공학석사 학위논문

오염물질 펄스 유입에 대비한 빗물 수집 시스템 설계 **및 작동** 개선

Improving the design and operations of rainwater harvesting systems in preparation for a pulse contaminant input

2021년 8월

서울대학교 대학원

건설환경공학부

Dissanayake Mudiyanselage Janith Madubasha Dissanayake

Improving the design and operations of rainwater harvesting systems in preparation for a pulse contaminant input

지도교수 **한 무 영**

이 논문을 공학석사 학위논문으로 제출함

2021년 **08**월

서울대학교 대학원

건설환경공학부

Dissanayake Mudiyanselage Janith Madubasha Dissanayake

Dissanayake Mudiyanselage Janith Madubasha Dissanayake

의 석사 학위논문을 인준함

2021년 **08**월

위 원 장	남 경 필
부 위 원 장	한 무 영
위 원	최 정 권

Improving the design and operations of rainwater harvesting systems in preparation for a pulse contaminant input

By

Dissanayake Mudiyanselage Janith Madubasha Dissanayake

Supervisor: Professor Mooyoung Han

A dissertation submitted in partial fulfilment of the requirements for the degree of Master in Department of Civil and Environmental Engineering.

Department of Civil and Environmental Engineering

College of Engineering

Seoul National University

August 2021

Abstract

Improving the design and operations of rainwater harvesting systems in preparation of a pulse contaminant input

Dissanayake Mudiyanselage Janith Madubasha Dissanayake

Dept. of Civil and Environmental Engineering

College of Engineering

Seoul National University

Rainwater harvesting (RWH) has attracted global attention as a solution for the urban water crisis; however, the water quality can be impacted by particulate matter and soluble contaminants. Therefore, the inlet and outlet configurations of the storage tank should be designed to minimize bottom sediment resuspension and prevent the transport of soluble contaminants. To overcome these issues pertaining to single tank systems, multiple tank systems with similar volumes have been implemented globally. However, limited research has been conducted to assess the effect of the number of tanks on harvested water quality under a sudden pollutant input. In addition, many researchers have investigated design and operational aspects of RWHs with respect to particulate matter removal, but not much research is available on how operations of RWHs affect the removal of soluble pollutants.

Thus, this study investigated the effects of the inlet and outlet configurations of a rainwater storage tank on particle resuspension and residence time distribution for an instantaneous input of a conservative tracer. It was observed that J type inlets can reduce sediment resuspension by more than 50% while detaining and mixing a conservative pollutant, thus preventing the concentration from reaching the outlet as a plug flow. Although inlet height did not have a significant influence on the quality of water at the outlet, parameters such as inflow velocity and outlet height exerted a considerable influence on sludge resuspension and residence time distribution. The experiments also highlighted the importance of regulating the initial water level of the storage tank and regular flushing of bottom sediment to maintain the stored water quality.

Next, the authors have investigated the effect of the number of tanks on particulate matter distribution in multi-tank systems and observed that more than 60% of the particle mass input was retained in the first tank. By increasing the number of tanks, the particle mass reaching the final tank becomes constant despite changes in the flowrate and influx particle mass. Furthermore, a soluble contaminant entering a multi-tank system was observed to reside within the system for a prolonged time by approximately a factor of two, which is favorable for developing a response strategy. It is recommended by the authors that at least three tanks should be used to gain the benefits of a multiple-tank RWH system.

Finally, this research tried to quantify the amount of soluble contaminant influx (salt) that can be removed when the drain is operated, and the water overflowed. More than 20% of the pollutant influx was removed when the drain was operated at half capacity level in a single tank system. In a multi-tank RWH system, operation of the drain in the second tank was more effective than using the drain of the first tank. A significant amount of soluble pollutants can be removed with overflow, specially, in a single tank system. The results of this study can be used to suggest operational and automation recommendations.

Keyword: rainwater harvesting; water quality; particle resuspension; residence time; inlet/outlet configurations; multiple tank system; low impact development; drain; particle separation

Student number: 2019-24401

Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

1.1. Background

1.1.1. Rainwater Harvesting and inlet/outlet configurations

Potable water is an essential human requirement. However, due to the spatial and temporal variation of water resources, at least 10% of the global population has no access to potable water (WHO/UNICEF, 2014). As a result, approximately 500,000 children die every year worldwide (UNICEF, 2014). This crisis is exacerbated by climate change, environmental pollution, and rapid urbanization, which cause existing water bodies to become depleted or unusable. Rainwater has been identified as an excellent alternative water source due to its short pollutant inflow route (Won et al., 2019). Rainwater can be collected from impervious surfaces, such as the roof of a house, as shown in Figure 1a, then stored and treated to meet the water quality standards for its intended use. This practice of rainwater harvesting (RWH) in urban centers has the potential to avert urban crises not only by providing an alternative source of water, but also by reducing urban runoff and the demand imposed on central drinking water supply systems (Coombes at al., 2002; Coombes at al., 2000; Campisano et al., 2017).

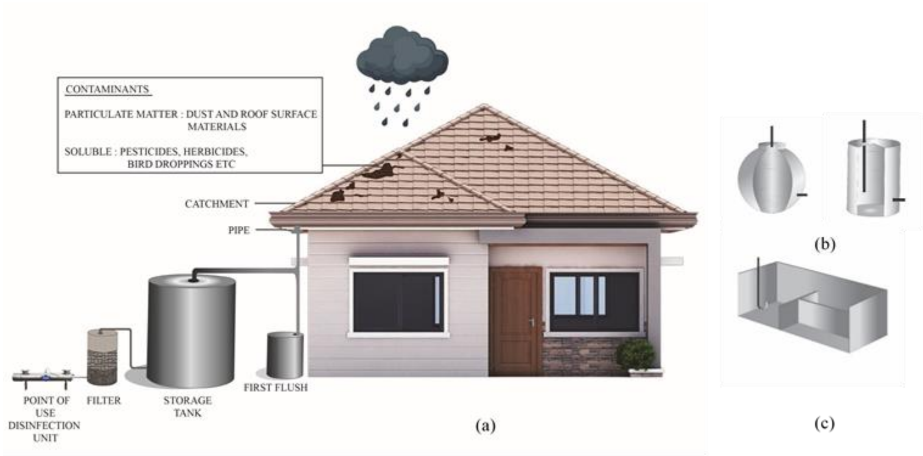


Figure 1 (a) Typical rainwater harvesting system (RWH), (b) typical inlet/outlet configurations in a storage tank, and (c) RWH system with a calmed inlet proposed by Won et al., 2019.

Although the benefits of RWH are significant, several have reported poor harvested rainwater quality due to high concentrations of particulate matter and chemicals such as herbicides and pesticides (Simmons et al., 2001; Sanchez et al., 2015). The majority of these pollutants enter the RWH system through wet and dry deposition on the roof surface, a lack of maintenance, and leaching from built materials, among which dry and wet deposition on the catchment surface represents the main pollutant source (Han et al., 2004; Lee et al., 2012). After a long dry period, the initial part of a storm event will transport very high concentrations of accumulated pollutants from the roof top to the RWH system (Spinks et al., 2003, Van Metre & Mahler, 2003). As particulate matter in the initial water inflow can affect the disinfection process and clog the piping system, the concentration of suspended solids in the water should be reduced by sedimentation during storage. Additionally, the soluble contaminants entering the system should be mixed, diluted, and retained to prevent the contaminants from rapidly reaching the end-use point in high concentrations. Therefore, the individual elements comprising RWH systems should be designed with these objectives in mind.

A common RWH system (Figure 1a) may contain a first-flush device, a storage tank, and a point-of-use disinfection unit. Of these units, the first-flush device and storage tank primarily contribute to removing particulate matter and diluting the instantaneous input of soluble contaminants. A first-flush unit can remove a significant amount of particulate matter and soluble contaminants from the initial part of rainfall; however, RWH systems in most developing countries are still primitive in design and do not contain a first-flush device (Thomas, 2014). Moreover, low rainfall intensity and prolonged dry periods may result in pulse contaminant inputs partially bypassing the first-flush device (Egodawatta et al., 2009). Therefore, the design of the storage tank in an RWH system is vital because any pollutants bypassing the first-flush device will enter the RWH tank. The most important process in a storage tank is the sedimentation of suspended solids, hydrocarbons, and heavy metals associated with particles. Sediment in an RWH tank can hold a significant amount of lead compared to the overlying water column (Spinks et al., 2005); therefore, resuspension of this bottom sediment could degrade the stored water quality, which can occur due to low cistern levels or the turbulent influx of rainwater during a rainfall event

(Scot & Waller, 1987). Therefore, there is a need of investigating how the design of inlet/outlet configurations affect these phenomena.

1.1.2. Evolution from single storage tank systems to multiple tank systems

Most modern RWH systems in the developed countries comprise energy intensive membrane filtration units to upgrade harvested rainwater quality to drinking water quality standard. However, as Campisano et al., 2017 has highlighted in their review, there is a need to develop low-cost treatment methods to overcome financial constraints in developing countries to encourage RWH. The review further illustrates the need to assess the benefits of RWH system designs beyond conservation of water. Alim et al., 2020a in their review discuss the suitability of harvested rainwater for drinking water purposes. While the study illustrates the economic feasibility of small scale RWH systems and importance of robust treatment of harvested rainwater prior to consumption, their review does not investigate the impact of design of elements of a RWH system on water quality. Therefore, design of elements of RWH systems in developing countries should be studied in detail to improve the harvested water quality. As climate change threaten the water security in low income regions, RWH systems was observed to have the potential to improve water security even in arid regions 80% of the time (Musayev et al., 2018). Frequent extreme precipitation events are to be expected in the future, which stress on the importance of ensuring the reliability of the performance of RWH systems. While many researches (Zhang et al, 2019, Alim et al., 2020a) emphasize on having larger tank sizes to ensure the reliability of RWH system in terms of water supply, they have overlooked how the design of the storage tank system can affect the water quality. To overcome challenges imposed by climate change and financial constraints in upgrading harvested rainwater quality to potable water quality, modern community-based RWH systems have adopted multiple storage tank systems.

1.1.3. Operations of RWH systems

Drain and Overflow are the two main operations of a RWH tank. By controlling these, we can remove pollutants such as particulate matter and soluble contaminants from the RWH system. With new building certifications such as LEED and BREEAM certifications recommending the harvesting of rainwater, the possibility of using the operations and automation of RWH systems should be investigated to upgrade the quality of harvested rainwater. However, the studies on this regard are very limited.

1.2. Objectives

The primary objective of this research is to find cost-effective solutions to improve the harvested rainwater quality in developing countries where treatment options are limited due to financial constraints. We have tried to attain that broader objective by breaking it down to three specific objectives as follows:

1. Determine the influence of different types of inlet/outlet configurations and operational parameters (initial water level and mass of bottom

sediment) on minimizing bottom sediment resuspension and maximizing residence time of a conservative pollutant (tracer).

2. Investigate the particulate matter distribution in single, two-tank, and three-tank RWH systems, under a pulse particle (kaolin clay) input, to assess which tank retains the highest percentage of particles, and to devise recommended operation guidelines. Besides, tracer tests using a conservative pollutant (salt) have been conducted to identify the influence of the number of tanks in an RWH system in maximizing the residence time of the conservative pollutant.
3. Quantify contaminant (salt) mass that can be removed using the drain and overflow operations of one, two and three tank RWH systems
4. The results of this study are used to propose recommendations for a new RWH tank design as well as modifications to existing tanks.

1.3. Research Scheme

This research thesis consists of 6 chapters. Chapter 1 contains the research background, objectives, and research scheme. A thorough literature review on research objectives is presented in chapter 2. Chapter 3 presents a discussion on the investigation carried out to assess the effect of inlet/outlet configurations on harvested in water quality. Chapter 4 describes the experiments carried out investigating the effect of number of tanks on harvested rainwater quality for multiple tank system under a sudden pollutant input. The operational parameters of RWH systems were investigated in Chapter 5, and the conclusions of the study are presented in Chapter 6.

Chapter 2. Literature review

2.1. Inlet/outlet configurations of RWH systems

Won et al., 2019; Master Plumbers and Mechanical Services Association of Australia, 2008; Novak, 2014; Haq, 2018 observe that, instead of a typical inlet arrangement (Figure 1b), a calmed inlet reduces the resuspension of sludge (Figure 1c). Further, Master Plumbers and Mechanical Services Association of Australia, 2008; Younos & Parece, 2016 suggest the use of floating outlets that allows the water near surface where suspended particles are at the lowest concentration to be taken up by pumps. However, the authors did not investigate the effect of inlet height/outlet height configurations on sediment resuspension. Magyar et al., 2011 extensively experimented with the effects of inlet position, outlet height, and inlet height with a normal I type inlet. The authors conclude that inlet height has no significant influence, and that high inflow rates, higher bottom sediment thickness, and centrally located inlets could increase the bottom sediment resuspension. However, their work did not investigate how the calm inlet could influence bottom sediment resuspension with varying inlet/outlet configurations. Similarly, no previous research discusses the effect of the inlet and outlet configurations of the storage tank of an RWH system on the dilution and residence time of a soluble pollutant input. RWH systems in developing countries consist of only an RWH tank due to financial constraints of people and the government (Amos et al., 2016; Kahinda & Taigbenu, 2011). If a change of inlet/outlet configurations could have a positive impact on water quality, it would be economically feasible to adopt them in developing countries. Moreover, organizations promoting rainwater, such as governments of developing countries and NGOs, will be able to assist communities financially in such an endeavor.

2.2. Multi-tank RWH systems

A multiple tank rainwater storage system is a system in which, instead of having one large storage tank for the designed volume, the volume is divided among several (two or more) small-sized storage tanks that are connected serially. When the volume is divided among small multiple tanks, the retention time in one tank becomes less. Further, the first tanks are expected to act as a retaining reservoir for pollutants entering the system, thus preventing the contaminants from reaching the other tanks. Many such systems have been deployed successfully around the world (Kim et al., 2016), especially in Vietnam (Dao et al., 2017; Thuy et al., 2019, Bak et al.,2020, Thuy et al., 2020). At Cukhe Elementary School in Vietnam, a two-tank RWH system has been implemented (Dao et al., 2017), and a three-tank RWH system has been implemented at Ly Nhan District Hospital in Vietnam (WHO, 2019) to provide drinking water from harvested rainwater. The published material on these projects demonstrates that the monitored water quality parameters are within the drinking water quality standards of Vietnam and the WHO. The number of tanks for these systems have been selected on an ad hoc basis; depending on the availability local resources. The monthly water quality parameters measured at the outlets of these systems do not reflect the improvement in particle separation efficiency over a single tank system. As pollutants enter in to RWH system as a pulse input, these multiple tank systems should be assessed for their particle separation efficiency.

2.3. Studies on Operations of RWH systems

(Commonwealth of Australia, 2010) recommended not to drain the tank frequently to utilize the biofilm to upgrade the harvested water quality. Similar recommendations were given by Kim and Han, 2016. However, these studies only focused on microbial water quality, therefore, a research gap exists on how we can utilize the drain and overflow operations of RWH tanks to improve the water quality.

Chapter 3. Effect of inlet/outlet configuration on water quality in a rainwater harvesting tank

3.1. Material and methods

3.1.1. Experimental Method

3.1.1.1. Sediment Resuspension Experiment

The shape, capacity, and dimensions of RWH tanks vary according to the manufacturer in each country. Therefore, a cylindrical acrylic laboratory scale RWH tank was fabricated with a diameter of 15 cm and a height of 20 cm for the purpose of the study. The tank was fabricated by downscaling by a factor of 10 from domestic scale cylindrical RWH tanks widely used in developing countries such as India and Sri Lanka, while keeping geometric similarity (Haq, 2018; Pe Plus, 2020). The height of the tank at a volume of 3 L (H) was calculated and outlets were made at 0.33 H and 0.6 H. Three types of inlets were fabricated, as shown in Figure 2, each with an internal diameter of 5 mm and a height of 25 cm. The inlet diameter was selected considering the pipe velocity range stipulated in (Housing and Building Research Institute, 2011). Then, 2 g of reagent-grade kaolin clay ($Al_2H_4O_9Si_2$, molecular weight: 258.156 g/mol) purchased from Deajung chemicals & Metals, South Korea, was mixed with 500 mL of double-distilled water. The solution was then introduced to the tank and another 500 mL of double-distilled water was added so that the kaolin concentration in the tank was 2 g/L. Then, the clay solution was left for 24 h to facilitate clay particle sedimentation. After 24 h, double-distilled water was introduced by a pump (FH100, Thermo scientific) until the tank reached its full capacity of 3 L. The inlet/outlet configurations were varied, but the other parameters were kept constant, as described in Table 1. Turbidity (Hach 2100Q, Loveland, CO, USA, standard error (∓2%) was measured at 30 s intervals after the water was introduced to the system by collecting 25 mL water samples from the outlet at 0.33 H for 2 min. As this study investigates the influence of inlet/outlet configurations on bottom sediment resuspension while there is an inflow, turbidity was measured until the tank reached full capacity. Further, to verify the resuspension of sediments, water was drained from a drain valve at a height of 1 cm from the bottom and then analyzed for suspended solids concentration. The 25 mL samples collected for turbidity measurement were also added to the drained water prior to the suspended solids analysis. The 25 mL samples collected for turbidity measurement were also added to the drained water prior to the suspended solids analysis.

Table 1 Specifications of the sediment resuspension experiments and tracer study experiments.

Experiment	Parameter Investigated	Inlet Type	Inlet Height/H	Flow Rate (L/min)	Initial Water Level/H	Amount of Kaolin Settled after 24 h (g)	Outlet Height/H
Sediment resuspension	Effect of inlet type	I, L, J	0.25	1.5	0.33	2	0.33
	Effect of inlet height	J	0.1, 0.25, 0.5	1.5	0.33	2	0.33
	Effect of flow rate	J	0.25	1.5, 2, 2.5	0.33	2	0.33
	Effect of initial water height	J	0.25	1.5	0.33, 0.5, 0.75	2	0.33
	Effect of amount of bottom sediment	J	0.25	1.5	0.33	0.5, 1, 2	0.33
Tracer test	Effect of inlet type	I, L, J	0.25	1.5	0.33	-	0.33
	Effect of inlet height	J	0.1, 0.25, 0.5	1.5	0.33	-	0.33
	Effect of flow rate	J	0.25	1.5, 2.2	0.33	-	0.33
	Effect of outlet height	J	0.25	1.5	0.33	-	0.33, 0.6

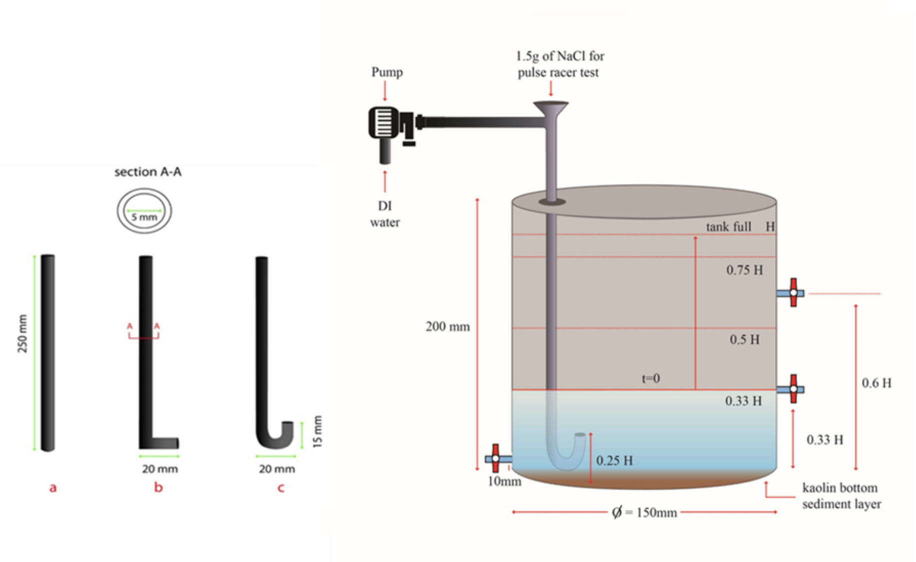


Figure 2 Inlet types considered (a, I type; b, L type; c, J type) in the particle and tracer experiments (left) and experimental set up (right). NaCl was added for the tracer test and kaolin clay bottom sediment was present only for the particle resuspension experiment

3.1.1.2. Pulse Conservative Tracer Experiment

The tank and the experimental set up (Figure 2) were similar to those of the sediment resuspension experiment. Double-distilled water was introduced at 1.5 L/min and 2.2 L/min using a metering pump (FH100, Thermo scientific). Flow rates were determined to capture the most frequent rainfall intensity of 70 mm/h (for a 100 m^2 surface) during summer in South Korea (Ministry of land, infrastructure and transport, 2016). Reagent-grade sodium chloride (salt), purchased from Daejung chemicals & metals, South Korea, was used as the conservative tracer. Sodium chloride was selected because it is found as a common pollutant in RWH systems near coastal areas and it is a conservative material that is widely used in tracer studies. The tracer was introduced to the system instantaneously after the system reached a steady state. Inflow was continued at a steady state, the inlet (I, L, J type inlets) was placed at 0.25 H, and the water level in the tank was maintained at 3 L. The outflow valve at 0.33 H was kept open and, after introduction of the tracer, a water sample was collected from the outlet every 30 s for 15 min. The samples collected were then analyzed for conductivity using a portable conductivity meter (Orion star A329, Beverly, MA, USA). The conductivity meter was calibrated using 1413 mg/L and 12.9 mg/L standard solutions. Conductivity was converted to concentrations using the inbuilt conversion function of the conductivity meter (with 0.5% of reading ±1-digit accuracy), which was validated by manual calculations.

To investigate the effect of inlet height, the J type inlet was placed at 0.25 H, 0.5 H, and 0.75 H and the tracer test was conducted using the method described above with the outlet fixed at 0.33 H. Similarly, the effect of outlet height was investigated by operating the outlets at 0.33 H and 0.6 H with the inlet fixed at 0.25 H. All experimental details are provided in Table 1.

3.1.2. Analysis Method: Residence Time Distribution (RTD)

The RTD represents the time a tracer spends in the reactor and can be used to analyze steady-flow systems with dimensionless parameters to describe concentration and time (Benjamin & Lawler, 2013). In the context of rainwater harvesting systems, a nonplug flow RTD with a higher residence time is preferable because it provides time for suspended particles to settle and prevents contaminants from reaching the outlet in high concentrations. Therefore, understanding the RTD of an RWH tank is beneficial and the RTD can be obtained by plotting the dimensionless tracer mass exiting the outlet with dimensionless time. The dimensionless mass (concentration) exiting the outlet (RTD function), E(t), can be defined as:

$$E(t) = \frac{C_i\,\bar{t}}{\sum_i C_k\,\Delta t_i} \tag{1}$$

where C_i is the measured tracer concentration at the outlet, C_k is 0.5 × (C_i + C_{i-1}), and $\bar{t}$ is the mean measured residence time, which is the average time tracer materials stay within the tank and can be calculated as:

$$\bar{t} = \frac{\sum_i t_i\,C_i\,\Delta t_i}{\sum_i C_i\,\Delta t_i} \tag{2}$$

Mean residence time of a tank or a reactor depends on the geometry, flow, and flow velocities. To make the RTD applicable for larger tanks with similar geometrical and flow conditions, a dimensionless parameter for time could be introduced where time is given as a fraction of mean residence time or hydraulic retention time of the tank. The dimensionless time parameter, θ, can be expressed as:

$$\theta_i = \frac{t_i}{\bar{t}} \tag{3}$$

A cumulative RTD (F), the cumulative fraction of tracer mass that has exited the tank, can be defined as:

$$F(t) = \frac{\sum_i E(t_i) + E(t_{i-1}) \Delta t_i}{2} \tag{4}$$

and the variance of the RTD curve σ^2 can be derived from the tracer data as follows:

$$\sigma^2 = \frac{\sum_i {t_i}^2 \ C_i \ \Delta t_i}{\sum_i \ C_i \ \Delta t_i} - \bar{t}^2 \tag{5}$$

3.2. Results & Discussion

2.2.1. Effect of Inlet type

When water was introduced to the system, turbidity first increased due to resuspension then decreased because of dilution (Figure 3). Further, with time, the rising water levels provide cushioning to the incoming water, preventing further resuspension. Thus, the initially resuspended particles get dispersed in a larger volume, resulting in a lower turbidity. However, the final turbidity level and the initial rise in turbidity in the tank with the J type inlet was approximately two times lower than that with an I type inlet (Figure 3). Designs in references Won et al, 2019; Master plumbers and mechanical services association of Australia, 2008; Novak et al., 2014; Haq et al., 2018 incorporated J type inlets, considering the benefit of reduced particle resuspension. Water flow from the inlet stirred the bottom sediments, forcing the settled particles to become resuspended in the water column. This phenomenon was further illustrated by the mass distribution of kaolin clay between the water column and the bottom sediment (Figure 3), i.e., the J type inlet exhibited the smallest amount of suspended particulate matter of all inlet types.

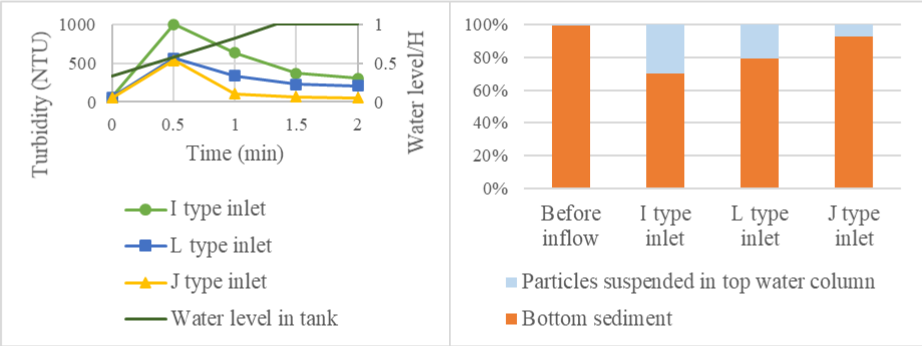
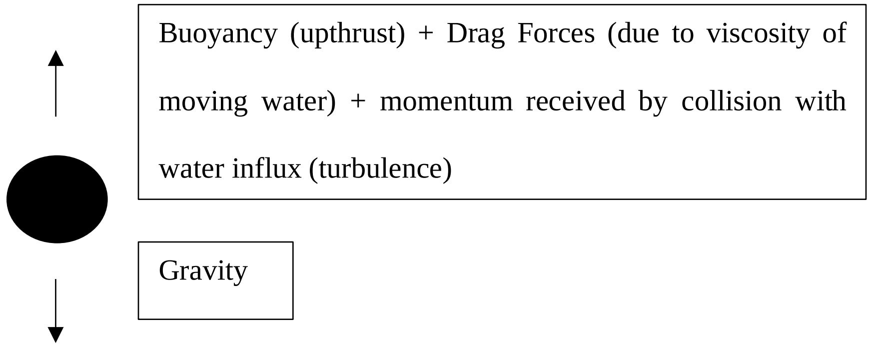


Figure 3 Turbidity variations and the distribution of kaolin mass according to inlet type

The forces acting on a settled particle is as follows:



In the lab scale tank velocity at the inlet ranged from 1.27-2.12 m/s; rising velocity in the tank ranged from 1.4-2.35 mm/s while in a real scale RWH tank it would range from 0.6-2.5 m/s and 0.8-3.2 mm/s respectively. Therefore, the velocities present in the lab scale tank is within the velocity ranges observed for RWH tanks under a 50-200 mm/hr rainfall event. Although, the rainfall events considered in the study represents the rainfall patterns in Korea, this may not represent the rainfall events in other regions. In tropical countries, more extreme precipitation event could occur, which may develop higher inlet and rising velocities. In such cases, a higher bottom sediment resuspension can be expected.

The normalized residence time calculated (Table 2) for the pulse salt tracer input for all inlet types was plotted for a flow rate of 2.2 L/min (Figure 4). The J type inlet exhibited almost identical performance to a continuous flow stirred-tank reactor (CSTR). This is probably due to the turbulence created at the J shaped bend in the inlet, which enabled uniform mixing of the fluids prior to entering the tank. The upward flow induced by the J shaped inlet allowed further mixing of the fluids, resulting in very similar behavior to the CSTR. With I and L type inlets, the RWH tank exhibited performance between that of a CSTR and a plug flow reactor (PFR) (Figure 4). Maus & Uhl, 2010 and Werner & Kadlec, 1996 reported similar results for sedimentation tanks and ponds with the typical inlet conditions used for storm water management.

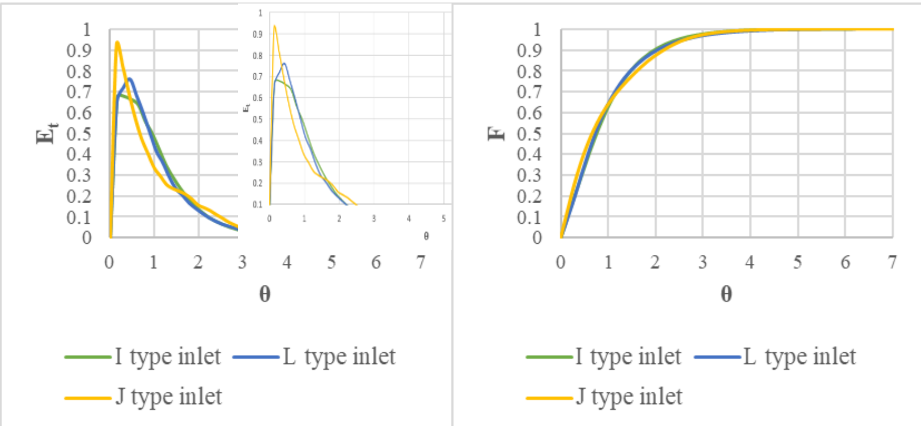


Figure 4 Residence time distribution (RTD) and cumulative RTD for three inlet types (inflow rate 1.5 L/min, inlet at 0.25 H, outlet at 0.33 H).

In addition, we conducted experiments to assess the effect of the curvature on reactor behavior. We modified the J type inlet with an expander and increased the curvature (Figure 5) to observe their effect.

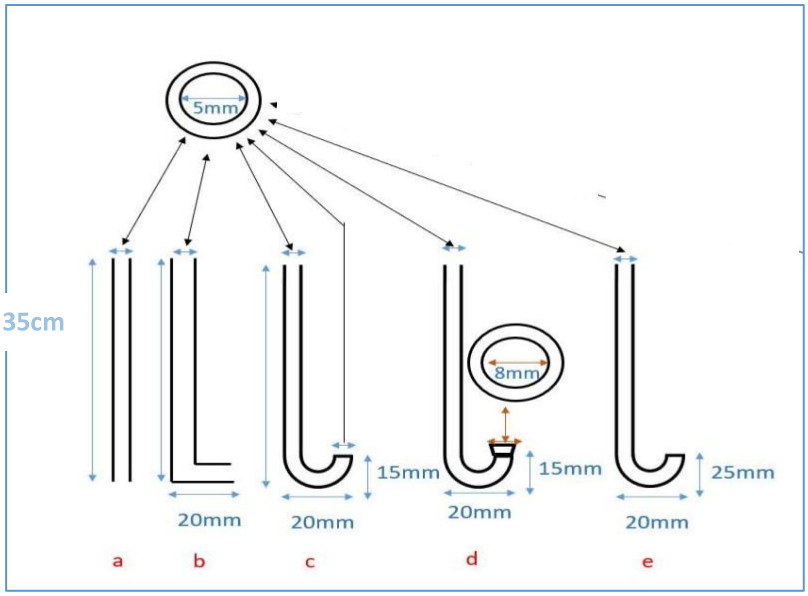
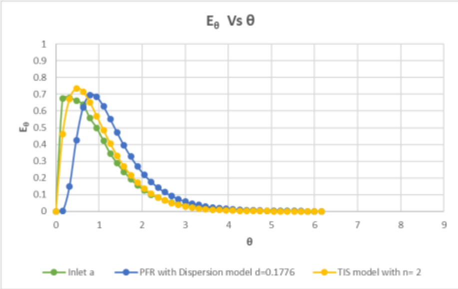
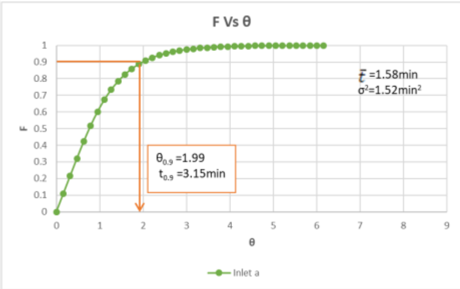


Figure 5 The schematics of the inlets considered in the study to assess their effect on reactor behavior

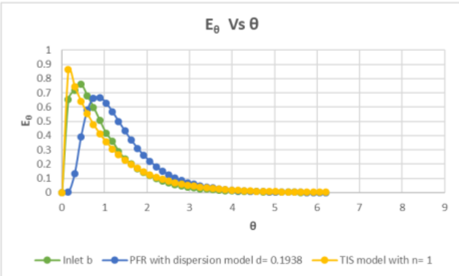
We used the tank in series model (TIS) and plug-flow with dispersion model (PFR) to model the behavior of the tracer when the tank was retrofitted with each inlet. The results demonstrated that the inlet type can affect the reactor behavior (Figure 6). When the curvature of the J type inlet increased, the reactor behavior approached a CSTR with long tails. Mass recovery also reduced when the curvature increased. However, when the J-inlet was retrofitted with a diffuser, the tracer behavior deviated a little from a CSTR (Figure 6).



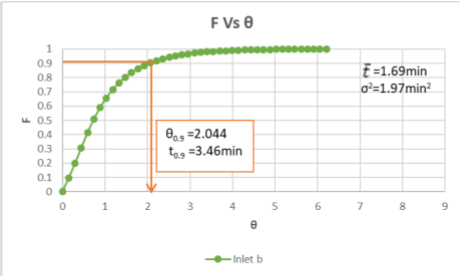
E_θ Vs θ
E_θ
θ
Inlet a
PFR with Dispersion model d=0.1776
TIS model with n= 2



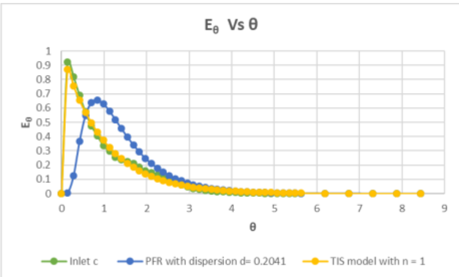
F Vs θ
F
θ
$\bar{t}$ =1.58min
σ^2=1.52min^2
$\theta_{0.9}$ =1.99
$t_{0.9}$ =3.15min
Inlet a



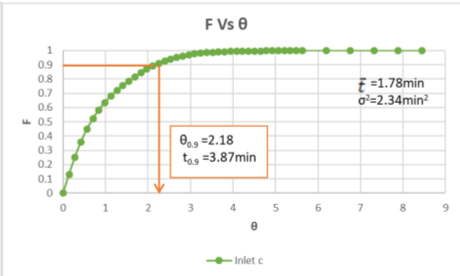
E_θ Vs θ
E_θ
θ
Inlet b
PFR with dispersion model d= 0.1938
TIS model with n= 1



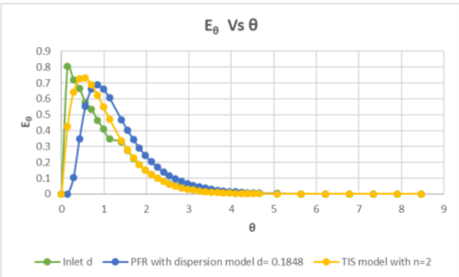
F Vs θ
F
θ
$\bar{t}$ =1.69min
σ^2=1.97min^2
$\theta_{0.9}$ =2.044
$t_{0.9}$ =3.46min
Inlet b



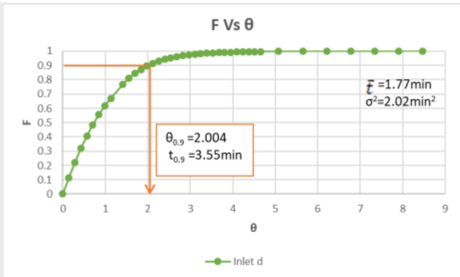
E_θ Vs θ
E_θ
θ
Inlet c
PFR with dispersion d= 0.2041
TIS model with n = 1



F Vs θ
F
θ
$\bar{t}$ =1.78min
σ^2=2.34min^2
$\theta_{0.9}$ =2.18
$t_{0.9}$ =3.87min
Inlet c



E_θ Vs θ
E_θ
θ
Inlet d
PFR with dispersion model d= 0.1848
TIS model with n=2



F Vs θ
F
θ
$\bar{t}$ =1.77min
σ^2=2.02min^2
$\theta_{0.9}$ =2.004
$t_{0.9}$ =3.55min
Inlet d

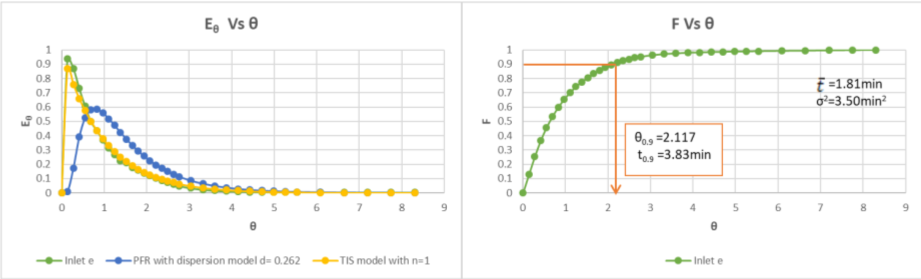


Figure 6 RTD for varying inlet conditions under a flow rate of 1 L/min. TIS and PFR with dispersion model were plotted along with the tracer test data for comparison

As illustrated in Figure 6, a pollutant (tracer) entering a RWH tank with a J-type inlet remains within the tank for a longer time. This is beneficial because a pollutant entering the tank may not reach the outlet in high concentrations. However, in the context of RWH systems, studying the residence time of a tracer does not give much valuable information. Having said that, these findings can be extended to chemical reactors. The results presented in the study demonstrated that inlet conditions can be manipulated to alter the behavior of the reactor to attain the performance of that of a CSTR.

Table 2 Example residence time distribution (RTD) calculations using the method described in Section 2.2 (inlet at 0.25 H, outlet at 0.33 H, flow rate of 2.2 L/min, I type inlet).

Time (min)	**Conductivity (μS/cm)**	**Concentration (mg/L)**	**Δt_i**	**C_k**	**θ**	**E_t**	**F**
0.25	1146.0	453.45	0.25	457.98	0.15	0.67	0.10
0.50	1149.0	454.95	0.25	454.20	0.31	0.67	0.21
0.75	1129.0	444.95	0.25	449.95	0.47	0.66	0.32
1.00	1095.0	427.95	0.25	436.45	0.63	0.63	0.42
1.25	988.4	374.65	0.25	401.30	0.78	0.55	0.51
1.50	908.0	334.45	0.25	354.55	0.94	0.49	0.60
1.75	804.3	282.60	0.25	308.52	1.10	0.42	0.67
2.0	702.0	231.45	0.25	257.02	1.26	0.34	0.73
2.25	624.9	192.90	0.25	212.17	1.42	0.28	0.78
2.50	556.8	158.85	0.25	175.88	1.58	0.24	0.83
2.75	498.9	129.90	0.25	144.38	1.74	0.19	0.86
3.00	446.3	103.60	0.25	166.75	1.89	0.15	0.89
3.25	408.0	84.45	0.25	94.03	2.05	0.13	0.91
3.50	373.1	67.00	0.25	75.73	2.21	0.10	0.93
3.75	348.4	54.65	0.25	60.83	2.37	0.08	0.94
4.00	327.3	44.10	0.25	49.38	2.53	0.07	0.95
4.25	309.5	35.20	0.25	39.65	2.68	0.05	0.96
4.50	295.6	28.25	0.25	31.72	2.84	0.04	0.97
4.75	284.5	22.70	0.25	25.48	3.00	0.03	0.98
5.00	274.6	17.75	0.25	20.22	3.16	0.03	0.98

The mean residence time ($\bar{t}$) increased from the I type inlet to the J type inlet by almost 18% (Table 3). Further, in Table 3, it can be observed that θ at 95% mass recovery has also increased. Therefore, a conservative pollutant concentration entering the RWH system with a J type inlet is likely to remain in the tank for a longer time. This is beneficial for preventing pollutants from entering another tank or other components of the RWH system by allowing the user more time to devise a response, for example, isolation of the contaminated unit or flushing of the tank. Further, higher residence time gives suspended solids in the incoming water more time to settle before reaching the outlet. RTD graphs for J type inlet revealed very long tails that were likely due to the dead space created. Fluids beneath the inlet would have been lightly disturbed, allowing the fluid below the inlet to become trapped within the RWH tank. This was further highlighted by the decreasing mean mass recovery rates (Table 3).

Table 3 Mean residence time, variance of RTD, and mass recovery for all types of inlet.

Inlet Type	$\bar{t}$ **(min)**	σ^2 **(min^2)**	**Mass Recovery %**	θ **at 95% Mass Recovery**
I	2.45	2.49	99.13	2.52
L	2.53	2.92	97.85	2.59
J	2.89	3.51	93.09	2.64

3.2.2. Effect of inlet height

Similar to observations by Magyar et al., 2011 with I type inlets, the inlet height had a minimal impact on sediment resuspension, which was also noted with a J type inlet. This was possibly due to the upward flow conditions created by the inlet, regardless of the height that the inlet was placed. However, there was a slight increase in both turbidity and suspended solids when the inlet height was increased from 0.1 to 0.5 H (Figure 7). The initial water height for this experiment was set at 0.33 H, which may be the reason for this observation. Water exiting the inlet enters the air; thus, impact with the air–water surface may create turbulence that disturbs the bottom sediment layer.

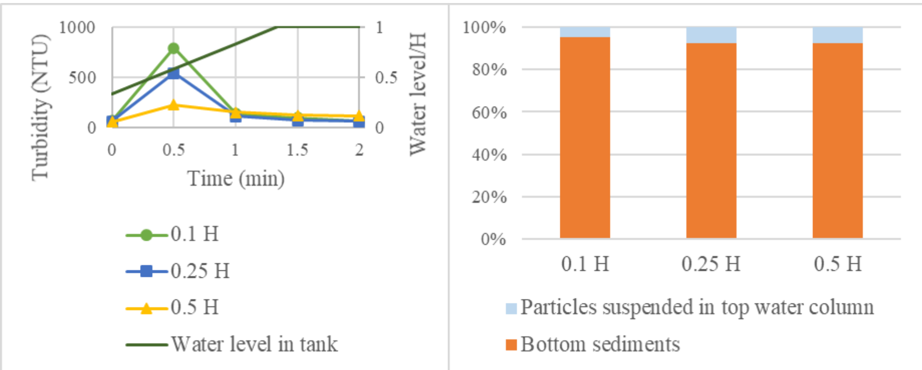


Figure 7 Turbidity variation and distribution of kaolin mass with inlet height (J type inlet).

For the tracer study, the inlet height had no significant influence on the residence time of the conservative tracer; the mean residence time was 2.84, 2.89, and 2.86 min at 0.1, 0.25, and 0.5 H, respectively. Therefore, RWH systems with J type inlets cannot be modified to increase the residence time by changing the inlet height. Furthermore, RWH system design should consider factors such as the structural stability of J type inlets, where vibrations occur due to local energy loss at the J bend. Therefore, placing the inlet at a lower height could be beneficial in terms of structural stability and less sediment resuspension.

3.2.3. Effect of flow rate

Suspended particles in the water column increased by a factor of greater than two (from 7.41% to 18.13%) with an increase in the flow rate from 1.5 to 2.5 L/min, as shown in the kaolin mass distribution (Figure 8). Greater resuspension of bottom sediment with increased flow rates were also observed by Magyar et al., 2011 for I inlets. As the pipe diameter was not changed, the inflow velocity increased from 1.27 m/s to 1.69 m/s and then 2.12 m/s to maintain continuity. This increase in velocity created higher turbulence, facilitating bottom sediment resuspension. Thus, when designing RWH inlets, the pipe diameter should consider the final flow velocity at the inlet. The tracer study showed no significant difference in RTD. Similar RTD curves were observed at higher flow rates but with higher mean residence times, i.e., 1.58, 1.69, and 1.78 min for inlet a, b, and c, respectively.

In this study we considered only J-type inlets. If a tank is retrofitted with an I-type inlet, we may experience a significant bottom sediment resuspension under a high flow rate. The momentum of the water influx can create more turbulence at the bottom, which may give particles settled enough momentum to break gravitational forces acting on it. Therefore, it would be better to go for an inlet with a larger diameter if manufacturers cannot switch to a J-type inlet.

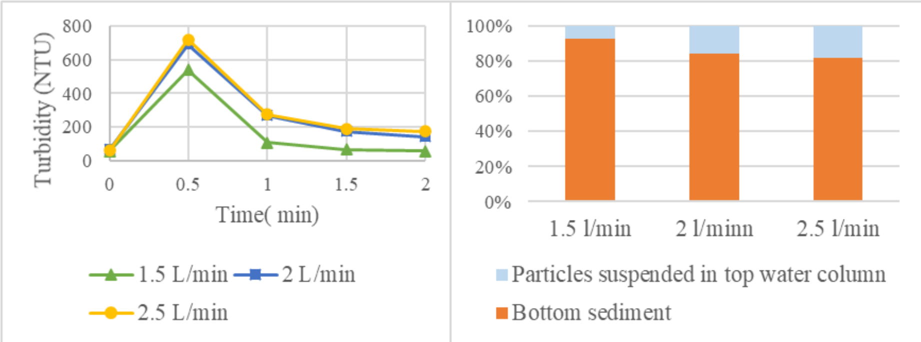


Figure 8 Turbidity variation and distribution of kaolin mass with inflow rate (J type inlet).

3.2.4. Effect of outlet height and initial water level

RTD and cumulative RTD curves obtained for all outlet conditions were almost identical to the graphs shown in Figure 4; thus, significant parameters derived from the RTD are summarized and presented in Table 4. The mean residence time $\bar{t}$ increased by more than 25% with increased outlet height. This was likely due to the increased retention capacity of the tank and dead space with higher outlet height. A conservative contaminant such as salt entering the RWH tank would be retained for a longer period of time, enabling it to be diluted or flushed. Thus, a higher outlet height might benefit a multitank system, but might not be beneficial for a single tank RWH system because a large proportion of the stored water in the tank would be inaccessible. The initial water level is an operational parameter that can provide a cushioning effect on incoming water. In this study, changing the initial water level from 0.33 H to 0.75 H led to an almost 40% reduction in the resuspension of bottom sediments; the mass of suspended solids in the top water column decreased from 7.41% to 4.67%.

Table 4 Mean residence time and variance of RTD for different outlet heights (J type inlet).

Outlet Height	$\bar{t}$ **(min)**	σ^2 **(min^2)**
0.33 H	1.9	2.51
0.6 H	2.4	4.92

3.2.5. Effect of bottom sediment

As expected, the initial turbidity level increased with increasing kaolin dosage. However, after an initial rise, the turbidity returned to almost the initial level for all kaolin doses. According to the mass distribution in Figure 9, a larger amount of particulate matter sediment at the bottom of the tank allowed more particulate matter to be resuspended in the water column. Therefore, it is important to maintain the sludge level of the storage tank at a minimum; this can be facilitated by including a drain valve in the tank design and having a proper maintenance schedule.

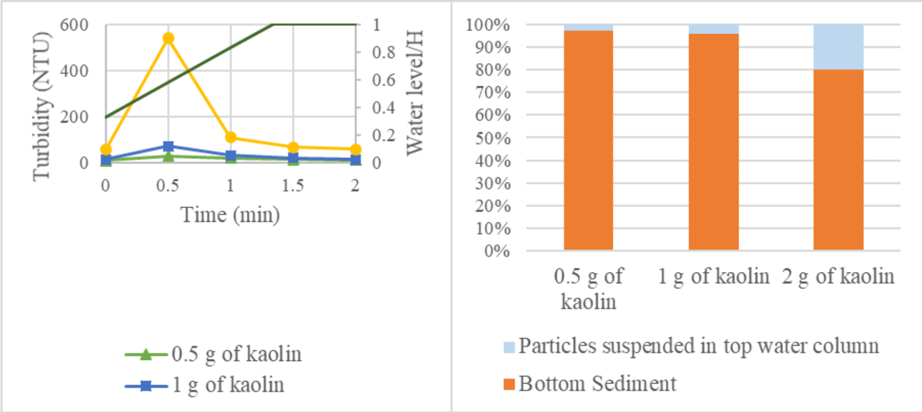


Figure 9 Turbidity variation and kaolin mass distribution for different doses of kaolin clay (J type inlet)

As highlighted in a previous sub-chapter in chapter 2, an I-type inlet create more turbulence at lower parts of the tank, therefore, having a thicker bottom sediment layer inside a tank that has an I-type inlet will re-suspend more particles into the water column. As majority of RWH systems in the world contain I type inlets, the importance of regular cleaning of RWH tank is recommended.

Chapter 4. The effect of number of tanks on water quality in RWH systems under sudden contaminant input

4.1. Material and methods

For the purpose of this study, a downscaled cylindrical, acrylic RWH tank was fabricated, with a diameter of 15 cm and a height of 20 cm, which is similar to the lab-scale RWH tank used in the previous chapter, as the 1- tank system. The height of the tank at a volume of 3 Liters (H) was calculated, and outlets were made at 0.33 H and 0.6 H. A J-type inlet with an inner diameter of 5 mm, placed at 0.25 H, was used to introduce water into the RWH system. The diameter was selected considering the recommended pipe velocity range stipulated by the Housing and Building Research Institute (2011). The flow conditions in the pipe were designed to be turbulent (Re> 4000), similar to the conditions that prevail in large-scale RWH systems. Next, two cylindrical acrylic tanks with diameters of 115 mm and heights of 160 mm were fabricated to be used as the 2-tank system. The height of the tanks at a cumulative volume of 3 Liters (H) was calculated, and outlets were made at 0.33 H and 0.6 H. Similarly, a 3-tank system was developed with tank diameters of 105 mm and heights of 135 mm. The outlet heights were at 0.33 H and 0.6 H, where H is the height corresponding to the 3 Liter cumulative capacity of the 3-tank system. Geometric similarity to the domestic-scale cylindrical tanks widely used in developing countries (Haq, 2018; PE-Plus, 2020) was maintained in all the tanks used in this experiment. The specifications and details of tank systems considered (experimental setup) are presented in Figure 1. Only up to 3- tank systems were considered because, 2- tank and 3- tank systems are the most implemented tank configurations in Africa and South East Asia. Double-distilled water was introduced to the tank systems at flow rates of 1.0 L/min and 2.0 L/min using a metering pump (FH100, Thermo scientific) to simulate the most frequent rainfall intensity during summer in South Korea (Ministry of Land, Infrastructure and Transport, 2016). Flow conditions within the downscaled tanks demonstrated laminar flow conditions (Re < 2100 and Fr <1), which resemble the flow conditions in large-scale RWH systems. When the water level reached 0.33 H, 2 g of reagent-grade kaolin clay ($Al_2H_4O_9Si_2$, molecular weight: 258.156 g/mol) purchased from Daejung Chemicals & Metals, South Korea, was instantaneously introduced to the RWH systems. On roof catchment, sand, clays, silts and dust can get accumulated during a prolonged dry period. While sand can be easily settled, fine particles such clays are hardly settled due to their shape and particle size. Thus, Kaolin clay was selected as the representative particulate matter for this study. Double-distilled water was added to the RWH system until the water level reached the 3 Liter full capacity level. Then, the clay solution was left for 24 h, after which the tanks in the multiple tank systems were isolated and analyzed for total kaolin mass retained in each tank by filtering through a glass microfiber filter. After keeping in the oven at 105 °C for 24 hours, mass retained on the filter was measured. We investigated the effects of flow rate, particle mass, and the outlet height of the first tank, on the mass distribution among the tanks in multiple tank systems. The experimental setup for pulse conservative tracer study, the tank system used, and the flow rates were similar to those of the particle experiment (Figure 10). The experiment procedure and the measuring devices used were similar to the pulse tracer tests conducted in Chapter 3. All experimental details related to both pulse particle and pulse tracer experiments are provided in Table 5.

Table 5 Specifications of pulse particle and conservative tracer experiments

Experiment	Parameter investigated	Flow rate	No. of tanks	Particle mass (kaolin clay)	Outlet height
Pulse particle input experiment	**Effect of no. of tanks**	1 L/min	1,2,3	2g	0.33H
	Effect of flow rate	1, 2 L/min	1,2,3	2g	0.33H
	Effect of particle (kaolin clay) mass input	1 L/min	1,2,3	0.5g, 1g, 2g	0.33H
	Effect of 1st tank outlet height	1 L/min	2	2g	0.6, 0.33H
Pulse conservative tracer studies	**Effect of no. of tanks**	1 L/min	1,2,3		0.33H
	Effect of flow rate	1,2 L/min	1,2,3		0.33H
	Effect of 1st tank outlet height	1 L/min	2		0.6, 0.33H

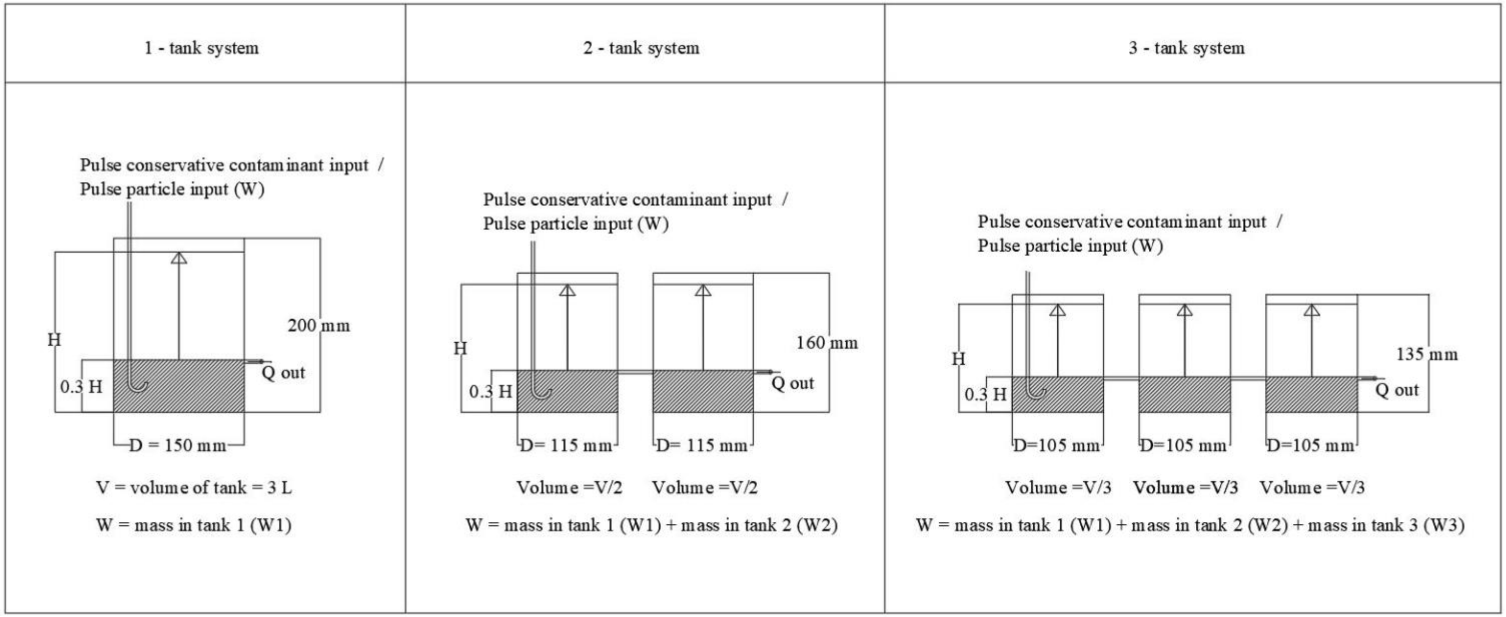


Figure 10 Experimental setup and the specifications of the multiple tank systems used in both pulse particle input and pulse tracer study experiment

4.2 Results & Discussion

4.2.1. Pulse Particle Input

4.2.1.1 Effect of the number of tanks

From the results of the pulse particle input experiment, it can be observed that tank 1 holds most (>60%) of the input particle mass as depicted in Figure 11. This is similar to the observations made by Dao Anh Dung (2019) in 2-tank RWH systems implemented at Cukhe Elementary School and Daicuong Elementary and Middle School in Vietnam. The turbidity of the water entering the first tank of these systems was reduced by a factor of 60-70%, while the total dissolved solids remained almost constant. Thus, the reduction in turbidity could be directly attributed to the reduction in suspended solids. When the number of tanks increased, the kaolin mass retained in tank 1 reduced from 100% to 68%. When the volume of tank 1 is reduced from 1- tank system to the 3-tank system, the retention time has reduced, allowing the particles entering tank 1 to reach the outlet of tank 1 faster. This phenomenon could be attributed to the reduction in kaolin mass retained in tank 1. Won and co-workers in 2019 investigated the effect of having an intermediate wall with varying height ratios and length ratios within a RWH tank to improve particle separation. They observed that when the intermediate wall was placed in the middle of the tank, 99% of the particles were retained even though the wall had a height of just 20% of the tank height. In a multiple tank system, tank wall acts as the intermediate wall employing the full height of the tank, and the diameter of a tank in 3- tank system is about 70 – 80% of 1-tank system tank diameter. The first tank of our 3- tank system managed to retain less than 70% of particle influx with outlet placed at 0.33 H which seems less efficient compared to an intermediate wall. Therefore, changing the geometry of the first tank of a multi-tank system to a small thinner tank with a higher outlet may increase particle separation efficiency. However, with a small thinner tank, retention time will be less, which would promote fast movement of particles from the first tank to other tanks. Therefore, the effect of geometry of the first tank on particle separation must be studied extensively.

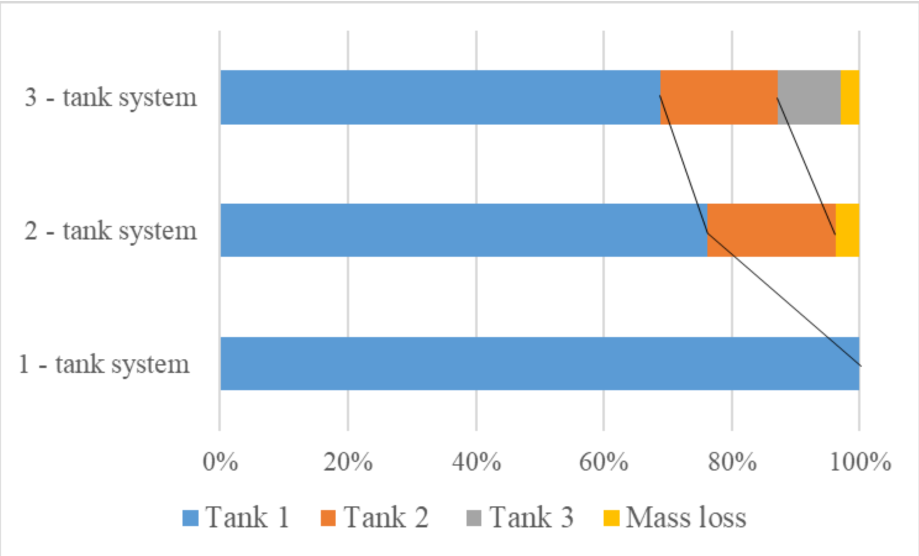


Figure 11 Distribution of 2 g of kaolin mass input among tank 1, tank 2 and tank 3 in 1-tank, 2-tank and 3-tank systems under a flow rate of 1 L/min

With time, particles retained in each tank will settle and get accumulated in the bottom sediment layer. As highlighted by the previous chapter and Magyar et al., 2011, a thicker bottom sediment layer will result in higher sediment resuspension. Therefore, systematic operation of drain valves in a multiple-tank system is important in maintaining good particulate water quality. Operation of the drain valve of tank 1 after a rainfall event would probably remove the majority of particulate matter entering the RWH system. Moreover, when the number of tanks was increased, particles carried on to the final tank of each system were reduced. This is favorable in an RWH system because filtration units could have a longer cycle time, and in developing countries where sophisticated filters do not exist, output water would be of better quality in terms of particulate matter. Furthermore, as particulate matter carried on to the last tank of 2- tank and 3- tank system is less, frequent draining of these tanks are not necessary. By doing so, wastage of stored rainwater can be mitigated. The surface area to volume ratio of the RWH system has increased by a factor of 1.8 from 1- tank system to 3- tank system, which would affect the biofilm growth within the tank system (Kim and Han, 2016). Biofilm growth can be attributed to the microbial water quality of harvested rainwater thus, how the number of tanks affect the biofilm growth and microbial water quality needs to be investigated. Regardless, a separate unit for disinfection of microbes is needed to ensure the safety of harvested rainwater for drinking water purposes.

4.2.1.2. Effect of flow rate

When the flow rate increased, the kaolin mass retained in the 2nd tank of the 2-tank system increased by a factor close to two (Figure 12). High flow rates create high turbulence and high velocities, which can prevent particles from settling and increase the re-suspension of already sedimented particles (Magyar et al., 2011; Maruejouls et al., 2013). This may have caused the increase in mass retained in tank 2. However, in Figure 3 it can be seen that in the 3-tank system there was no significant difference in mass distribution. The mass retained in tanks 2 and 3 increased only by approximately 7% and 4%, respectively. This demonstrates that when the number of tanks increases, the RWH system is able to perform consistently under changing flow rates. In the context of RWH, the flow rates could vary drastically due to unpredictable rainfall intensities (Alim et al., 2020a); an RWH system that can perform consistently is therefore preferable.

The flowrates we have considered in this study correspond to rainfall intensities in South Korea. Consequently, these results may vary in countries where the rainfall intensities change. In tropical countries where the rainfall intensities are high, we can expect a higher number of particles to reach the last tank, whereas in countries that receive rainfall at low intensities can expect majority of particulate matter to be retained in the first tank. At low rainfall intensities Reynold's number is low suggesting that the flow is less turbulent. This gives particulate matter the opportunity to settle down while traversing across the width of the tank. In contrast, we can expect a higher particle mass to be retained in the last tanks when Reynold's number is higher.

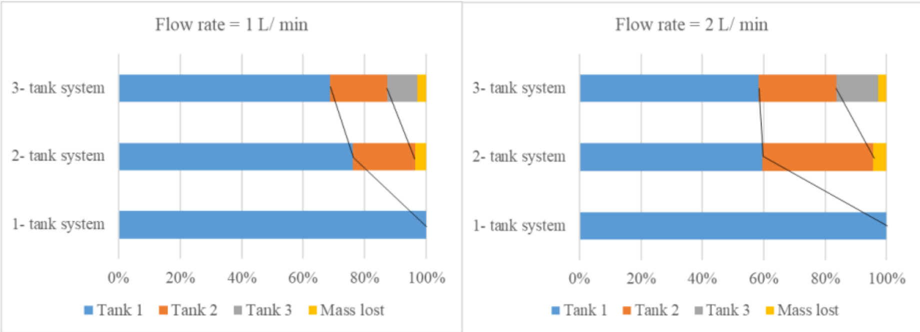


Figure 12 Distribution of 2 g of pulse kaolin mass input in 1-tank, 2-tank and 3-tank systems under 1 L/min and 2 L/min flow rates

4.2.1.3. Effect of particle mass input

When the kaolin mass input increased, more mass tended to be retained in the first tank of the 3-tank RWH systems (Figure 13). For 2- tank system, when kaolin dose increased, the increase of kaolin mass retained in tank 1 was insignificant. The kaolin mass retained in tank 3 of 3- tank system reduced from 12% to 9% when the kaolin dose increased. This is a desirable effect because prolonged dry periods could bring a significant amount of particulate matter into the RWH system, especially if the catchment area is not properly maintained. In contrast, when the particle input is low (such as the case of 0.5 g of kaolin input), a slight increase in the particle proportion in the third tank of a 3-tank system was observed. This is due to the lower probability of colliding and agglomerating with other particulate matter in previous tanks, resulting in Brownian motion and advective forces carrying particles to the last tank. Overall, under all kaolin mass inputs, all RWH systems seem to perform consistently, with negligible variations.

The negligible changes in the mass distribution observed when the particle mass influx increased, may be due to bottlenecking at connection pipes. Besides, the transportation of the particles is governed by the movement of water. Despite the mass increase, the Reynold’s number in the system remains constant, thus the forces acting on particles remains the same. This may also be a reason why the system showed an indifference towards the change of mass influx.

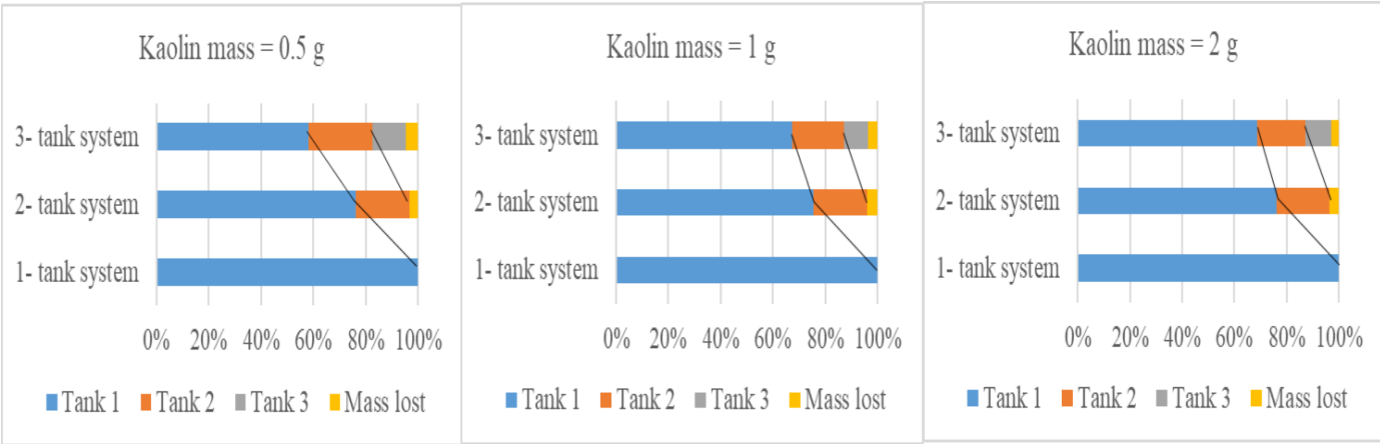


Figure 13 Distribution of varying pulse kaolin mass inputs (0.5 g, 1 g, 2 g) in 1- tank, 2- tank and 3- tank systems under a flow rate of 1 L/min

4.2.2. Pulse conservative tracer study

4.2.2.1. Effect of the number of tanks

The normalized residence time calculated (Table 6) for the pulse tracer test for all tank arrangements considered in this study was plotted for a flow rate of 1.0 L/min (Figure 14). It can be observed that the 1-tank system exhibited almost identical performance to a continuous flow stirred-tank reactor (CSTR) owing to the turbulence created by the calm inlet. However, when the number of tanks was increased, the performance of the overall system deviated from an ideal CSTR. Similar results have been observed by many researchers for sedimentation tanks and ponds connected in series (Maus and Uhl, 2010; Werner and Kadlec, 1996). In Figure 14, it can be observed that the peak of the residence time was reduced when the number of tanks increased. This is desirable in the context of an RWH system, as it prevents a sudden pollutant input from reaching the outlet at a high concentration. Furthermore, the mean residence time (the average time a tracer stays within the tank) increases by a factor of almost two from the 1-tank system to the 3- tank system (Table 7). This is further illustrated by the increment of θ at 50% mass recovery by a factor greater than two. This may have been due to previous tanks retaining part of the tracer within the volume of the tank. While the results obtained in this study can be extended to other conservative pollutants, the findings of this study are hardly applicable to non-conservative pollutants such as natural organic matter. There are other processes such as biodegradation and photo degradation that must be considered for such chemicals and investigating this is an interesting topic for future studies. Further, this study only investigates the behavior of a conservative pollutant input in a multi-tank system, and it does not investigate how soluble contaminants can be removed although, particle removal could indirectly affect the removal of some soluble contaminants. Therefore, community based multiple tank RWH systems can incorporate a gravity fed activated charcoal filter such as the filter suggested by Alim et al., 2020b to ensure the removal of chemicals present in harvested rainwater.

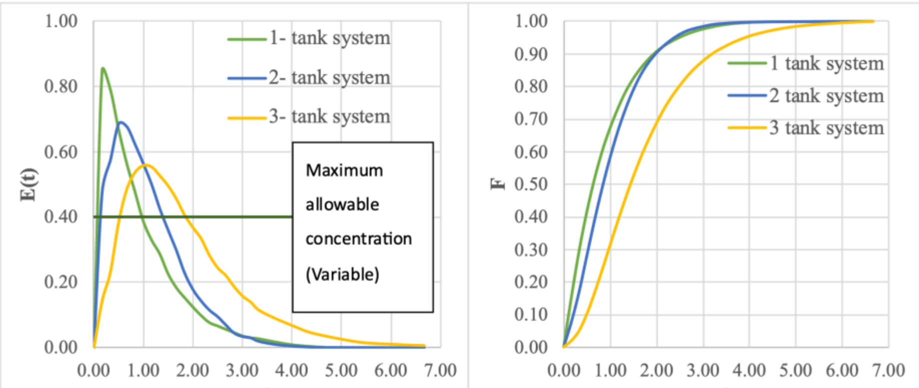


Figure 14 Residence time distribution (RTD) (E(t)) and cumulative residence time distribution (F) for 1, 2 and 3-tank systems for an inflow rate 1 L /min, and outlet height at 0.33 H

Table 6 A sample calculation of normalized residence time distribution (2-tank system, flow rate: 1 L/min, outlet height at 0.33 H)

Time	Conductivity (μS/cm)	Concentration (mg/L)	Δt_i	$C_i\Delta t_i$	$t_iC_i\Delta t_i$	$t_i^2C_i\Delta t_i$	C_k	θ	$C_k\Delta t_i$	E(t)	F(t)
0.00	224.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.50	1240.40	558.80	0.50	279.40	139.70	69.85	558.80	0.17	279.40	0.85	0.15
1.00	1100.70	481.97	0.50	240.98	240.98	240.98	520.38	0.33	260.19	0.79	0.30
1.50	948.20	398.09	0.50	199.05	298.57	447.85	440.03	0.50	220.01	0.67	0.42
2.00	848.50	343.26	0.50	171.63	343.26	686.51	370.67	0.67	185.34	0.56	0.52
2.50	739.60	283.36	0.50	141.68	354.20	885.50	313.31	0.83	156.65	0.48	0.60
3.00	634.90	225.78	0.50	112.89	338.66	1015.99	254.57	1.00	127.28	0.39	0.67
3.50	603.10	208.29	0.50	104.14	364.50	1275.75	217.03	1.17	108.52	0.33	0.73
4.00	531.70	169.02	0.50	84.51	338.03	1352.12	188.65	1.33	94.33	0.29	0.78
4.50	458.50	128.76	0.50	64.38	289.70	1303.64	148.89	1.50	74.44	0.23	0.82
5.00	430.10	113.14	0.50	56.57	282.84	1414.19	120.95	1.67	60.47	0.18	0.86
5.50	385.50	88.61	0.50	44.30	243.66	1340.15	100.87	1.83	50.44	0.15	0.89
6.00	362.40	75.90	0.50	37.95	227.70	1366.20	82.25	2.00	41.13	0.12	0.91
6.50	322.60	54.01	0.50	27.01	175.53	1140.96	64.96	2.17	32.48	0.10	0.93
7.00	310.90	47.58	0.50	23.79	166.51	1165.59	50.79	2.33	25.40	0.08	0.94
7.50	298.00	40.48	0.50	20.24	151.80	1138.50	44.03	2.50	22.01	0.07	0.95
8.00	285.90	33.83	0.50	16.91	135.30	1082.40	37.15	2.67	18.58	0.06	0.96
8.50	274.40	27.50	0.50	13.75	116.88	993.44	30.66	2.83	15.33	0.05	0.97
9.00	261.60	20.46	0.50	10.23	92.07	828.63	23.98	3.00	11.99	0.04	0.98
9.50	261.30	20.30	0.50	10.15	96.40	915.81	20.38	3.17	10.19	0.03	0.98
10.00	253.70	16.12	0.50	8.06	80.58	805.75	18.21	3.33	9.10	0.03	0.99

Table 7 Mean residence time, variation and θ at 50% mass recovery for 1,2 and 3- tank systems for the flow rate 1 L/min and outlet height at 0.33 H

	$\dot{t}$	σ^2	Θ at 50% mass recovery
1-tank system	2.71	5.31	0.64
2-tank system	3.1	4.44	0.85
3-tank system	5.07	11.28	1.44

4.2.2.2 Effect of outlet height in the first tank

We observed a 25% increase in mean residence time of the salt tracer when the outlet height was increased to 0.6 H from 0.33 H. This implies that a conservative contaminant entering the system would require a longer time to reach the outlet, which would be beneficial in devising a response strategy, particularly in an automated system. In addition, we observed an 11% reduction in kaolin mass in the second tank of the 2-tank system when the outlet height of the first tank was increased. This may be due to the increase in retention capacity and dead space in the first tank with increasing outlet height. This corroborates with the findings of Magyar et al., 2011 where the water collected from an outlet at a higher level demonstrated lesser amount of suspended solids.

Nevertheless, the study emphasized that having a higher outlet will not be economical for a single tank system due to water loss. However, for a multi-tank system, having a higher outlet in the first tank could provide a multitude of benefits which should be weighed against economic loss of water loss. Further, the possibility of having a first tank with reduced capacity could make the higher outlet economical, which needs to be investigated.

Chapter 5. Behavior of a sudden inflow of soluble pollutants in multi tank RWH systems and remedial strategy during operation

5.1 Materials and Methods

we used a downscaled cylindrical, acrylic RWH tank, with a diameter of 15 cm and a height of 20 cm, which is similar to the lab-scale RWH tank used by us in the previous chapters. Geometric similarity to the domestic-scale cylindrical tanks widely used in developing countries (Haq, 2018; PE-Plus, 2020) was maintained in all the tanks used in this experiment. The height of the tank at a volume of 3 Liters (H) was calculated, and outlets were made at 0.33 H and H. A J-type inlet with an inner diameter of 5 mm, placed at 0.25 H, was used to introduce water into the RWH system. The diameter was selected considering the recommended pipe velocity range stipulated by the Housing and Building Research Institute (2011) for self-cleaning under the flow rates considered in this study. The flow rates considered (1.0 L/min and 2.0 L/min) in this study correspond to the most frequent rainfall intensity during summer in South Korea (Ministry of Land, Infrastructure and Transport, 2016). Under those flow rates, the flow conditions in the pipe were turbulent (Re> 4000), similar to the conditions that prevail in large-scale RWH systems. Next, two and three cylindrical acrylic tanks with similar diameters as previous were fabricated to be used as the 2 and 3-tank systems. A drain valve with an inner diameter of 5 mm was placed at the bottom of each tank. The specifications and details of tank systems considered (experimental setup) are presented in Figure 15. Only up to 3- tank systems were considered because, they are the most common systems in Africa and South East Asia.

The initial water level was maintained at 0.33 H for all tank configurations. Double-distilled water was introduced to the tank systems using a metering pump (FH100, Thermo scientific), and the resulting flow conditions within the downscaled tanks demonstrated laminar flow conditions (Re < 2100 and Fr <1), which resemble the flow conditions in large-scale RWH systems. Reagent-grade sodium chloride (salt), purchased from Daejung Chemicals & Metals, South Korea, was used as the conservative pollutant as it is a common pollutant in coastal regions. A dose of 1.5 g of sodium chloride was introduced instantaneously and uniformly over a period of one minute along with the water inflow. A conductivity sensor purchased from NeuLog, Isreal (NeuLog NUL-215) was placed at 0.3 H height for continuous measurement of conductivity. We verified the data collected by the sensor by repeating the test and measuring the conductivity every 10 seconds using a portable conductivity meter (Orion star A329, Beverly, MA, USA). Conductivity was converted to concentrations using the meter's built-in conversion function (with 0.5% of reading ±1-digit accuracy), which was validated by manual calculations. We simulated three scenarios for all three tank arrangements. First scenario (scenario A) simulated how the salt concentration changed when water level rose from the initial (0.33 H) level to the maximum (H) level in the last tank of each tank arrangement. Second scenario (scenario B) investigated, in depth, the percentage of salt mass that could be removed using the operation of drain valves at different water levels. After draining, the tanks were filled to the full capacity and the salt mass remaining in the tank system was measured. The water level at which the drain was operated, and the drained water volume is presented in Table 8. Finally, the third scenario (scenario B) investigated the amount of salt mass exiting the tank with different overflow water volumes. We were conservative with the drained water volume as we need to minimize the water loss, however, in the overflowing scenario, we considered a higher volume because overflown water does not affect the stored water volume. A graphical representation of the scenarios simulated is presented in Figure 16.

Table 8 The specifications of Scenarios simulated in this study

	Scenario A	Scenario B	Scenario C
Flow Rates	1, 2 L/min	1, 2 L/min	1, 2 L/min
Water level at which the drain was opened	X	0.33 H, 0.5 H, 0.75 H	X
Drained water volume	X	0.125, 0.25 V	X
Overflow water volume	X	X	0.25, 0.5 V

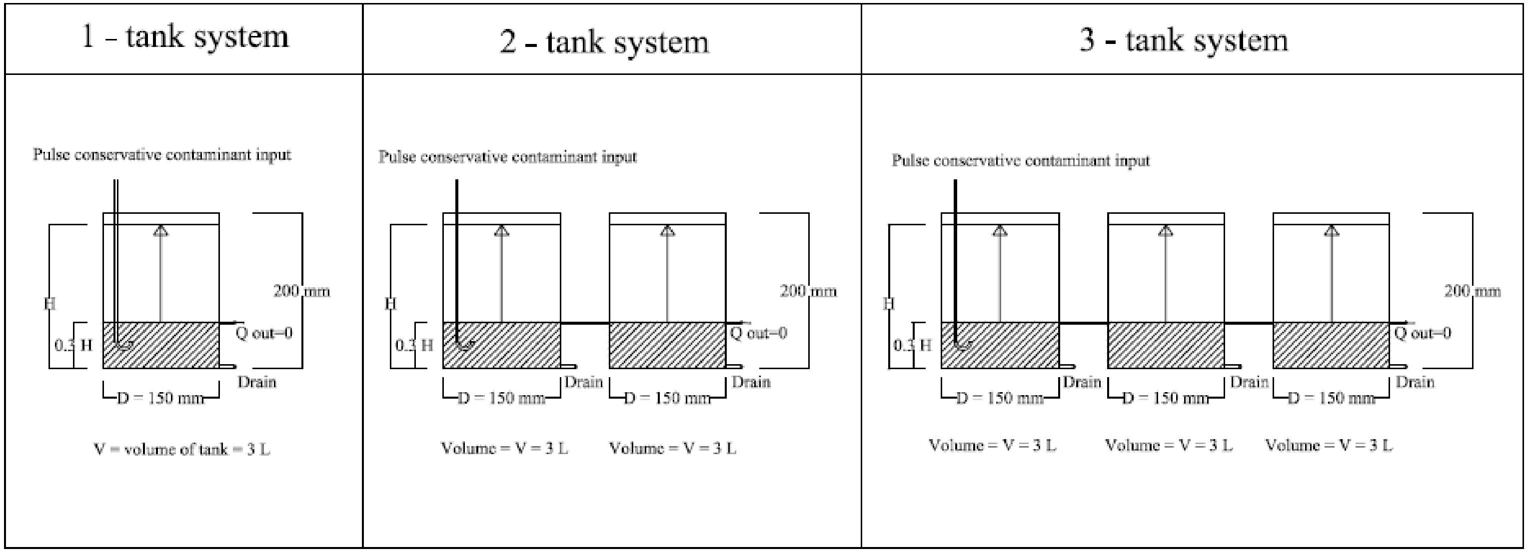


Figure 15 The specifications of 1-tank, 2-tank and 3-tank system

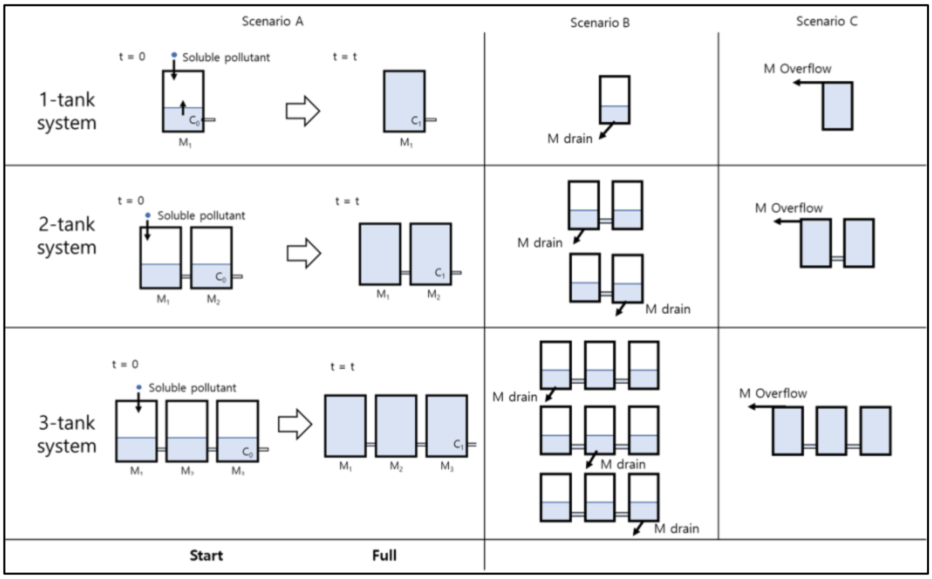


Figure 16 Graphical representation of the scenarios simulated; Scenario A: tank systems were filled from the initial water level (0.33 H) to the maximum (H), scenario B: While the tank was being filled, a specific amount of water was drained (0.125, 0.25 V) after which the tank was filled to the maximum level, scenario C: water was introduced until a specific volume of water was collected as overflow.

5.2 Results & Discussion

5.2.1 Tracer (salt) mass distribution during tank filling

The final salt concentration in the last tank (the expected salt concentration after a long period of storage) of all tank configurations can be derived by simply dividing the salt mass by the total volume of the tank arrangement (i.e. final salt concentration in the two tank system is given by salt mass (M)/ 2 X volume of a single tank (V)). However, immediately after a rainfall event, temporary concentration differences may exist among tanks in a multi-tank system as there is no sufficient time for diffusion to balance the concentration differences. Besides, previous tanks can act as retaining reservoirs preventing salt from reaching the last tank in the tank configuration. This phenomenon can be observed in Figure 17 and Figure 18, where the salt concentration and the mass percentage in the last tank of the 3-tank system deviates from the expected final salt concentration (M/ 3 V).

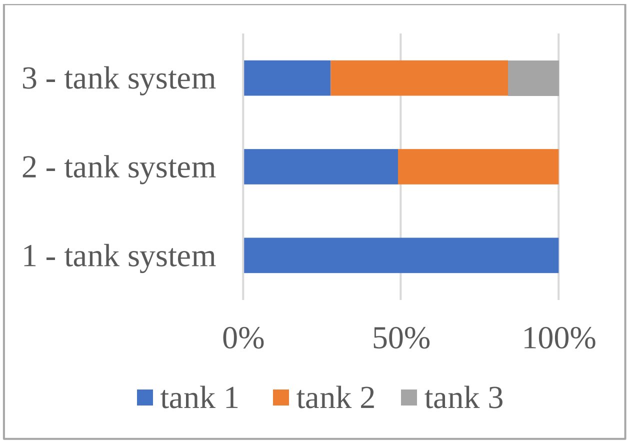


Figure 17 Mass distribution among tanks for different tank systems under a flow rate Q= 2 Liters/ min for scenario A

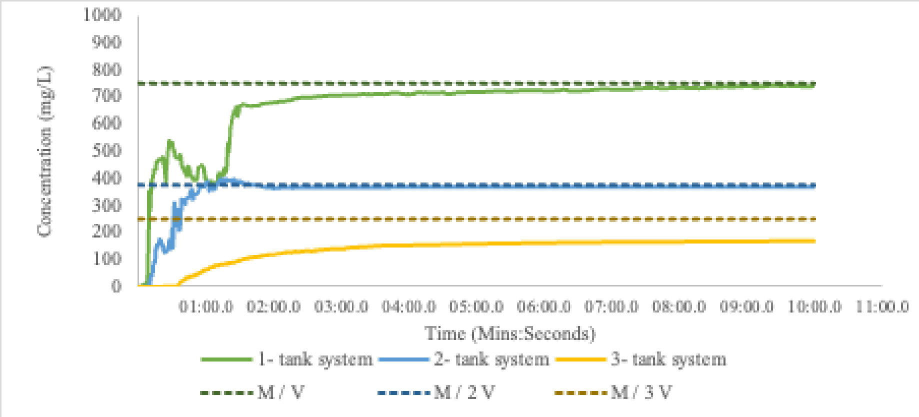


Figure 18 Concentration in the last tank of a 1-tank, 2-tank, 3- tank RWH system for Scenario A under a flow rate Q= 2 Liters/ min

For two and three tank systems, majority of the pollutant was retained by the second tank. First tank had a J-type inlet thus, it projects the water column upward until its momentum is lost due to resistance from the water body. Now the top water column is mixed with salt which creates a denser liquid at the top. This dense water column starts to go down as the density of the water at the bottom is less. While moving down, some of the pollutants reach the outlet of tank 1. The connection between tank 1 and tank 2 resembles a L-type inlet where the flow is mostly horizontal. Furthermore, this water flow is a laminar flow. The denser water reaching the second tank via the L-type connection with the first tank, now remains at the bottom without much mixing. Consequently, more soluble pollutants get trapped at the bottom of the second tank. This phenomenon can be exploited to remove soluble contaminants from the RWH system by automating the system to either isolate the first tank or open the drain valves of the first two tanks. Although some amount of water will be lost, the remaining water will be of higher quality. In this study, we focused only on salt as a pollutant, but this can be extended to most of the soluble contaminants.

5.2.2 Variation of tracer (salt) concentration with drained water volume

When the drain valve was opened, immediately upon the influx of water (water level at 30%), the tracer mass transported with the water was about 10%, and 19% for 0.125 V and 0.25 V drained water volumes, respectively (Figure 19). When the drain valve was operated at a higher water level (ie. 50% or 75% of H), the tracer mass carried out with the drained water volume was much higher (>20%) compared to that when drain was operated at 30% of the tank volume (0.3 H). This may be due to the upward flow (Figure 20) created by the J-type inlet. As the water flow is upwards, tracer and the water column beneath the inlet does not get mixed immediately. Therefore, opening the drain immediately with the water influx is not effective. When we drained at higher water levels (50% and 75% of H), however, we could observe that there is no difference between the masses carried out with drained water volume.

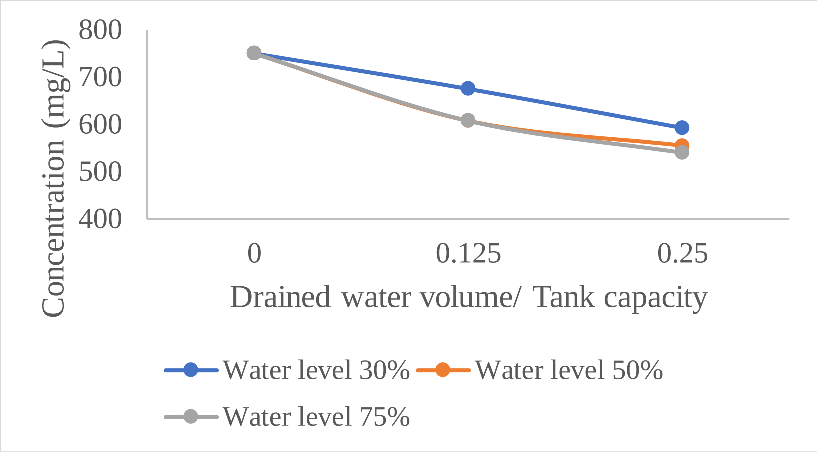


Figure 19 Salt concentration in the last tank of RWH system when the drain was operated at different water levels draining 0.125 V and 0.25 V for one tank system, for inflow velocity of 1 L/min

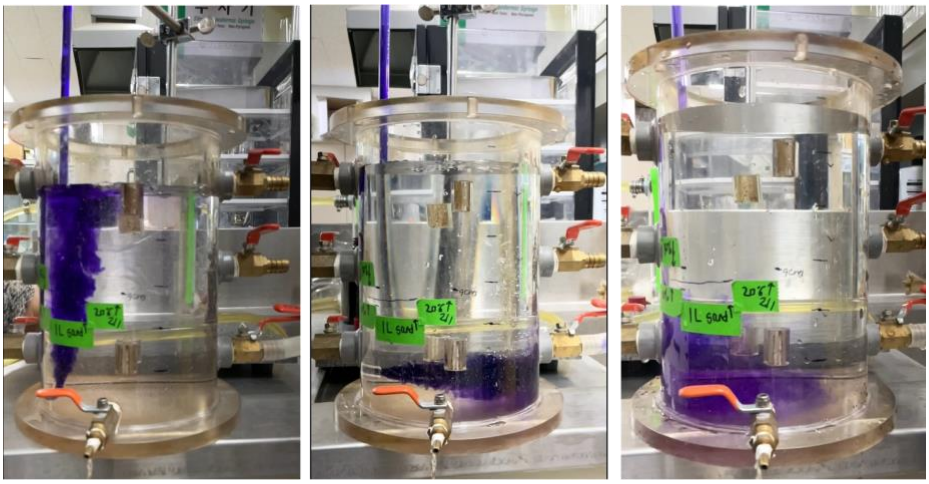


Figure 20 Flow patterns under different inlet arrangements; J-type (Left), L-type (Middle), I-type (right)

When the number of tanks increased, we observed a similar behavior to one tank arrangement. Operating the drain at a higher (50% or 75% of H) level proved to be more effective compared to opening the drain immediately upon introducing water into the system (Figure 21). Nevertheless, we observed that operation of the drain of the second tank in the 2-tank system was more effective. By operating the drain of the second tank, more tracer mass (4 to 5%) was removed. This may be due to tracer getting transported to the second tank due to advective forces from tank one. Further, this can be attributed to the scale effect also, as the retention time is low compared to a larger tank. However, in real-scale tanks the flow rates can become much higher that could result in shorter retention times than what this study has considered. When the flow rates increased from 1 L/min to 2 L/min, operation of the second tank drain became more effective. The same phenomenon was observed for the 3-tank system. The operation of the drain of the second tank was more effective.

Dao 2017 in their study demonstrated that most of the incoming particulate matter is retained by the first two tanks in a multiple tank system. Therefore, operating the drain of the first two tanks can remove not only soluble pollutants, but also a significant amount of particulate matter coming into the system as well. However, in this study we introduced salt to the system over a ten second interval whereas in real-scale tanks this may be higher (Lopez-patino, 2009). In such a circumstance, the percentage of pollutants that can be removed by operating the drain valve is lower than the values observed in this study. However, the simultaneous isolation of the first tank and operation of the drain valve may be the best solution to prevent the soluble contaminants from migrating to the next tank which needs further investigation.

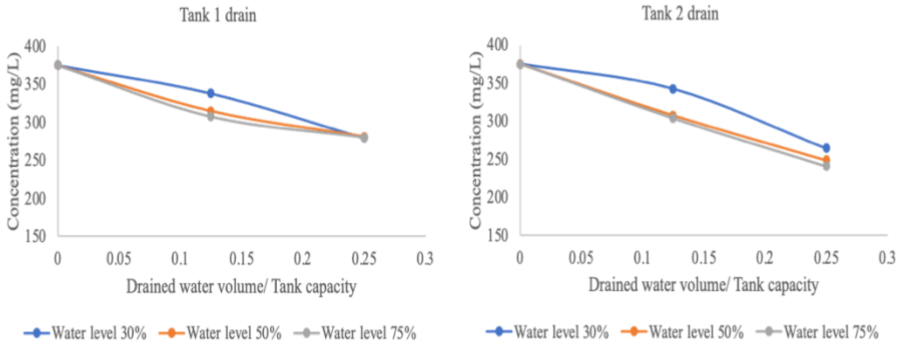


Figure 21 Salt concentration in the last tank of the 2-tank RWH system when the drain was operated at different water levels draining 0.125 V and 0.25 V under a flow rate of 1 L/min

5.2.3 Variation of tracer (salt) concentration with overflow

When water overflows, the percentage of salt mass transported reduced when the number of tanks increased (Figure 22). When the number of tanks increased, salt concentration gets diluted and gets retained by first few tanks. Consequently, the mass that gets transported with a specific overflow water volume reduced. Overflow seemed less effective compared to draining. This can be resulting from the effects of dilution. Drain valve was operated when the tank was not full, thus the pollutant concentration was much higher. When we removed some volume from that concentrated solution, we removed a higher amount of pollutant compared to removing the same volume of water when the tank was at full capacity.

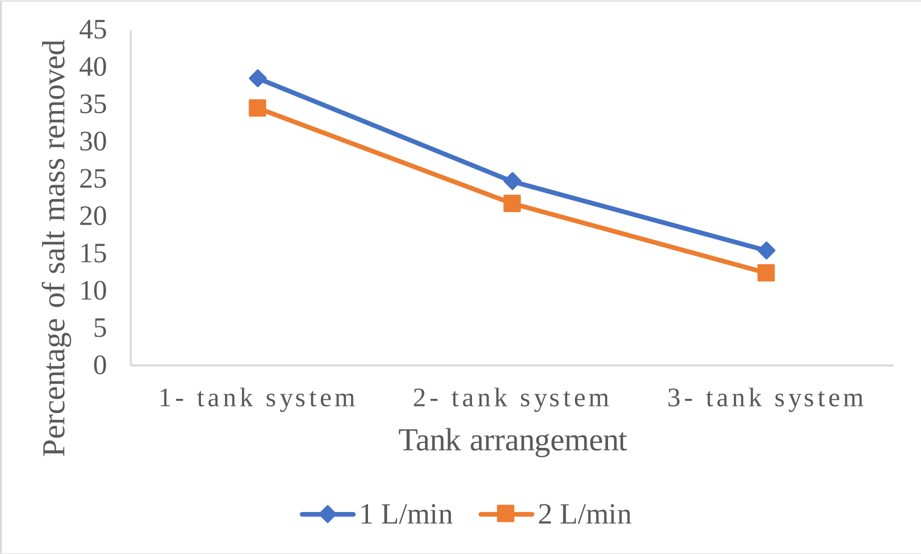


Figure 22 Percentage of salt mass transported with an overflow of 0. 5 V in different tank arrangements

Some RWH system designs incorporate flow diverters to divert the excess water after the tank reaches its full capacity to the drain. However, as demonstrated in this study, by allowing the water to overflow can enhance the water quality, thus we can recommend not to include a flow diverter for overflow.

Chapter 6. Conclusions

6.1 Effect of inlet/outlet configurations

6.1.1 Conclusions of the study

The third chapter of this study analyzed the inlet and outlet configurations of a typical rainwater harvesting tank in the developing world that affect the water quality of stored water. Installation of a J type inlet resulted in less bottom sediment resuspension and enabled conservative materials to reside within the RWH tank for a longer period than conventional I type inlets, while also releasing the conservative material in low concentrations. This is beneficial for providing users with a higher response time to either isolate the tank from other units of the RWH system or drain the stored water if a conservative pollutant enters the RWH tank. The inlet height had no significant influence on bottom sediment resuspension or RTD; however, a J type inlet placed near the bottom of the tank may allow the initial water height to provide a cushioning effect. The inflow velocity is critical when managing the water quality of stored rainwater. When selecting the pipe diameter, it is recommended to set the inflow velocity below 1.3 m/s to prevent bottom sediment resuspension. However, it is advised to maintain the flow velocity above 0.6 m/s for self-cleaning of the inlet. The outlet height is significant for retaining conservative materials because the retention capacity of the tank is proportional to the outlet height. However, a higher outlet height might not be cost effective for a single tank RWH system; hence, two outlets could be provided as suggested. For a multitank RWH system, a higher outlet height in the first tank can provide a multitude of benefits. If rainwater storage tanks can be properly maintained by regulating the water level in the tank at half-filled conditions using the two outlet system and by regularly draining the bottom sediment, the quality of stored water can be significantly improved at a lower cost. Based on the findings of this chapter, we can recommend the following design for single tank systems (Figure 23). Magyar et al., 2011 suggested a conical base for better sediment removal; therefore, the bottom of the tank should be designed according to Figure 8 to improve the flushing of bottom sediment.

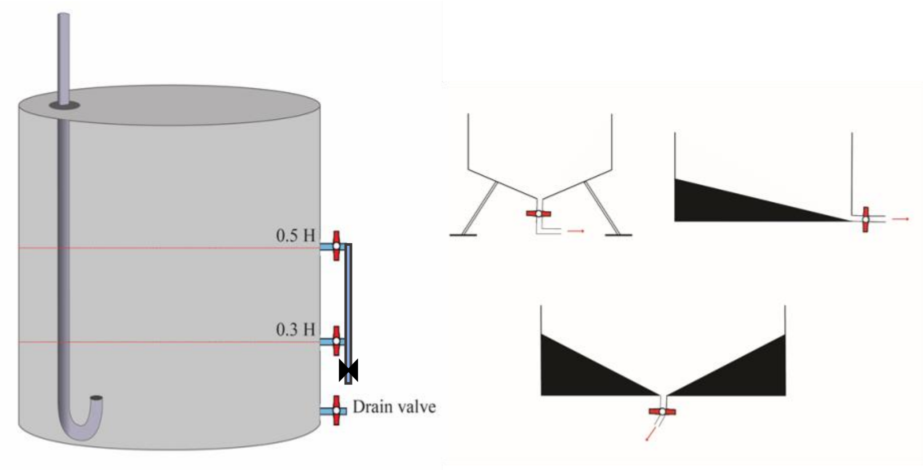


Figure 23 Recommended inlet/outlet design for rainwater storage tanks (left) and drain valve design for improved bottom sediment removal (right).

6.1.2 Limitations & further studies

This research did not investigate the influence of bottom sediment on the removal of other contaminants, and whether desludging could assist the removal of other contaminants from RWH tank, which needs to be investigated. Further, the authors focused only on a narrow range of Reynolds numbers. In large scale tanks, Reynolds can vary from laminar flows to turbulent flows. This needs to be investigated further in detail along with a numerical analysis that account for the scouring effect of outlet heights.

6.2 Effect of number of tanks

6.2.1 Conclusions of the study

The fourth chapter analyzed the effect of the number of tanks on water quality under a sudden particle input and a conservative pollutant input. A higher number of tanks could potentially benefit the users by reducing the amount of particulate matter reaching the final tank/outlet and retaining a conservative pollutant for a longer duration compared with a single tank system. In addition, the concentration peaks of a conservative pollutant reaching the outlet could be dampened, thus maintaining water quality within permissible limits. Furthermore, it can be concluded that by having a multi-tank system, a consistent particulate water quality can be achieved under varying flow rates and particulate matter influx concentrations. Having a higher outlet (at 0.6 H) for the first tank is also recommended to improve the particulate water quality and to achieve a longer residence time for conservative pollutants. The first tank of a multiple-tank system would hold the majority (>60%) of an incoming particulate pollutant; therefore, it is recommended to operate the drain valve to flush out the particulate matter after a rainfall event. The drain valve of the second tank also needs to be operated (though not as frequently as for the first tank) to maintain good water quality at the outlet. For a soluble contaminant, once it enters an RWH system, it is difficult to remove. However, a multi-tank rainwater harvesting system could be automated to isolate the first tank and then drain it, to prevent contamination of the other tanks. It is recommended to have a properly designed first-flush unit or an inflow diverter to prevent the first few millimeters of a rainfall from reaching the storage tank. In developing countries where the use of energy intensive filtration devices is not economically feasible, community-based multiple tank RWH systems could improve the harvested rainwater water quality thus, contributing towards achieving sustainable development goal number six: clean water and sanitation.

6.2.2 Limitations & further studies

We have not investigated whether desludging could influence the removal of contaminants during a rainfall event. In addition, feasibility of a multiple tank system depends on factors such as the scale of RWH system, land space availability and the cost associated with the project. Therefore, it is recommended to carry out a cost benefit analysis for existing multiple tank RWH systems, to understand how the aforementioned factors affect the economic feasibility of multi-tank systems. Further, the geometry of the tanks may affect the particle separation of the system that needs further investigation.

The tracer study data needs to be verified by numerical modelling that is a limitation of this study. A numerical model will give insightful information on how we can improve the design of the system and also, analyze larger systems.

6.3 Removal of a soluble pollutant during operations

6.3.1 Conclusions of the study

In chapter five, we demonstrated that opening the drain during the first rainfall event could remove more than 20% of soluble contaminants such as salt. Furthermore, the operation of drain was observed to be not effective when the drain was operated immediately with the influx of water. The operation of the drain of the second tank in a multi-tank system was effective in removing a soluble contaminant. Authors recommend not to incorporate a flow diverter to divert the flow when the tanks are full to employ the overflow for removing a soluble contaminant. Though this study did not investigate the particulate matter removal, the operation of the drain during the rainfall event will remove particulate matter influx which would help in improving the runtime of the filter. It is authors opinion that these findings could serve as a platform for the automation of operation of RWH systems.

6.3.2 Limitations & further studies

It is recommended to assess the effects of drain operation in terms of microbial water quality. Also, a computational fluid dynamics analysis for the RWH systems considered in this is needed for validation. As the behavior of a soluble pollutant is unique to each tank (due to changes in inlet/outlet arrangements, geometry and flow conditions), we recommend a thorough analysis on this matter prior to arriving at any conclusions.

Publications

1. Dissanayake, J.& Han, M. Effect of Inlet/Outlet Configuration on Water Quality in a Rainwater Harvesting Tank. Water. *12*, 1970 (2020).
2. Dissanayake, J. & Han, M. The effect of number of tanks on water quality in rainwater harvesting systems under sudden contaminant input. Sci. Total Environ. 769, 144553 (2021).

국문초록

빗물 수집(RWH)은 도시 물 위기에 대한 해결책으로 세계적인 주목을 받고 있지만, 수질은 입자 물질과 수용성 오염물질에 의해 영향을 받을 수 있다. 따라서 저장 탱크의 입구 및 출구 구성은 바닥 침전물 재지연을 최소화하고 수용성 오염물질의 이동을 방지하도록 설계되어야 한다. 단일 탱크 시스템과 관련된 이러한 문제를 극복하기 위해 유사한 용량의 여러 탱크 시스템이 전세계적으로 구현되었다. 다만 갑작스러운 오염물질 유입에 따라 탱크 수가 수확된 수질에 미치는 영향을 평가하기 위한 연구는 제한적으로 이뤄졌다. 또한 많은 연구자들이 입자 물질 제거와 관련하여 RWH 의 설계 및 작동 측면을 조사했지만, RWH 의 작동이 수용성 오염물질 제거에 어떻게 영향을 미치는지에 대한 연구는 많지 않다.

따라서, 이 연구는 보수적인 추적자의 즉각적인 입력에 대한 빗물 저장 탱크의 입구 및 출구 구성이 입자 재서스펜션 및 거주 시간 분포에 미치는 영향을 조사하였다. J 형 흡입구는 침전물 재서스펜션을 50% 이상 줄일

수 있는 동시에 보수적인 오염물질을 억제·혼합할 수 있어 플러그 흐름으로 농도가 배출구에 도달하는 것을 방지할 수 있는 것으로 관찰됐다. 입구 높이는 출구의 수질에 큰 영향을 미치지 않았지만, 유입 속도 및 출구 높이와 같은 매개변수는 sludge 재지연 및 거주 시간 분포에 상당한 영향을 미쳤다. 실험은 또한 저장 탱크의 초기 수위를 조절하고 저장된 수질을 유지하기 위해 바닥 침전물을 정기적으로 flushing 하는 것이 중요하다는 것을 강조했다.

다음으로, 저자들은 다중 탱크 시스템의 입자 물질 분포에 대한 탱크 수의 영향을 조사했으며, 첫 번째 탱크에는 입자 질량 입력의 60% 이상이 유지된다는 것을 관찰했다. 탱크의 수를 증가시킴으로써, 유속과 유입 입자 질량의 변화에도 불구하고 최종 탱크에 도달하는 입자 질량은 일정해진다. 또한 다중 탱크 시스템에 유입되는 수용성 오염물질이 시스템 내에 약 2 배 정도 오랫동안 존재하는 것으로 확인되었으며, 이는 대응 전략을 수립하는 데 유리한다. 저자들은 다중 탱크 RWH 시스템의 이점을 얻기 위해 최소한 세 개의 탱크를 사용해야 한다고 권고한다.

마지막으로, 본 연구는 배수구가 작동되고 물이 넘칠 때 제거할 수 있는 수용성 오염물질 유입량(소금)을 정량 화하려고 시도했다. 단일 탱크 시스템에서 배수구를 절반 용량으로 가동하면 오염물질 유입량의 20% 이상이 제거될 수 있었다. 다중 탱크 RWH 시스템에서는 두 번째 탱크의 배수구 작동이 첫 번째 탱크의 배수구보다 더 효과적이었다. 특히 단일 탱크 시스템에서 상당한 양의 수용성 오염 물질을 오버플로로 제거할 수 있다. 이 연구 결과를 사용하여 운영 및 자동화 권장 사항을 제안할 수 있다.

주요어 : 빗물 수집, 수질, 입자 재서스펜션, 거주 시간, 입/출구 구성, 다중 탱크 시스템, 저충격 개발, 배수, 입자 분리

학번 : 2019-24401

Acknowledgement

Firstly, I would like to extend my gratitude to my academic advisor, Professor Mooyoung Han for his guidance, advice and support without which, this achievement would have been impossible. Also, I would like to express my sincere gratitude to my thesis committee: Professor Kyungphile Nam and Professor Jongkwon Choe, whose insightful comments were paramount in strengthening the arguments presented in this thesis. Further, I would like to thank Professor Yongju Choi for his challenging questions, which widened my perspectives, despite their perplexities. I am humbled and grateful to learn under the invaluable advice of the faculty at the Department of Civil and Environmental Engineering, Seoul National University.

If I say, "I could have done this without the help of Waterfirst Lab family", that will be a lie. You all were wonderful, and the energy you guys projected onto me was what propelled my enthusiasm during this journey. To Jin, for making me a better team player and for all the bittersweet memories we shared. You were a better "Panjang". To Voni, for sharing all the hardships together and for joining me in adventure sports. We graduated; a task that seemed impossible. To Malwina, for being there whenever I was sailing in rough seas. You were our motivation. To Bang, for being a really great friend that I could count on. To Ester, for all your support and laughter. Also, thank you for not breaking my bones during Judo sessions. To Yunn, for all the joyful conversations. To Gippeum, for your support and your very warm personality which made us feel welcomed. It meant a lot, specially at SNU. To Hakyung, for taking the burden of administrative work off our shoulders. Thank you all.

Next, I want to thank my closest friends at SNU: Ceci, Mari, Jyoti, Shreya and Chris for being there for me when I needed them the most. With you all, I shared my life outside the Lab; conquering mountains and frequenting places where people gather to investigate the effects of spirits. There is a saying, “all work, no play, makes Jack a dull boy”. My life would have been dull indeed, if not for your companionship.

Thank you, Ondo, for being my hiking partner, and for being a friend that I could count on. Thank you, Niki, for being the kindest Hungarian in Seoul whose friendship I was lucky to have. Among my Konyang friends, I am really grateful for the support and motivation given by KumKum, Ivana, Ilgaz, Zohra, Ava, Dimithri, Godwin, Mohamed, Ebi, Eldin and Alex.

To my best friends: Ravindu, Samud and Sumadhurie for listening to my laments and tolerating me. You guys gave me the courage to keep charging. I would like to thank all my friends and relatives in Sri Lanka, Thailand and Canada for their support.

To my Korea based support team; Yoon: the cool SNU “sonbae”, SKOLA friends, and World Reporters members and mentors, thank you for your friendship. To Dane, for being the person who always believed in me.

Final, but most heartfelt acknowledgement, to my parents, my brother, my grandfather and my cousins. I do not have words to express how grateful I am to you all. Just know that I love you all.

I dedicate this achievement to my late grandmother, Pathma Gamage, who always wished for my success!

References

1. Alim, M. A., Rahman, A., Tao, Z., Samali, B., Khan, M. M., & Shirin, S. Suitability of Roof Harvested Rainwater for Potential Potable Water Production: A Scoping Review. Journal of Cleaner Production 2020a, 248, 119-226.
2. Amos, C.; Rahman, A.; Gathenya, J. Economic analysis and feasibility of rainwater harvesting systems in urban and peri-urban environments: A review of the global situation with a special focus on Australia and Kenya. Water 2016, 8, 149.
3. Bak, Gippeum; Dao, Anh Dzung; Han, Mooyoung. Improving the hydrological performance of a rainwater for drinking (RFD) system at a rural hospital in Vietnam. Journal of Water, Sanitation and Hygiene for Development 2020. doi: https://doi.org/10.2166/washdev.2020.104
4. Benjamin, M.; Lawler, M.; Desmond, F. Continuous Flow Reactors: Hydraulic Characteristics. In Water Quality Engineering: Physical/Chemical Treatment Processes; 1st ed.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2013; pp. 29–70. ISBN 978-1-118-16965-0.
5. Campisano, A.; Butler, D.; Ward, S.; Burns, M.J.; Friedler, E.; DeBusk, K.; Fisher-Jeffes, L.N.; Ghisi, E.; Rahman, A.; Furumai, H.; et al. Urban rainwater harvesting systems: Research, implementation and future perspectives. Water Res. 2017, 121, 195–209.

6. Commonwealth of Australia, 2010. Guidance on use of rainwater tanks. enHealth

7. Coombes, P.J.; Kuczera, G.; Kalma, J.D.; Dunstan, R.H. Rainwater quality from roofs, tanks and hot water systems at Figtree Place. In Proceedings of the 3rd International Hydrology and Water Resource Symposium, Perth, Australia, 20–23 November 2000; pp. 1042–1047.

8. Coombes, P.J.; Kuczera, G.; Kalma, J.D.; Argue, J.R. An evaluation of the benefits of source control measures at the regional scale. Urb. Water 2002, 4, 307–320.

9. Dao, Anh Dzung. A strategy to promote sustainable drinking water in Vietnam by rainwater harvesting. Doctoral thesis, Seoul National University, Gwanak-gu, Seoul, South Korea 2017.

10. Dao, Anh Dzung; Nguyen, Duc Canh; Han, MooYoung. Design and operation of a rainwater for drinking (RFD) project in a rural area: case study at Cukhe Elementary School, Vietnam. J water sanit hyg de. 2017, 7(4), 651–658.

11. Egodawatta, P.; Thomas, E.; Goonetilleke, A. Understanding the physical processes of pollutant build-up and wash-off on roof surfaces. Sci. Total Environ. 2009, 407, 1834–1841.

12. Han, M.Y.; Saleh, H.I.; Lee, I.Y.; Kim, Y.J. Characterization of harvested rainwater quality from Seoul city-Korea. In Proceedings of the 8th International Water Technology Conference, Alexandria, Egypt, 26–28 March 2004.

13. Haq, S.A. Harvesting Rainwater from Buildings, Reprint; Springer International Publishing: Berlin, Germany, 2018; ISBN 978-3-319-46362-9.
14. Housing and Building Research Institute. Bangladesh National Building Code; Housing and Building Research Institute: Dhaka, Bangladesh, 2011.
15. Kahinda, J.M.; Taigbenu, A.E. Rainwater harvesting in South Africa: Challenges and opportunities. Phys. Chem. Earth Parts A/B/C 2011, 36, 968–976.
16. Kim, Yongkyun; Han, Mooyoung; Kabubi, Julius; Sohn, Hong-Gyoo; Nguyen, Duc-Canh. Community-based rainwater harvesting (CB-RWH) to supply drinking water in developing countries: lessons learned from case studies in Africa and Asia. Water Supply 2016, 16 (4), 1110–1121.
17. Mikyeong Kim and Mooyoung Han (July 13th 2016). Role of Biofilm in Rainwater Tank, Microbial Biofilms - Importance and Applications, Dharumadurai Dhanasekaran and Nooruddin Thajuddin, IntechOpen, DOI: 10.5772/63373.
18. Lee, J.Y.; Bak, G.; Han, M. Quality of roof-harvested rainwater—Comparison of different roofing materials. Environ. Pollut. 2012, 162, 422–429.
19. López-Patiño, G., Martínez-Solano, F. J., López-Jiménez, P. A. & Fuertes-Miquel, V. S. A method for sizing first flushwater diverters

tanks in rainwater harvesting systems. Environ. Hydraul. Theor. Exp. Comput. Solut. - Proc. Int. Work. Environ. Hydraul. IWEH 2009 311–314 (2010) doi:10.1201/b10999-77.

20. Magyar, M.; Ladson, T.; Mitchell, V.; Diaper, C. The effect of rainwater tank design on outlet water quality. Aust. J. Water Res. 2011, 15, 71–84.
21. Master Plumbers and Mechanical Services Association of Australia. Rainwater Tank Design and Installation Handbook; Standards Australia: Sydney, NSW, Australia, 2008.
22. Maruéjouls, Thibaud; Vanrolleghem, Peter A.; Pelletier, Geneviève; Lessard, Paul. Characterisation of retention tank water quality: particle settling velocity distribution and retention time. Water Quality Research Journal 2013, 48 (4), 321–332.
23. Maus, C.; Uhl, M. Tracer studies for the modelling of sedimentation tanks. In Proceedings of the Seventh International Conference on Sustainable Techniques and Strategies in Urban Water Management, Lyon, France, 27 June–1 July 2010; GRAIE: Lyon, France, 2010.
24. Ministry of Land, Infrastructure and Transport. Korea Precipitation Frequency Data; Ministry of Land, Infrastructure and Transport: Sejong, Korea, 2016.
25. Musayev, S., Burgess, E., & Mellor, J. A global performance assessment of rainwater harvesting under climate change. Resources Conservation and Recycling 2018, 132, 62-70.

26. Novak, C.A.; Van Giesen, E.; DeBusk, K.M. Designing Rainwater Harvesting Systems: Integrating Rainwater into Building Systems, Reprint; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2014; ISBN 978-1-118-41047-9.
27. Pe Plus- Products- Water Tanks. Available online: http://www.peplus.lk/products/watertanks.html (accessed on 29 May 2020).
28. Sanchez, A.S.; Cohim, E.; Kalid, R.A. A review on physiochemical and microbiological contamination of roof-harvested rainwater in urban areas. Sustain. Water Qual. Ecol. 2015, 6, 119–137.
29. Scott, R.; Waller, D. water quality analysis of a rainwater cistern system in Nova Scotia, Canada. In Proceedings of the 3rd International Rainwater Collection System Association Conference. Section F: Water Quality, Khon Kaen, Thailand, 14–16 January 1987, pp. 1–16.
30. Simmons, G.; Hope, V.; Lewis, G.; Whitmore, J.; Wanzhen, G. Contamination of potable roof collected rainwater in Auckland, New Zealand. Water Res. 2001, 35, 1518–1524.
31. Spinks, A.T.; Coombes, P.; Dunstan, R.H.; Kuczera, G. Water quality treatment processes in domestic rainwater harvesting systems. In Proceedings of the 28th International Hydrology and Water Resources Symposium: About Water, Barton, ACT, Australia, 1 January 2003; Boyd, M.J., Ball, J.E., Babister, M.K., Green, J., Eds.; Institution of Engineers: Kolkata, India, pp. 2227–2234; ISBN 0858240602.

32. Spinks, A.; Berghout, B.; Dunstan, R.; Coombes, P.; Kuczera, G. Tank sludge as a sink for bacterial and heavy metal contaminants and its capacity for settlement, re-suspension and flocculation enhancement. In Proceedings of the 12th International Rainwater Catchment Systems Association Conference, New Delhi, India, 15-18 November 2005.
33. Thomas, T. The limitations of roofwater harvesting in developing countries. Waterlines 2014, 33, 139–145.
34. Thuy, Bui Thi; Dao, Anh Dung; Han, Mooyong; Nguyen, Duc Canh; Nguyen, Viet Anh; Park, Hyunju; Luan, Pham Dang Manh Hong; Duyen, Nguyen Thi Thanh; Nguyen, Hong Quan. Rainwater for drinking in Vietnam: barriers and strategies. Journal of Water Supply: Research and Technology-Aqua 1 2019, 68 (7), 585–594.
35. Thi Thuy Bui, Duc Canh Nguyen, Mooyoung Han, Mikyeong Kim, Hyunju Park. Rainwater as a source of drinking water: A resource recovery case study from Vietnam, Journal of Water Process Engineering 2020,101740, ISSN 2214-7144, https://doi.org/10.1016/j.jwpe.2020.101740.
36. UNICEF. Committing to Child Survival: A Promise Renewed—Progress Report; UNICEF: New York, NY, USA, 2014.
37. Van Metre, P.C.; Mahler, B.J. The contribution of particles washed from rooftops to contaminant loading to urban streams. Chemosphere 2003, 52, 1727–1742.

38. Werner, T.M.; Kadlec, R.H. Application of residence time distributions to stormwater treatment systems. Ecol. Eng. 1996, 7, 213–234.
39. WHO/UNICEF. Joint Monitoring Programme (JMP) Report; WHO: Geneva, Switzerland; UNICEF: New York, NY, USA, 2014.
40. WHO. WHO, SNU and VIHEMA collaborate to improve WASH in Ly Nhan district hospital, Ha Nam province. Available online: https://www.who.int/vietnam/news/detail/31-08-2019-who-snu-and-vihema-collaborate-to-improve-wash-in-ly-nhan-district-hospital-ha-nam-province (accessed on 20th August 2020).
41. Won, Y.; Han, M.; Park, H.; Kim, M. Optimal rainwater tank design for control of particulate contaminants. Water Sci. Tech.-Water Sup. 2019, 19, 574–579.
42. Younos, T.; Parece, T.E. Sustainable Water Management in Urban Environments, the Handbook of Environmental Chemistry, Springer: Berlin, Germany, 2016; Volume 47, pp. 209–231. ISBN 978-3-319-29337-0.
43. Zhang, S., Zhang, J., Yue, T., Jing, X. Impacts of climate change on urban rainwater harvesting systems. Sci. Total Environ.2019, 665, 262-274.