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Seasonal Performance of Constructed Wetland for Nonpoint Source Pollution Control

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The field scale experiment was performed to examine the performance of the constructed wetland for nonpoint source (NPS) pollution loading reduction. Four sets (each set of 0.88 ha) of wetland (0.8 ha) and pond (0.08 ha) systems were used. Water flowing into the Seokmoon estuarine reservoir from the Dangjin stream was pumped into wetland systems. Water depth was maintained at 0.3-0.5 m and hydraulic retention time was managed to about 2-5 days; emergent plants were allowed to grow in the wetland. The wetland effluent concentrations of BOD_5, TSS, and T-N were higher in winter than in the growing season excepting the T-P, and effluent BOD_5 concentration was higher than influents in winter. Mass retention of T-N and T-P was stable throughout the year, whereas mass retention of BOD_5 and TSS was decreased in winter. BOD_5, TSS, T-N, and T-P performance of the experi-mental system was compared with the existing database (North American Treatment Wetland Database), and was within the range of general system performance. From the first-order analysis, T-P was virtually not temperature dependent, and BOD5 and TSS were more temperature dependent than T-N. Overall, the wetland system was found to be an adequate alternative for treating polluted stream water with stable removal efficiency and recommended as a NPS control measures.

Key words : constructed wetland, seasonal performance, NADB, first-order model, mass retention

INTRODUCTION

Large scale polder projects have been practiced to develop additional agricultural land and water resources during the last decades in Korean peninsula. After closure of the dikes, much pollutant loads from the watershed has been transported by streams and ditches to the estuarine reservoir, and most estuarine reservoirs are suffering from eutrophication in Korea. Nonpoint source (NPS) of nutrients are becoming more and more recognized as significant contributors to the eutrophication of lakes, reservoirs, and estuary (Jørgensen *et al.*, 1988). Numerous researches have shown that wetland restoration and construction are considered effective measures to combat the eutrophication of aquatic ecosystems and reduce nutrient loads to lakes and reservoirs (Kadlec and Knight, 1996; Mitsch *et al.*, 2000).

Pollutants are removed through a combination of physical, chemical, and biological processes including sedimentation, precipitation, adsorption to soil particles, assimilation by the plant tissue, and microbial transformations in the wetlands (Brix, 1993; Reed *et al.*, 1995). The water temperature in the wetlands controls the rate of pollutant removal for those biological reactions that are temperature dependent. Dormant vegetation and a slow reaction rate for soil or aquatic micro-

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bes at low temperatures may reduce both physical and biological activity and thus, the performance during winter months might be reduced.

However, the soil or aquatic microbes in winter still have the capacity to decompose organic and nutrient contaminants even though the outside temperature is comparably lower. Therefore, if a constructed wetland is insulated from the weather, substantial reductions of pollutants still might be possible at low ambient temperatures. Thus, it would be possible to successfully use constructed wetlands for pollutant treatment in cold climates (Jenssen *et al*., 1993; Wittgren and Mæhlum, 1997; Werker *et al*., 2002). Constructed wetlands can be insulated both by natural material (e.g. straw, ice, snow) and artificial material (e.g., rockwool, polystyrene foam). If the plant material in the wetland is not harvested, it also will provide insulation, as will snow and ice within the system (Mitsch and Gosselink, 2000).

In the warm temperate region (mean temperature of coldest months: −3-18°C), winter problems are only occasional and the design of the wetlands to compensate for poor performance during winter raises capital and operating costs. Although the relatively poor quality effluent discharges to receiving waters, it has less influent on algal blooms in lakes and reservoirs during winter than during other season. In this study we review how cold weather conditions affect wetland processes and treatment results, and how the impacts can be handled in design and operation.

MATERIALS AND METHODS

Four sets of 0.88 ha experimental wetland systems were constructed at the mouth of the Seokmoon estuarine reservoir in Choongnam Province located on the west coast of the Korean peninsula and have been in operation since 2002 to evaluate their efficiency in controlling NPS pollutant loads from the watershed (Fig. 1). Wetland types can be grouped into surface flow (SF) and subsurface flow (SSF) wetlands, and in this study surface flow type wetland was used. Water from the Dangjin stream flowing into the Seokmoon estuarine reservoir was pumped into the wetland. Water depth of the wetland was maintained at 0.3-0.5 m, hydraulic loading rate was about at 6.25-18.75 cm day^{-1}, and retention time was managed at about 3-5 days, during the study period. Emergent plants are allowed to grow in the wetland. The ponds have a permanent pool of water and are designed to have a hydraulic detention time of about two days, which might be enough for the settling of solids. The pond size was 0.08 ha in surface area and 2.0 m deep, which is 1/10 of the wetland surface area. The reservoir watershed area of 22,700 ha is composed of 14% residential, 40% agricultural, and 33% forested lands. The 1,600 ha polder area includes an 870 ha estuarine reservoir with average depth of 2.2 m. During the last five years (2001-2005), the mean annual precipitation and temperature averaged 1,412 mm and 11.8°C, respectively.

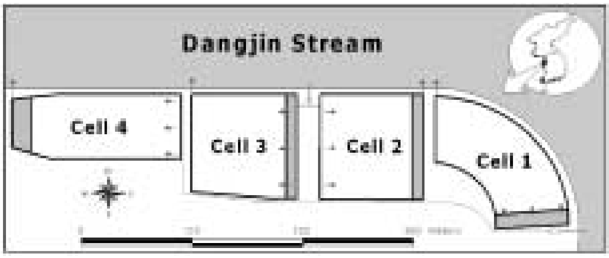

Fig. 1. Seokmoon watershed and experimental facility.

Water samples were taken at inlet and outlet of each wetland cell twice a month during the study periods of June 2002 to June 2004. Conventional water quality parameters including temperature, pH, EC, DO, BOD_5, TSS, T-N, T-P, and Chl-*a* were analyzed by Standard Methods (APHA, 1998). Two years of experimental data (June 2002-June 2004) from four wetland system were used for analysis. The data were divided into two groups: winter (December-February) and growing season (March-November) to analyze seasonal performance. ANOVA and t-tests were used to examine differences between data groups, and statistical analyses were performed using SPSS for windows version 10.0.

RESULTS AND DISCUSSION

1. Concentration

As shown in Fig. 2, the effluent concentrations of water quality constituents generally were lower in the growing season than during winter. However, the corresponding influent concentra-

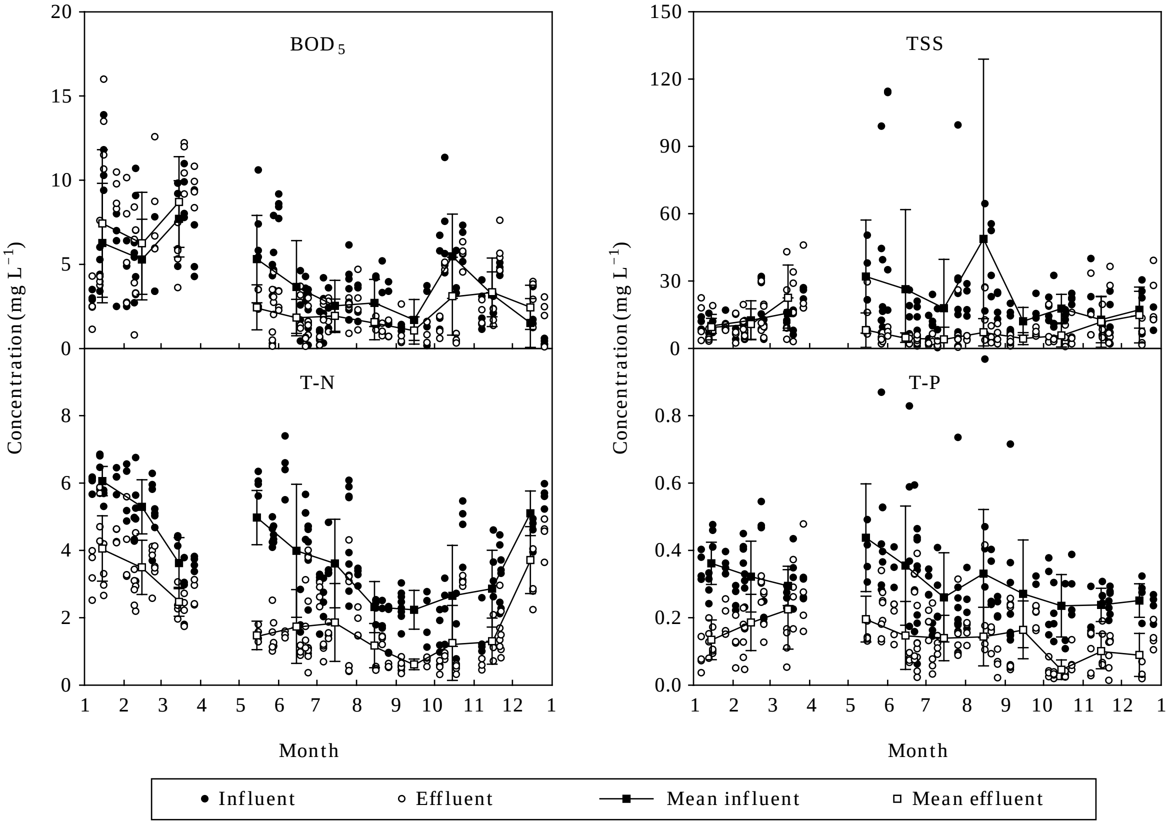

Fig. 2. Influent, effluent, and monthly mean concentration.

tions displayed similar seasonal patterns. As a result performance evaluation based solely on effluent concentrations may not be appropriate. Therefore, the seasonal performance of the system was analyzed by equivalent measures and the results are summarized in Table 1.

The system worked without freezing even under −10°C air temperature conditions, as long as water was flowing. While the mean air temperature was below 0°C (−0.1±3.81°C) in winter of the study period, the mean water temperature was 3.7°C. This value is less than the effluent temperature of SSF wetlands (mean 8.1°C) located in Seoul, Korea (Ham *et al.*, 2004). SSF wetlands can provide greater thermal protection than SF systems due to the insulation effect of the unsaturated surface layer (Wittgren and Mæhlum, 1997). A approximately 0.1 m ice cap was formed in December at the top of the pond and wetland, and melted in mid-February. The ice is held in place by the vegetation; the volume available for flow will be reduced as the ice layer thickens. The constriction of flow beneath the ice layer leads to subsequent flooding, freezing and hydraulic failure. It might be beneficial to operate the wetlands with a higher water level at the time of freezing and thus create space for both water and air beneath the ice (Kadlec and Knight, 1996; Wittgren and Mæhlum, 1997). In this study, water levels were raised in the early winter to about 0.5 m. The presence of some ice on treatment wetlands can be a benefit in that the ice layer provides insulation and slows the cooling of the underlying water. The standing dead vegetation acts as an effective snow trap which collects drifting and falling snow (Wittgren and Mæhlum, 1997).

Effluent BOD_5 concentration was higher than influent ($p < 0.05$, $n = 44$) in winter, whereas in the growing season, effluent BOD_5 was lower than influent with about a 20% removal rate. The reason for the higher BOD_5 effluent concentration in the winter season might be that low temperatures restrained microorganism activity, and the organic body from the withered plants and algae flowed out of the system. Although

Table 1. Seasonal comparison of concentration of the constructed wetland.

Constituents		Concentration (mean ± S.D.[a])		p-value	n
		Growing season	Winter season		
Temp. (°C)	Inf.	20.2±8.02	23.7±0.76	0.000[b]	172
	Eff.	20.3±8.5	4.3±0.58	0.000[b]	172
BOD$_5$ (mg L^{-1})	Inf.	4.0±2.66	4.4±3.28	0.460	172
	Eff.	2.9±2.63	5.4±3.77	0.000[b]	172
	Removal (%)	22.0±53.55	−19.2±58.44	0.000[b]	172
TSS (mg L^{-1})	Inf.	23.1±35.81	13.2±7.72	0.005[b]	172
	Eff.	8.0±9.06	11.7±8.78	0.015[b]	172
	Removal (%)	49.6±51.90	10.3±57.01	0.000[b]	172
T-N (mg L^{-1})	Inf.	3.3±1.48	5.5±0.76	0.000[b]	172
	Eff.	1.5±0.96	3.7±0.92	0.000[b]	172
	Removal (%)	51.5±26.4	31.7±13.64	0.000[b]	172
T-P (mg L^{-1})	Inf.	0.30±0.149	0.31±0.089	0.595	172
	Eff.	0.14±0.092	0.14±0.080	0.998	172
	Removal (%)	50.6±29.58	53.0±29.26	0.628	172

[a] Standard deviation.
[b] Significantly different at p=0.05.

effluent BOD$_5$ concentration was higher than influent during winter, effluent concentration (5.4 mg L^{-1}) was sufficiently low to conserve reservoir water quality.

The effects of temperature on the properties of water are not sufficient to significantly affect the removal efficiency of TSS in SSF wetlands, because TSS is mainly removed by physical processes (Kadlec and Knight, 1996; Ham *et al.*, 2004), whereas temperature does appear to be a factor in the reduction of TSS in SF wetlands due to the generation processes (Kadlec and Knight, 1996). TSS concentrations of influent and effluent were in the same range from November to February, whereas the effluent TSS concentration was stable from May to October (Fig. 1). In October, plants and periphyton were dead, and periphyton can be easily decayed during winter. Dead organisms disintegrated into particulate form, and large particles were broken down into smaller and smaller particles (Vymazal, 1994). Due to this reason, effluent TSS concentration was increased in this period (November-February). Effluent TSS concentration was higher than influent in March due to decompo-sition, resuspension by wind mixing, and the freezing/thawing effects of bottom sediment. Freezing/thawing of soil induces transient pulses of high biological activity after thawing, due to physical disruption of the soil structure. The frequency of freeze/thaw cycles is likely to show a large year-to-year variation, and may possibly cause large variation in nutrient losses from soil-plant systems (Wittgren and Mæhlum, 1997).

Influent T-N concentration had a reverse trend with water temperature; influent T-N concentration was at its highest value in May, for the growing season (Fig. 1). Normally, the T-N and T-P concentrations of the streams were at their highest value from mid-May to mid-June, due to the practice of heavy fertilization in the paddy rice field. The drainage from the paddy rice fields has a large influence on water quality because irrigation for paddy rice culture ranks first among the water uses, and it is responsible for over 50% of the total water consumption in Korea (Yoon *et al.*, 2001). Effluent T-N concentration displayed a trend similar to the influent (Fig. 1); effluent T-N concentration was higher in winter than in the growing season (Table 1). Limited biological activity due to low temperature and high influent concentration might contribute to the high effluent T-N concentration. The processes of ammonification, nitrification, and denitrification have all been shown to be temperature dependent in treatment wetlands; therefore, rates of total nitrogen reduction will also be temperature dependent (Kadlec and Knight, 1996; Werker *et al.*, 2002). Nitrification rates appear to be inhibited at water temperatures around 10°C, and rates drop rapidly to zero below approximately 6°C (Herskowitz *et al*., 1987). Denitrification has been observed to occur at temperatures as low as 5°C (Brodrichk *et al*., 1988). In this study, although mean water temperature was 3.7°C in winter, the removal rate of T-N was about 32%. According to Gumbricht (1992), other studies indicate N removal capacities of about 40% at air temperatures around zero.

T-P concentrations of influent and effluent were stable, and there was no difference in concentrations of influent and effluent between the growing season and winter ($p > 0.05$, n=172). Herskowitz (1986) reported that for P the removal rates were about equal for summer and winter, while N removal rates were up to twice as high in the summer as compared to the winter for the SF wetlands, which receives secondary effluent. Phosphorus removal, being largely a physical (sedimentation) and chemical (adsorption) process, is less directly sensitive to temperature, but may be influenced by the oxygen availability due to the sometimes large role played by redox sensitive adsorption to ferrous/ferric oxides (Wittgren and Mæhlum, 1997).

2. Mass retention

Influent loading, effluent loading, and mass retention in constructed wetlands are summarized in Table 2.

There was no difference in the hydraulic loading rate and hydraulic residence time between the growing season and winter ($p > 0.05$, n=172). The effluent BOD_5 loading rate was higher in winter than in the growing season, whereas no significant differences existed in influent loading rate between the two. During winter the effluent loading rate was larger than the influent loading rate. TSS mass retention was significantly higher in the growing season than in winter, due to low influent TSS concentration, decomposition of plants and periphyton litter, and lack of vegetation cover in winter. Over a seven year period, Knight *et al*. (1987) reported an average 77% mass retention in a natural wetland processing municipal wastewater in Reedy Creek, FL, USA. The TSS removal rate was highly correlated to the loading rate in that study.

There was no difference in T-N mass retention between the winter and growing seasons, whereas influent and effluent T-N mass loading rates were higher in winter than in the growing season ($p < 0.05$, n=172). High influent concentration and loading rate contributed to high T-N mass retention in winter. The daily T-N loading on our wetlands (mean 3.4±2.22 kg ha^{-1} day^{-1}) is comparatively high. Hammer and Knight (1994) reported 43 constructed and natural treatment wetlands with individual average loadings of

Table 2. Seasonal comparison of mass retention in constructed wetland.

Components		Growing season	Winter	*p*-value	n
		Mean±S.D.[a]			
Hydraulic loading (cm day^{-1})		7.97±3.367	9.04±3.218	0.053	172
Hydraulic residence time (days)		4.99±4.134	4.98±1.676	0.991	172
BOD_5 (kg ha^{-1} day^{-1})	Inf. loading rate	3.05±2.609	4.06±3.708	0.091	172
	Eff. loading rate	2.18±2.472	4.99±4.365	0.000[b]	172
	Retention	0.87±2.097	−0.93±1.879	0.000[b]	172
TSS (kg ha^{-1} day^{-1})	Inf. loading rate	16.83±15.561	11.17±6.112	0.030[b]	172
	Eff. loading rate	6.01±8.184	9.69±6.894	0.005[b]	172
	Retention	10.82±15.205	1.48±7.138	0.000[b]	172
T-N (kg ha^{-1} day^{-1})	Inf. loading rate	2.76±2.023	4.96±1.898	0.000[b]	172
	Eff. loading rate	1.30±1.254	3.45±1.637	0.000[b]	172
	Retention	1.46±1.340	1.51±0.709	0.749	172
T-P (kg ha^{-1} day^{-1})	Inf. loading rate	0.23±0.128	0.28±0.139	0.018[b]	172
	Eff. loading rate	0.12±0.106	0.11±0.084	0.512	172
	Retention	0.12±0.092	0.16±0.115	0.013[b]	172

[a] Standard deviation.

[b] Significantly different at p=0.05.

0.81-1.42 kg N ha^{-1} day^{-1}. Wittgren and Tobiason (1995) loaded a treatment wetland with approximately 5 kg N ha^{-1} day^{-1}, while Johnston (1991) considered a high load to be 2 kg N/ha/day and low to be 0.005 kg N ha^{-1} day^{-1}. The influent T-P loading rate and retention T-P loading were higher in winter than in the growing season ($p < 0.05$, $n = 172$). The mean retention loadings of the growing season and winter were 0.12±0.092 and 0.16±0.115 kg ha^{-1} day^{-1}, whereas the mean T-P loadings of the growing season and winter to the constructed wetland were approximately 0.23±0.128 and 0.28±0.139 kg ha^{-1} day^{-1}, respectively (Table 2). For two wetlands receiving inflow from the Olentangy River (T-P-0.17 mg L^{-1}), Nairn and Mitsch (2000) reported that T-P loadings were between 0.23 and 0.27 kg ha^{-1} day^{-1}, and wetlands retained approximately 0.15 kg ha^{-1} day^{-1}.

3. Comparison loading and effluent concentration with NADB

Loading rates of this study were compared with the existing wetland performance database (NADB, North American Treatment Wetland Database) in Fig. 3. Although sometimes effluent concentration was lower in the same loading rate than the NADB rate, all of the experimental data were in the same range with NADB rates. Generally the influent loading rate and effluent concentration was higher in winter than in the growing season. Because effluent concentrations of BOD_5, T-N, and T-P were lower or in the same range with NADB in the growing season, although influent loading rates were decreased, it might be difficult to decrease effluent concentration. Increasing the influent loading rate in the growing season in order to maximize the rate of nutrient retention is a better choice, although effluent concentration is increased, whereas reducing

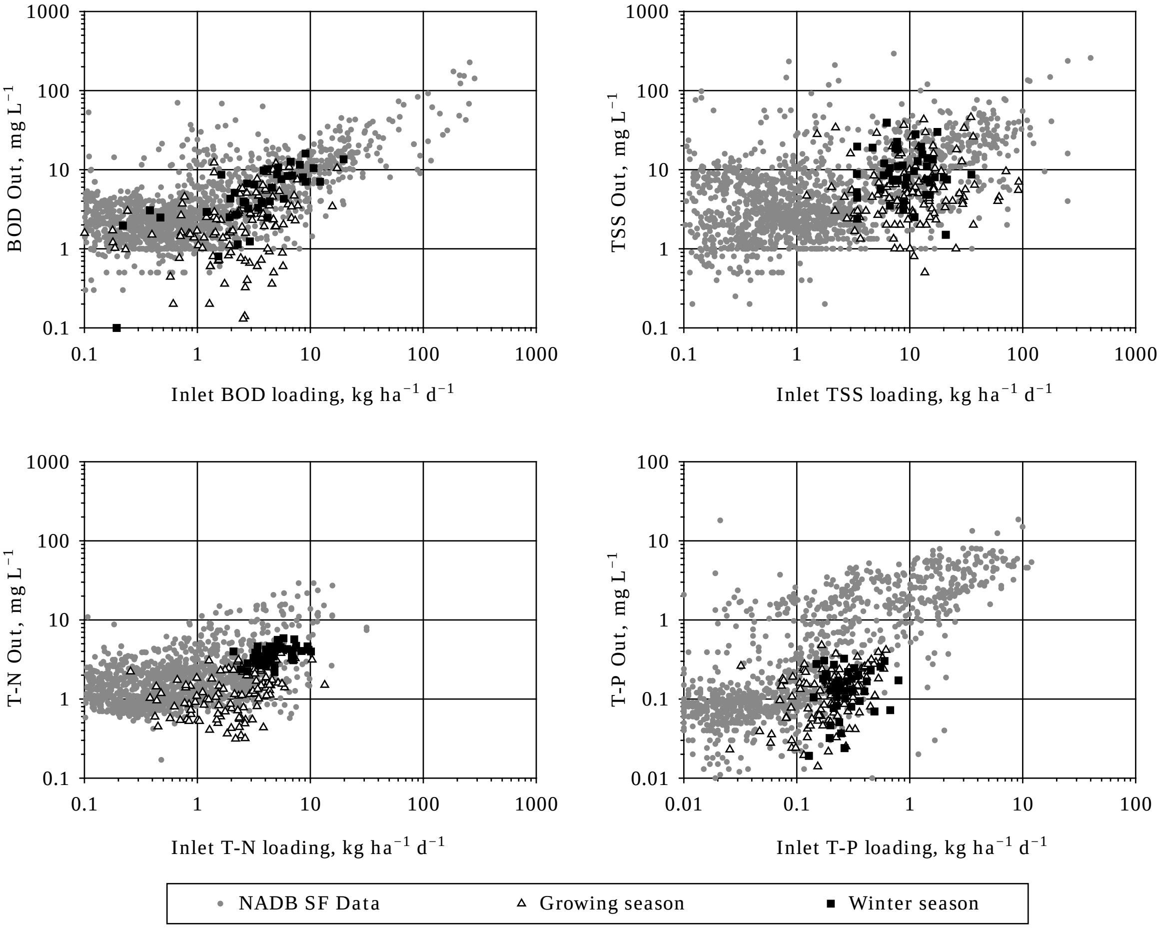

Fig. 3. Comparison of experimental data with NADB.

influent loading rates in winter could have further lowered the effluent concentrations of water quality constituents.

4. First-order model

Many pollutants decline exponentially to a background concentration (C*) on passage through a wetland (Kadlec *et al.*, 2000). Accordingly, a biological reaction is usually described as first-order. In this study, the wetland performance was evaluated for seasonal performance and temperature effect using a first-order area-based model (Kadlec and Knight, 1996; Kadlec *et al.*, 2000).

$$C_o = C^* + (C_i - C^*)\exp(-kA/Q) \qquad (1)$$

where C_o=outflow concentration (mg L^{-1}); C_i= inflow concentration (mg L^{-1}); C^*=background concentration in the wetland (mg L^{-1}); k=first-order areal rate constant for removal (m yr^{-1}); A =area of the wetland (m^2); and Q=water flow (m^3 yr^{-1}). The lowest concentration observed during the study was used as a background concentration, and temperature dependence of reaction rate constants was considered using the modified Arrhenius equation (Chapra, 1997; Kadlec *et al.*, 2000).

$$k_T = k_{20} \times \theta^{(T-20)} \qquad (2)$$

where k_T and k_{20}=first-order rate constants at temperatures T and 20°C θ=the temperature coefficient. Nonlinear regression was applied for experimental data to obtain k_{20} and θ values. Table 3 lists k values from this study and literature for BOD_5, TSS, T-N, and T-P (Kadlec and Knight, 1996).

Mean k values of T-N and T-P from this study were higher than literature values while lower values for BOD_5, but they were within the expected range. Low influent BOD_5 (mean 4.1 mg L^{-1}) might contribute to the low mean k value for BOD_5. The low mean k value of BOD_5 was not important in the constructed wetland for control of nonpoint sources, because these kinds of wetlands mainly focus on retention of nitrogen and phosphorus.

Values for k for removal of T-P in this study were high compared with the mean k (11.9 m yr^{-1}) referenced (Kadlec and Knight, 1996). During the initial operation of wetlands, removal of P can be inflated because of rapid storage of P on soil sorption sites and in growing vegetative biomass (Kadlec and Knight, 1996). However, this phenomenon did not operate in this study it was difficult for the bottom soil to adsorb P due to accumulated sediment cover (about 9 mm yr^{-1}), and there was no significant difference in P removal between the first and second year of the study. After several years the P removal rate and k value might decrease due to the release of soluble phosphorus from the sediment.

First-order areal rate constants (k) were significantly lower in winter than in the growing season ($p<0.05$, $n=172$), except for T-P. The estimated θ for T-P was close to 1, which implies that temperature effects might be minimal in T-P removal. In this study T-N was less temperature dependent and estimated θ was lower than BOD_5 and TSS.

5. Seasonal operation

In this study, effluent concentration of all of conventional water quality, except T-P, was higher in winter than in the growing season (Table 1). This pattern had potential benefits. The problem of lake and reservoir enrichment downstream of the wetlands was decreased in the summer, the time of the most serious algal blooms in lakes and reservoirs. Algal blooms had trend similar to the removal rate variation of wetlands.

In Korea, winter is the drought season and the

Table 3. Mean values for first-order areal rate constants.

	Growing season k (m yr^{-1}) (mean±S.D.)	Winter k (m yr^{-1}) (mean±S.D.)	p-value	k_{20}	θ	Reference[b] k (m yr^{-1}) (mean±S.D.)
BOD_5	11.2±24.97	−10.0±23.19	0.000[a]	7.09	1.131	32.0±20.49
TSS	31.1±33.14	9.9±31.27	0.000[a]	25.52	1.082	–
T-N	32.5±28.48	13.7±6.94	0.000[a]	32.90	1.035	15.4±14.57
T-P	27.2±22.23	36.7±31.37	0.051	27.60	1.006	11.9±5.91

[a] Significantly different at p=0.05.

[b] Kadlec and Knight, 1996.

flow rate of the river decreased notably from November in each year, increasing the concentrations of constituents in the water. This phenomenon usually disappears when the rainy season begins in the following summer. If large scale constructed wetlands (>0.1% of watershed area) are installed and operated, hydraulic loading rates could be decreased due to the decrease of the river flow rate. As a result, the influent loading rate of wetlands will be decreased, and the effluent concentration of wetlands could also be decreased.

In some cases, constructed wetlands could act as nutrient sinks during the growing season and as nutrient sources in winter (Mitsch and Gosselink, 2000). Although the influent loading rate decreases, if wetlands act as a nutrient source in winter, it might be feasible to altogether bypass the wetland during the winter. It might be economically and ecologically reasonable to treat waters for nutrient removal only during the growing season, allowing the wetland to be the nutrient removal system when it is acting as a sink.

CONCLUSIONS

The effluent concentrations of the wetland were higher in winter than in the growing season except T-P, and the effluent BOD_5 was often even higher than the influent in winter. The reason for a higher BOD_5 effluent concentration in the winter season might be that low temperatures restrained microorganism activity and organic bodies from withered plants and algae flowed out. Except the result of the BOD_5, the effectiveness of water quality improvement in the winter season was satisfactory for treating polluted stream waters, and the BOD_5 variation was also within the range of acceptable concentration.

Mass retention of T-N and T-P was stable throughout the year, whereas mass retention of BOD_5 and TSS was decreased in winter. Performance of the experimental system was compared with an existing database (NADB), and was within the range of general system performance. To obtain low effluent concentration in winter, a lower influent hydraulic loading rate and nutrient loading rate should be applied than in the growing season. The wetland performance demonstrated the effectiveness of water quality improvement and was satisfactory for treating polluted stream waters. From the first-order analysis, T-P (θ=1.01) was virtually not temperature dependent, and BOD_5 (θ=1.13) and TSS (θ=1.08) were more temperature dependent than T-N (θ=1.04). More knowledge about purification processes and long term performance at low temperatures is needed, in order to refine design criteria for systems operating under cold conditions.

Overall, the wetland system was found to be adequate for treating a polluted river with stable removal efficiency even during the winter period. Most of the nonpoint pollutions from watershed are transported by streams or ditches, which could be controlled by a constructed wetland system before entering into the lake or reservoir.

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<국문적요>

비점오염원 제어를 위한 인공습지의 계절변화에 따른 처리효율 평가

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비점오염원 제어를 위한 현장실험을 실시하였다. 연구시설은 인공습지와 유수지를 각각 4개씩 조성하였으며, 각각의 면적은 0.8 ha와 0.08 ha이고, 총 면적은 약 3.6 ha이다. 습지의 유입수는 충남 당진군의 석문담수호로 유입되는 당진천의 물을 펌핑하여 사용하였다. 습지의 수심은 웨어를 이용하여 생장기 (3월~8월)과 동절기 (12월~2월)에 각각 0.3 m와 0.5 m를 유지하였으며, 체루시간은 2~5일이었다. TP를 제외한 대부분의 수질항목에서 (BOD_5, TSS, TN)생장기보다 동절기에 더 높은 농도를 나타내는 것으로 나타났으며, BOD_5는 동절기 동안에 유출수의 농도가 유입수보다 더 높은 농도를 나타냈다. 동절기 동안에 제거된 부하량은 BOD_5, TSS는 감소한 반면에 TN과 TP는 감소하지 않고 생장기과 비슷한 값을 나타내었다. 다른 연구자에 의한 연구결과인 NADB (North American Treatment Wetland Database)와 비교해 보면 BOD_5, TSS, TN, TP모두 동일 유입부하량에 대해 대부분 NADB와 비슷하거나 약간 낮은 유출수의 농도를 나타내었다. 동절기 동안에 생장기와 비슷한 농도의 유출수를 얻기 위해서는 유입부하량은 생장기보다 감소시켜 적용하면 가능할 것으로 판단된다. 따라서 본 연구결과 인공습지는 동절기에도 안정적인 처리율을 얻을 수 있으며, 비점오염제어에 적합할 것으로 판단된다.