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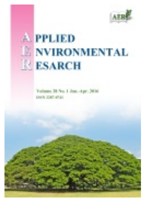

Case Study of Modular Pre-cast Concrete On-Site Stormwater Detention System during Monsoon Season in Southeast Asia

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Abstract

On-site stormwater detention system within a residential property is meant for an environmental protection device that temporarily stores stormwater within the property lot to mitigate flash flood, particularly during rainy seasons brought by the northeast monsoon. A field test was constructed in a house's car porch with a 4.40 m x 4.70 m x 0.45 m tank filled with precast-concrete modular units with an effective storage volume of 3.97 m^3. The system received water from a 95 m^2 house roof via 0.1 m diameter pipe, discharged water via 0.05 m diameter pipe. It had recorded six observed storm events coincided with the 2019/2020 monsoon season that consisted 20–50 mm peak hourly rainfall, 0.0007–0.0018 $m^3\ s^{-1}$ inflow, 0.0005–0.0012 $m^3\ s^{-1}$ outflow and 0.21–0.47 m water level. Another four historical storm events coincided with the monsoon from 2015–2017 were sourced to augment the analysis. A computer model developed using the storm water management model was calibrated and verified using the six observed events. The Kolmogorov-Smirnov goodness of fit tests between the observed and modelled cumulative distributions had produced 0.01–0.14 maximum vertical distances that were lower than the 0.41–0.68 critical values indicating close matches. As such, the calibrated and verified model was used to simulate the historical storm events with 40–50 mm peak hourly rainfall and produced 0.0010–0.0013 $m^3\ s^{-1}$ inflow, 0.00072–0.00076 $m^3\ s^{-1}$ outflow and 0.41–0.45 m water level. By combining the field test and computer simulation model, it was found the system was able to contain all stormwaters from northeast monsoon. However, it had a weakness which the system was approaching its maximum capacity once the peak hourly rainfall exceeded 45 mm. With such a procedure in place, improvement could be carried out.

Keywords: Field test; Inflow; Outflow; Rainfall; StormPav; SWMM; Water level

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Introduction

On-site stormwater detention system is an environmental protection device that mimics the natural function of the soil layer to absorb stormwater [1–2]. Referring to Figure 1 for a simple stormwater detention system, stormwater generated by rainfall enters the system via an inlet and leaves via an outlet. As a result, the rate of water through the inlet could be defined as an inflow hydrograph; while, the rate of water through the outlet, as an outflow hydrograph. These hydrographs are influenced by the size of the catchment that receives the rainfall and locality of the catchment as distribution of rainfall varies due to geographical factors [3–4]. By absorbing parts of stormwater within the system like the natural soil layer, less water is released to the urban environment so that in turn, it reduces the incidences of flooding, soil erosion and pollution [5]. This method of volume reduction is preferred for addressing the quantity and quality issues of stormwater management [6].

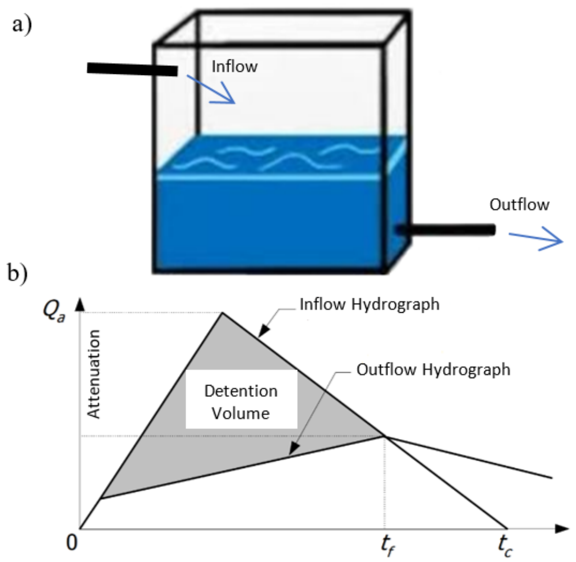

Figure 1 Fundamental design of stormwater on-site detention system (Modified from [7-8]).

Comparing the two synthetic hydrographs (Figure 1b), the peak outflow is purposefully lowered than the peak inflow and the difference between the two peaks is termed attenuation. The higher the attenuation, the higher the detention volume achieved. Another parameter associated with the inflow and outflow is the detained water level hydrograph in the water tank. Calculated inflow, outflow and water level hydrographs are usually presented in triangular or trapezoidal in shapes depending on the computational methods.

On the other hand, observed inflow, outflow and water level hydrographs have different outlooks that are irregular in shapes and differ from storm to storm. These are rarely available in the literatures. Observed data from a stormwater detention system in the field is expensive to obtain due to procurement of devices, installation and implementation of the data collection that may require several personnel over the monitoring period. As such, it is most likely a short-term than a long-term monitoring program.

In the normal practices, computer modelling is a common tool to simulate the relationships from rainfall to inflow, outflow and water level. Often, the relationships could be verified based on fundamentals of fluid mechanics and laboratory experiments [9], in which are relatively easier to carry out compared to field monitoring. Synthetic hydrographs are generally favoured for the design of stormwater systems based on the assumptions that the synthetic hydrographs are adequately representing a system.

Nevertheless, observed data are the best data to represent the actual behaviours of a system. Even with limited observed data from a short-term monitoring program, a computer model could be verified to better represent the system under study [10]. The verified model could be used to explore various aspects of the system. In the context of this paper, combined field test and application of computer model was demonstrated to evaluate a modular-based stormwater detention system during monsoon season. Such a system could be described as having multiple ready-made units fitted in the empty tank depicted in Figure 1a that was further described in the next section.

Materials and methods

1) Site descriptions

The afore-mentioned ready-made units were referring to a specific type of precast-concrete modular unit named StormPav Green Pavement System, or in short, StormPav [11] (Figure 2a and Figure 2b). Each of the StormPav modular unit consisted of three layers, namely a hexagonal cover as top layer, a hollow cylinder as the middle layer and another hexagonal cover as the bottom layer.

StormPav was first designed as road pavement, in which the top layer functioned as road surface, the middle layer as the water storage chamber and the bottom layer as the foundation. Its salient features included a cylinder height of 0.3 m that was calculated to store all stormwater generated by 3-hour 10-year Average Recurrent Interval (ARI) design storm on a single-lane low volume road; consequently, a water storage capacity of 0.19 m^3 per pavement area was based on the geometry of the modular units; and a draining capacity of 10,000 mm s^{-1} was laboratory tested for its service inlet on the hexagonal cover that directed water to the cylinder underground [12–13].

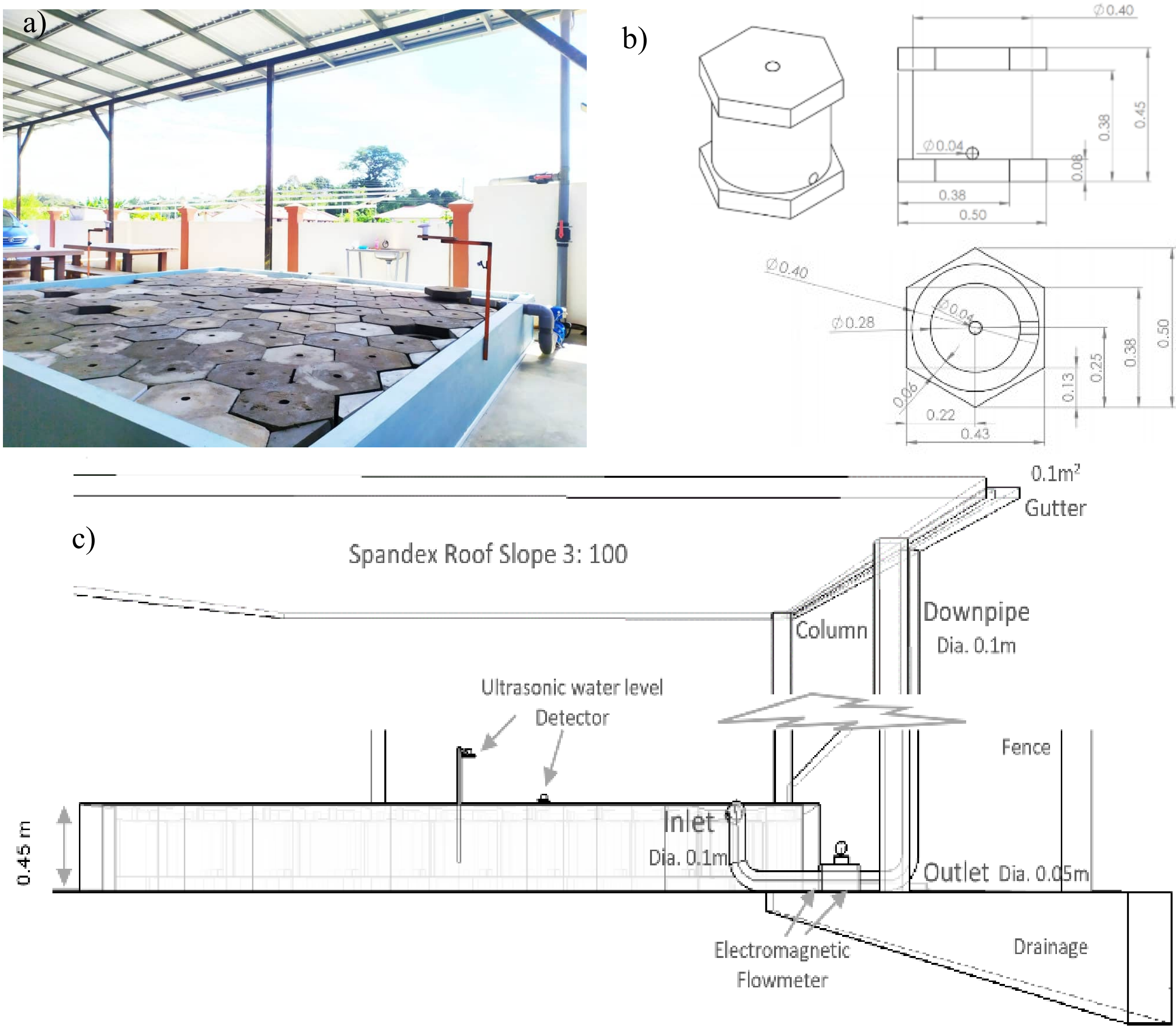

Figure 2 On-site stormwater detention system at Merdang Gayam housing estate, a) completed system, b) dimensions of the modular unit and c) technical drawing.

Continuing with the same modular size, StormPav was then studied as part of a house's car porch to detain stormwater from the house's roof. A small-scale laboratory test of the said system was reported in Ngu et al. [14] and a followed computer simulation effort was reported in Ngu et al. [15]. The current study was an extension from the two studies, in which a full-scale field test was constructed (Figure 2a and Figure 2c). The field test was primarily made up of a water storage tank 4.40 m in width, 4.70 m in length and 0.45 m in depth. The surface area was determined based on the size of two cars parked side-by-side. There were 114 full modular units and 12 half modular units within the tank, which registered an effective storage volume of 3.97 m^3 against the gross tank volume of 9.30 m^3.

The tank was constructed above the ground level as part of the agreement with the voluntary property owner to use the car porch area for research purposes. It received rainwater from a 95 m^2 roof above the tank. Water entering the system took the shape of the tank and filled the cylindrical chambers in between. This was achieved by having the modular units resting freely on the tank bottom. The inlet was equipped with a 0.1 m diameter PVC pipeline that was ensured of without surcharges in the connected downpipe from the roof. The outlet was a 0.05 m diameter PVC pipeline that flowed to a nearby drain.

2) Rainfall and flow measurement

The locality is Sarawak, Malaysia, situated on the northwest of Borneo Island, facing the South China Sea. Sarawak experiences northeast monsoon as wet season from October to April; and Southwest Monsoon as dry season from May till September annually [16]. Hourly rainfall data for this study was collected from December 2019 – April 2020 at Merdang Gayam housing estate, located in the coastal Samarahan district in Sarawak (Figure 3).

Figure 3 Hourly rainfall data at Merdang Gayam housing estate, Samarahan district in a) 1 December 2019 – 15 February 2020 and b) 16 February 2020 – 30 April 2020. Redlined marks indicate hourly rainfall at 20, 30 and 40 mm.

Monthly total rainfall was recorded at 687.3 mm in December, 883.4 mm in January, 499.9 mm in February, 420.0 mm in March and 231.5 mm in April. The monsoon season of 2019/2020 peaked in January 2020. Over the five months, a total of 165 storm events were recorded. From Figure 3, each of the bar represented hourly total rainfall at the field test site. It was found 90% (147) of the storms were having peak hourly rainfall below 20mm, 5% (9) between 20–30mm, 4% (7) between 30–40mm and 1% (2) above 40mm. Six storm events were selected, in which Events 1, 3 and 5 were used for model calibration; Events 2, 4 and 6 were for model verification (Table 1). These events had peak hourly rainfall between 20–50 mm. However, storm events with peak values below 20 mm were not selected because the magnitudes of these events were so small that no water detention was observed.

The maximum rainfall recorded was 48mm (Event 6). It was a common practice to use the maximum value for the evaluation of stormwater system presumed as the worst-case scenario. However, only two storm events with peak hourly rainfall over 40 mm were recorded (Events 5 and 6). The two observed storm events were not a sufficient gauge of the stormwater detention system's performance and reliability. Therefore, four historical storm events with similar range of peak hourly rainfall values (Events 7 to 10) were sourced from the Department of Irrigation and Drainage Sarawak to augment the analysis and report the reliability of the system. These historical storms occurred during the northeast monsoon seasons. Storm events that happened on 18.01.2015 were two consecutive storms with a one-hour halt in between. Therefore, the events were separated into 18.01.2015(1) and 18.01.2015(2). The availability of field data allowed the calibration and verification of a computer model [17-18]; and the verified model had then enabled the flow simulation due to the historical storm events to be carried out [19].

A smart rain gauge (WS1041 Weather Forecaster) was installed next to the roof to record the rainfall. Two electromagnetic flow-meters were installed, one at the inlet (100 mm WFD Yantai Auto) to record the rate of water entering the tank and another one at the outlet (50 mm WFD Yantai Auto) to record the rate of water leaving the tank. An ultrasonic water level detector (Walfront) was installed at the tank to record the water level. As such, the field test collected first-hand rainfall, inflow, outflow and water level data. Theoretically, due to the fixed geometry of the tank and modular units, the volume of water detained in the tank could be calculated by relating it to the water level

Table 1 Selected storm events

Storm Event	Date of occurrence	Storm duration (hour)	Peak hourly rainfall (mm)	Total rainfall per storm (mm)
Event 1	22.01.2020	4	22.6	32.8
Event 2	01.12.2019	7	29.6	42.5
Event 3	18.01.2020	8	34.4	66.4
Event 4	20.01.2020	11	37.2	85.6
Event 5	16.01.2020	4	41.6	52.6
Event 6	22.02.2020	10	47.6	117.5
Event 7	18.01.2015(1)	11	38.5	107.5
Event 8	18.01.2015(2)	14	43	188
Event 9	01.01.2016	6	51	89.5
Event 10	17.12.2017	15	47.5	178.5

3) Model descriptions

The United States Environmental Protection Agency's Storm Water Management Model (SWMM version 5.1) was acquired for the analysis. The SWMM model for a detention storage underneath a car porch was first developed by [14]. Referring to Figures 4a and 4b, previous study had described the flow path of stormwater that generated by the front roof of a detached house. The water flowed through a downpipe attached to a column to an underground tank. The final discharge point was set at the tank's outlet. Basically, the model covered only the front roof and underground tank.

SWMM was divided into components, and in this case, it had three components (Figure 4c). The first component started with the "rain gage", where rainfall data was entered. The rainfall data were linked to the "catchment" which the characteristics of the roof catchment were defined. This component was the hydrological simulation of rainfall-runoff relationship. SWMM was based on nonlinear reservoir representation to compute the runoff from the catchment [20]:

$$Q = W\frac{1.49}{n}\left(d - d_p\right)^{5/3}S^{1/2} \qquad \text{(Eq. 1)}$$

Where; Q = runoff generated by the associated catchment ($m^3 s^{-1}$), W = catchment width (m), S = slope (m), n = Manning roughness value (unitless), d_p = Maximum depression storage (m), and d = Depth of water over the catchment (m).

From the "catchment", the calculated runoff was transferred to the second component that was the stormwater detention tank. The roof gutter and downpipe were not explicitly modelled but embedded in the "catchment". The stormwater detention tank was represented as a "storage unit". The application of "storage unit" defined the water storage volume according to the dimension of the designed tank. In this case, the effective storage volume of StormPav modular units was applied [21–23]. "Storage unit" functioned like a middleman, in which the calculated runoff from the first component was treated as inflow to the tank, and the captured water or outflow was transferred to the third component – the outlet:

$$St = \sum_i (Q - Q_o)\Delta t \qquad \text{(Eq. 2)}$$

Where; St = Storage volume (m^3), Q = Inflow ($m^3 s^{-1}$), Q_o = Outflow ($m^3 s^{-1}$), Δt = Duration of storm (s).

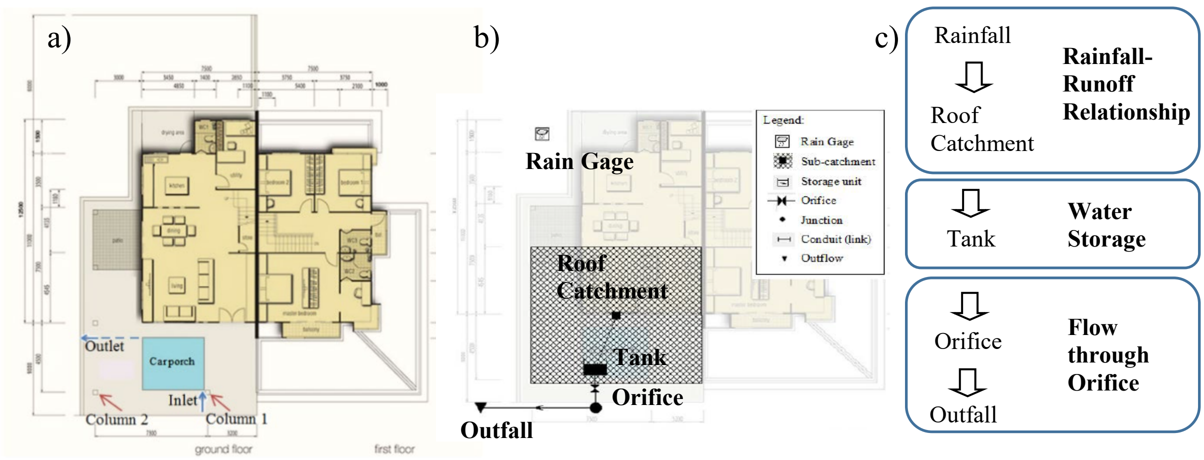

Figure 4 SWMM model, a) concept of layout, b) developed model and c) model components (Modified from [14–15]).

The outlet was represented as an "orifice". After the "orifice", it was connected to an "outfall" or the final discharge point. No "link" was included as no channel was needed explicitly in the mentioned water flow process. Flow through the "orifice" or the outflow from the stormwater detention tank was defined as:

$$Q_o = A_o C_o \sqrt{2 H_o g} \qquad \text{(Eq. 3)}$$

Where; Q_o= Orifice discharge rate (m^3 s^{-1}), A_o = Orifice diameter (m^2), C_o = Discharge coefficient (m^2), H_o = Maximum head to the centre of the orifice (m), g = Acceleration due to gravity (9.81 m s^{-2}).

4) Model calibration and verification

Referring to Eq. 1 to determine the inflow (Q), the parameters of catchment width (W), slope (S) and maximum depression storage (d_p) were measurable based on the field test setting. Depth of water (d) was continuously updated with time by solving numerically by the model. The remaining parameter, Manning roughness value (n) was a variable [24]. Therefore, calibration was carried out on the n values, and it was suggested a range of 0.022 to 0.026 for smooth plain metal roof surfaces [20].

Whilst referring to Eq. 3 to determine the outflow (Q_o), the parameters of orifice diameter (A_o) and water head (H_o) were measurable. The acceleration was constant at 9.81 m s^{-2}. The parameter of discharge coefficient (C_o) was a variable. Calibration was carried out on the Co values, and it was suggested a range of 0.060 to 0.065 for sharp crested orifice [20].

Eq. 3 calculated the storage volume of the stormwater detention tank based on the inflow and outflow determined from Eq. 1 and 2, respectively. No calibration of any parameter was carried out. However, water level in the tank was computed based on the storage volume and tank's dimension. This computed water level could be compared with observed water level for verification purposes.

To measure the comparison of modelled and observed values, the study then employed the Kolmogorov-Smirnov statistical test (K-S test) to quantify the goodness of fit [25]. The sample size for some of the storm events was small, for example, 4 h storm in Events 1 and 5. K-S test could cater for small sample size [26]. The method rationalised the sample to produce a cumulative distribution that ranged from 0 to 1. Comparison of the observed and modelled cumulative distributions was to determine the maximum vertical distance (D_{max}) for inflow, outflow and water level.

Results

1) Calibration and verification results

Observed storm events were run through the developed SWMM model. Figure 5 shows the plots of inflow/outflow and water level, in which the observed data were plotted with markers, while the modelled data were shown in lines. The developed SWMM model was first calibrated with three observed storm events and the best results are depicted in Figures 5a, 5b and 5c with n value at 0.022 for inflow and C_o value at 0.061 for outflow.

The calibrated SWMM model was then verified with another three observed storm events. The verification results are depicted in Figures 5d, 5e and 5f. In general, the modelled and observed inflow, outflow and water level for both calibration and verification were closely matched. Measurements of the goodness of fit using K-S test were described in the following section.

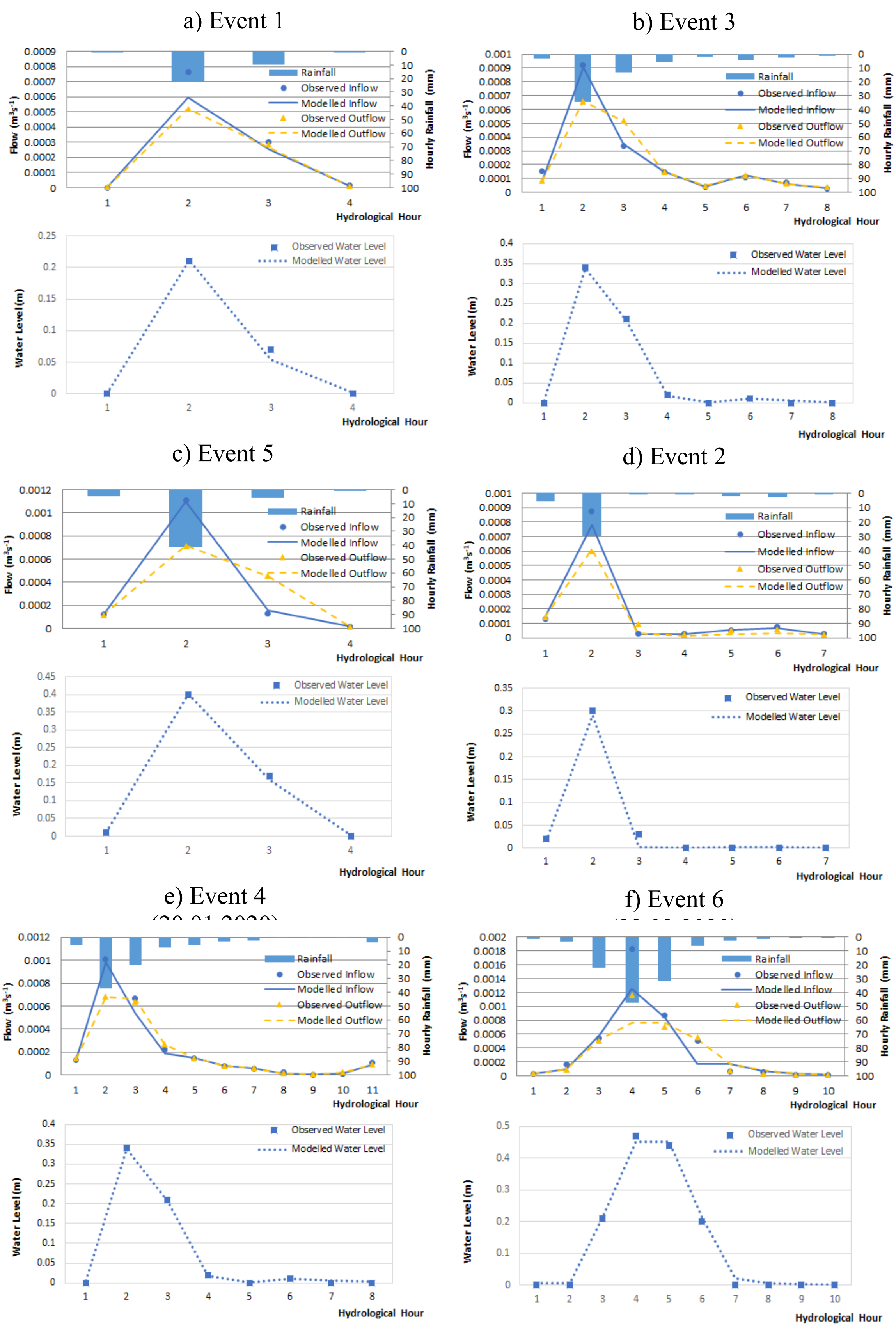

Figure 5 Model calibration with a) Event 1, b) Event 3 and c) Event 5. Model verification with d) Event 2, e) Event 4 and f) Event 6.

2) K-S test results

A null hypothesis assumed that there was no significant difference between the observed and modelled values in terms of inflow, outflow and water level. An alternative hypothesis, on the other hand, assumed that significant difference existed between the said observed and modelled values. Significance level (α) was set at 0.5. It was found that the D_{max} values in Table 2 were smaller than the Critical D values across the board. As such, the null hypothesis was accepted, or in other words, the inflow, outflow and water level were of a good match. The smaller the D_{max}, the better the goodness of fit.

3) Model application

Modelling results of the four historical storm events with the verified model are presented in Figure 6.

Table 2 K-S test results

Storm event	n	Critical D *	D_{max}			Remarks
			Inflow	Outflow	Water level	
Calibration						
Event 1: 22.01.2020	4	0.68	0.01	0.02	0.04	All D_{max}s were smaller than Critical D (No significant difference).
Event 3: 18.01.2020	8	0.48	0.04	0.01	0.02	
Event 5: 16.01.2020	4	0.68	0.02	0.01	0.01	
Verification						
Event 2: 01.12.2019	7	0.51	0.03	0.14	0.02	
Event 4: 20.01.2020	11	0.41	0.01	0.01	0.03	
Event 6: 22.02.2020	10	0.43	0.05	0.09	0.03	

Note: * Critical D at 5% significance level is calculated by $\frac{1.36}{\sqrt{n}}$

a) Event 7 (18.01.2015(1)) b) Event 8 (18.01.2015(2))

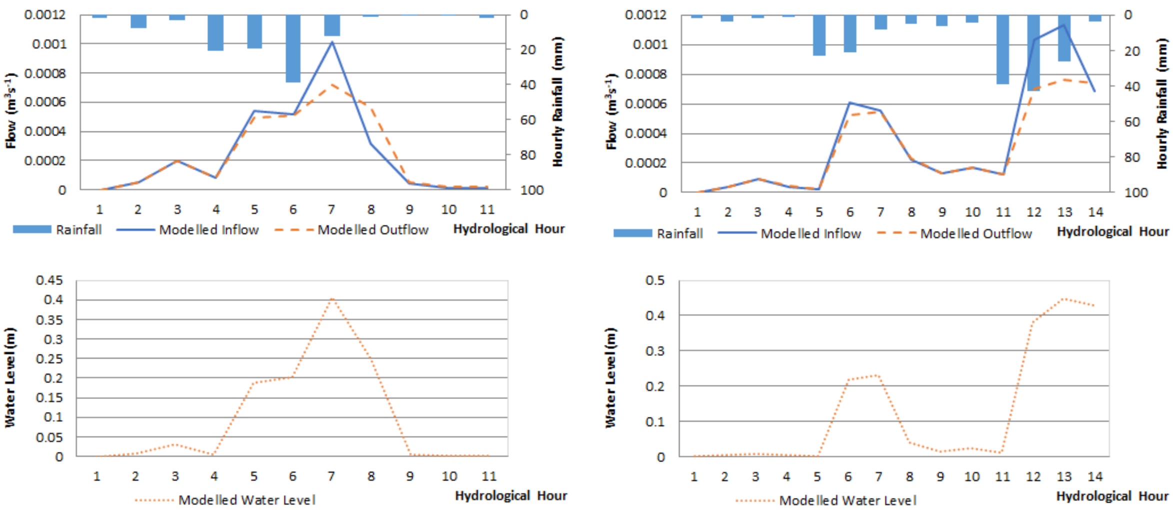

Figure 6 Modelled inflow, outflow and water level for a) Event 7, b) Event 8, c) Event 9 and d) Event 10.

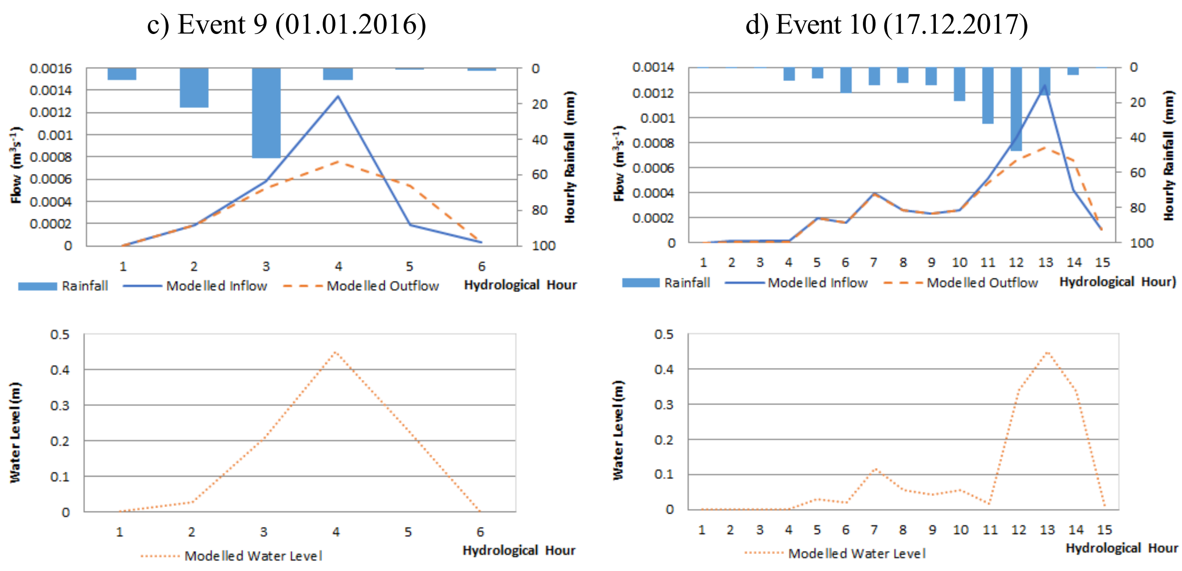

Figure 6 Modelled inflow, outflow and water level for a) Event 7, b) Event 8, c) Event 9 and d) Event 10 *(continued)*.

Discussion

Consolidation of results from the field test and SWMM are presented in Figure 7. The numbering appeared in the figures were referring to the storm event number designated in Table 1. The ten storm events were depicted plotting the peak inflow and outflow against peak hourly rainfall in Figure 7a, and the peak water level against peak hourly rainfall in Figure 7b. Events 1 to 6 were using the observed data, while Events 7 to 10 were using the modelled data. If the field test continued to collect data for a few more years, that would have eliminated the needs to use secondary data.

The ranges of 20–50 mm peak hourly rainfall had generated 0.0007–0.0018 m^3 s^{-1} inflow, 0.0005–0.0012 m^3 s^{-1} outflow and 0.21–0.47 m water level. Comparing the peak inflow and outflow, the associated attenuation rates were found to range between 15–77%. Yet referring to Event 6, it had produced peculiar patterns in the inflow and outflow plots, in which the readings were found furthest away from the trends of other nine readings. The reading of water level for Event 6 was the only storm event that exceeded the maximum water level of the stormwater detention tank. As such, it was justified a wise move to include the four historical storm events to the analysis. It was found that Events 7 to 10 had inflow, outflow and water level patterns fitted reasonably with other readings than Event 6. This lessened the strong statement portrayed by Event 6 that suggested overflowing from the system.

If Event 6 was treated as outlier, the stormwater detention system under study was found to contain the stormwaters from northeast monsoon experienced in the region. It also pointed out that the system was approaching its maximum capacity once the peak hourly rainfall exceeded 45 mm. In this regard, there was a need to lower the water level to 0.40 m, allowing a minimum freeboard of 0.05 m. Authors would like to state that overflow pipes were absence in the current setting of field test. Improvement to the system to deal with peak hourly rainfall exceeded 45 mm could explore on the overflow pipe or modification to the outlet size. Changing the dimensioning of the tank was unfavourable due to the limited spaces in a house's car porch.

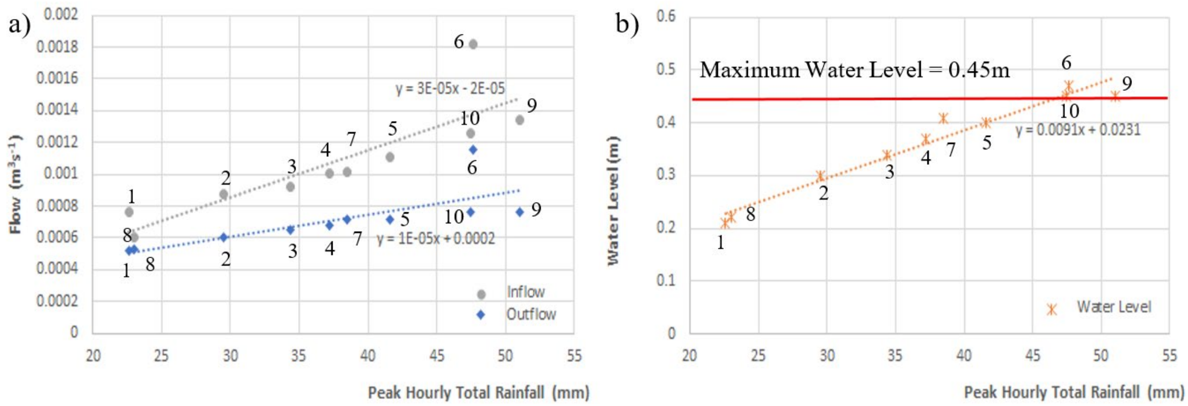

Figure 7 Impacts of monsoon season on: a) inflow and outflow, b) water level.

Conclusion

Northeast Monsoon season was known as the wettest months in Samarahan district, Sarawak; and the rainfall it brought was assumed a challenge to stormwater systems. A field test to a modular-based stormwater detention system housed in a car porch was subjected to rainfall from December 2019 to April 2020 that coincided with the said monsoon. Six observed storm events with peak hourly rainfall between 20–50 mm were selected. The field test had the associated inflow, outflow and water level readings recorded. Due to the short five-month monitoring program, there was a lack in storm events beyond 40 mm, additional four historical events with peak hourly rainfall between 40–50 mm were sourced that were coincided with the northeast monsoon from 2015–2017. A SWMM model was calibrated and verified using the said observed storm events, then it was used to produce inflow, outflow and water level for the historical storm events.

Combined efforts of field test and SWMM simulation were demonstrated to allow an analysis of the system under study during northeast monsoon. It identified that the current set up of the modular-based stormwater detention system was able to detain stormwaters generated by a range of 20–50 mm peak hourly rainfall during the said monsoon season. It also identified a weakness which the system was found to approach its full capacity once the peak hourly rainfall exceeded 45 mm.

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