Optimal rainwater tank design for control of particulate contaminants

Yusik Won, Mooyoung Han, Hyunju Park and Mikyeong Kim

ABSTRACT

Rainwater systems, which collect rainfall from the roof surface, are an attractive alternative technology, and one of the cleanest water resources. Microorganisms can be treated by disinfection processes or by inducing a biofilm, but particulate matter can only be easily removed with effective storage tank design parameters. In this study, therefore, the effects of rainwater tank design parameters on the treatment of particulate contaminants are analyzed. The J-type inlet pipe seems to maintain stable rainwater quality by suppressing the resuspension of bottom sediments during rainfall inflow. The intermediate wall can prevent sediment from spreading to the whole storage tank, and provide functions such as securing the stable water quality of the outflow area and managing sediment flow to the inflow region. The baffles can simplify tank management such as sediment drainage and tank cleaning by leading to more sedimentation of particles in the unit area. Based on the water quality monitoring results of pH, biochemical oxygen demand (BOD), suspended solids (SS), and turbidity at the field scale, it is possible to supply a certain quality of water by optimizing tank design parameters alone even if particulate contaminants flow into the rainwater tank.

Key words | baffle, inlet pipe, intermediate wall, particulate contaminants, rainwater tank

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INTRODUCTION

Water resources are decreasing all around the world (IPCC 2014). Alternatives and solutions are required to address the 660 million people, mainly living in underdeveloped countries, suffering from serious drinking water problems. Moreover, countries with a sufficient water supply still require improved technologies that can respond flexibly to climate change and future demand growth (WHO 2011). Rainwater systems, which collect rainfall from the roof surface, are an attractive alternative technology (Mun *et al.* 2007; Lee *et al.* 2012) and one of the cleanest water resources due to the short pollutant inflow route. Collected water can be used for drinking water as well as living water (Kus *et al.* 2011).

After rainwater is collected from the roof, it flows through a pipe, and is treated by a first flush treatment apparatus, before being stored in a tank (Handia *et al.* 2003). However, the water in the tank is often turbid, containing suspended solids or even tiny insects that are easily observed by the naked eye (IWA 2015). For these reasons, particulate matter and microorganism contaminants should be removed from the rainwater tank. Microorganisms can be treated by disinfection processes or by inducing a biofilm (Kim & Han 2015), but particulate matter can only be removed with effective storage tank design parameters (Mun & Han 2009). Therefore, the authors analyzed the effect of design parameters on the treatment of particulate contaminants, and built and verified a field-scale prototype rainwater tank.

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MATERIALS AND METHODS

Preparation of reactor and raw water

A laboratory-scale acrylic reactor (25 cm × 50 cm × 25 cm) was fabricated. To define the raw water input, the concentration of suspended solids (SS) in the initial rainwater was measured on the roof of building 35 of Seoul National University in Korea. Then, dust (including sand and soil) was collected at the same location. Because large particles are easily precipitated, they are not suitable for evaluating the effect of design factors. Therefore, only particles less than 250 μm were separated using a standard sieve. The samples were dried at 105 °C for 2 hours, then mixed with distilled water and stirred to prepare SS concentrations similar to those of the initial rainwater (Lee *et al.* 2017).

Effect of design parameters

J-type inlet pipe

A J-type inlet pipe and I-type inlet pipe (general pipe) were used in the reactor (Figure 1(a)). Considering the specifications of the reactor, the two types of inlet pipe have the same inner diameter of 3 mm and a length of 20 cm. Both were placed at a point 20% (5 cm) from the bottom of the reactor. Raw water was filled up to 40% (12.5 L) of the height of the reactor and allowed to stand for 1 hour to allow sufficient precipitation of particles in the water. Then, distilled water was introduced into each pipe at a rainfall intensity of 70 mm/hr (70 L/m^2*hr), which occurs frequently in summer in Korea (Ministry of Land, Infrastructure and Transport 2016), using a metering pump (FH100, Thermo Scientific) for 5 minutes. The turbidity (US/2100D, Hach) was measured by sampling 10 mL of the sample each minute for 15 minutes to measure the degree of sediment resuspension near the inlet pipe, located 5 cm from the bottom of the reactor and repeated three times.

Intermediate wall

The particles that enter through the pipe are precipitated in the reactor. Thus, an intermediate wall is expected to improve the quality of the water over the wall by inducing sedimentation (Amin *et al.* 2013). The schematic design of the wall is shown in Figure 1(b). Intermediate walls were installed with varying distance ratios (DR) and height ratios(HR). Water flowed into the empty reactor for 60 minutes at a rainfall intensity of 70 mm/hr (70 L/m^2*hr), until the storage volume of 22 L. Then, the sediments on the bottom were sampled in front of and behind the wall. Samples were then filtered using a vacuum pump (DOA-P704-AC, GAST) and GF/C filter. The filtered sediments were dried at 105 °C for 2 hours before being weighed and compared.

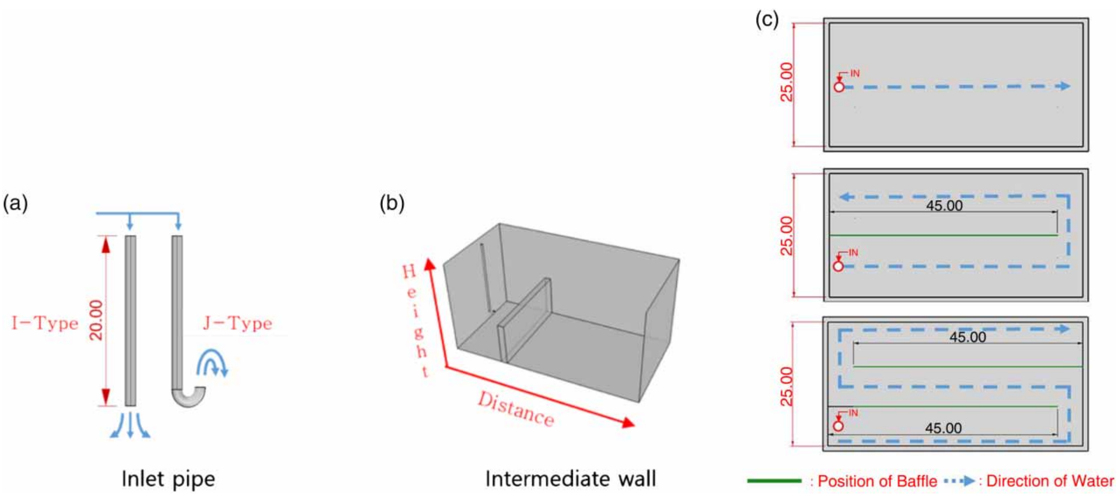

Figure 1 | Schematic showing the design parameters.

Baffle

The baffle is a plate placed at a certain interval in the reactor, which can plug rainwater flow in a specific direction. Baffles can suppress the diffusion of sediments and remove particles by increasing the interface of the reactor surface (Ahmed *et al.* 1996). Schematic designs of baffles are shown in Figure 1(c). The design of the baffle is expressed as an L/W ratio according to the number of baffles. This L/W ratio is calculated by dividing the moving distance of water by the width of the reactor. After the tank was filled with rainwater, the sediments precipitated at the bottom 1 cm^2 of the tank were sampled using a pipette at 10 cm intervals from the inlet to the outlet. The samples were filtered using a vacuum pump and GF/C filter, and dried at 105 °C for 2 hours, before weighing and comparison.

RESULTS AND DISCUSSION

Results of design factor analysis in laboratory scale

Effect of J-type inlet pipe on sediment resuspension

A comparison of the water turbidity before and after rainfall showed that the arrangement with the I-type inlet pipe had an average value of 3.6 NTU (2.1–5.3 NTU) during rainfall and 2.7 NTU (2.0–3.1 NTU) after rainfall (Figure 2). The turbidity continued to increase during rainfall inflow and decreased after the end of rainfall. Conversely, the J-type inlet pipe had an average water turbidity of 2.1 NTU (2.0–2.3 NTU) during rainfall and 2.0 NTU (1.9–2.1 NTU) after rainfall. Turbidity maintained a constant level during rainfall inflow and after the end of rainfall. Therefore, the J-type pipe was less affected by influent. With the I-type inflow pipe, the existing sediments were re-suspended, which can degrade rainwater quality. In addition, the resettling and stabilizing of re-suspended sediments took longer. Thus, the J-type inlet pipe seems to maintain a stable rainwater quality by suppressing the resuspension of bottom sediments during rainfall.

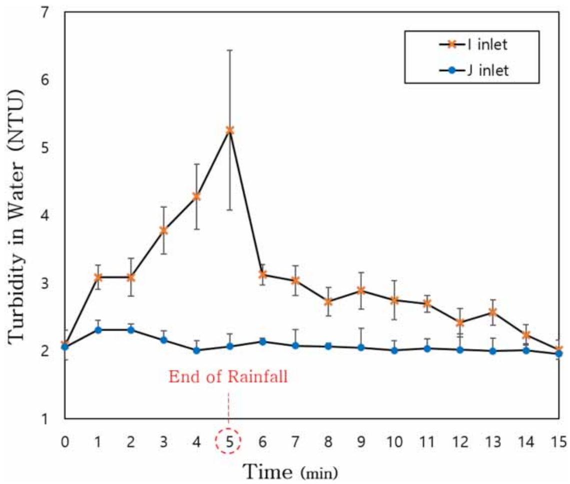

Figure 2 | Comparison of turbidity before and after rainfall for I-type and J-type inlet pipes.

Effect of the intermediate wall on inducing sedimentation

Figure 3 shows the variation in the ratio of sediment and stagnant water in front of and behind the intermediate wall. The efficiency was calculated by dividing sediments in front of the wall to total sediments in the reactor. For the smallest distance and height (LR 0.1, HR 0.2), the efficiency was 74.2%. However, 99.6% efficiency was obtained with the largest distance and height (LR 0.5, HR 0.4). Assuming that particles settle independently, particle sedimentation efficiency generally follows the Hazen

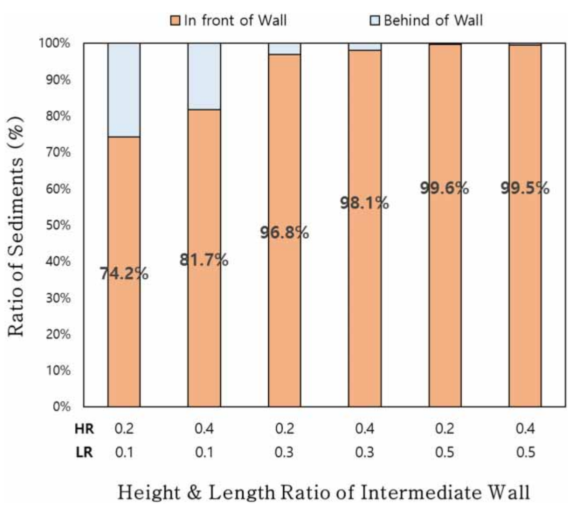

Figure 3 | Changes in the ratio of sediment in front of and behind the intermediate wall with variable distance and height ratios.

sediment theory, in that a wider sedimentation area leads to more efficient sedimentation (Kowalski 2004). In this study, the proportion of sediment particles increased as the distance between the inlet and the wall increased because of a wider surface area. For a LR of 0.3, more than 95% of the particles settled.

The amount of sediment was compared at two different heights (HR 0.2 and 0.4) at each distance, and increased with the height of the wall, by 7.5% at a LR of 0.1 and 1.3% at a distance ratio of 0.3. Little difference was observed with the height of the wall at an LR of 0.5. This is because most particles settled naturally within an LR of 0.3, so they were less influenced by the intermediate wall.

When maintenance is considered, it is advantageous to install the intermediate wall close to the inlet. Therefore, an optimal design would maximize the height of the intermediate wall, and create an orifice at a suitable position to minimize stagnant water.

Effect of baffle on particle spreading

For the same amount of raw water introduced into the reactor, the sedimentation area was 562.5 cm^2 with 0 baffles, 312.5 cm^2 with 1 baffle, and 162.5 cm^2 with 2 baffles (Figure 4). With no baffle, particles settled over a large area with a low concentration. However, as the number of baffles increased, sedimentation occurred in a narrower area with a higher concentration. Furthermore, as the number of baffles increased, the L/W ratio increased proportionally, and the amount of particles remaining in the water was as high as 45% with 0 baffles, 25% with 1 baffle, and 15% with 2 baffles. Most of the particles settled in the first half of the reactor under all conditions, and the amount of sediment decreased as the raw water moved through the reactor. Thus, as the number of baffles and the L/W ratio increases, sedimentation can be induced at a higher concentration in a narrower area, and baffles can simplify management of the tank, including sediment drainage and cleaning the inside of the tank. Therefore, baffles are a required design parameter when considering economical operation and removal efficiency.

Prototype application and monitoring

Using the design parameters optimized for particulate matter treatment by the laboratory experiments, a prototype of STS304 material capable of storing 1 tonne (1 m × 1 m × 1 m) of rainwater was manufactured including a J-type inlet, intermediate wall and two baffles (Figure 5). Rainwater collected from the concrete surface (10 m × 3 m) of the upper roof flows into the tank, and the stored rainwater is designed to automatically supply rainwater to the connected pipe through potential energy. This prototype was installed on the roof of Seoul National University and monitored at

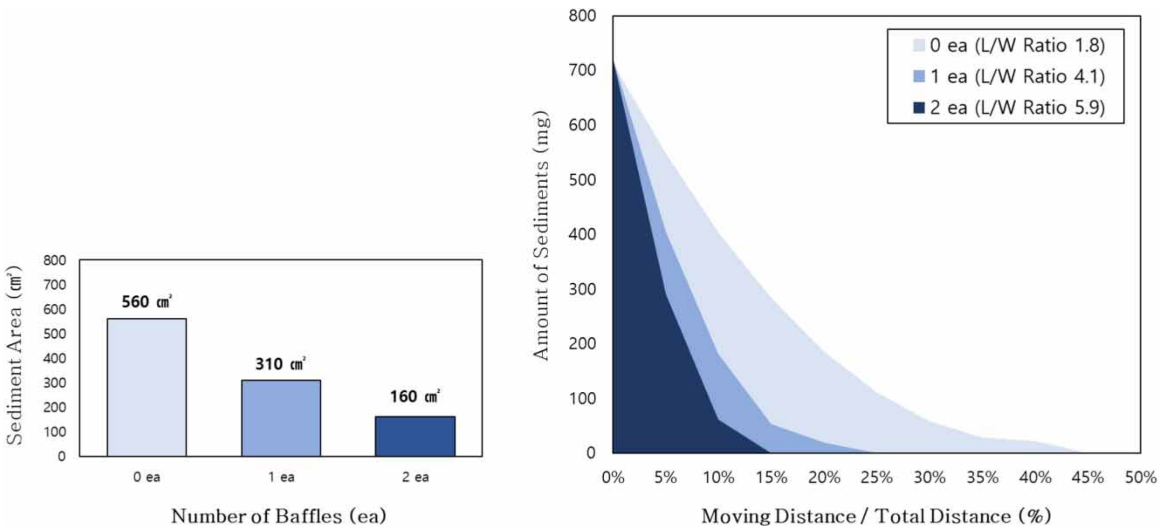

Figure 4 | Sediment settling area and volume according to the number of baffles.

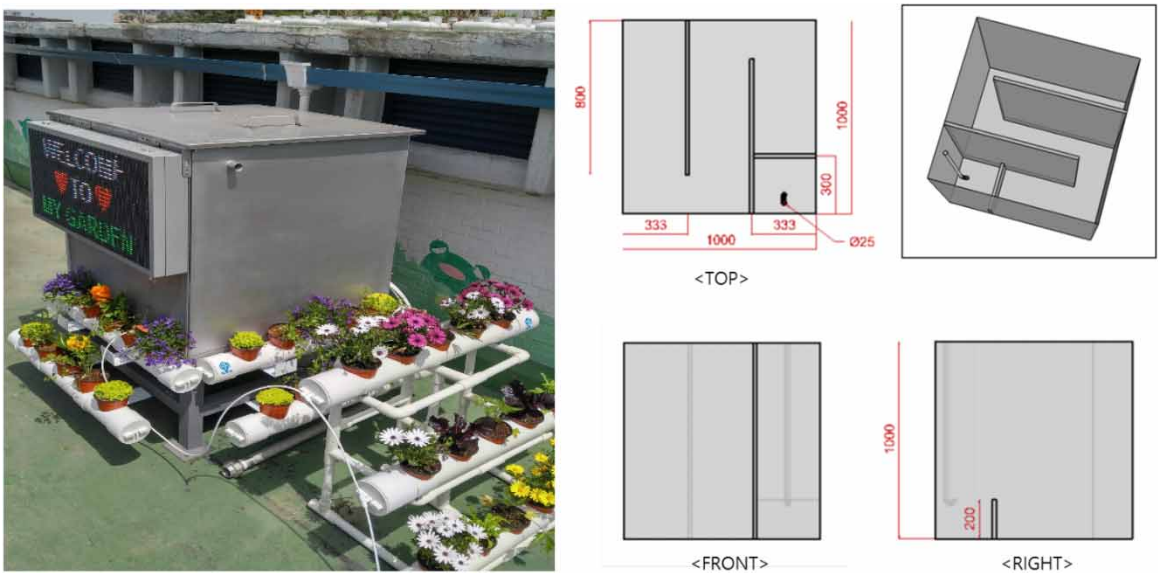

Figure 5 | Prototype rainwater tank used for the for field scale tests.

nine times for four months from May to August 2017. Using a water sampler (WS304, World Medi), samples were collected from the inlet and outlet, and pH (HM-31P, DKK-TOA), biochemical oxygen demand (BOD), suspended solids, and turbidity (US/2100D, Hach) were measured using the water quality test method (Ministry of Environment 2016).

Table 1 shows the water quality results using samples taken from the inlet and outlet of the 1 m^3 prototype rainwater tank. The pH was slightly acidic (6.1) at the inlet due to the initial rainwater pH. However, it gradually neutralized while flowing through the storage tank, and was 6.6 at the outlet. The pH of the rainwater was low, but increased during storage in the rainwater tank. Since the rainwater tank is not wide and has a short moving distance from the catchment area to the tank, it maintains a low pH until the beginning of inflow. However, as in other studies (Kim *et al.* 2004; Nguyen *et al.* 2013), the rainwater reacts with the particles while moving inside the storage tank, and is diluted with existing rainwater so that the pH of the supplied water becomes neutral.

The BOD was 4.6 mg/L due to contaminants, and decreased by 67% at the outlet to 1.5 mg/L. The SS concentration at the inlet was 11.6 mg/L due to resin powder, but decreased by 87% at the outlet to 1.5 mg/L. Turbidity was 26.4 NTU at the inlet, but 1.9 NTU at the outlet due to sedimentation during flow. Therefore, even if particulate contaminants inflow into the tank, it is possible to supply a certain quality of water by optimizing the design parameters of the tank. For future applications, the system should be designed according to the specific conditions of the site, considering economic efficiency and the various combinations of the three design elements. To do this, additional studies are required that analyze the effects of various design combinations.

Table 1 | Water quality measurement results

	Inlet			**Outlet**			
	Average	**Range**	**Standard deviation**	**Average**	**Range**	**Standard deviation**	**Removal rate**
pH	6.1	4.3–6.6	0.7	6.6	6.2–7.4	0.9	
BOD (mg/L)	4.6	0.5–14.8	5.0	1.5	0.3–3.0	1.0	67%
SS (mg/L)	11.6	1.0–40.0	14.0	1.5	0.0–3.6	1.3	87%
Turbidity (NTU)	26.4	0.7–85.4	31.5	1.9	0.6–3.6	1.1	92%

CONCLUSIONS

In this study, the authors analyzed the effects of changing the design parameters of a rainwater storage tank on improving the quality of stored rainwater. They then built and verified a rainwater tank prototype based on these results. The conclusions are as follows.

(1) The J-type inlet pipe can suppress sediment resuspension during rainfall inflows, thereby maintaining a stable water quality in the rainwater tank.
(2) The intermediate wall induces sedimentation. As most particles settle naturally within an LR of 0.3 from the inlet, an effective intermediate wall should be installed at a short distance and have a substantial height.
(3) As the number of baffles increases, so does the L/W ratio, leading to more sedimentation of particles in the unit area. This can simplify tank management such as sediment drainage and tank cleaning.
(4) Water quality monitoring results indicate that, even if particulate contaminants flow into the rainwater tank, it is possible to supply a certain quality of water by optimizing tank design parameters. For future applications, additional studies are required to analyze the effects of various design combinations.

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REFERENCES

Ahmed, F. H., Kamel, A. & Abdel Jawad, S. 1996 Experimental determination of the optimal location and contraction of sedimentation tank baffles. *Water, Air, and Soil Pollution* **92** (3–4), 251–271.

Amin, M. T., Kim, T. I., Amin, M. N. & Han, M. Y. 2013 Effects of catchment, first-flush, storage conditions, and time on microbial quality in rainwater harvesting systems. *Water Environment Research* **85** (12), 2317–2329.

Handia, L., Tembo, J. M. & Mwiindwa, C. 2003 Potential of rainwater harvesting in urban Zambia. *Physics and Chemistry of the Earth, Parts A/B/C* **28** (20), 893–896.

IPCC 2014 *Climate Change 2014 Synthesis Report*. Approved Summary for Policy Makers. IPCC Fifth 389 Assessment Synthesis Report. November 1, 2014, SPM-1.

IWA 2015 *Alternative Water Resources: A Review of Concepts, Solutions and Experiences*. Alternative Water Resources Cluster, IWA, London, UK.

Kim, M. K. & Han, M. Y. 2015 Role of biofilms in improving microbial quality in rainwater tank. *Desalination and Water Treatment* **53** (10), 2579–2584.

Kim, Y. W., Kim, Y. I., Park, S. W. & Han, M. Y. 2004 The operational status of rainwater utilization facility in dormitories in Seoul National University. *Journal of the Korean Society of Water and Wastewater* **E-11**, 53–62.

Kowalski, W. P. 2004 The method of calculations of the sedimentation efficiency in tanks with lamella packets. *Archives of Hydro-Engineering and Environmental Mechanics* **51** (4), 371–385.

Kus, B., Kandasamy, J., Vigneswaran, S. & Shon, H. K. 2011 Water quality in rainwater tanks in rural and metropolitan areas of New South Wales, Australia. *Journal of Sustainable Water* **1** (1), 33–43.

Lee, J. Y., Bak, G. & Han, M. Y., 2012 Quality of roof-harvested rainwater–comparison of different roofing materials. *Environ. Pollut.* **162**, 422–429.

Lee, M. J., Kim, M. K., Kim, Y. H. & Han, M. Y. 2017 Consideration of rainwater quality parameters for drinking purposes: a case study in rural Vietnam. *Journal of Environmental Management* **200**, 400–406.

Ministry of Environment 2016 *Water Pollution Process Test Standard*, Korea.

Ministry of Land, Infrastructure and Transport 2016 *Korea Precipitation Frequency Data*.

Mun, J. S. & Han, M. Y. 2009 An economical analysis of the rainwater harvesting (RWH) system at the residential and commercial complex. *Journal of the Architectural Institute of Korea* **25** (12), 173–181.

Mun, J. S., Yu, H. G. & Han, M. Y. 2007 Particle removal in a rainwater storage tank, and suggestions for operation. *Journal of the Korean Society of Water and Wastewater* **21** (1), 131–138.

Nguyen, D. C., Dao, A. D., Kim, T. & Han, M. Y. 2013 A sustainability assessment of the rainwater harvesting system for drinking water supply: a case study of Cukhe village, Hanoi, Vietnam. *Environmental Engineering Research* **18** (2), 109–114.

WHO 2011 *Guidelines for Drinking Water Quality*. Geneva.

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