Field data analysis of a flooding household stormwater detention system

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Abstract

This study describes the analysis being carried out for a field test of household stormwater detention system. The set up included a $0.95m^2$ house roof and a 4.40m x 4.70m x 0.45m on-site detention tank. Roof gutter and 0.1m diameter downpipe were installed connecting the roof to tank while 0.05m diameter pipe was connected to the tank as outlet. A total of 114 full units and 12 half units of precast concrete pieces named StormPav Green Pavement were laid within the tank. Two observed events are highlighted. Storm event happened on 22 February 2020 with a 48mm peak rainfall causing a flash flood within the housing estate of the field test site. Another storm event on 16 January 2020 had a 42mm peak rainfall but no flooding occured. Both observed storm events were classified as heavy storms for having rainfall depth over 40mm.

Comparisons were made to the design data corresponding to the 15-minute 10-year ARI design rainfall that was estimated at 46mm. Upon investigation, the main cause of flooding was due to the underestimation of design water level determined at 0.35m. This is due to the uncommon detention storage spaces provided by the StormPav Green Pavament with multiple chambers created by precast concrete pieces. The observed water level was recorded at 0.47m for 22 February 2020, a level with 0.02m exceeding the 0.45m tank-full level while the recorded water level was 0.40m for 16 January 2020 leaving a tight 0.05m vertical gap before the tank-full level. As such, the field test had demonstrated its values in rectifying the design data.

Keywords: Drainage, Field test, Flash flood, On-site detention, StormPav, Urban runoff.

Introduction

A field test was completed in a housing estate in Samarahan, Sarawak, Malaysia for a household stormwater detention system (Figure 1a and figure 1b). Being in a household environment, any overflowing from such a system shall create disturbance to the residents. However, during the course of data collection, the research team had encountered one storm event that caused the flooding of the system (Figure 1c). This study was a post-mortem analysis of the said system.

The stormwater facility was meant to be placed at the car porch in Malaysian houses[16,17]. Stormwater runoff from the roof was channelled via roof gutter and downpipe to enter an on-site detention (OSD) tank for temporary storage before being discharged to urban drain via an outlet [11]. The OSD tank was supposed to be built underground. However, in this case, it was constructed above ground so that it could be removed once the study ended as permitted by the voluntary property owner. Within the OSD tank, multiple precast concrete pieces were assembled. These were named StormPav Green Pavement System, or in short, StormPav[14].

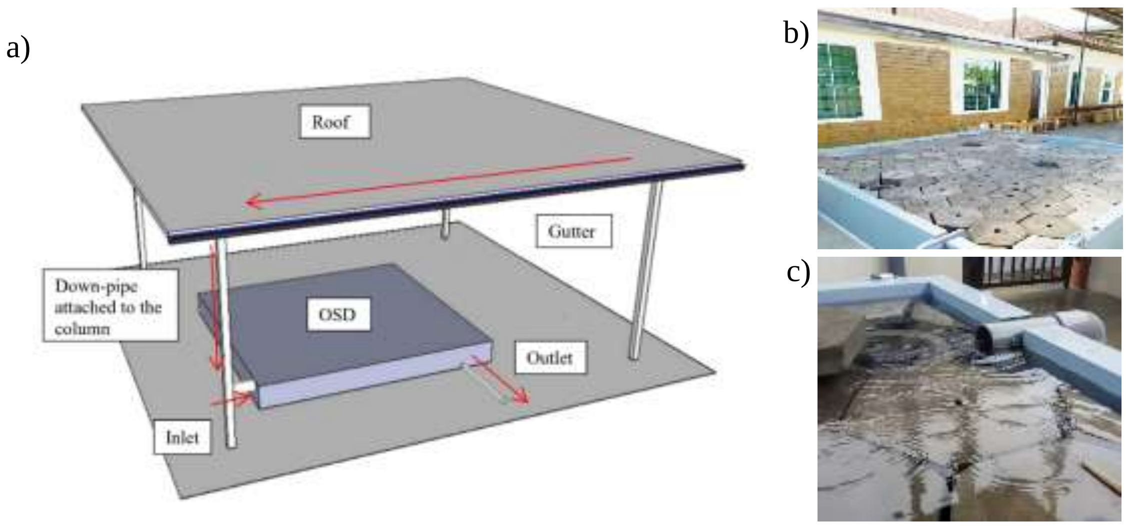

Figure 1: Field test for household stormwater detention system, a) Schematic drawing b) Completed set up and c) Overflowing event

The R and D product had gone through laboratory experiments[1,12] and computer simulations [10, 13] before this field test was implemented as the first prototype meant for household stormwater detention. It was made up of three layers (Figure 2), namely a cylinder sandwiched by two plates to form a single modular unit. Empty spaces created in between these pieces were used to store water.

The afore-mentioned system was an effort to support the urban stormwater management louded by the Malaysian government. OSD was an artificial structure made to replace the natural ability of soil layer to absorb stormwater that was lost due to urbanization[3,10,18]. It came in different forms and in the context of this study, StormPav was used. It was placed near to the source of stormwater[7]. For example, in this case, the stormwater was generated from the roof and therefore the OSD was placed under the roof to detain fully or partially the water so that less volume of water was released to unburden the existing urban drains. It is also a strategy to lessen the happening of flash flood in urban areas[20].

Material and Methods

Field Test Set Up: This field test was an extension from Ngu et al.[16] The sizing of the OSD tank was previously determined as 4.40m in width, 4.70m in length and 0.45m in depth. The surface area was based on the spaces for two cars side by side, a common features among the Malaysian houses. The depth was based on the cylinder with 0.30m high and the two plates with 0.075m high each. The base of the tank was flat. The tank was filled with 114 full modular units and 12 half modular units that came with an effective storage volume of 3.97m^3. Following the previous studies, the roof had a catchment area of 0.95m^2, primarily made of spandex with a slope of 3:100. Roof gutter was installed specifically for the selected roof areas connected to a 0.1m diameter PVC downpipe. Another 0.05m diameter PVC pipeline was connected to the outlet that discharged water to the house perimeter drain. These sizing of inlet and outlet were designed and reported by Ngu et al.[17]

To accommodate data collection, an automated rain gauge was installed just beside the roof. As rainfall was known to be non-uniformly distributed, the rain gauge was necessary to record the exact rainfall amount on the spot. Two flowmeters were acquired in which one was put at the inlet to record the inflow and another at the outlet to record the outflow. There was no direct way to measure the detention volume. However, water level sensor was installed, in which the recorded water level could be used to calculate the detention volume[11].

Engineering Design: According to the design manual[4,19], stormwater system began with rainfall. Engineering hydrological design applied the concept of design rainfall related to average recurrent interval (ARI) and design storm duration. For a minor system like the field test, it considered 10-year ARI and a short duration storm duration between 5-15 minutes. The OSD tank was designed up to 15-minute 10-year ARI design rainfall with assumption that the volume of water generated from the design rainfall was the worse-case scenario. By calculation, the said design rainfall was determined at 46mm. Any rainfall beyond 46mm shall cause the system to fail (overflow).

From the design rainfall, design runoff shall be generated by the intercepting catchment and guided to a stormwater facility. For a simple OSD tank depicted in figure 3, how much water flowing through the inlet could be represented as an inflow hydrograph. Similarly, how much water flowing through the outlet could be represented as an outflow hydrograph. The graph area bordered by the inflow and outflow hydrographs was the detention volume. It also pointed that the greater is the distance between the peak inflow and peak outflow (or attenuation rate), the greater the detention volume could be achieved.

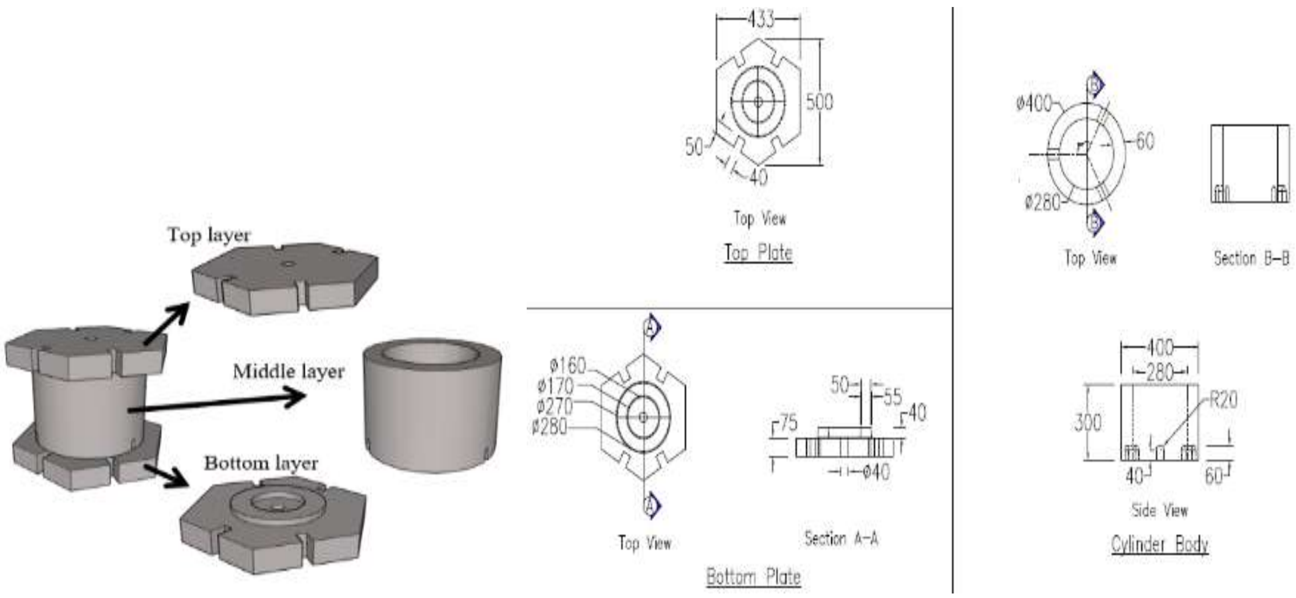

Figure 2: StormPav green pavement system

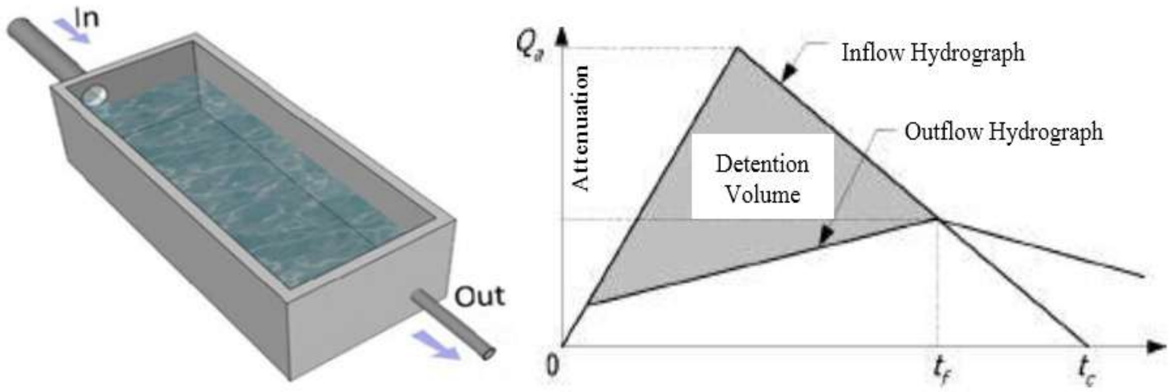

Figure 3: Storage design for OSD tank with single inlet and outlet

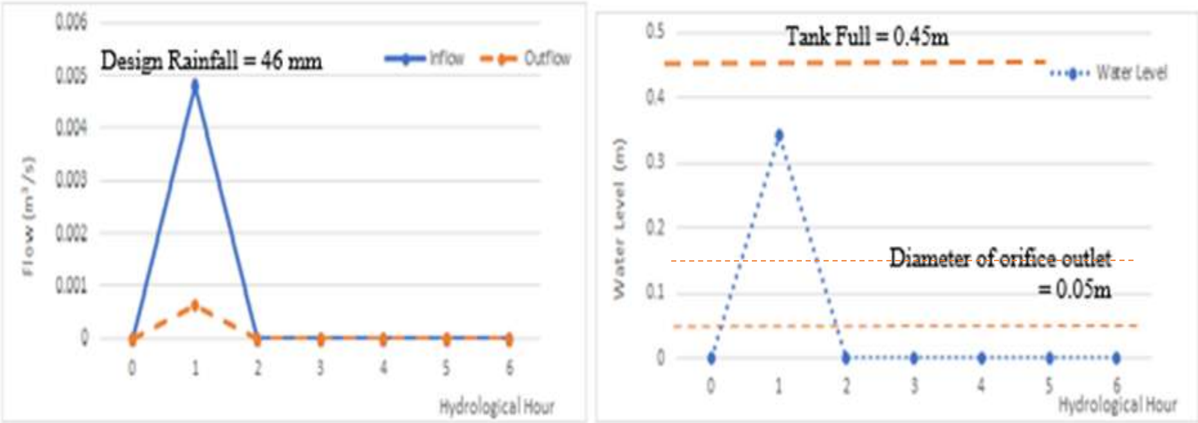

Figure 4: Inflow, outflow and water level hydrographs for 15-min 10-year ARI design rainfall

The computed design data for OSD tank were presented in figure 4. A design rainfall of 46mm had resulted in a peak inflow of $0.0048m^3/s$ and a peak outflow of $0.0006m^3/s$. The attenuation rate was estimated at 88%. The two peaks happened at the same timeframe due to short distance between the inlet and outlet for a small OSD system. The amount of roof runoff generated was estimated at $4.37m^3$. The highest design water level in the OSD tank was estimated at 0.35m and that stood for a detention volume of $3.22m^3$. It was expected to be close to 75% of generated roof runoff to be captured in the OSD tank.

Data Collection: Sarawak experienced Northeast Monsoon from October till March every year [15]. The research team was working on the construction of the OSD system in October and November 2019. Data collection started in December 2019 in which it was generally perceived that December and January were the peak of the monsoon. Collected hourly rainfall plots were presented in figure 5.

December 2019 had the most distribution of rainfall throughout the month with 687mm of total monthly rainfall (Figure 5a). Compared with December 2019, January 2020 had a lesser distribution of rainfall but the rainfall volume in the second half the month increased that caused 883mm of total monthly rainfall (Figure 5b). February and March 2020 were approaching the tail of the monsson season that each had a total monthly rainfall of 500mm and 420mm respectively (Figure 5c and figure 5d).

Two marks were added to each of the sub-figures, namely at rainfall depths of 20mm and 40mm. It should be noted that 80-90% of the rainfall for the four months were below 20mm; 10-20% were between 20-40mm; less than 5% were found to reach the 40mm. According to the local authority [5], the 40mm was classified as “heavy storm” or orange-flag event. Such a storm was close to 15-minute 10-year ARI design rainfall. As such, the assumption in design approach of taking 15 minutes as a worse-case scenario was appropriate.

Heavy Storm Events: Only two events with more than 40mm rainfall depth were observed during the monsoon season of 2019/2020. Therefore, these two events were selected for analysis. The first one occurred on 16 January 2020 with a peak rainfall of 42mm (Figure 6a). It spanned for four hours with a total rainfall of 53mm.

The second one occurred on 22 February 2020 with a peak rainfall of 48mm (Figure 6b). It spanned for ten hours with a total rainfall of 118mm. In terms of total rainfall, the second event was double of the first event. Both events were not the “very heavy storm” or red-flag event (more than 60mm).

However, one of them, namely the 22 February 2020 event had caused flash flood (Figure 7) within the housing estate of the field test site that should warrant equal attention[2].

Results and Discussion

Inflow, outflow and detained water level hydrographs obtained from the field test for 16 January 2020 and 22 February 2020 were presented in figure 8. Comparisons with the design data were made by referring to figure 4.

Peak inflow values from the observed storm events were recorded at $0.0011 m^3/s$ for 16 January 2020 and $0.0018 m^3/s$ for 22 February 2020. These two values were found 60-80% lower than the design peak inflow ($0.0048 m^3/s$). The vast difference was due to the different approach in obtaining the values. Design rainfall approach was assuming continous 15 minutes of rainfall befalling onto the catchment in which this rarely happened in reality. Actual rainfall varied according to time.

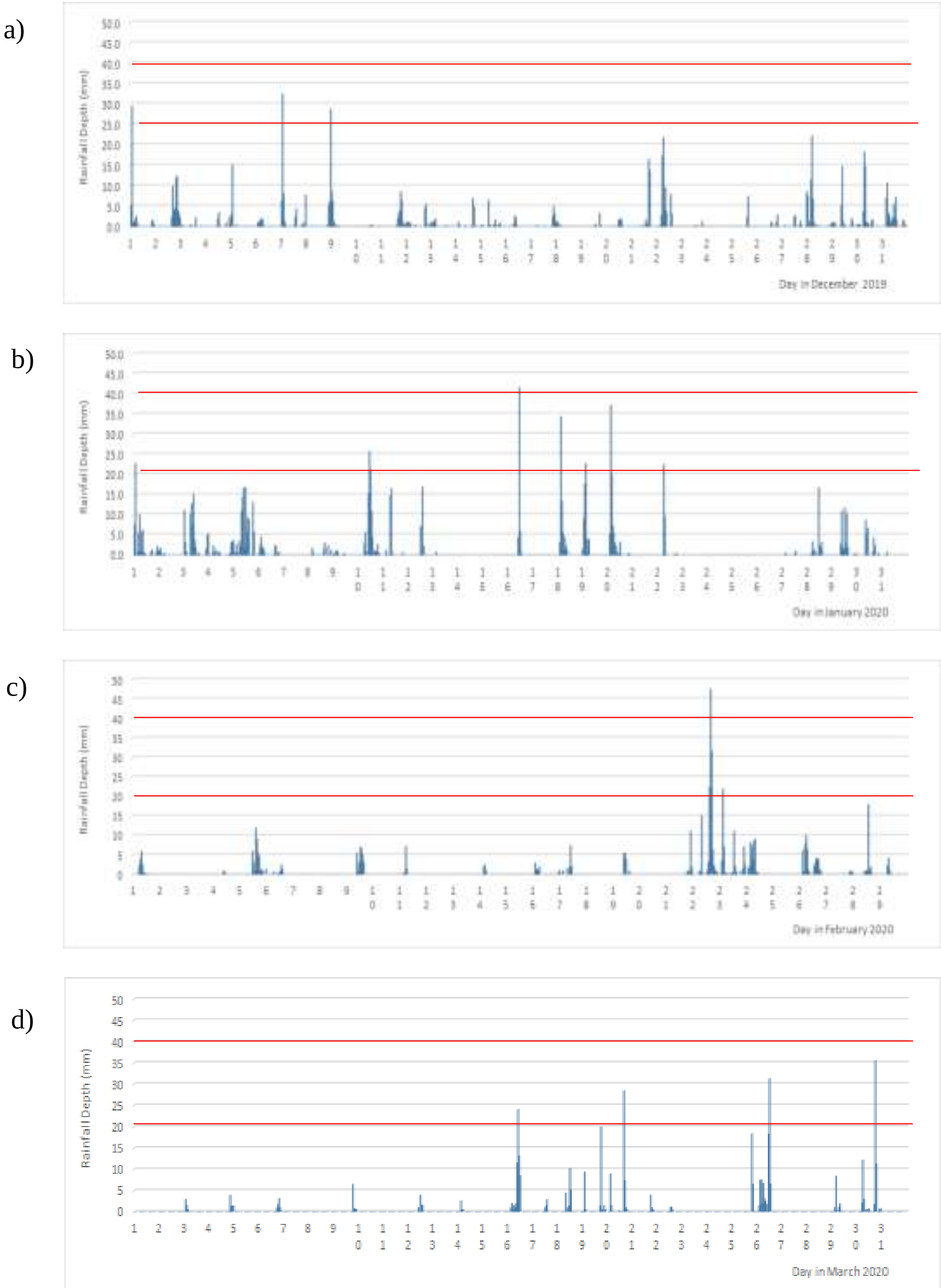

Figure 5: Hourly rainfall for a) December 2019, b) January 2020, c) February 2020 and d) March 2020

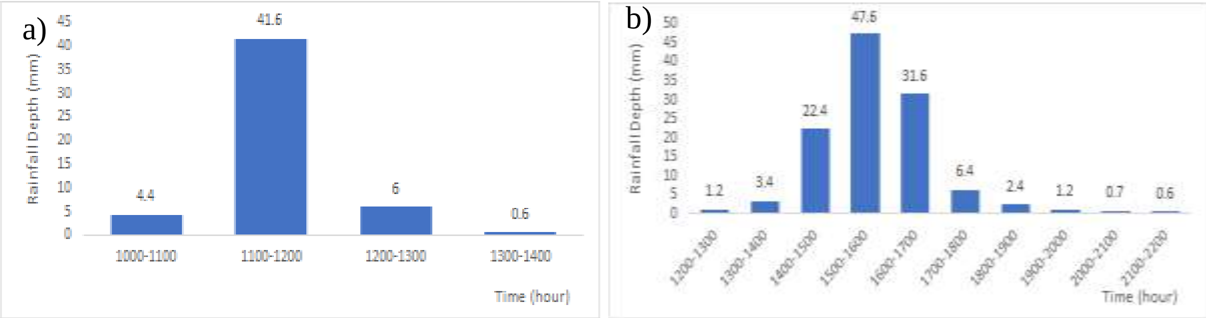

Figure 6: Hourly rainfall for a) 16 January 2020 and b) 22 February 2020 storm events

Figure 7: Flash flood due to 22 February 2020 storm event

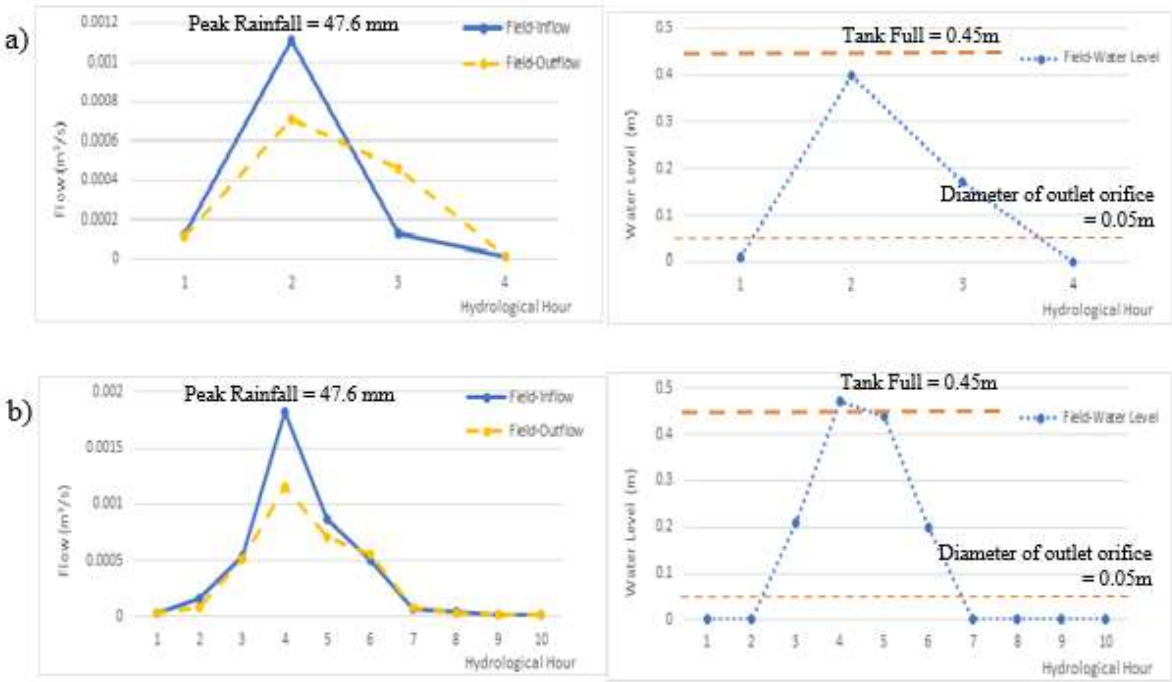

Figure 8: Inflow, outflow and water level hydrographs for a) 16 January 2020 and b) 22 February 2020 storm events

With the lowering of observed peak inflow values, the attenuation of the observed events was low compared to design data (attenuation at 88%). The attenuation rates were 36% for 16 January 2020 and 33% for 22 February 2020.

Peak outflow, on the other hand, was not influenced by the rainfall data but by the sizing of the outlet and the water pressure asserted by the water mass. The outlet size was determined at 0.05m. By calculation, the 16 January 2020 event with 53mm total monthly rainfall was estimated to produce 4.99m^3 of roof runoff volume while the 22 February 2020 event with 118mm total monthly rainfall was estimated at 11.16m^3. The latter was slightly more than double of the runoff volume of the former. Assuming the calculated water masses were appropriate, its consequences were reflected in the observed peak outflow values that were recorded at $0.0007m^3/s$ for 16 January 2020 and $0.0012m^3/s$ for 22 February 2020. Similar pattern was observed that the latter was also about double of the former.

Considering the observations above, it could be deduced that the spike-up value of design inflow was inclusive of safety factor in its computation process. In engineering hydrology, the calculated short-duration design rainfall depth was intentionally made higher than long-duration design rainfall depth. In return, the rainfall depth also estimated higher inflow. The resulted design outflow value ($0.0006m^3/s$) was found to match with the observed peak outflow of 16 January 2020 ($0.0007m^3/s$). However, the observed peak outflow value of 22 February 2020 ($0.0012m^3/s$) was doubled of the design value due to twice the amount of water mass produced by the storm event.

In terms of water level limitted by the current setup of field test, the 16 January 2020 storm event with 42mm peak rainfall had produced 0.40m water level. It had a tight vertical gap of 0.05m before reaching the tank-full level at 0.45m. The 22 February 2020 storm event with 48mm peak rainfall had produced 0.47m water level.

It exceeded the tank-full level by 0.02m. Both events had indicated system failure posing flood risk to the household environment. Comparing with the design data with 46mm peak rainfall, it was estimated to have 0.35m water level. It was clear that the design water level was underestimated. The water storing spaces provided by the StormPav modular units were difficult to be represented by any formula or model at the moment that caused the undesired discrepancy. By calculation, detention volumes were $3.68m^3$ or 74% of runoff volume for 16 January 2020 and $4.33m^3$ or 39% of runoff volume for 22 February 2020.

Highlighted issues mentioned above were reiterating findings from Drumond et al[6] and Hunt et al[8]. Field tests were rare and expensive. Demonstrated here, field data that represented the actual behaviour of a system could provide valuable insights into the existing design procedures for opportunities to further research.

Conclusion

The field test had produced observed values for four parameters, namely rainfall depth, inflow, outflow and water level. Other parameters like runoff volume, detention volume and attenuation rate were calculated. With only two heavy storm events, the research team admitted that the data were limitted and more data would be needed. However, two points of shortcomings were observed namely:

a) Design data did not consider the influence of water mass. This was demonstrated in the comparison of 16 January 2020 and 22 February 2020 storm events. Although both shared the same range of rainfall depth (between 40-50mm), its generated runoff volume had vast difference with the 22 February 2020 event for having twice the amount of water mass as of 16 January 2020 event. Therefore, the observed outflow of 22 February 2020 event was found way off the design outflow (+100%);

b) Design water level could be calculated due to the various types and forms of storage facilities in the market. In this case with StormPav that was providing empty spaces in between precast concrete pieces for water storage, the associated design water level was underestimated. A field test was found as the best way to obtain correct data.

Acknowledgement

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