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Catchment Size to Effective Tank Volume Relationships for Individual Lot Stormwater Detention System in Malaysian Detached House

Darrien Y. S. Mah[1], Johnny O. K. Ngu[2], P. D. Caroline[3], M. A. Malek[4]
[1]Faculty of Engineering, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia, Email: ysmah@unimas.my
[2]Faculty of Engineering, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia, Email: Johnnyngu91@gmail.com
[3]Faculty of Civil Engineering, Universiti Teknologi MARA, 94300 Kota Samarahan, Sarawak, Malaysia, Email: carolinepeter968@uitm.edu.my
[4]Institute of Sustainable Energy, Universiti Tenaga Nasional, 43000 Kajang, Selangor, Malaysia, Email: Marlinda@uniten.edu.my

ABSTRACT
This paper describes an individual lot stormwater detention system that consists of multiple precast concrete modular green pavement units, developed by the authors. The tank size is determined at 4.40 m W, 4.70 m L and 0.45 m D with an effective tank volume of 3.93 m^3 after being filled with the said modular units. The small tank size allows the system to be inserted into a residential house's car porch. Maintaining the same tank size, exploration into different catchment sizes that drain water to the tank is carried out using two model intermediate and corner double-storey detached houses. The investigation is intended to figure out the optimum catchment size that could achieve the lowering of peak runoff caused by post-development condition to near pre-development condition. A computer model using Storm Water Management Model version 5.0 is developed to simulate scenarios of 40:60, 50:50 and 60:40 representing the contributing to non-contributing catchment ratios for intermediate and corner lots. Analysis of the simulation results show that 65% of the property lot designated as contributing catchment would contribute to achieve the desired pre-development condition.

Key words : Car porch, Drainage, StormPav, Sustainable development, Urban stormwater, Water management.

1. INTRODUCTION

An individual lot refers to a single property boundary defined by the land and survey authority, while a stormwater detention system refers to a manmade structure designed to hold stormwater [1]. A stormwater detention system within a property lot is tailored to mimic the ability of natural soil layer to absorb stormwater, in which the ability is lost due to the built-up area that blocks water to seep underground [2].

Manmade stormwater storage facilities come in different shapes and forms. Figure 1a features an example of such a system using precast concrete [3], in which it could be installed underground within the house yard. The tank volume per single precast concrete unit is 12 m^3 and therefore it could receive water from a large contributing catchment.

Figure 1b features another example using high-strength polyethylene (PE). Each PE piece has relatively small water storage volume between 0.25-0.35 m^3. It is intended to be installed as part of the building's floor slab to cater for a smaller contributing catchment [4].

Figure 1: Types of individual lot stormwater detention system using a) Precast concrete and b) Polyethylene [3,4].

A third example is a system developed by the authors. It has an even smaller water storage volume of 0.03 m^3 per single modular unit [5]. One unit is made up of three pieces that consist of two identical hexagonal plates and one hollow cylinder. Its compact size allows them to be fitted as pavement to a house's car porch in Figure 2a. The figure depicts a field test in a voluntary detached house that was constructed above ground instead of underground for easy removal later.

Figure 2b shows its dimensions, in which the surface area of the modular unit is 0.16 m^2 and the depth is 0.45 m. Each of the unit could withstand a loading up to 100 kN. Therefore, the hexagonal plate at the top layer could function as pavement to support traffics or other loads. The hollow cylinder in the middle layer functions as water storage chamber, while the other hexagonal plate at the bottom layer functions as the base [6,7].

Having the modular green pavement units in a detached house with limited spaces, it could only cater for a limited catchment size. This paper intends to explore on the said aspect to achieve stormwater control.

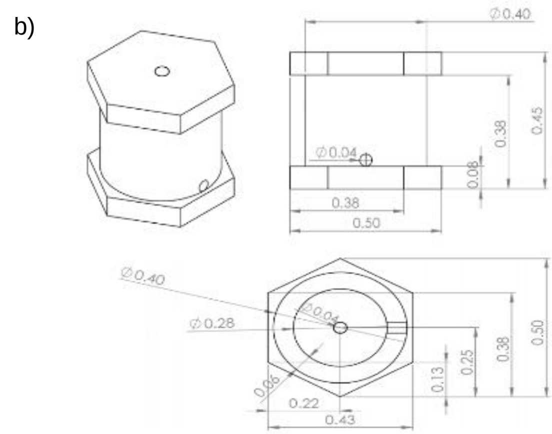

Figure 2: Modular green pavement, a) Field test and b) Modular dimension.

2. MATERIALS AND METHODS

2.1 Malaysian Detached House

A model of double-storey detached house is depicted in Figure 3. This model house is used to demonstrate how an individual lot stormwater detention system could be incorporated in the property. The research team has no relation with any entities related to the model house. The names of the housing estate and its developer are made anonymous. However, using their drawing and floor plan do not infringe their benefits as the materials are freely distributed.

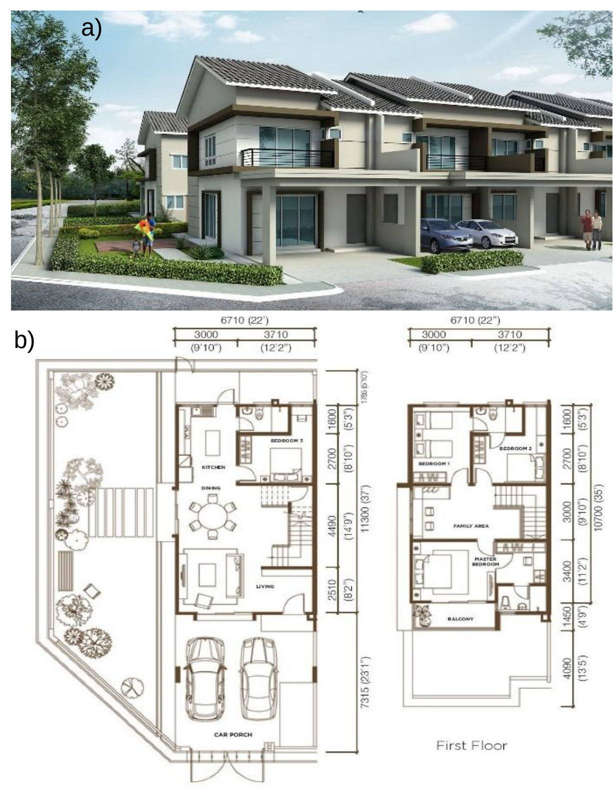

Figure 3: Model of Malaysian double-storey detached house, a) Artist impression and b) Floor plan.

The length (18.62 m) and width (6.71 m) of the detached houses are the same for intermediate and corner lots. The difference is the latter has a 20 m^2 side yard. Referring to Figure 3a, the house is designed with a simple gable roof (pitch = 6/12), and therefore it is calculated that 51.30 m^2 of its plain sloped to the front yard, and another 51.30 m^2 to the back yard. Because of this design, the roof drainage is directed following the two directions. The front yard is also erected with a 27.40 m^2 flat-roof car porch. As such, the roof area that drains to the front yard is combining the front roof and car porch that could be rounded to about 80 m^2.

It can be observed in Figure 3a, a car porch that could fit in two cars is one of the features to attract buyers. A large car porch is becoming a household's necessity nowadays. The car porch is found in Figure 3b to have a surface area of 6.71 m x 7.32 m. This area could be used to install an intended 4.40 m x 4.70 m stormwater detention system previously reported in [8,9] that was delineated based on area required by two side-by-side cars. The surface area occupied by the system is smaller than the overall size of the car porch so that it allows spaces for brickwork encasing the tank and other structures. With a depth of 0.45 m, it is estimated to have 3.93 m^3 of effective tank volume.

2.2 Stormwater Detention Design

The research team is referring to two design manuals, namely one from Singapore [10], and one from Malaysia [11]. The two neighbouring countries have similar weather patterns. For roof catchment of detached house, both manuals are recommending 5-minute design storm with 10-year Average Recurrent Interval (ARI). The goal of having stormwater control is to lower post-development peak stormwater runoff, Q_{post} to near pre-development condition, Q_{pre}, as presented in Figure 4.

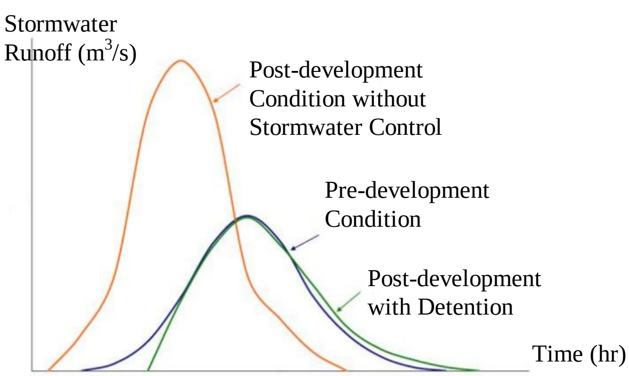

Figure 4: Stormwater runoff hydrograph responses.

The peak stormwater runoff is calculated via the following equation:

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

To calculate Q_{pre}, a discharge coefficient C value of 0.4 is applied according to [10]. To calculate Q_{post} without any stormwater control, a C value of 1.0 is applied with an assumption that water losses in the roof catchment is negligible [11]. Therefore, equation 1 could be rewritten in the following forms:

$$Q_{pre} = \frac{0.4\,I\,A}{360} \tag{2}$$

$$Q_{post} = \frac{IA}{360} \tag{3}$$

where, I is the rainfall intensity (mm/hr) and A is the catchment area (ha).

On the other hand, the post-development condition with detention involves flow through a stormwater detention tank. Referring to a rectangular detention tank in Figure 5, the tank receives water from the roof catchment, therefore Q_{post} in equation 3 is applied here. The tank releases water via an orifice, Q_o and it could be calculated using the next equation:

Figure 5: Rectangular stormwater detention tank [10].

$$Q_o \quad A_o C_o \sqrt{2H_o g} \tag{4}$$

where,
Q_o= Orifice discharge rate (m^3/s);
A_o = Orifice diameter (m^2);
C_o = Discharge coefficient (unitless);
H_o = Maximum head to the centre of the orifice (m);
g = Acceleration due to gravity (9.81 m/s^2).

The water storage volume within the tank is governed by the equation below:

$$St = \sum_i (Q_{post} - Q_o)\Delta t \tag{5}$$

where,
St = Storage volume (m^3);
Q_{post} = Inflow (m^3/s);
Q_o = Outflow (m^3/s);
Δt = Duration of storm (s).

2.3 Computer Model Building

A computer simulation software under the license of United States Environmental Protection Agency named Storm Water Management Model (SWMM) version 5.0 is utilized to assist the intended investigation.

Previous study [9] had developed a SWMM model for the modular green pavement system (Figure 6a). Referring to the numbering in the figure, component (1) is the rain gage where rainfall data are entered. Component (2) is the front roof that contributes water to the detention tank following equation 3. Component (3) is a storage unit that simulates the stormwater detention tank following equation 5. A study by [12] had reported that storage unit was suitable to represent the modular green pavement system under study. Another study by [13,14] had indicated that the modular green pavement could be represented using its effective storage volume provided by the water storage chambers within the modular units. Component (4) is the orifice outlet that follows equation 4. Study by [8] had reported that an inlet of 0.10 m diameter pipe and an outlet of 0.05 m diameter pipe were the best combination to provide the planned water detention, in which the inlet was not causing surcharge in the upstream pipeline and the outlet was not causing any congestion as too small an outlet shall cause the undesired overflowing. Component (5) is the final discharge point.

Contrary to previous study, the current study is taking into consideration the whole property lot. Referring to Figure 6b for an intermediate lot, components i to iv are similar to components 1 to 4 in Figure 6a. The back roof (component v) that is not contributing water is added following equation 3. Eventually, the whole system discharges water at the final discharge point (component vi). Referring to Figure 6c for a corner lot compared with the model in Figure 6b, the side yard (component vii) is added following equation 2.

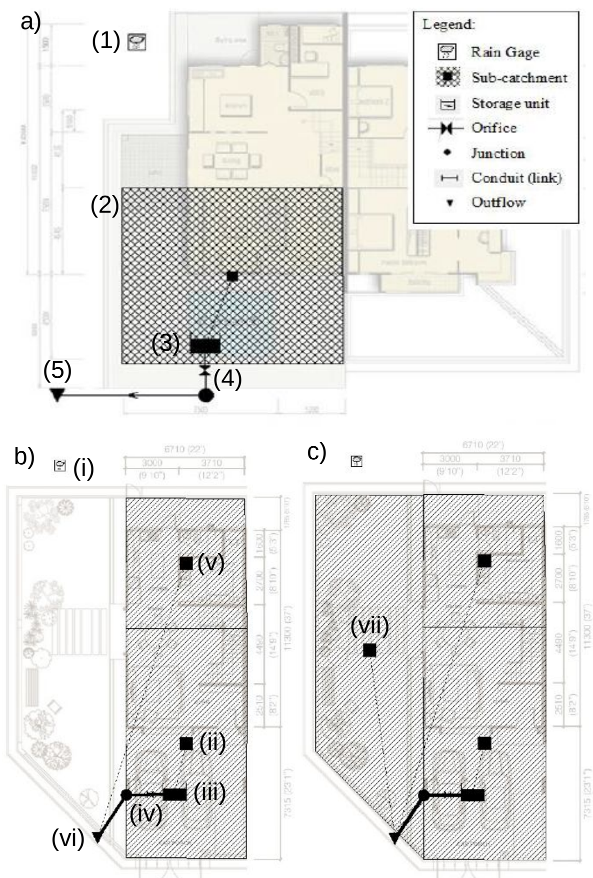

Figure 6: SWMM model for modular green pavement in a) Previous study considering contributing catchment (Modified from [9]). Current study considering contributing and non-contributing catchments for b) Intermediate lot and c) Corner lot.

3. RESULTS AND DISCUSSION

The 5-min, 10-year ARI design rainfall is obtained from the Intensity-Duration-Frequency (IDF) curve developed by the Malaysian Department of Irrigation and Drainage. The rainfall intensity is determined at 278 mm/hr and the associated rainfall depth at 23 mm.

The design rainfall is subjected to the property lots of the model double-storey detached house mentioned earlier. The surface area occupied by the intermediate lot is 130 m^2, in which the composition comprises 27.40 m^2 for car porch (CP), 51.30 m^2 for front roof (FR) and 51.30 m^2 for back roof (BR). The surface area for the corner lot is 150 m^2, in which it comprises an extra 20 m^2 for side yard (SY).

Take the intermediate lot, water generated by the FR and CP could be directed to the stormwater detention tank located underneath the car porch. Thus, FR and CP are contributing catchments. Water generated by the BR is logically drained to the back yard instead of to the front yard. Thus, BR is non-contributing catchment. Take the corner lot, while it is possible to connect water from the back to the front, it is a normal practice to split the roof drainage into front and back, separately.

The research team maintains the 4.40 m x 4.70 m x 0.45 m stormwater detention tank size as the optimum size. This two-car size is stressed in [15] as the most common size in Malaysia for low-cost and medium-cost housing estates. However, the roof sizes could come in a variety of architectural designs. Because of this factor, we develop scenarios of various sizes of FR and BR in Table 1. It is possible to have a shorter FR and longer BR, or vice versa. Investigation into the different sizes of FR and BR shall provide the optimum catchment size that contributes water to the said tank.

Table 1: Scenarios of catchment areas.

Scenario	**Contributing Catchment (m^2)**	**%**	**Non-Contributing Catchment (m^2)**	**%**
Intermediate				
Scenario A1	CP 27.40 FR 24.60	40	BR 78.00	60
Scenario A2	CP 27.40 FR 37.60	50	BR 65.00	50
Scenario A3	CP 27.40 FR 50.60	60	BR 52.00	40
Corner				
Scenario B1	CP 27.40 FR 32.60	40	SY 20.00 BR 70.00	60
Scenario B2	CP 27.40 FR 47.60	50	SY 20.00 BR 55.00	50
Scenario B3	CP 27.40 FR 62.60	60	SY 20.00 BR 40.00	40

3.1 Intermediate Lot

Simulations of roof drainage for intermediate lot are presented in Figure 7. These runoff hydrographs are extracted from the final discharge point that representing water flowing out of the property lot.

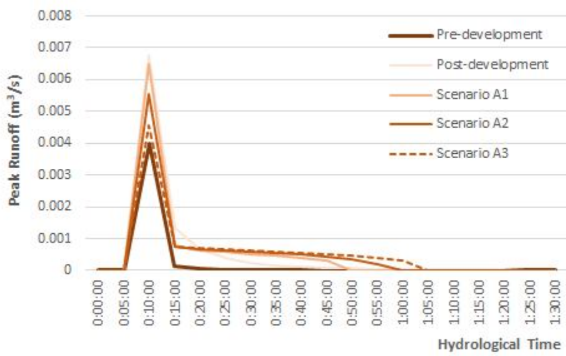

Figure 7: Simulated runoff hydrographs for intermediate lot.

It could be observed from the figure, Q_{pre} for intermediate lot is estimated at 0.0040 m^3/s and this value is taken as the target for the stormwater detention system. Scenario A3 (dotted line) with a combination of 60% contributing catchment and 40% non-contributing catchment has a peak runoff of 0.0046 m^3/s, the nearest value to the Q_{pre} among the three scenarios.

3.2 Corner Lot

Simulations of roof and land drainage for corner lot are presented in Figure 8. The difference of this scenario compared with the former is the presence of a pervious side yard. The computed hydrographs are taken at the final discharge point.

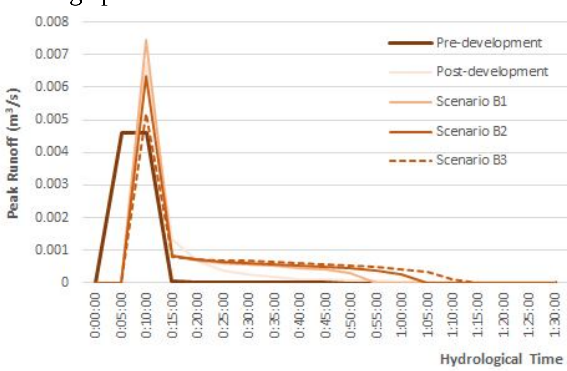

Figure 8: Simulated runoff hydrographs for corner lot.

The SWMM model has estimated the Q_{pre} for corner lot at 0.0046 m^3/s. Scenario B3 (dotted line) with a combination of 60% contributing catchment and 40% non-contributing catchment has a peak runoff of 0.0052 m^3/s, the nearest value to the Q_{pre} compared to other scenarios.

3.3 Catchment Size Relationships

Referring to Figure 7 and Figure 8, the Q_{post} values for intermediate and corner lots are estimated at 0.0067 m^3/s and 0.0070 m^3/s, respectively; while the Q_{pre} values are estimated at 0.0040 m^3/s and 0.0046 m^3/s, respectively. These indicate that to achieve the target of lowering Q_{post} to near Q_{pre}, a reduction of 70% of peak runoff is required for intermediate lot; and a reduction of 45% of peak runoff for corner lot. Achieving these reductions are a form of the urban flood mitigation strategies [16].The 150 m^2 corner lot has a higher surface area than the 120 m^2 intermediate lot. Logically, the generated runoff is expected to be much higher in the corner lot than the intermediate lot. However, the estimated values for the two type of residential lots are in close range due to the assumption made to take the side yard in the corner lot as a green area.

Malaysians have the tendency to convert the side yard to have concrete surfaces. In this regard, the authors calculate that if the whole corner lot is impervious, the Q_{post} is estimated at 0.0113 m^3/s. An effort of reducing 145% of the Q_{post} is required. The current set up of stormwater detention tank could not meet the said peak runoff reduction, and it is not included in the modelling.

The effort of having an individual lot stormwater detention system in a residential house is in line with the concept of green building promoted by [17]. It is demonstrated in Figure 7 and Figure 8, the peak runoff values from the property lots are progressively decreased with the increases of contributing catchment.

For the immediate lot, it is estimated to have 0.0065 m^3/s for 40% contributing catchment, 0.0055 m^3/s for 50% contributing catchment, and 0.0046 m^3/s for 60% contributing catchment. Whilst for the corner lot, it is estimated to have 0.0074 m^3/s for 40% contributing catchment, 0.0063 m^3/s for 50% contributing catchment, and 0.0052 m^3/s for 60% contributing catchment. These peak runoff values are plotted in Figure 9.

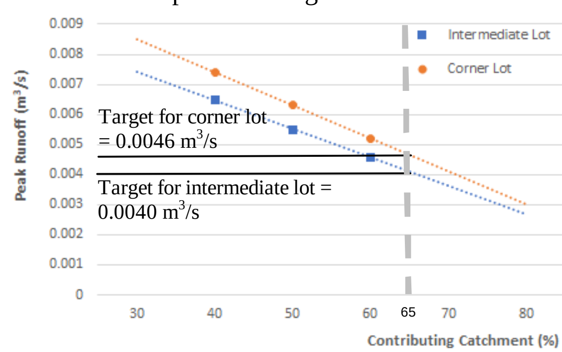

Figure 9: Relationships of catchment size to peak runoff associated with 3.93 m^3 of effective tank volume.

Based on Figure 9, the peak runoff values for intermediate lot are plotted with square marker; while the corner lot, with circular markers. Extrapolation from the points allow a glimpse into other possible peak runoff values and its catchment sizes. The targeted peak runoff values based on the determined Q_{pre} values are added in the same figure.

It is found that about 65% contributing catchment is needed to achieve the intended target limited by the 3.93 m^3 effective tank volume in both intermediate and corner lots. In another word, the optimum contributing catchment size is 65% of the property lot limited by the current effective stormwater detention tank size, in which water from the catchment is directed to temporary storage and slow release; and such a strategy is proven to lower the peak runoff from the intermediate and corner lots to Q_{pre} conditions.

4. CONCLUSION

A demonstration is carried out to incorporate 4.40 m x 4.70 m x 0.45 m stormwater detention system with 3.93 m^3 effective tank volume in 130 m^2 intermediate lot and 150 m^2 corner lot for double-storey detached house. The main purpose of the system is to lower Q_{post} to near Q_{pre} to achieve stormwater control. Modelling efforts via the SWMM model show that stormwater generated by 65% of the property lot for intermediate and corner lots due to 5-min, 10-year ARI design rainfall should be detained in order to achieve the Q_{pre} condition.

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