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Comparative analysis on reduction of agricultural non-point pollution by riparian buffer strips in the Paldang Watershed, Korea

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ABSTRACT

A riparian buffer strip (RBS) that locates in boundaries between streams and lands efficiently and sustainably performs ecological functions and reduces non-point pollution as a multipurpose practice. The present paper investigates the feasibility of introducing a riparian buffering strip for protection of the Paldang Lake and the Han River in Korea from worsening ecological environment and water quality. For experiments, a pilot RBS (five types of plants) appropriate for the conditions of targeted watersheds was set up and tested according to the pollution loads and area precipitation. The measurements show that suspended solids (SS), total nitrogen (T-N), and total phosphorus (T-P) decrease by more than 50% within the 20 m width of the pilot RBS and, at the maximum, decline by up to 84%, 87%, and 98% respectively depending on a plant type in the pilot RBS. The catchment area per 1 ha in the pilot RBS was 12 ha. In case a 20-m wide RBS is set up in the watershed with the biggest agricultural area (72,049 ha) among the three unit-watersheds in the upper reaches of the Paldang Lake, the catchment area per the RBS of 1 ha can be estimated as 4 ha leading to reduction of agricultural non-point pollution loads by more than 79%. From the findings, the introduction of RBS is expected to be appropriate and versatile for reduction of agricultural non-point pollution and improvement of ecological conditions.

Keywords: Riparian buffer strip; Ecological function; Non-point pollution; Sustainable multipurpose practice; Water quality; Agriculture; Suspended solids; Nitrogen; Phosphorus

1. Introduction

With national demand for the improvement of water quality and conservation of the ecosystem rapidly increasing since the 1990s, the Korean government has steadily taken countermeasures against point source pollution such as extension of sewage treatment plants in the upper reaches of the source stream and strengthening of emission standards. Even in 2000, however, the water quality of major supply sources did not satisfy the set goals. The water quality of public water areas such as streams has not been sufficiently improved, and this has led to the perception that non-point pollution accounting for 22–37% of the total pollution loads is the

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reason [1]. Thus, the government is providing political alternatives including restrictions on development and pollution-causing activities in certain areas as well as on the amount of pesticides and fertilizers used. It is also actively supporting the development of eco-friendly stream restoration technologies, non-point pollution reduction technologies, watershed management technologies, etc.

Riparian Buffer Strip and Vegetative Filter Strip are the strips of permanent vegetation, which are considered to be one of the methods of efficiently removing agricultural non-point source pollution containing nutrients such as nitrogen, phosphorus and sediment, etc. RBS, however, is adjacent to water bodies (stream or lakes, wetlands) and therefore it may exert unique ecosystem effects such as the function of stabilizing bank erosion and biotope function, etc. in addition [2–6]. Uniformly presenting the ranges and effectiveness of RBS is difficult because it differs in the characteristics of weather, precipitation, non-point pollution material, plant, and soil, and basin scale, etc. depending on the region and mechanism for reduction is very difficult in terms of physical, chemical, and biological aspects [6,7]. A variety of studies on the reduction of pollutants of RBS and VFS have been done by many researchers.

Young *et al.* (1980) [8] investigated the cases of width of 21.3m and 27.4m with a same slope of 4%. A rainulator was used to test vegetative buffer strips for their ability to control pollution from feedlot runoff. Cropped buffer strips on a 4% slope reduced runoff and total solids transported from a feedlot by 67 and 79%, respectively. Total N and P were reduced by an average of 84 and 83%, respectively. Ammonium-N and PO_4^-P were similarly reduced, but average NO_3^-N in the runoff increased because some NO_3^-N was gained from the sorghum-sudan grass and the oat buffer strips.

Dillaha *et al.* (1988) [9] found that 81% and 91% of sediment was removed respectively from 4.6 m and 9.1 m width as result of studying the effect of reduction of sediment, T-N, T-P, soluble N and P using rainfall simulation and grass VFS of silt loam soil. In addition, T-N showed 58 and 69%, and T-P showed 64 and 74% in their removal efficiencies respectively, but soluble nitrogen and phosphorus were not removed effectively, which even showed higher than the input concentration. Furthermore, it is reported that surface runoff from feedlot results in excellent effect of reduction when it is shallow and uniform.

Schwer and Clausen (1989) [10] reported regarding pollutant concentration the effect of reduction from subsurface runoff was better showing the decrease of 92, 86, and 83% respectively from surface runoff while 97, 92, and 93% respectively from subsurface runoff as result of using the grass filter of 2% loam soil, 26 m long, 10.6 m width in the analysis of the effect of reduction of solids of milkhouse, P, and N for 2 years. In addition it reported that the effectiveness of filter strip treatment is governed by hydraulic loading rate when 2.94cm/week was maintained using level lip spreader. It was reported that nutrient uptake rate by the plants are approx. 2.5%, 15%, etc. in P, and N respectively.

Magette *et al*. (1989) [11] reported, as result of analyzing pollutant removal effectiveness in grass VFS formed from sandy loam soil, TSS, T-N, and T-P were reduced by 66, 0, and 27% at the length of 4.6 m, which indicates it is more effective for removing sediment than nutrient. At the length of 9.2 m, it showed more removal effectiveness in the case of sediment. But its removal effectiveness was not so good compared with the initial value input in the case of nutrient. Furthermore, the comparison between bare plot and vegetated plot indicated that as unvegetated area increased VFS performance decreased while as nutrient removals decreased as the number of runoff events increased.

Lowrance *et al*. (1997) [12] reported that RFBS had superior control over polluting substances diffused in NPS (particularly, agricultural watershed), including sediment, nitrogen and phosphorus. In addition, they found that slope was the major factor affecting RFBS' ability to eliminate polluting substances and the pollution-reducing effects would improve on zoning of the area into the zone 1 (undisturbed forest), zone 2 (managed forest) and zone 3 (runoff control) from the waterside. In this case, they also recommended deeply rooted trees in the zone 1 for biological activities and grass in the zone 3 for flow-spreading.

Schumitt *et al*. (1999) [13] reported, in the study on width 7.5 and 15 m, fine textured-soil, 6–7% slop using vegetated filter strip and simulated runoff event, 76–93% of sediment, 55–79% of T-P, 24–48% of nitrate, 19–43% of dissolved P, 5–43% of herbicide such as atrazine contained in runoff were reduced. In the case of grass with 2-yr-old and 25-yr-old among a variety of plants used for vegetation, 25-yr-old was reported to have better filter performance.

On the other hand, there was a study that analyzed the plant nutrient removal effectiveness separately from soil.

Mitsch (1992) [14] reported, in the study on non-point source controlling using natural riparian wetlands, nitrogen may be mainly removed by denitrification process in soil as well as plant uptake, while phosphorus is mainly removed by precipitation of soil particles.

Omari and Fayyad (2003) [15] reported, in the study on domestic wastewater treatment through subsurface flow of constructed wetlands, nitrate nitrogen is reduced by denitrification, plant uptake, and conversion to bacteria cell, but plant uptake and incorporation into bacteria cell mass are relatively small.

Keffla and Ghrabi (2005) [16] reported, in the study on nitrogen removal effectiveness using constructed

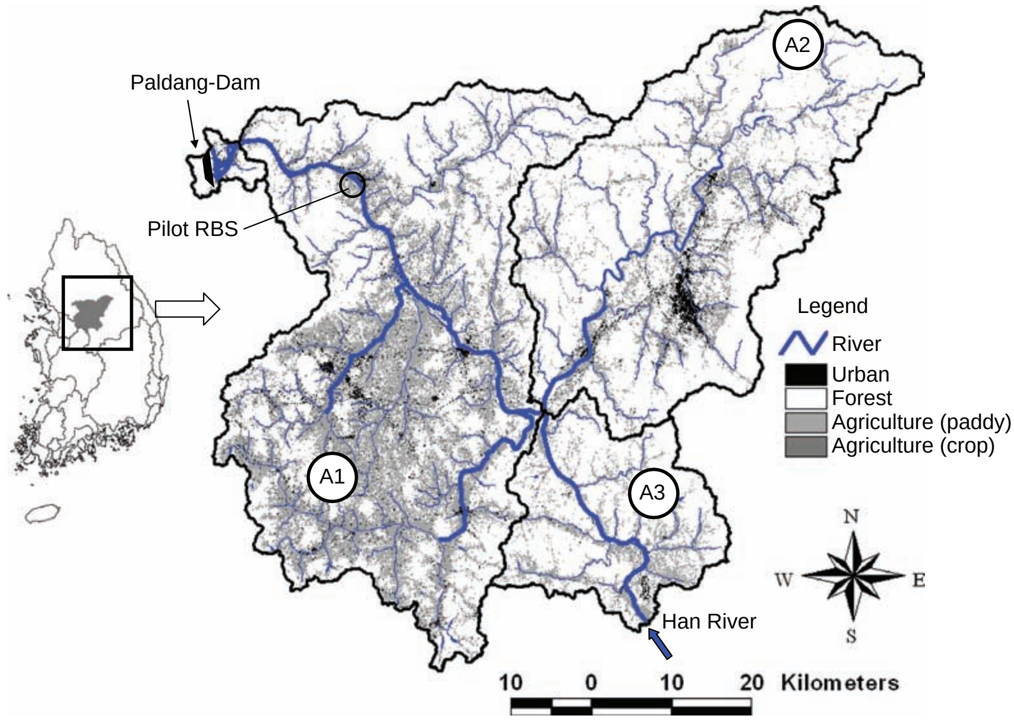

Fig. 1. Three unit watersheds of the upper reaches of Paldang Dam and distribution map of land use.

wetlands planted and unplanted, it showed the removals of 27 and 5% for TKN(nitrogen Kjeldahl), 19 and 6% for nitrogen ammonia(NH_4^+), 4 and 13% for nitrate-nitrite (NO_2^-,NO_3^-) respectively representing that the removal effectiveness of nitrogen by plant was low. It also reported that even in the wetlands filtration and sediment that is physical process, nitrification and denitrification mechanism that are chemical/biological process contributed to the removal of nitrogen.

According to the afore-mentioned precedent studies, most of them adopted artificial run-off simulation in accordance with the rainfall characteristic of subject area, used grass as the plant in the width(or length) of approx. 4.6–27.4 m. Most of them applied gentle slope in the range of 10% or less for the width and length, and adopted the soil of silt loam or sandy loam that is easily drained. Removal effectiveness was high in all of SS, T-N, and T-P, but especially high in the sediment. In the case of Nitrogen, ion compounds (NH_4^+, NO_2^-, NO_3^-) removal effectiveness was not satisfactory, and part of them was reported to have increased. In the RBS(or VFS) consisting of plant and soil, major removal mechanism of sediment, T, and P includes infiltration, deposition, adsorption, and absorption, but plant uptake is reported to be minimal.

RBS are to be an effective, sustainable means of buffering aquatic ecosystems(water quality) against nutrient stressors and thus are considered a best management practice (BMP) by State and Federal Government (i.e., US EPA, USDA, US Army ERDC) [7].

This Study is intended to derive the extent of sediment, nitrogen, and phosphorus that can be removed in relation with which are discharged to the stream in high concentration together with runoff when it rains in the agricultural area densely located at the riverside in Korea through the experiment conducted in 5 types of pilot RBS. And then through the results the assumption was made about their feasibility as non point source pollutants removal facility, and the effect when it would be applied to all the streams in Paldang Reservoir that is the major water supply source in Korea.

2. Methods

2.1. Study area

Han River (total length: 391.16 km) runs from east to west of Korea passing through Seoul, the capital region. Paldang Dam (37°31′ N, 127°16′ E) is located 95 km from the end of the river; the resulting Paldang Reservoir is the major water supply source for the capital region. The water quality of these areas has stagnated due to non-point source pollution for the last decade.

Table 1
Area and ratio of each land use in the A1 area.

Type	Total	Water Area	Urban Area	Vacant Land	Wetland	Forests	Green Area	Agriculture (Paddies)	Agriculture (Crops)
Km^2	2072.72	23.87	45.9	47.44	0	1017.97	154.97	720.49	62.08
%	100	1	2	2	0	50	7	35	3

The government recently considers inducing non point source pollutants such as percolation trench (highway area), media filter (urban area), hydrodynamic devices (residential area), vegetated filter strips, etc. for which a pilot scale facility is under operation [17]. The upper reaches of Paldang Reservoir are rich in water resources; many agricultural areas have been created from the past, and especially they are located riverside. Fig. 1 shows these characteristics with 3 unit watersheds (A1–A3) adjacent to the upper reaches of Paldang Dam.

The A1 watershed is closest to Paldang Dam. The urban area of the Al watershed is smaller than that of A2, but the agricultural area of Al is the largest. The gross area of the A1 watershed is 2072.72km^2, the urban area accounts for 2%, and the agricultural area, 38%. Forests make up for 50% (Table 1), although most of them are mountainous areas; they cannot carry out functions as RBS while retaining high ecological values.

Summer in Korea is characterized by hot and humid weather with a lot of rain due to the monsoon. The annual average precipitation of the A1 watershed for the past decade (1997–2006) was 1390 mm/yr, and 70% of the rainfall occurs from June to August (Fig. 2). The average monthly changes in the water quality of Han River as the main stream of the Al watershed were studied to determine the relationship between the precipitation patterns and diffuse of non-point pollution. Fig. 3 shows the pattern of average monthly change in water quality of 1998 and 2003 as measured in the adjacent area of the pilot RBS in the lower reaches of the A1 watershed. In comparing Figs. 2 and 3, the precipitation and patterns of changes in the water quality of the A1 watershed were found to be consistent. The pollution level in the area increases from June to August when precipitation intensifies and use of fertilizers for farming increases considerably.

2.2. Design and implementation of the pilot RBS

The pilot RBS (37°30′ N, 127°27′ E) was constructed on the left side of Han River about 20 km from the upper reaches of Paldang Dam (Fig. 1 for the location) in 2004 spring. The soil of this area is silt loam characterized with sound drainage, where local native (dominant) plants such as pussy willows, reeds, and kuzu vines are distributed irregularly on uneven lie of the land along the riverside. At backside of the pilot, catchment area in large and small scales composed of paddy fields are distributed. But these don't influence on experimental condition and pilot in the event of natural rainfall as run off by-passes the pilot. The pilot RBS were formed along Han River in five plots depending on the kind of plant and the type of vegetation in a line. In each of 1–5 plot, grass, reed, shrub (pussy willows), mixed plant (grass-shrub; pussy willows), and

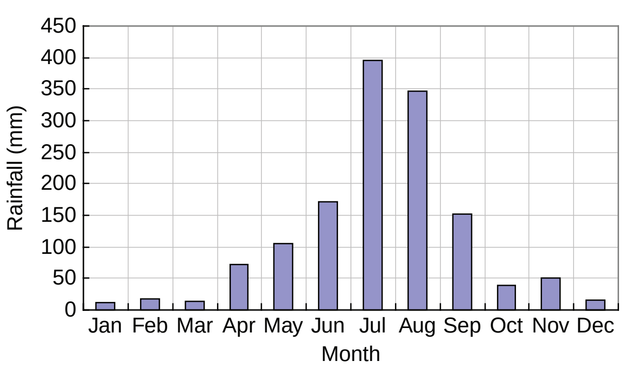

Fig. 2. Changes in the average monthly precipitation in the A1 watershed for the past decade (1997–2006).

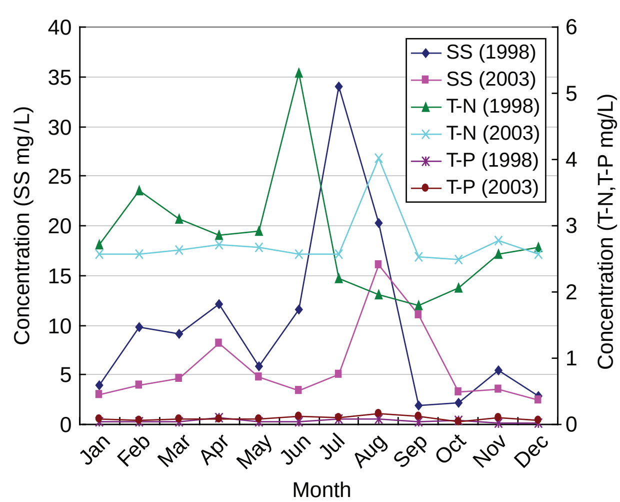

Fig. 3. Monthly changes in density of non-point pollutants in the A1 watershed (1998 and 2003).

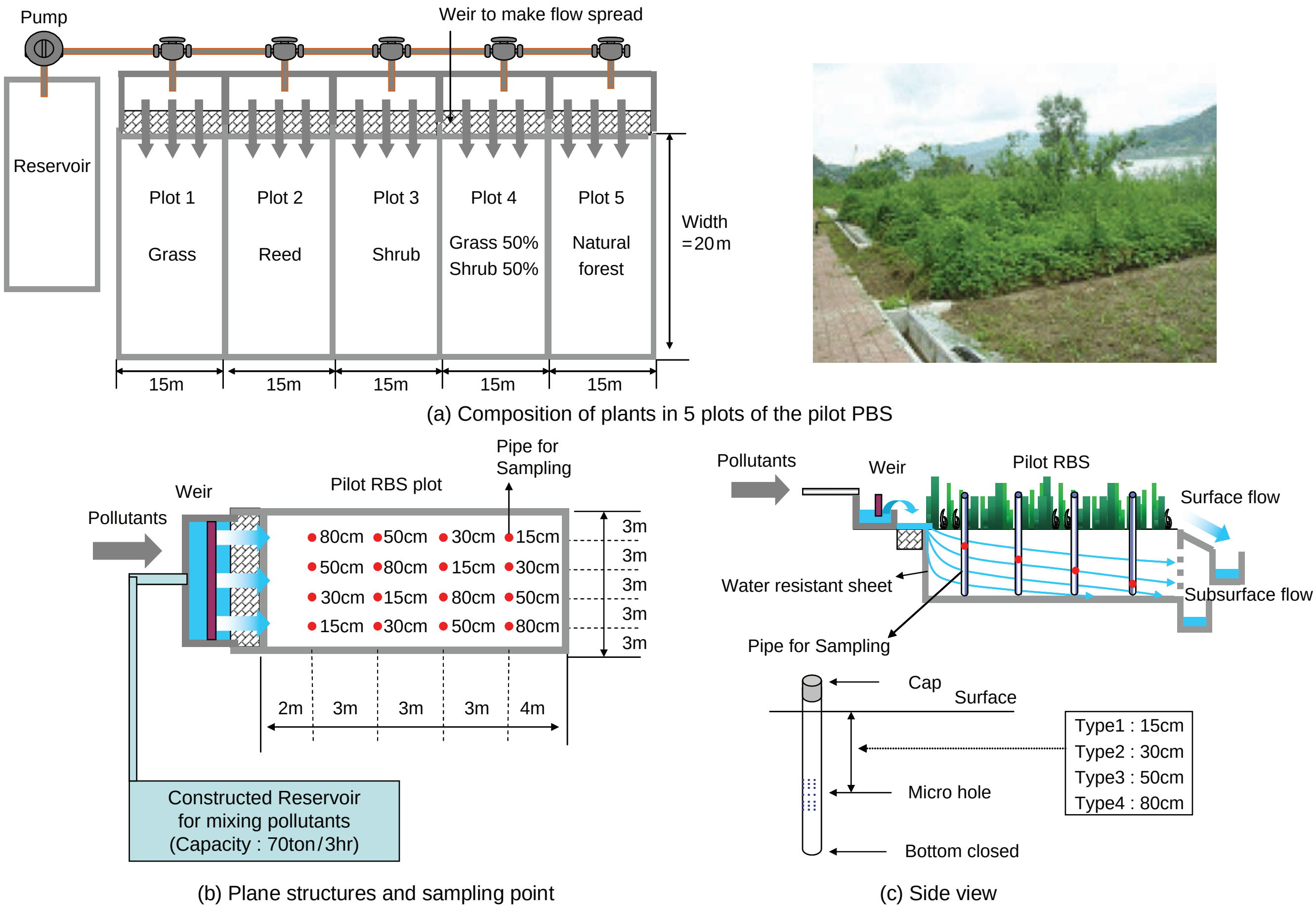

Fig. 4. Composition, scale, and structure of the pilot RBS.

natural plant were planted in order (Fig. 4(a)). In selecting the plant, dominant plant in that region was used in order for stable survival and effective management. The size of each plot was 15 m long × 20 m wide, where the following preparations were carried out before vegetation. In order to prevent any influence of surface flow and subsurface flow in the event of artificial runoff of the other plot, the level of ground surface between each plot was heightened to 20 cm, and 3 mm thick PE water resistant sheet was laid on the bottom 1 m underground of each plot and the side from 1 m underground boundary between plots to 0.2 m level above ground, except natural plot. In addition, the ground surface that was uneven with the average slope in 8% was flattened and changed into 5% slope before vegetation (except natural plot). At the side of plot, the reservoir with water resistant sheet in 70m^3 scale laid on was installed to control artificial run-off supply and artificial pollution concentration, and the underwater motor (1.5 HP) was installed at the bottom of reservoir to keep on mix artificial fertilizers. Above each plot, U-type flume pipe and weir were installed horizontally so that artificial run-off is supplied and spread evenly on the plot. In order for sediment, T, and P to be effectively removed from VFS, surface runoff should be spread in slow and uniform manner [9]. artificial run-off was arranged to be independently supplied to each plot through 50 mm diameter PE pipe from reservoir by electric pump (3 HP) so that the volume of supply can be controlled by regulator. After such civil engineering works are done, the plants were vegetated on four plots except natural plot. In the case of grass, the patch already grown up was moved from the other area, while in the case of reed and shrub (pussy willows), approx. 1 m high young plants were moved from the neighborhood. Plot 4 (grass-shrub mixed) was composed of grass at upper area for 6 m, pussy willows at central area for 10 m, and grass at lower area for 4 m again. And then, the pipe for sampling to collect specimen was laid at the spots of 2, 5,

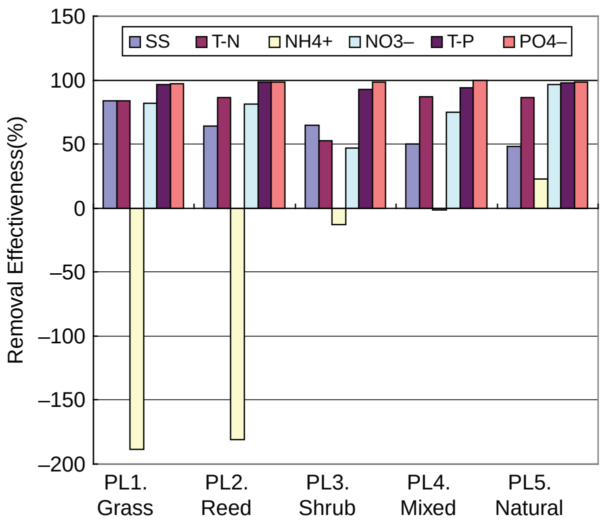

Fig. 5. Pilot RBS' pollution removal efficiency for each plot pilot (within width of 11 m).

8, 11, and 15 m of each plot in the width direction with 3m interval in the length direction (Fig. 4(b)). The pipe for sampling has micro hole at the spot of 15, 30, 50, and 80 cm from the surface to the ground by four types to collect the runoff infiltrated to the soil by depths (Fig. 4(c)). Experiments in full scale were advanced from June 2006 when the summer starts and the vegetated plants grew to some degree. At this time the height of reed was approx. 2m, while pussy willows was 1.5m high with branches grown in abundance. As for the vegetation density, natural plot was most abundant, herbaceous and woody plant on which already grew for 10 years or more in natural condition. Until the vegetated plant survives to some extent at initial stage, the weeds such as reed and kuzu vines were periodically removed. In reed plot only kuzu vines were removed while nothing was removed in natural plot. After vegetated plants grew to some degree, the weeds such as kuzu vines didn't appear, possibly because vegetated plants were the dominant plant in that area. Furthermore, these were typical riverine plant and not necessary to have separate care except the removal of weeds for experiment, and were characterized with fast-growing and strong viability.

2.3. Experiment and analysis

In this experiment, artificial run-off simulation and artificial fertilizer were used to find out pollutant removal effectiveness of the plot in stable and quantitative manner. As for the rainfall condition, water prepared in reservoir was flown to the plot for 3 hat 13 ton h^{-1} assuming that it rains 20mm for 3 h on 2,000m^2 paddy field being spread to RBS. For the rainfall frequency in this area, 70% of rainfall events during the period of 1997–2006 showed 15–20 mm d^{-1}. Pollutant concentration of artificial run-off was controlled so that they can be within 40–112, 10–40, and 5–15 mg L^{-1} for SS, T-N, and T-P respectively, and artificial fertilizer was used to control such concentration. This range of concentration is the result from several measurements of the concentration of pollutants contained in runoff at the time of summer rainfall in the catchment area composed of the paddy fields in this area. On the other hand, the subject items of measurement such as SS, T-N, and T-P are the major pollutants that fall under the standard discharged water quality in Korea. As for specimen sampling, influent water was collected from wier, while effluent water from each pipe for sampling and its ground surface respectively, which were transported under cold storage condition in 1 L polyethylene bottle, and then analyzed. The analysis was made for SS using vacuum filtration (glass fiber filters, GF/C), for T-N using Ultraviolet spectrophotometric screening method (SHIMADZU, UV-1601 PC), for NH_4^+ and NO_3^- using Ion Chromatograph (Metrohm, 792 Basic IC), for T-P using Ascorbic Acid Method (SHIMADZU, UV-1601 PC), and for PO_4^- using Ion Chromatograph (Metrohm, 792 Basic IC). Ion Chromatograph was adopted in the case where the amount of sampling was small.

3. Results and discussion

Experimental condition was well maintained where the concentration of pollutants inlet to five plots were 57.357–113.258mg L^{-1}, 13.5–24.813mg L^{-1}, 0.534–8.375mg L^{-1}, 0.084–0.298mg L^{-1}, 2.959–12.943mg L^{-1}, and1.64–5.13 mg L^{-1} for SS, T-N, NH_4^+, NO_3^-, T-P, and PO_4^-. Moreover, Tables 3–6 summarize the analysis on concentration and removal efficiency of pollutants by width and depth.

As result of experimental analysis, pollutant removal effectiveness of pilot RBS proved to be excellent in general (Fig. 5). In the width 11 m, removal effectiveness of pilot RBS for six pollutants (SS, T-N, NH_4^+, NO_3^-, T-P, PO_4^-) was 57% on average in total. They were 62, 79, –72, 76, 96, and 98% respectively by pollutants showing best removal effect for PO_4^- while least for NH_4^+. On the other hand, the ability of removing pollutant in the case of five pilot RBS were 43, 41, 57, 67, and 75% showing best in natural plot, while lease in reed plot. The average deviation of removal effectiveness between plots was –14 –18 showing significant level. The removal efficiency of pilot RBS against only three categories (SS, T-N, T-P) was 79% on average where removal ratio of 1–5 plot were 88, 83, 70, 77, and 77% respectively where grass was the highest while shrub was the lowest. Average deviation of reduction efficiency between plots was –7 to 9 showing no significant level.

The reason that the average removal effectiveness of 6 categories was shown lower by 22% than that

Table 2
Experimental conditions.

Analyzed Items	SS, T-N, NH_4^+, NO_3^-, T-P, PO_4^-
Range of input concentration	SS: 40–112mg L^{-1} T-N: 10–40mg L^{-1} T-P: 5–15mg L^{-1}
Flowing flux	13 metric tons/h/plot × 3 h
Condition (Scenario)	20mm 3 h^{-1} in 2,000m^2 catchment area
Sampling point	Width: 2m, 5m, 8m, 11m, 15m, 20m Depth: 15cm, 30cm, 50cm, 80cm

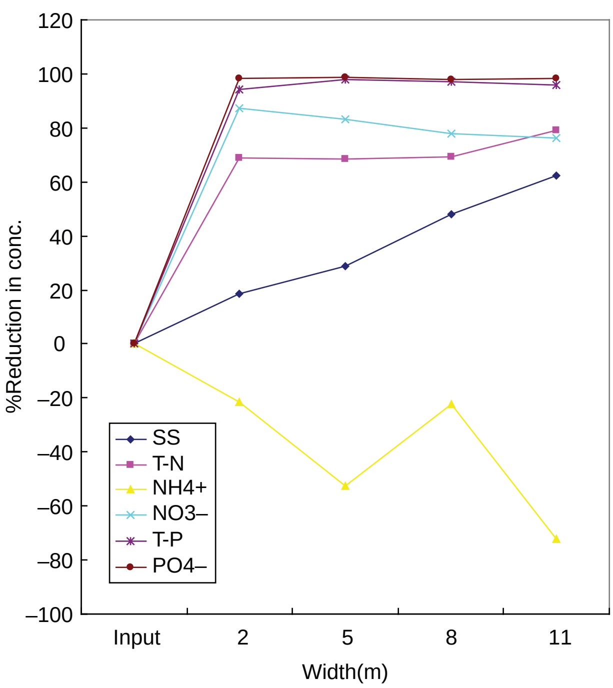

Fig. 6. Changes in removal efficiency (%) by pollutants based on the increase in the RBS width.

of 3 categories is low removal effectiveness of ion compound. In the width 11 m, the removal effectiveness of ion compound (NH_4^+, NO_3^-, PO_4^-) showed 34% on average. The removal ratio of 1–5 plot showed –3, 0, 44, 58, and 73% respectively representing highest level in natural while lowest in grass. The average deviation of reduction efficiency between plots was –37 to 39 showing highly significant level.

3.1. Removal effects according to the width of RBS

In the 20 m wide pilot RBS, the pollutant removal effectiveness tended to improve as the width rises to 2, 5, 8, and 11 m gradually. Only from the width 15 m, the amount of sampling is small or none in part, and therefore the tendency in 15 and 20 m was not extracted. First of all, the overall tendency of SS, T-N, NH_4^+, NO_3^-, T-P, and PO_4^- removal effectiveness following the increased width of pilot RBS is as shown in the Fig. 6, which well represents the characteristics by pollutants. In this case, SS reduction efficiency improved in proportion with the increase of width the tendency of which was stable and distinct. In the case of T-N and T-P, the reduction efficiency was high (69, 94%) at the width 2m respectively, but improved in remarkably small range or even fell in the width 2–11m. In ion compound, however, NH_4^+ removal effectiveness rather fell as the width increased, while NO_3^- and PO_4^- removal effectiveness showed similar tendency to those of T-N and T-P. Exceptionally NO_3^- removal effectiveness showed decreasing tendency from the width 2 m or more. In general, SS, T-N, T-P, and PO_4^- were correlated with the width but less correlation was shown in NH_4^+ and NO_3^- that is ion compound of N.

Generally major reduction mechanism for sediment and nutrient of RBS (VFS) consists of infiltration, deposition, adsorption, and absorption. This mechanism may differ in each reaction depending on RBS (VFS) condition, and a certain mechanism could be specially effective for a certain pollutant. The analysis was made against the characteristic and difference of pollutant reduction in 1–5 plot having different characteristics in their vegetation and the results are as follow (Fig. 7);

In the case of SS, it showed most stable and consistent removal effectiveness as the width increase in all plots, which is because of the property of SS that depends on physical reduction mechanism. Removal effectiveness was shown at highest level (84%) in grass plot while lowest (48%) in natural plot. Grass, among five plots, had the highest surface vegetation density, which is due to the fact the filtering mechanism by soil is well advanced as it effectively slows down the surface flow velocity of runoff having sediment to be deposited on the plot surface, part of them adsorbed on the plant surface, and the remainder infiltrated to the subsurface. On the contrary, low removal effectiveness of natural plot is deemed to be caused by topographic problem of natural plot rather than reduction mechanism. This plot was preserved in its original feature when pilot RBS was formed, and therefore its topography and surface are more or less irregular. For this reason, it is thought that runoff surface flow spread and supplied from weir has been concentrated, resulting in insufficient contact area and staying time for the plot with the surface.

T-N reduction efficiency rapidly increased in all plots in the width 2m but slightly increased from its excessive width. In the width 2m, the reduction efficiency of grass, reed, and natural plot was 82, 88, and 90% showing significantly higher than shrub and mixed plot (43%).

However, in the case of removal effectiveness for NH_4^+ that is ion compound of N in five plots they

Fig. 7. Removal effectiveness of pollutants by width of each plot. X-axis corresponds to pollutants, while the Y-axis corresponds to removal efficiency (%).

showed extreme difference by plots. In all the plots except natural, there was no removal effectiveness but it increased by maximum 188% rather than input concentration. It is possibly because organic N in part among N that is influent or contained in soil has been converted into NH_4^+, and nitrification that is 'the process NH_4^+ is converted into NO_2^- and $NO_3^{-\prime}$ has not been effectively conducted. On the other hand in natural plot there was no specific tendency as the width increased, but relatively good removal effectiveness was observed from the width 2, 5, 8, and 11 m among five plots showing 44, 35, 49, and 23% respectively. The reason is possibly due to its nitrification and absorption (plant uptake) was in relatively better condition. Nitrification condition generally includes aerobic condition and the reaction of micro-organism such as nitrosomonas and nitrobacter. The abundant roots of shrub and trees in natural plot that were 10 years or more old are deemed to have well created underground soil environment from long time before and provided the inhabitation condition of micro-fauna, and further carried out plant uptake well.

In the case of NO_3^- it showed good removal effectiveness in all the plots and its tendency of removal was similar to that of T-N showing significant reduction efficiency in the width 2m and then decreased. In general, NO_3^- shows denitrification under anaerobic condition,

Table 3
Concentration (mg L^{-1}) of pollutants by width for each plot.

Plot	Width (m)	Concentration (mg L^{-1})					
		SS	T-N	NH_4^+	NO_3^-	T-P	PO_4^-
Grass	Input	59.729	23.835	0.122	1.641	12.943	5.115
	2	40.018	4.351	0.205	0.149	0.155	0.054
	5	33.448	1.141	0.224	0.195	0.091	0.027
	8	20.308	4.378	0.192	0.243	0.591	0.259
	11	9.557	3.875	0.353	0.301	0.418	0.137
Reed	Input	83.474	24.813	0.084	1.457	10.753	4.291
	2	63.440	3.069	0.159	0.319	0.356	0.099
	5	52.589	4.560	0.195	0.313	0.203	0.086
	8	40.902	2.575	0.151	0.361	0.129	0.036
	11	30.051	3.389	0.237	0.273	0.169	0.061
Shrub	Input	57.357	13.500	0.203	0.534	2.959	1.640
	2	53.342	7.703	0.211	0.065	0.396	0.049
	5	49.327	7.020	0.297	0.212	0.154	0.032
	8	29.826	8.255	0.242	0.294	0.179	0.049
	11	20.075	6.418	0.230	0.283	0.221	0.027
Mixed	Input	113.258	15.694	0.159	0.846	9.954	5.130
	2	91.739	8.996	0.147	0.141	0.581	0.035
	5	81.546	9.635	0.220	0.058	0.067	0.027
	8	62.292	8.783	0.168	0.101	0.055	0.023
	11	56.629	2.011	0.161	0.213	0.616	0.022
Natural	Input	84.342	24.760	0.298	8.375	8.003	4.445
	2	76.751	2.576	0.166	0.329	0.346	0.099
	5	66.630	5.100	0.192	0.306	0.191	0.080
	8	59.039	2.074	0.151	0.361	0.129	0.036
	11	43.858	3.419	0.231	0.279	0.174	0.068

being converted into nitrous oxide (N_2O) gas or dinitrogen (N_2) gas, and are then removed from soil or converted into NH_4^+ by micro-organism.

In addition, it is absorbed (uptake) by plant, or accumulated into soil, or lost into deep soil. But NO_3^- is not adsorbed into soil. NO_3^- not removed moves through underground along the subsurface flow. If pregnant woman happens to drink such underground water, it causes Methemoglobinemia (Blue Baby Syndrome) to the fetus, or it causes eutrophication when spread into the stream. Because of these characteristics, NO_3^- is specially highlighted as environmental issue among nutrient [7].

As result of analyzing Nitrogen, insoluble N is known to be influenced by the width. Because soluble type of NH_4^+ and NO_3^- didn't show a certain tendency as the width increased but T-N containing insoluble N showed somewhat increasing tendency of removal effectiveness.

On the other hand, plant uptake reactions as well as the reaction within soil (nitrification, denitrification) contribute to soluble N removal to some degree, which was known from the comparison of NO_3^- and NH_4^+ removal tendencies by plots. NO_3^- was well removed in all the plots but NH_4^+ was removed in natural plot only and rather increased in the other plots. In view that five plots had all the same soil and they showed good NO_3^- removal effectiveness, it is deemed that denitrification rather than nitrification more actively occurred in underground soil layer of all the plots. Therefore excellent NH_4^+ removal effectiveness of natural plot can be explained from active uptake effect of abundant plant roots. This study did not analyze plant uptake separately but according to the precedent study [10, 16] it reported uptake ratio of plant against nutrient; 15–22% for N, 13% for nitrogen ammonia (NH_4^+), –9% for nitrate-nitrite (NO_2^-, NO_3^-), and approximately 2.5% for P.

In the case of Phosphorus, however, it was removed in 90% or more in all the plots representing significantly high level of removal effectiveness. Such effect was shown in the width 2 m of all the plots, where the change in the effect was minimal in spite of the increased width. The average removal rate for T-P, PO_4^- in five plots was 96, and 98% respectively showing higher ratio of ion compound. Difference of reduction efficiency between plots was maximum 6 and 1% only respectively for T-P, and PO_4^-.

In general, Phosphorus is one of essential components required for plant together with N and K. In

Table 4
Pollution removal efficiency (%) by width for each plot.

Plot	Width (m)	% Reduction in concentration							
		SS	T-N	NH_4^+	NO_3^-	T-P	PO_4^-	Ave. (all)	Ave. (S,T,P)
Grass	Input								
	2	33	82	–67	91	99	99	56	71
	5	44	95	–83	88	99	99	57	80
	8	66	82	–57	85	95	95	61	81
	11	84	84	–188	82	97	97	43	88
Reed	Input								
	2	24	88	–88	78	97	98	49	69
	5	37	82	–131	79	98	98	44	72
	8	51	90	–79	75	99	99	56	80
	11	64	86	–181	81	98	99	41	83
Shrub	Input								
	2	7	43	–4	88	87	97	53	46
	5	14	48	–46	60	95	98	45	52
	8	48	39	–19	45	94	97	51	60
	11	65	52	–13	47	93	98	57	70
Mixed	Input								
	2	19	43	7	83	94	99	58	52
	5	28	39	–38	93	99	99	53	55
	8	45	44	–6	88	99	100	62	63
	11	50	87	–2	75	94	100	67	77
Natural	Input								
	2	9	90	44	96	96	98	72	65
	5	21	79	35	96	98	98	71	66
	8	30	92	49	96	98	99	77	73
	11	48	86	23	97	98	98	75	77
Ave. all	Input	0	0	0	0	0	0		
	2	18	69	–22	87	94	98	58	61
	5	29	69	–52	83	98	99	54	65
	8	48	69	–22	78	97	98	61	71
	11	62	79	–72	76	96	98	57	79

addition, it is well combined with soil and sediment, and therefore not moved by leaching normally. Phosphorus also contributes to neutrophication, but neutrophication of surface water caused by phosphorus contained in water is often highlighted as environment problem rather than underground water polluted by phosphorus. It is deemed that such characteristic of phosphorus resulted in the highest removal effectiveness out of the pollutants in this experiment.

On the other hand, for SS that showed most distinctive removal effectiveness as the width increased, the expected removal effectiveness for the width of more than 11m was estimated. For this estimation, formula and tendency line was derived using the experiment data up to the width 2–11m. Fig. 8 (a) is the result of the straight line equation being applied, the gradient indicates the increase of efficiency following the increase of width, and R^2 means the stability of the equation. The degree of increase in efficiency was estimated to be 6.9 (highest) for shrub and 5.8 (second highest) for grass. In the actual width 2–11m, the highest removal efficiency was shown in grass, but with this equation applied to grass plot, it could be estimated that 99% of SS is removed in the width 14m while reduction efficiency is higher in the width 28m and up in the case of shrub plot. In the meantime R^2 value was shown as 0.9998, 0.9849 for reed, grass respectively representing the equation to be relatively stable. This is the estimation only. As there exist a number of variables in fact, it should be verified through actual experiments. For references, the result of other precedent studies show limitation in the improvement of width as per the increased of width, which is caused by re-leaching of SS and occurrence of flow concentrations in general. For this reason, the equation and tendency line were derived from somewhat conservative aspect as shown from Fig. 8 (b).

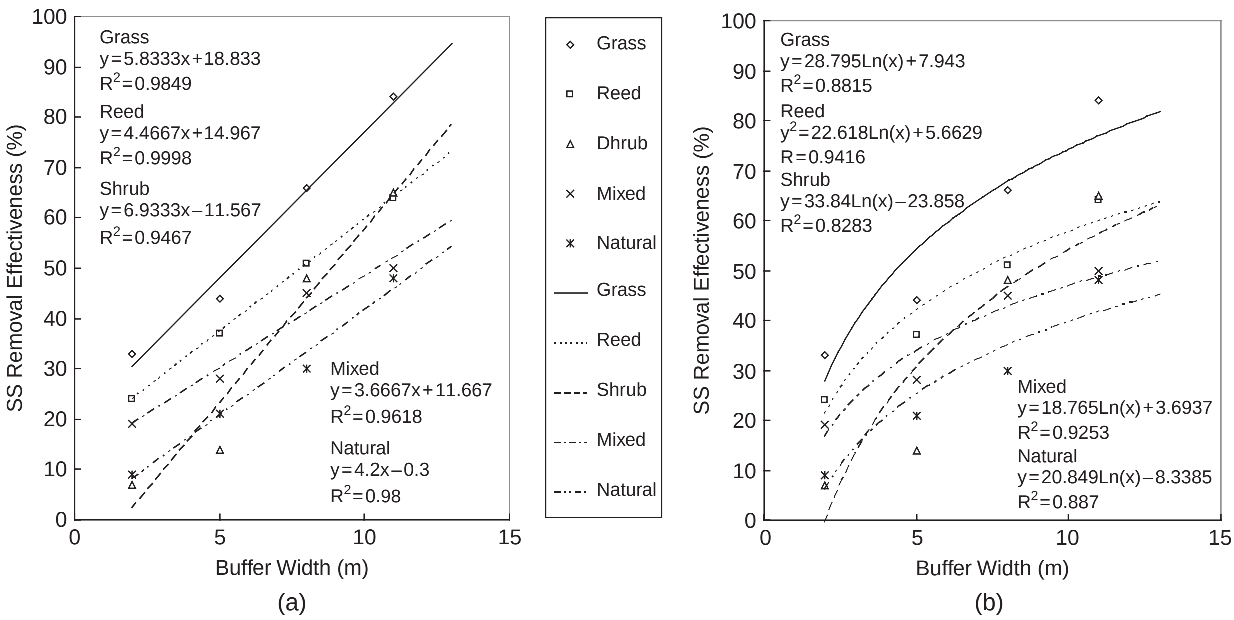

Fig. 8. Correlation between the increase in width and removal efficiency (%) of SS.

3.2 Removal effects according to the depth of RBS.

In the afore-mentioned discussion, correlation with RBS width was observed highest for SS, more or less for insoluble N and P, and lowest for ionic N and P. In the following section, nutrient removal effects and its tendency according to the depth (surface, 15, 30, 50, 80cm) will be analyzed.

Fig. 9 shows the tendency of change in nutrient reduction efficiency according to the increased depth of pilot RBS. Removal effectiveness of T-N, NO_3^-, T-P, PO_4^- except NH_4^+ appeared to significantly increase at the depth 15cm and then slowly increase as it gets deeper therefrom. The fact that removal effectiveness suddenly increased at initial stage was similar to the change by depths, but it is notable for the case of NO_3^- that removal effectiveness decreased more or less as the length increased while removal effectiveness increased as its gets deeper. This is possibly because of the condition that more activates denitrification as the soil layer below the ground surface of pilot RBS gets deeper. Because of this, NH_4^+ removal effectiveness appeared lower as it gets deeper. Removal effectiveness of phosphorus and its ion compounds that well adsorb to soil and sediment was 98 and 99% respectively at the depth 80cm showing significantly high level.

The result of comparison by plots is shown similar to overall tendency (Fig. 10). At the depth 80 cm of grass T-N, NH_4^+, NO_3^-, T-P, and PO_4^- removal effectiveness was 94, −238, 98, 99, and 100% respectively, representing very high level in general but far lower in the case of NH_4^+ as usual. Even in the case of reed, shrub, mixed plot, the tendency was shown similar although it differed a little. As shown from the change by lengths, natural plot showed high nutrient removal effectiveness showing 89, 13, 97, 98, and 99% or removal effectiveness for T-N, NH_4^+, NO_3^-, T-P, and PO_4^- at the depth 80cm.

In view of the tendency by lengths that 1–4 plots showed lower NH_4^+ removal effectiveness as it got deeper while higher NO_3^- removal effectiveness as it got deeper in all the plots, it is assumed that the underground soil of pilot RBS was under anaerobic condition, and such condition became stronger as it got deeper. Notable fact, however, is removal effectiveness for both NH_4^+ and NO_3^- was good in natural plot, but NH_4^+ removal effectiveness gradually increased as it got deeper showing 52% at the depth 30cm but started slowly falling from 50 cm again. In view that main removal mechanism for NH_4^+ is nitrification and uptake under aerobic condition, this phenomenon can be well explained. The plants in natural plot are 10 years or more old and therefore the roots are distributed deep and wide in the soil. But the vegetation in other plots is approx 3 years old only and therefore the roots are small in its depth and width compared with those in natural plot. It is thought that relatively vivid activity of plant roots might have accelerated uptake and microbial immobilization in natural plot. Especially such activity is assumed to be more active in the soil layer at the depth 30–50cm.

On the other hand, total nitrogen and phosphorus removal ratio at the surface was 16, 8% for grass respectively showing the highest level among plots. This was the

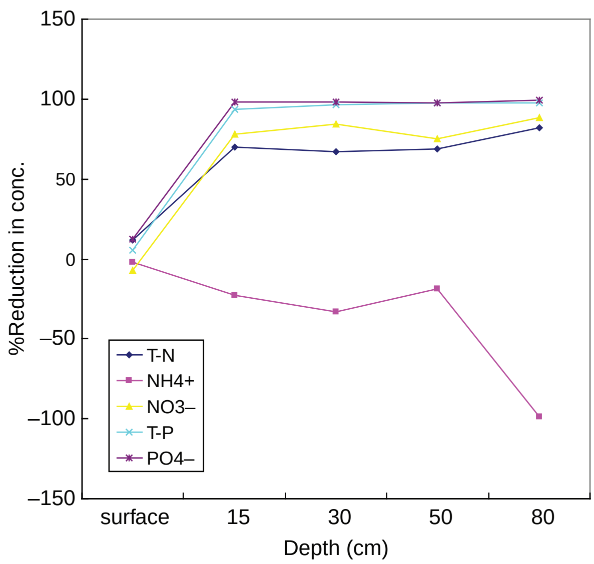

Fig. 9. Changes in removal efficiency (%) by nutrients based on the increase in the RBS depth.

result similar to the comparison by widths showing that physical mechanism also contributed to the removal of insoluble materials contained in nitrogen and phosphorus.

In the analysis by depths, notable facts were the importance of the role of micro-organism and plant roots for simultaneously removing NH_4^+ and NO_3^- because the conditions of aerobic and anaerobic conditions cannot be established concurrently at the equal depth zone as well as the importance of the infiltration into the soil for nutrient removal.

3.3. Examination of the feasibility of applying RBS in Paldang watershed

In the case of RBS, it provides excellent effect of treating SS, nitrogen, phosphorus, etc. that are non-point source pollutants, costs inexpensive, and produces good landscape, and therefore Korean government is positively promoting its introduction. Nevertheless the verification and installation standard are not enough to review its full scale introduction as wastewater treatment facility. The items specified in the standard discharged water quality include BOD, COD, SS, T-N, T-P, and count of coliform group indicating 10, 40, 10, 20, 2mg L^{-1}, and 3000 germs mL^{-1} respectively in Korea [18]. This is the standard for Paldang Watershed tested in this study that is normally applied to Water Protection Zone in Korea. Therefore this standard is stricter than that for other area. According to the result derived from this test RBS almost meets the standard discharged water quality in this area. SS was input to grass plot in the amount of 59.729mg L^{-1} but 84% was removed and then 9.557mg L^{-1} was discharged. T-N was discharged in all the plots in the amount of minimum 2.011 mg L^{-1} (mixed plot) to maximum 6.418mg L^{-1} (shrub) and T-P was also discharged in the amount of minimum 0.169mg L^{-1} (reed) to 0.616mg L^{-1} (mixed) resulting in the discharge of nutrient being sufficiently treated to the standard level or less in all the plots. Such treatment effect appeared from five types of vegetation in the soil of width 11 m, depth 0.8m. Based on the experimental results the application of RBS design can be attempted to improve the treatment effect of RBS and adopt it in actual field . That is, in RBS with the length of 20m in total, the grasses that are effective for removing SS and spreading surface flow can be planted in the upper end 10m and then woody plants that are effective for removing nutrient in the lower end 10m in combined type. The importance of woody plant lies in its roots. As result of experiment, the roots worked higher in the area where woody plants got older in abundance, and therefore the sufficient removal effectiveness can be expected when at least 3 years passed by since vegetation. Such fact was verified from the plot 5.

On the other hand, when RBS is used as water treatment facility, effective management and monitoring should be considered simultaneously. RBS is the facility in natural type taking advantage of the mechanism of soil, plant, and micro-organism. Its advantages are effectiveness in removing non point source pollutants, easier maintenance than artificial facility, and cheap cost. But it has disadvantages such as variable treatment efficiency depending on region, season or management method. Especially in winter season, it is impossible to operate or its efficiency is extremely limited. It is reported that nitrate reduction efficiency in summer and winter are 74% and 12% respectively [7]. From the aspect of management, soil efficiency drops when its pore is gradually clogged by influent sediment. In this case, it requires periodical plough for soil, and routine harvest or grazing for plant to increase nitrogen removal effectiveness [12, 19]. The result from precedent study shows that the VFS requires fertilizing or reseeding every 2 or 3 years [20]. As RBS is located along the waterside, if native dominant species can be selected it would not be difficult in growing the plant or managing them during dry season which was known from plant monitoring and management for 3 years since pilot RBS was established. Furthermore, it was also known that the removal of weeds at the beginning since vegetation is helpful for effective early growth of the plant. In addition it would be advantageous to introduce small-scale sediment pond, for example artificial (constructed) wetland at the upper end of RBS in order to reduce sediment load and prevent clogging, and weir introduction and surface flattening work could be considered to prevent concentration of surface flow and expedite its spreading, which could be known from the comparison between plot 1 and plot 5.

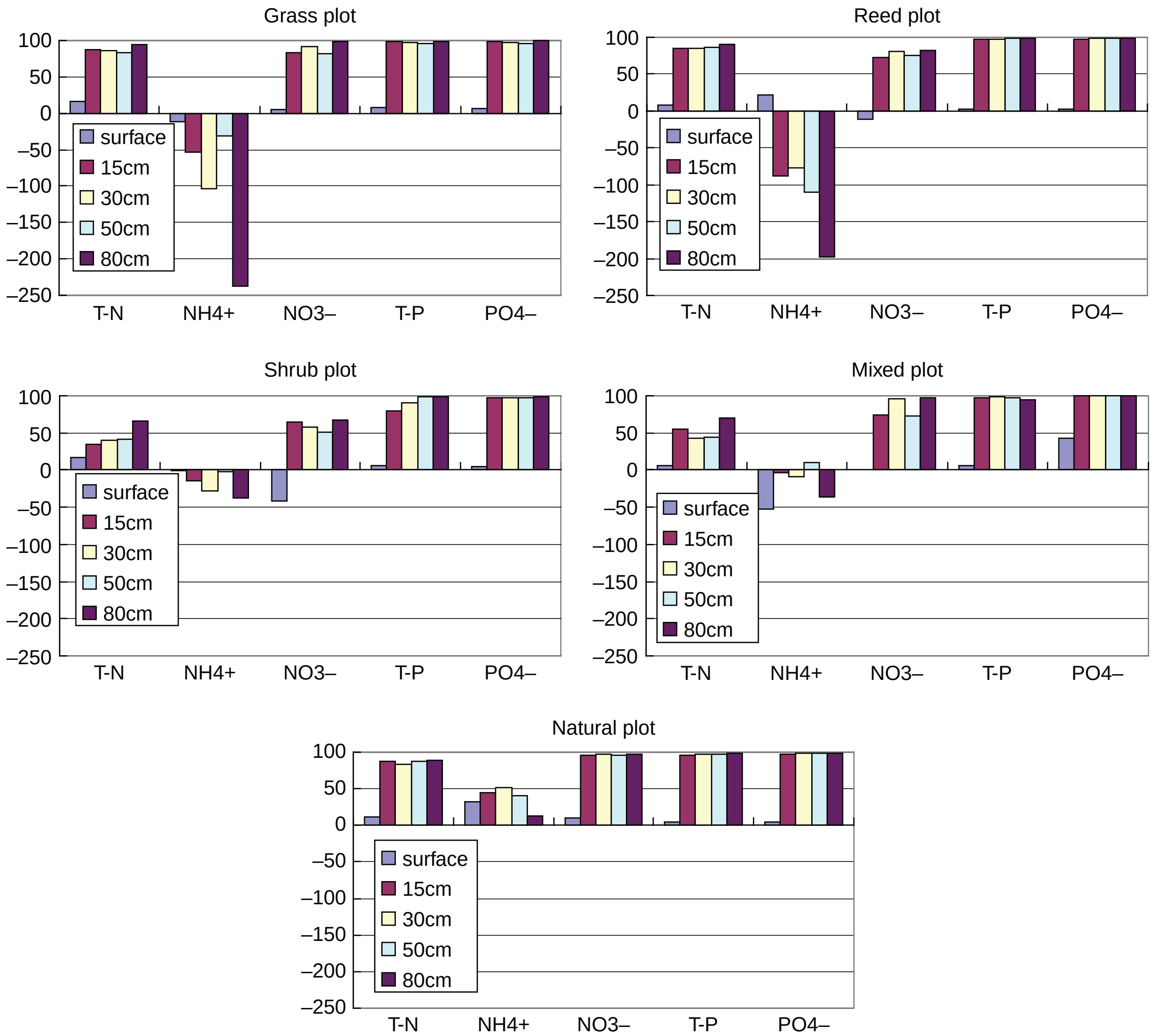

Fig. 10. Removal effectiveness of pollutants (nutrients) by depth of each plot. X-axis corresponds to pollutants (nutrients), while the Y-axis corresponds to removal efficiency (%).

Based on the afore-mentioned results, the possibility and effect was theoretically estimated if it can be applied to Paldang Watershed as follow;

The size of the five plots of RBS applied to the experiment was 300m^2 (20m width × 15m length) each, and they accounted for non-point source pollution of 2,000m^2 each (rice paddies) in the most regular condition of the target area. Nevertheless effective performance was shown in the width 11m, and eventually RBS was found to be able to reduce by more than average 70% of non-point source pollutants (SS, T-N, T-P) diffused from the catchment area, which is 12 times bigger than the RBS area in Paldang watershed. In the experiment, the runoff coefficient of paddies was assumed to be 1; if it is assumed to be 0.7–0.9, the catchment area that can be dealt with seems to increase. The size of agricultural land in the A1 watershed whose agricultural land was the biggest among the unit watersheds in Paldang Lake was 72,049 ha. Han River in the A1 watershed accounted for 61 km, but the length was 4,650km including a certain size of branch streams as recognized by the state. Accordingly, if RBSs are introduced on the left and right sides of all streams in the Al watershed, a total of 18,240 ha (182,400,000m^2 = 9,120,000m × 20m width) RBSs can be created. Calculating by the proportion of area, agricultural land (paddies) (72,049 ha)/ RBSs (18,240 ha) = 4. The area load that can be treated by RBS (paddies ha / RBS 1 ha) was 12 in the experiment; if RBS is applied

Table 5
Concentration (mg L^{-1}) of pollutants by depth for each plot.

Plot	Depth (cm)	Concentration (mg L^{-1})				
		T–N	NH_4^+	NO_3^-	T–P	PO_4^-
Grass	Input	23.835	0.122	1.641	12.943	5.115
	surface	20.013	0.137	1.565	11.885	4.794
	15	3.140	0.188	0.275	0.224	0.068
	30	3.163	0.248	0.139	0.339	0.140
	50	3.912	0.160	0.295	0.490	0.245
	80	1.468	0.413	0.029	0.124	0.025
Reed	Input	24.813	0.084	1.457	10.753	4.291
	surface	22.780	0.066	1.615	10.523	4.170
	15	3.894	0.158	0.393	0.307	0.101
	30	3.894	0.149	0.283	0.223	0.088
	50	3.343	0.177	0.359	0.141	0.055
	80	2.452	0.250	0.250	0.184	0.0 34
Shrub	Input	13.500	0.203	0.534	2.959	1.640
	surface	11.300	0.204	0.756	2.770	1.558
	15	8.825	0.233	0.192	0.586	0.044
	30	8.093	0.260	0.227	0.296	0.044
	50	7.920	0.207	0.260	0.039	0.045
	80	4.558	0.279	0.175	0.029	0.024
Mixed	Input	15.694	0.159	0.846	9.954	5.130
	surface	14.692	0.243	0.843	9.413	2.947
	15	6.992	0.164	0.214	0.327	0.022
	30	8.988	0.173	0.038	0.095	0.027
	50	8.706	0.143	0.233	0.302	0.035
	80	4.738	0.216	0.027	0.594	0.022
Natural	Input	24.750	0.298	8.375	8.003	4.445
	surface	22.000	0.200	7.475	7.600	4.250
	15	3.101	0.163	0.382	0.293	0.102
	30	4.227	0.143	0.281	0.212	0.085
	50	3.186	0.176	0.350	0.171	0.061
	80	2.654	0.258	0.261	0.162	0.035

to the A1 watershed, however, the area load will only be 4, and the pollutant removal effectiveness are likely to be far more than the result of the experiment. In addition, if herbaceous plant and woody plant are to be vegetated in combination, its efficiency is estimated to be improved more. This is the assumption from theoretic aspect, requiring sufficient verification in addition.

4. Conclusion

In this study, five types of pilot RBS were actually constructed in Paldang Watershed and then comparative analysis on pollutants removal effectiveness by widths and depths was made with actual precipitation and pollution conditions simulated. Based on such results, the possibility of applying them as agricultural non-point source pollutants treatment facility and its method of improvement were derived, and finally the effect was reviewed assuming that RBS would be prepared along the agricultural land and streamside of the relevant watershed. In result, the conclusion was obtained as follow:

– RBS is excellent in removing sediment and nutrient that occur in agricultural area. The results showed that SS removal efficiency was highest in grass RBS in the width 11m (84%) where its tendency as per the width was significant. T-N and T-P removal efficiency in five RBS were 86 and 98% on average respectively showing excellent level where removal efficiency was influenced by its depth.
– In order to effectively remove NH_4^+ and NO_3^- that are ion compound of nitrogen simultaneously, the role of woody plant's root, that is, uptake is very important. It is because, the result of experiment showed NH_4^+ was not removed well while NO_3^- was removed successfully, but such mechanism as nitrification and denitrification may not exist con-

Table 6
Pollution removal efficiency (%) by depth for each plot.

Plot	Depth (cm)	% Reduction in concentration						
		T-N	NH_4^+	NO_3^-	T-P	PO_4^-	Ave. (all)	Ave. (T,P)
Grass	Input							
	surface	16	–2	5	8	6	5	12
	15	87	–54	83	98	99	63	93
	30	87	–103	92	97	97	54	92
	50	84	–31	82	96	95	65	90
	80	94	–238	98	99	100	31	96
Reed	Input							
	surface	8	22	–11	2	3	5	5
	15	84	–88	73	97	98	53	91
	30	84	–77	81	98	98	57	91
	50	87	–110	75	99	99	50	93
	80	90	–197	83	98	99	35	94
Shrub	Input							
	surface	16	–0	–42	6	5	–3	11
	15	35	–15	64	80	97	52	57
	30	40	–28	58	90	97	51	65
	50	41	–2	51	99	97	57	70
	80	66	–38	67	99	99	59	83
Mixed	Input							
	surface	6	–53	0	5	43	0	6
	15	55	–3	75	97	100	65	76
	30	43	–9	95	99	99	66	71
	50	45	10	72	97	99	65	71
	80	70	–36	97	94	100	65	82
Natural	Input							
	surface	11	33	11	5	4	13	8
	15	87	45	95	96	98	84	92
	30	83	52	97	97	98	85	90
	50	87	41	96	98	99	84	92
	80	89	13	97	98	99	79	94
	Input							
Ave. all	surface	12	–2	–7	5	12	4	9
	15	70	–23	78	94	98	63	82
	30	67	–33	84	96	98	63	82
	50	69	–18	75	98	98	64	83
	80	82	–99	88	98	99	54	90

currently in the same soil environment and layer, and furthermore it is difficult to artificially control aerobic and anaerobic condition in the soil.

— To effectively remove the sediment, it is necessary to improve width, topography and surface vegetation to spread surface flow and prevent its concentration too. In the case of nutrient, it requires the consideration so that removal mechanism can be sufficiently carried out using depth, soil condition and the root of woody plant.
– RBS is of sufficient value that can be considered as a facility to treat non-point source pollutants diffused in agricultural area. In experimental result, simulated runoff passing through RBS met strict water quality standard required for discharged water of wastewater treatment plant in the relevant watershed. Nevertheless, in order to apply it to actual field, factors of seasonal restriction, influent structure of pollutant, topographic structure, etc. should be sufficiently taken into account.
– In order to improve RBS efficiency it could be considered to connect it with combined vegetation structure or other facility. In experimental result, natural forest was proved effective in removing nutrient while grass was effective in removing

sediment. Therefore combined vegetation of herbaceous and woody plant could be considered. In addition, preliminary treatment of pollution load using artificial (constructed) wetland, and improvement of flow structure through weir installation could be considered.

– Assuming RBS installation on the side of all streams at Paldang Watershed, theoretically it is expected to remove at least 79% of non-point source pollutants in agricultural area. The ground of this estimation is that experimental results showed SS, T-N, and T-P removal efficiency on average was 79%, and the load of the treated area of the watershed applied to the assumption reaches 1/3 of the load of tested area only.

In sum, the creation of RBS in the upper reaches of Paldang Dam in the watershed of Han River appeared very feasible as a sustainable and effective method of reducing non-point source pollutants with sufficient effects. Future study should focus on seasonal variations with a longer-term observation.

Acknowledgments

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