powdery Thalia and Canna of three colors, which grew well all the year round with good performance, but are vulnerable to cold weather.

The system showed considerably high removal efficiencies for organic pollutants. This was ascribed to the bed material, vegetation and microbes of the wetland that worked together to use their respective purification capability to reach a better performance.

The main mechanisms for total nitrogen removal in the wetland system were mainly plant uptake and biological denitrification. High phosphorus removal in the wetland mainly achieved by chemical processes that took place in bed material (weathering stone).

DO value of wetland water imposed key affects both to the treatment efficiency of wetland and growth of wetland vegetation. Too low DO value not only significantly affected the treatment efficiency, but also caused root rotting and the accumulation of H_2S, NH_3-N and volatile acids, which were harmful to the growth of plants.

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(Received for review April 8, 2003. Accepted October 8, 2003)

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