Particle behaviour consideration to maximize the settling capacity of rainwater storage tanks

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Abstract Design of a rainwater storage tank is mostly based on the mass balance of rainwater with respect to the tank, considering aspects such as rainfall runoff, water usage and overflow. So far, however, little information is available on the quality aspects of the stored rainwater, such as the behavior of particles, the effect of retention time of the water in the tank and possible influences of system configuration on water quality in the storage tank. In this study, we showed that the performance of rainwater storage tanks could be maximized by recognizing the importance of water quality improvement by sedimentation and the importance of the system configuration within the tank, as well as the efficient collection of runoff.
The efficiency of removal of the particles was increased by there being a considerable distance between the inlet and the outlet in the rainwater storage tank. Furthermore, it is recommended that the effective water depth in a rainwater tank be designed to be more than 3 m and that the rainwater be drawn from as close to the water surface as possible by using a floating suction device. An operation method that increases the retention time by stopping rainwater supply when the turbidity of rainwater runoff is high will ensure low turbidity in the rainwater collected from the tank.
Keywords Particle behaviour; particle removal; rainwater storage tank; sedimentation,

Introduction

The need for rainwater storage to mitigate various water problems such as flooding, drought, fire fighting and water shortage has become more obvious in recent times. Hence, rainwater management laws and regulations have been promoted in several countries, including the Republic of Korea. A rainwater utilization facility to use stored rainwater consists of its catchment area, a treatment facility, a storage tank, a supply facility and pipes. The stored rainwater is used for flushing toilets, watering gardening and washing (Han and Lee, 2005). The major factors that affect the design of a rainwater utilization facility are the rainfall pattern, atmospheric conditions, catchment conditions, the organization of the rainwater utilization system, conditions of rainwater use and the method of operating the system (Lindberg and Lovett, 1985; Park, 1995; Tanner, 2002; Polkowska *et al.*, 2002; Han *et al.*, 2003). If they are well designed, rainwater storage facilities require little or no electricity, chemicals or maintenance. Design of a rainwater storage tank is mostly based on the mass balance of water in the tank, taking into account such factors as rainfall runoff, water usage and overflow. So far, however, little information is available on the quality aspects of the stored rainwater, such as the behavior of particles, the effect of retention time of the water in the tank and possible influences of system configuration on water quality in the storage tank (Jurgen, 1996; Han *et al.*, 2003). Water quality is an important consideration in designing rainwater tanks, because it will not only determine the mode of water usage and treatment and the maintenance of the tank, but it will also affect the degree to which people accept this form of water.

A rainwater storage tank has the capacity to settle solids, but it operates under different conditions from those of settling tanks in a drinking water treatment plant (Kim, 2005).

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Conditions in rainwater tanks include no use of chemicals, a long average retention time, an intermittent inflow and outflow, irregular fluctuations of water level, different kinds of incoming particles and a long cycle for sludge removal.

This study was performed to compare water quality in two rainwater storage tanks that have different catchment areas and conditions, retention times and operating conditions. The study also investigated the removal efficiency and behavior of particles under sedimentation in an operating rainwater storage tank with a fixed water level in the absence of inflow and outflow. Finally, several suggestions were made to optimize the design and operation of a rainwater storage tank.

Materials and methods

Rainwater management facilities

Seoul National University (SNU) has two rainwater storage and supply systems, which are located in the dormitory and in Building #39 on its campus. The dormitory complex at SNU has a 200 m^3 rainwater storage tank and rooftop catchment area of 2.098 m^2, and was constructed in November 2003. It provides water for the toilets of 167 households and for the garden (Han *et al.*, 2006). The rainwater storage tank is made of reinforced concrete divided into two basins, and its effective water depth is 2 m.

In October 2005, another rainwater storage and supply system was constructed in Building #39 at SNU. There are about 1000 full-time staff and students occupying the building, and the amount of water consumed per day for toilet flushing is about 60–90 m^3/day. The building's rainwater system consists of a catchment area, a main storage tank, an extra storage tank and supply facilities. The catchment area is 3.652 m^2, and the capacities of the main storage tank, extra tank and supply tank are 250 m^3, 27 m^3 and 4 m^3, respectively. Rainwater collected from the roof of one part of the building (area of 960 m^2) flows into the main tank, which has an effective water depth of 4.25 m. Rainwater collected from the roof of another part of the building (area of 1.868 m^2) and the terrace (824 m^2) flows into the extra tank and then, when the depth of water in the extra tank reaches 1.2 m, water is transported to the main tank by pumping. A schematic diagram of rainwater storage and supply systems at SNU is shown in Figure 1.

Two filters, WFF100 (Rainharvesting Systems Ltd., Woodchester, UK) with mesh size of 280 μm and AFS200 (Wavin Co., Zwolle, Netherlands), were installed in the main tank. Rainwater from the roof catchment area flowed into the main tank through the two filters and, when the extra tank was full, rainwater from the extra tank flowed into the main tank through the AFS200 filter. The water levels in each of the main tank, the extra tank and the supply tank were monitored using a floating level transmitter (HT-100R, Hitrol Co., Ltd, Paju, Korea). An automatic remote control operation was carried out by

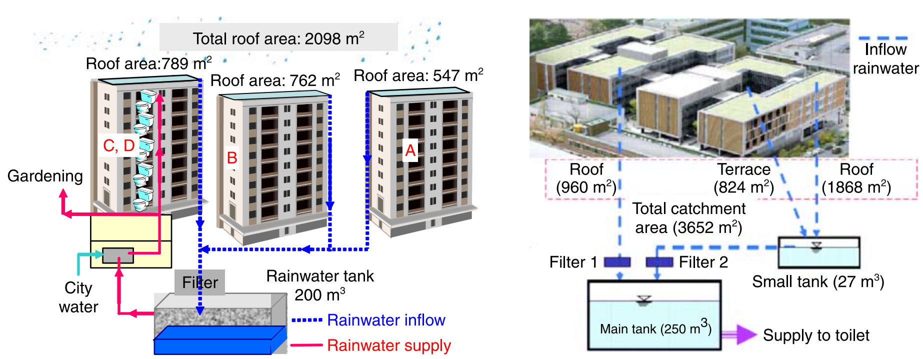

Figure 1 Schematic diagram of rainwater storage and supply systems at SNU

an HMI (Human Machine Interface) program (Wonderware In Touch v. 9.0, Maha net Co., Ltd., Sungnam, Korea).

Experimental conditions

The turbidity and pH of roof runoff through a filter with mesh size of 550 μm and of rainwater in the storage tank were measured in the dormitory rainwater storage system once a week or once a month from March 2004 to April 2005. The turbidity and pH of the rainwater were measured at the inlet (T1) and outlet (T2) of the main tank in the Building #39 system once a week or once a month from May to August 2006.

Sedimentation experiments were performed in the rainwater storage tank in the Building #39 system from June to August 2006 using three rainfall events (Table 1). To examine the removal efficiency and behavior of particles during sedimentation in the main tank, a fixed water level was maintained in the main tank by stopping runoff from the catchment area to the tank, thus stopping inflow. Turbidity, pH, temperature and particle size distribution (PSD) were analyzed over various retention times and depths of sampling. Water samples were taken from close to the inlet (T1) and close to the outlet (T2), and from 1 m, 2 m and 3 m above the bottom of the main tank. The distance between T1 and T2 was designed to be 15 m. The experimental conditions are shown in Table 1.

Turbidity and PSD were measured using a Turbidimeter (Hach 2100, USA) and a Coulter Multisizer (USA), and pH and water temperature were measured using a pH meter (Hach Sension 1, USA).

Results and discussion

Water quality in the rainwater storage tank in operating

The turbidity of roof runoff and stored rainwater in the dormitory system is shown in Figure 2.

Turbidity of roof runoff through the 550 μm filter showed a wide variation from 11 to 207 NTU (Nephelometric Turbidity Unit), but the average turbidity of stored rainwater was around 2 NTU, with individual measurements ranging from 1.3 to 2.4 NTU. Generally, the turbidity of roof runoff through the filter ranged from 10–30 NTU, but in May, this increased to as high as 207 NTU due to the inflow of pine pollen. The pH of roof runoff and stored rainwater was 6.5 to 9.0 and 6.8 to 8.4, respectively, for a year. Water quality of the stored rainwater in the dormitory was fit to be used for flushing toilets and for supplying to the garden due to the relatively clean rooftop catchment and the long retention time in the rainwater tank.

Figure 3 shows the turbidity and pH of stored rainwater near the inlet (T1) and the outlet (T2) in the main tank in the Building #39 system. The turbidity of rainwater at T1 was 1 to 20 NTU, and at T2 was 1 to 11 NTU. The pH of stored rainwater was 10.1 to

Table 1 Conditions in sedimentation experiments

Case	Sampling period (retention time) 2006 year	Rainfall (preceding dry days)	Sampling points (height above bottom, m)	Initial rainwater turbidity (NTU)	Water depth(m)
1	9 Jun. 20:40 to 10 Jun. 9:40 (17 hr)	6 mm (13 days)	F1, F2 T1(1)T2(1)	T1(1)11.2 T2(1) 6.49	2.45
2	11 Jul. 11:00 to 15 Jul. 16:00 (100 hr)	10 mm (3 days)	T1(1)T1(2) T1(3) T2(1)	T1(1) 6.28 T2(1) 4.18	3.32
3	31 Jul. 11:00 to 4 Aug 20:00 (105 hr)	Over 300 mm	T2(2) T2(3)	T(1)2.12 T2(1) 1.39	3.15

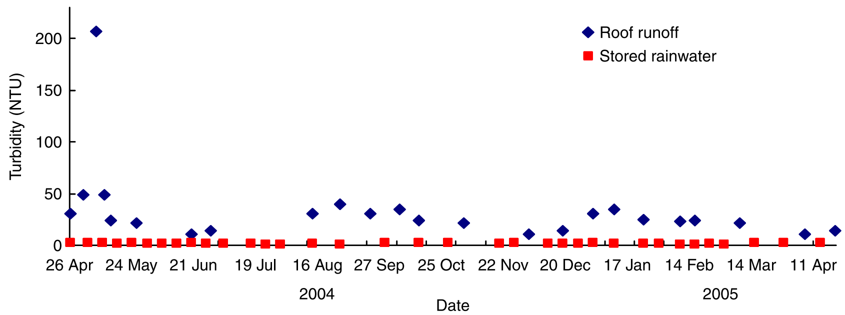

Figure 2 Turbidity of roof runoff and stored rainwater over a one-year period in a dormitory

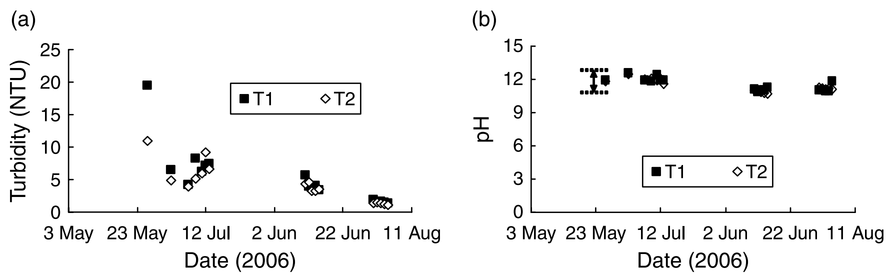

Figure 3 Turbidity and pH of stored rainwater in the main tank of the Building #39. (a) Turbidity and (b) pH

12.5 due to runoff from a marble terrace catchment area. The temperature of the stored rainwater was 19–24 °C.

The turbidity of stored rainwater for supplying Building #39 was a little high due to the runoff from the marble terrace. Therefore, we considered sedimentation in the rainwater tank to improve water quality.

Particle removal and behavior in a rainwater tank

Particle behavior and the removal rate by sedimentation in the rainwater tank were examined for Case 1, where there had been a long period (13 days) of dry days followed by low rainfall ((10 mm). The retention time was 12 hr without inflow and outflow. Samples were taken from a point 1 m from the bottom near the inlet (T1) and outlet (T2) of the tank. The initial turbidities at T1 and T2 were 11.5 and 6.5 NTU; that is, the turbidity of the water at T1 was approximately double that at T2. The removal rate increased rapidly during the first 2 hr and increased slowly thereafter. After a settlement time of 12 hr, the turbidities (removal rate) at T1 and T2 were 8.3 NTU (25.8%) and 4.1 NTU (36.5%), respectively (Figure 4 (a)).

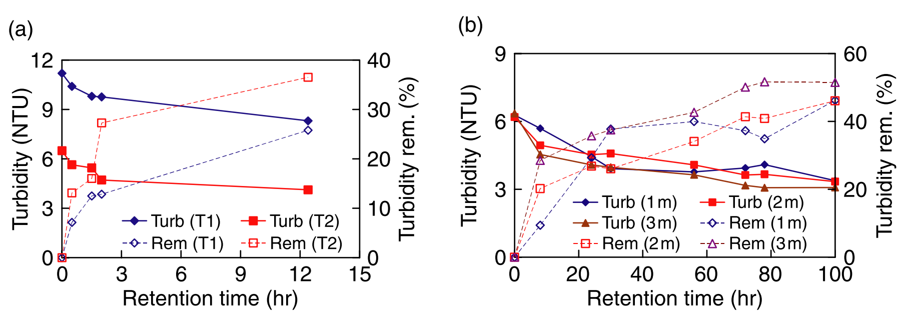

Figure 4 Turbidity and particle removal rate in rainfall Case 1 and 2. (a) Case 1 and (b) T1 at case 2

Particle behaviour and removal rate by sedimentation in the tank was examined under conditions of a short dry period preceding the rainfall event (3 days) followed by rainfall of about 10 mm. The retention time was 100 hr without inflow and outflow. Samples were taken from points 1 m, 2 m and 3 m above the bottom near the inlet and outlet of the tank. The initial turbidity at T1 was 6.4 NTU. The removal rate increased rapidly over the first 8 hr and then increased more slowly thereafter. The removal rates at the 1 m, 2 m and 3 m points were 30–40% after 30 hr, increasing slowly after this, reaching 50% (Figure 4(b)).

Lastly, particle behavior and removal rate by sedimentation in the tank was examined following heavy rainfall of 300 mm (Case 3). The retention time was 105 hr without inflow and outflow. The initial turbidities at T1 and T2 were 2.12 and 1.39 NTU. Removal rate relative to retention time tended to increase steadily at T1 and T2. After 105 hr retention time, the turbidity (removal rate) at T1 was 1.12–1.33 (37–40%) and at T2 was 0.85–1.01 (23–34%) (Figure 5).

As retention time increased, particle numbers tended to decrease at each sampling depth. Additionally, the higher the sampling points above the bottom of the tank, the lower the particle number. At T1, the initial numbers of particles in each of four particle size groups were different at each sampling depth. At a retention time of 100 hr, there were no longer any significant differences in the particles numbers between the particle size groups at any sampling depth (Figure 6).

Design and operation considerations for a rainwater tank

The turbidity at T1 and T2, which are 15 m apart, were compared in Cases 1 and 3 to examine the efficiency of particle removal relative to the distance between T1 and T2 (Table 2). In Case 1, T2:T1 ratios were 0.59 and 0.50 at retention times of 0 and 12 hr.

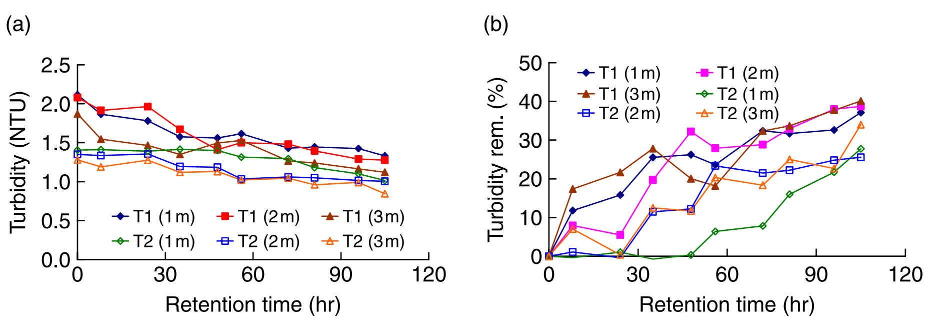

Figure 5 Turbidity and particle removal rate in rainfall Case 3. (a)Turbidity and (b) Turbidity removal rate

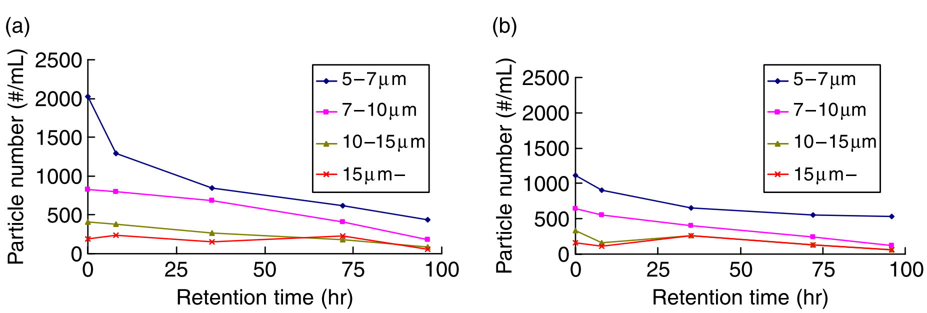

Figure 6 Particle size distribution by size category in stored rainwater in T1, based on retention time in Case 3. (a) 1 m from bottom and (b) 3 m from bottom

Table 2 Comparison of turbidity at T1 and T2 at 1 m above the bottom of the tank in Cases 1 and 3

	Case 1: High initial turbidity			Case 3: Low conc. Initial turbidity		
	Retention time 0 hr	Retention time 12 hr	Removal rate (%)	Retention time 0 hr	Retention time 105 hr	Removal rate (%)
T1	11.2	8.31	25.8	2.12	1.33	37.1
T2	6.6	4.12	36.5	1.39	1.02	26.7
T2:T1	0.59	0.50		0.66	0.77	

The particle removal efficiency was increased by up to 50% with the greater distance. In Case 3, T2:T1 ratios were 0.66 and 0.77 at retention times of 0 and 105 hr. The particle removal efficiency was increased by 34% with the greater distance.

Consequently, under conditions of a long dry period leading up to the rainfall event followed by low rainfall (i.e. high contamination) such as in Case 1, the particle removal efficiency was high over the distance between the inlet and the outlet. We conclude that it is necessary to have an adequate distance between inlet and outlet. The higher the initial turbidity of the water, the larger the difference in turbidity between points 3 m from the bottom and 1 m and 2 m from the bottom in Cases 2 and 3. Therefore, if possible, it is better to design an effective water depth of over 3 m, and it is better to supply rainwater from near the water surface by using a floating suction device.

In this study, it is recommended that the effective retention time in a rainwater tank is over 30 hr, based on consideration of Case 2 where there was an initial turbidity of 6 NTU in the rainwater tank. In reality, the optimum retention time in a rainwater tank depends on the weather conditions, the design of the rainwater tank and its operation conditions. In Case 1, where the initial stored rainwater had a turbidity of 11 NTU, the appropriate distance from inlet to outlet should also be considered in addition to the appropriate retention time.

Conclusions

The performance of a rainwater storage tank can be maximized by recognizing the importance of water quality improvement by sedimentation within the tank, as well as the efficient collection of runoff. In this study, we examined particle removal by sedimentation and the effects of catchment area in two operating rainwater storage tanks at SNU, each of which has a different catchment area, retention time and operating conditions. The pH and turbidity of stored rainwater in the dormitory at SNU were 6.8 to 8.4 and around 2 NTU respectively, which is appropriate for the supply of water for flushing toilets and for watering gardens, due to the relatively clean rooftop catchment and long retention time in the rainwater tank. On the other hand, the pH and turbidity of stored rainwater in the Building #39 rainwater storage system were a little high due to the runoff from the marble terrace. The sedimentation test was performed in the rainwater storage tank in the Building #39 system without inflow and outflow, after stopping the access of runoff to examine the removal efficiency and behavior of particles during sedimentation. The removal rate of particles increased consistently with retention time where the stored rainwater had an initial turbidity of around 2 NTU, the removal rate being 30% to 40%. However, where the stored rainwater had an initial turbidity of 6–11 NTU, the removal rate increased rapidly initially, but then increased more slowly, the removal rate being 30% to 50%. The particle number in stored rainwater decreased with greater retention time, and the proportion of larger particles generally decreased more rapidly than the proportion of small particles.

The removal efficiency of particles was increased by having a considerable distance between inlet and outlet, even when there was a long dry period followed by little rainfall. It is recommended that the effective water depth of the storage tank be designed to be over 3 m whenever possible and to supply rainwater from near the water surface by using a floating suction device. Efficient operation of a rainwater tank can be expected even with a small length to width ratio if a settler is established in the rainwater tank.

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