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Seasonal treatment efficiency of surface flow constructed wetland receiving high nitrogen content wastewater

Soyoung Lee[a], Marla C. Maniquiz[a], Jiyeon Choi[a], Joo-Hyon Kang[b], Sangman Jeong[a], Lee-Hyung Kim[a,*]

[a]*Department of Civil and Environmental Engineering, Kongju National University, 275 Budae-dong, Cheonan, Chungnamdo 330-717, South Korea*
Tel. +82 41 521-9312; Mobile +82 10 3895-2642; Fax +82 41 568-0287; e-mail: leehyung@kongju.ac.kr
[b]*Department of Civil and Environmental Engineering, Dongguk University – Seoul, Seoul 100-715, South Korea*

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ABSTRACT

This research investigated the performance of a constructed wetland (CW) that functions as a post-treatment unit for the secondary effluent of a piggery wastewater treatment facility. The pollutant mass removal efficiency was evaluated from 37 sampling events on non-rainy days during 2008–2010. Based on the findings, the pollutant concentrations decreased somewhat along the cells from the influent to the effluent while DO and pH increased along the cells and appeared to peak at the deep marsh region during the spring season. The overall cumulative treatment efficiencies for the entire monitoring period were 53% for total suspended solids; 35–37% for biological oxygen demand and chemical oxygen demand; 33% for total phosphorous; and 17–21% for total nitrogen and other nitrogen forms. The main reason for the low treatment performance was attributed to the low carbon to nutrient ratio (i.e., the COD/BOD:TN:TP ratio) in the CW influent. Moreover, algal bloom was frequently observed in the deep marsh region primarily due to the relatively long retention time at the open water zones in the CW. To further improve the treatment performance of the CW treating secondary piggery wastewater, it is necessary to ensure that the influent characteristics meet the desirable organics and nutrient requirements to maximize the biological functions of the wetland.

Keywords: Free water surface flow; Constructed wetland; Secondary effluent; Livestock wastewater; High nutrient content; Nonpoint source pollution

1. Introduction

Livestock wastes have been of great concern because the effluent concentration from treatment facilities of livestock wastewaters generally exceeds the national effluent standards, thus considered as the main cause of eutrophication in many surface water bodies in Korea [1]. Livestock wastewaters are usually high in organic and nutrient contents, adversely affecting the water environment unless properly treated [2]. Livestock wastes can also diffuse into the receiving water bodies in the form of non-point source (NPS) from watershed areas with livestock landuses during storm events. In conventional biological wastewater treatment

*Corresponding author.

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processes, raw livestock wastewaters are tenacious because they contain high non-biodegradable organics compared to other wastewaters [3]. In addition, low carbon to nitrogen ratio of the livestock wastewaters is known to be the reason behind the low efficiency of most treatment plants in Korea. The Korean Ministry of Environment (MOE) established a new program to reduce excess pollutant loads with an emphasis on nutrients and organics, which incorporates constructed wetlands (CWs) or retention ponds in the treatment train as post-treatment facilities. The new water quality control programs such as the total maximum daily load (TMDL) and the NPS management were enacted in the Act of Water Quality and Aqua-ecosystem Conservation in 2006. These programs require the post-treatment facilities for most of wastewater treatment plants.

A CW is an alternative post-treatment method for wastewaters with high organic and nutrient content [4,5]. CWs have widely been used for decades, mostly for treating domestic or municipal wastewaters. However, application of CWs recently has expanded to many other types of wastewaters including industrial and agricultural wastewaters, landfill leachate and stormwater runoff [6]. A CW uses natural treatment mechanisms such as sedimentation, vegetation and microbial degradation [4]. CWs can be categorized into several different types – free water surface flow (FWS), horizontal subsurface flow (HSSF), vertical subsurface flow (VSSF) and hybrid systems – according to their configurations. The FWS CW is relatively shallow and is vegetated with a combination of emergent, floating and submerged aquatic plants. It is applicable to wastewaters with high concentrations of particulates, organics and nutrients such as the secondary piggery wastewater effluent from water treatment plants [7]. Alternatively, the VSSF and HSSF CW can be applied to treat relatively weak wastewater such as municipal wastewaters [8,9]. Treatment capacity of VSSF CWs and HSSF CWs are comparatively small due to clogging problems in the pores of media [10].

Several studies on the CWs applicable to livestock wastewater and sewage in Korea have begun in 2000 [11–13]. Lab scale and pilot scale studies were applied using CWs. This research is part of the on-going monitoring works in Korea being conducted in a FWS CW and the main objective was to evaluate the treatment performance of the CW. Characteristics of pollutant reduction in each treatment cells of the CW were investigated. In addition, the applicability of a FWS CW as a post-treatment process for the secondary piggery wastewater effluent was assessed.

2. Materials and methods

2.1. Study site

The FWS CW was constructed to reduce the pollutant concentration of the secondary piggery wastewater by the MOE in 2007 and the operation started in September 2008. The FWS CW is located at latitude 36°0712″N and longitude 127°08′15″E in Nonsan City, South Chungcheong Province, Korea (see Fig. 1). The climate of the region is monsoon and temperate, and is characterized by annual rainfall of 1382 mm of which more than half was concentrated during the summer season from June until August. The mean seasonal temperatures for the region in 2009 were 12.0 °C in spring, 23.5 °C in summer, 13.7 °C in fall and 0.5 °C in winter. The CW was designed as the final stage of the piggery wastewater treatment plant (WWTP) during dry days and stormwater runoff from a livestock landuse area during wet days. Therefore, influent flowing through the CW is contaminated with organic matters, nutrients and

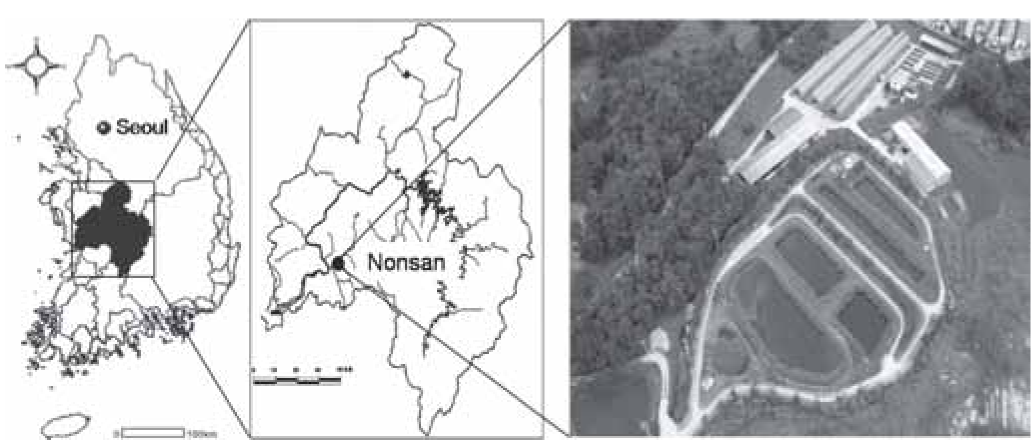

Fig. 1. Location of constructed wetland in Nonsan city, Korea.

pollutants coming from livestock waste and stormwater runoff.

2.2. Constructed wetland characteristics

The profile of the treatment cells in the CW is provided in Table 1. The CW consists of six cells, each of which performs a specific treatment function as follows: sedimentation of particulates in Cell 1, enhanced biological treatment using aeration in Cell 2, and sedimentation of organics in the subsequent Cells 3–6. In Cell 2, a coarse-bubble diffuser system was installed to provide bubble aeration for biological treatment. The influent flows from a channel equipped with a grid which removes large particles. Thereafter, the influent wastewater enters into the settling basin 1 (Cell 1) and finally discharges to the Geum River. The CW has a total surface area of 4492 m^2 and a total storage volume of 4006 m^3 treating a catchment area of 110,000 m^2 which is mostly paved. Fig. 2 shows the process flow diagram with the dominant plant species. The CW cells were planted with three types of wetland plants (i.e., *Phragmites australis*, *Miscanthus sacchariflorus* and *Typha orientalis*), which play a role in sediment retention, nutrient uptake and pollutant removal. The initial average vegetation density was 2.7 kg/m^2 although the vegetation density seasonally varied from 6.7 kg/m^2 in spring to 0.9 kg/m^2 winter.

2.3. Monitoring and data analysis

The CW constantly received secondary effluent from the piggery WWTP during the duration of the monitoring period from October 2008 to September 2010 except during the period between January and April 2010 when there was no influent from the piggery WWTP thus the CW only received stormwater runoff during wet days. Water quality samples were collected at six sampling points (i.e., the inlet of Cell 1, Cell 2, Cell 4, Cell 5, Cell 6 and the end point of the CW). The influent water to the CW during days has high pollutant concentrations compared to rainy days, which means the CW analysis during dry days is important. In order to prevent the runoff impact on water quality in the CW, the monitoring of dry days was performed on minimum 4 days after a storm. Samples were analyzed for water quality parameters including pH, conductivity, dissolved oxygen (DO) and temperature which were all measured on site using portable meters. Samples were then transported to the laboratory for analysis of typical water quality parameters such as biological oxygen demand (BOD), chemical oxygen demand (COD), total nitrogen (TN), total Kjeldahl nitrogen (TKN), ammonium nitrogen (NH_4-N), nitrate (NO_3-N), total phosphorus (TP) and phosphate (PO_4-P). Analyses were conducted in accordance with the American Society for

Table 1
Characteristics of the constructed wetland

Cell No.	Treatment region	Surface area (m^2)	Storage volume (m^3)	Water depth (cm)	HRT* for design flow (h)	HRT for peak flow (h)
Cell 1	Settling basin	560	453	80.9	5.5	1.6
Cell 2	Aeration pond	776	565	72.8	6.8	2.0
Cell 3	Deep marsh	805	810	100.6	9.8	2.9
Cell 4	Shallow marsh	527	280	53.1	3.4	1.0
Cell 5	Deep marsh	1474	1626	110.3	19.6	5.8
Cell 6	Settling basin	350	272	77.7	3.3	1.0
Total	–	4492	4006	–	48.4	14.3

*HRT = hydraulic retention time.

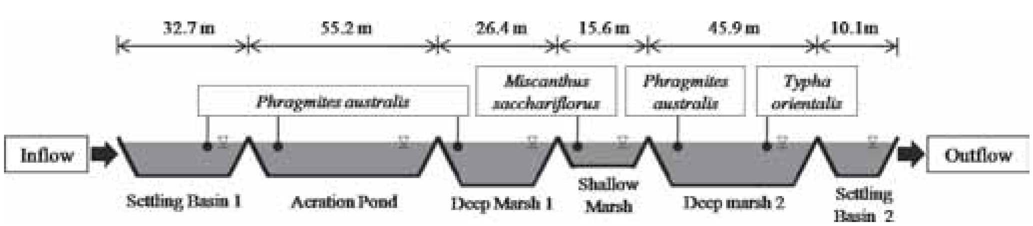

Fig. 2. Composition of the FWS CW and the dominant plant species.

Testing and Material (ASTM) standard methods for the examination of water and wastewater. Meteorological data for study site were collected from the Korea Meteorological Administration (KMA).

The treatment efficiency was calculated as the percent removal R for each parameter, which was calculated by $R = (1 - C_e)/C_i \times 100$, where C_i and C_e are the influent and effluent concentration in mg/L. All statistical analyses were performed using SYSTAT 9.0 (Chicago, IL, USA)

3. Results and discussion

3.1. Characteristics of influent wastewater

Table 2 summarizes the influent concentration of pollutants from the piggery WWTP to the CW. The mean influent pollutant concentrations were higher during winter and spring (TSS: 67.7 ± 28.0 mg/L in winter; BOD: 90.1 ± 42.4 mg/L in winter; TN: 151.5 ± 53.0 mg/L in spring; TP: 5.9 ± 1.1 mg/L in winter) and lower during summer and fall (TSS: 50.7 ± 24.1 mg/L in fall; BOD: 35.1 ± 14.6 mg/L in summer; TN: 111.2 ± 55.8 mg/L in fall; TP: 4.4 ± 2.6 mg/L in fall). The CW treats occasionally the stormwater runoff from the livestock treatment sites during storm events. When the rainfall occurs, the washed-off concentration from the site generally decreases with time. Therefore, the concentrations of piggery wastewater and contaminated stormwater were low during wet seasons.

The CW was designed to include an aeration pond (Cell 2) to enhance biological treatment. When biologically treating wastewater, it is usually stated that the ratio of COD:TN:TP in the wastewater to be treated should be approximately 100:5:1 [1]. The importance of knowing the ratio of organics particularly COD and BOD to nutrients like TN and TP concentration of influent is necessary to determine the biological activity of microorganisms especially their growth aspect [14,15]. Table 3 compares the ratio of organics to nutrients in different types of wastewater in Korea. Generally, the COD:TN:TP ratio of raw piggery wastewater is 53:5:1 while the BOD:TN:TP ratio is 28:5:1. In comparison, the nitrogen concentration is too high compared to organic concentration which means that

Table 2
Characteristics of influent (mean ± S.D.) into the constructed wetland

Parameter	Spring (Mar–May)	Summer (Jun–Aug)	Fall (Sep–Nov)	Winter (Dec–Feb)
Physico-chemical parameters				
pH	8.0 ± 0.3	8.0 ± 0.6	7.8 ± 0.6	8.4 ± 0.3
DO (mg/L)	4.9 ± 1.0	2.8 ± 1.6	1.3 ± 0.4	4.3 ± 1.9
Temperature (°C)	15.8 ± 5.5	26.7 ± 2.4	20.5 ± 4.2	9.8 ± 4.7
Water quality parameters				
TSS (mg/L)	67.4 ± 22.0	50.8 ± 34.7	50.7 ± 24.1	67.7 ± 28.0
BOD (mg/L)	54.6 ± 24.5	35.1 ± 14.6	53.6 ± 27.3	90.1 ± 42.4
COD (mg/L)	116.9 ± 50.3	85.4 ± 48.3	128.7 ± 55.8	164.3 ± 64.2
TN (mg/L)	151.5 ± 53.0	138.3 ± 39.0	111.2 ± 27.1	140.8 ± 57.6
TKN (mg/L)	81.0 ± 24.6	101.6 ± 33.6	73.0 ± 15.7	77.4 ± 22.6
NH_4-N (mg/L)	42.9 ± 18.9	54.6 ± 23.1	37.7 ± 20.6	46.6 ± 19.3
NO_3-N (mg/L)	9.3 ± 2.5	11.4 ± 2.8	12.6 ± 1.7	10.9 ± 1.3
TP (mg/L)	4.7 ± 2.0	4.7 ± 2.0	4.4 ± 2.6	5.9 ± 1.1
PO_4-P (mg/L)	1.0 ± 0.8	1.1 ±0.5	1.5 ± 0.7	2.2 ± 1.3

Table 3
Ratio of organics to nutrients in different types of wastewater in Korea

Type of wastewater	Reference	BOD:TN:TP	COD:TN:TP	TN:TP
Raw livestock wastewater	MOE, 2004 [1]	28:5:1	53:5:1	5
Municipal wastewater (separate sewer system)	MOE, 2001	28:7:1	–	7
Influent wastewater to CW	This study (average)	13:29:1	28:29:1	29

the biological treatment cannot greatly remove the nitrogen. Consequently, this would probably lead to a low treatment efficiency of the CW.

3.2. Water quality changes

The seasonal changes of water quality in each set of cells during the monitoring period are shown in Fig. 3. As shown in the figures, the pollutant concentrations gradually decreased along the cells from the influent to the effluent during summer, fall and winter seasons except during spring. Particularly, the DO, TSS and pH increased along the cells and appeared to peak at Cell 5 in spring. This was attributable to the sedimentation and aeration treatment from the prior cells and to algae photosynthesis in the cell itself [15]. It was observed that most of the algae bloomed at the deep marsh 2 (Cell 5). Elevated pH and DO of the wetland surface during the dry season were generally caused by algal bloom especially during the spring. Sawyer and McCarty [16] reported that in ponds during day time, algae use carbon dioxide for photosynthesis and release oxygen increasing the pH and DO levels as the carbonate–bicarbonate equilibrium is destabilized. During night time hours this process is generally reversed when algae and plants stop producing oxygen but start using the available oxygen while carbon dioxide is released. Due to this phenomenon, the TSS concentration was lowest

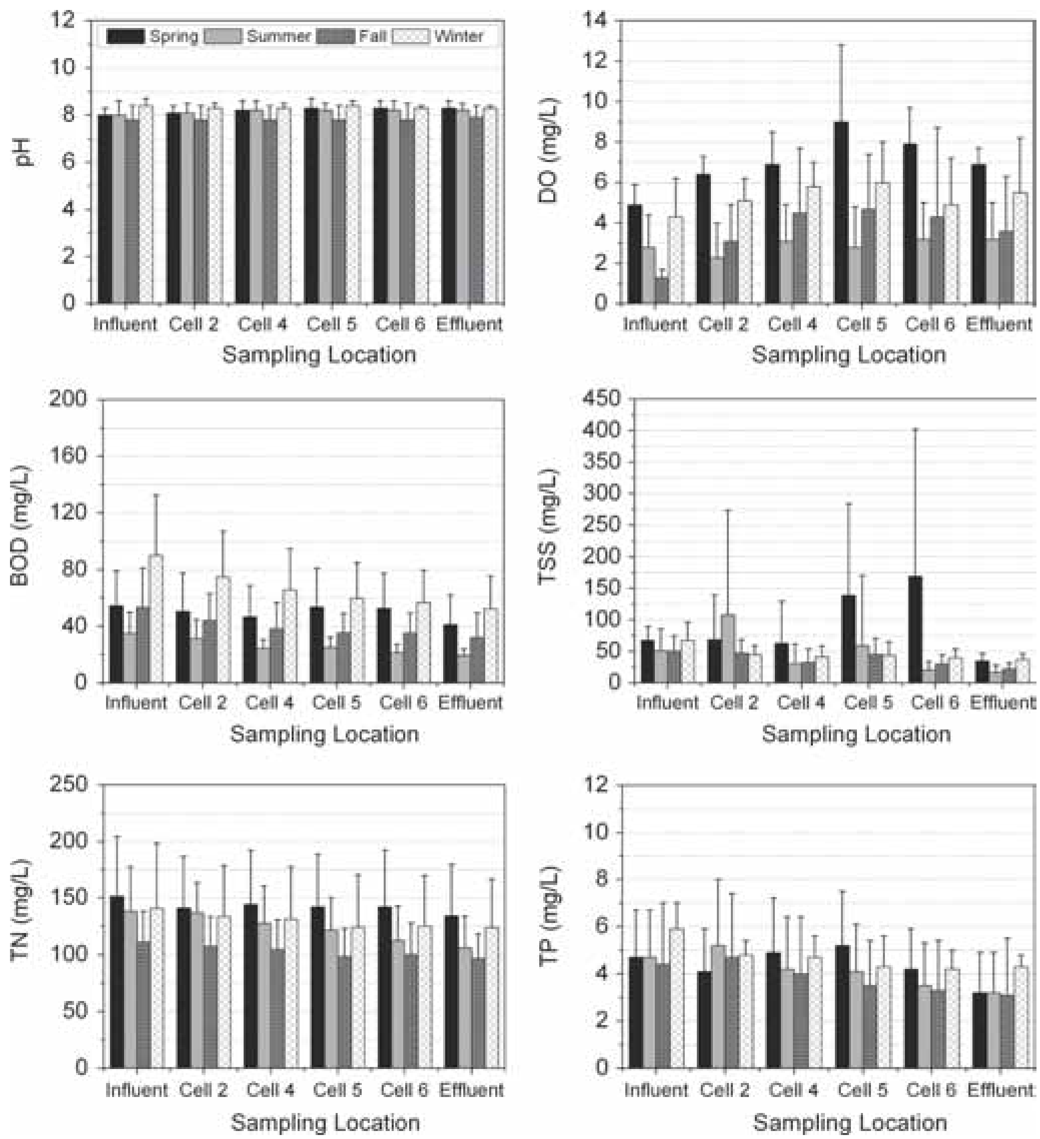

Fig. 3. Seasonal changes of water quality (mean ± S.D.) along the CW flow path during dry days.

between the influent of Cell 1 and Cell 4 and highest between the influent of Cell 5 and Cell 6.

3.3. Treatment performance

The changes in values of physico-chemical constituents such as water and air temperature, DO and pH during monitoring period (between October 2008 and August 2010) is presented in Fig. 4. The mean values of influent and effluent temperatures were 20.4 ± 7.5 °C and 20.1 ± 8.8 °C, respectively, while the mean air temperature was 12.2 ± 9.7 °C. It was observed that the water temperature was higher than air temperature. In this study, the respective correlations with atmospheric temperature are 0.86 and 0.92 for the influent and effluent, respectively. Kadlec [17] reported that wetland water temperature had a tendency to approach to the mean air temperature depending on humidity. This parameter presented an inverse variation with temperature and this can be explained by the combined effects of lower solubility of DO in the CW at higher temperature [18]. The monthly temperatures in the influent and effluent of the CW were not significantly different with each other. Seasonal fluctuations of the wetland water temperature could influence the processes of microbial transformation [19]. The pH is an important factor for water quality, exerting a great influence over the aquatic ecosystem. The pH of the effluent increased slightly towards the end of the life cycle of the macrophytes, from 8.1 ± 0.5 to 8.2 ± 0.4. In general, pH showed no significant change between the influent and effluent. The CW showed good efficiency to raise the DO concentration of the treated effluent that was confirmed by the significant difference between inlet (3.5 ± 2.2 mg/L) and outlet (5.1 ± 3.1 mg/L) levels of DO. The highest DO (12.9 mg/L) was achieved in July 2009 due to vast algal growth which resulted from excessive amount of nutrient inputs from the livestock waste and stormwater runoff. Moreover, the influent DO levels were increased from April to May 2010. It was observed that most of algae bloomed at the deep marsh 2 (Cell 5) especially during the spring season.

Fig. 5 shows the summary of the seasonal pollutant removal efficiency of the CW. The mean removal efficiency was calculated from the relevant influent and effluent pollutant loadings that have been analyzed statistically for the 37 dry sampled events. The mean pollutant removal efficiencies were high in summer and fall. The maximum removal efficiencies were as follows: TSS = 62 ± 18% in summer, BOD = 41 ± 10% in fall, TN = 23 ± 10% in summer, TP = 36 ± 16% in fall. The pollutant removal efficiencies were low in winter and spring. These minimum removal efficiencies were as follows: TSS = 34 ± 34% in winter, BOD = 23 ± 15% in spring, TN = 10 ± 11% in winter, TP = 26 ± 11% in winter. Wetlands are affected by solar radiation and ambient temperature, which cycle on an annual and daily basis. The temperature of wetland waters influences both the physical and biological processes within a FWS CW. It can be observed that generally for all pollutants, lower removal efficiencies correspond to lower temperatures and vice versa [20]. In addition, the mean removal efficiencies except TSS were below

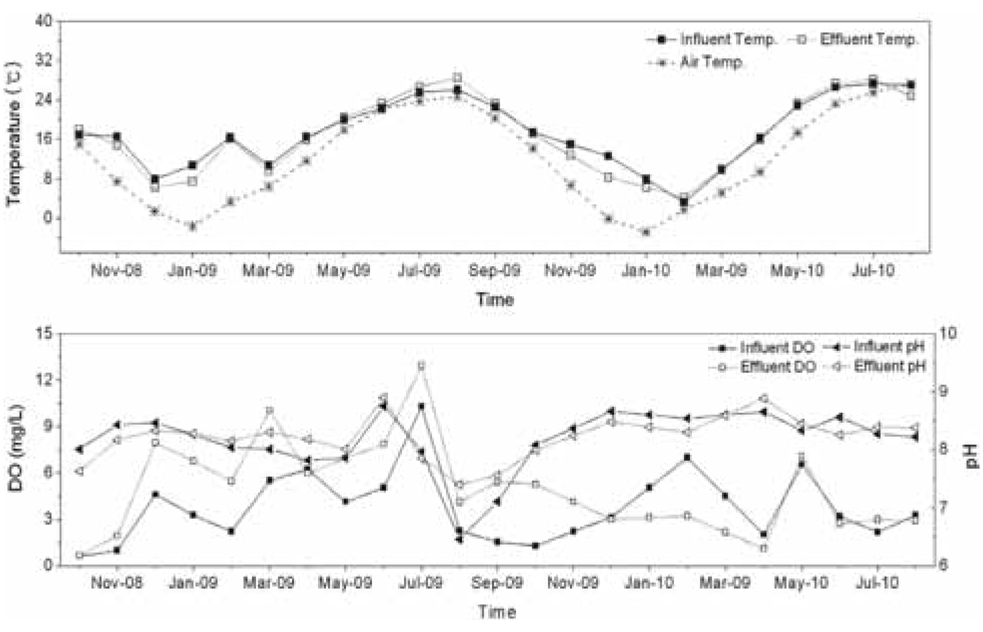

Fig. 4. Distribution of (a) air and water temperature (b) pH and DO in the CW.

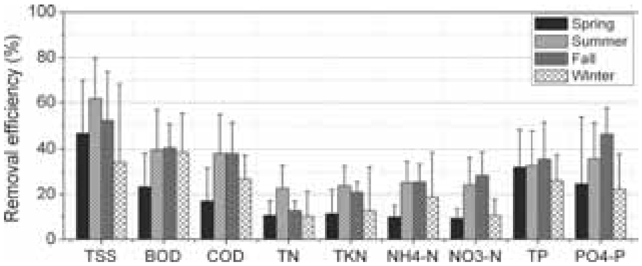

Fig. 5. Seasonal removal efficiency (mean ± S.D.) in the CW.

50% having TN as the poorest in terms of removal performance. The main reason for the low nutrient efficiencies is that the influent concentration coming from the treated piggery wastewater is high in concentrations of nitrogen and phosphorus and low in organic content resulted from the prior treatment. Overall cumulative treatment efficiencies during the 22-month monitoring on the CW are as follows: TSS, 53%; BOD, 37%; COD, 32%; TP, 33%; TN and other N forms, 17–21%. In comparison to other wetland studies in literature, the performance results of CW in this study are lower but fairly reasonable. The study of Greenway and Woolley [21] on eight FWS wetland sites in Queensland, Australia during a 22 month period resulted to average treatment efficiency values of 14–77% for TSS, 23–80% for BOD, 29–93% for NH_4-N, 50–83% for TN and less than 18% for TP.

4. Conclusions

This research was performed to investigate the treatment performance of the FWS CW. The results indicate that:

1. The BOD:TN:TP ratio in the influent of the CW was 13:29:1. The influent nitrogen concentration was too high compared to organic concentration indicating that the biological treatment cannot effectively remove the nitrogen.
2. The pollutant concentrations decreased somewhat along the cells from the influent to the effluent during summer, fall and winter seasons.
3. DO concentration and pH generally increased along the flow path from inflow to Cell 5, and then slightly decreased thereafter. In spring, TSS concentration was much greater compared to the other seasons being greatest at deep marsh region (Cell 5) due to vast algae bloom.
4. The mean pollutant removal efficiencies in summer and fall were higher than winter and spring seasons. In addition, the mean removal efficiencies except TSS were below 50% with TN and N forms as the poorest in terms of removal performance. The main reason for the low nutrient efficiencies is that the influent concentration coming from the treated piggery wastewater usually contain high amount of nitrogen and phosphorus and low organic contents resulted from the prior treatment.

Continuous monitoring will be performed to improve the nutrient treatment efficiencies and to support further assessment of the CW system and design.

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