Korean J. Limnol. 39 (4):481~488 (2006)

Early Stage Performance of Constructed Wetland System 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 (0.88 ha each) of wetland and pond system were used. After three growing seasons of the wetland construction, plant coverage increased to about 90% even without plantation from bare soil surfaces at the initial stage. During the start up period of constructed wetlands, lower water levels should be maintained to avoid flooding newly plants, if wetland plants are to start from germinating seeds. The average removal rate of BOD_5, TSS, T-N and T-P during the first two years was 5.6%, 46.6%, 45.7%, and 54.8%, respectively. The BOD_5 removal rate was low and it might be attributed to the low influent concentration. The early stage of wetland performance demonstrated the effectiveness of water quality improvement and was satisfactory for treating polluted stream waters. From the first-order analysis, T-P was virtually not temperature dependent, and BOD_5 and TSS were more temperature dependent than T-N. A pond-wetland system was more effective than a wetland-pond or a wetland alone system in water quality improvement, particularly to reduce T-P. Overall, the wetland system was found to be an adequate alternative for treating a polluted stream water with stable removal efficiency and recommended as a NPS control measures.

Key words : constructed wetland, nonpoint source pollution, nutrient removal, plant cover, pond

INTRODUCTION

Korea is a land limited country and large scale polder projects have been practiced to dike, drain, and reclaim coastal tidelands to develop additional agricultural land and water resources during the last decades in Korean peninsula. Polders are effective to compensate the farmland loss caused by rapid expansion of residential and industrial areas, however, environmental concerns are arising and polder projects are currently under severe national debate. Water quality problem of estuarine reservoir inside the polder is one of the major concerns at polders. After closure of the dikes, part of the area remains under water and transformed into a fresh water reservoir which is used for the irrigation of agricultural lands as well as for municipal purposes. Much pollutant loading from the watershed has been transported by streams and ditches to the estuarine reservoir, and most estuarine reservoirs are suffering from eutrophication. Reservoirs usually have a large watershed and high-volume in incoming streams. The watershed may carry extensive agricultural nonpoint nutrients, silts, and organic matter discharges, making loading very high and difficult to protect water quality

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(USEPA, 1997).

Lake and reservoir restoration strategies are primarily aimed at reduction of the external nutrient loadings. The construction of new wetlands for NPS pollution control was therefore proposed for water quality protection, but relatively few studies have discussed about the NPS control compared to the abundant literature on point source control using natural and constructed wetlands (Yin and Shen, 1995; Kadlec and Knight, 1996; Wittgren and Mæhlum, 1997; Mitsch and Gosselink, 2000). The construction of wetlands for NPS pollution control contributes to two important goals of cleaning up our waterways and adding to the world's wetland reserves. Obviously wildlife enhancement and flood mitigation are ancillary benefits of constructed wetlands (Knight, 1992). Constructing wetlands for NPS pollution control is a good alternative, but there are some disturbing indications that wetlands have not been constructed correctly in the past, especially when they have been built to replace the function of wetlands lost for some type of human development project (Roberts, 1993). Proper design, construction, and restoration of a wetland needs to be done in an ecologically sound and predictable way (Mitsch and Jørgensen, 1989; Mitsch and Gosselink, 2000; Arheimer and Wittrgen, 2002). The research was initiated to investigate the wetland performance for NPS control, and this paper presents the result of first two years operation from wetland construction.

MATERIALS AND METHODS

An experimental facility was constructed at the mouth of Seokmoon reservoir which locates at the Seokmoon polder on the west coast of the Korean peninsula (Fig. 1). The Seokmoon polder watershed area is 22,700 ha and is mainly composed of 14% urban, 40% agricultural, and 33% forested lands. The polder area is 1,600 ha, and the reservoir surface area is 870 ha and the average depth is 2.2 m. There are two large incoming streams, the Dangjin and Yuk streams. During the last five years, mean annual precipitation and temperature was 1,412 mm and 11.8°C, respectively.

The total experimental facility involves about 25 ha, in which rice culture has been practiced on 20 ha of experimental paddy field, and four sets of wetland system (wetland combined with pond) were constructed at the mouth of Seokmoon reservoir with 0.88 ha (0.8 ha wetland, 0.08 ha

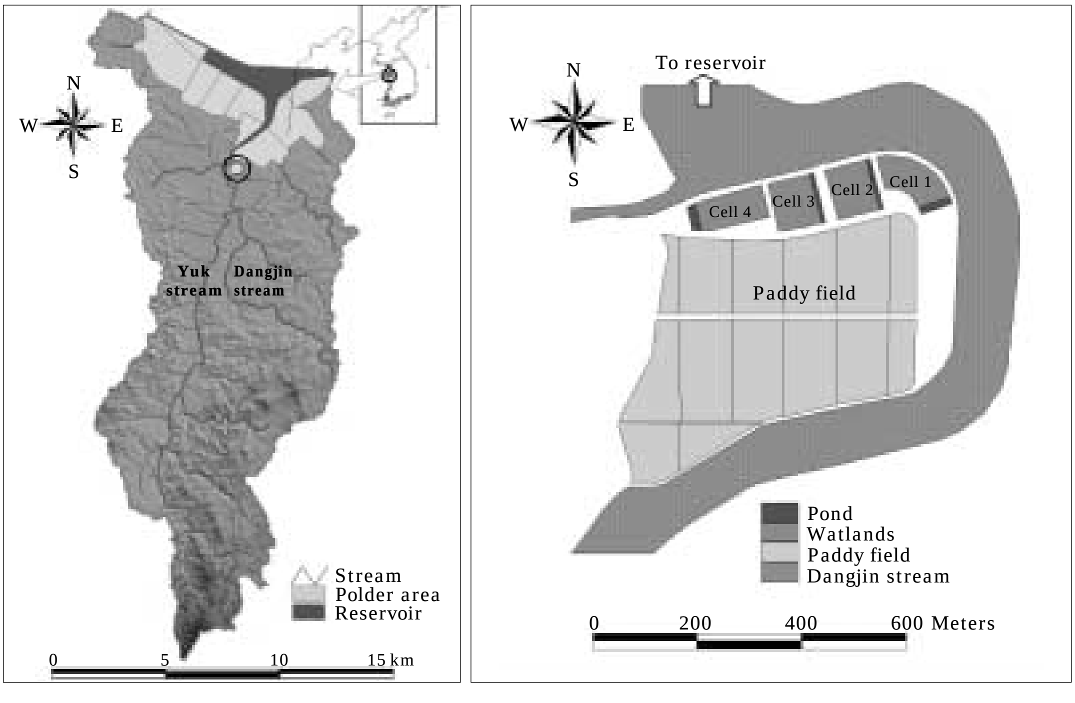

Fig. 1. Seokmoon watershed and experimental facility.

Table 1. Design parameters of constructed wetland systems.

	System	Width (m)	Length (m)	Depth (m)	Detention time (days)	Flow (m^3 day^{-1})	Hydraulic loading (cm day^{-1})
Cell 1	Pond-Wetland	64	125.0	0.3-0.5	3-5	500-1,500	6.25-18.75
Cell 2	Wetland-Pond	101	79.2	0.3-0.5	3-5	500-1,500	6.25-18.75
Cell 3	Pond-Wetland	101	79.2	0.3-0.5	3-5	500-1,500	6.25-18.75
Cell 4	Wetland-Pond	61	131.1	0.3-0.5	3-5	500-1,500	6.25-18.75

pond) each. Wetland types can be grouped into surface flow and subsurface flow wetlands, and in this study surface flow type wetland was used. 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. Emergent plants are allowed to grow in the wetlands. 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. Table 1 summarizes the design parameter of the wetland systems.

Two types of wetland and pond configuration were studied; a wetland-pond system where influent water flows into the wetland first and then drains to the detention pond, and a pond-wetland system where water flows vice versa. Wetland performance might be less satisfactory due to low temperature during winter and the effluent might need further polishing before discharge into the receiving water bodies. Therefore, a wetland-pond system was designed for wetland effluent to flow into the subsequent pond for further polishing. Surface flow wetland can be filled up with solids over time, and a filling process can be accelerated if the influent contains a high concentration of suspended solids. A pond can provides for pre-settling and is more easily cleaned than an emergent macrophyte bed. This pre-settling pond may require infrequent dredging to remove the accumulated deposits (Kadlec and Knight, 1996). The pond-wetland system was designed to remove suspended solids in the pond by settling prior to the wetland.

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). In each of the four wetlands, six 4 m^2 monitoring plots were installed to estimate vegetation cover and average plant height. Vegetation cover is an estimate of the percentage of the total ground area covered by stems and leaves.

RESULTS

1. Vegetation

The study area was used to be a tidal land and reclaimed for farmland. *Scirpus* spp., *Phragmites* spp., and other weedy upland plant species dominated the site and vegetation cover was less than 20% before the construction of the wetlands. During construction of the wetlands, the topsoil from the site was stockpiled and replaced within the wetland to form a rooting medium, because topsoil contains seeds and roots of the wetland plants of the region, which may assist in vegetating the wetland. All the wetlands were unplanted and allowed to develop naturally from the seeds and roots which were contained in the topsoil. During the construction of wetlands (2001), average vegetation cover was less than 5%. For optimal vegetation growth, wetland soil was fully or partially saturated with water during the spring (April) from 2002, and the water level was gradually increased up to 0.3 m using outlet water level control weirs as the wetland vegetation grew in height. Unfortunately the water level of cell-4 could not be controlled and was maintained at about 0.3 m due to a malfunction of the outlet weirs. As a result the vegetation cover of cell-4 was smaller than other wetlands (Fig. 2). Too much water during spring resulted in oxygen depletion in the root zone and a consequent slow growth or plant death because of insufficient oxygen for root metabolism.

After three years, vegetation cover exceeded 90% in the constructed wetlands except cell-4 (84%). The best technique for establishing rapid vegetation cover is to maintain saturated soil conditions without surface flooding during spring (Kadlec and Knight, 1996). Start up periods for the establishment of plants may take two to three years, and an adequate litter sediment compartment may take another two to three years after that (Mitsch and Gosselink, 2000). In this study, essentially almost full vegetation cover was achieved in three years from nearly bare soil of wetland construction with careful moisture control for proper plant establishment.

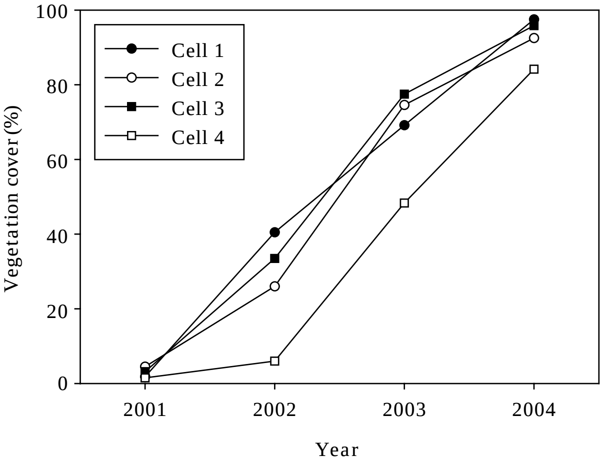

Fig. 2. Development of vegetation cover in the constructed wetlands.

2. Wetland performance

Table 2 summarize the seasonal performance of experimental wetland system. The system worked without freezing even under −10°C air temperature, as long as water was flowing. While the mean air temperature was below 0°C (−0.1 ±3.81°C) in winter (December to March), the mean water temperature was 3.7°C. Approximately 10 cm ice cap was formed in December at the top of the pond and wetland, and melted in mid-February.

The effluent DO of the constructed wetlands was supersaturated (>23 mg L^{-1}) in winter until the ice cap melted, and then dropped dramatically. Increased solubility, low consumption of DO by respiration, and increased water pressure due to the ice cap might contribute the DO increase in the winter. Although influent BOD_5 concentration was different among the constructed wetlands, effluent BOD_5 concentration remained fairly constant near the background concentration in the during growing season. It might be difficult to achieve the effluent BOD_5

Table 2. Seasonal comparison of concentration of the wetlands.

	Constituents	Concentration (mean±S.D.)		*p*-value	n
		Growing season	Winter season		
DO (mg L^{-1})	Inf.	10.8±3.64	14.9±2.56	0.000[a]	172
	Eff.	9.8±3.99	20.7±6.59	0.000[a]	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[a]	172
	Removal (%)	22.0±53.55	−19.2±58.44	0.000[a]	172
TSS (mg L^{-1})	Inf.	23.1±35.81	13.2±7.72	0.005[a]	172
	Eff.	8.0±9.06	11.7±8.78	0.015[a]	172
	Removal (%)	49.6±51.90	10.3±57.01	0.000[a]	172
Chl-*a* (μg L^{-1})	Inf.	23.6±22.91	34.7±30.21	0.010[a]	172
	Eff.	9.4±17.28	36.3±36.30	0.000[a]	172
	Removal (%)	44.2±62.94	−6.5±66.87	0.000[a]	172
T-N (mg L^{-1})	Inf.	3.3±1.48	5.5±0.76	0.000[a]	172
	Eff.	1.5±0.96	3.7±0.92	0.000[a]	172
	Removal (%)	51.5±26.4	31.7±13.64	0.000[a]	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] Significantly different at $p=0.05$.

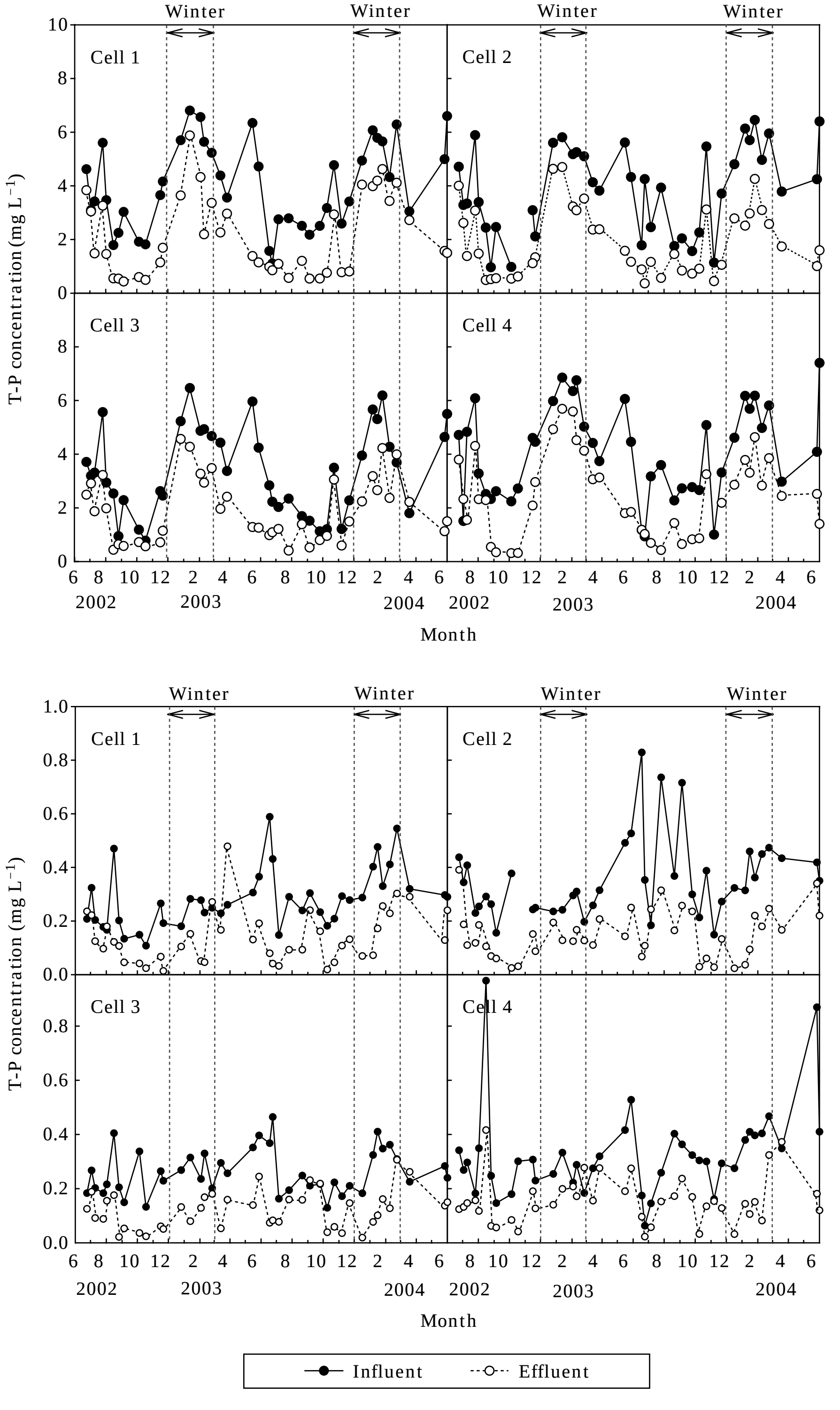

Fig. 3. Nutrient concentration of the constructed wetland systems.

concentration less than 3 mg L^{-1} in wetland systems working in natural way.

The effluent TSS was stable around 10 mg L^{-1} although influent TSS often dramatically increased during intensive rainfall showing about 50% removal in growing season. The influent

Chl-*a* of cell 1 and cell 3 (pond-wetland system) was higher than cell 2 and cell 4 (wetland-pond system), because algae increased with enough nutrient and light in the pond. The effluent Chl-*a* concentration was higher in winter than in the growing season ($p < 0.05$, n=172) due to the lack of vegetation cover. Phytoplankton might uptake more dissolved nutrients in winter than in the growing season due to the high biomass of phytoplankton. The effluent TSS increased in March due to high wind speed, no vegetation cover, and degradation of dead vegetation and periphyton. In shallow lakes and wetlands, resuspension has been determined to be a significant factor in sedimentation dynamics. Also, many water fowl found food in the bottom sediment in March where the water depth was about 0.3 m. This resulted in increased water column turbidity and export of higher turbidity water on several occasions. Generally the effluent TSS was stable during the experimental period even with wide variation of influent TSS concentration.

Fig. 3 shows variation of nutrient concentration in the wetland systems. Average effluent T-N concentration in the growing season and winter was 1.5 mg L^{-1} and 3.7 mg L^{-1}, respectively. The amount of T-N removed in winter was higher than in the growing season ($p < 0.05$, n=172), whereas the average removal rate in winter (about 30%) was lower than in the growing season (about 50%). There was no difference in the influent T-N concentration of the constructed wetland between the pond-wetland system (cell 1 and 3) and the wetland-pond system (cell 2 and 4), and T-N reduction using pond as a pre-treatment before wetland was negligible. 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 (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). The removal rate of T-N during winter was about 32%, which is in the range of other studies of about 40% at air temperatures around zero (Gumbricht, 1992).

The influent T-P concentrations were often high due to stormwater in summer rainy season, however, the effluent T-P concentration of the constructed wetland remained relatively stable. Average influent and effluent T-P concentration was 0.30 mg L^{-1} and 0.15 mg L^{-1}, respectively, showing about 50% removal rate. There was no difference in the effluent T-P and T-P removal rate between the growing season and winter ($p > 0.05$, n=172). 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).

3. First-order model

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 concen-

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

	Growing season k (m yr^{-1}) (mean±S.D.[a])	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.

tration, and temperature dependence of reaction rate constants was assumed to follow the modified Arrhenius equation (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 analysis was applied for experimental data to obtain k_{20} and θ values, and the values are summarized in Table 3.

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 k values of T-P in this study were high compared with the reference value. 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). 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.

DISCUSSION

After three years of operation, wetland plant coverage increased to about 90% from a bare soil surface at the initial stage even without plantation. Water level and moisture control especially start up period was critical, and maintaining saturated soil conditions not flooding during spring was needed for rapid establishment of wetland plant cover. The average removal rate of BOD_5, TSS, T-N and T-P during the study period was 5.6%, 46.6%, 45.7%, and 54.8%, respectively. The BOD_5 removal rate was low and it might be attributed to the low influent concentration, and the T-P removal rate of was about 10% higher than the T-N removal rate. 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 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) had virtually no temperature dependence, and T-N (θ=1.04) was less temperature dependent than BOD_5 (θ=1.13) and TSS (θ=1.08). A pond-wetland system was more effective and may require a smaller area than a wetland-pond system or a wetland alone system in water quality improvement, particularly to reduce T-P. Overall, the wetland system was found to be an adequate alternative for treating a polluted stream water with stable removal efficiency including winter period.

ACKNOWLEDMENT

This study was supported by Korea Rural Community and Agriculture Corporation (Development of water quality improvement measures using constructed wetland system).

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(Manuscript received 10 November 2006,
Revision accepted 15 December 2006)

< 국문적요 >

비점원오염 제어를 위한 인공습지의 초기단계 연구

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최근 우리나라에서는 유역단위로 배출되는 오염원의 40% 이상을 차지하고 있는 비점오염원의 제어가 중요해졌다. 유역의 비점오염원제어를 위해 전세계적으로 인공습지가 많이 이용되고 있다. 본 연구에서는 비점오염원 제어를 위한 현장실험을 2002년 6월부터 2004년 6월까지 실시하였다. 인공습지와 유수지가 하나의 시설로써 각각 4개씩 조성되어있으며, 면적은 0.88 ha이다. 습지의 식생은 식재를 하지 않고, 자연적 활착을 유도하였으며, 3번의 생장기를 거친 2004년도 식생조사 결과 각 습지별로 평균 약 90% 정도의 식생피도를 나타내었다. BOD_5, TSS, TN, TP의 평균 제거율은 각각 5.6%, 46.6%, 45.7%, 54.8%로 나타났다. BOD_5의 제거율은 낮게 나타났는데, 이는 유입수의 농도가 낮기 때문에 제거효율이 낮게 나타난 것으로 판단된다. 유수지-습지의 배치가 습지-유수지 배치보다 전체적으로 더 좋은 수질을 나타내었다. 일차반응모형(First-order analysis)결과 TP는 온도에 많은 영향을 받지 않으며, BOD_5와 TSS는 TN보다는 온도에 영향을 받는 것으로 나타났다. 본 연구 결과 인공습지는 유역에서 유입되는 비점오염원의 처리시설로 효과적인 것으로 생각된다.