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Examining the impacts of individual lot stormwater detention in a housing estate

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Abstract

This paper describes the Storm Water Management Model (SWMM) simulations of three individual lot stormwater detention systems under the car porches of houses. These three systems consist of ready-made modular units presumably fitted under 49 m^2 car porches of 204 double-story terrace houses. The 37,032 m^2 housing estate is calculated to have 75% of land covered with houses, 25% with roads and other infrastructures. The housing estate was subjected to 5-minute, 10-year Average Recurrent Interval (ARI) short-duration design rainfall. The model predicted that all three systems could reduce the peak runoff at outfall from 2.79 to 0.38 m^3/s. It indicated that any of the system could cause 86% reduction of the runoff for the whole housing estate. In order to differentiate the performance of the three systems, the housing lot was further investigated. When Type 1 system (1.15 m high with 49 m^3 per lot) was analysed by the SWMM model, only 8% of its storage volume was filled that highlights an over design. Type 2 system (0.3 m high with 6 m^3 per lot) modelled at 84% while Type 3 system (0.3 m high with 9 m^3 per lot), at 54%. The difference in heights between the systems explained the low percentage of filling for the Type 1 system. Comparing Type 2 and Type 3, concrete structure within Type 3 had only half of its volume filled. In this light, the Type 2 system made of polyethylene pieces was found the most efficient in lowering post-development peak runoff.

Keywords: Car porch, Drainage, Mekarsari, Modular, Sustainable development, Urban runoff

1. Introduction

Modifications to natural land cover cause changes to the flow mechanism of the local water cycle [1]. Forested land that is often a representation of pre-development condition could absorb runoff via the soil layers and plant roots. The resulted hydrograph in the presence of rooted plants has a low peak runoff and longer time to peak. Its baseflow is large due to the slow releases of water from the soils and plant roots [2,3]. Once the vegetations are replaced with buildings and roads, the built-up surfaces block water from infiltrating to the soils. Therefore, this so-called post-development condition causes a hike in both peak runoff and time to peak as well as a significant increase in the volume of runoff. Accumulated runoffs in the form of flash flooding come and go rapidly, a phenomenon often observed in the urban areas [4].

One of goals of urban stormwater management is to lower the post-development peak runoff to near the pre-development condition [5]. Stormwater detention is one of the practices to mimic the natural function of soils and plant roots [6]. In this paper, attention is paid to individual lots of stormwater detention systems. As the name suggests, this is a system installed within a private property's lot [7]. When portions of the stormwater runoff were captured at a lot scale, significant reduction in the discharge volume was achieved based on a case study in Western Australia [8]. Lot scaled devices were reported as locally efficient to reduce the flooding risks in another case study in China [9], reinstating the finding from the Western Australian study. However, in addition, appropriate locations to install the lot scaled devices were vital on reducing the impacts on a catchment's hydrographs [10]. This study is proposing the manipulation of common Malaysian house car porches to capture stormwater from the roof. The said lot scaled devices come in various forms and sizes. Three different types of individual lot stormwater detention systems were investigated in this paper and goes beyond the property lot scale to cover a larger area that includes a housing estate with 204 property lots and the surrounding two-lane roads.

2. Materials and methods

2.1 Selected housing estate

The Mekarsari housing estate located in a Bertam township of Malaysia with 204 units of double-storey terrace houses was selected as case study, and is depicted in (Figure 1). The materials in the figure are freely distributed and therefore, there is no conflict from any parties. Of the 37,032 m^2 total land area, 27,936 m^2 (75%) of the land masses are occupied with houses while the remaining 9,096 m^2 (25%) are with roads and other infrastructures. Out of the 204 units, 171 units (84%) are intermediate lots while 33 units (16%) are corner lots. The built-up area of an intermediate lot is 6.7 m (22') x 20.4 m (67'). A corner lot has the similar built-up area but with an additional 20 m^2 or 10 m^2 of a side yard.

Due to the high number of intermediate lots, the intended individual lot stormwater detention systems shall cater for these lots rather than the corner lots. It is also evident that a wide car porch that could fit two cars is provided for both intermediate and corner lots (Figure 1A). Therefore, it is wise to install an underground system, making use of the 6.7 m x 7.3 m surface area available for each of the house's car porch (Figure 1B).

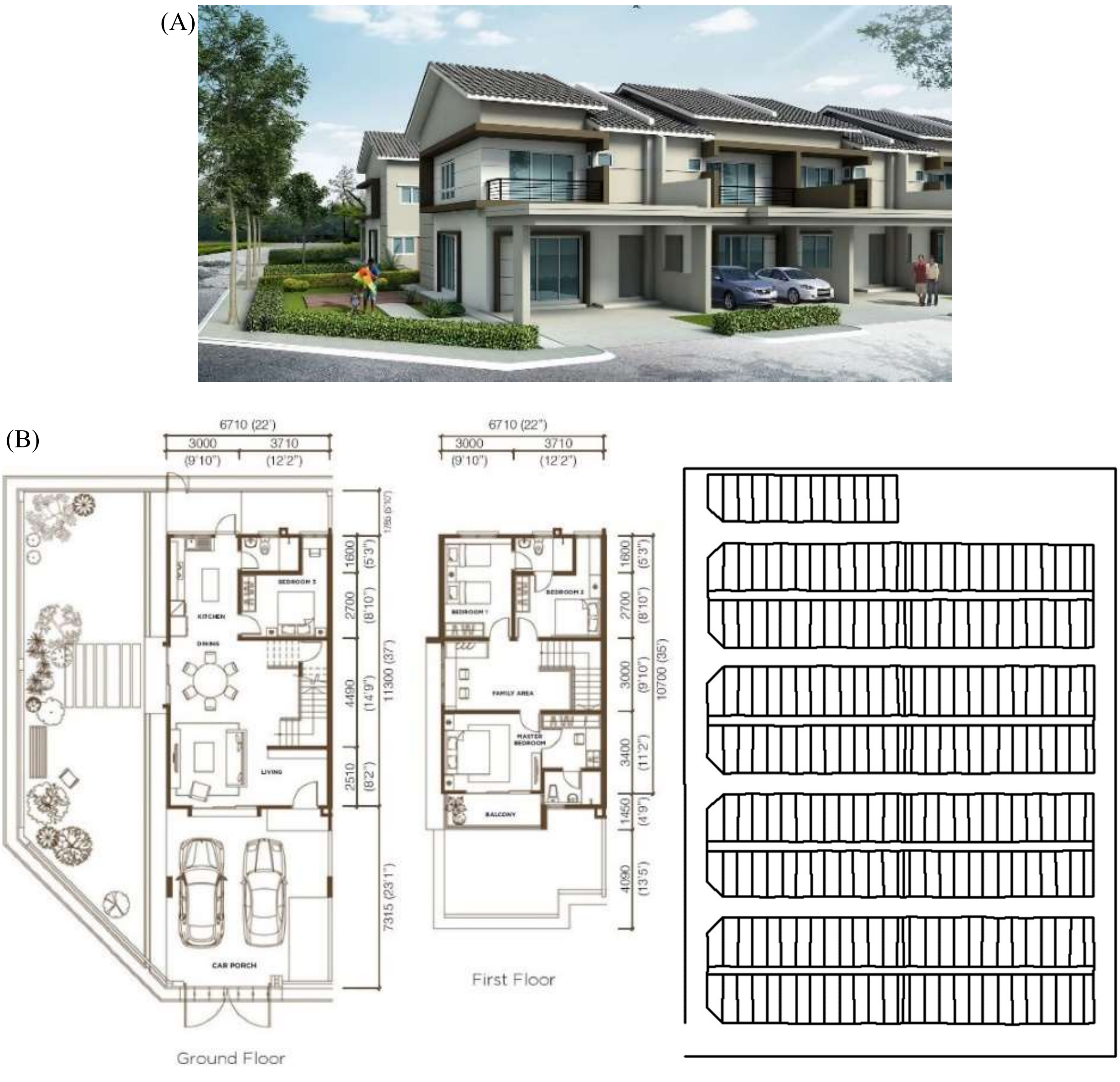

Figure 1 Study area, (A) Artist impression of model house, (B) Floor plan and Housing plan.

2.2 Selected stormwater detention system

Selection of the stormwater detention system was based on the suitability of the system to be fitted underground within the limit of a car porch. Three modular-based products were chosen for investigation (Figure 2). These are termed as Type 1, Type 2 and Type 3 products henceforth.

Type 1 is made of concrete [11], whereby the rectangular pre-casted modular concrete units are manufactured and delivered to the project site for assembling. The units are large and require machinery to assist in their installation (Figure 2A). The smallest size available has an effective storage volume of 7 m^3 with a dimension of 2.02 m in width, 3.30 m in length and 1.15 m in height. It requires 7 units of the Type 1 product to fill up the car porch area which is equivalent to 49 m^3 of an effective storage volume.

Type 2 is made of high-strength polyethylene [12]. The modular plastic units are designed to be fitted into concrete slabs of a building (Figure 2B). Each of the square modular unit comes in 1.10 m in width, 1.10 m in length and 0.30 m in height. Each modular unit has an effective storage volume of 0.35 m^3. Contrary to the remaining two products, Type 2 has a standard spacing of 1.44 m^2 per modular unit. It requires 18 units of the Type 2 product to fill up the car porch area which is equivalent to 6 m^3 of effective storage volume.

Type 3 is another product made of concrete [13] and has the smallest size. A single modular unit consists of three pieces, namely a hexagonal plate on the top layer that acts as a pavement, a hollow cylinder in the middle layer as a water storage chamber and another hexagonal plate on the bottom layer as the foundation (Figure 2C). The surface area of the hexagonal plate is 0.16 m^2. The height of the hollow cylinder is 0.3 m with an effective storage volume of 0.03 m^3 per modular unit. It requires 301 units of the Type 3 product to fill up the car porch area, which is equivalent to 9 m^3 of effective storage volume.

Figure 2 Selected individual lot stormwater detention systems, (A) Type 1, (B) Type 2 and (C) Type 3.

2.3 Stormwater drainage modelling

The U.S. Environmental Protection Agency's Storm Water Management Model (SWMM) Version 5.0 was selected to model a runoff through the three selected systems. SWMM 5.0 has been used to model stormwater detention systems in [14,15]. The software is reported to best represent a stormwater detention as a storage unit [16]. A general model structure in SWMM 5.0 starts with a rain gauge in which rainfall data are defined; followed by the catchments that receive the rainfall; and the generated runoff is directed to drains until it reaches an outfall as the final discharge point (Figure 3).

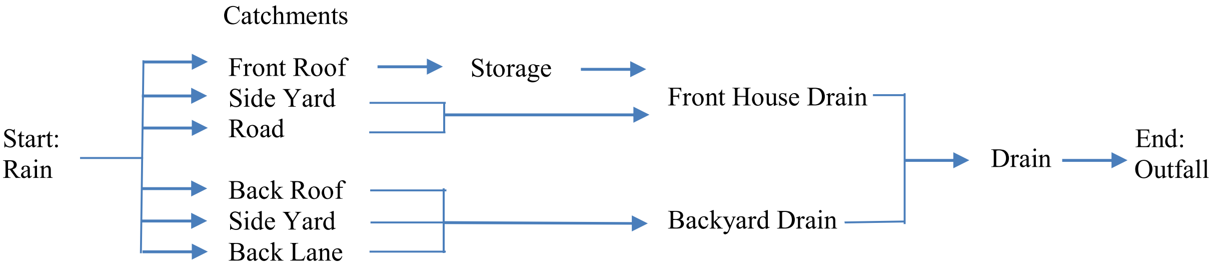

Figure 3 Flow chart of SWMM modelling.

In reference to (Figure 4A), the first model that simulates the existing drainage system started with a rain gauge, shown at the top left corner of (Figure 4). Due to the small rainfall-receiving catchment (described in the next paragraph), only a 5-minute rainfall design under the intensity of a 10-year ARI was used as suggested in [17,18]. The designed rainfall was determined as 278 mm/h based on the local rainfall intensity-duration-frequency curve.

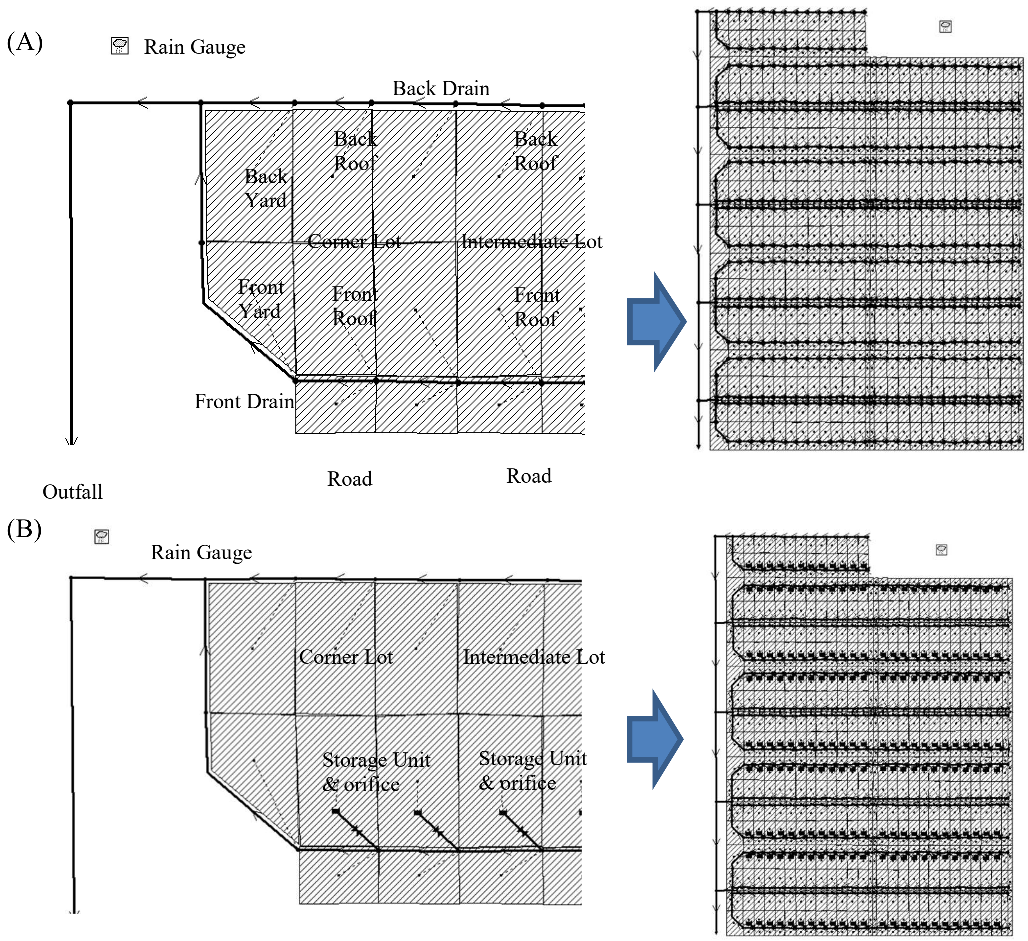

Figure 4 Modelling approaches for (A) Existing drainage system and (B) Addition of individual lot stormwater detention system.

Each property lot was modelled in detail, where the gable roofs were separated into front and back parts. The front part and the car porch formed the front roof of the house that contributed water to the intended stormwater detention system. The system required at least 60% of the property lot area as the contributing catchment, to achieve a lower post-development peak runoff that value is nearer to the pre-development peak runoff from one property lot itself [19].

For both intermediate and corner lots, the front roof was calculated as 78.7 m^2, and the back roof was 51.3 m^2. With a roof pitch of 4/12, the slope of the roof was calculated at 33%. The imperviousness of the roof was taken as 100%, assuming the losses were minute and negligible. However, the corner lots had a side yard, in which half of the 20 m^2 or 10 m^2 of this yard was modelled to drain to the front, and another half to the back. The grassed (green) area was assumed to have a minimal slope at 0.01% and the imperviousness of the side yard was taken as 70%.

In addition, the roads were also included. The road catchment was split at the road's centreline. Demonstrated in (Figure 4A), runoff that was generated by half of the road in front of the property lot, inclusive of the road carriageway and road shoulder, was directed to the drain at the front of the property. The width of the road was measured at 3.6 m from the crown to the shoulder. The slope that followed the crown of the road was measured at 2%. The imperviousness of the road was taken as 100%, assuming the losses was negligible. The other half of the road was modelled as part of the opposite row's house and drain.

The Rational Method was the most used formula to calculate runoff from the catchment (Equation 1). The *C* values were suggested as 0.4 and 1.0 for pre-development and post-development conditions, respectively [17,18], as in:

$$Q = \frac{CIA}{360} \tag{1}$$

where,

Q = generated runoff (m^3/s);
C = discharge coefficient (unitless);
I = rainfall intensity (mm/hr);
A = catchment area (ha).

However, SWMM computed the runoff, Q as a function of the catchment's characteristics in Equation 2. The Q value produced by both equations were almost similar. Manning's n values were determined as 0.022 and 0.030 for roof/road surfaces and grassed side yard, respectively. The Manning's n values were based on a past study [20] which had a similar setup of a housing estate. The roof materials and the garden plants used were those commonly found throughout Malaysia, which may not be the same for other countries. The other parameters were determined based on the site conditions of the selected housing estate.

$$Q = \frac{W}{n}\left(d - d_p\right)^{5/3} S^{1/2} \tag{2}$$

where,

Q = generated runoff (m^3/s);
W = catchment width (m);
S = slope (m);
n = Manning's roughness value (unitless);
dp = Maximum depression storage (m);
d = Depth of water over the catchment (m).

The generated runoff was directed to nodes and channels, where it was routed through from channel to channel until it reached the outfall. SWMM routed the runoff using a kinematic wave approximation as shown in Equation 3:

$$q = \frac{\partial A}{\partial t} + \alpha m A^{(m-1)} \frac{\partial A}{\partial x} \tag{3}$$

where,

q = routed flow (m^3/s);
A = cross sectional area of channel (m^2);
x = distance along the flow path (m);
t = time step (s);
α = flow geometry (unitless);
m = surface roughness (unitless).

The second model, depicted in (Figure 4B), was a repetition of the first model but with the addition of a storage unit and orifice after the front roof and before the node and channel. In this model, the generated *Q* from the front roof was treated as inflow to the storage unit, while the captured water left the storage unit via an orifice outlet and thus treated as the outlet. Hence, taking into consideration these aspects, the storage volume was defined as in Equation 4:

$$St = \sum_i (Q - Q_o)\Delta t \tag{4}$$

where,

St = Storage volume (m^3);
Q = Inflow (m^3/s);
Qo = Outflow (m^3/s);
Δt = Duration of storm (s).

Flow through the orifice outlet or the outflow was defined as in Equation 5. Based on the study carried out in [20], the orifice size, *Ao* was determined at 0.05 m in diameter, with the discharge coefficient, *Co* determined at 0.060. *Ho* followed the heights of Type 1, Type 2 and Type 3 products.

$$Q_o = A_o C_o \sqrt{2H_o g} \tag{5}$$

where,

Qo = Flow through orifice (m^3/s);
Ao = Orifice size (m^2);
Co = Discharge coefficient (unitless);
Ho = Maximum head to the centre of the orifice (m);
g = Acceleration due to gravity (9.81 m/s^2).

3. Results and discussion

The first SWMM model simulating the existing drainage system is presented in (Figure 4A). The 37, 032 m^2 area was divided into 961 catchments. The drains in the front and back of the houses were designed to 0.5 m × 0.5 m. These drains were connected by 0.9 m × 0.5 m culverts crossing the road to a series of 1.5 m × 1.5 m drains visible in (Figure 4A). The second SWMM model is presented in (Figure 4B) that had 204 storage units included in each of the property lot while maintaining the other features of catchments and drainage networks.

3.1 Pre-development condition

The pre-development condition of the study area was assumed to be a grassed land with small bushes. Based on rational method (Equation 1), this condition was estimated to produce a peak runoff, Q_{pre} of 1.14 m^3/s. On the other hand, using a simple SWMM model (with a lump catchment), had estimated a value of 1.22 m^3/s (Equation 2). The difference between the two values was 7%, which indicates that the model was giving an acceptable estimation.

3.2 Post-development condition (without stormwater detention)

Based on Rational Method (Equation 1), the post-development peak runoff, Q_{post} was estimated at 2.86 m^3/s. The first SWMM model produced a value of 2.79 m^3/s (Equation 2), creating a difference of a mere 2.5%. These estimations reiterated a statement by [16], that both Equations 1 and 2 generally produce values that are close to each other, thus making them a good verifying tool for the models.

3.3 Post-development condition (with stormwater detention)

The second model was used to explore the impacts of Type 1, Type 2 and Type 3 products as individual lot stormwater detention systems. Therefore, three sub-models were derived from the second model, in which each was defined with a different storage volume in the storage unit. Runoff hydrographs at the final discharge point, representing the flow condition of the whole housing estate are presented in (Figure 5). Peak runoff values due to Type 1, Type 2 and Type 3 products were estimated at 0.3863, 0.3837 and 0.3844 m^3/s, respectively. The model had predicted that the stormwater detention systems caused a drop of 600% in peak runoff compared to Q_{post} (2.79 m^3/s), and a delay of 20 minutes in the time to peak.

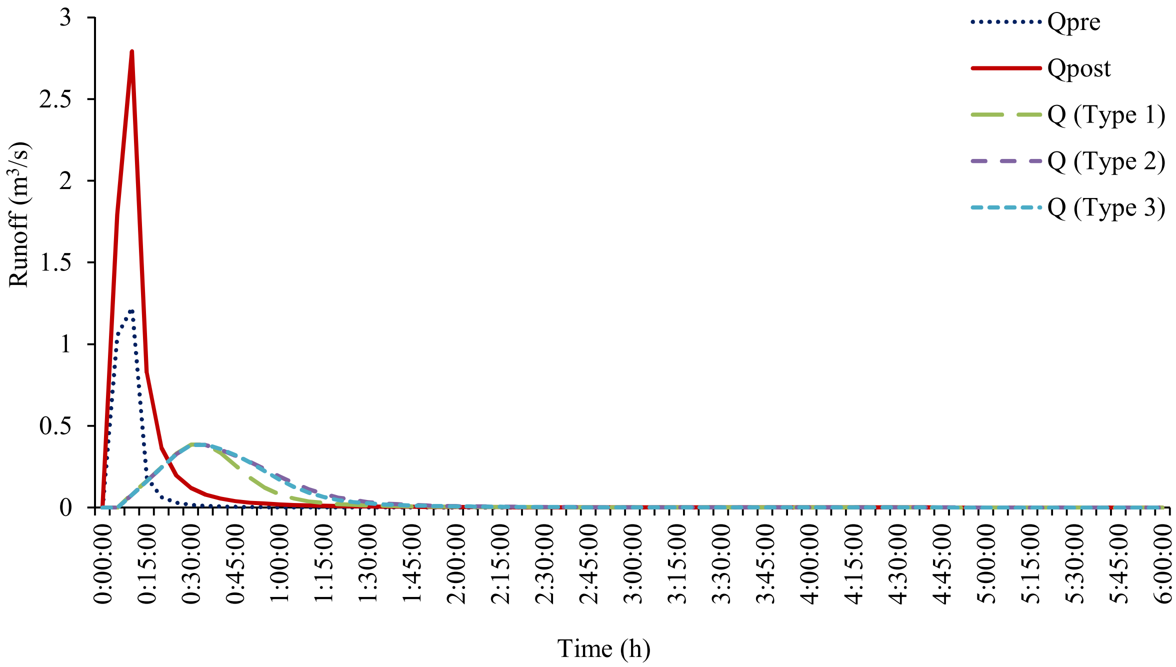

Figure 5 SWMM simulated hydrographs at outfall.

Readings were taken at the end of the 200 m front drain of one row of houses. The runoff hydrographs representing this row of 24 terrace houses are presented in (Figure 6). Peak runoff at the said end point without any intervention was estimated at 0.0511 m^3/s. Inclusion of Type 1, Type 2 and Type 3 systems had produced peak runoff values of 0.0367, 0.0345 and 0.0347 m^3/s, respectively. The model had predicted a 40% drop of peak runoff and a pro-longed peak of 40 minutes due to regulated flow from the orifice outlets of the stormwater detention systems.

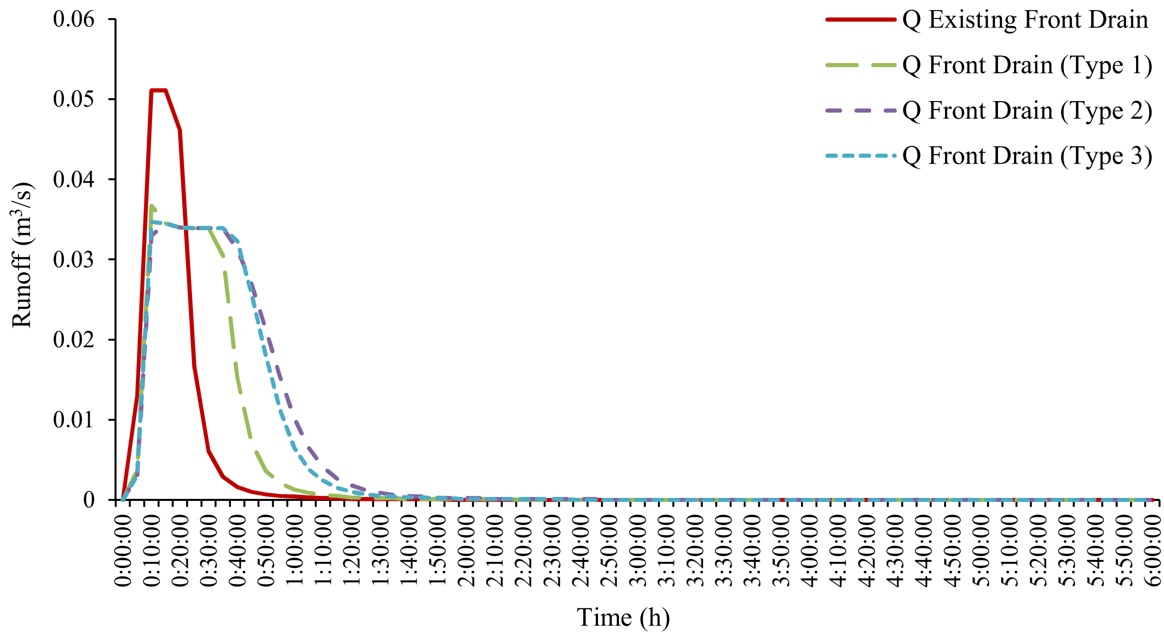

Figure 6 SWMM simulated hydrographs at the end of a row of houses.

Another reading was taken at one intermediate lot. Water leaving the property lot are presented in (Figure 7). Post-development peak runoff generated by the building was estimated at 0.088 m^3/s. Post-development with intervention's peak runoff values with the Type 1, Type 2 and Type 3 products were estimated at 0.0066, 0.0055 and 0.0057 m^3/s, respectively. Type 1 had a 30% reduction, while Type 2 and Type 3 had 50-60% in reduction of peak runoffs from the values comparing the post-development with and without intervention scenarios. The time to peak was found to be at 10 minutes and was shared by all three systems. No change in time to peak was observed in the figure, as the 20 m length of property lot was considered as a short travelling distance for flowing water. The lower peak reduction for the Type 1 system was due to higher depth in its modular unit. This produced relatively larger H_o and eventually resulted in relatively higher Q_o (Equation 5). This was the reason the Type 1 system had a steeper recession limb, consistently throughout the three figures compared to Types 2 and 3.

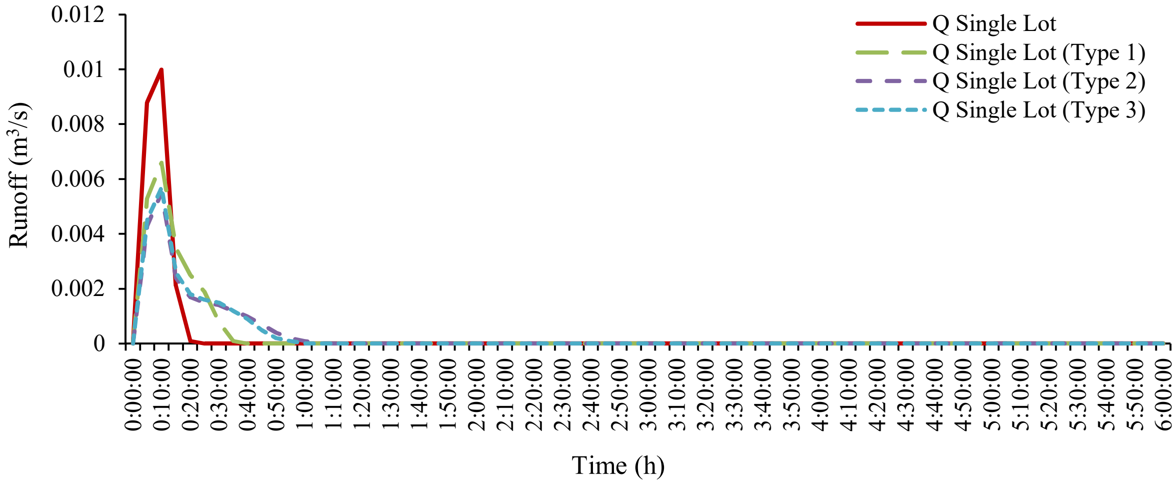

Figure 7 SWMM simulated hydrographs out of a single intermediate lot.

It can also be observed in (Figures 5-7) that the three products under study produced hydrographs with a similar peak and shape. Connecting the three figures illustrated the flow patterns from the house lots to the drains and from the drains to the discharge point. (Figure 7) points out that the orifice outlets generally required 40 minutes to discharge captured water after reaching its peak. The 40-minute duration of orifice discharges were reflected in the 40-minute prolonged peak in (Figure 6), in which the orifice discharges were a constant flow for the specified duration. Although the orifice size and discharge coefficient were constant, Type 1 system had a small spike in its hydrograph compared to Types 2 and 3. This was due to the relatively larger H_o. The orifice discharges for Types 2 and 3 were similar, as both systems shared a similar height and H_o. At the final discharge point, water had been flowing overland while travelling at distances ranging from the nearest 250 m to the furthest 400 m to result in the attenuation effects observed in (Figure 5). While travelling these distances, the drains played a role by providing storage volume in the channel depending on the drains' dimension and slope.

Judging from the runoff hydrographs for all three systems in the three figures, it could be deduced that all three products had produced a similar hydrological impact for the selected housing estate. In order to investigate further, readings were taken at the modelled storage unit. Water level hydrographs extracted from a single storage unit are presented in (Figure 8). It shows that the Type 1 system had the highest peak water level at 0.27 m for the reason of having relatively larger H_o than the others. Types 2 and 3 generated peak water levels at 0.12 and 0.14 m, respectively.

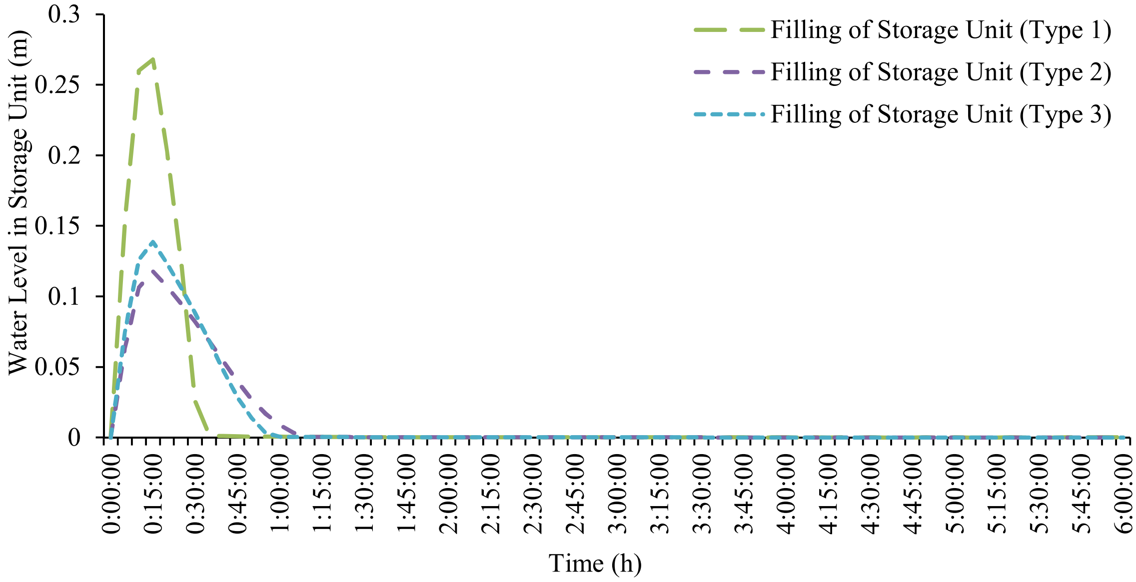

Figure 8 SWMM simulated hydrographs in a storage unit.

Based on the water level, it was found that Type 1 had 8% of its storage volume filled. Type 2 had 84%, while Type 3 was at 54%. In the occasion of a short duration storm such as a 5-minute, 10-year ARI design rainfall applied here, Type 1 appeared to be overdesigned. However, it may not be an overdesign in the case of a long duration storm which is yet to be carried out for the three products. The large size of Type 1 is probably more suited for a community scaled use rather than for a lot scaled storm water detention system. When similarly subjected to a short duration storm, it appeared that Type 2 was the best design with 84% of its storage volume being utilised and 16% of unutilised volume as a reserve for climate uncertainties. A disadvantage of the Type 2 system was its spacing requirement during assembly of its modular units, that constituted to a 50% lesser storage volume in the 50 m^2 car porch area compared to Type 3. The Type 3 product, on the other hand, had a larger storage volume as provided by the hollow cylinder chamber itself and the spaces in between the cylinder pieces. A disadvantage of the Type 3 system was its high number of modular units, calculated at 301 units for a 50 m^2 car porch area, as compared to Type 2 with only requiring 18 units.

The findings from this study also implied that the perception that the deeper the storage, the higher the water volume being captured, was unlikely for this case of draining water storage structure. As the surface area of the car porches was the same for all three types of systems, it was demonstrated that the highest 1.15 m depth available in the Type 1 system was underutilised. Instead, the lower 0.3 m depth in Types 2 and 3 was appropriately utilised.

4. Conclusion

The SWMM modelling efforts of subjecting a housing estate to a 5-minute, 10-year ARI design rainfall had demonstrated a reduction of 86% of peak runoff at outfall when stormwater detention system was added to each property lot. The Type 1, Type 2 and Type 3 products produced similar hydrological impacts while the same catchment size, surface area of detention system and orifice outlet size were maintained. The difference between the systems lied in the storage volume provided by the products. Type 1 was found to be underutilised for having only 8% of its storage volume being filled throughout the course of the 5-minute design rainfall. Type 2 was found to be a more efficient system for having 84% of its storage volume filled, compared to Type 3 that had 54% of filled storage volume. The short duration design rainfall was appropriate in the 961 catchments for an area of 37,032 m^2 in total land area, in which the single catchment was small (in average 0.004 ha each). It is recommended to further test these systems under actual rainfall conditions of varying intensities and durations.

5. Acknowledgements

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