Simulation of Various Baffle Types in a Constructed Wetland Sedimentation Tank using CFD

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Abstract

Constructed wetlands are widely applied in urban and rural areas for various purposes such as pollutants reduction, acquisition of eco-spaces and habitats, flooding reduction, acquisition of water resources and environmental education. Since the design of constructed wetlands utilizes ecosystems, special consideration must be given to ecological mechanisms, environmental mechanisms and hydrological mechanisms. To ensure the sustainable functionality of constructed wetlands, it is necessary to achieve stable flow rate and velocity, and remove sediments to ensure sufficient space for detention. To enhance the efficiency of constructed wetland sedimentation basins, this study determined the optimal position for baffle installation, and applied Computational Fluid Dynamics (CFD) to the cross-sectional design of wetlands. CFD analysis revealed that the decrease in flow velocity with baffle installation enhanced the efficiency of sedimentation of particulate matters. Vertical baffles had higher sedimentation efficiency than those with an inclined angle. When vertical baffles were installed in the sedimentation basin of a hybrid constructed wetland to reduce non-point source pollutants in urban areas, the average flow velocity within the basin decreased by 10~30%, while the sedimentation efficiency improved by 1.3~1.5 times. The application of CFD to constructed wetlands is expected to improve the cost efficiency of designing hybrid constructed wetlands with high removal efficiency.

Key words: Baffle, Computational Fluid Dynamics, Constructed wetlands, Particles, Sedimentation

1. Introduction

The size of particulate matter in urban runoff is generally less than 50um, and the average TSS concentration is reported to be 50~200 mg/L (Cho, 2007). The source of particulate matter in urban runoff is sediments from green zones, particles accumulated in the dry season due to vehicles on the roads and in parking lots, and atmospheric deposition. Particulate matter in urban runoff that flows into rivers contains nutrients, hydrocarbons, heavy metals and other non-point source
pollutants. They can cause a deterioration of water quality and have adverse effects on the photosynthesis, respiration and growth of aquatic organisms (Kim et al., 2008; Lee et al., 2009). To minimize the degradation of water quality caused by non-point source pollutants in urban areas, the Ministry of Environment has included various policies for the management of non-point sources pollutants in the Water Quality and Ecosystem Conservation Act, and is promoting Low Impact Development (LID) techniques (Moon, 2015). LID techniques refer to techniques used for the efficient management of runoff and non-point source pollutants while maintaining natural mechanisms (infiltration, detention, evaporation/ transpiration) that existed before development (Yu, 2015; US EPA, 2000). LID techniques, which manage water circulation and non-point source pollutants using soil, media, and the physiochemical and biological functions of plants and microorganisms, can be in the form of wetlands, infiltration trenches, rain gardens and infiltration planters. Among the aforementioned LID techniques, wetlands have been introduced in various areas for runoff management due to their ecological properties, landscape aesthetics, ease of maintenance, and environmental value. In general, wetlands are classified into two categories, free water surface flow (FWS) and horizontal or vertical sub-surface flow (HSSF). For enhanced efficiency, hybrid systems comprised of both free water surface flow and sub-surface flow are being more widely used (Lee, 2011). However, they cannot fully remove the particulate matter contained in runoff, and thus resulting to weaker wetland efficiency by causing the blockage of pores, low photosynthesis, and interference with the respiration of microorganisms. The manual on non-point pollutants removal equipment (MOE, 2014) by the Ministry of Environment requires the installation of a sedimentation basin in wetland design, including specifications such as a capacity equivalent to 10% of water quality volume, a depth of 1.2~1.8m, and a minimum length/width ratio of 2:1.

The management of sediments and vegetation in the sedimentation basin is a key area requiring maintenance to ensure normal pre-treatment function. According to the manual, sediments must be removed if more than 50% of the dredge is buried compared to the volume of the sedimentation basin, and must not exceed 10% of the water quality volume (WQv). Because the manual does not specify how much of the particulate matter must be removed from the sedimentation basin, they continue to enter the wetland, thus lowering the wetland efficiency. The large width of the flow entering the wetland also interferes with quantitative optimal design.

The development of CFD, however, has enabled the optimal design of wetland sedimentation basins (Hwang, 2014). Schamber and Larock (1981) performed a finite element computation of turbulent flows in a rectangular sedimentation basin without baffles, while Yang (2003) employed numerical analysis to compare the sedimentation efficiency of normal settlers, inclination plate settlers, and inclination plate settler stick fins. Stovin and Saul (1998) used Fluent to predict the efficiency of sedimentation in storage chambers, and Koskiaho (2003) found that hydraulic efficiency is highly improved by the installation of baffles in wetlands. In Korea, the commercial CFD package Fluent was used to determine the flow characteristics of a sedimentation basin, and particle tracking was utilized to assess sedimentation efficiency (Lee and Kim, 2004). Another study used the particle tracking technique of the commercial CFD code FLOW-3D to review the flow characteristics and sedimentation efficiency of a sedimentation basin (Kim, 2010).

Most numerical analysis studies have applied particle tracking to predict sedimentation efficiency, but this requires heavy programs and time-consuming calculations. As such, the present study employed the Eulerian model in Fluent to determine the optimal position and size of baffles in hybrid constructed wetlands to improve sedimentation efficiency.

2. Materials and method

2.1 Simulation of Baffles for Enhanced Sedimentation Efficiency

A wetland with horizontal subsurface flow (HSSF), located in a university in Cheonan, Chungnam Province, was selected for numerical simulations. Fig. 1 shows the schematic of the selected HSSF wetland. The sedimentation basin has a size of $0.4 \times 2 \times 0.7 \ (W \times L \times D, m)$ and a capacity of 0.56 $m^3$.

Three scenarios were set for numerical simulations of the behavior of flow and particulate matter in the basin. Case 1 is the existing wetland sedimentation tank without any baffles, Case 2 is the sedimentation tank with vertical baffles, and Case 3 is the sedimentation tank with baffles at an angle of 45˚ and 60˚. The position and shape of the baffles are presented in Table 1, with each baffle measuring $0.4 \times 0.4 \ (W \times H, m)$. The tank had a rectangular mesh, and the size of each mesh was set as 10 mm.

Fig. 1. Schematic of the HSSF wetland
Velocity-inlet conditions were applied to allow mixtures of fluid and particulate matter to flow at the inlet of the sedimentation tanks. As the velocity-inlet boundary condition, the flow velocity was set as 0.05 m/s based on the average inlet velocity (0.042 m/s) over ten observations of the HSSF wetland facility. Inflow was consisted of water and particulate metal which were 70% and 30%, respectively. The outlet was assumed to have constant pressure, and the pressure-outlet boundary condition was set as 0 Pa. Since silicon-solids are the main ingredient of the particulate matter, the materials were subjected to additional conditions. Laminar flow was used instead of turbulent flow because viscosity is associated with low velocity.

### 2.2 Efficiency Assessment of Hybrid Wetlands with Baffle as Variable

Using the optimal position and installation angle of baffles derived from applying CFD to the hybrid wetlands, the velocity of water and concentration of pollutants were simulated. Table 2 shows the two hybrid constructed wetlands with and without baffles. Numerical simulations were performed to obtain the flow velocity of water and concentration of pollutants for each case. The boundary conditions were the same as those applied in the prior baffle installation (Section 2.1).

#### 3. Results and Discussion

##### 3.1 Change in Flow Velocity in Relation to Baffle Installation

In general, gravity causes particulate matter to settle, and sedimentation velocity is affected by fluid viscosity, flow velocity, particle size and density. Sedimentation is greatly influenced by the flow velocity of water, and there tends to be less sedimentation at higher velocity. Fig. 2 shows the velocity profiles for hybrid wetlands in relation to the presence of baffles and installation angle. Compared to Case 1 without any baffles, Case 2 and Case 3 had slower flow velocities. The outlet flow velocity of Case 1 was in the range of 0.088~0.118 m/s, but this fell to 0.048~0.093 m/s and 0.058~0.099 m/s for Case 2 and Case 3 respectively. The flow velocity decreased by 33% for Case 2 and 25% for Case 3. As shown in the simulation of flow velocity at 170 seconds in Fig. 2, the decrease in flow velocity is caused by eddy currents generated by the blocking of influent water by the baffles. The blocking from the baffles lowers the flow velocity of the water, and ultimately has a positive effect on particle sedimentation. The excessive blocking in Case 3 interferes with flow during heavy rain and may lead to flooding. As such, the concentration of particulate matter must be considered to ensure adequate flow velocity when designing sedimentation basins.
3.2 Sedimentation Characteristics of Particles in Relation to Baffle Installation

To analyze the sedimentation characteristics of particles in relation to baffle installation, numerical simulations were performed using CFD. Fig. 3 shows the movement and changes of particles over time. The concentration of particles at the outlet was 3.481~6.681 mol/m$^3$ for Case 1, 2.210~2.946 mol/m$^3$ for Case 2 with vertical baffles, and 2.671~3.531 mol/m$^3$ for Case 3 with baffles installed at different angles. Case 2 and Case 3 exhibited higher sedimentation efficiency with most large particles settling, due to the blocking effect the baffles have on particulate matter entering through the inlet. Case 3 was expected to have higher sedimentation efficiency than Case 2 with the baffle at 60° preventing particles from overflowing, but had
3.3 Application of CFD to Design High-Efficiency Hybrid Constructed Wetlands

CFD was found to be highly efficient for the optimal design of baffles to facilitate the sedimentation of particles in sedimentation basins. CFD analysis was performed to improve the treatment of runoff in the hybrid constructed wetlands. Because the hybrid constructed wetland does not contain baffles in the sedimentation basin, two hybrid wetlands with vertical baffles (hybrid wetland 1) and angled baffles (hybrid wetland 2) were used in CFD simulations to examine the flow velocity of water and changes in the concentration of particles. Fig. 4 presents the results of CFD simulations for water flow in the hybrid wetlands. Hybrid Wetland 2 with vertical baffles reduced the flow velocity of water by 10~30% compared to Hybrid Wetland 1. Fig. 5 shows the changes in concentration of particles in the two hybrid wetlands. Hybrid Wetland 2 with vertical baffles had a higher removal efficiency by 30~40% compared to Hybrid Wetland 1.

4. Conclusion

Constructed wetlands are facilities that remove sediments, nutrients and organic matter based on biochemical and physical pollutant reduction mechanisms. The early removal of particles is important to maintain wetland efficiency. When designing constructed wetlands, special considerations must be given to sedimentation basins, which function as a pre-treatment facility for the removal of sediments and pollutants. However, many constructed wetlands overlook the function of sedimentation basins, thus lowering the
overall efficiency and causing difficulties in maintenance. Therefore, this study applied CFD to improve the sedimentation efficiency of sedimentation basins in constructed wetlands and to ensure the high efficiency of hybrid constructed wetlands. Baffles were installed to improve sedimentation efficiency, and the following conclusions were derived.

- Optimal positions and shapes of the baffles were derived by applying CFD to analyze the flow of water and particles in sedimentation basins.
- A CFD-based analysis of flow velocity in sedimentation tanks with and without baffles showed that baffles contributed to higher sedimentation efficiency by lowering the flow velocity of water. Vertical baffles decreased the average flow velocity by 33%, and were more efficient than inclined baffles since they generated less eddy currents.
- The installation of vertical baffles in hybrid constructed wetlands, aimed at reducing non-point source pollutants in urban runoff, lowered the flow velocity of water by 10~30%. This decrease in flow velocity influenced the overall removal of pollutants, and hybrid constructed wetlands with baffles achieved a higher removal efficiency by 30~40% than those without baffles.

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