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Purification Characteristics and Hydraulic Conditions in an Artificial Wetland System

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The purpose of this study was to evaluate the relationships between purification characteristics and hydraulic conditions, and to clarify the basic and essential factors required to be considered in the construction and management of artificial wetland system for the improvement of reservoir water quality. The artificial wetland system was composed of a pumping station and six sequential plants beds with five species of macrophytes: *Oenanthe javanica, Acorus calamus, Zizania latifolia, Typha angustifolia,* and *Phragmites australis.* The system was operated on free surface-flow system, and operation conditions were 3,444-4,166 m^3/d of inflow rate, 0.5-2.0 hr of HRT, 0.1-0.2 m of water depth, 6.0-9.4 m/d of hydraulic loading, and relatively low nutrients concentration (0.224-2.462 mgN/L, 0.145-0.164 mgP/L) of inflow water. The mean purification efficiencies of TN ranged from 12.1% to 14.3% by showing the highest efficiency at the Phragmites australis bed, and these of TP were 6.3-9.5% by showing the similar ranges of efficiencies among all species. The mean purification efficiencies of SS and Chl-*a* ranged from 17.4% to 38.5% and from 12.6% to 20.2%, respectively, and the Oenanthe javanica bed showed the highest efficiency with higher concentration of influent than others. The mean purification amount per day of each pollutant were 9.8-4.1 g · m^{-2} · d^{-1} in BOD, 1.299-2.343 g · m^{-2} · d^{-1} in TN, 0.085-1.821 g · m^{-2} · d^{-1} in TP, 17.9-111.6 g · m^{-2} · d^{-1} in SS and 0.011-0.094 g · m^{-2} · d^{-1} in Chl-*a*. The purification amount per day of TN revealed the highest level at the *Zizania latifolia* bed, and TP showed at the *Acrous calamus* bed. SS and Chl-*a*, as particulate materials, revealed the highest purification amount per day at the *Oenanthe javanica* bed that was high on the whole parameters. It was estimated that the purification amount per day was increased with the high concentration of influent and shoot density of macrophytes, as was shown in the purification efficiency. Correlation coefficients between purification efficiencies and hydraulic conditions (HRT and inflow rate) were 0.016-0.731 of R^2 in terms of HRT, and 0.015-0.868 of R^2 daily inflow rate. Correlation coefficients of purification amounts per day with hydraulic conditions were 0.173-0.763 of R^2 in terms of HRT, and 0.209-0.770 daily inflow rate. Among the correlation coefficients between purification efficiency and hydraulic condition, the percentages of over 0.5 range of R^2 were 20% in HRT and in daily inflow rate. However, the percentages of over 0.5 range of correlation coefficients (R^2) between purification amount per day and hydraulic conditions were 53% in HRT and 73% in daily inflow rate. The relationships between purification amount per day and hydraulic condition were more significant than those of purification efficiency. In this study, high hydraulic conditions (HRT and inflow rate) are

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not likely to affect significantly the purification efficiency of nutrient. Therefore, the emphasis should be on the purification amounts per day with high hydraulic loadings (HRT and inflow rate) for the improvement of eutrophic reservoir with relatively low nutrients concentration and large quantity to be treated.

Key words : reservoir, water quality, artificial wetland system, hydraulic loadings, macrophytes, purification, Masan Reservoir

INTRODUCTION

Wetlands remove aquatic pollutants through a variety of complex biological, physical, and chemical processes. The major mechanisms for pollutant removal in the wetland systems include both biological transformation and physico-chemical processes including absorption, precipitation and sedimentation (Chan *et al*., 1982).

Although macrophytic plants are the most obvious biological components of wetland ecosystems, recent reports in the literature highlight that the uptake of pollutants by wetland vegetation cannot by itself account fit the high pollutant removal efficiencies often observed at the high loading rate characteristics of many treatment processes (Stephensen *et al*., 1980; Nichols, 1983). Wetland plants play an important role in providing substrates to support the algae and bacterial populations that provide wastewater treatment capability and reliability in a created wetland community environment (Corbitt *et al*., 1994).

Natural and constructed wetlands are recognized as an energy-efficient and operationally simple waste-treatment method that can provide high purification efficiencies (Middlebrooks *et al*., 1981; Nicholas, 1983; Burgoon *et al*., 1991). The performance of wetlands for wastewater treatment will depend on: influent characteristics and the desired loading/discharge rates, the storage capacity of components, the transfer rate between components, system design and hydrology, and the environmental factors (light, temperature) that affect these components and processes (Bowmer, 1987; Breen, 1990). Design of constructed wetland system can ensure specific hydrologic and hydraulic conditions, and provide for targeted treatment of specific parameters.

During the last decade, there have been numerous studies on artificial wetlands applied to treat the wastewater from livestock, sewage and industry. Most of the studies in Korea are associated with the application on wastewater treatment of livestock and rural sewage water with high concentration influent ($>$20 mgN/L, $>$5 mgP/L), and long HRT ($>$2 days) (Yoon *et al*., 2000; Yang *et al*., 2000; Ham *et al*., 2000). There are several studies on the purification of eutrophic reservoirs by artificial wetland system in Japan and North America (Aizaki and Nakazato, 1997; Okino, 1997; Eriksson *et al*., 1997; Nakazato, 1998; Public Works Research Institute, 1998; Advice Center for Rural Environmental Support, 1995; Jenssen *et al*., 1993). However, those kind of studies are relatively very few in Korea.

This study intends to clarify important factors to be considered in the construction and management of artificial wetland system to improve reservoir water quality with energy-efficiency and capability to treat large amount of nutrients. The eutrophic agricultural reservoir, in this study, has relatively low level of nutrients ($<$5 mgN/L, $<$0.5 mgP/L) with large storage volume compared with wastewater. Due to low concentration of nutrients of in the influent, the system could not exceed a certain level. Therefore, it is desirable that the artificial wetland system be focused on purification amounts per day with high hydraulic loading, not on purification efficiency with low hydraulic loading.

The artificial wetland system in this study was systematically constructed at the side of a eutrophic reservoir in Korea. In order to investigate adequate techniques for efficient purification of eutrophic reservoir water, the system was operated in the conditions of short HRT with large daily flow rate, and efficiencies and purification amounts per day were measured. In addition, correlation analysis was conducted between purification activity and hydraulic loading parameters.

MATERIALS AND METHODS

1. Design of the artificial wetland system

The artificial wetland system was composed of a pumping station and six sequential aquatic plant beds. Metalimnitic water of the reservoir was pumped, and flowed through the wetland units where different types of macrophytes were planted. The treated water by wetlands system flowed back to the reservoir. Size of each plant bed in the artificial wetland system were 30 m × 15 m in the first, the second, and the third, and 33 m × 20 m in the 4th, the 5th, and the 6th. Aquatic macrophytes introduced in this system were *Typha angustifolia*, *Phragmites australis*, *Zizania latifolia*, *Oenanthe javanica*, and *Acorus calamus*. Bed soil was composed of paddy field soil, sandy−loam, and mixture of sand and small gravel. The factors considered in the operation of the wetland system were retention time, hydraulic loading, and loading rate of water quality parameters.

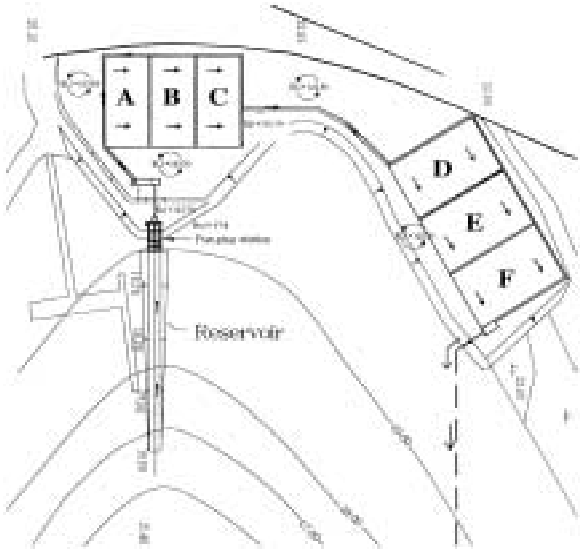

Fig. 1. Schematic layout of the artificial wetland system (Bio−Park) in Masan Reservoir. A; *Oenanthe javanica* bed, B; *Acorus calamus* bed, C; *Zizania latifolia* bed, D; *Typha angustifolia* bed, E; *Phragmites australis* bed, F; Pond, ⟶; direction of water flow.

The system was operated on free surface−flow system, and operation conditions were 3,444−4,166 m^3/d of inflow rate, 0.5−2.0 hr of HRT, 0.1−0.2 m of water depth (Table 1), and relatively low nutrients concentration (0.224−2.462 mgN/L, 0.145−0.164 mgP/L) of inflow water. Compared with most of hydraulic loading of artificial wetlands with free surface−flow system in North America (below 2.0 m/d) (Yang *et al.*, 2002), this system was operated on high hydraulic loading (6.0−9.4 m/d).

The macrophytes germinated in vinyl pots were transplanted in the five plant beds in the winter of 1998. Measurements were carried out monthly from April 1999 to December 2000. By analyzing the differences between pollutant concentration of influent and effluent, efficiency and amount of purification dependent on inflow rate were analyzed for each water quality parameters and macrophytes beds.

3. Measurements of water quality parameters and correlation analysis

Water samples were collected by adding H_2SO_4 (final pH 2) for chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), and filtering through 47 mm Whatman GF/C for suspended solid (SS), chlorophyll−*a* (Chl−*a*) (APHA, 1995). The water samples were transported to the laboratory at 4°C in dark container, and analyzed immediately. Inflow rate, water depth, and HRT of each system were calculated. The water temperature and electric conductivity were measured in situ by conductivity meter (YSI 30), pH by pH meter (YSI 630), and dissolved oxygen by DO meter (Orion 830). Biochemical oxygen demand (BOD) was determined using modified Winkler's Azide Method (APHA, 1995), and COD

Table 1. Experimental conditions of each macrophyte of the artificial wetland system (mean ± SD).

Beds	Water depth (m)	HRT (hr)	Inflow rate (m^3/day)	Hydraulic loading (m/d)
Oenanthe javanica bed	0.12 ± 0.02	0.50 ± 0.37	3,704 ± 2,587	9.1 ± 6.2
Zizania latifolia bed	0.13 ± 0.03	0.64 ± 0.40	3,444 ± 2,700	9.4 ± 6.7
Typha angustifolia bed	0.18 ± 0.05	0.72 ± 0.50	4,166 ± 2,791	6.1 ± 4.5
Phragmites australis bed	0.18 ± 0.06	0.90 ± 0.74	3,640 ± 2,507	6.0 ± 4.4
Acorus calamus bed	0.12 ± 0.04	0.55 ± 0.34	3,673 ± 2,616	8.6 ± 6.3

by acidic digestion by $KMnO_4$. TN and TP were determined by persulfate method and ascorbic acid method, respectively (APHA, 1995). SS was determined by drying filters at 103−105°C, and Chl−*a* by the spectrophotometric determination method (APHA, 1995).

The water purification efficiency and amounts per day were analyzed by computing the differences between concentrations of influent and effluent water quality parameters. The correlation coefficients were calculated by the lines or curve linear regressions between purification efficiency and hydraulic conditions (HRT and inflow rate), and between purification amount and hydraulic conditions on the major chemical parameters in the each macrophyte bed at the artificial wetland system.

RESULTS AND DISCUSSION

1. Water purification characteristics in the artificial wetland system

Lake water quality variation as influent of the artificial wetland system was shown in Fig. 2. Annual mean COD varied from 7.8 to 23.2 mg/L, TN 0.892−2.377 mg/L, and TP 0.084−1.762 mg/L, respectively. However, the mean concentrations of influent into the each plant bed on artificial wetland system were 3.6−6.3 mg/L in BOD, 9.5−10.7 mg/L in COD, and 14.2−36.1 mg/L in SS, and TN and TP, as nutrients, were 2.224−2.462 mg/L and 0.145−0.164 mg/L (Table 2).

The mean purification efficiency of BOD and COD in all macrophyte beds ranged 1.3−13.7%, and 9.5−10.7%, respectively. It seems that high hydraulic loadings with short HRT decreased the purification efficiency of organic material. However, the *Oenanthe javanica* bed showed the highest efficiency with high concentration of organic material in influent. The mean purification efficiency of TN ranged 12.1−14.3%, and the highest efficiency occurred in the *Phragmites australis* bed. Wathugala *et al.* (1987) and Yang *et al.* (2002) also found high purification capacity of the *Phragmites australis*. The mean purification efficiency of TP ranged 6.3−9.5%, and all beds showed the similar range of efficiencies. The mean purification efficiency of SS and Chl−*a* ranged 17.4−38.5% and 12.6−20.2%, respecti-

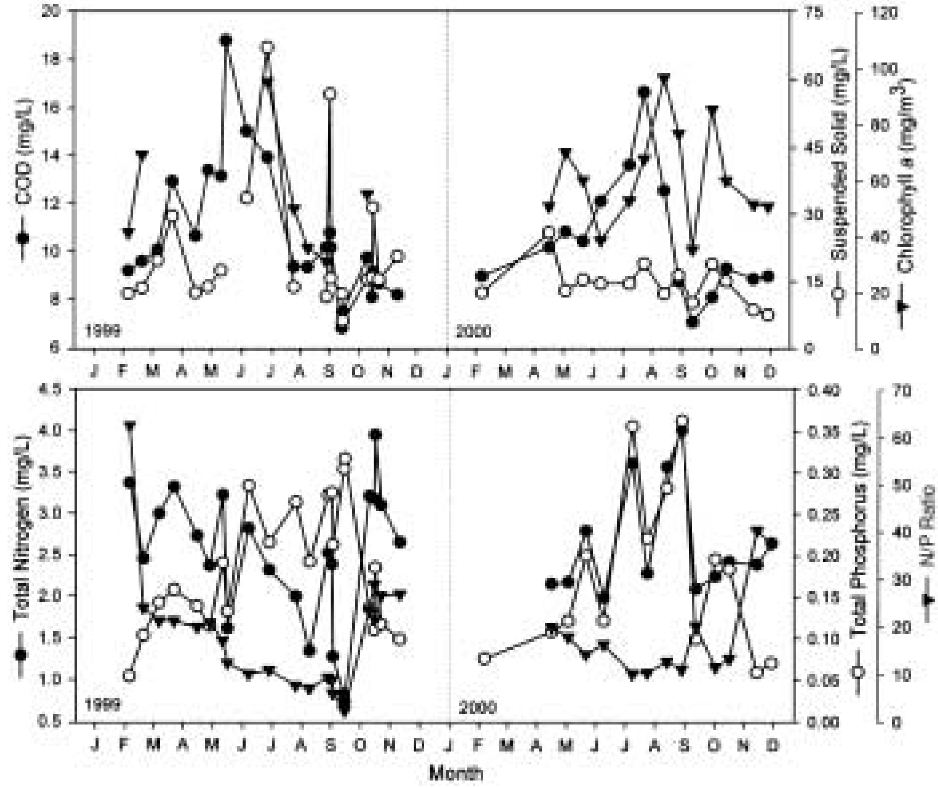

Fig. 2. Monthly variation of water quality parameters on Masan Reservoir.

vely. The *Oenanthe javanica* bed showed the highest efficiency with higher concentration of influent. About 50% of SS on influent was removed immediately by the wetland (Hosomi, 1994).

The wetland system using *Phragmites australis* in Watarase Reservoir (Public Works Research Institute, 1998) was operated by 0.1−0.2 m in water depth, 2.5 hr in HRT, and relatively low nutrient concentrations of influent (TN 1.35−1.78 mg/L, TP 0.058−0.102 mg/L). The purification efficiencies of Chl−*a*, TN, and TP were 10−50%, 0−30%, 0−25%, respectively, and the results of Watarase Reservoir was similar to those of this study.

Typha angustifolia fell down during the heavy rain season, from August to September, after growing up with the highest biomass. In this period, considerable amounts of nutrients could be released into water via decomposition process, and relatively lower purification efficiency and smaller purification amounts per day than others were observed, however, data not show.

Amount of mean purification per day of each pollutant ranged 9.8−24.1 $g \cdot m^{-2} \cdot d^{-1}$ in BOD, 1.299−2.343 $g \cdot m^{-2} \cdot d^{-1}$ in TN, 0.085−1.821 $g \cdot m^{-2} \cdot d^{-1}$ in TP, 17.9−111.6 $g \cdot m^{-2} \cdot d^{-1}$ in SS, and 0.011−0.094 $g \cdot m^{-2} \cdot d^{-1}$ in Chl−*a* (Table 2).

Amount per day of TN purification in this study revealed the highest level in the *Zizania latifolia* bed, and TP showed the highest in the *Acrous calamus* bed. The purification amount per day of SS and Chl−*a*, as particulate materials, revealed the highest level at the *Oenanthe javanica* bed, and the bed showed high values in other parameters. It was estimated that the purification amount per day was increased by high concentration of influent and high shoot density of macrophytes, as was shown in the

Table 2. Efficiency and amount per day of purification in various water quality parameters in each macrophyte bed of the artificial wetland system.

Macrophyte beds		*n*	Conc. of influent (mg/L)	Conc. of effluent (mg/L)	Purification efficiency (%)	Purification amount per day ($g \cdot m^{-2} \cdot d^{-1}$)
BOD	*Oenanthe javanica*	13	6.3 ± 1.8	4.7 ± 1.5	13.7 ± 17.8	24.1 ± 15.1
	Zizania latifolia	6	3.6 ± 1.4	2.9 ± 1.5	4.7 ± 4.6	20.4 ± 19.4
	Typha angustifolia	8	4.2 ± 1.9	3.9 ± 2.0	1.3 ± 1.3	9.8 ± 7.8
	Phragmites australis	9	3.6 ± 0.9	2.9 ± 1.0	2.9 ± 1.8	22.0 ± 9.9
	Acorus calamus	12	5.5 ± 2.4	4.3 ± 1.3	6.4 ± 8.3	17.8 ± 15.9
COD	*Oenanthe javanica*	26	10.7 ± 2.5	9.7 ± 2.2	8.3 ± 7.8	7.3 ± 7.4
	Zizania latifolia	19	9.8 ± 2.0	9.4 ± 2.0	4.2 ± 3.2	2.9 ± 2.0
	Typha angustifolia	18	9.5 ± 2.2	8.9 ± 2.1	5.9 ± 7.3	2.9 ± 2.8
	Phragmites australis	21	10.1 ± 2.7	9.7 ± 2.7	4.4 ± 4.0	4.3 ± 4.8
	Acorus calamus	22	10.3 ± 2.5	9.4 ± 2.3	8.3 ± 9.5	7.1 ± 7.7
TN	*Oenanthe javanica*	21	2.406 ± 0.742	2.120 ± 0.796	13.4 ± 13.7	2.170 ± 2.432
	Zizania latifolia	24	2.462 ± 0.652	2.153 ± 0.661	13.4 ± 12.1	2.343 ± 2.739
	Typha angustifolia	16	2.224 ± 0.661	1.981 ± 0.771	12.1 ± 16.5	1.299 ± 1.202
	Phragmites australis	22	2.254 ± 0.685	1.948 ± 0.700	14.3 ± 12.6	1.330 ± 1.065
	Acorus calamus	20	2.390 ± 0.632	2.125 ± 0.671	12.1 ± 10.4	1.821 ± 1.664
TP	*Oenanthe javanica*	31	0.164 ± 0.073	0.149 ± 0.070	9.5 ± 7.4	0.123 ± 0.151
	Zizania latifolia	25	0.153 ± 0.078	0.141 ± 0.075	8.8 ± 6.7	0.099 ± 0.146
	Typha angustifolia	23	0.146 ± 0.076	0.137 ± 0.071	6.3 ± 4.8	0.114 ± 0.160
	Phragmites australis	23	0.145 ± 0.065	0.133 ± 0.063	8.3 ± 5.6	0.085 ± 0.103
	Acorus calamus	25	0.158 ± 0.073	0.144 ± 0.067	9.0 ± 6.9	0.138 ± 0.164
SS	*Oenanthe javanica*	33	36.1 ± 30.2	21.3 ± 16.7	38.5 ± 16.2	111.6 ± 115.5
	Zizania latifolia	25	16.8 ± 14.7	14.1 ± 13.8	17.6 ± 11.8	17.9 ± 15.8
	Typha angustifolia	21	15.7 ± 14.3	13.4 ± 13.3	17.4 ± 10.9	24.5 ± 44.1
	Phragmites australis	22	14.2 ± 12.8	11.3 ± 10.7	20.7 ± 10.3	28.5 ± 55.6
	Acorus calamus	29	20.9 ± 17.5	15.7 ± 13.5	24.0 ± 12.8	49.2 ± 98.1
Chl−*a*	*Oenanthe javanica*	14	0.061 ± 0.019	0.048 ± 0.017	20.2 ± 16.1	0.094 ± 0.136
	Zizania latifolia	13	0.042 ± 0.016	0.035 ± 0.018	20.0 ± 20.6	0.056 ± 0.064
	Typha angustifolia	14	0.033 ± 0.013	0.030 ± 0.013	12.6 ± 17.0	0.011 ± 0.010
	Phragmites australis	15	0.033 ± 0.014	0.028 ± 0.014	14.1 ± 10.6	0.021 ± 0.020
	Acorus calamus	14	0.048 ± 0.017	0.041 ± 0.016	17.7 ± 14.4	0.073 ± 0.088

purification efficiency.

Aizaki and Nakazato (1997) used a wetland system with shallow water depth and high hydraulic loadings (HRT 0.5 hr) to increase the removal of nutrient in the eutrophic reservoir, Lake Kasumigaura. The macrophytes were *Ipomoea aquatica*, *Nasturtium officinale*, *Onanthe javanica*, and *Mentha spicata*, and influent concentration of SS, Chl-*a*, TN, and TP were 26.7−61.8 mg/L, 141−311 mg/m^3, 2.25−5.27 mg/L, 0.077−0.197 mg/L, respectively. Purification efficiencies of SS, Chl-*a*, TN and TP were 17−78%, 1−76%, 3−49%, and −49−35%, respectively, which were relatively higher or similar values to those of this study. However, the *Onanthe javanica*, the same macrophyte used in this study showed SS 39%, Chl-*a* 22%, TN 12%, and TP −12% in purification efficiencies, which were relatively lower than or similar to those of this study, respectively. The purification amounts per day of TN and TP were 0.66−3.05 $g \cdot m^{-2} \cdot d^{-1}$ and −0.013−0.095 $g \cdot m^{-2} \cdot d^{-1}$ in Lake Kasumigaura wetland system, and 1.821−2.343 $g \cdot m^{-2} \cdot d^{-1}$ and 0.085−0.138 $g \cdot m^{-2} \cdot d^{-1}$ in this study. Compared with those of Lake Kasumigaura wetland system, the purification amounts per day of TN in this study was low, but TP was high, and except the purification amounts per day of *Ipomoea aquatica* (TN 3.05 $g \cdot m^{-2} \cdot d^{-1}$, TP 0.095 $g \cdot m^{-2} \cdot d^{-1}$), purification amounts per day in this study were very high. Especially, the purification amounts per day of TN and TP on the *Onanthe javanica* bed in Lake Kasumigaura wetland system showed 0.66 $g \cdot m^{-2} \cdot d^{-1}$ and −0.013 $g \cdot m^{-2} \cdot d^{-1}$, which were much lower val-ues than those in this study (TN 2.170 $g \cdot m^{-2} \cdot d^{-1}$, TP 0.123 $g \cdot m^{-2} \cdot d^{-1}$).

In Lake Kasumigaura wetland, TN, TP and SS of influent were 1.5−2.5 mg/L, 0.07−0.18 mg/L and 15−45 mg/L, respectively (Nakazato, 1998), which were similar to those of this study. And the annual mean purification amounts per day of TN, TP, and SS were 0.094 $g \cdot m^{-2} \cdot d^{-1}$, 0.16 $g \cdot m^{-2} \cdot d^{-1}$, and 50 $g \cdot m^{-2} \cdot d^{-1}$, respectively, which were also relatively similar to the results of this study.

In addition, Advice Center for Rural Environmental Support (1995) reported that the purification amounts per day of TN and TP on a paddy field wetland were 0.1−0.2 $g \cdot m^{-2} \cdot d^{-1}$ and 0.01−0.02 $g \cdot m^{-2} \cdot d^{-1}$ with 3 mgTN/L and 0.5 mgTP/L in influent. These reports proved that our artificial wetland system is very effective, and purification activity is relatively higher than that of other similar studies.

2. Water purification property and hydraulic conditions

With many variables in the artificial wetland systems, such as water depth, HRT, hydraulic loading, flow rate, water temperature, influent water quality, etc., most of the correlation coefficients in this study showed relatively low value. Correlation coefficients between purification efficiency and hydraulic conditions (HRT and inflow rate) varied from 0.016 to 0.731 of R^2 in hydraulic retention time, and from 0.015 to 0.868 of R^2 in daily inflow rate (Table 3). Among the correlation coefficients, BOD, directly related with the biological degradation of organic matter, showed the highest correlation coefficients with hydraulic retention time and daily inflow rate in most of macrophyte beds. The *Zizania latifolia* beds showed high correlation coefficients with hydraulic retention time and daily inflow rate on water quality parameters, except TN.

Correlation coefficients of purification amount per day with hydraulic parameters were 0.173−0.763 of R^2 in HRT and 0.209−0.771 of R^2 in daily inflow rate (Table 4). Among the correlation coefficients between purification efficiency and hydraulic condition, the percentages of over 0.5 range of R^2 were 20% in HRT and in daily inflow rate, respectively, and the mean of R^2 showed low level as 0.336 in HRT and 0.350 in daily inflow. However, the percentages of over 0.5 range of the correlation coefficients (R^2) on purification amount per day were 53% in HRT and 73% in daily inflow rate, and the mean of R^2 showed relatively higher value with 0.495 in HRT and 0.541 in daily inflow than in those of purification efficiency. The relationships between purification amounts per day and hydraulic parameters (HRT and inflow rate), therefore, were more significant than those between purification efficiency and hydraulic parameters. High hydraulic conditions did not critically affect the purification efficiency of pollutant in this study.

Relationships between purification amounts per day and hydraulic condition in TN were weaker than other water quality parameters in the plant especially in *Typha angustifolia* and *Phragmites australis*. TP (Table 4) showed more signi-

Table 3. Regression equation and correlation coefficients in the macrophyte beds between hydraulic parameters and purification efficiency in water quality parameters.

Macrophyte beds		Purification efficiency (%)					
		Hydraulic Retention Time (hr)			Daily Inflow Rate (m^3/d)		
		Equation	R^2	p	Equation	R^2	p
BOD	*Oenanthe javanica*	$y = 3.6076x^{-1.1092}$	0.625	<0.05	$y = 6E-05x^{1.5179}$	0.868	<0.05
	Zizania latifolia	$y = 0.7637x^{-1.7528}$	0.609	<0.05	$y = 0.0003x^{1.161}$	0.424	<0.05
	Typha angustifolia	$y = -1.2236\mathrm{Ln}(x) + 1.2587$	0.473	<0.05	$y = 0.0006x - 0.2966$	0.691	<0.05
	Phragmites australis	$y = -1.7724\mathrm{Ln}(x) + 2.965$	0.557	<0.05	$y = 1.1472e^{0.0002x}$	0.762	<0.05
	Acorus calamus	$y = 24.734x - 2.3232$	0.731	<0.05	$y = 1.0556e^{0.0004x}$	0.626	<0.05
COD	Oenanthe javanica	$y = 4.4311e^{0.9562x}$	0.169	<0.05	$y = -3.7504\mathrm{Ln}(x) + 39.623$	0.132	<0.05
	Zizania latifolia	$y = 3.9026x + 2.128$	0.250	<0.05	$y = 7.6011e^{-0.0002x}$	0.424	<0.05
	Typha angustifolia	$y = 7.77641x + 0.7245$	0.287	<0.05	$y = 1487.5x^{-0.7095}$	0.346	<0.05
	Phragmites australis	$y = 2.004x + 2.7522$	0.124	<0.05	$y = 2.788e^{3E-05x}$	0.015	<0.05
	Acorus calamus	$y = 21.608x + 0.1139$	0.323	<0.05	$y = -6.4584\mathrm{Ln}(x) + 64.004$	0.200	<0.05
TN	*Oenanthe javanica*	$y = 15.933x^{0.9766}$	0.268	<0.05	$y = 33.939e^{-0.0004x}$	0.514	<0.05
	Zizania latifolia	$y = 5.2352e^{1.0289x}$	0.115	<0.05	$y = -9.7621\mathrm{Ln}(x) + 91.286$	0.397	<0.05
	Typha angustifolia	$y = 14.911x^{1.0771}$	0.489	<0.05	$y = 27303x^{-0.9971}$	0.484	<0.05
	Phragmites australis	$y = 15.965x + 0.3584$	0.677	<0.05	$y = 23.243e^{-0.0002x}$	0.373	<0.05
	Acorus calamus	$y = 21.586x^{0.8512}$	0.475	<0.05	$y = -9.1317\mathrm{Ln}(x) + 88.755$	0.429	<0.05
TP	*Oenanthe javanica*	$y = 14.879x^{0.622}$	0.289	<0.05	$y = 2541.6x^{-0.7177}$	0.305	<0.05
	Zizania latifolia	$y = 8.6157x + 3.7846$	0.233	<0.05	$y = -6.581\mathrm{Ln}(x) + 62.293$	0.425	<0.05
	Typha angustifolia	$y = 3.7905x^{-0.3653}$	0.117	<0.05	$y = 3.813e^{5E-05x}$	0.041	<0.05
	Phragmites australis	$y = 4.3405x + 6.0644$	0.229	<0.05	$y = -4.1115\mathrm{Ln}(x) + 42.772$	0.261	<0.05
	Acorus calamus	$y = 14.554x^{0.5834}$	0.226	<0.05	$y = 15.971e^{-0.0001x}$	0.265	<0.05
SS	*Oenanthe javanica*	$y = 38.05e^{-0.1723x}$	0.016	<0.05	$y = 42.006e^{-3E-05x}$	0.037	<0.05
	Zizania latifolia	$y = 24.499x^{0.6247}$	0.369	<0.05	$y = 32.935e^{-0.0002x}$	0.576	<0.05
	Typha angustifolia	$y = 11.008e^{0.2438x}$	0.033	<0.05	$y = -4.8763\mathrm{Ln}(x) + 58.433$	0.096	<0.05
	Phragmites australis	$y = -4.453x + 24.646$	0.102	<0.05	$y = 0.0023x + 14.186$	0.288	<0.05
	Acorus calamus	$y = 31.374x^{0.3716}$	0.148	<0.05	$y = 886.65x^{-0.4761}$	0.249	<0.05
Chl-*a*	*Oenanthe javanica*	$y = 48.296x + 4.7043$	0.456	<0.05	$y = -11.103\mathrm{Ln}(x) + 110.03$	0.221	<0.05
	Zizania latifolia	$y = 24.394x + 4.7369$	0.565	<0.05	$y = -14.975\mathrm{Ln}(x) + 142.64$	0.372	<0.05
	Typha angustifolia	$y = 3.2017e^{0.9916x}$	0.372	<0.05	$y = 1387.6x^{-0.6539}$	0.234	<0.05
	Phragmites australis	$y = 25.283e^{-0.4928x}$	0.428	<0.05	$y = 0.2184x^{0.5314}$	0.323	<0.05
	Acorus calamus	$y = 31.972x^{0.925}$	0.319	<0.05	$y = 0.0022x + 9.9437$	0.123	<0.05

ficant relationship between HRT and purification amount per day, and between inflow rate and purification amount per day than TN in the nutrients. SS showed also more significant relationship between HRT and purification amount per day, and between inflow rate and purification amount per day than COD in the organic materials. The purification amounts per day increased as the HRT gets shorter, and as the daily inflow rate gets higher.

Hata *et al.* (1996) reported relationships among HRT, purification efficiency, purification amount, and the dependence of influent nutrient concentration in channel-like wetland system that operated with 0.08 m in water depth, 2-24 hr in HRT, 5 mgTN/L, and 1 mgTP/L in influent. The results showed stated that the purification efficiency in each HRT decreased as nutrient concentration of influent increased, and the purification efficiency in the same concentration of influent increased as HRT increased. The purification amount per day decreased as HRT increased on the contrary.

According to the report by Advice Center for Rural Environmental Support (1995), purification efficiency of nutrient decreased as inflow rate per area increased, and increased as HRT increased. It showed that the purification efficiency of nutrient did not increase more than 50% when 5 hr HRT elapsed. However, the purification efficiency of nutrient increased by about 20% during 0.5-2.0 hr of HRT. The results of Advice Center for Rural Environmental Support (1995) were quite similar to those of this study

Table 4. Regression equations and correlation coefficients in the macrophyte beds between amount per day of purification and hydraulic parameters in water quality parameters.

Macrophyte beds		Purification amount per day $(g \cdot m^{-2} \cdot d^{-1})$					
		Hydraulic Retention Time (hr)			Daily Inflow Rate (m^3/d)		
		Equation	R^2	p	Equation	R^2	p
BOD	*Oenanthe javanica*	$y = -9.3607Ln(x) + 20.841$	0.173	<0.05	$y = 0.0059x + 9.117$	0.498	<0.05
	Zizania latifolia	$y = -7.7723Ln(x) + 9.5131$	0.217	<0.05	$y = 0.005x^{1.0403}$	0.337	<0.05
	Typha angustifolia	$y = 6.5622x + 0.5654$	0.717	<0.05	$y = 0.0036x^{-4.6333}$	0.553	<0.05
	Phragmites australis	$y = 7.9465x + 11.243$	0.534	<0.05	$y = -8.8994Ln(x) + 90.836$	0.435	<0.05
	Acorus calamus	$y = 28.076x0.9814$	0.700	<0.05	$y = 643.01x^{-0.47}$	0.209	<0.05
COD	*Oenanthe javanica*	$y = 1.8554x^{-0.909}$	0.357	<0.05	$y = 0.0017x + 0.4547$	0.453	<0.05
	Zizania latifolia	$y = 6.3287e^{-2.1146x}$	0.547	<0.05	$y = 0.0002x^{1.1514}$	0.588	<0.05
	Typha angustifolia	$y = 5.7729e^{-1.3548}$	0.643	<0.05	$y = 0.0002x^{1.1455}$	0.712	<0.05
	Phragmites australis	$y = 1.4969x^{-1.0189}$	0.462	<0.05	$y = 0.6825e^{0.0002x}$	0.531	<0.05
	Acorus calamus	$y = 21.741e^{-3.5931x}$	0.519	<0.05	$y = 3E-05x^{1.4657}$	0.609	<0.05
TN	*Oenanthe javanica*	$y = 9.7822e^{-3.382x}$	0.658	<0.05	$y = 0.0008x^{-0.3779}$	0.617	<0.05
	Zizania latifolia	$y = 0.8222x^{-0.9566}$	0.404	<0.05	$y = 0.0008x^{-0.3468}$	0.617	<0.05
	Typha angustifolia	$y = 0.7374x^{-0.6067}$	0.381	<0.05	$y = 0.0099x^{0.562}$	0.268	<0.05
	Phragmites australis	$y = 0.9989x^{-0.6715}$	0.314	<0.05	$y = 0.0104x^{0.5865}$	0.318	<0.05
	Acorus calamus	$y = -1.4274Ln(x) + 1.0796$	0.325	<0.05	$y = 0.0006x + 0.0935$	0.619	<0.05
TP	*Oenanthe javanica*	$y = 0.2329e^{-1.944x}$	0.413	<0.05	$y = 2E-05x^{1.0432}$	0.391	<0.05
	Zizania latifolia	$y = 0.0368x^{-0.8751}$	0.344	<0.05	$y = 5E-05x^{-0.073}$	0.666	<0.05
	Typha angustifolia	$y = 0.0148x1.7341$	0.711	<0.05	$y = 0.0061e^{0.0004x}$	0.662	<0.05
	Phragmites australis	$y = 0.0361x^{-0.8579}$	0.492	<0.05	$y = 1E-05x^{1.0216}$	0.514	<0.05
	Acorus calamus	$y = 0.0219x^{-1.6117}$	0.549	<0.05	$y = 0.0213e^{0.0003x}$	0.507	<0.05
SS	*Oenanthe javanica*	$y = 25.671x^{-1.1474}$	0.532	<0.05	$y = 0.0344x^{-24.853}$	0.636	<0.05
	Zizania latifolia	$y = -14.243Ln(x) + 9.4093$	0.411	<0.05	$y = 0.0049x + 1.1429$	0.663	<0.05
	Typha angustifolia	$y = 5.2636x^{-1.4157}$	0.704	<0.05	$y = 2.3941e^{0.0004x}$	0.737	<0.05
	Phragmites australis	$y = 5.0193x^{-1.3598}$	0.687	<0.05	$y = 7E-05x^{1.4799}$	0.521	<0.05
	Acorus calamus	$y = -38.445Ln(x) + 8.8673$	0.523	<0.05	$y = 0.0095x^{-1.0618}$	0.523	<0.05
Chl-*a*	*Oenanthe javanica*	$y = 29.617x^{-1.1493}$	0.606	<0.05	$y = 13.047e^{0.0004x}$	0.752	<0.05
	Zizania latifolia	$y = 12.56x^{-1.6297}$	0.374	<0.05	$y = 3E-05x^{1.7945}$	0.663	<0.05
	Typha angustifolia	$y = 13.54e^{-0.4885x}$	0.173	<0.05	$y = 0.0026x + 2.5744$	0.313	<0.05
	Phragmites australis	$y = 0.066e^{-1.1406x}$	0.763	<0.05	$y = 5E-08x^{1.6037}$	0.543	<0.05
	Acorus calamus	$y = 11.246x^{-2.1312}$	0.622	<0.05	$y = 0.0343x^{-30.532}$	0.771	<0.05

by revealing about 20% increase of purification efficiency in TN and TP for the initial 0.5-2.0 hr period. Therefore, this study need to carry out for the 5 hr duration to examine the probability of 50% increase of purification efficiency of nutrients as shown by Advice Center for Rural Environmental Support (1995), and the economic analysis between purification amounts per day and HRT also need be accomplished under the same condition. In addition, a further study needs be carried out to find out how the purification efficiency and purification amounts per day are related with influent concentration and flow distance in this wetland system.

CONCLUSIONS

The water quality improvement of eutrophic reservoir differs from that of the treatment of livestock wastewater and small-sized rural sewage water with high concentration influents (>20 mgN/L, >5 mgP/L) and long HRT (>2 days). To achieve high energy-efficiency and large capacity of nutrients removal, an artificial wetland system was operated with low nutrient concentrations (<5 mgN/L, <0.5 mgP/L) and large quantity of water with short HRT (0.5-2 hr).

As a result of regression analysis between purification characteristic and hydraulic conditions, the purification amount per day appears to be more significantly related with HRT and daily inflow rate than purification efficiency. It is evident that the hydraulic parameters such as HRT and daily inflow rate are slightly related to purification efficiency of agricultural reservoir water with low nutrient concentrations. The purification amount per day increased as the HRT gets shorter, and as the daily inflow rate gets higher. Therefore, efforts should be focused on to keep high hydraulic conditions to increase the purification amount per unit area per day.

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<국문초록>

인공습지시스템에서 수리학적 조건과 수질정화특성

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본 연구는 농업용저수지의 수질개선을 위한 인공습지 시스템에서 수리학적 부하조건과 수질정화 특성간의 상관관계를 평가하고, 습지의 조성과 관리에 관한 기본적이며 주요 인자들을 규명하고자 하였다. 인공습지시스템은 저수지 중층수를 유입시키기 위한 양수장과 미나리, 창포, 줄, 부들, 갈대 등의 정수식물을 식재한 6개의 개별습지로 구성되어 있다. 시스템은 자유수면흐름방식으로 유입처리유량 0.012–0.122 m^3/s, 수리학적 체류시간 0.5–2.0 hr의 수리학적 고부하조건으로 운영하였으며, 수심은 0.1–0.2 m, 유입수질은 저수지를 대상으로 하여 비교적 낮은 영양염류 농도(TN 2.224–2.462 mg/L, TP 0.145–0.164 mg/L)를 가지고 있다. 본 연구기간 중 각 개별습지의 평균 수질정화효율은 TN 12.1–14.3%로 갈대조에서 높게 나타났으며, TP는 6.3–9.5%로 식물 종에 따른 큰 차이가 없었다. SS는 17.4–38.5%, Chl–a는 12.6–20.2%로 미나리조에서 높게 나타났는데, 이는 유입수 농도가 다소 높은 때문으로 판단된다. 시간당 정화량은 TN 1.299–2.343 $g \cdot m^{-2} \cdot d^{-1}$, TP 0.085–1.821 $g \cdot m^{-2} \cdot d^{-1}$, SS는 17.9–111.6 $g \cdot m^{-2} \cdot d^{-1}$, Chl–$a$는 0.011–0.094 $g \cdot m^{-2} \cdot d^{-1}$로 정화효율에서와 달리 TN은 줄에서 가장 높았고, TP는 창포에서 높았다. 침강성 물질인 SS 와 Chl–a는 미나리에서 높게 나타났으며, 미나리는 BOD, COD, TN, TP 등 다른 수질항목에서도 높은 값을 보여주고 있어 정화효율에서와 같이 유입수농도가 습지내 물질제거에 영향이 있음을 보여준다. 정화효율 및 시간당 정화량과 수리학적 조건간의 상관관계는 수심, 체류시간, 일유입량, 수리학적 부하량, 유입수 농도, 온도 등 다양한 변수에 의한 영향으로 비교적 낮게 나타났다. 정화효율과 수리학적 조건간의 상관계수(R^2)는 수리학적 체류시간과 0.016–0.731, 일처리유량과는 0.015–0.868을 나타내었으며, 시간당 정화량과 수리학적 조건간의 상관계수(R^2)는 수리학적 체류시간과는 0.173–0.763, 일처리유량과는 0.209–0.770의 범위를 나타내었다. 정화효율과 수리학적 부하조건간의 상관계수(R^2)가 0.5 이상을 나타내는 각 수생식물 습지별 수질항목은 체류시간과 일처리유량에 대해 각각 20%, 정화속도와 수리학적 조건간의 상관계수는 체류시간에 대해 53%, 일처리유량에 대해 73%가 0.5 이상을 보이고 있어 시간당 정화량과 수리학적 조건간의 상관관계가 정화효율과의 상관관계보다 좀더 유의성 있게 나타났다. 이것은 높은 수리학적 부하조건이 영양염류 등의 정화효율에는 크게 영향을 미치지 않음을 보여주고 있으며, 따라서 비교적 낮은 농도의 영양염류를 가지고 있고, 많은 처리수량을 요구하는 부영양화된 저수지의 수질개선을 위해서는 높은 수리학적 부하조건에서 시간당 정화량을 늘리는 관리방법이 경제적이며, 이에 초점을 맞추어 나가야 할 것으로 사료된다.