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Case Study of Stormwater Control by Permeable Road in Commercial Centre under Equatorial Climate

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ABSTRACT

This paper describes the investigation into stormwater control measures of a 3,425 m^2 commercial centre of 61% of which were tarred surfaces and targeting these surfaces, areas from 10 to 34% of which were permeable roads of various coverage areas of permeable roads of various surface areas were modelled using Storm Water Management Model version 5.0. Testing the permeable roads for very-short duration storms ranging from 5 to 15 minutes, it was found that the catchment area contributing water for detention purposes played a major role in stormwater control. Other than that, the orifice outlet attached to the storage facility was major factor in determining the flow.

Keywords: Drainage, hydrograph, urban runoff, post-development, pre-development, sustainable development.

1. INTRODUCTION

Located in the equatorial region, Sarawak receives 3,000 mm of rainfall anuually. Urban stormwater drainage system over the region is separated into two distinct systems, namely the major drainage system which is designed to 50- or 100-year Average Recurrent Interval (ARI), and minor drainage system which is designed to 10-year ARI design storms [1], [2]. This paper reports the stormwater control over a commercial centre surrounded by parking spaces and roads which is clasified as a minor drainage system (Figure 1).

According to a local study [3] conducted from December 2019 to February 2020 in conjunction with the Northeast Monsoon, it was reported that 90% of the recorded rainfall

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were below 20 mm, 5% between 20-30 mm, 4% between 30-40 mm and 1% between 40-50 mm. The values of 10-year ARI design storms for 5-, 10- and 15-min are estimated as 23, 36 and 46 mm, as intense rainfalls. As such, the minor drainage system should be tested against the very-short duration design storms.

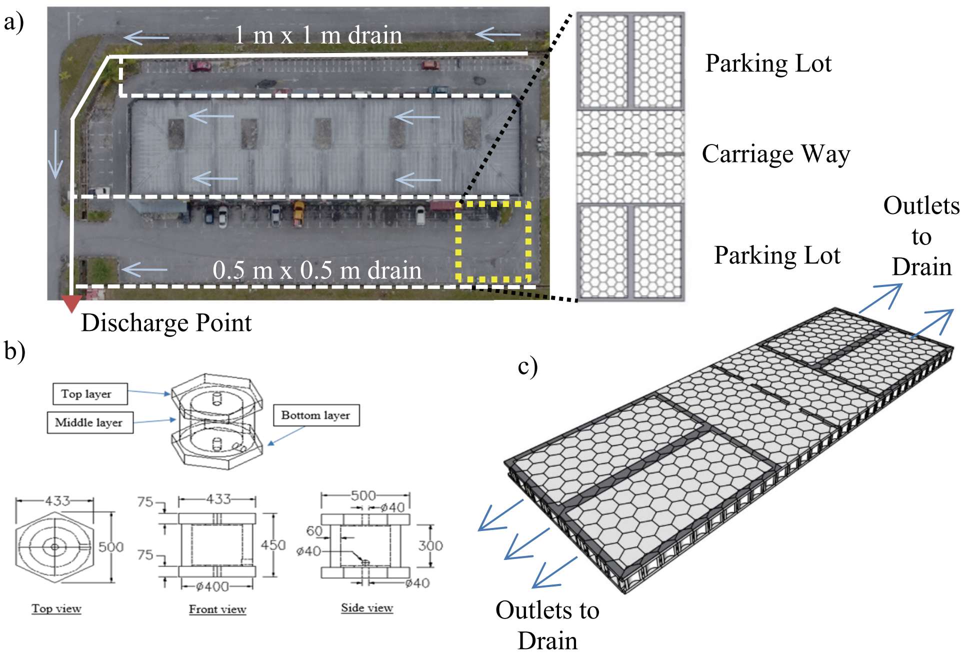


Figure 1 - Case study in commercial centre, (a) Study area and indication of permeable road at the parking spaces and carriage way in front of the shop building, (b) Dimension of a modular unit of chosen permeable road and c) 3D view of the assembled permeable road.

It is common in Malaysia to have two rows of roadside parking spaces in front of the shop building. In this case, the road is flanked by parking spaces. On one side attached to the shop building, a stretch of the urban drain is constructed to convey stormwater from both roof and road surfaces. On the other side of the road, another stretch of urban drain-cum-road shoulder is constructed to convey stormwater from the road surface. It is found that the land area occupied by road and parking spaces is more than half of the total catchment area, which is further described in the study area. In this case study, applying intervention to the tarred surfaces is more appropriate than on the shop building.

Having a manmade structure underneath the road surfaces to capture the stormwater is mimicking the natural function of the soil layer to absorb excess water. According to a study for a residential property lot [4], it was recommended to have at least 60% of the total catchment area directed for detention to achieve the intended lowering the peak of post-development hydrograph. Another study in the design of stormwater detention reported the capacity of the water receiving structure is related to the connected drainage catchment[5]. It was also reported elsewhere that the water receiving structure was limited by available land spaces and therefore the area of contributing catchment should also in line with the limitation[6]. A study of Low Impact Development (LID) water infrastructure, [7], had reported that the effectiveness of the structure in stormwater control decreased with increasing catchment area and the structure had better performance when closer to the source.

2. MATERIALS AND METHODS

2.1. Study Area

A commercial centre was selected as a case study (Figure 1a). It is called Palm Square beside Dato' Mohd Musa Road, Kota Samarahan, at the outskirt of Kuching city, Sarawak, Malaysia. The total catchment area of Palm Square is calculated as 3,425 m^2. The centre has ten (10) units of shop buildings, in which the eight (8) intermediate lots are 18 m x 7 m each while the two (2) corner lots are 18 m x 9 m each. As such, the catchment area occupied by the shop buildings is calculated as 1,332 m^2, about 39% of the total catchment area.

The remaining 61% of the catchment area is covered by tarred surfaces. At the front of Palm Square, it has 5 m wide car parking spaces on both sides of the road and a 4 m wide carriageway in the middle. At the back, it has a 4 m wide motorcycle parking space and a 4 m wide carriageway. The minor drainage system consists of two drain sizes, namely the 0.5 m x 0.5 m and 1 m x 1 m concrete drains. The minor system discharges runoff to a major drainage system which is not covered in this study. These measurements have provided a realistic basis to support the simulation efforts that followed [8].

2.2. Permeable Road

A length of 84 m road in front of the shop building was selected for intervention. One of the stormwater control measures that suitable for a road is a permeable road. Its general structure consisted of a top layer of permeable pavement allowing water to seep through and a bottom layer of storage facility allowing water to be stored temporarily under the road [9]. The outflow of the storage layer was through a 50 mm diameter orifice.

The type of permeable road chosen for this study was a non-commercialised R&D product developed by Universiti Malaysia Sarawak and collaborators. It was made up of micro detention structure in the form of a hollow cylindrical tube which sandwiched between two hexagonal plates (Figure 1b). The storage facility had a solid-framed structure but hollow within, thus having a porosity as high as 0.9. Such a storage structure was reported by [10].

The hollow cylindrical tube had an inner diameter of 313 mm and a wall thickness of 60 mm; while the hexagonal plate had a width of 500 mm and a height of 433 mm which contributed an area of 0.1624 m^2 per plate. The mentioned three pieces formed a singular modular unit and when combined, the hexagonal plates formed honeycomb-patterned plane. The top plane functioned as the road surfaces with 40 mm diameter service inlet on each hexagonal plate to drain water to the hollow cylindrical tube. The bottom plane functioned as a raft foundation which allowed water infiltration to the surrounding soil. The permeable road was not built but based on what-if simulation scenarios. It was a common practice to manipulate what-if scenarios to obtain insights into the workability of engineering measures [11].

2.3. Design Storm

The small total catchment area of the commercial centre (0.3 ha) fell under the catchment category of 0.2 - 4 ha according to the Singaporean Public Utilities Board (PUB) [1]. The Singaporean manual suggested a time of concentration of 5 min for the category. Therefore, 5 min was adopted as the design storm duration based on the assumption all parts of the catchment were contributing to the outflow, thus achieving a condition of storm duration was equal to the time of concentration. Similarly, a Malaysian manual according to the Department of Irrigation and Drainage (DID) [2] also reinstated the recommendation under equatorial region. Malaysian authority recommended that drainage system within a commercial centre as a minor system to be designed to 10-year Average Recurrent Interval (ARI) under local climate. The case study was subjected to a range of 10-year ARI design storms starting from 5 to 15 min.

2.4. Modelling Approach

Stormwater runoff processes through catchments and drainage systems were simulated using Storm Water Management Model version 5.0 (SWMM5). It begun with rainfall (design storms described in section 2.3) and ended with an outlet. Other than that, it involved components like catchment (roof and road), drainage (urban drain) and storage (storage facility in the permeable road) (Figure 2).

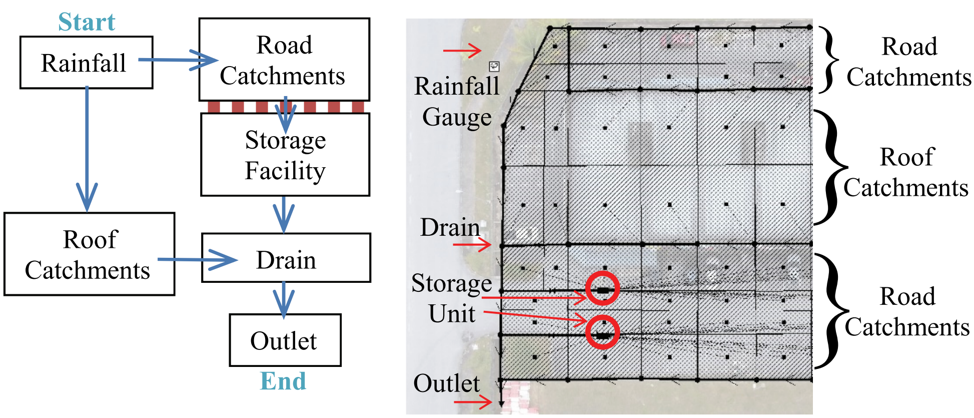


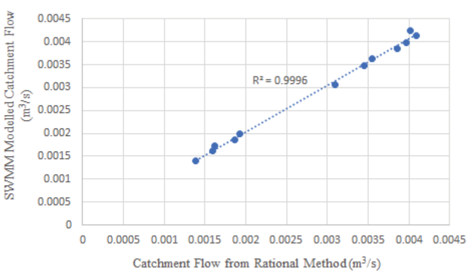
Figure 2 - Modelling approach that involves rainfall, catchment, permeable road, drain and outlet. The permeable road is modelled as storage units that receive water from the tarred surfaces and release water via orifice to the concrete drain.

The chosen permeable road (Section 2.2) was different from the conventional permeable roads. SWMM5 was chosen because it could represent the layer of multiple hollow cylinder tubes in the permeable road as storage units, quite well by defining the storage volume of the mentioned layer [12]. Firstly, the permeable road was assumed with different depths of the storage layer. Usually, a conventional permeable road was designed to about 0.5 - 0.6 m of storage layer [13]. As such, the common depth range was benchmarked for the assumption here. The research team was applying 0.2 m, 0.4 m and 0.6 m of storage heights, plus the thickness of hexagonal plates.

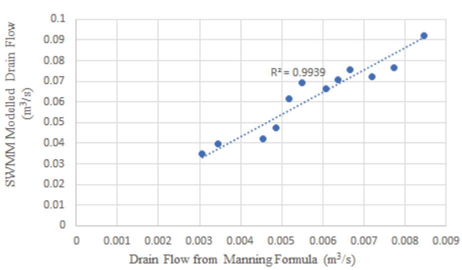
Secondly, scenarios of installing permeable roads in front of the shop building were set. Measure 1 was having one row of parking spaces that constituted 420 m^2 (84 m x 5 m) or 12% of the total catchment. Measure 2 was inclusive of two rows of parking spaces that constituted 840 m^2 (84 m x 10 m) or 25% of the total catchment. Measure 3 considered only the carriageway that comprised 336 m^2 (84 m x 4 m) or 10% of the total catchment. Lastly, Measure 4 took in all parking spaces and carriageway that made up of 1176 m^2 (84 m x 14 m) or 34% of the total catchment.

Flow in a catchment was computed by SWMM engine using a non-linear reservoir runoff method which treated the catchment as a shallow reservoir and its runoff flow as a non-linear function of water depth of the reservoir [14]. In practice, engineers used the rational method to generate catchment flow, in which PUB [1] suggested using 0.4 as the runoff coefficient assuming the catchment was naturally grassed for pre-development conditions, while DID [2] suggested using 1.0 for impervious surfaces like roof and road, assuming the loss of water over the course of runoff was negligible for post-development conditions. Comparison of catchment flow from the two methods is presented in Figure 3a.

From the catchment, runoff was directed to enter the drain and storage unit. The runoff was routed through urban drains from point to point by SWMM engine using kinematic wave routing method [15], [16]. On the other hand, engineers used Manning formula to calculate flow in drain. Comparison of the drain flow from the two methods is presented in Figure 3b. The coefficient of determination, R-square values, are depicted in the same figure which were larger than 0.9 for both. These R-square values indicated highly satisfactory good fit [17].



a)



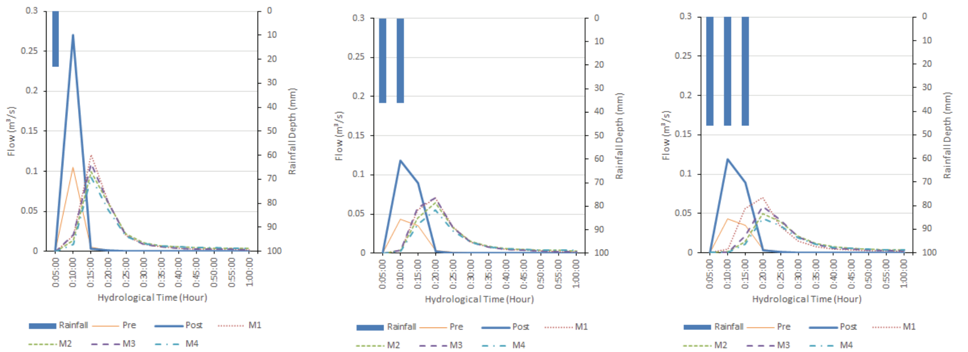
b)

Figure 3 - Verification of SWMM modelled results for a) Catchment flow and b) Drain flow.

3. RESULTS AND DISCUSSION

3.1. Flow Pattern

It is demonstrated that the shorter the duration, the more the intensity of the design storm (Figure 4). It makes sense that the 5-minute duration which produced the highest peak flow, is recommended as a reference for engineering design. Among the four intervention measures, Measure 4 that received water from the largest catchment area is repeatedly demonstrated to have the lowest peak hydrographs (0.04 - 0.09 m^3/s) when subjected to very-short duration design storms. Measure 2 is demonstrated to have a peak hydrograph above Measure 4 (0.05 - 0.09 m^3/s) in all different storm durations for having the second-largest catchment area. Measures 1 and 3 are having the highest peak hydrographs (0.05 - 0.12 m^3/s) for having the least catchment areas.



a) *b)* *c)*

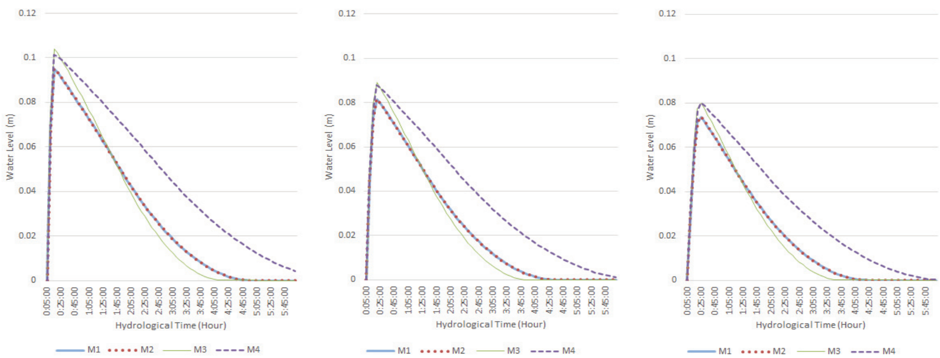
Figure 4 - Flow hydrographs at outlet for 0.2 m deep permeable road subjected to 10-year ARI design storm with durations of a) 5 min, b) 10 min and c) 15 min.

It can be deduced that the size of the catchment area of the permeable road has a key role in the effectiveness of lowering the peak hydrograph. It is found that for larger catchment areas higher runoff control could be achieved. This finding is in line with the report of [7]. Another deduction from Figure 4 is the attenuation of peak hydrographs from Measures 1 to 4 from the pre- and post-development hydrographs. Having the runoff being captured within the permeable road has slowed down the flow out of the commercial centre. The ranges of attenuation are estimated to delay 5 minutes for 5-min storm, 10 minutes for 10- and 15-min design storms for 0.2 m storage depth on the permeable road.

Since the observed flow patterns were similar for storage depths of 0.4 m and 0.6 m the respective attenuations are not reported. However, outcomes for all storage depths are presented below for the facilitation of a through understanding.

3.2. Water Level Pattern

The associated water level data in the storage unit corresponding to the previous flow patterns are depicted in Figure 5. Conforming to report of [6], these water level graphs are used to verify the limitation of storing capacity for 0.2 m storage depth. The graphs show that of maximum water levels ranges from 0.07 - 0.1 m. It means for the 10-year ARI design storm at most 50% of the storage capacity is utilized.



a) b) c)

Figure 5 - Water level plots in storage unit for 0.2 m deep permeable road subjected to 10-year ARI design storm with durations of a) 5 min, b) 10 min and c) 15 min.

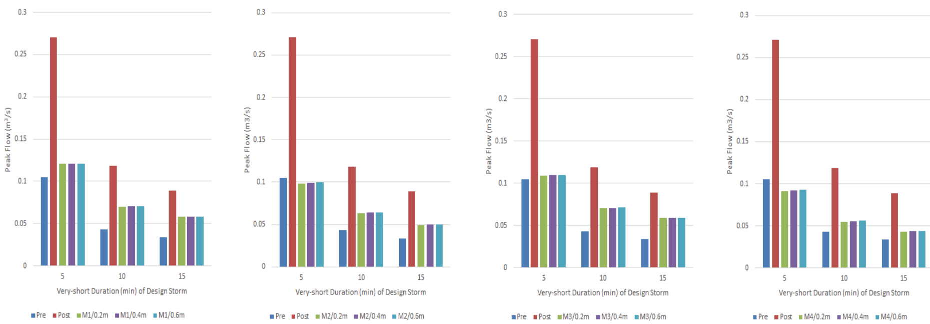
Measure 4, that is the largest contributing catchment area, is repeatedly exhibited the highest water level and largest hydrograph base as compared to the rest of the measures. Since the catchment area is the highest, the higher volume of runoff and higher water level are expected in the storage unit. Measures 1 to 3 share similar hydrograph shapes. These three measures have closely packed hydrograph patterns as depicted in Figure 5.

Another observation worth to mention is that Measure 4 has demonstrated a detention time of six hours for all 10-year ARI design storms and Measures 1 to 3 have a detention time of four hours. Since the observed flow patterns were similar for storage depths as previously stated, the water level graphs are limited to 0.2 m storage depth.

3.3. Comparison of Measures

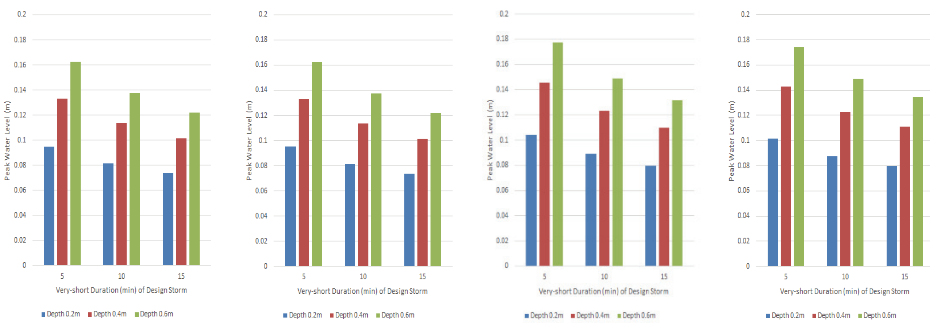
Peak hydrographs, as depicted in Figure 6, for the measures 1 through 4 are almost identical. This is due to the use of the same outlet orifice size for all storage depths. It is found that Measure 4 with the largest catchment area, 34% of total commercial area, performs the best than other measures. Measure 4 produces the highest reduction of post-development peak hydrograph and nearing pre-development condition.

The maximum water levels (MWL) are presented in Figure 7. The MWL increases slightly with storage depth in equilibrium. A storage depth of 0.2 m with 0.05 m orifice outlet is found adequate to contain water from road surfaces. The highest water levels estimated are below 0.2 m after testing through the three storage depths. It suggests that runoff from sources other than the road surfaces could still be directed to the underground storage since less than 50% of the storage spaces are utilized in all cases.



a) *b)* *c)* *d)*

Figure 6 - Peak flow values at outlet for a) Measure 1, b) Measure 2, c) Measure 3 and d) Measure 4



a) *b)* *c)* *d)*

Figure 7 - Peak water level values at storage unit for a) Measure 1, b) Measure 2, c) Measure 3 and d) Measure 4

4. CONCLUSION

The study was conducted to assess the capability and effectiveness of the chosen permeable road being incorporated into minor drainage system in the commercial centre. Modelling through SWMM5 was carried out to simulate the hydrological processes acted upon various surface areas of the permeable road when subjected to very-short duration design storms. The verification of the model was performed using the coefficient of determination, R-squared values, which were satisfactory and met the study requirements.

Under the weather patterns of equatorial region, the analyses of flow hydrographs at outfall showed the permeable road was able to lower the peak hydrographs compared to peak hydrograph of post-development and nearing pre-development condition for all scenarios. The analyses of storage unit were also performed to assess the capability of the permeable road. It indicated the permeable road could withstand the induced weather patterns to accommodate the generated runoff volume for all four scenarios, without overflowing from the permeable road.

Acknowledgement

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