

Testing the Concept of Mitigating Urban Flooding with Permeable Road: Case Study of Tong Wei Tah Street, Kuching City, Sarawak, Malaysia

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Abstract

This paper describes the investigation of permeable road as a mitigation measure for urban flooding. The study involves the reconstruction of a historical case of inundation, namely the 11 December 2019 flood event along the Tong Wei Tah Street in Greater Kuching City, Sarawak, Malaysia. The Storm Water Management Model version 5.0 was used as the platform to describe the flooding at the selected site and the functionality of permeable road to alleviate flooding. A permeable road with a dimension of 200 m long, 6 m wide and 1 m deep was simulated along the whole stretch of Tong Wei Tah Street. The model results show that flooding was caused by a backwater effect in the drainage system. Models predicted 0.1 to 0.5 m flood depths which matched the observed 0.3 m flood depth account of a local resident. The permeable road exhibited capability to absorb all the out-of-drain floodwaters, leaving no water due to the 11 December 2019 flood on the street. Modelling efforts demonstrated that the floodwater hydrographs in the drain rose and fell within 7 h, while the underground storage, filled and drained within 13 h. Moreover, the storage of permeable road was found to fill up to 75 %, reserving the unfilled 25 % for adverse weathers.

Keywords: Drain, Flash flood, Permeable road, River, Stormwater detention, Urban runoff

Introduction

Flood mitigation is human intervention that may consist of one or more measures to lessen the impacts of flooding [1,2]. The impacts usually mean losses of lives, damages to goods or properties and disturbances to daily activities. One of the ways to mitigate flood is to divert the floodwaters away so that it would not accumulate on the urban surfaces [3]. Permeable road designed with an underground water structure is an example of a flood mitigation measure. It could help divert floodwaters from above-ground surfaces to the underground structure. A permeable road could alleviate the impacts of flash flooding by providing a temporary water holding place and the waters could be released once the waterway is cleared of congested running water [4,5].

This paper intends to model the flooding processes that involve water transitioning between the waterway to permeable road. Evaluation of the flood model depends on the flood level [6], which is generated by rainfall delivered to the affected area. In this regard, the rainfall data could be in terms of statistically generated design rainfall which the authors had previously reported [7]; or alternatively using a historical rainfall event, such as the one described in the following section.

Materials and methods

Permeable road

Generally, a permeable road consists of 2 layers, namely a top layer of permeable pavement that allows floodwater to drain through; and a 2nd layer of underground storage that is equipped under the pavement to capture and hold floodwater [8]. Its general concept is illustrated in **Figure 1**. Once the

floodwaters appear, it could be absorbed by the road, like a sponge, hence ensuing the concept of sponge city [9].

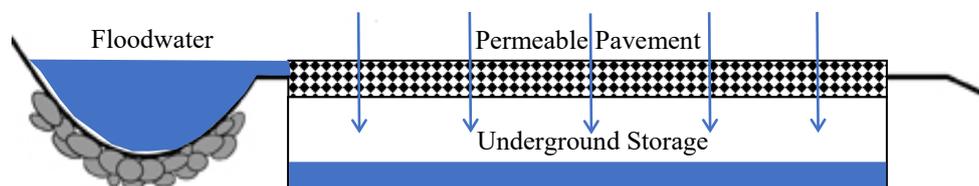


Figure 1 Concept of permeable road.



Figure 2 Examples of permeable road in the form of: (a) Permeable pavers (<https://acfenvironmental.com>) and (b) Underground concrete chamber (<https://oldcastleinfrastructure.com>).

Two examples of permeable road are presented in **Figure 2**. The one on the left of the figure (**Figure 2(a)**) is comprising of a top layer of concrete pavers, followed by a 2nd layer of aggregates. This is known as the conventional permeable road system, in which drainage voids are created in between the pavers so that water could seep through; and voids in between the aggregates are the intended spaces to store water that seeps through the pavers [10].

The other sub-figure on the right (**Figure 2(b)**), on the other hand, is visually contradicting with the former. Yet, these concrete blocks when assembled has a similar function of a permeable road. The concrete surfaces that appear as the top part of the blocks could be used for traffic passing on it. Service inlets are provided at strategic locations to drain water from the surface to the underground chambers provided by the interlocking concrete blocks [11].

Nevertheless, both provides underground storage under the road. The concrete block-type permeable road has a larger effective storage volume than the paver-type road. For the purposes of this study, the authors avoid choosing any specific design of permeable road, but describing only the possible of storage volume. Based on the 2 examples illustrated above, the range of storage volume is vast, in which it could be low to the accumulation of aggregates to high as exhibited in the empty chamber within a concrete block. As such, the choices of storage volume are opened for exploration.

Flood event

Flooding was reported along Tong Wei Tah Street located within the Kuching city on 11 December 2019 (**Figure 3**). The date of occurrence coincided with the Northeast Monsoon experienced in the Southeast Asian region from November to April yearly. According to the rainfall record of Ulu Maong Rainfall Station of the Department of Irrigation and Drainage Sarawak, located about 500 m away from the site, the rainfall event for that day spanned for 4 h. Recorded rainfall data were 8, 70.5, 20 and 6 mm

for each hour [8]. According to the Central Park Water Level Station located about 500 m downstream, a surge of water level was recorded on 11 December 2019. The peak of 3.44 m happened for 1646 h (**Figure 4**) [12] and coincided with the occurrence of flooding at Tong Wei Tah Street.



(a)



(b)

Figure 3 Tong Wei Tah Street during (a) Flash flooding on 11 Dec 2019 and (b) Under normal weather (date unknown).

A site visit to Tong Wei Tah Street was also carried out on 15 December 2019 to validate the records at Central Park Water Level Station where a drawdown of water level was observed for 1646 h (**Figure 4**) [12]. The eyewitness account of a resident revealed that the rainfall event started slightly for 1600 h and continued for about 30 - 40 min with maximum flood level observed at about 0.3 m.

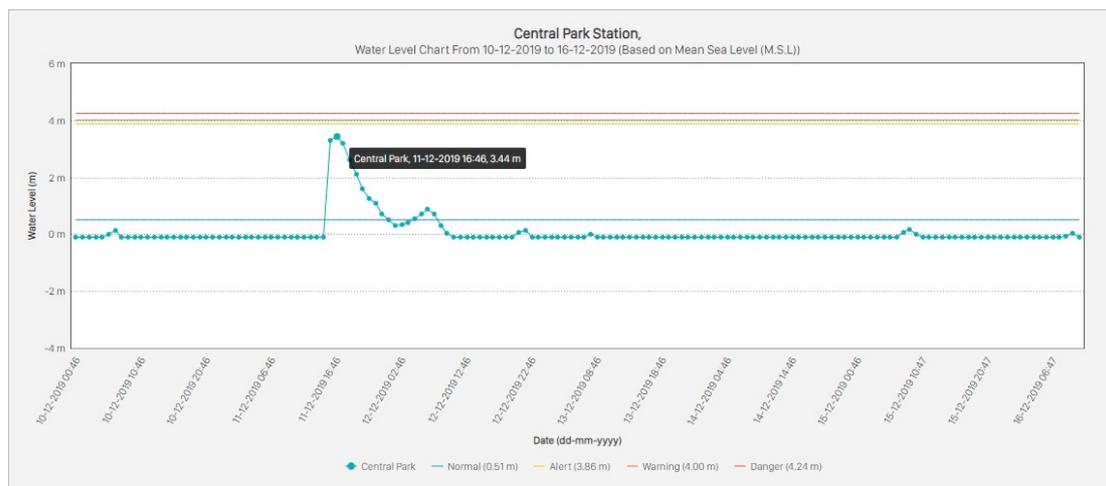


Figure 4 Water level readings at Central Park Station for 0000 h of 10 December 2019 till 0700 h of 16 December 2019 [12].

Flooded site

The 200 m long and 6 m wide Tong Wei Tah Street (highlighted with a yellow band in **Figure 5**) is in a residential area with 10 bungalows (8,000 m²) on the west side and 7 bungalows (5,200 m²) on the east side of the road. The direction of flow is to the north for drains alongside Tong Wei Tah Street. Drainage waters flow along two 0.5 m wide and 1 m deep concrete drains beside the street (**Figure 6(a)**) to the opposite end and discharge to a 3 m wide and 2 m deep stone-walled small stream (**Figure 6(b)**). From the small stream, the waters discharge to Ulu Maong River. The flood on 11 December 2019 began along the Tong Wei Tai Street and covered much of the residential areas in the vicinity (**Figure 3**).



Figure 5 Aerial map of study area (www.maps.google.com).



(a)



(b)

Figure 6 Drainage conditions at the study area: (a) $0.5 \times 1 \text{ m}^2$ concrete drain and (b) $3 \times 2 \text{ m}^2$ stone-walled stream.

Model building

Storm Water Management Model (SWMM) version 5.0 was used to model the flood of Tong Wei Tah Street. The software had been well known to represent urban stormwater drainage systems [13]. Two models were developed to simulate the effect of the use of a permeable road. The 1st model represented a conventional drainage system and the 2nd modelled a permeable road. In the 2nd model, the width and length of the underground structure followed the measurements of the existing street whereas the depth of the structure was assumed at 1 m.

In the 1st model (**Figure 7(a)**), a “Rain Gauge” input was used to model rainfall delivered to the catchment. This in turn generates runoff calculated in the model via Eq. (1). The Manning’s n value used for the catchment was 0.022 based on a past study [14]. Runoff connected to the “Nodes” and “Links” that represented the drain where water flow was simulated along the drain using the Kinematic Wave approximation (Eq. (2)) at a time step of 30 s. The nodes and links joined the stream and eventually reached the “Outfall” as the final discharge point [15].

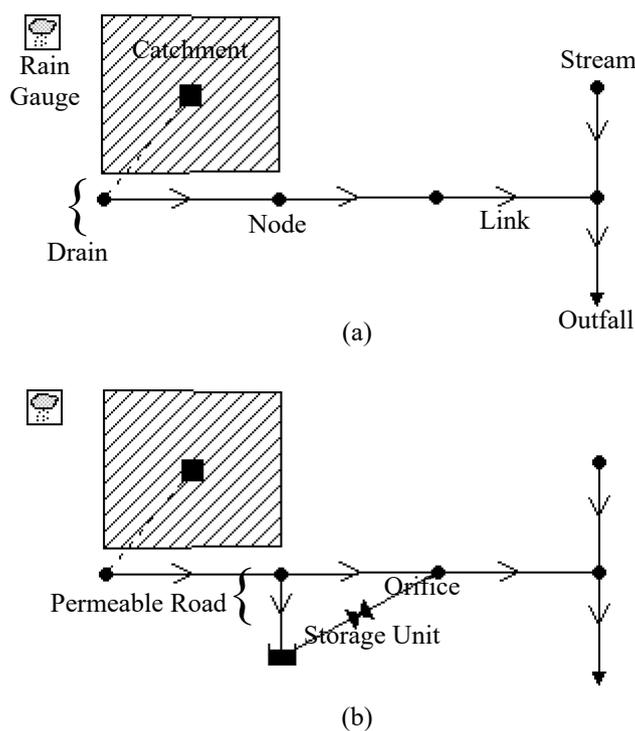


Figure 7 Modelling approaches for (a) Conventional drainage and (b) Inclusion of permeable road.

Eqs. (1) and (2) are presented below:

$$Q = W \frac{1.49}{n} (d - d_p)^{5/3} S^{1/2} \quad (1)$$

where,

Q = Water flow from catchment (m³/s);
 W = Width of roof or street (m);
 S = Slope of roof or street (m);
 n = Manning roughness value (unitless);
 d_p = Maximum depression storage (m);
 d = Depth of water over the catchment (m); and

$$q = \frac{\partial A}{\partial t} + \alpha m A^{(m-1)} \frac{\partial A}{\partial x} \quad (2)$$

where,

q = Routed water flow (m³/s);
 A = Cross sectional area of drain (m²);
 x = Distance along the flow path (m);
 t = Time step (s);
 α = Flow geometry due to drain (unitless);
 m = Surface roughness of drain (unitless).

The modelling approach for the permeable road is similar to the model of the conventional model but with the addition of a Storage Unit and its Orifice Outlet to represent the sponge road (**Figure 7(b)**). The method of a compartmentalized stormwater detention system using SWMM5 was used because it has been reported in the literature to best represent permeable road in drainage models [16]. The storage unit and orifice outlet were modelled using Eqs. (3) and (4) using a discharge coefficient of 0.060 placed at the orifice outlet [17].

$$St = \sum_i (q - Q_o) \Delta t \quad (3)$$

where,

St = Storage volume (m^3);

q = Inflow/routed water flow (m^3/s);

Q_o = Outflow/flow from orifice outlet (m^3/s);

t = Duration of storm (s); and

$$Q_o = A_o C_o \sqrt{2H_o g} \quad (4)$$

where,

Q_o = Flow from orifice outlet (m^3/s);

A_o = Orifice diameter (m^2);

C_o = Discharge coefficient of orifice (unitless);

H_o = Maximum head to the centre of the orifice (m);

g = Acceleration due to gravity ($9.81 m/s^2$).

Results and discussion

Flood reconstruction

The conventional drainage model (**Figure 8**) takes into account the peak rainfall which was recorded at 70.5 mm and classified as a red alert event (> 60 mm) [18]. Modelling of the 4-h rainfall on 11 December 2019 over Tong Wei Tah Street had indicated that the rainfall itself was not adequate to cause out-of-drain flooding along the street (**Figure 10(a)**). This is shown in long section view where the water level pattern of the drain on the west side does not exceed the height of the road level. The results of the model for the drain on the west side are similar to the water level patterns obtained for the drain on the east side.

The model simulations reveal that flooding emanated from the nearby stone-walled stream where the drains emptied. Congestion of flow was expected at the confluence of the stream and Ulu Maong River as the river water level continued to rise. This rise in river water level was recorded from the onset of the rainfall event (**Figure 4**). We deduce that the slow releases of floodwater from the stream into Ulu Maong River may have led to backwater effects in both the stream and drain and caused the flooding.

A part of the stone-walled stream was also included in the model with its downstream end having a river water level with the same values as recorded at Central Park station. However, a complete model of the stone-walled stream's catchment area was not possible at the time of writing. Trial and error simulation runs that could result in at least 0.3 m of flood depth in Tong Wei Tah Street were made to estimate the upstream flow.

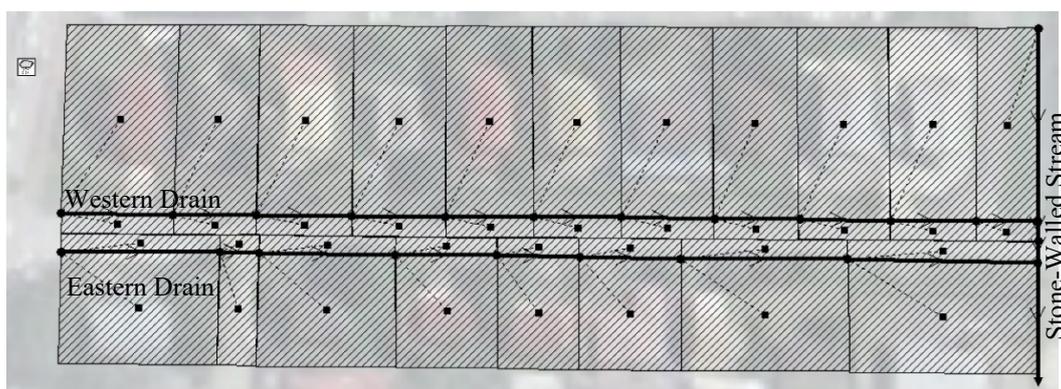


Figure 8 Conventional drainage model.

Simulations showing the backwater effect predicted only 120 m of flooding along Tong Wei Tah Street (**Figure 10(b)**). Based on the road level as reference, the model predicted flood depths ranging from 0.1 to 0.5 m, which were slightly different from the actual observed flooding throughout the 200 m length of the street. The maximum observed flooding had a 0.3 m flood depth. Although the model was

close to the observed flooding, the results could still be improved with better hydrological data and more reference elevation points of drains and streams. The predicted hydrographs are shown for reference of simulated flood depths from the road (Figure 11).

Impacts of permeable road

The drains of the site were overwhelmed and overflowed to the streets. To mitigate flooding in the future, floodwaters accumulated on the road could be diverted to a manmade storage under the road (Figure 9). In the models that were created, the storage unit received the diverted floodwaters from the 2 drains along Tong Wei Tah Street (Figure 7(b)).

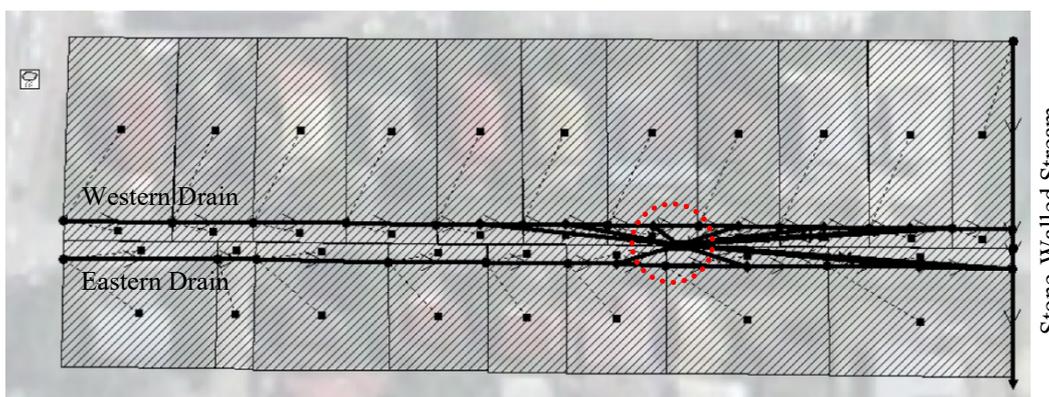


Figure 9 Drainage model with permeable road.

The stretches of drain that divert floodwaters were identified as stretches from 80 to 200 m. Diversion nodes were inserted throughout this stretch of road. Because of the storage unit, floodwater levels were reduced to below the road level, cutting down the flooding on the road (Figure 10(c)). SWMM, however, could not model the flow through the permeable pavement, thus floodwaters were assumed to have been able to flow through the layer easily. The 0.1 to 0.5 m floodwaters on the road modelled in previous simulations (Figure 10(b)) were held within the storage unit (Figure 12).

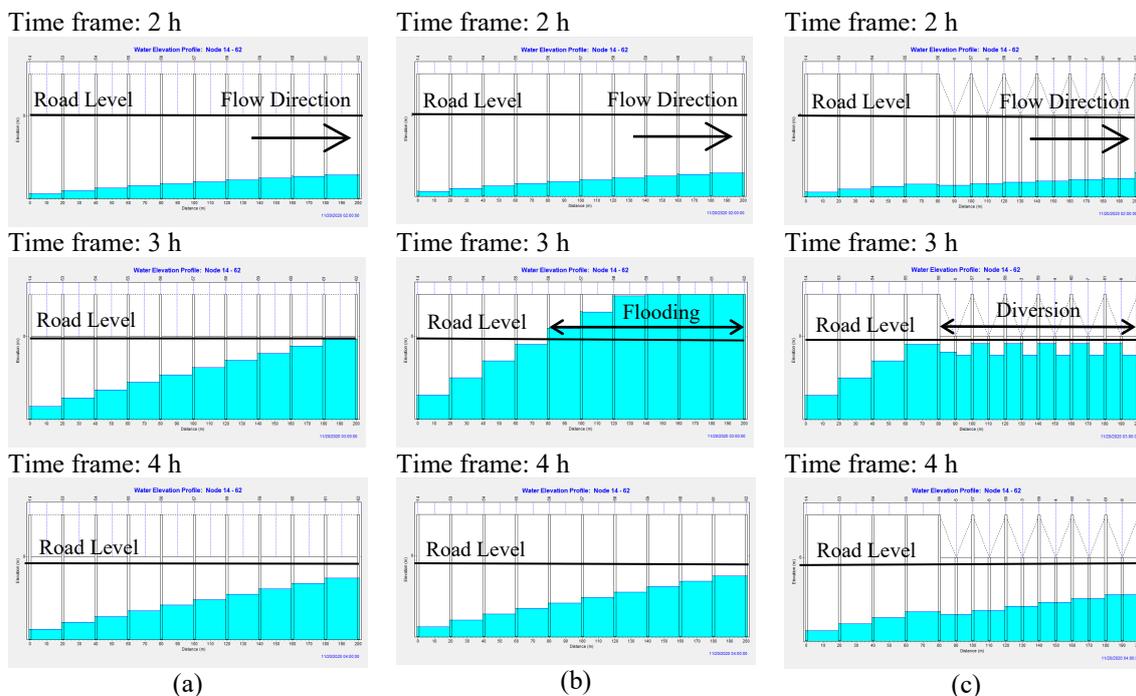


Figure 10 Simulated flooding along Tong Wei Tah Street for (a) Free-flowing conventional drainage model, (b) Conventional drainage model with backwater effect and (c) Drainage model with permeable road subjected to backwater effect.

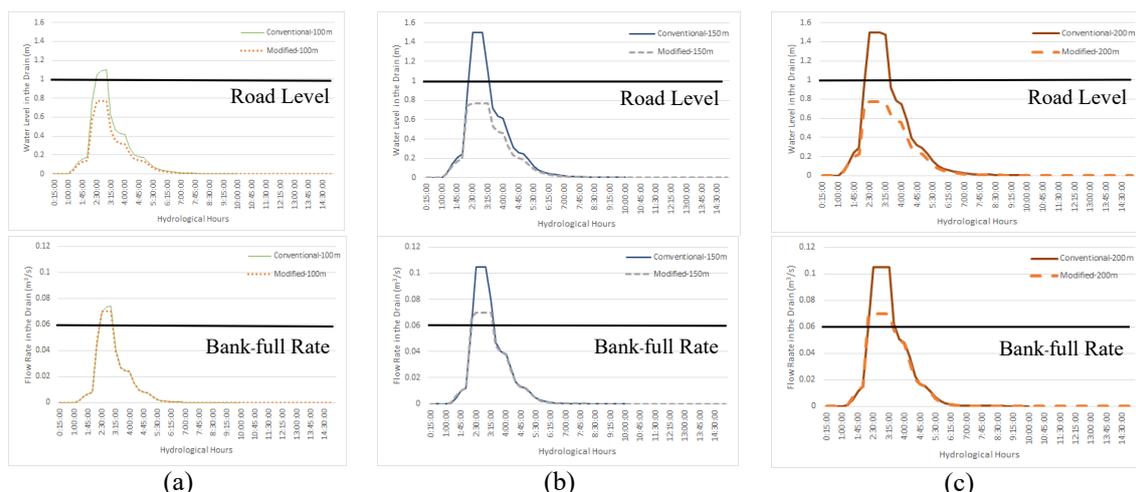


Figure 11 Water level and hydrographs of the selected western drain. Simulated water level and flow hydrographs at (a) 100 m, (b) 150 m and (c) 200 m point of drain.

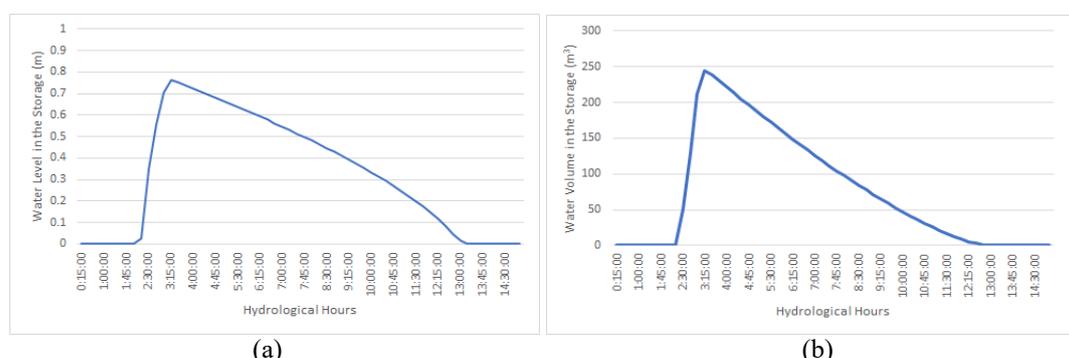


Figure 12 Simulated filling processes of underground storage in terms of (a) Water level and (b) Storage volume.

The SWMM was able to model the floodwater diversion based on the flow rate (**Figure 11**). As such, the bank-full flow rate was identified from the conventional model and imposed on the 2nd model. However, the associated water levels after the diversion were found to be deviated. The predicted readings were about 0.2 below the road level against the expected exactly on the road level. It was encouraging to see the drop of water level that eliminates the presence of floodwater on the road. In the hydrograph analyses, the stone-walled stream was excluded, because the changes in the upstream flow of the stream were small compared to the drains along Tong Wei Tah Street, in which SWMM predicted little influence of the permeable road upon the stream.

Processes within the underground storage are presented separately as captured water level and water volume (**Figure 12**). Water level in the storage reached a maximum level of 0.75 m that translated to 250 m³ of water. The storage structure was found to fill up to 75 % of the storage volume due to the 11 December 2019 flood event. The remaining 25 % storage volume could be reserved for climatic variation, which was an adaptive strategy towards climate change. Besides, the hydrograph bases for both water level and volume indicated a detention time span of 11 h. Compared with the hydrograph shown in **Figure 9**, those in the drain remained there for about 6 h. The 1 m depth of the underground storage was found appropriate considering its long detention time, which is the attenuation than the drain’s carrying capacity. After the hydrographs diminished at the time frame of 7 h, the storage continued to release water up to 13 h after.

Conclusions

The reconstruction of the 11 December 2019 flood event using SWMM was found to be moderately acceptable. However, the model was able to demonstrate that stitching pieces of post-flood information is able to provide a glimpse into the characteristics of the flood event. The model indicated that the cause of flooding was due to the backwater effect at the confluence of the Ulu Maong River and an unnamed stream. Further modelling shows that inserting a permeable road can eliminate flash flooding on Tong Wei Tah Street. The models discussed in this study showed that the 200 m wide, 6 m wide and 1 m deep storage could hold all the floodwaters underground, reversing the scenario of floods along the road.

Acknowledgement

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