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A Novel Buffer Tank to Attenuate the Peak Flow of Runoff

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Abstract

Impermeable pavements and roofs in urban areas convert most rainfall to runoff, which is commonly discharged to local sewers pipes and finally to the nearby streams and rivers. In case of heavy rain, the peak flow of runoff usually exceeds the carrying capacity of the local sewer pipes, leading to urban flooding. Traditional facilities, such as green roofs, permeable pavements, soakaways, rainwater tanks, rain barrels, and others reduce the runoff volume in case of a small rain but fail in case of a heavy rain. Here we propose a novel rainwater buffer tank to detain runoff from the nearby sealed surfaces in case of heavy rain and then to discharge rainwater from an orifice at the tank's bottom. We found that considering a 100 m^2 rooftop with 0.80 runoff coefficient and a 10cm rainfall depth for an hour, a cubic tank with internal edge side of a square of 2 m attenuates the peak flow about 45%. To reduce a desirable peak flow, the outlet orifice of the buffer tank must be optimized according to site-specific conditions. The orifice can be set at an elevation from the tank's bottom to create a dead storage for harvesting rainwater.

Keywords: Urban Flooding; Runoff; Rainwater Tank; Rainwater Management; Peak Flow.

1. Introduction

Urbanization has sealed natural permeable surfaces with pavements, roofs, and other impermeable surfaces. Rainwater falling on these surfaces generates runoff, which is diverted to local sewer pipes and finally ends up at nearby streams or rivers. In the case of a heavy rain, the runoff-discharging rate commonly exceeds the carrying capacity of the sewer pipes, resulting in urban flooding. Urban flooding subsequently causes a series of serious negative consequences such as traffic jams, loss of human life, damage to property, loss of livestock, and deterioration of health conditions owing to waterborne diseases, and others [1]. Across the globe, rainwater management techniques have widely employed to mitigate urban flooding. Mainstream techniques include Low Impact Development [2], Best Management Practices [3], Water Sensitive Urban Design [4], Sponge Cities [5], and other similar projects [6-8]. While their names of these projects are different, the purposes of these techniques are similar. That is, on-source techniques are developed to retain, detain, infiltrate, harvest, evaporate, transpire, and/or re-use rainwater for reducing the runoff volume and the peak flow.

The specific rainwater management techniques include green roofs, permeable pavements, bio-retentions, soakaways, rainwater tanks, rainwater barrels, and others. A green roof consists of a vegetated layer and a growing medium layer above a roof deck, over which both layers cannot further retain rainwater after they get saturated [9]. Green roofs therefore effectively reduce the runoff volume and the peak flow in case of a small rain but fail in case of a

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heavy rain [10, 11]. A permeable pavement consists of a permeable surface layer that allows rainwater passing through it to the base layer, where rainwater stores and infiltrates to the subgrade layer slowly [12]. Similar to green roofs, permeable pavements lead to overflow in case that the water-storing base saturates [13]. Soakaways are buried chambers filled with gravels, rubber, and stones that store water in the cavities of the fillers and discharge the water by infiltration [14]. The cavities of the fillers are limited so the buffering capacity of a soakaway is inadequate to store a large volume of water [15]. A bio-retention unit is a bowled land backfilled with a vegetated surface layer and with a filter intermediate layer upon natural soils. A bio-retention unit ponds rainwater in the bowled lands for subsequent infiltration [16]. As the infiltration is controlled by the permeability of the soils, overflow occurs in case of a heavy rain if the permeability is small [16, 17]. Rainwater tanks or rainwater barrels are small water-storage units collecting rainwater from nearby sealed surfaces [18]. While these rainwater storage units can store a great amount of water, they must be frequently emptied artificially for re-storing rainwater at the next rain [19, 20]. In seasons of heavy and intense rainfall, these units are commonly failed to be emptied [21]. Therefore, it is desirable if rainwater tanks or rainwater barrels can be emptied automatically before the next rainfall event.

Here we propose a novel water buffer tank to temporarily store rainwater in case of heavy rain. The design of this tank is schematically shown in Figure **1**ure 1. For instance, the tank can be connected to a downspout to detain rainwater from a rooftop. The retained water in the tank can be discharged to nearby sewer pipes or gutters. The outlet orifice is set smaller than the inlet pipe. In case of small rain, this tank loses the buffering capacity because the inflow to the tank is equal to the outflow. In case of heavy rain, the outflow to the tank is smaller than the inflow, with some storing in the tank and the surplus discharging from the outlet orifice. The discharging rate increases as the water head in the tank increases. After rainfall stops, the detained water continually drains from the outlet orifice until the tank is emptied. Therefore, the tank serves as a buffer to attenuate the peak flow. By optimizing the outlet orifice, a buffer tank always keeps emptied, automatically resetting to attenuate the peak flow of runoff from nearby sealed surfaces for mitigating urban flooding.

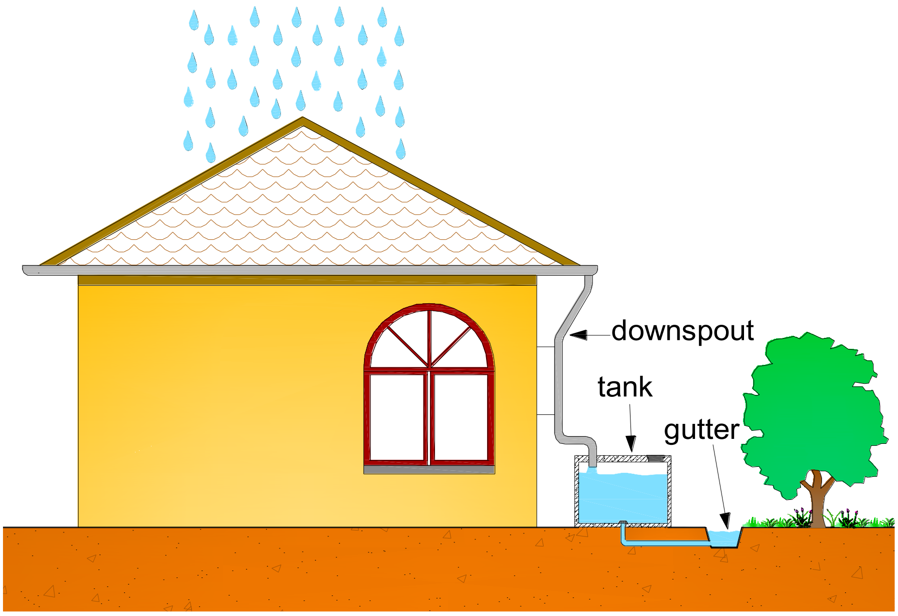


Figure 1. A buffer tank is set to temporarily storing runoff from a house's rooftop

2. Research Methodology

2.1. Theory

As shown in Figure 1, runoff enters the buffer tank, in which a factor of runoff is detained and the surplus drains through the outlet orifice. According to the Torricelli Law, the outflow speed from the outlet orifice is proportional to the square root of the water head difference from the orifice to the water level in the tank, that is

$$v = \sqrt{2gh} \tag{1}$$

Where h (m^2) is the water head difference, g (m^2/s) is gravitational acceleration, g = 9.81. The corresponding outflow rate, q_o (m^3/s), is

$$q_o = a\sqrt{2gh} \tag{2}$$

Where a (m^2) is the cross-sectional area of the outlet orifice.

Considering a rainfall intensity of p (m/s) and a runoff coefficient of r (-), the inflow to the buffer tank, q_i (m^3/s), is;

$$q_i = pAr \tag{3}$$

Where A (m^2) is the cross-sectional area of the sealed surfaces

According to the law of conservation of mass, one has;

$$pAr - a\sqrt{2gh} = A_t\frac{dh}{dt} \tag{4}$$

Where t (s) is time; A_t (m^2) is the internal cross-sectional area of the tank.

As both the precipitation p and the water head difference h are variables of time, it is difficult to find the analytic solution of h in Equation 4. The practical solution is to find h via the numerical differentiation. After finding the water head h, one can further find the water flowing rate q_o and q_i, both of which are time series. The attenuation ratio, θ (-), of the peak flow can be estimated accordingly, which is

$$\theta = 1 - \max(q_o) / \max(q_i) \tag{5}$$

Where the operator max (x) finds the maximum value from a time series of x.

2.2. Experiments

We conducted indoor experiments to verify Equation 4. Two cubic tanks with an internal size of 0.5×0.5×0.5m were prepared (Figure 1). One tank was set at a high-lying position. The entire tank was watertight except a 6.0mm in diameter orifice at the tank bottom. Water discharging from this outlet was controlled by a faucet (Figure 2). The tip of the faucet was connected to a soft corrugated pipe to route the discharging water to the other tank, which was set at a lower position (Figure 2). Similarly, the low-lying tank was also watertight except that an orifice with 2.5mm in diameter was open at the tank's bottom. Both tanks and the corrugated pipe were set to minimize the dynamical water circulation in the low-lying tank, and to ensure that water enters to the low-lying tank through gravitational flow. In this setup, the water discharging from the high-lying tank could be deemed as runoff from a sealed surface, such as a rooftop. The low-lying tank was the buffer tank that otherwise allows runoff discharging directly to the gutter without buffering. Except for the water volume detained in the tank, the surplus water in the low-lying tank drained from an orifice at the bottom of the buffer tank (Figure 2).

In the experiment, the high-lying tank was filled with water, while the low-lying one was empty. When the faucet was opened, water drained through the corrugated pipe to the low-lying tank. The faucet was controlled artificially. Several trials were repeated until the water outflow from the high-lying tank rose gradually from zero to a peak and then fell to zero, and until the receding limb was longer than the rising limb. The inflow and outflow from the buffer tank could be found by weighting the weight of the high- and low-lying tanks. However, considering that the dynamical water circulation in the tank varied the weight of the tank, the mass of the inflow and outflow water was not weighted directly. In addition, as the experiment lasted for hours, placing a weighting object on a scale for hours would increase the zero drift of the scale. Instead, the weight of water in both tanks was estimated through the water head in both tanks. The water head of each tank was measured using a water level meter in an interval of 1min. After the high-lying tank was emptied, the reading interval was 2-4 mins because at this stage, the outflow of the low-lying tank was small.

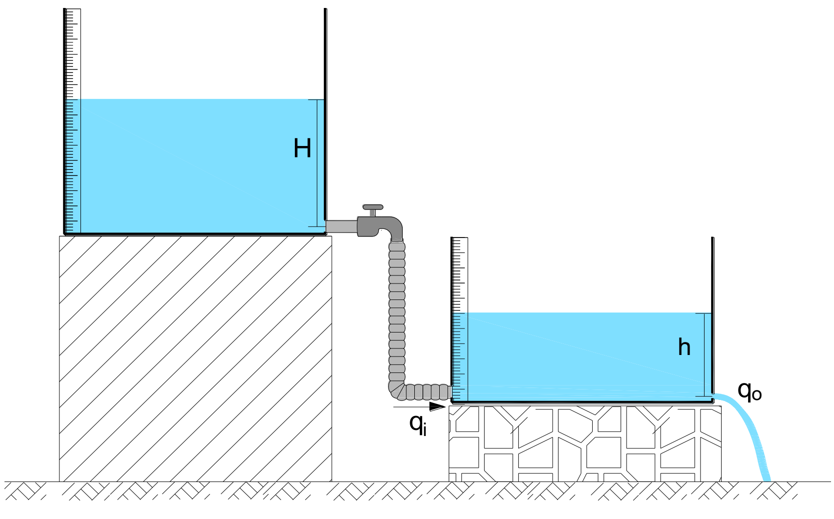


Figure 2. Experimental setups to observe the inflow and outflow from a buffer tank

3. Results

3.1. The Observed Water Head and the Water Flow Rate

In the experiment, only the water heads in high- and low-lying tanks are measured. These heads are used to derive the water-inflow and -outflow rates of the buffer tank. The inflow to the low-lying tank is estimated using the derivative of the water head in the high-lying tank with respect to time. The water storage in the low-tank is a derivative of the water head and is found by using the forward difference method. The outflow to the buffer tank is estimated using the Equation 2. As a result, the inflow fluctuates slightly. Ignoring these slight variations, the inflow rate gradually increases from zero to a peak flow of 57 ml/s, and then drops to zero. The inflow to the buffer tank lasts for about one hour. The hydrograph, as indicated in Figure 3a, with the rising limb shorter than the receding limb. The inflow to the buffer tank increases fast, which exceeds outflow for an hour (Figure 3a). As a result, the water head in the buffer tank rises gradually. The rise of water head continues until the inflow is equal to the outflow (Figure 3a and 3b).

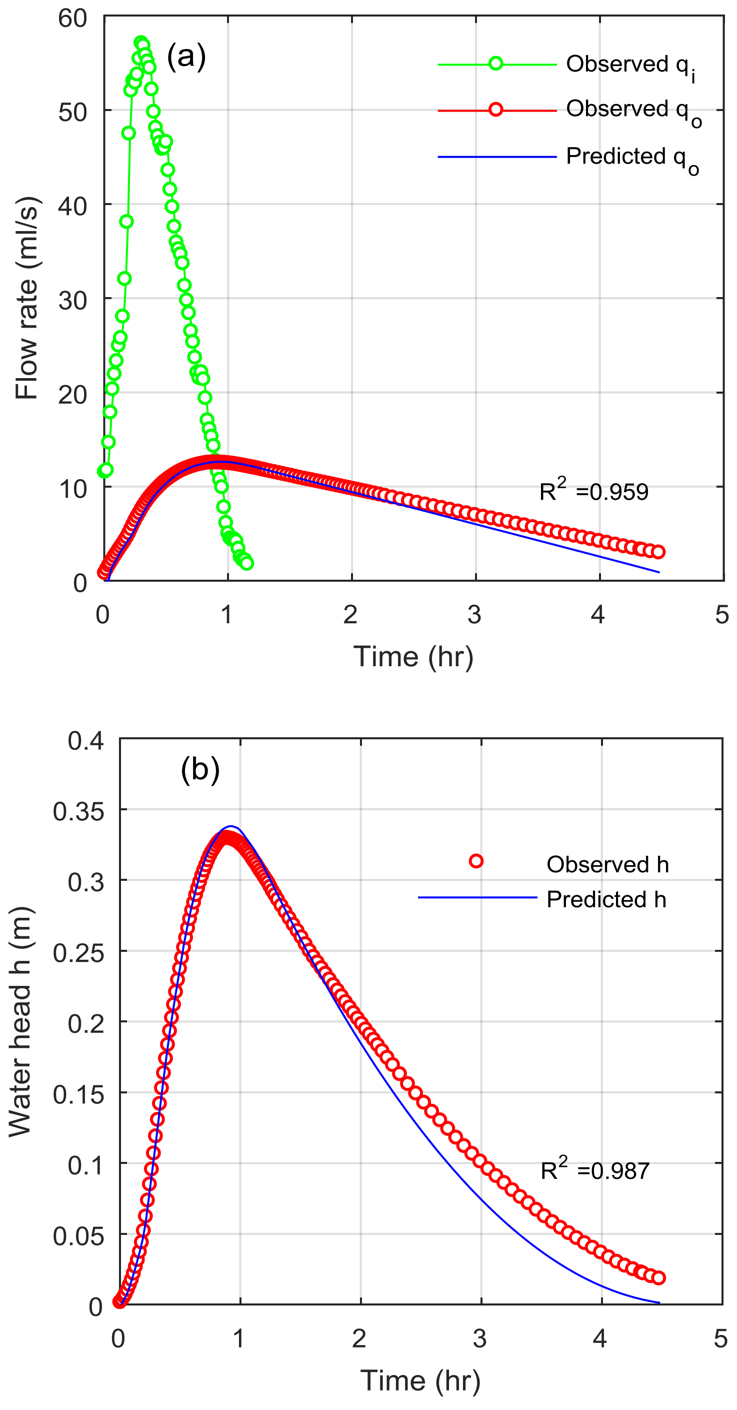


Figure 3. The observed water head and flow rate of the buffer tank (a) inflow and outflow rates of the buffer tank, (b) water head in the buffer tank

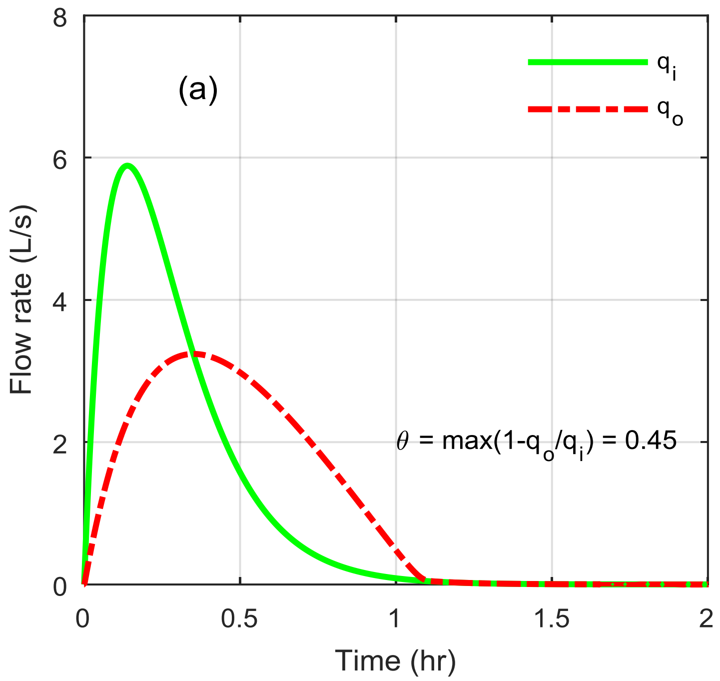
While the water heads in high-lying and low-lying tanks are measured, only the water head in the low-lying (buffer) tank is of concern. It can be seen that the water head of the buffer tank rises to a peak about 0.33m. Recording that both tanks have the same size of 0.5m×0.5m×0.5m and that the high-lying tank is full of water before starting the experiment, the buffer tank needs to be 0.33m height only (dotted data in Figure 3b). Using this buffer tank, the peak flow is attenuated from 55ml/s to 13ml/s, which is equal to a peak-flow attenuation ratio of 76.4% (1-13/55). Correspondingly, the discharge from the buffer tank extends to 4.5 hours, which is about 3.5 hours longer than the rainfall duration. Considering that the intermission between two adjacent heavy rains is commonly larger than the rainfall duration, the use of the buffer tank is thus helpful to attenuate the peak flow of runoff.

The line plots in Figure 3 are the predicted data, which is estimated by using the observed inflow to the buffer tank as the input of Equation 4 to calculate the outflow and water head of the buffer tank. The predicted data (dotted data in Figure 3) is coincident well with the observed data, with a R^2 value greater than 0.95. The coincidence suggests that the discharge of water from the buffer tank can be deemed as an ideal fluid following the Torricelli Law. The coincidence is high when the water head is high (Figure 3). In case of a low water head, the observations deviate somewhat from the predictions because the viscous flow dominates in case of a small water flow. As the small discharge rate is not of concern in flooding, the outflow and the water head in the buffer tank can be predicted using the Torricelli Law.

3.2. The Buffer Tank Effectively Attenuates the Peak Flow in Case of Heavy Rain

The size of the buffer tank in the above experiment is relatively small. Here we simulate the use of a larger buffer tank to detain the runoff from a 100 m^2 sealed surface. We assume a rainfall depth of 100mm for an hour, which represents a typical heavy rain. We assume the instantaneous rainfall intensity as a gamma distribution, which is controlled by two constants α and β. Different α and β values are tried until the rainfall distribution curve, in shape, is similar to the inflow in Figure 3a. Finally, α =2 and β =500 are selected. According to this assumed rainfall intensity distribution and the mean rainfall, the peak instantaneous rainfall is 264.8 mm/hr. The runoff coefficient is assumed as 0.80. Using this assumed runoff as the input to Equation 4, a suite of simulations is conducted considering cubic buffer tanks with different outlet orifices. We found that if a cubic buffer tank has an internal edge length of 1.41m (√2) and an outlet orifice of 2.8cm in diameter, it can attenuate 45% of the peak flow (Figure 4a) and that the water head in the tank peaks at 1.41m (Figure 4b).

In a buffer tank, both the peak-flow attenuation and the peak water head are influenced by the outlet orifice. This influence is further simulated by using all the simulated factors in Figure 4 except the outlet orifice, which is set 2-4 cm. The simulation results showed that both the water head in the buffer tank and the attenuation of the peak flow decrease as the diameter of the outlet orifice increases (Figure 5). This correlation means that a large outlet orifice in the buffer tank requires a dwarf tank but results in a low peak-flow attenuation rate. This also means that an improperly large outlet orifice could make the tank losing the buffering capacity. Therefore, the outlet orifice and height of a buffer tank must be tailored such that the peak flow is attenuated to be lower than the carrying capacity of the local sewer pipe.



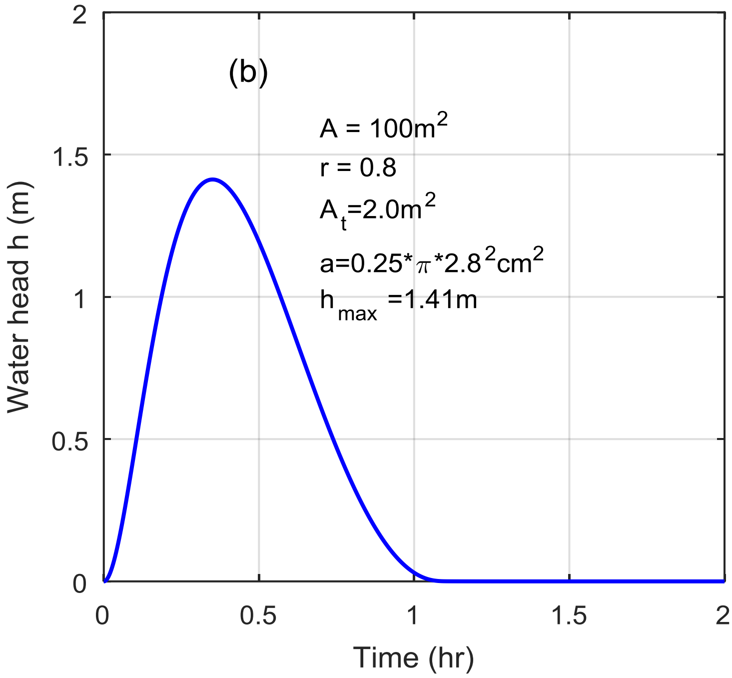


Figure 4. The water head and the flow rate of a buffer tank that is set to detain runoff from a 100m² rooftop subjected a rainfall depth of 10cm for an hour, (a) inflow and outflow of the buffer tank, (b) water heads in the buffer tank

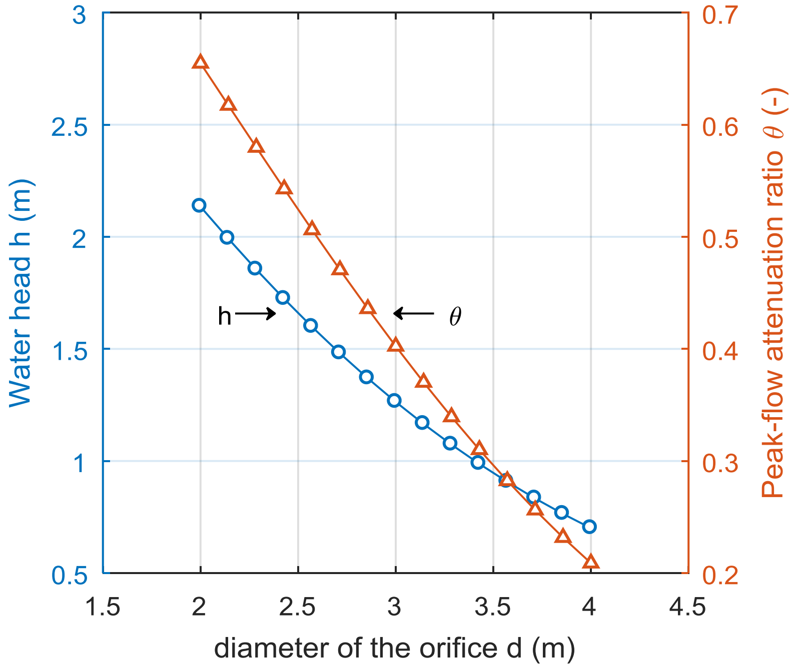


Figure 5. Either the water head in the buffer tank and the peak-flow attenuation decrease as the diameter of or outlet orifice increases

3.3. The Buffer Tank Fails to Attenuate the Peak Flow in Case of Small Rain

There is a critical rainfall intensity in which the outflow of the buffer tank is equal to the inflow. As a result, the rainwater volume in the buffer tank is unchanged, that is, dh/dt=0. Substituting dh/dt=0 to Equation 4, one has;

$$h = \frac{p^2 A^2 r^2}{2g} \tag{6}$$

According to Equation 6, this critical water head, h, linearly increases with the square of the rainfall intensity, of a specific catchment area A, and of a constant runoff coefficient r. To verify this correlation, we simulate the water heads, outflow, and inflow of the buffer tank. The bottom area of the buffer tank is set as 2.0 m^2. The height of the buffer tank is assumed as 1.41m. Rainfall lasts for two hours. The rainfall intensity is assumed as a constant, which is sequentially set as 20, 40, 60, 80, 100 mm/hr in each simulation.

The simulation verifies that the water heads in the buffer tank increase with the square of the rainfall intensity, as indicated in Figure 6a; that is, the height of the buffer tank increases as the rainfall intensity increases. For a specific rainfall intensity, the water head in the buffer tank gradually rises first and then becomes a constant at a specific water head until the inflow is equal to the outflow (Figure 6a). The time reaching this balance increases as the rainfall intensity increases (Figure 6a), meaning that the buffer tank stores a large amount of runoff in case of heavy rain but a small volume in case of a small rain. As a result, a small long-lasting rainfall cannot fill the tank, which always preserves spaces for buffering runoff in case of a heavy rain.

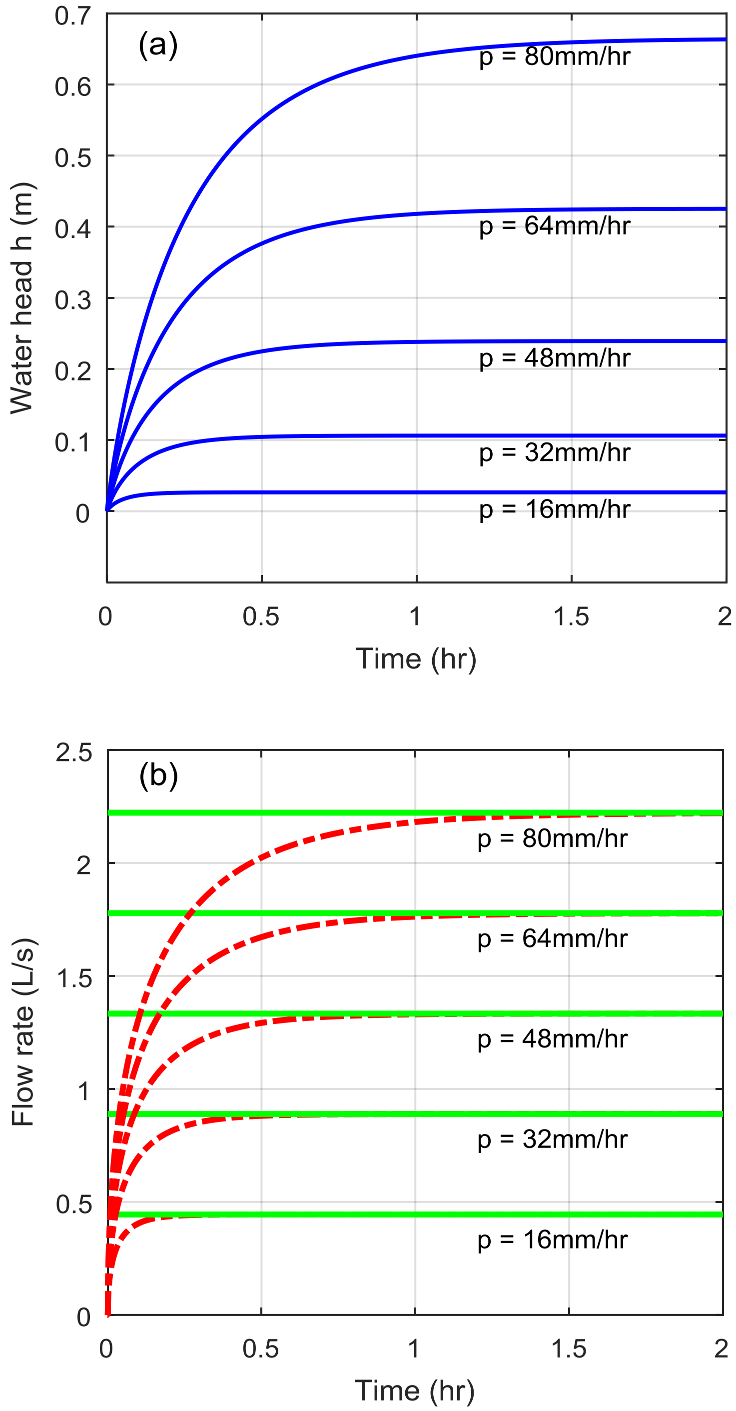


Figure 6. Water head and flow rate of a buffer tank that is used to detain runoff from a 100m^2 sealed surface subjected to different rainfall intensity. (a) water head, (b) outflow and inflow, in which the dashed lines represent the outflow and straight lines, the inflow

4. Discussion

We have shown that runoff from a 100 m^2 rooftop can be detained by a buffer tank for attenuating the peak flow about 20-70%. The volume of the buffer tank can be 2-3.5 m^3, depending on the anticipated degree of peak-flow attenuation. In practice, the sealed surface can be greatly larger than 100 m^2, and thus a tank with a larger volume is required. The advantage of building a large tank is that the rainwater water can be treated (if necessary) collectively. However, as a buffer tank shall be buried at shallow ground for facilitating gravitational flow, a tank with larger volume means a greater base area for the tank, which required reinforced beams and columns to support the slabs that gap the tank. A large tank with this configuration will increases the construction cost. Therefore, in practice, rainwater runoff from a large sealed surface can be routed to a group of small tank, whose volume shall be designed according to the local site condition. Doing so, the urban flooding problem can be mitigated on sources. While the size and deployment of the buffer tanks, as well as the quality of water outflow from the tank, remain unknown, this study is starting point of the use of buffer tanks to mitigate urban flooding.

The tank can be set either above ground or underground to collect rainwater from the nearby catchment. As indicated in Figure 1, the tank can be set above ground to detain runoff from a rooftop. The discharge of water from the tank can be routed to a nearby gutter, where rainwater is diverted to local sewer pipes. The gutter still possibly overflows when the outflow from the buffer tank is large. Site-specific conditions need to be considered to avoid overflow by adopting a proper tank size and a proper outlet orifice. Another alternative is to bury the buffer tank underground and then to convert the outflow from the outlet orifice to the local sewer pipes. In this case, the runoff from the rooftop and other sealed surfaces (such as pavements) can be diverted to the buffer tank via gravitational flow. The outflow of the buffer tank also depends on the carrying capacity of the sewer pipes. If this capacity is lower than the instantaneous outflow of the buffer tank, the outflow is constrained and is equal to the carrying capacity. The true outflow and water head would be different from the simulation results in this study.

The buffer tank can be designed to attenuate the peak flow of runoff and to harvest rainwater simultaneously. The outlet orifice is not necessarily set at the bottom of the buffer tank. It can be placed at some elevations above the tank's bottom to create a dead storage below the orifice, where the volume above the orifice is the live storage from attenuating the peak flow. Water stored in the dead storage can be extracted for non-portable water uses such as irrigations. In this scenario, the theory and results presenting in this study are only available to the live storage of the buffer tank. The height of the buffer tank and that of the outlet orifice need to be optimized to harvest an anticipated amount of rainwater and to attenuate a desirable peak flow rate. A buffer tank for this purpose may be beneficial of improving the quality of the outflow water. Water-carrying particles would settle at the bottom of the buffer tank because the water circulation rate in the tank is far lower than the speed of the inflow. Other contaminants may settle together with the settling particles at the bottom of the tank as well. Another setup of the buffer tank for harvesting rainwater and attenuating peak flow is illustrated in Figure 7. The tank is partitioned to two chambers. Water first filled the left chamber, where water is stored for reuse. After this chamber is filled, water automatically enters the right chamber, where a factor of water is detained and the remaining water drains from an outlet at the tank's bottom. Further studies are needed to understand the performance of buffer tanks for attenuating the peak flow of runoff and harvesting rainwater.

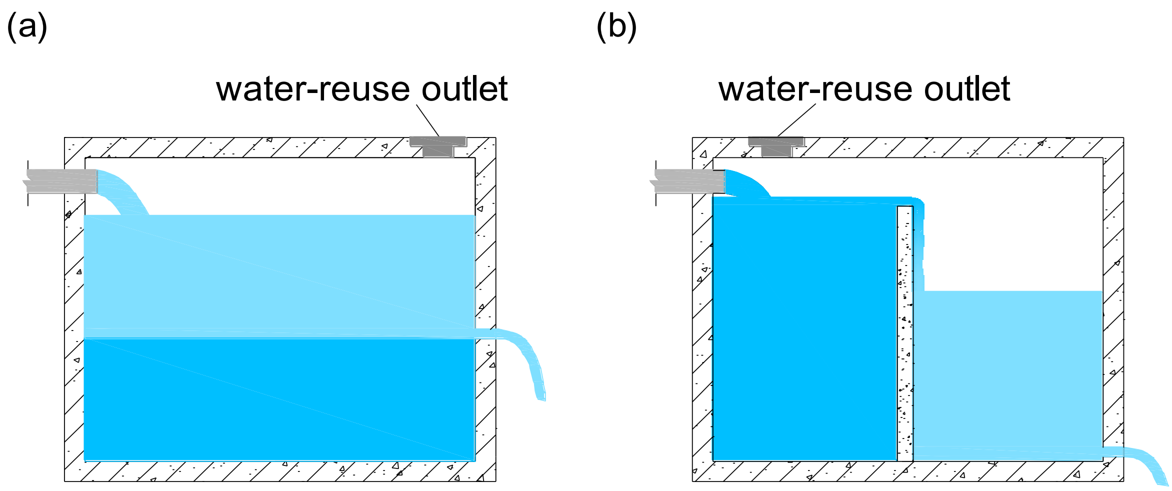


Figure 7. The buffer tank can be set to attenuate runoff and harvest rainwater simultaneously. (a) The outlet orifice is set at an elevation from the tank bottom to create a dead storage for harvesting rainwater, (b) the tank is partitioned to a dead space for harvesting rainwater and a live storage for attenuating runoff

5. Conclusion

This study proposes a novel-rainwater buffering tank to store rainwater for reducing the peak-flow discharge of the runoff from the nearby sealed surface. Runoff is converted to the tank and is then discharged from an outlet orifice that sets at the tank's bottom. In case of a small rain, the outflow could be equal to the inflow such that the tank fails to attenuate the peak flow. In case of a heavy rain, the inflow is greater than the outflow, with a part of rainwater being detained in the buffer tank and with the surplus discharging from the outlet orifice. After rainfall stops, the water detained in the buffer tank drains automatically from the outlet orifice. The buffer tank is thus always emptied to temporarily detain runoff in case of a heavy rain.

A theoretical model on the basis of the Torricelli Law is developed to calculate the water head in the buffer tank and to estimate the discharging rate. Experimental observations confirm that the outflow from the buffer tank obeys the Torricelli Law. Considering a 100 m^2 rooftop with 0.8 runoff coefficient subjected to 100mm for an hour, a cubic tank with internal edge side of a square of 2.0 m attenuates the peak flow about 45%. The attenuation rate decreases as the outlet orifice increases. The orifice thus must be tailored to attenuate the peak flow according to site-specific conditions. In practice, the buffer tank can be set above ground to store runoff from rooftops, or be buried underground to collect runoff from rooftops and other sealed surfaces. The outflow from a buried buffer tank needs to be further studied in case that the outflow exceeds the carrying capacity of the local sewer pipes. In addition, the tank can be designed to attenuate the peak flow of runoff and harvest rainwater simultaneously.

6. Funding

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7. Conflicts of Interest

The authors declare no conflict of interest.

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