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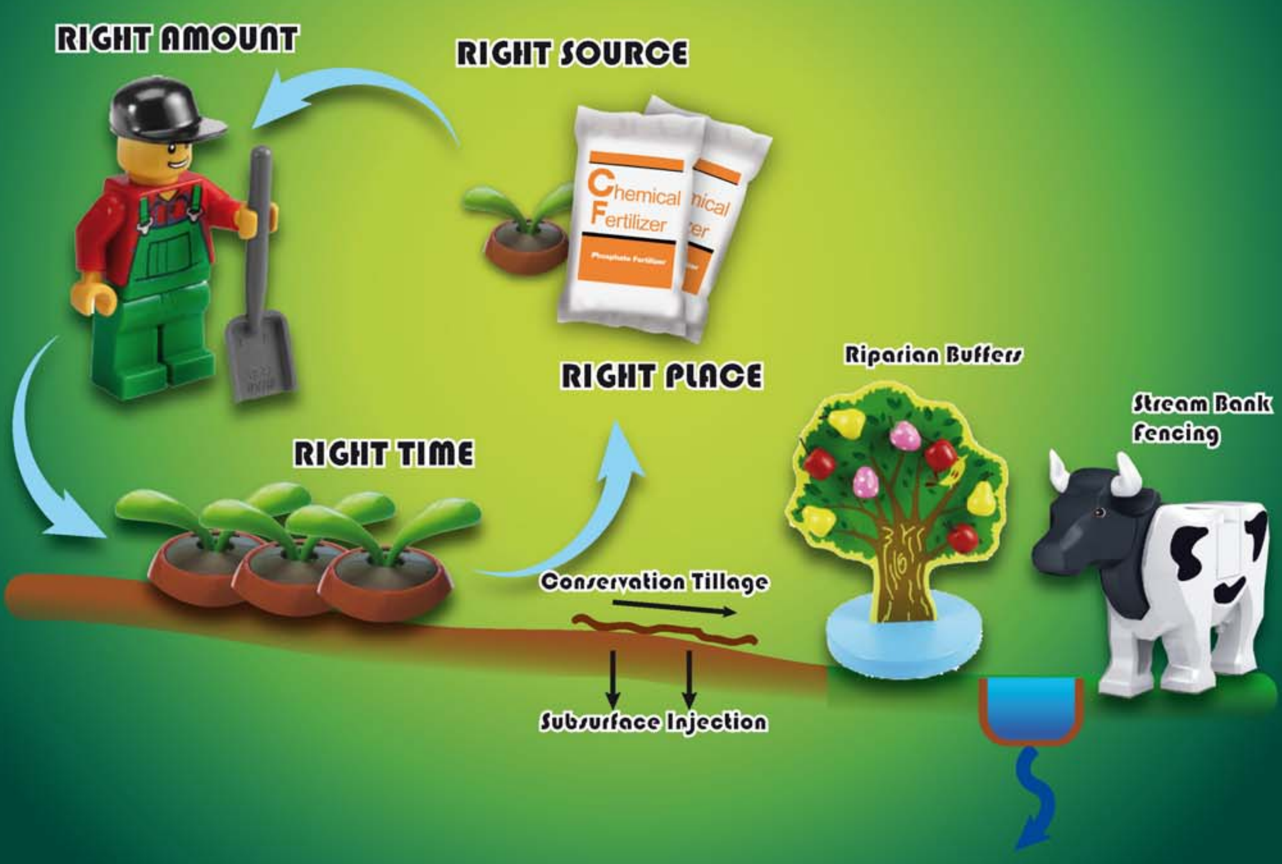

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Settling basin design in a constructed wetland using TSS removal efficiency and hydraulic retention time

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ABSTRACT

Using total suspended solid (TSS) removal efficiency and hydraulic retention time (HRT) as design parameters a design guideline of a settling basin in a constructed wetland (CW) was suggested; as well as management of sediment and particle in the settling basin. The CW was designed to treat the piggery wastewater effluent from a wastewater treatment plant during dry days and stormwater runoff from the surrounding paved area during wet days. The first settling basin (FSB) in the CW was theoretically designed with a total storage volume (TSV) of 453 m^3 and HRT of 5.5 hr. The amount of sediment and particles settled at the FSB was high due to the sedimentation and interception of plants in the CW. Dredging of sediments was performed when the retention rate at the FSB decreased to approximately 80%. Findings showed that the mean flow rate was 21.8 m^3/hr less than the designed flow rate of 82.8 m^3/hr indicating that the FSB was oversize and operated with longer HRT (20.7 hr) compared to the design HRT. An empirical model to estimate the length of the settling basin in the CW was developed as a function of HRT and desired TSS removal efficiency. Using the minimum tolerable TSS removal efficiency of 30%, the length of the FSB was estimated to be 31.2 m with 11.8 hr HRT.

Introduction

Constructed wetlands (CWs) are artificial wastewater treatment systems composed of a shallow basin filled with substrate, such as soil or gravel, and planted with vegetation tolerant of saturated soil conditions (Davis, 1995; Lazareva and Pichler, 2010). Many CW designs incorporate a sedimentation basin to trap sediments and large particulates before they enter the wetland. Wetlands act as settling basins and biological filters, can reduce turbidity, and can be used as water treatment systems. This can extend the life of the constructed wetland and ultimately enhance treatment efficiency (Kadlec and Wallace, 2009). Settling basins are suggested where space is available and construction costs are manageable. Due to the operation of a sedimentation basin, regular clean out and removal of accumulated sediment by dredging are required.

Sediment accumulation is one of the few processes in wetland treatment that has a foreseeable requirement for maintenance. More than 70% of the pollutant removal in the CW is attained because of sedimentation enhanced by long hydraulic retention time (HRT) and interception of plants. Therefore, the removal of accumulated sediments during maintenance is vital to improve the water quality in the CWs (Swash and Monhemius, 2005; Kadlec and Wallace, 2009). Sediments in the CW may accumulate over long periods and can act as new pollutant sources to the overlying water (Lijklema et al., 1993). It could uptake or release contaminants when the environmental conditions change such as pH (low or high), temperature and dissolved oxygen concentration in the water

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(Golterman, 1977; Lijklema, 1977). Sediment re-suspension or pollutant desorption may be an important source of pollutant to the water column, and this potential release is a growing concern. The characteristics of sediments, as well as overlying water quality, could affect the release rate. Numerous studies have reported several characteristics of accumulated sediment in CW such as its phosphorus storage, distribution, and associations to metals (White et al., 2000; Dunne et al., 2005; Maine et al., 2007; Lee et al., 2010).

The settling basin design has relied on empirically derived criteria such as basin overflow rate, depth, surface geometry, HRT, and weir rate (Kadlec and Wallace, 2009). These criteria were helpful for designers but are not accurate enough to permit prediction of actual settling performance. The settling basins sized at average flow conditions should be checked at extreme flow conditions (e.g., peak storm flows with recycle flows and basins out of service) to verify that operating parameters are acceptable. Degraded performance at peak flows should be considered in the design of secondary treatment processes. Design of settling basins must identify and take into account the flow characteristics of the flow stream. The settling basin functions as a pretreatment process by reducing the mass of particulate materials before entering the next process (Moshiri, 1993; Kadlec and Wallace, 2009). Knowing the characteristics of sediment is important because accumulated particles on the catchment area during dry periods are the main sources of particulate matter during a storm and are affecting as serious pollutants on the receiving waters (Tuccillo, 2006). Information about particle size distributions of sediment and water is also important to design the treatment facilities on the purpose of managing nonpoint source pollution.

This study has focused a great deal of attention on settling basin of the CW as a pretreatment process. The main objectives were to suggest a settling basin design guideline using total suspended solid (TSS) removal efficiency and HRT to effectively manage the sediment and particles in the water of the settling basin in the CW.

1. Materials and methods

1.1. Description of the first settling basin

The surface flow CW site was located in Nonsan City, South Chungcheong Province, Korea having a total surface area (TSA) of 4492 m^2, total storage volume (TSV) of 4006 m^3 and design HRT of 48 hr draining a catchment area of 110,000 m^2. The climate of the region is monsoon and temperate, and is characterized by annual rainfall of approximately 1400 mm of which more than half was concentrated during the summer season from June until August. The mean seasonal temperatures for the region were 12.0 °C in spring (March to May), 23.5 °C in summer (June to August), 13.7 °C in fall (September to November) and 0.5 °C in winter (December to February) (Lee et al., 2012). The influent water has slightly higher temperature than the ambient air temperature with temperatures of 15.8, 26.7, 20.5, and 9.8 °C for spring, summer, fall and winter, respectively (Lee et al., 2012). The CW was designed as the final stage of a wastewater treatment plant treating piggery wastewater during dry days and stormwater runoff from the paved area during wet days. The influent wastewater to the CW has average (mean ± standard deviation) concentrations of 7.9 ± 0.6, 4.2 ± 2.4, 62.2 ± 25.8, 68.7 ± 37.2, 137.7 ± 61.4, 146.2 ± 46.7, and 5.5 ± 2.1 mg/L for pH, dissolved oxygen, TSS, biochemical oxygen demand, chemical oxygen demand, total nitrogen and total phosphorus, respectively (Lee et al., 2010). Fig. 1 shows the watershed area and treatment units of the CW. The CW was composed of six cells in series starting with the first settling basin or FSB (Cell 1), followed by an aeration pond (Cell 2), deep marsh (Cell 3), shallow marsh (Cell 4), deep marsh (Cell 5) and final settling basin (Cell 6). The FSB has a TSA of 560 m^2, a TSV of 453 m^3 and an average depth of 0.8 m. The design HRT of treating wastewater from the inlet to the outlet of the FSB is approximately 5.5 hr. The FSB was planted with *Phragmites australis* surrounding the water zone. During monitoring period, the average proportion of plant coverage to surface area in FSB was 6.4%.

1.2. Monitoring method

Undisturbed sediment sample was collected at the inlet and outlet parts of the FSB since February 2009 to October 2012 using an acryl tube 5 cm in diameter and 50 cm long. Undisturbed sediment samples were separated to determine the pollutant amount in soil layer (SL) and accumulated sediment (AS) at the bottom soil layer. The depth of each sample was measured and the particle size was analyzed. Particle size distributions of sediment samples were analyzed using standard sieves and Beckman Coulter LS230 particle size analyzer (Kim et al., 2006). Undisturbed sediment samples of the FSB were air-dried and wet sieved using stainless steel test sieves of sizes of 2000, 1000, 850, 425, 250, 180, 150 and 75 μm. This procedure resulted to seven sub-sets of particle ranges 0–75, 75–150, 150–180, 180–250, 250–425, 425–850, and 850–2000 μm. Water quality samples were collected at the inlet and outlet of the FSB for TSS analysis and particle size distributions using laser diffraction particle size analyzer (Beckman Coulter LS230, International Equipment Trading Ltd., Illinois, USA) of sizes from 0 to 2000 μm.

1.3. Statistical analyses

All statistical analyses were performed using SYSTAT 9.0 and OriginPro 8 package software. One-way analysis of variance was used to analyze the difference between variance of particle size data. The difference was tested at 95% confidence level, which signifies that probability p value was less than 0.05.

2. Results and discussion

2.1. Particle size distributions of influent and effluent

The particle size distributions of size from 0 to 2000 μm for influent and effluent in the CW are summarized in Table 1. The particle size of influent and effluent showed no significant difference ($p > 0.05$). The mean particle size of influent (107.6 ± 142.7 μm) was higher than effluent particle size (39.76 ± 49.15 μm). The mean d_{50} (50% diameter) of influent and effluent were observed to be 57.65 and 24.56 μm, respectively. The findings showed that the particulate materials were decreased by sedimentation and interception of plants in the CW. The settled particulate matters decreased along the hydrologic path of settling basin (El-Sheikh et al., 2010). The complex and integrated environment of CWs provided great number of mechanisms to remove contaminants from water.

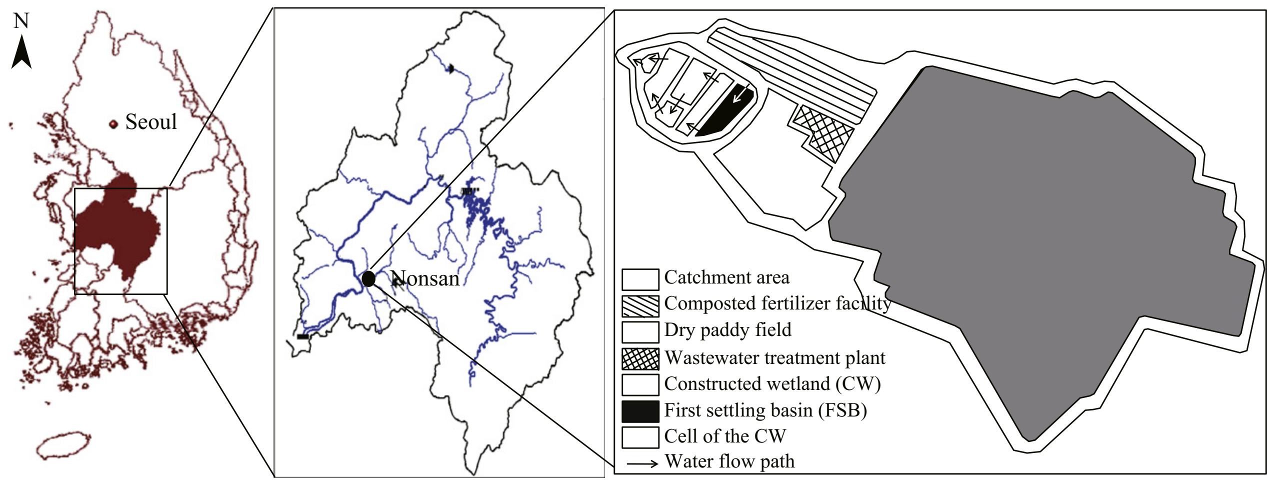

Fig. 1 – Location of study area and illustration showing the watershed area and schematic representation of the CW with water flow path.

The most important treatment process common to all wetland systems was the physical settling of suspended particulate matters such as silt or clay, or fine particles of organic and inorganic matters (Moshiri, 1993). These pollutants were adsorbed into the sediments that accumulated at the bottom of the wetland.

2.2. Particle size distribution of sediment at the first settling basin

Fig. 2 shows the cumulative particle size volumes of SL and AS at the bottom soil layer of the FSB. Comparing the results of AS and SL particles, the amount of fine particles in AS were greater than SL but no significant difference was identified ($p > 0.05$). The particles higher than size 150 μm was greater in AS (out) compared to AS (in) while less in the particles ranging from 150 to 2000 μm. This result was due to the slow settling of fine particles at the bottom along flow path. The particle size distributions for each sediment sample at the FSB are presented in Fig. 3. The highest amount of AS and SL particles collected was below 75 μm while lower amount of particles was observed in the 850–1000 μm size range. It is likely that the characteristics of the accumulated materials on paved areas are known to have enriched coarser particles through the re-suspension and loss of finer sediment taking into account (Sartor and Boyd, 1972). The influent concentration from livestock wastewater (dry days) and combined livestock wastewater and stormwater runoff (wet days) appreciably contains high amount of particulates of 115.4 ± 112.3 and 159.3 ± 115.6 mg/L, respectively and was directed into the CW. The amount of particles was relatively high in FSB because the main mechanism of pollutant removal in the CW is sedimentation.

Table 1 – Summary of particle size distributions of influent and effluent in the CW (unit: μm).

	Mean	Standard deviation	d_{10}	d_{50}	d_{90}
Influent	107.6	142.7	12.50	57.65	263.3
Effluent	39.76	49.15	6.129	24.56	87.54

d_{50}: mass median diameter; d_{10} and d_{90}: grain diameter at which 10% and 90% of the sediment sample is finer than

2.3. Sediment accumulation at the first settling basin

Sediment accumulation is important when determining the long-term maintenance requirements over the lifetime of CW. Fig. 4 provides the changes in the depth of AS at the inlet and outlet of FSB during the operation period. The sediment accumulation was increased to 19.5 cm on June 13, 2012. The particulate materials precipitated at the FSB as this process acted as the main pollutant removal mechanism at the FSB of the CW. The sediment accumulation was low in July 2009, November 2010 and June 2012 due to the dredging operation that took place at that time. As can be seen in Fig. 4, the sediment depth was apparently reduced after the dredging operation. According to Boyd and Queiroz (2001), when sediment accumulation begins to encroach on the HRT volume, the sediment should be removed and properly disposed. The dredging times were determined when the retention rates of the FSB were decreased to approximately 80%. After the

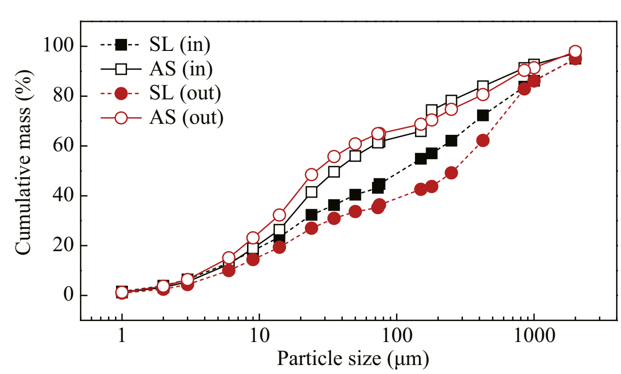

Fig. 2 – Cumulative particle size volumes of soil layer (SL) and accumulated sediment (AS) at the FSB.

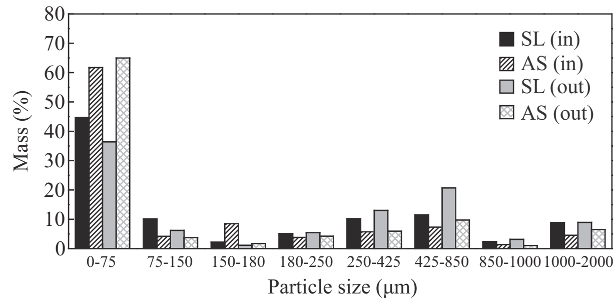

Fig. 3 – Particle size distribution of soil layer (SL) and accumulated sediment (AS) at the FSB.

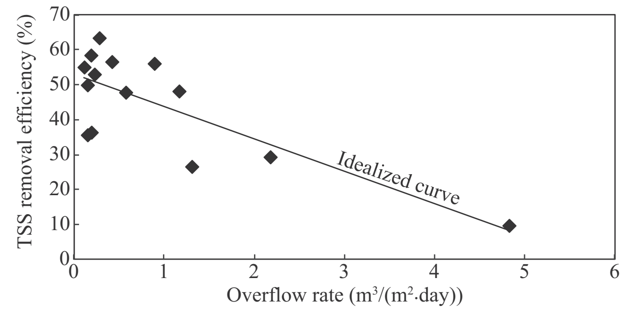

Fig. 5 – TSS removal efficiency versus overflow rates at the FSB showing idealized curve with data.

dredging operation, retention rates increased between 90% and 95%. During the third dredging operation on June 18, 2012, the unit sediment loads removed was determined to be 182 kg/(m^2·yr) of which 17.6, 0.6 and 1.0 kg/(m^2·yr) were the amount of organic matters, nitrogen and phosphorus. The analysis of physico-chemical characteristics of the sediment accumulated at the FSB is important to predict the removal efficiency of the next treatment unit in the CW and to determine efficient operation and management.

2.4. TSS removal efficiency with overflow rates at the first settling basin

The overflow rate represents the minimum settling velocity necessary for sedimentation. Hence, all particles with a terminal-settling velocity (V_s) equal to or greater than the overflow rate (V_0) will settle in the basin; only the fraction (V_s/V_0) of the particles with a velocity less than the overflow rate will settle in the basin (USWEF and ASCE, 1992). A graphical representation of the relationship between the overflow rate (or surface loading rate) and TSS removal performance on an idealized basis is shown by the curve in Fig. 5. TSS removal efficiencies of 9.8% to 63.5% were achieved with overflow rates between 0.11 and 4.83 m^3/(m^2·day). Such performance was not always achieved because many conditions were not accounted for by the theory that affects the performance of operating facilities which include inappropriate application of design details, loading variability, soluble-to-insoluble ratio of organic content, volatile/inert proportions, and recycle flow proportions (USWEF and ASCE, 1992). Therefore, use of overflow/performance relationships calls for caution, recognizing that more favorable ratios require careful and prudent consideration of the many other factors that affect performance.

2.5. Designing the first settling basin

A settling basin was typically designed considering HRT which is an important factor affecting the TSS removal efficiency. In order to determine the real operation HRT, monitoring was performed for four years during dry days. The mean inflow rate was determined to be 21.8 m^3/hr, which was less than the designed flow rate (82.8 m^3/hr) indicating that the FSB was operated with long HRT (20.7 hr) compared to the design HRT (5.5 hr). As a result, approximately 44% of TSS was removed at the FSB, which was greater than that of originally expected removal efficiency (less than 35%). However, the long HRT can also have a disadvantage such as oversized design. The calculated HRT in the CW showed that the

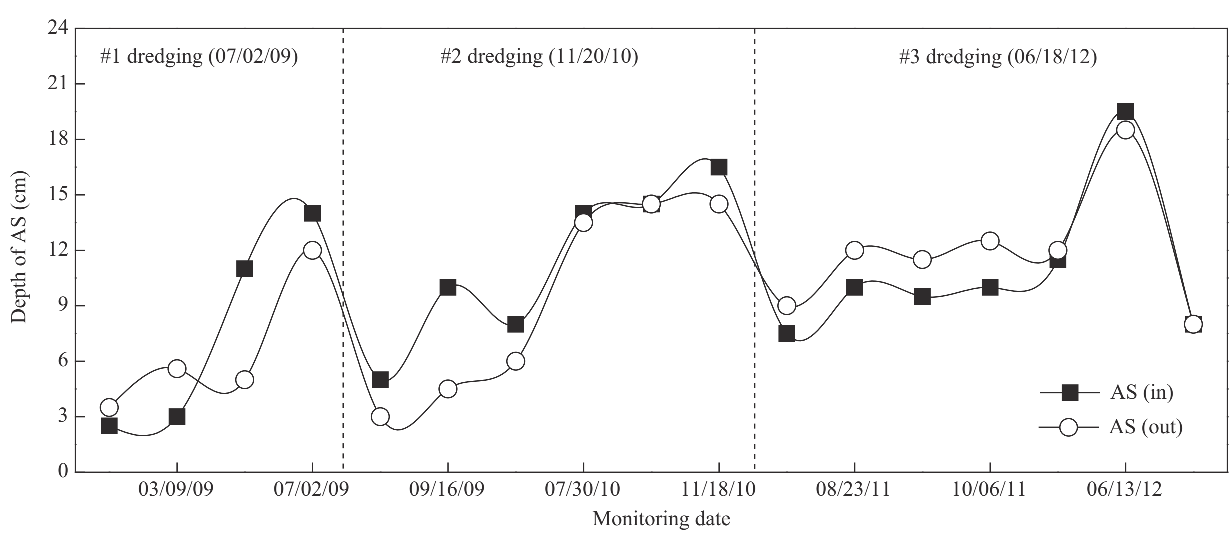

Fig. 4 – Changes in the depth of accumulated sediment (AS) at the FSB.

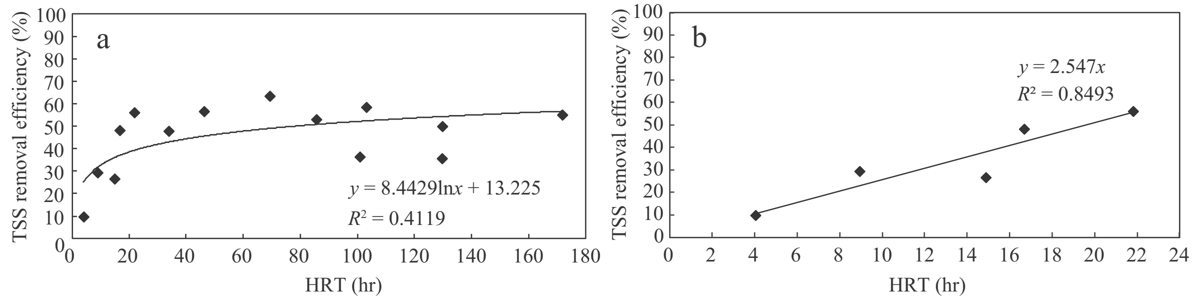

Fig. 6 – TSS removal efficiency versus overflow rates at the FSB showing idealized curve with the (a) pooled data, and (b) truncated data (less than 24 hr).

constructed FSB was oversized. The oversized space can be used for other purposes to increase the pollutant removal efficiency. In order to find the excess oversized space, efficient sizing study for settling basin was needed.

Fig. 6 shows TSS removal efficiency with HRT changes during monitoring. The TSS removal efficiency was increased by increasing the HRT. When the TSS removal efficiency was about 44%, the HRT was determined to be 17.3 hr. A 44% TSS removal efficiency was relatively high compared to other wastewater treatment plants. When the removal efficiencies were between 20% and 30%, the HRT ranged from 7.9 to 11.8 hr. Boyd and Queiroz (2001) suggested that minimum HRT should be 8 hr but a HRT of 24 hr or longer will provide better treatment. As shown in Fig. 6a the TSS removal efficiency is proportional to HRT. However, when the TSS removal efficiencies were less than 44%, the trend was linearly increasing. The HRT can be determined by Fig. 6b.

The HRT was dependent on the volume of settling basin and inflow rate. The volume can be determined by multiplying of depth, width and length of settling basin. Among the dimensional parameters, length was a design factor for volume sizing because the depth was limited to 1 m and width was also limited due to flow. Therefore, the length (m) can be the actual parameter for designing the settling basin. Depending on a fixed inflow rate, the length of FSB could be a function of HRT as shown in Fig. 7a. The optimal length of the FSB was determined to be 31.2 m with 11.8 hr HRT when the required TSS removal efficiency was 30%. Based on Fig. 7b, an empirical model for determining the required length (l, m) of the settling basin in the CW was developed as a function of HRT (hr) and desired TSS removal efficiency (RE_{TSS}, %) as shown in Eqs. (1) and (2).

$$\mathrm{HRT} = \frac{\mathrm{RE_{TSS}}}{2.547} \tag{1}$$

$$l = 6.2\,\mathrm{RE_{TSS}}\exp(-0.22\,\mathrm{HRT}) + 0.579\,\mathrm{RE_{TSS}} \tag{2}$$

3. Conclusions

This study was performed to suggest an optimum settling basin as a pretreatment process using TSS removal efficiency and HRT and to manage the sediment and particles in the water of the settling basin in the CW. The highest amount of AS and SL particles collected was below 75 μm (SL: 35%–40%, AS: 60%–65%). The amount of sediment and particles at the FSB was high due to the sedimentation process identified as the main pollutant removal mechanism in FSB. Wetlands promote sedimentation by decreasing the water velocity and the filtering effect of plant stems and leaves. The main activity of maintenance in settling basin was dredging to remove accumulated sediments and to recover the possible volume of settling basin. The determination of amount of sediment accumulation and frequency of maintenance were the main concerns in settling basin. The optimal dredging time was determined by analyzing the monitored data.

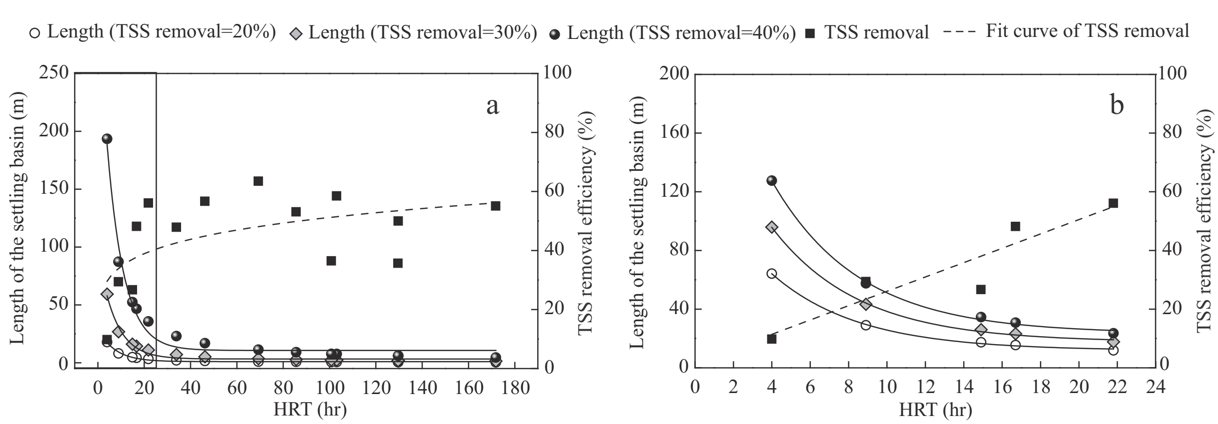

Fig. 7 – Length of the FSB with respect to HRT and TSS removal using (a) pooled data, and (b) truncated data (less than 24 hr).

Sedimentation dredging was performed when the retention rate of the FSB was decreased to approximately 80%. The unit sediment loads removed was determined to be 182 kg/(m^2·yr) of which 17.6, 0.6 and 1.0 kg/(m^2·yr) were the amount of organic matters, nitrogen and phosphorus. The settling basin has an important function in CW because TSS was mainly removed in the basin. During the monitoring period, the TSS removal efficiency for influent and the reduction of TSS load influenced with generated TSS load were considerable. Efficiency of TSS removal was proportional to the particle settling velocity and length of the wetland. Considering the calculated HRT at the FSB, the CW was determined to be oversized compared to the results of the monitored data. Therefore, an empirical model was developed to determine the required length of settling basin with function of HRT and TSS removal efficiency. The required length of the FSB was determined to be 31.2 m which corresponded to 11.8 hr HRT when the required TSS removal efficiency was 30%. The findings of this study were useful in designing the settling basin of the CW applicable as a pretreatment process.

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