P-ISSN 2586-9000
E-ISSN 2586-9027
Homepage : https://tci-thaijo.org/index.php/SciTechAsia
Science & Technology Asia
Vol.26 No.3 July - September 2021
Page: [77-89]

Original research article

Modelling the Outlet of Multi-Chamber Stormwater Detention System

Darrien Yau Seng Mah[1,*], Johnny Ong King Ngu[1], Norazlina Bateni[1], Frederik Josep Putuhena[2]

[1]*Faculty of Engineering, Universiti Malaysia Sarawak, Sarawak 94300, Malaysia*
[2]*Pembangunan Jaya Center for Urban Studies, Universitas Pembangunan Jaya, Tangerang Selatan 15413, Indonesia*

Received 3 May 2020; Received in revised form 21 January 2021
Accepted 5 February 2021; Available online 6 September 2021

ABSTRACT

Outlet size influences the detention volume that is crucial in a stormwater system. This paper describes an application of improving the outlet size of such a system. A field test is built in a terraced house that consists of a 4.40m × 4.70m × 0.45m multi-chamber stormwater detention tank connected to 0.1m diameter inlet and 0.05m diameter outlet. During field monitoring, an overtopping event is observed that puts a quest to re-look into its design. The field test has enabled the data collection of ten storm events with peak rainfall ranging from 20-48mm. A stormwater detention model is developed using the US Environmental Protection Agency's Storm Water Management Model (SWMM). Calibration of the model with the observed storm events has returned with good matches with R Square values more than 0.9. With the calibrated model, investigations into the outlet sizes of 0.050m, 0.055m and 0.063m are carried out. The existing field test setup with the outlet size of 0.050m has water levels in the detention tank higher than the expected design values; and therefore, overtopping is observed for rainfall depth over 40mm. By simulating a scenario of enlarging the outlet size to 0.055m, the system is improved to accommodate rainfall depth up to 45mm, but overtopping is expected for rainfall depth over 45mm. By simulating another scenario of enlarging the outlet size further to 0.063m, the possibility of overtopping is eliminated but at a cost of achieving only in average 10% of attenuation between peak inflow and peak outflow. It is the least attenuation rate compared to average 30% for 0.050m and 20% for 0.055m. In short, the modelling efforts are demonstrated as a practical solution to the improvement of the intended stormwater detention system.

Keywords: Field test; On-site detention; Outflow; StormPav; SWMM; Water level

***Corresponding author:** ysmah@unimas.my
doi: 10.14456/scitechasia.2021.48

1. Introduction

Stormwater detention systems are basically water storage devices used to control the rate and volume of running water in urban areas [1-2]. The appropriate size of their outlets contributes to controlling the quantity and quality of urban stormwater at the minimum cost [3]. With the outlets, free-flowing water are transformed to regulated flow that allows measurement and control of flow rates and relevant parameters [4]. Lucas and Sample [5] applied the outlet controls to mitigate a sewer overflowing situation. Moreover, Kong et al. [6] showed further application of the outlets to provide optimization patterns for future urban growth in terms of hydrological responses to land use changes.

This paper is written after overtopping of a field test of multi-chamber stormwater detention system is observed (Fig. 1). The detention system is designed according to the theoretical method; however, field data analysis often points out differences between theoretical and actual performances [7-9]. Efforts are made to improve the system by exploring the outlet sizes.

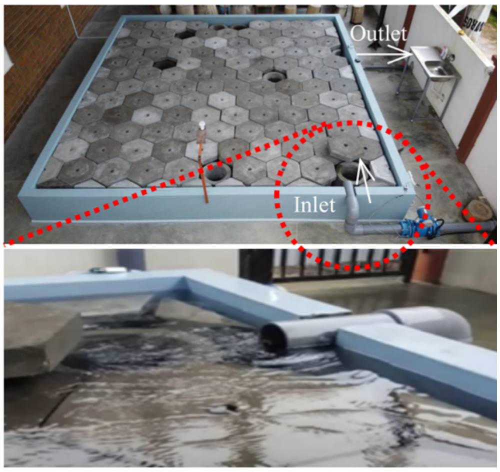

Fig. 1. Field test of multi-chamber stormwater detention system.

The field test depicted in Fig. 1 is a tank constructed at the car porch of a terraced house in Kuching, Sarawak, Malaysia. Extending from initial studies in [10-11], it is the first in-field prototype for such a household-based system. The tank is supposed to be underground. In mind of dismantling upon completion of study, it is constructed aboveground upon the existing ground level. StormPav precast concrete modular units [12] depicted in Fig. 2, are installed within the tank. The modular units create multiple chambers for water storage.

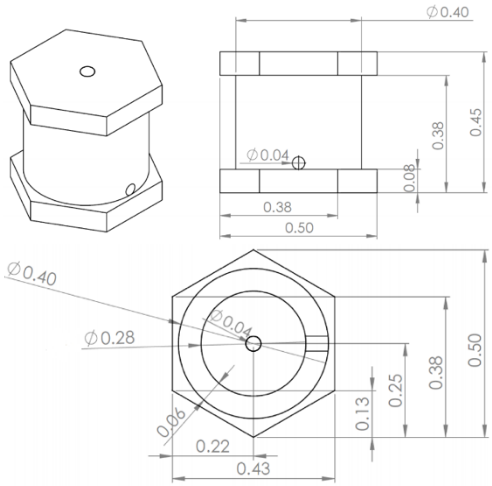

Fig. 2. Dimensions of StormPav precast concrete modular unit.

The tank is 4.40m in width, 4.70m in length and 0.45m in depth. A total number of 114 full modular units and 12 half modular units are utilized that constitute an effective storage volume of 3.97m^3. The tank receives water via an inlet that could be traced to the house's 95m^2 front roof, 0.1m x 0.1m roof gutter and 0.1m diameter downpipe. It releases water via an outlet that consists of a 0.05m diameter pipeline discharging to a nearby drain.

The working mechanism of the tank is depicted in Fig. 3. According to the principle of mass balance, the rate of water entering the tank, Q_{in}, is equal to the rate of water leaving the tank, Q_{out}. As water continues to flow in, the volume of water in the tank increases. To maintain the mass balance, water level in the tank increases due to the volume of water. Under normal circumstances, water continues to flow out to cause the water level to decrease over time until the tank is emptied.

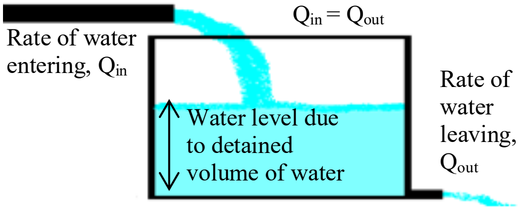

Fig. 3. Concept of a draining tank.

Under unfavorable circumstances, the rate of water flowing out is overwhelmed by the volume of water that causes the water level to continue to rise until overtopping. It means flooding that inconveniences the residents hosting the detention system. To avoid overtopping, either the tank size or the outlet size could be improved.

In the case of our field test, the precast concrete modular units are not cemented but rested freely on each other. Detained water mass is taking the shape of the tank, filling the empty chambers provided by the modular units. Therefore, the effective storage volume is applied here [13-14]. The current tank size and effective storage volume are considered at best limited by the spaces available at any terraced house [10]. However, the outlet size that is commercially available could be explored to lower occurrence possibility of overtopping [15].

2. Materials and Methods

2.1 Design method

Design procedures for stormwater detention tanks are referred to design manuals in [16-17]. The field test in a terraced house is classified as a minor system to be designed to 10-year average recurrent interval (ARI) design rainfall. Its associated storm duration is designed for short duration storms, usually between 5 to 15 minutes. The amount of runoff, generated by the design rainfall within the selected storm duration, is routed through the tank. As a result, design inflow, outflow and retained water levels could be produced. The rule of thumb is the tank must be able to withstand consequences due to the design rainfall [18]. The 10-year ARI design rainfall values are calculated at 23mm for 5-min, 36mm for 10-min and 46mm for 15-min storm durations.

2.2 Field test

The field test setup is illustrated in Fig. 4. The stormwater system starts with rainfall. A rainfall gauge is used to record the amount of rainfall at the field test site. Once they land on the roof, raindrops turn into running water that flows into the roof gutter and downpipe. A flowmeter is installed at the downpipe before the running water enters the tank to record its inflow rate. A second flowmeter is installed at the outlet pipe to record its outflow rate. Water accumulated in the tank is sensed by a level indicator. As such, the field test provides first-hand data in terms of rainfall, inflow, outflow and water level (in Fig. 6).

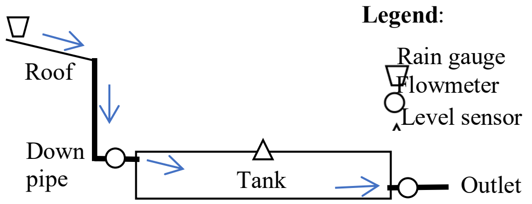

Fig. 4. Schematic diagram of field test setup.

2.3 Model building

Modification to the existing tank could destroy the water resistance layer on the tank while the data collection is still on-going at the time of writing. The authors therefore attempted computer simulation to address the overtopping issue. SWMM is used for modelling the system [19-20]. The model building is illustrated in Fig. 5.

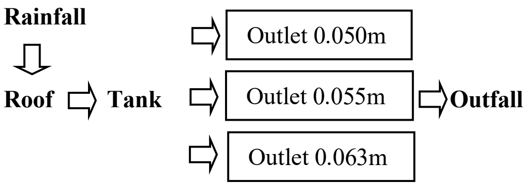

Fig. 5. Schematic diagram of model building.

The roof is represented as a catchment in SWMM that receives the rainfall. The tank is represented as a storage unit in SWMM, while the outlet is represented as a bottom orifice attached to the storage unit. Three scenarios are presented here, for the outlet size of 0.050m which is the current setup in the field test, while the remaining two proposed sizes are modelled for investigation.

2.4 Model calibration

Model calibration is made possible with the availability of field data. Ten observed storm events are selected with peak rainfalls ranging from 22-48mm that are in line with the design rainfall values. Among the ten, 16 Jan 2020 and 22 Feb 2020 storm events were the heaviest rainfall events recorded during the monitoring period.

These storm events are run through SWMM and comparisons are made between the model and field datasets. Fig. 6 shows the graphical representations of inflow/outflow and water level hydrographs in two separate sub-figures for each storm event. Visually, the graphs are found to have close match. Goodness of fit for the datasets is quantified via scatter plots of observed and predicted values in Fig. 7. The matches are better informed, in which the plots for inflow, outflow and water level are separated into three sub-figures for each storm event.

Coefficients of determination, R^2 values are inserted the sub-figures. The R^2 values range from the lowest 0.91 to the highest 0.99. They indicate acceptable small differences between the observed and the model's predicted values. It also means that the model datasets are found with good fit with the field datasets and therefore, calibration is deemed completed.

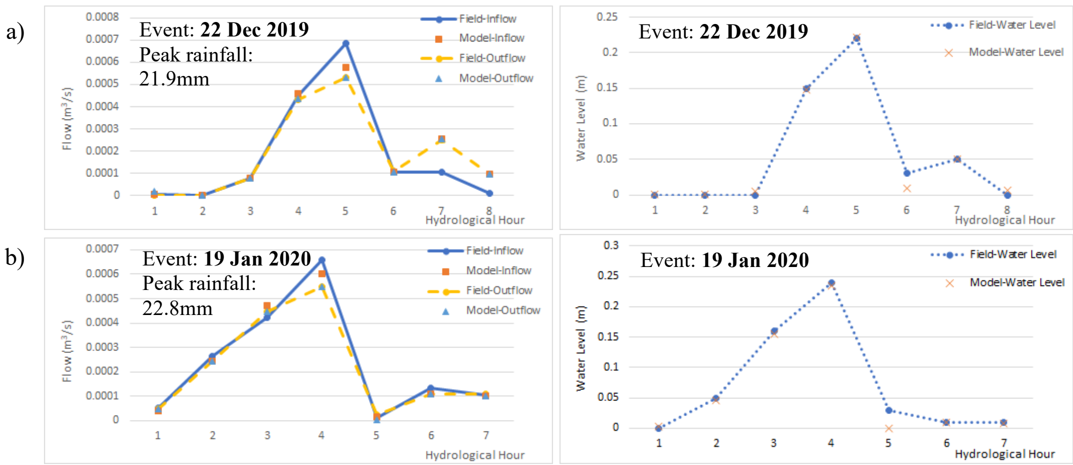

Fig. 6. Model calibration for a) 22 Dec 2019, b) 19 Jan 2020, c) 10 Jan 2020, d) 8&9 Dec 2019, e) 1 Dec 2019, f) 7 Dec 2019, g) 18 Jan 2020, h)20 Jan 2020, i) 16 Jan 2020 and j) 22 Feb 2020 storm events.

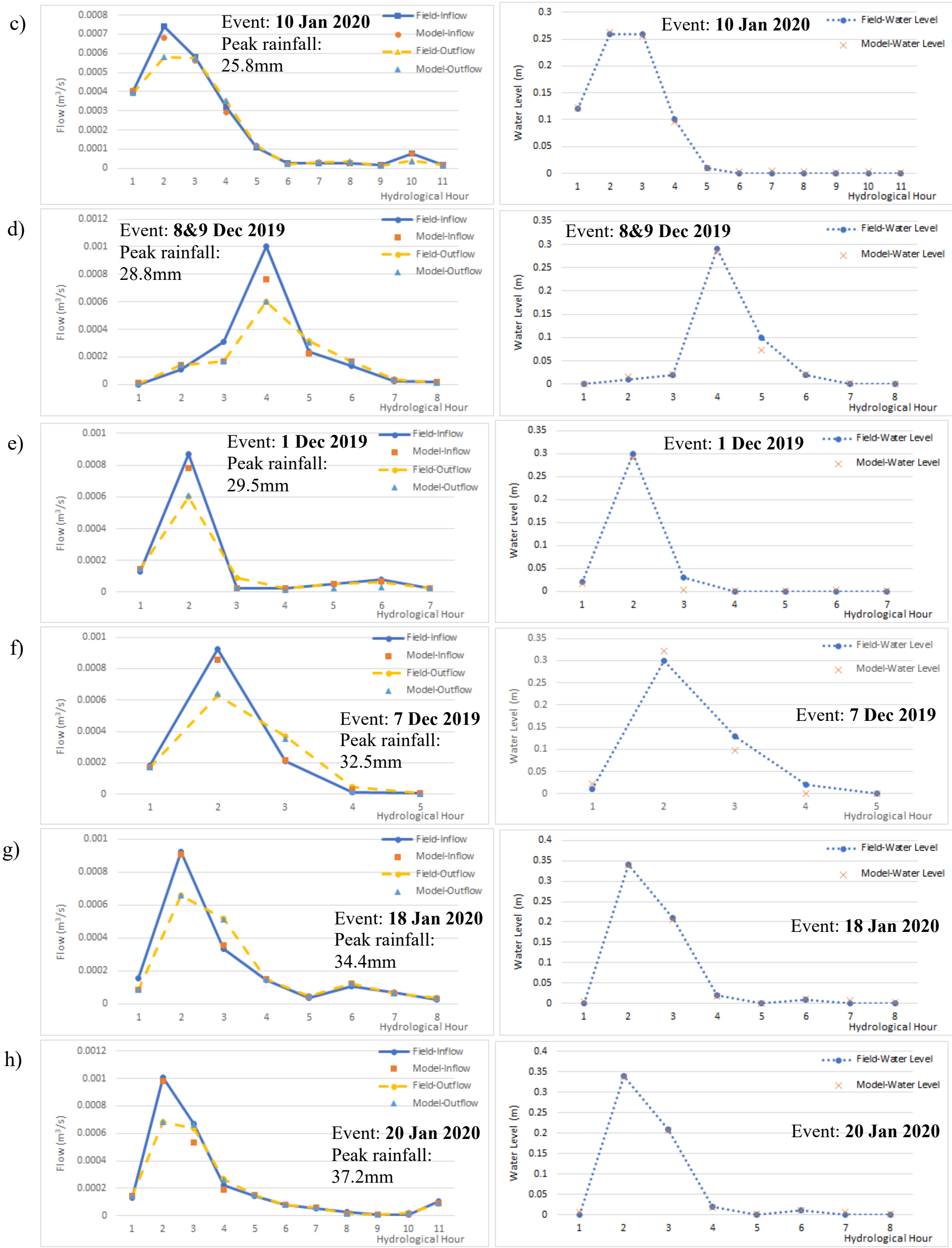

Fig. 6. (Continued).

i)

j)

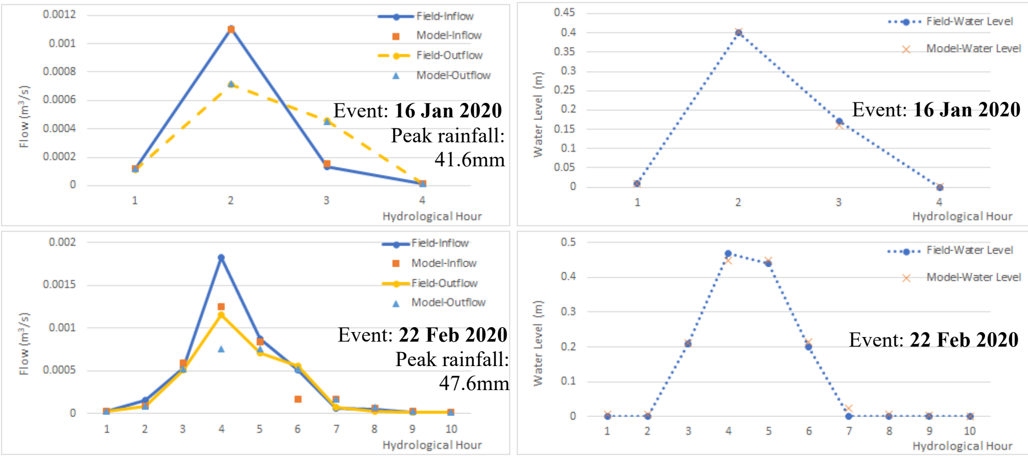

Fig. 6. (Continued).

Inflow | Outflow | Water Level

a)

b)

c)

d)

e)

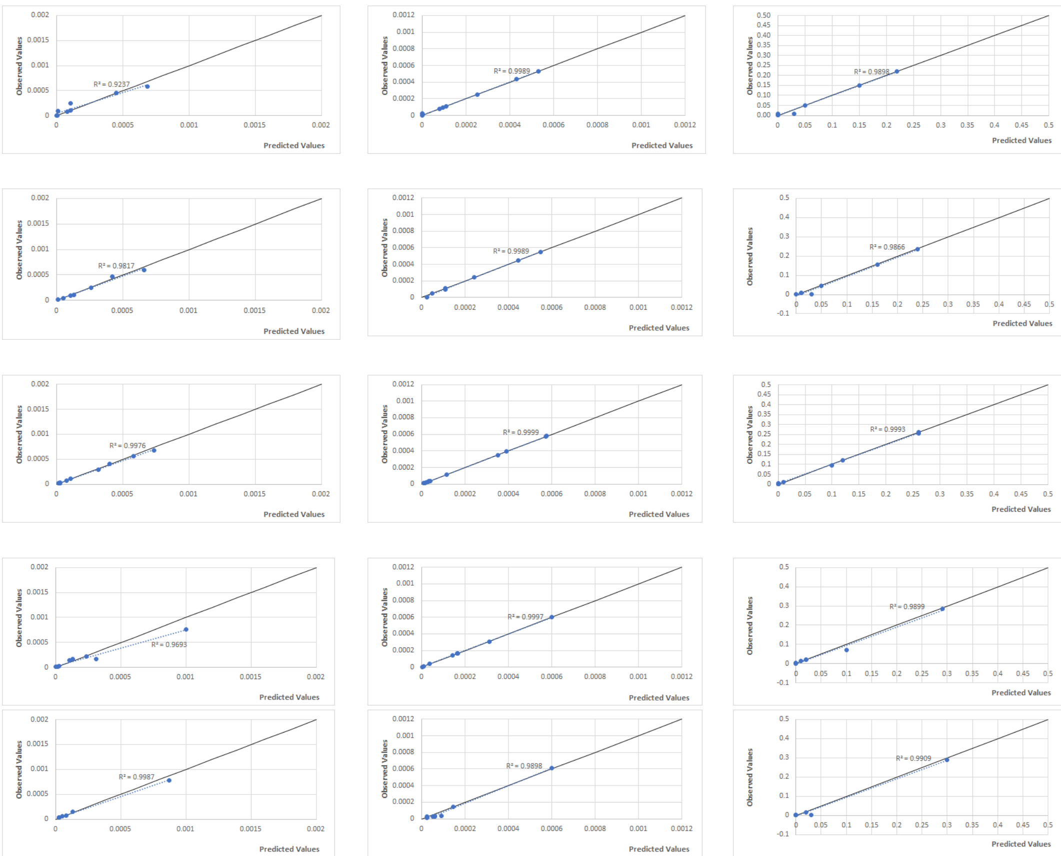

Fig. 7. Scatter plots of observed and predicted values for a) 22 Dec 2019, b) 19 Jan 2020, c) 10 Jan 2020, d) 8&9 Dec 2019, e) 1 Dec 2019, f) 7 Dec 2019, g) 18 Jan 2020, h)20 Jan 2020, i) 16 Jan 2020 and j) 22 Feb 2020 storm events.

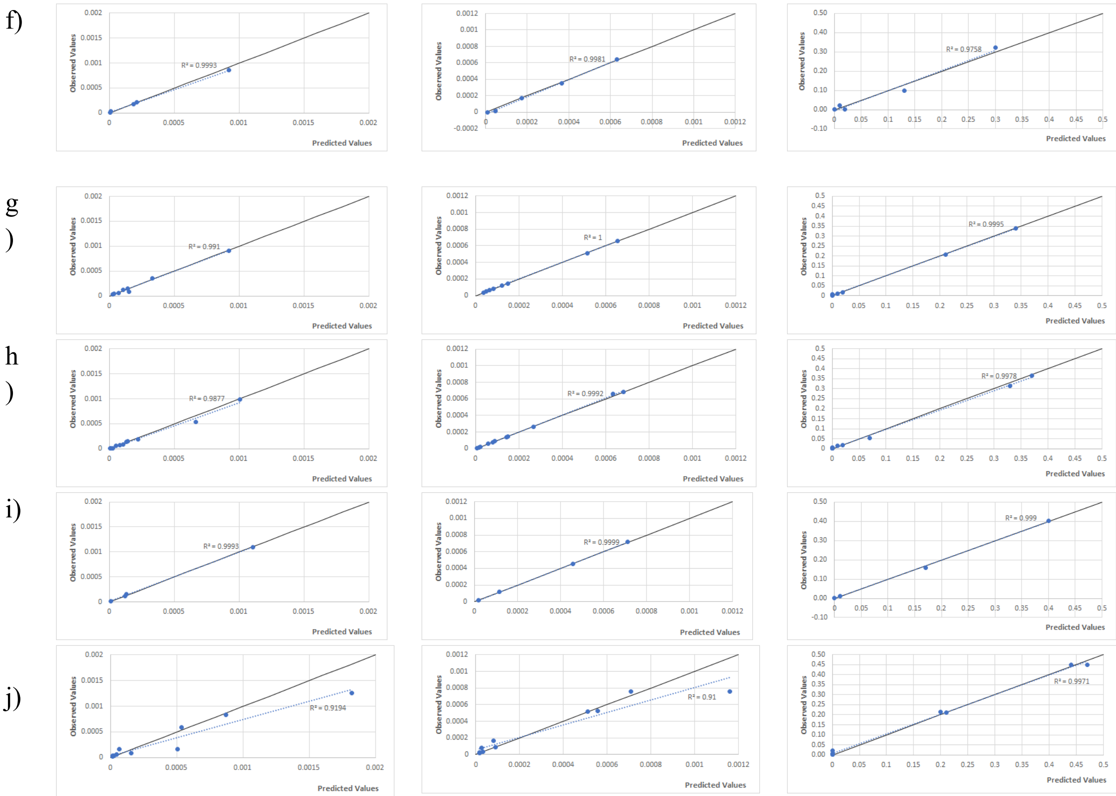

Fig. 7. (Continued).

3. Results and Discussion

With the confidence gained from the K-S tests, the calibrated SWMM model is then applied to investigate the impacts of other outlet sizes. Two pipeline sizes bigger than the current setup (0.050m) are 0.055m and 0.063m are selected for being readily available in the market (following the recommendation in Ref. [15]). Outflow and water level hydrographs as a result of the three outlet sizes are plotted in Fig. 8. Outlet size does not influence the inflow, but inflow hydrographs are plotted along. Generally, it is observed the bigger the size of outlet, the faster the release of water from the tank. As such, the outflow and water level values decrease with the enlarging outlet sizes.

Based on the sub-figure of inflow/outflow plot, the difference of peak inflow and peak outflow is termed the attenuation. Attenuation is an indication of how well a system could detain water, in which the greater the attenuation, the greater detention could be achieved. Based on the sub-figure of water level plot, the level could be used to calculate the detention volume of water in the tank because of the fixed and known geometry of the precast concrete modular units.

In order to better gauge the effectiveness of the outlet sizes, the authors are referring to the two parameters, namely the attenuation (Fig. 9) and detention volume (Fig. 10). Discussion of their suitability is therefore based on the two parameters as selection criteria.

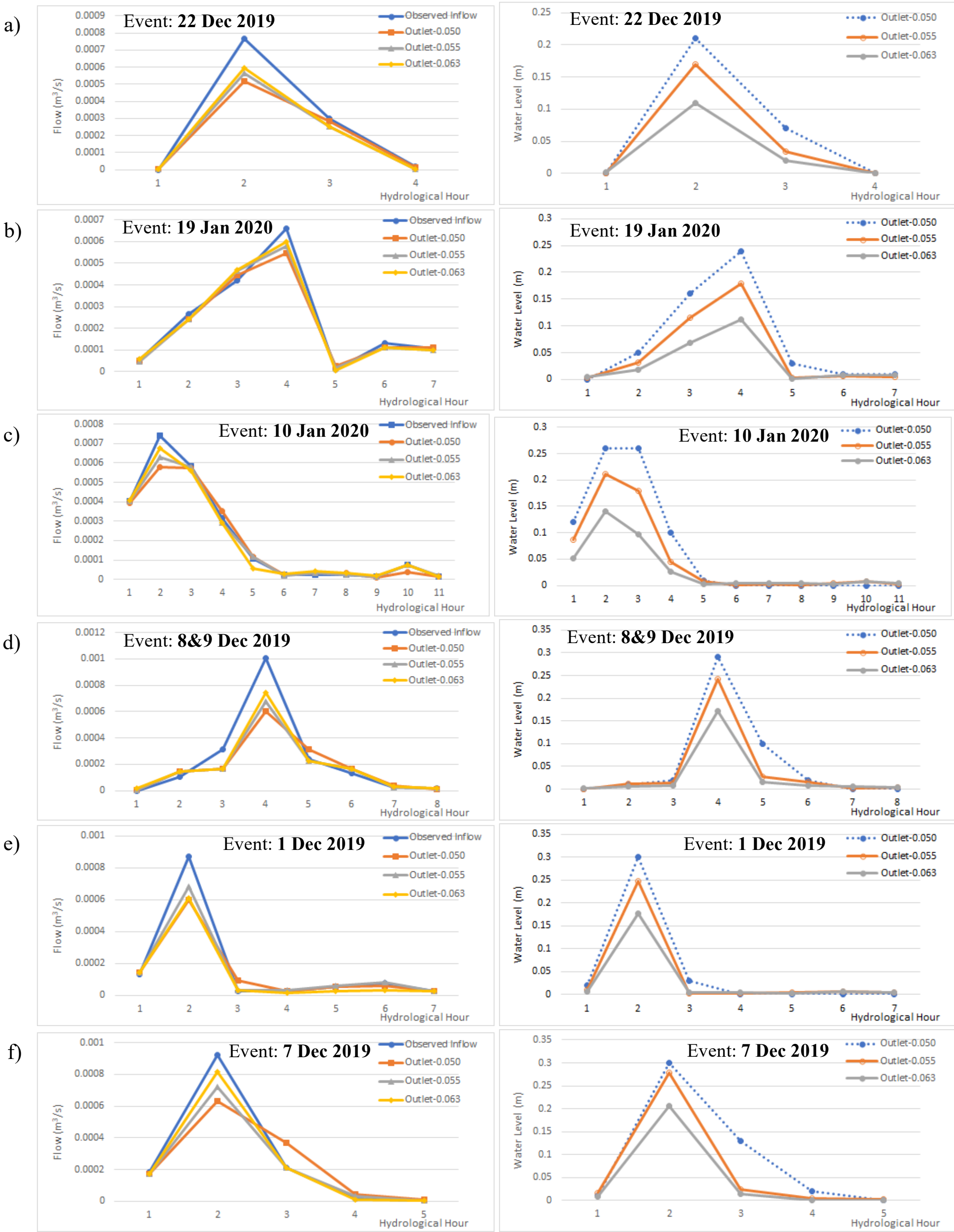

Fig. 8. Modelling outputs of outlets for a) 22 Dec 2019, b) 19 Jan 2020, c) 10 Jan 2020, d) 8&9 Dec 2019, e) 1 Dec 2019, f) 7 Dec 2019, g) 18 Jan 2020, h)20 Jan 2020, i) 16 Jan 2020 and j) 22 Feb 2020 storm events.

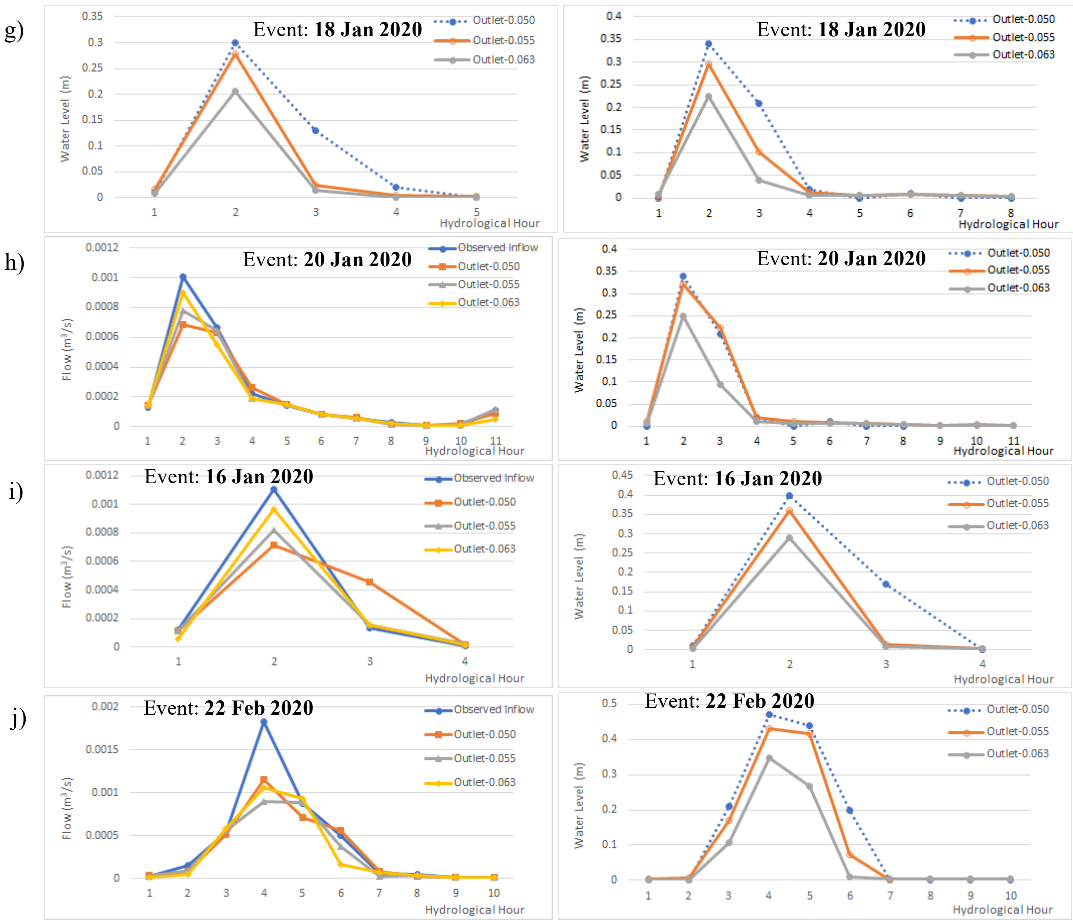

Fig. 8. (Continued).

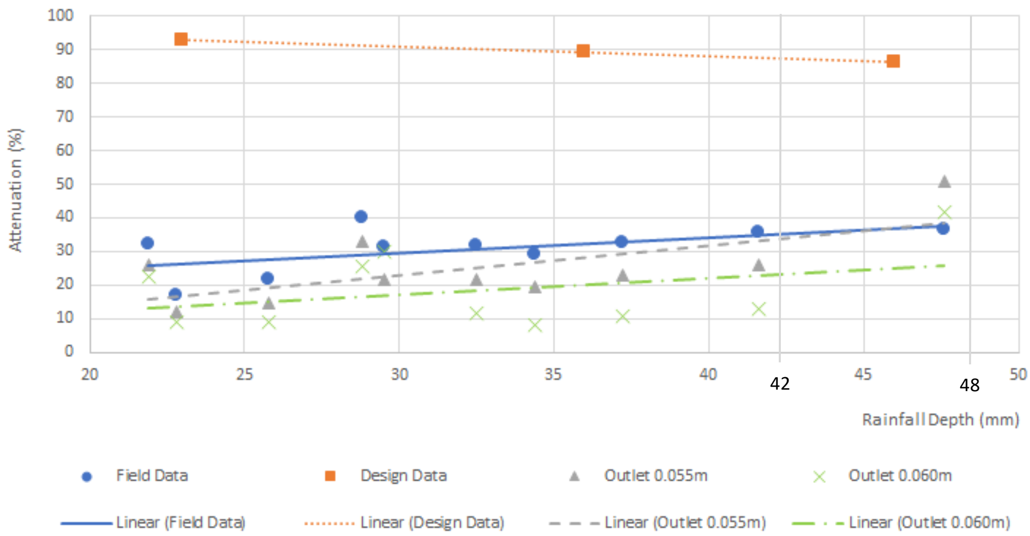

Fig. 9. Relationships of rainfall depth and attenuation according to outlet sizes.

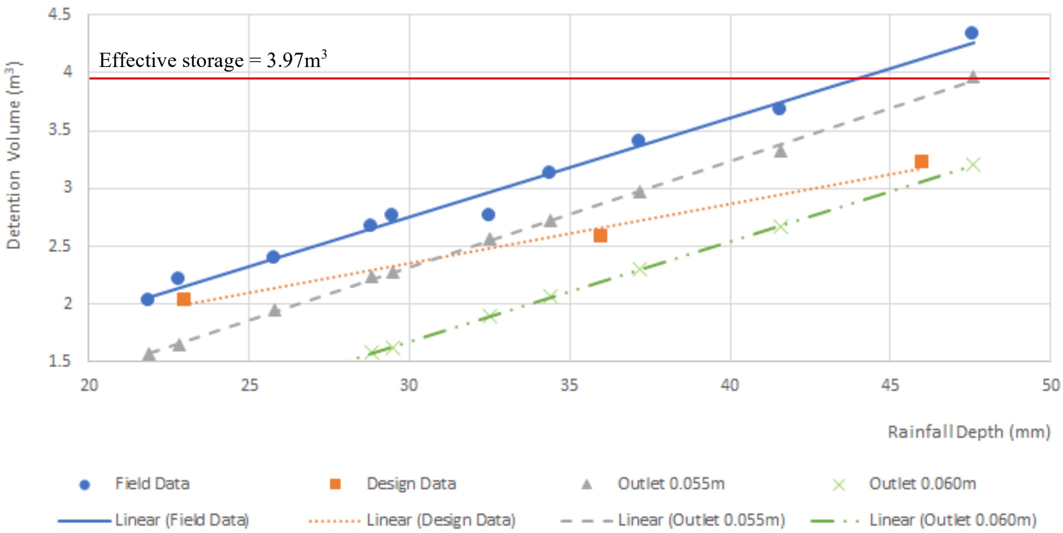

Fig. 10. Relationships of rainfall depth and detention volume according to outlet sizes.

3.1 Attenuation

Fig. 9 is bounded to the field test setup that is subjected to different rainfall depths and outlet sizes. Design data (of 5-minute storm duration under the intensity of 10-year ARI) are estimating attenuation of between 80-90% which is apparently an overestimation. The difference is due to the computation assumption made in the design rainfall, in which the estimated design rainfall is assumed to be constant throughout the short storm duration that resulted in higher inflow. Such a phenomena does not exist in actual rainfall that observed a lower inflow. This lower inflow causes the attenuation values for cases of the three outlets.

Despite this, the design data plotted in the figure illustrates that the attenuation rates decrease with the increase of rainfall depths. Theoretically, the higher the rainfall depth, the higher the water level and detention volume. This causes the peak of outflow to increase and, subsequently, the attenuation rate to decrease. A decreasing pattern is portrayed by the design data plot that is taken as the theorized pattern. The authors would like to point out that the decreases are small as the data are tightly ranged between 80-90%.

On the other hand, the plots from the three inlet sizes seem to portray an opposite pattern compared with the design data. The authors are going to discuss below the outputs separately according to outlet sizes. Firstly, we look at the field data with the circular markers. Ignoring the trendline, the data are also tightly ranged between 20-30%, a characteristic similar to the design dataset. More circular points are found to be centered around 30%.

Secondly, the predicted values for the outlet size of 0.055m are presented in triangular markers. A repeated pattern from the field data could be observed, in which the data are tightly ranged between 10-20% with more of its triangular markers concentrated around 20%. The authors would like to mention that there is an attenuation point that may be over-estimated at rainfall depth of 48mm. This point has caused the trendline to incline upward instead of the expected downward trend.

Thirdly, the predicted values for outlet size of 0.060m are presented in x markers. It can be said that the data are tightly ranged between 10-20% but centered more around 10%. The attenuation point at rainfall depth of 48mm is predicted higher and secluded from other points. Similar to the second scenario above, this point has caused the trendline to incline upward from left to right.

As such, the authors deduce that the trendlines are only for crude references. The outputs for the three outlet sizes are based on actual rainfall with varied intensity. It is different from the constant design rainfall. Therefore, the output plots are more scattered than the design data. Furthermore, the trait of tightly ranged data produced by the current field test setup may make it difficult to discern a clear upward or downward trend within the scattered plot. The general patterns still bear resemblance to the theorized pattern.

The attenuation point at 48mm above is referring to the 22 Feb 2020 storm event. Together with the 16 Jan 2020 storm (point at 42mm), these two are the only heavy rainfall events (more than 40mm) that coincided with the 2019/2020 Northeast Monsoon season that the research team managed to collect. The authors assume the two storm events as extreme events. It is a limitation of this study for having only two extreme events and the shortcoming is reflected in the trendlines. Having a few more points (more than 40mm) would have improved the trendlines. However, the authors can only continue to collect field data in the following 2020/2021 Northeast Monsoon season in hope of supplementing the analysis.

3.2 Detention volume

Fig. 10 is also bounded to the field test setup but subjected to different rainfall depths and detention volumes. The design data are estimating 2-3.2m^3 detention volumes that are underestimated compared to observed field data. The field data are found ranging from 2-4.3m^3 due to higher observed water levels.

Taking the effective storage volume of 3.97m^3 in mind, there is one point (22 Feb 2020 storm event) that is found exceeding the effective storage volume, namely the overtopping event. By enlarging the outlet size to 0.055m, this small 0.005m increase (compared to field test) has the detention volume lowered and contained. By enlarging the outlet further to 0.063m, the 0.013m increase (compared to field test) has a drastic drop of detention volume to below the design data. As such, the 0.063m outlet would result in the smallest detention volume making it again the least favorable choice.

4. Conclusion

This work is realized with the field data and computer simulation model. Based on the principle that the SWMM model is mimicking well the actual behaviors of a multi-chamber stormwater detention system, investigation into the three outlet sizes is successfully carried out. The results show that the 0.055m outlet gives reasonable performance in withstanding rainfall depths between 20-45mm which are equivalent to 5-, 10- and 15-min 10-year ARI design rainfall. Unfortunately, it is too near the limit of the effective storage volume for rainfall depth over 45mm. In the absence of a better solution, the 0.055m outlet appears a more subtle choice than the 0.063m one under a consideration on attenuation.

Acknowledgement

The authors acknowledge the financial support from the Post-Graduate Research Grant Scheme (Project ID F02/PGRG/1911/2019) rendered by Universiti Malaysia Sarawak.

References

[1] Drake J, Young D, McIntosh N. Performance of an underground stormwater detention chamber and comparison with stormwater management ponds. Water 2016;8(5):211.

[2] Ronalds R, Rowlands A, Zhang H. On-site stormwater detention for Australian

development projects: Does it meet frequent flow management objectives. Water Science and Engineering 2019;12(1):1-10.

[3] Shamsudin S, Dan'azumi S, Aris A, Yusop Z. Optimum combination of pond volume and outlet capacity of a stormwater detention pond using particle swarm optimization. Urban Water Journal 2014;11(2):127-36.

[4] Muschalla D, Vallet B, Anctil F, Lessard P, Pelletier G, Vanrolleghem PA. Ecohydraulic-driven real-time control of stormwater basins. Journal of Hydrology 2014;511:82-91.

[5] Lucas WC, Sample DJ. Reducing combined sewer overflows by using outlet controls for green stormwater infrastructure: Case study in Richmond, Virginia. Journal of Hydrology 2015;520:473-88.

[6] Kong F, Ban Y, Yin H, James P, Dronova I. Modeling stormwater management at the city district level in response to changes in land use and low impact development. Environmental Modelling and Software 2017;95:132-42.

[7] Zhang R, Zhou WB, Li J, Yu SL. Field evaluation of an innovative stormwater treatment device – the Stormvault™ system. Environmental Monitoring and Assessment 2010;169:113-23.

[8] Madarang K, Kang J-H. Accuracy of a stormwater monitoring program for urban landuses. Water Environment Research 2013; 85(9):815-22.

[9] Drumond PDP, Moura PM, Coelho MMLP. Comparison the monitoring data of an on-site stormwater detention (OSD) and the results in the use of theoretical methods for its design. Brazilian Journal of Water Resources 2018;23:e18.

[10] Ngu JOK, Mah DYS, Bong CHJ. Flow characteristics of individual lot stormwater detention. Water Practice and Technology 2016;11(4):721-7.

[11] Ngu JOK, Mah DYS, Liow CV, Ngu IT. Modelling of on-site stormwater detention underneath a car porch. International Journal of Innovative Technology and Exploring Engineering 2019;8(12):4304-7.

[12] Mannan MA, Bateni N, Teo DCL, Mah DYS, Putuhena FJ, Ng CK, Bustami RA, Ibrahim WHW, Lee CLF, Lim HL. System and method of green pavement (Patent application number PI2016704420). Kuala Lumpur: Malaysian Intellectual Property Corporation; 2016.

[13] Mah DYS. Potential of road subsurface on-site stormwater detention system. Kota Samarahan: Universiti Malaysia Sarawak Publisher; 2016.

[14] Liow CV, Mah DYS, Malek MA. Flow characteristics of StormPav green pavement. International Journal of Innovative Technology and Exploring Engineering 2019;8(8):1288-92.

[15] Drumond PP, Ball JE, Moura P, Coelho MMLP. Are the current on-site stormwater detention (OSD) policies the best solution for source control stormwater management? A case study of Australian and Brazilian cities. Urban Water Journal 2020;17(3):273-81.

[16] Public Utilities Board of Singapore. Technical guide for on-site storm water detention tank systems. Singapore: National Water Agency; 2010.

[17] Department of Irrigation and Drainage Malaysia. Urban stormwater management manual for Malaysia. Kuala Lumpur: Percetakan Nasional Malaysia; 2012.

[18] Mah DYS, Ngu JOK, Taib SNL, Mannan MA. Modelling of compartmentalized household stormwater detention system using SWMM5. International Journal of

Emerging Trends in Engineering Research 2020;8(2):344-9.

[19] Liow CV, Mah DYS, Mohd Arif Zainol MRR. Modelling of StormPav green pavement with Storm Water Management Model and InfoWorks Collection System. International Journal of Recent Technology and Engineering 2019;8(2):1449-52.

[20] Liow CV, Mah DYS, Malek MA. Modelling of StormPav green pavement system using Storm Water Management Model and SolidWorks Flow Simulation. International Journal of Recent Technology and Engineering 2019;8(2):4673-9.