

Rainfall-Storage-Utilization-Discharge model for flood mitigation and water conservation

Duc Canh Nguyen and Mooyoung Han

ABSTRACT

Climate change and the increase of impermeable surfaces due to urbanization have led to an increase in the frequency of flooding events. The occurrence of water shortage problems is attributed to an increased population and water pollution. Traditional methods of draining rainwater from rooftops, based on the Rainfall-Discharge (R-D) model, are challenged. By storing some of the rainfall that falls on building rooftops, flooding of nearby sewer systems can be mitigated, and the reduction of peak runoff can then be calculated using the Rainfall-Storage-Discharge (R-S-D) model. By utilizing stored rainfall in or near a building, flooding can be further mitigated while conserving water, and the reduction of peak runoff and the amount of used rainwater can also be calculated using the Rainfall-Storage-Utilization-Discharge (R-S-U-D) model. The R-S-U-D model uses site-specific rainfall characteristics; thus, we take Seoul, Korea as a study case. The reduced peak flow and increased design return period for a combination of tank volume and utilization rate can be calculated and presented by a curve, which can be used in the design and operation of sewer systems. Results from the R-S-U-D model can help in designing methods to reduce the flooding risk in existing sewer systems without increasing their capacity, thus reducing expenses. Water conservation is an additional benefit.

Key words | peak runoff, rainwater storage tank, R-S-D model, R-S-U-D model, sewer system, urban flooding, water conservation

Duc Canh Nguyen (corresponding author)
Sustainable Management of Natural Resources
and Environment Research Group,
Faculty of Environment and Labour Safety,
Ton Duc Thang University,
19 Nguyen Huu Tho Street, Tan Phong Ward,
District 7, Ho Chi Minh City,
Vietnam
E-mail: nguyenducanh@tdt.edu.vn

Duc Canh Nguyen
Mooyoung Han
Department of Civil and Environment Engineering
#35-518,
Seoul National University,
599 Gwanak-ro, Gwanak-gu, Seoul 151-742,
Republic of Korea

INTRODUCTION

Flood events are becoming increasingly frequent due to climate change and urbanization, which results in an increase of impermeable surface area. The number of affected people and the financial, economic, and insurance-related damages due to flooding have also increased. In 2010 alone, approximately 178 million people were affected and the total losses due to flooding were reported to be over \$40 billion (Jha *et al.* 2011). Moreover, rapid population growth and water quality degradation necessitate greater attention being given to water conservation.

The conventional centralized end-of-pipe system is a regional runoff control system that manages downstream flows in drainage pipe networks using large channelization and underground detention basins. While this system has

been popular in industrial and urbanized areas over the last 100 years, its drawbacks include high-cost maintenance, uncertainty of rainfall, and a lack of sustainability. This system focuses only on the prevention of flooding and is designed to drain rainwater as fast as possible (R-D model); while water conservation by collecting rainwater is never considered (Appendix 1, available with the online version of this paper).

Recently, the micro-scale rainwater management (RWM) approach using rainwater storage tanks (Appendix 2, available with the online version of this paper) has gained interest as a potential complement or replacement to the conventional sewer system. It has the potential to address problems faced by the existing conventional sewer system (Han *et al.* 2009). Micro-scale RWM is regarded as a type of source control, as

it collects rainwater close to its source. The need for micro-scale RWM systems to mitigate various problems such as urban flooding and water shortage has become more urgent in recent times (Kim & Han 2008; Han *et al.* 2004, 2009; Kim *et al.* 2015). On a micro-scale, if an RWM system is installed in a building, the system would connect to the urban sewer system and the water supply system of the building. Kim & Han (2008) proposed and developed the Rainfall-Storage-Discharge (R-S-D) process in order to estimate the control effect of a rainwater retention tank. The results showed that an R-S-D system can control runoff from building rooftops and effectively mitigate urban flooding.

Besides the flood alleviation function, micro-scale RWM also helps conserve water. Due to its small scale, rainwater is safely collected from building rooftops and stored. Rainwater is of good enough quality to be utilized for tasks such as toilet flushing, gardening, cleaning, and emergencies (Fewkes 1999; Mwenge Kahinda *et al.* 2007; Song *et al.* 2009; UNEP 2009; Tabatabaee & Han 2010; Julius *et al.* 2013; Nguyen *et al.* 2013; Nguyen & Han 2014; Kim *et al.* 2016). Rooftop harvested rainwater is a good drinking water source that requires little to no treatment for emergencies or normal daily use in both developing and developed countries (Coombes *et al.* 2006; Amin & Han 2009; Lee *et al.* 2012). Timely utilization of rainwater stored in tanks can also serve to reduce peak runoff flows.

The objectives of this study were to propose a Rainfall-Storage-Utilization-Discharge (R-S-U-D) model that considered rainwater as a water resource, and to develop a method for designing tank capacity and utilization to control runoff from building rooftops for both flood mitigation and water conservation.

DESIGN OF R-S-U-D SYSTEM

Figure 1 shows a schematic of an R-S-U-D system for a building. It consists of a rooftop, downpipe, storage tank, water supply, and the overflow is connected to a nearby sewer system. The R-S-U-D system controls the storage, utilization, and discharge of rainwater into the receiving water bodies. The volume of rainwater discharged to the sewer system can be controlled by the amount of water in the rainwater tank, which is then supplied for domestic utilization. The R-S-U-D system can contribute to both flood mitigation and water conservation.

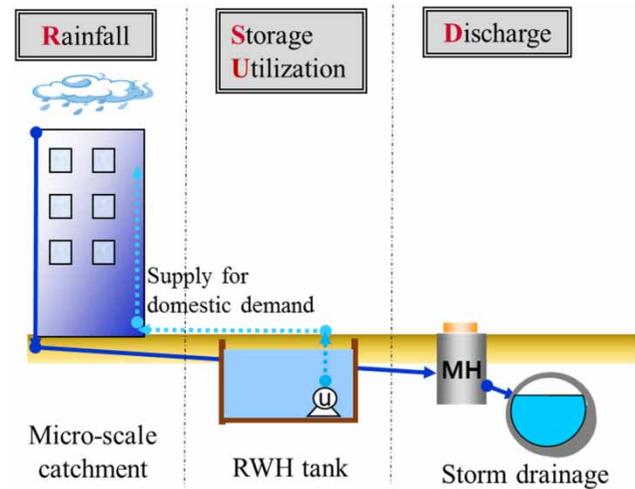


Figure 1 | Rainfall-Storage-Utilization-Discharge (R-S-U-D) system.

The R-S-U-D model is a new numerical model, used for the analysis and design of RWM systems for flood control considering the simultaneous storage and utilization of the rainwater. Because the rainfall characteristics are site specific, the rainfall data should be tailored to suit each area. In this paper, Seoul, Korea, is taken as a study area, and the data were obtained from the Korean Meteorological Administration (KMA).

METHODOLOGY OF R-S-U-D MODEL DEVELOPMENT

Design of rainfall distribution and runoff analysis

Hydraulic structures using conventional hydrology were developed for a large area (>10 ha), and were designed to be used with stochastic rainfall characteristics, as rainfall distributions are not generally uniform over a huge spatial area. Spatial distribution reduction factors are generally taken into consideration during the construction of a hyetograph. However, in the case of the micro-scale RWM system, which has a rather small area (0.01–1 ha), the rainfall distribution is uniform over the catchment area, making the need for spatial distribution reduction factors unnecessary in the development of the rainfall hyetograph.

In this study, rainfall hyetographs were constructed following the Huff method (Huff 1967), since it is comprehensive and suited to Seoul's meteorological

conditions (MOCT 2000). Following the procedure for constructing rainfall hyetographs for rainwater retention facilities (Kim *et al.* 2015), this study draws the hyetographs on the 2nd-quartile, with a 10% probability rainfall cumulative curve. This pattern and probability were proposed as a reasonable rainfall analysis method for designing rainwater retention facilities for Seoul (Nguyen 2016). The hyetographs were constructed from data with return periods of 2, 5, 10, 30, 50, and 100 years. Figure 2 shows the design rainfall curve hyetographs for different durations of a 100-year frequency rainfall event for Seoul city area.

A building rooftop is an artificial, impervious surface designed to drain water rapidly without any detention effect, meaning that the runoff flow is the same as the rainfall volume. Some loss of stored water could occur due to faulty pipe connections and valves. An experimental formula for micro-scale cumulative runoff analysis on a flat building roof (2,000 m²) for on-site RWM was expressed with a runoff coefficient of 0.90–0.95 by Kim *et al.* (2009) (Equation (1)).

$$Q_t = I_t \times A \times C \times 0.001 \tag{1}$$

where Q_t is the runoff from a catchment area (m³/h) at time t . A is the catchment area (m²). C is the runoff coefficient. I_t is the rainfall intensity (mm/h) at time t .

Utilization control tank capacity design

To simulate water flow in a rainwater tank system, the water balance is analyzed with respect to the system conditions

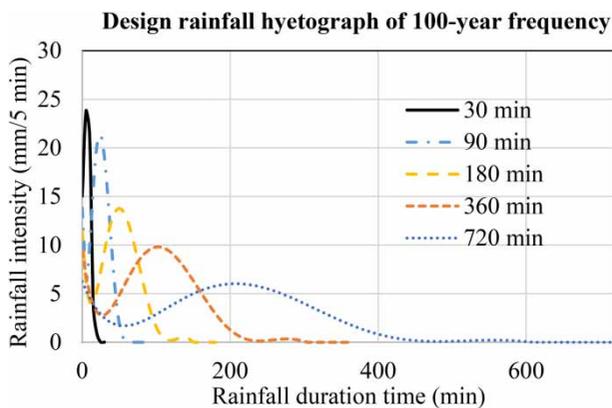


Figure 2 | Design rainfall hyetographs for variation durations of a 100-y frequency for Seoul City.

(Figure 3) as shown below:

$$V_t = V_{t-1} + Q_{in,t}\Delta t - Q_{out,t}\Delta t - Q_{sup,t}\Delta t \tag{2}$$

where V_t is the cumulative water stored in the tank (m³) at time t . V_{t-1} is the cumulative water stored in the tank (m³) at time $t - 1$. Δt is the time increment (h). In determining retention volumes, small time increments are more useful than large time increments to avoid underestimation of the cumulative rainfall depth from hyetographs with the latter. In this study, a time increment of 5 min, which is generally the smallest value, was used. $Q_{in,t}$ is the inflow rate into the rainwater tank (m³/h) at time t and is the same as the runoff flow rate from the roof, as in Equation (1). $Q_{sup,t}$ is the water supply rate to the building from the rainwater tank (m³/h) at time t . $Q_{out,t}$ is the overflow rate from the tank to urban storm drainage (m³/h) at time t . $Q_{sup,t}$ and $Q_{out,t}$ can be mathematically described as follows:

$$\text{If } V_t \leq 0, Q_{sup,t} = 0, \tag{3}$$

if $V_t > 0$, the water supply is limited by the cumulative water stored and inflow quantity in the tank.

$$V_{t-1} + Q_{in,t}\Delta t < Q_{Utilization}\Delta t \rightarrow Q_{sup,t}\Delta t = V_{t-1} + Q_{in,t}\Delta t \tag{4}$$

$$V_{t-1} + Q_{in,t}\Delta t \geq Q_{Utilization}\Delta t \rightarrow Q_{sup,t} = Q_{Utilization} \tag{5}$$

$$\text{If } V_t \leq V, Q_{out,t} = 0 \tag{6}$$

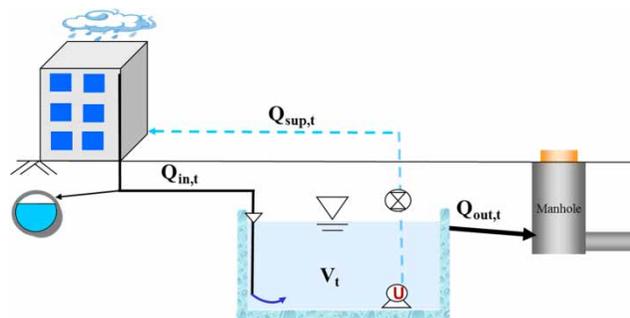


Figure 3 | Structure and water flow of a rainwater tank.

If $V_t > V$, the tank is full,

$$Q_{out,t}\Delta t = V_{t-1} - V + Q_{in,t}\Delta t - Q_{sup,t}\Delta t \quad (7)$$

where V is the capacity of the rainwater tank (m^3). $Q_{Utilization}$ is the utilization rate (m^3/h). This study calculates data with utilization rates of 5, 10, 15, and 20 L/min. The outflow from the RWM system under various factors is calculated by simulations using an algorithm based on the above equations (which are shown in Figure 4).

RESULTS AND DISCUSSION

R-S-D system

Duration determination

Application of the most conventional method of duration determination requires that the duration of the design rainfall event be equal to the time of concentration in the basin. The time of concentration, T_c , is the time taken for

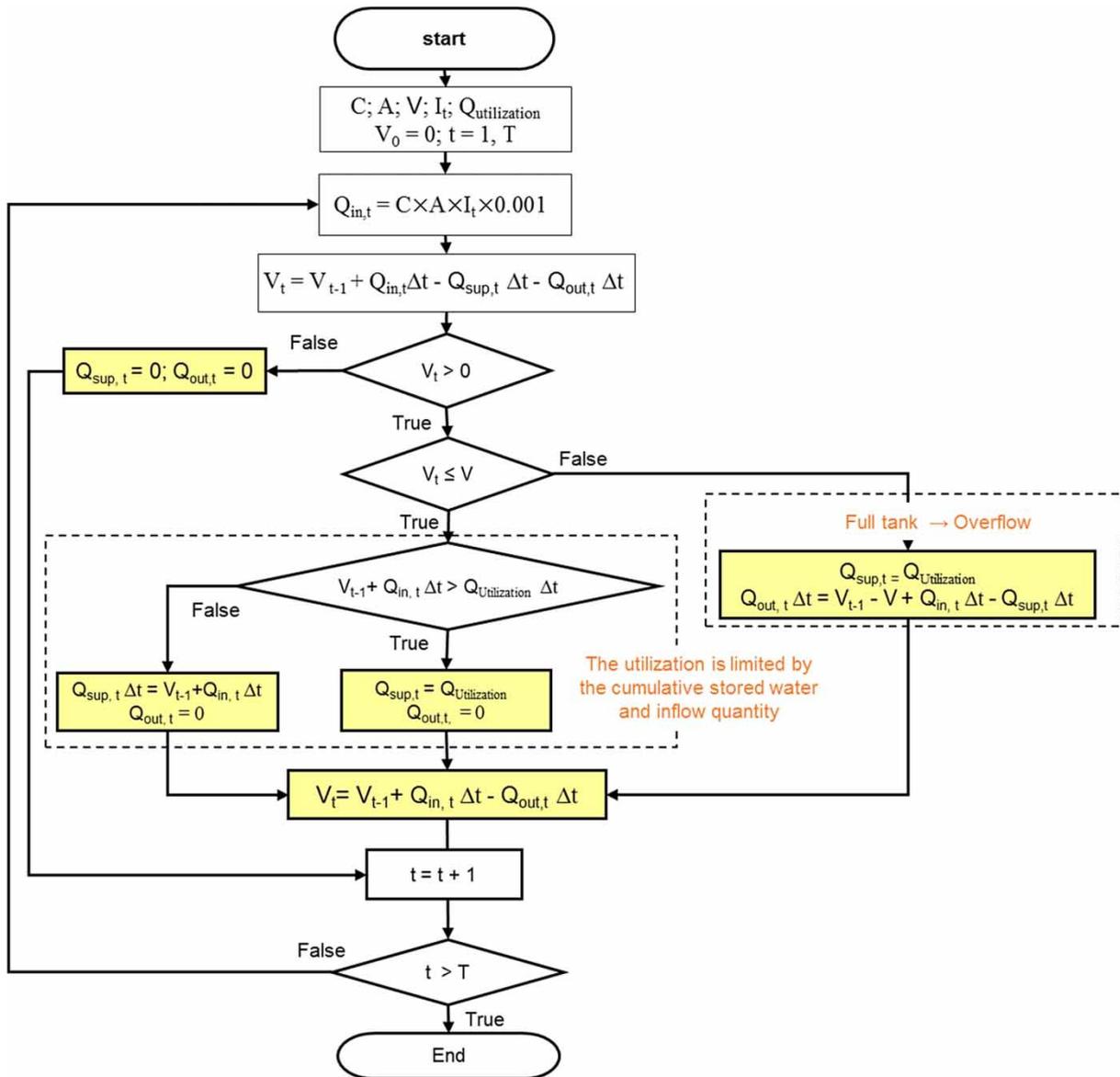


Figure 4 | Flow chart used to determine outflow from R-S-U-D system. T is the simulation period.

the surface water runoff to reach the design point from the furthest point of the catchment. It is assumed that with a uniform intensity storm, the entire catchment fully contributes to the maximum discharge at the design point for any given probability of occurrence. However, this definition ignores the relative runoff-producing capabilities of pervious and impervious surfaces, and possible variations in rainfall intensity. In fact, micro-scale RWM systems have small catchment areas of building rooftops, usually about 0.01–1 ha in area. The time required for rainwater to travel from the roof to the rainwater tank inlet is assumed to be negligible. According to Kim & Han (2008), the actual time measured is usually around 5–10 minutes. However, 5–10 minutes cannot be used to reasonably estimate the inflow conditions for rainwater systems (Kim *et al.* 2015). It is a good practice to select several rainfall durations and compute the runoff for each, as it is not possible to determine in advance whether the design of a hydraulic structure will be more sensitive to peak runoff rates or to runoff volumes. Therefore, this study takes into account all types of rainfall events with the 24-h system operation time for designing the micro-scale RWM system.

Rainwater tank volume versus peak discharge for various rainfall return periods

In order to study the effect of the rainwater tank volume of an R-S-D system on peak flow reduction, peak flow rates were calculated by the R-S-D model using various tank volumes (0–20 m³) and rainfall duration times (30–1,440 min) under different design rainfall periods as input, as shown in Figure 5. The case study of a 100 m² catchment area with a runoff coefficient of 0.9 was applied throughout the study. Figure 5(a) shows how peak flow rates are reduced by increasing the tank volume (m³/100 m² roof catchment area) for the design of a 100-year return period in Seoul for different rainfall duration times. Dotted lines connect the peak runoff values, following tank volume variation to the corresponding rainfall duration times. Each line follows the standardized rainfall for a duration of time. The thick curve represents the designed peak runoff, which shows the maximum runoff flow for the design inflow curves of all duration times less than 24 h for a 100-year return period. When the tank volume is 0 m³ (R-D model), the peak is 26 m³/h, but

in the R-S-D model, where the tank volume is 11 m³/100 m², the peak is reduced to 11 m³/h.

Similarly, the peak runoff curves for the different rainfall events of 2, 5, 10, 30, 50 and 100-year return periods were determined using the R-S-D model and are shown in Figure 5(b). It shows that when the design rainfall period is longer, the peak flow increases; and when the tank volume increases, the peak flow reduces. For example, the peak flow for a 100-year design without a tank is 26 m³/h (Point A in Figure 5(b)). However, when the tank size is 11 m³/100 m² (Point B), the peak flow for the same 100-year design period reduces to 11 m³/h (Point C), which is equivalent to the peak flow at rainfall with a 2-year return period (Point D). Kim & Han (2008) and Kim *et al.* (2015) have reported similar results.

The result shows that by installing rainwater tanks, the nearby sewer system can mitigate flooding risks without increasing the capacity of the existing sewer system, thus saving time and reducing costs.

R-S-U-D system

If the stored water is emptied by utilizing the stored rainwater for domestic non-drinking or drinking purposes, the runoff can be reduced, thus mitigating flooding. To understand the effect of utilization rate in an R-S-U-D system on peak outflow reduction, peak outflow rates were calculated by the R-S-U-D model using various utilization rates and tank volumes, under different design rainfall periods as input, as shown in Figure 6. Figure 6(a) shows tank capacity vs. peak outflow curves under different utilization rates for a 100-year design period in Seoul. 0–20 L/min (equal to 0–28.8 m³/day) of water consumption is a reasonable range for multistorey buildings. The line for No Utilization stands for the R-S-D model. With a higher tank capacity or a higher utilization rate, discharge flow is reduced. The solid black line represents the peak runoff flow for the 2-year design rainfall. The minimum tank capacity without utilization to control a 100-year peak flow for 2 years is 11 m³/100 m². The tank capacity can be reduced to 10 and 9 m³/100 m² with utilization rates of 10 and 20 L/min, respectively. Utilization rates as low as 5 L/min have almost no effect on high rainfall events of a 100-year frequency.

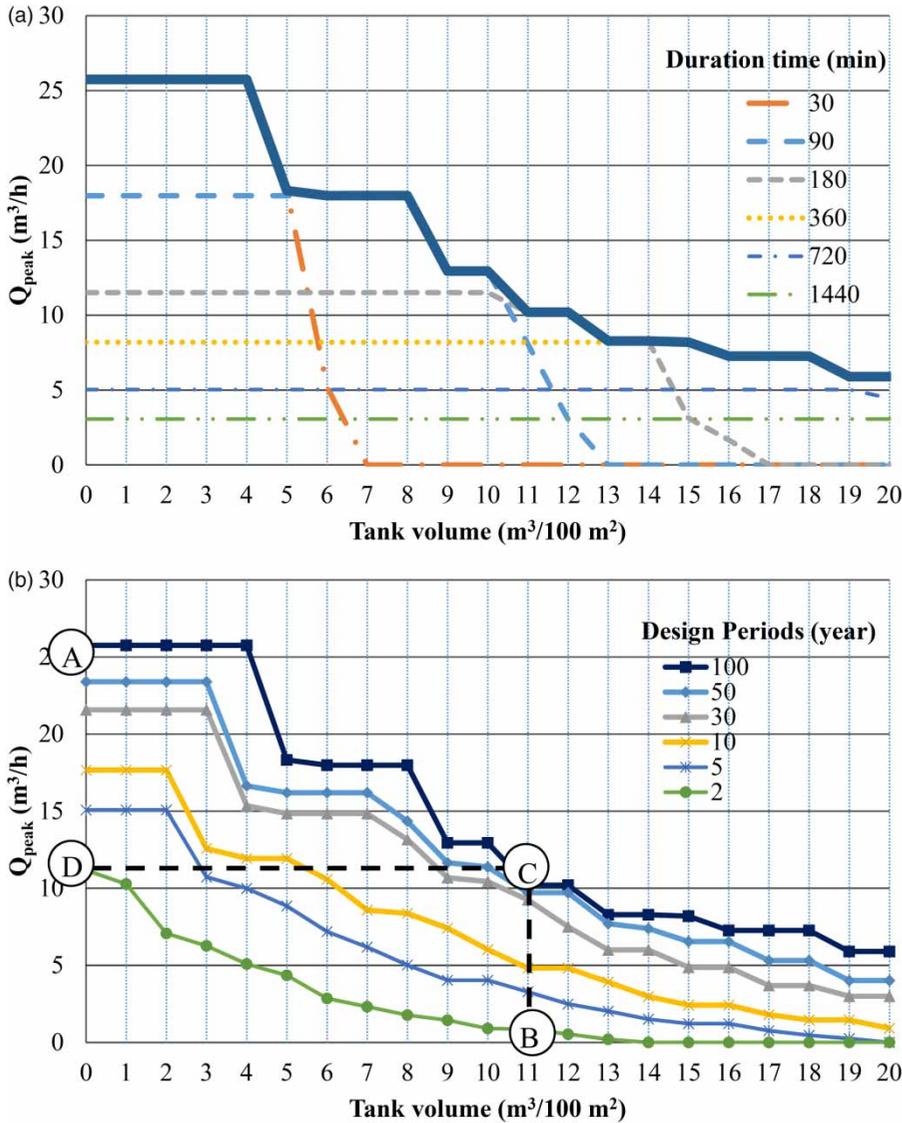


Figure 5 | Tank volume vs. peak runoff curves for (a) 100-year frequency; and (b) various design periods in Seoul.

Figure 6(b) and 6(c) show practical case studies for 50-year and 30-year return period design rainfalls. For the 50-year return period rainfall, the minimum tank volume to control peak flows into 2-year return periods is $10 m^3/100 m^2$, when no utilization is considered (R-S-D model). The tank volume can be reduced to 9 and $8 m^3/100 m^2$ with utilization rates of 10 and 20 L/min, respectively (R-S-U-D model). For the 30-year return period, the tank capacity can be reduced from 9 and $7 m^3/100 m^2$ with utilization rates of 10 and 20 L/min, respectively.

For more simple and practical design of an RWM system, the necessary tank volumes that are required to

control heavy rainfalls of various design periods being safe under different utilization rates were summarized from the above results as shown in Figure 7. Figure 7 shows a Tank volume-Utilization rate-Design period (TUD) curve which presents how tank volume and utilization rates can reduce the peak flow so that the sewer system can be safe even for longer design periods, without increasing the capacity of the sewer system. For example, for a sewer system designed for a 2-year return period rainfall, a rainwater tank with $9 m^3/100 m^2$ (point A) is installed, and the sewer system can be safe even at the stronger rainfall of a 30-year return period with an R-S-D model (point B). If

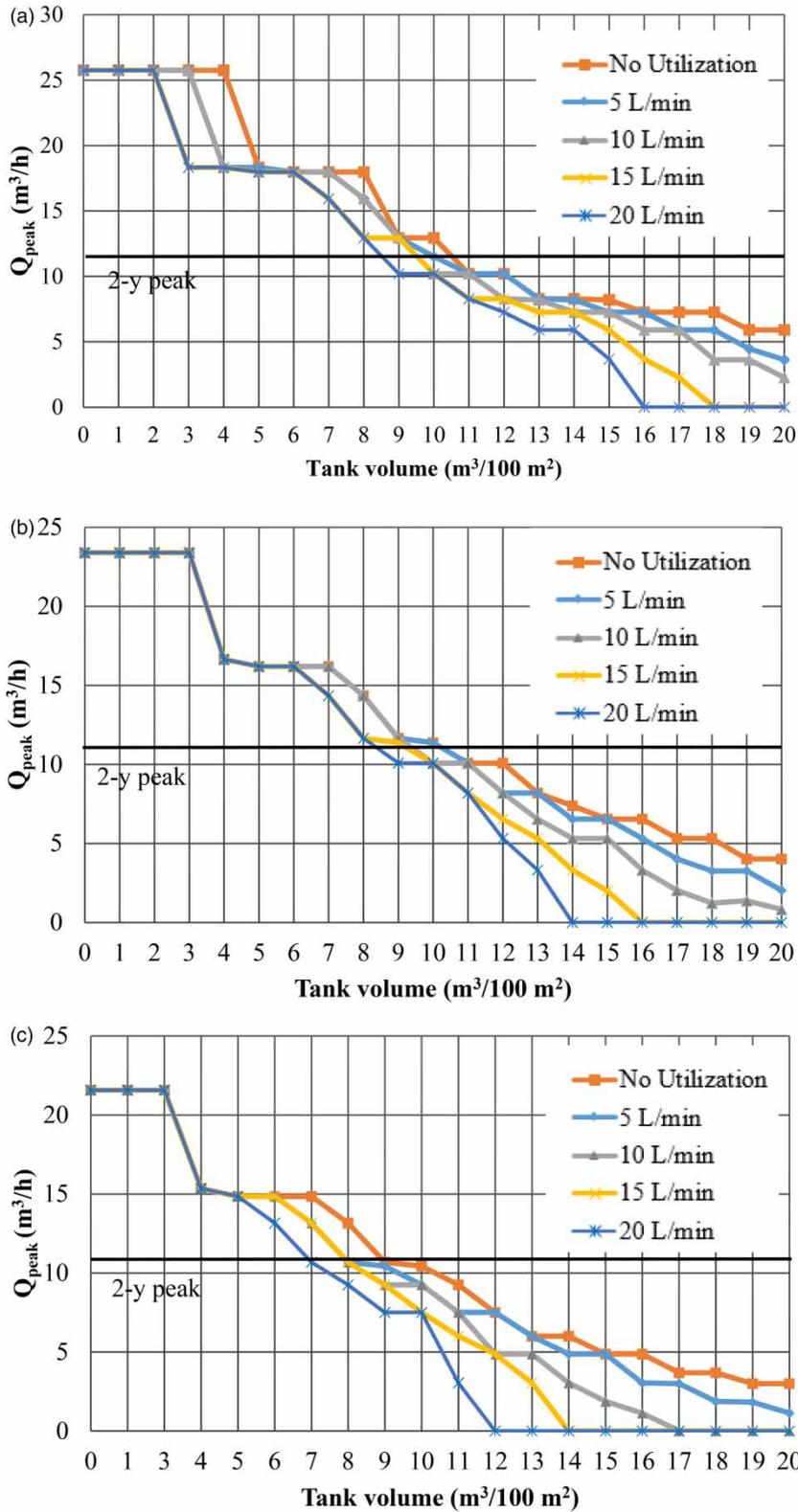


Figure 6 | Tank volume-Utilization rate-Peak outflow (TUP) curves for (a) 100-year; (b) 50-year; and (c) 30-year design periods in Seoul.

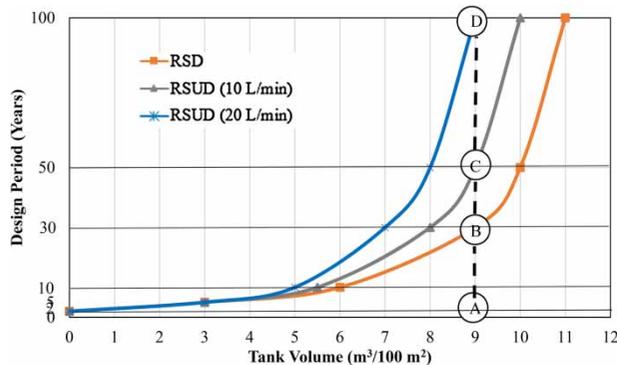


Figure 7 | Tank volume and utilization rate to match peak runoff flow for different rainfall periods with a 2-year rainfall event (Tank volume-Utilization rate-Design period (TUD) curve).

the stored rainwater is designed to be utilized at rates of 10 and 20 L/min, the sewer system can become safe even with a higher return rainfall of 50-year and 100-year periods (point C and point D), respectively.

Both Tank volume-Utilization rate-Peak outflow (TUP) and TUD curves can be easily developed for any city using the local rainfall data, and can be used to design and operate sewer systems for flood mitigation plans and strategies by city planners, designers, and even politicians.

Water conservation effect

R-S-U-D systems not only mitigate flooding, but also conserve water. Stored rainwater in the tank can be conserved and supplied to meet the building water demand. Figure 8 shows the annual water savings that were calculated by the daily water balance simulation (Mun & Han 2012) for

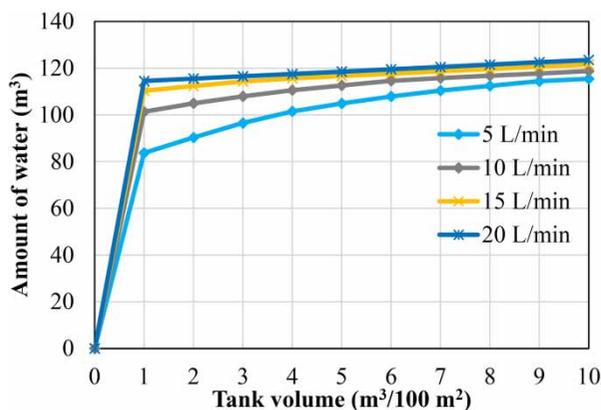


Figure 8 | Annual water saving in R-S-U-D system, case study of Seoul.

Seoul rainfall conditions under different utilization rates. With a tank size of 5 m³, the annual water saving of an R-S-U-D system is 116.7 m³ and 118.5 m³ (83% and 86% rainwater utilization ratio) with a utilization rate of 10 and 20 L/min, respectively. The more the rainwater conserved, the more the tap water saved. In areas where freshwater resources are limited and sometimes seriously under threat, water conservation from widespread R-S-U-D systems are significant.

CONCLUSION

Traditional methods of draining rainwater from rooftops, based on the R-D (Rainfall-Discharge) model, are challenged. Storing some of the rainfall that falls on building rooftops can mitigate flooding of nearby sewer systems. The stored water can later be used in or near the building, thus conserving water.

An R-S-D (Rainfall-Storage-Discharge) model that can predict the reduction of peak runoff by installing rainwater tank for flooding mitigation was developed. Furthermore, the R-S-U-D (Rainfall-Storage-Utilization-Discharge) model, which includes rainwater utilization, can be used for both flood mitigation and water conservation.

From the R-S-D model, a tank volume-peak flow (TP) curve is developed for a site-specific rainfall characteristic, which can be used to determine the required tank volume to reduce the peak flow down to a certain design period rainfall. Existing sewer systems can be made safe under heavier rainfall by installing rainwater tanks without increasing the existing sewer capacity.

From the R-S-U-D model, TUP curves and TUD curves are developed to determine the peak flow reduction when utilization is included. These curves will be used in the design and operation of rainwater systems in areas of limited sewer capacity or for climate change adaptation. Additionally, total annual water conservation in R-S-U-D systems can be calculated as a supplement of existing water supply systems.

The R-S-U-D model can be used to increase the resilience of existing sewer systems against urbanization and climate change, resulting in a solution for Sustainable Development Goals (SDGs 6 and 11).

ACKNOWLEDGEMENTS

This research was supported by the 'Development of Nano-Micro Bubble Dual System for Restoration of Self-purification and Sustainable Management in lake' project funded by the Republic of Korea Ministry of Environment; Institute of Construction and Environmental Engineering at Seoul National University; and Vietnam National University Ho Chi Minh City (VNU-HCM) under grant number C2017-48-03. The authors wish to express their gratitude for the support.

REFERENCES

- Amin, M. T. & Han, M. Y. 2009 [Roof-harvested rainwater for potable purposes: application of solar collector disinfection \(SOCO-DIS\)](#). *Water Research* **43** (20), 5225–5235.
- Coombes, P. J., Dunstan, H., Spinks, A., Evans, C., Martin, A. & Harrison, T. 2006 Insight from a decade of research into the quality of rainwater supplies collected from roofs. In: *The Sixth International Workshop on Rainwater Harvesting and Management*, August 24, 2006, Seoul, Korea.
- Fewkes, A. 1999 [The use of rainwater for WC flushing: the field testing of a collection system](#). *Building and Environment* **34** (6), 765–772.
- Han, M. Y., Han, M. S. & Kim, S. G. 2004 A consideration in determining the tank size of rainwater harvesting system in buildings. *Journal of Korean Society of Water and Wastewater* **18** (2), 99–109.
- Han, M. Y., Mun, J. S. & Kim, T. I. 2009 Climate change adaptation strategy by multipurpose, proactive rainwater management and case studies in Korea. *Journal of Korean Society of Water and Wastewater* **23** (2), 223–230.
- Huff, F. A. 1967 Time distribution of rainfall in heavy storms. *Water Resources Research* **3** (44), 1007–1019.
- Jha, A., Lamond, J., Bloch, R., Bhattacharya, N., Lopez, A., Papachristodoulou, N., Bird, A., Proverbs, D., Davies, J. & Barker, R. 2011 *Five Feet High and Rising: Cities and Flooding in the 21st Century*. Policy Research Working Paper 5648, World Bank, Washington, DC.
- Julius, J. R., Prabhavathy, R. A. & Ravikumar, G. 2013 Rainwater harvesting (RWH) – a review. *International Journal of Scientific & Engineering Research* **4** (8), 276–282.
- Kim, Y. J. & Han, M. Y. 2008 [Rainwater storage tank as a remedy for a local urban flood control](#). *Water Science and Technology: Water Supply* **8** (1), 31–36.
- Kim, Y. J., Han, M. Y., Kim, Y. H. & Mun, J. S. 2009 [An experimental runoff formula in building roof area for on-site rainwater management](#). *Journal of Korea Water Resources Association* **42** (2), 171–176.
- Kim, Y., Kim, T., Park, H. & Han, M. 2015 [Design method for determining rainwater tank retention volumes to control runoff from building rooftops](#). *KSCE Journal of Civil Engineering* **19** (6), 1585–1590.
- Kim, Y., Han, M., Kabubi, J., Sohn, H. G. & Nguyen, D. C. 2016 [Community-based rainwater harvesting \(CB-RWH\) to supply drinking water in developing countries: lessons learned from case studies in Africa and Asia](#). *Water Science and Technology: Water Supply* **16** (4), 1110–1121.
- Lee, J. Y., Bak, G. P. & Han, M. Y. 2012 [Quality of roof-harvested rainwater – comparison of different roofing materials](#). *Environmental Pollution* **162**, 422–429.
- Ministry of Construction and Transportation 2000 *1999 Report of Research and Survey on Water Resources Management and Development Method*. Republic of Korea.
- Mun, J. & Han, M. 2012 [Design and operational parameters of a rooftop rainwater harvesting system: Definition, sensitivity and verification](#). *Journal of Environmental Management* **93** (1), 147–153.
- Mwenge Kahinda, J., Taigbenu, A. E. & Broto, J. R. 2007 [Domestic rainwater harvesting to improve water supply in rural South Africa](#). *Physics and Chemistry of the Earth* **32**, 1050–1057.
- Nguyen, D. C. 2016 *Micro-Scale Hydrology Modelling for Multipurpose Rainwater Management*. Doctoral Dissertation, Seoul National University, Seoul, Korea.
- Nguyen, D. C. & Han, M. 2014 [Design of dual water supply system using rainwater and groundwater at arsenic contaminated area in Vietnam](#). *Journal of Water Supply: Research and Technology-AQUA* **63** (7), 578–585.
- Nguyen, D. C., Dao, A. D., Kim, C. & Han, M. Y. 2013 [A sustainability assessment of the rainwater harvesting system for drinking water supply – a case study of Cukhe Village, Hanoi, Vietnam](#). *Environmental Engineering Research Journal* **18** (2), 109–114.
- Song, J., Han, M., Kim, T. & Song, J. 2009 [Rainwater harvesting as a sustainable water supply option in Banda Aceh](#). *Desalination* **251**, 233–240.
- Tabatabaee, J. & Han, M. 2010 [Rainwater harvesting potentials for drought mitigation in Iran](#). *Water Science and Technology* **62** (4), 816–821.
- UNEP 2009 *Rainwater Harvesting: A Lifeline for Human Well-Being*. Stockholm Environment Institute. University of York, York, UK.

First received 21 April 2017; accepted in revised form 21 August 2017. Available online 25 September 2017