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Development of a Multifunctional Design Concept to Improve Constructed Wetland Performance

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인공습지의 성능향상을 위한 다기능 설계기법 개발

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Abstract

Constructed wetlands (CWs) are widely used to solve water quality problems caused by diffuse pollution from agricultural areas; however, phytoplankton blooms in CW systems can occur due to long hydraulic retention time (HRT), high nutrient loading, and exposure to sunlight. This study was conducted to evaluate the efficiency of a CW designed to treat agricultural diffuse pollution and develop a design concept to improve the nature-based capabilities of the system. Monitoring was conducted to assess contribution of individual wetland components (i.e. water, sediments, and plants) in the treatment performance of the system. During dry days, the turbidity and particulates concentration in the CW increased by 80 to 197% and 10 to 87%, respectively, due to the excessive growth of phytoplankton. On storm events, the concentration of particulates, organics, and nutrients were reduced by 43% to 70%, 22% to 49%, and 15% to 69% due to adequate water circulation and constant flushing of pollutants in the system. Based on the results, adequate water circulation is necessary to improve the performance of the CW. Free water surface CWs are usually designed to have a constant water level; however, the climate in South Korea is characterized by distinct dry and rainy seasons, which may not be suitable for this conventional design. This study presented a concept of multifunctional design in order to solve current CW design problems and improve the flood control, water quality management, and environmental functions of the facility.

Key words : Constructed wetland design; macrophytes; nature-based solution; sediments; water quality

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요 약

농업비점오염에 의한 수질문제 해결을 위하여 인공습지 조성이 늘어나고 있으나 긴 체류시간과 긴 일조량 등으로 인하여 습지내 조류 발생 등의 문제가 지속적으로 발생하고 있다. 본 연구는 농업 비점오염원관리를 위하여 조성된 인공습지의 효율을 평가하여 자연기반 능력이 향상된 고도화된 인공습지 개선방안을 제시하고자 수행되었다. 인공습지의 성능평가는 구성성분(물, 퇴적물 및 식물)의 모니터링을 통해 구성성분이 시스템의 처리 성능에 주는 기여도 평가를 통해 수행되었다. 건기시에는 식물성 플랑크톤의 과다성장, 긴 체류시간 및 일조량 과다로 습지내 탁도 및 미립자 농도가 각각 80~197 % 및 10~ 87 % 정도 증가하는 것으로 나타났다. 그러나 강우시에는 습지내 적절한 물 순환과 지속적인 물 흐름으로 미립자, 유기물 및 영양분의 농도가 43 ~ 70 %, 22 ~ 49 %, 15 ~ 69 % 정도 감소하는 것으로 나타났다. 이러한 연구결과로 볼 때 인공습지가 가진 문제해결을 위해서는 자연습지가 가진 안정적 물 흐름이 필요하다는 것을 알수 있다. 그러나 일정수심을 유지하도록 되어있는 인공습지 설계기준은 건기와 강우기가 뚜렷하게 나타나는 한국적 기후상황에 타당하지 않다. 따라서 본 연구에서는 인공습지가 가진 문제를 해결하고 홍수관리, 수질 관리 및 환경 기능을 지속적으로 유지할 수 있도록 다기능 설계기법을 개념화하였다.

핵심용어 : 습지식물; 인공습지 설계; 인공습지 수질; 자연기반해법; 퇴적물

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1. Introduction

Rivers and other dynamic water bodies are capable of self-purification through the complex physicochemical processes such as dilution, deposition, adsorption, and continuous flow. However, if input pollutant loads exceed the self-purification of receiving water bodies, ecological imbalance and water quality degradation can occur (Tian et al., 2011; Bae & Seo 2018). Agricultural areas are one of the major and consistent sources of high nutrient loadings in the environment. Agricultural systems are highly-dependent on artificial sources of nitrogen (N) due to the absence of naturally-occurring N forms necessary for crop yield and production (Ribaudo et al., 2012). Excessive N concentrations from fertilizers became one of the leading causes of groundwater contamination over the past decades (Su et al., 2013). Chemical leaching from fertilizer-infused soils pollutes groundwater, thereby posing health and environmental issues in many parts of the world. Farmlands can also be considerable sources of Phosphorus (P) loads in the environment. According to Boyd (2015), total phosphorus concentrations 0.005 mg/L to 0.05 mg/L can result to phytoplankton blooms in lakes. In agricultural landscapes, surface runoff and subsurface flow are the major pathways of P deposition in natural water bodies (King et al., 2015). Generally, nutrient-rich agricultural runoff and sediment deposits can result to eutrophication of surface water bodies. N and P fluxes from farmlands that directly discharge into streams can degrade water quality and cause excessive growth of algae and other aquatic plants (Jarvie et al., 2013; Mercado et al., 2013).

Approximately 16.4% of South Korea's total land area was designated to agriculture. Significant amounts of agrichemicals for soil enrichment and pest control are utilized by farmlands in order to sustain the massive production of agricultural products. Eutrophication is one of the most profound problems in South Korea's waterways. Algal blooms were frequently observed in some of Korea's major rivers, such as Nakdong, Geum, and Yeongsan Rivers (Tobio et al., 2012; Srivastava et al., 2015; Kim et al., 2019). Apart from large nutrient loads, agricultural areas can also be significant sources of toxic substances from agrichemicals. Heavy metals that accumulated in agricultural soils are incorporated in the natural environment through biomass exportation, leaching, and runoff (Shi et al., 2018). Exposure to toxic heavy metals affects the survivability, growth rates, and cause deformities of aquatic animals (Sfakianakis et al., 2015). Moreover, heavy metals can also accumulate in human tissues since fishes and other aquatic animals are essential parts of human diet. Generally, unmanaged runoff from agricultural areas may lead to grave environmental impacts and health concerns.

Recent developments in environmental technology exhibited progress in mitigating the effects of excessive chemical and nutrient release from agricultural areas using low impact development (LID) techniques. LID employs nature-based solutions in managing various pollution sources by providing flow attenuation functions and water treatment capabilities. One of the most commonly-used LID facilities in managing agricultural discharges is the constructed wetland (CW). CWs utilize physicochemical and biological treatment mechanisms to reduce pollutant concentrations in water (Alihan et al., 2017). The Ministry of Environment in South Korea also adopted this type of technology to reduce pollutant loads entering the natural streams (Lee et al., 2011). At present, several studies regarding the effectiveness of wetlands in stormwater management and pollution control has been established. The overall pollutant reduction capabilities and design criteria for a CW treating water from a runoff impacted stream were discussed in detail by Maniquiz et al. (2012) and Mercado et al. (2017); however, in-depth assessments of individual wetland components were not critically considered. Moreover, a multifunctional design was not yet conceptualized to improve CW processes. This study evaluated the contributory factors affecting the treatment performance of a CW by examining the vital components of the facility. A multifunctional design concept was also developed based on the assessment of the current CW design in order to optimize facility functions and operations.

2. Materials and Methods

2.1 Site Selection and Description

The CW utilized in the study is a free water surface CW located midstream of Geum River at Gongju City, South Korea. The facility was designed and operated by the Ministry of Environment to treat a portion of an intermittent stream impacted by agricultural activities. On storm events, combined stream discharge and stormwater runoff from a 465-ha catchment area composed of 73% forest, 25% agricultural, and 2% urban land use types was also redirected to the CW for treatment. The facility has a surface area of 3,282 m^2, storage volume amounting to 2,957 m^3, and a design hydraulic retention time (HRT) of 16.8 hours. The first treatment unit was consisted of a sedimentation zone intended to remove large particles by means of gravitational settling. The sedimentation zone was succeeded by winding units of shallow and deep marshes to achieve maximum HRT and reduced flow velocity. Since no mechanical intervention was incorporated in the facility design, the wetland bed was sloped gently to facilitate movement of water within each treatment zone while maintaining

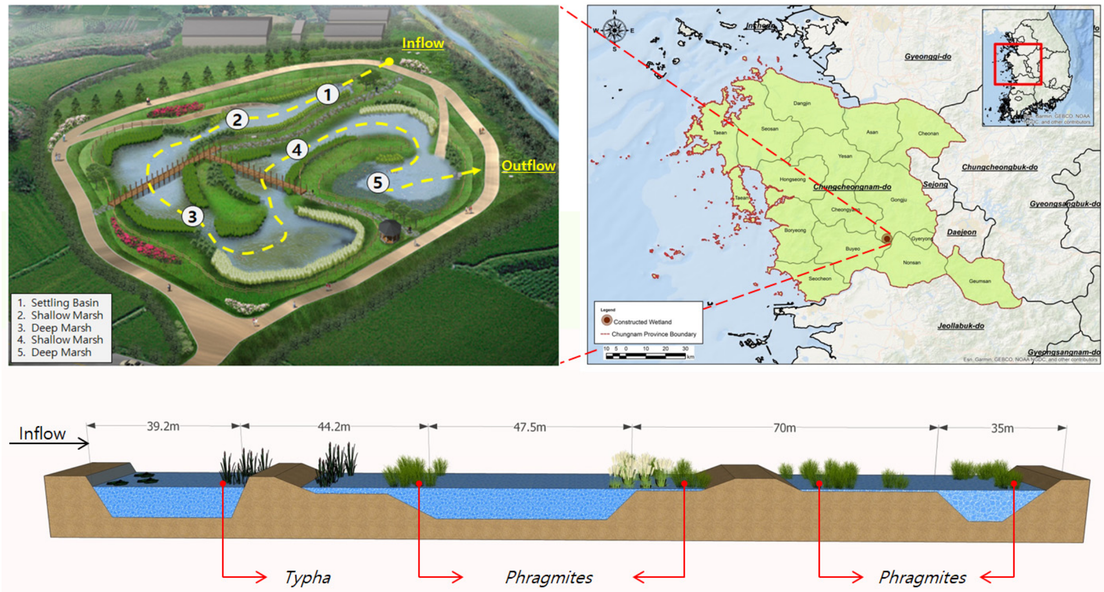

Fig. 1. Site location and schematic diagram of the CW

low flow velocity. Various emerging macrophytes native to Korea were also planted in each treatment zone of the CW. Specifically, *Typha* and *Phragmites* were the dominant macrophytes in the CW. The site location and schematic diagram of the CW with the dominant macrophyte species in each basin were illustrated in Figure 1.

2.2 Sample Collection and Analyses

A total of 28 events (11 storm events and 17 dry days) from April 2009 to June 2011 were monitored to assess the treatment performance of the CW. Water, sediment, and plant samples were collected at the different CW sections exhibited in Figure 2. Water samples were collected through manual grab sampling. During storm events, the first sample was collected after an observed increase in water level to account for the runoff delay in the catchment area. Succeeding samples were collected at 5, 10, 15, 30, and 60-minute intervals. Additional six samples were collected at an hourly interval to complete the 12 inflow and outflow samples. Turbidity was measured on-site, whereas other physico-chemical parameters such as total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP) were analyzed using the standard methods for the examination of water and wastewater prescribed by the American Public Health Association, 1990.

Undisturbed sediment samples were collected seven times throughout the monitoring period using acryl tubes (5 cm diameter and 50 cm long). Nutrients (TN and TP) and organics (COD and loss on ignition) content of CW sediments were determined using the soil sampling and methods of analyses proposed by Carter and Gregorich (2007). In order to examine the potential accumulation of heavy metals in CW sediments, inductively coupled plasma spectrometry was utilized to quantify trace concentrations of arsenic (As), cadmium, (Cd), copper

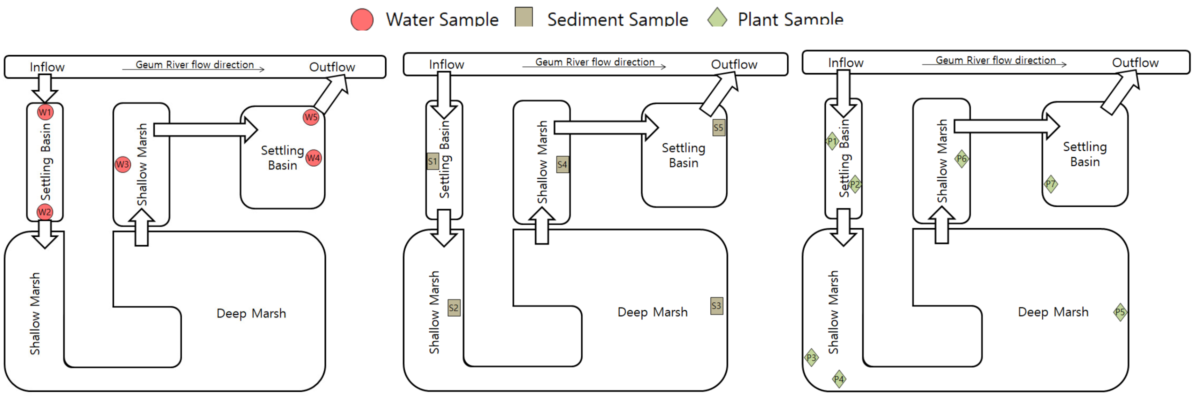

Fig. 2. Location of monitoring and sampling points in the CW

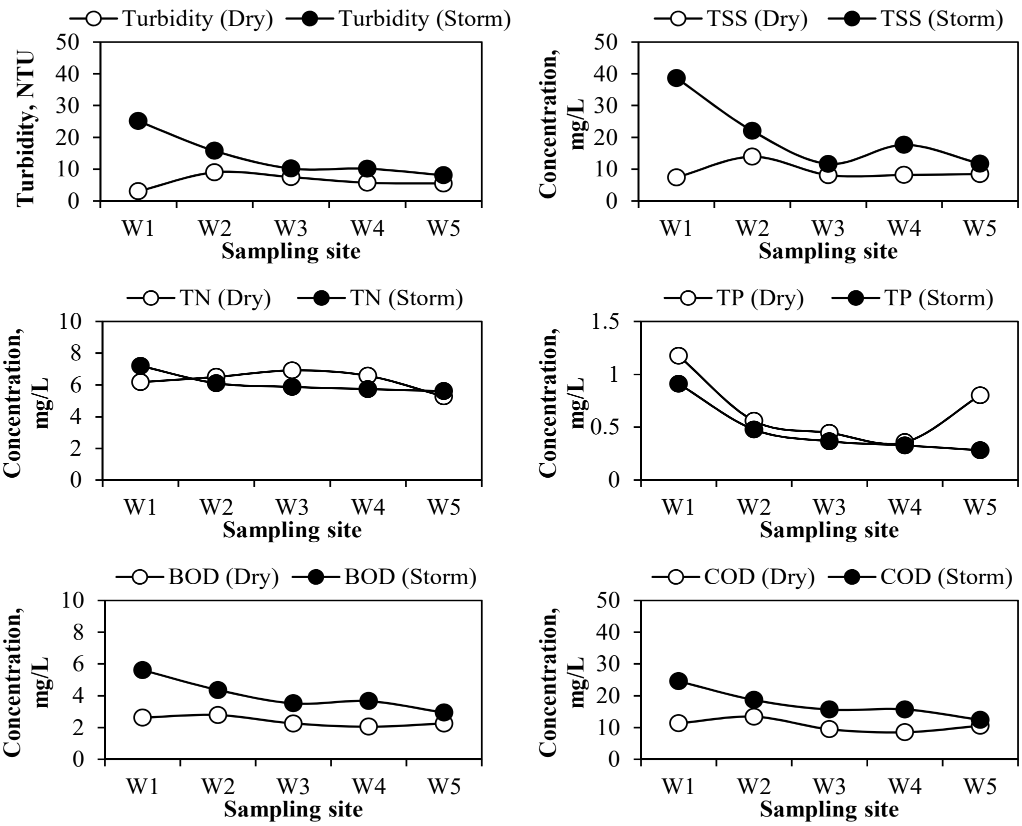

Fig. 3. Changes in pollutant concentration at different treatment zones of the CW

(Cu), chromium (Cr), mercury (Hg), and lead (Pb). Macrophytes are essential components of CWs due to their capability to enhance the treatment efficiency of the system. Biomass and height were measured periodically to determine the adaptability of different plant genera in each CW. To effectively count the number of plants per unit area and measure the biomass of plants, 30cm x 30cm cells or quadrants situated at different areas within the CWs were established. Plant samples were also collected for laboratory analyses. Representative samples were cut to ground level and oven-dried to determine the plant biomass. Kjeldahl method was used to quantify N and P concentrations in plant tissues.

3. Results and Discussion

3.1 Pollutant concentration at different treatment zones and seasonal treatment performance of the CW

The changes in pollutant concentration along the treatment zones of the CW were exhibited in Figure 2. For monitored dry day periods, the concentration of turbidity and TSS increased by 80% to 197% and 10% to 87% respectively. The largest increase in concentration was observed in the shallow marsh (W2), wherein water level is significantly decreased during periods of low streamflow. Prolonged HRT, excessive nutrient deposits, and exposure to sunlight prompted phytoplankton growth, thereby increasing the mass of suspended particles and turbidity. BOD and COD concentrations also exhibited 6% and 18% increase in W2, respectively. The process of phytoplankton decay generate labile organic matter and stimulate bacterial growth, thereby resulting to elevated BOD and COD levels in water (Mallin et al., 2015; Luo et al., 2019). Initial TP concentration was reduced by 32% to 69% after passing through different treatment zones. P compounds from agricultural areas predominantly exist in particulate form. Sedimentation mechanisms in CWs can reduce P concentrations in water through gravitational settling of sediment-bound P compounds (Johannesson et al., 2015). The removal of N in CW systems is governed by complex nitrification and denitrification processes. Continuous transformation of N compounds into particulate, soluble, and gaseous phases resulted to fluctuations in TN concentrations. Generally, the CW effluent had 15% to 32% and 7% to 14% lower mean nutrients and organics concentration as compared to the pollutant concentrations in the influent. Aside from nutrient uptake, macrophytes serve as natural substrates for microorganism responsible for nitrification and denitrification process and remineralization of P (Yan et al., 2018; Chaurand, 2019). The oxygen released in the rhizosphere of wetland plants also increases the dissolved oxygen concentration in water to aid in the biological processes of pollutant removal (Rehman et al., 2016). Due to the sparse distribution of macrophytes in the system, the CW exhibited low nutrient removal capabilities.

Storm events increase the water level in the stream, resulting to a more efficient conveyance of water from the stream into the CW. As compared to dry day efficiency, increased pollutant removal performance within the treatment zones of the CW was observed. Significant reduction ($p<0.05$) in mean TN and TP concentrations, amounting to 15% to 22% and 47% to 69%, respectively, were noted in all treatment zones. Nutrient compounds bound on sediments settled throughout the course of the CW. Removal of particulates in water consequently reduced the nutrient concentration along the system. Mean pollutant concentrations at W5 were relatively lower than the mean pollutant concentrations at W1, indicating a considerable treatment efficiency throughout the course of the CW. Mean turbidity, TSS, BOD, COD, TN, and TP concentrations were decreased from 25.10 NTU, 38.69 mg/L, 7.21 mg/L, 0.91 mg/L, 5.62 mg/L, and 24.57 mg/L to 8.07 NTU, 11.72 mg/L, 5.62 mg/L, 0.28 mg/L, 2.94 mg/L, and 12.42 mg/L, respectively in the effluent. The movement of water within the CW facilitated more efficient water treatment in the CW by preventing stagnation of water and the proliferation of algal species. Based on a study conducted by Jung et al., (2016), high flushing rate and lower hydraulic residence time can limit phytoplankton growth and density in a confined system. Despite the overall increase in the pollutant removal performance of the CW, it can be noticed that spikes in TSS, BOD, and COD concentrations occurred at W4. During dry days, most of the algae that accumulated in other treatment zones were transported in this region. Aside from increasing the turbidity and TSS, decomposition of algae can increase BOD and COD due to microbial degradation of organic matter.

3.2 Characterization and accumulation of pollutants in CW sediments

One of the major treatment mechanisms employed in CW systems is sedimentation. For large wetlands, low flow velocity and long HRT enable greater sediment deposition rates (Geranmayeh et al., 2018). Sediments are significant repositories of pollutants inside CWs; however, accumulated sediments in the wetland bed can serve as internal sources of pollution in the CW after long-term operations since pollutants tend to leach from sediments when disturbed or remobilized (Dong et al., 2013). The study conducted by Kasak et al. (2018) confirmed that P can be released in CW sediments subjected under anaerobic conditions. Heavy metals adsorbed on sediments can also be released back into the water column. Mwanyika et al. (2016) and Šíma et al. (2017) observed a considerable increase in Pb concentrations of the overlying water due to the secondary pollution from sediments. Decomposition by-products can increase the acidity of water in wetlands, which can lead to dissolution of insoluble compounds.

The pollutant concentrations in the CW sediments were illustrated in Figure 4. The mean pH of the collected samples amounted to 6.39, indicating that the sediments are acidic in nature. Application of agrichemicals, such as ammonium-based fertilizers and urea, can cause soil acidification in agricultural areas (Goulding, 2016; Zhang, 2017). Moreover, decrease in sediment pH within CW systems can occur due to respiration of microorganisms (Travaini-Lima & Sipaúba-Tavares, 2012).Sediment pH is an essential sediment characteristic that affects a wide range of functions in CW systems including removal of toxic organics, regulating soil sorption, and degradation of phenols (Reddy & D'angelo, 1997). The mean loss on ignition (LOI) and COD concentration of CW sediments were 7.21% and 15,093.87 mg/kg, respectively. LOI and COD were commonly used to indirectly measure the organic content of sediments. High LOI and COD values of sediments can have detrimental effects in water quality, since higher organic matter content may deplete oxygen in the process of microbial degradation. Mean sediment TN and TP concentrations in the CW sediments amounted to 3,165.31 mg/kg and 979.41 mg/kg, respectively. The sediments transported in the CW may contain considerable amount of nutrients and organics due to the nature of its catchment area. Agricultural soils are usually rich in organic matter, since it promotes favorable environments for crop growth and water retention (Mulligan et al., 2009). Moreover, the nutrients bound on sediments can be transported on receiving water bodies through soil erosion or wash-off from the surrounding agricultural areas.

Heavy metals in agricultural areas can be mainly sourced from agrichemicals. The mean concentrations of As, Cd, Cr, Cu, Hg, Pb, and Zn in the CW were found to be 0.14 mg/kg, 0.01 mg/kg, 0.20 mg/kg, 1.71 mg/kg, 0.01 mg/kg, 4.84 mg/kg, and 5.54 mg/kg, respectively. Cu, Pb, and Zn had the largest concentrations in sediments. These heavy metal species are usually associated with intensive fertilizer inputs in agricultural areas (Hashmi et al., 2013). Particle- and sediment-bound heavy metals from tile drainage and return flows from agricultural areas were trapped inside facility, leading to accumulation of heavy metals in the system. Apart from the profound effects of intensive use of agrichemicals, atmospheric deposition also contributed greatly in the accumulation of Pb even in the forest. In forested catchments, atmospheric deposition on the leaves of plants can

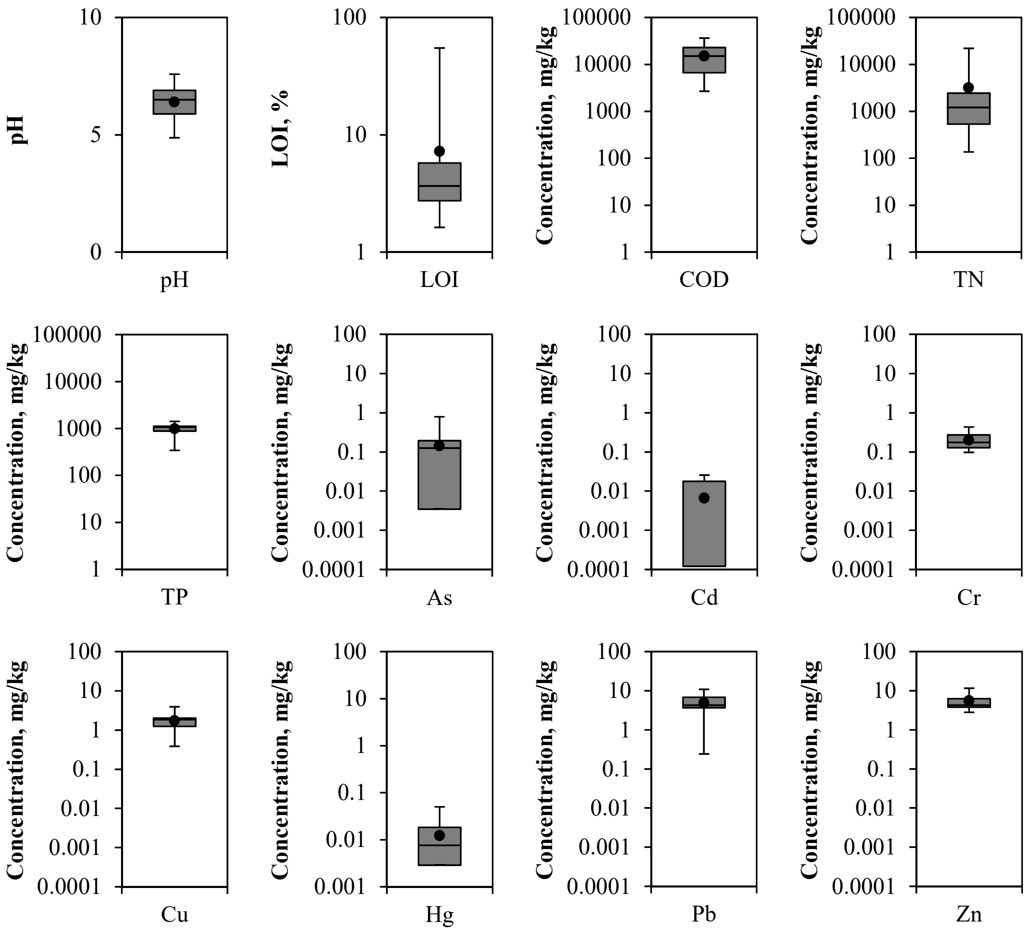

Fig. 4. Pollutant concentrations in CW sediments

be the major pathway of Pb accumulation and contamination of receiving water bodies (Zhou et al., 2019).

3.3 Growth rates and nutrient uptake capabilities of CW macrophytes

Several plant species are very sensitive to environmental conditions. CW macrophytes were selected on the bases of adaptability, nutrient uptake capability, and availability in a localized setting. The growth rates of plants in the CW were exhibited in Figure 5. The proliferation and growth rates of *Typha* and *Phragmites* were most profound during the months of late spring (May) up to the beginning of fall season (September). During this period, the maximum area covered by PJ and TA was observed to be 876 m^2 and 40.5 m^2, which corresponded to 27% and 1.23% of the CW's total surface area, respectively. In South Korea, the period from late spring, summer, and early fall seasons was defined by an abundance of rainfall and exposure to sunlight. On rainfall events, stormwater deposited significant amount of nutrients in wetland systems that are necessary for plant growth. In addition to the enhanced supply of nutrients, the average photosynthetic rate and light intensities were higher as compared to other seasons, thereby promoting environmental conditions conducive to plant growth. Despite the relative abundance during the months of highest productivity, macrophyte coverage was limited due to constraints in hydraulic loading patterns in the CW. During high flow conditions, some of the macrophyte colonies were completely submerged for extended periods of time, thus resulting to plant mortality or decay. Low flow conditions in the CW also resulted to the death of CW plants due insufficient water necessary plant growth. Generally, the CW design does not include provisions in maximizing the benefits derived from the macrophyte colonies.

One of the most significant functions of macrophytes in CWs systems is the sequestration of nutrients. N and P uptake of *Phragmites* was 86% to 48% greater than that of *Typha's*. This observation was similar to the results of the studies by Ge et al. (2017) and Dzakpasu et al. (2015) listed in Table 1. *Phragmites* also exhibited more efficient shoot growth than *Typha*. Moreover, in a study conducted by Chun and Choi (2009), proliferation and shoot growth of *Typha* was mostly associated with spring season, whereas the shoot density of

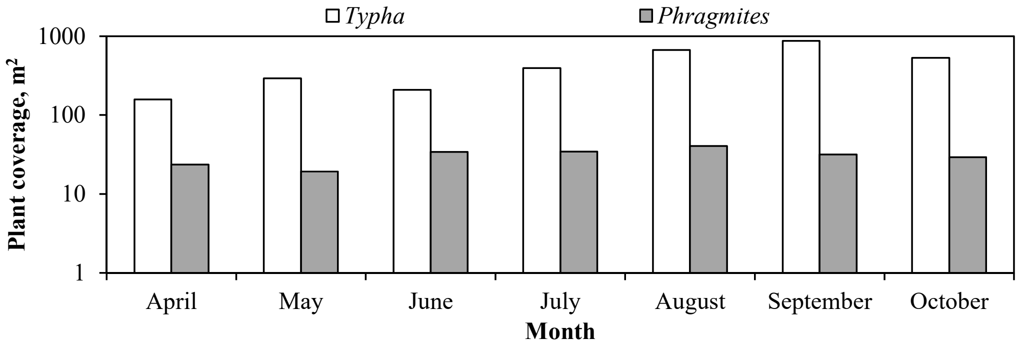

Fig. 5. Macrophyte coverage area

Table 1. Comparison of nutrient uptake of different plant species from different studies

Plant Genera	Nutrient uptake, mg/m²		Reference
	N	P	
Phragmites *Typha*	2723 378	251 129	This study
Phragmites *Typha*	62400 10200	1400 320	Ge et al., 2017
Typha	-	1290 to 2550	Emery & Perry, 1995
Phragmites	18400	5160	Vymazal & Kröpfelová, 2008
Typha	11200 to 2830	2500 to 4100	Jeke et al., 2019
Typha	46800	12500	Ulrich & Burton, 1988
Typha *Phragmites*	20800 to 37600 31700 to 79900	2500 to 4200 3000 to 7300	Dzakpasu et al., 2015
Phragmites	34000 to 74500	4000 to 7300	Zhao et al., 2013

Phragmites was not governed by seasonal flooding. As presented in Table 1, the nutrient uptake of the plants in the CW were lower than most observations on published literatures. Low nutrient uptake can be attributed to the low macrophyte coverage area and intermittent loading in the CW that limited the availability of nutrients for plants.

3.4 Multifunctional CW design

One of the main advantage of utilizing CWs for water quality management is its high flexibility in terms of design and construction. CWs can be modified or designed to achieve optimum operating conditions and significant water quality improvement. However, inadequate water circulation is a common problem in CW systems. As illustrated in Figure 6a, natural wetlands experience frequent water level fluctuations. Natural wetlands have several outfalls at varying depths which allow constant flushing of pollutants and prevent natural wetlands from developing anaerobic condition due to accumulation of pollutants in the wetland bed. Contrary to natural wetlands, free water surface CWs typically have constant water levels since the facilities were designed to have single influent and effluent ports (Figure 6b). The climate in South Korea is characterized by distinct dry and rainy seasons, which may not be suitable for this conventional design. The CW utilized in this study experienced water stagnation and developed a pond-like state during periods of low flow. Moreover, pollutant release from the sediments that accumulated on wetland bed can occur due to low water mobility or the presence of dead zones. The current CW design also provided inadequate provisions for promoting plant growth due to the limitations set by water level conditions; thus, resulting to low nutrient removal efficiency of the system. The concept of multifunctional design was developed to solve the observed problems in the current CW design. Multifunctional design will allow the CW system to provide flood control and pollution control benefits while performing ecological functions. As exhibited in Figure 6c, a CW design with varying cell depths and outlet elevations can be beneficial in optimizing the facility operation. During periods of high flow, the multifunctional CW system can effectively serve as detention ponds to attenuate flooding conditions and improve water quality. Multifunctional design also allows favorable environment for plants. Varying depths can improve denitrification and water circulation process in the CW due to the more efficient distribution of macrophytes and enhanced plant coverage (Weisner et al., 1994; Song et al., 2019). On low flow conditions, the minimum water depth

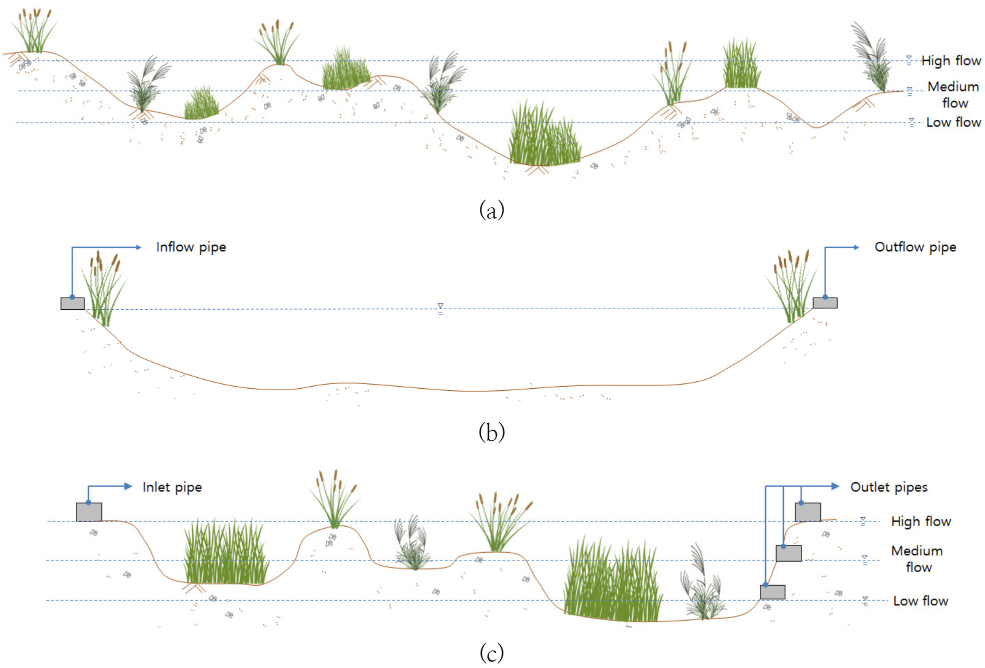

Fig. 6. Schematic representations of a) natural wetland, b) typical CW design, and c) multifunctional CW design Conclusion

required to sustain environmental flow within the system can also be maintained. Whereas the specifications (i.e. minimum water level requirement, cell size, type of macrophyte) may vary depending on the site conditions or watershed characteristics, the concept of multifunctional design can be applied to improve the overall facility performance.

Agricultural areas can contribute greatly to the amount of pollutant loads in natural streams. Improper discharge and runoff management can lead to grave impacts in the environemnt. Nature-based approaches provide effective and low-cost alternatives for treating polluted water. This study successfully evaluated the performance of a CW in reducing pollutant loads from a polluted river through an in-depth analyses of primary wetland components. During dry days, lack of inflow prompted stagnation of water and proliferation of phytoplankton in the system which resulted to 80% to 197% and 10% to 87% increase in turbidity and TSS concentrations, respectively, at different treatment zones. On the other hand, sufficient inflow on storm events prompted positive removal efficiency for particulates (43% to 70%), organics (22% to 49%), and nutrients (15% to 69%). Generally, the pollutant removal peroformance of the CW was limited by poor water circulation and low macrophyte coverage. Traces of heavy metals (0.051 mg/kg to 5.54 mg/kg), organics (15,093.87 mg/kg), and nutrients (979.41 mg/kg to 3,165.31 mg/kg) were found on the CW sediments. Pollutant-rich sediments can be transported to receiving water bodies through erosion, surface washoff, and deposition processes. Macrophytes also enhanced the nutrient removal efficiency of the system through nutrient uptake mechanisms; however, intermittent loading may limit the uptake capabilities of the plants. Based on the patterns of pollutant removal and analyses of wetland components, a multifunctional design was conceptualized to improve the flood control, water quality management, and environmental functions of the CW. Varying water levels in wetland cells and different elevation of outlet ports in the CW design can induce effective water circulation and provide a favorable environment for the biotic components of CW systems.

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