SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V13I8P130

Volume 13 Issue 8, 519-525, August 2026

Short Communication

Modelling of Stormwater Detention Pond Outlet for Dry and Wet Seasons

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Received: 13 April 2026 Revised: 11 June 2026 Accepted: 12 August 2026 Published: 31 August 2026

Abstract *- Existing large stormwater detention pond outlets are designed to cater for high flow, for example, due to 100-year ARI design storms. As such, the outlets are usually large, which are unable to detain smaller storms. To improve the outlet design to have dual function to sustain both small and extreme storms, a new outlet design is proposed with two separate orifice openings within a single outlet. An early investigation was conducted by applying a case study, in which a real-life detention pond was selected and simulated in Storm Water Management Model embedded with scenarios of existing outlet with 0.45 m diameter orifice opening, and another with proposed 0.1 m diameter orifice opening before the existing orifice. The model was run through with 10-year ARI design storm according to the local equatorial climate. The modelled outflow indicated that the existing orifice produced a peak of 0.35 m^3/s, while the new orifice was found to succeed the existing orifice to produce 0.03 m^3/s, a ten times reduction. Further comparison between the two outlet designs, improvement to the detention capability was obtained, to mention a few parameters: delayed time to peak from 40 minutes by existing orifice to 60 minutes by new orifice and expanded hydrograph base time from 6 hours by existing orifice to 12 hours by the new orifice. The modelling efforts indicated that the smaller orifice to augment the existing orifice would achieve better stormwater control objectives in detaining the urban runoff on site.*

Keywords *- Nature-based solutions, Orifice Plate, Sustainable Development, SWMM, Urban runoff.*

1. Introduction

Stormwater outlet is commonly designed as one fixed size. A significant research gap exists, and this paper describes the modelling efforts of introducing two distinctive opening sizes at a single outlet in a large stormwater detention pond. The objective is to illustrate the initial findings on the impact of the mentioned outlet for smaller storms.

In the urban environment, the surface runoff is directed to go through a series of pits and tanks, both above or below land surfaces. These manmade stormwater facilities are designed to temporarily store the runoff and control the rate at which it is discharged to the civil drain [1, 2]. In most site drainage systems, the lowest point of the system is the discharge control pit, from where stormwater leaves the site [3]. On one of the pit's side walls is an orifice plate that controls the discharge rate, as in Figure 1.

For a large pond or storage structure, it could be designed to sustain flow produced by 100-year Average Recurrent Interval (ARI) design storm [4] from which the Permissible Site Discharge (PSD) could be determined [5]. The PSD value is taken as the target outflow.

Fig. 1 Example of stormwater detention pond, inlet depicts the pond outlet with a multiple-orifice plate

It should be noted, 100-year ARI design storm don't happen often. The day-to-day storms are usually nearing the intensities of 10- to 20-year ARIs. That one determined orifice size may function to its design occasionally, while most of the time, under-performed due to its large size, in which normal storms just flow through with little control.

It is rare to have two orifice plates in a single pond outlet. It is timely to modify the existing design as a way to combat climate change which there are reports of forecasting more and more small-intensity storms in the equatorial region [6].

This novel new pond outlet design is equipped with side-by-side a minimal opening for dry seasons with smaller storms and a maximum opening for wet seasons with extreme storms.

2. Materials and Methods

The methods used to materialize this study involved three components, as presented in Figure 2. It started with the determination of rainfall data. Next, a real-life stormwater detention pond was identified as study area. The rainfall and pond data were then simulated using Storm Water Management Model (SWMM) to obtain the pond's flow processes from rainfall to runoff. The outputs from the modelling effort were the pond's water profiles and associate stage and flow hydrographs.

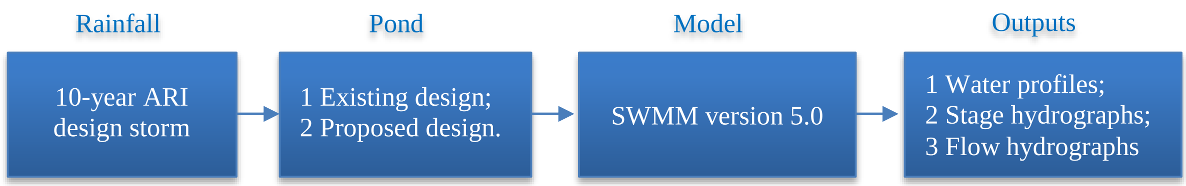


Fig. 2 Flowchart of methods

2.1. Rainfall

A local study was conducted in December 2019 to collect field hourly rainfall data at Kota Samarahan. The total rainfall for the month was recorded at 687.3 mm. It was found that out of 58 storm events, 91% of the storms were below 20 mm while 9% were above 20-40 mm.

Drainage engineers in Malaysia are referring to a local guideline named Urban Stormwater Management Manual in Malaysia or *Manual Saliran Mesra Alam* (MSMA) [7]. In the design of stormwater facilities, the rainfall depths considered are much higher, taking into account of safety factor and weather adversity. Rainfall depths of Kota Samarahan, Sarawak was calculated at 62.8 mm for a 30-minute duration, 10-year ARI and 96.3 mm for a 30-minute duration, 100-year ARI design storms.

2.2. Study Area

The stormwater detention pond selected as study area was located at the campus of *Institut Kemajuan Desa*, Kota Samarahan. Such a real-life and functioning pond allowed for a realistic representation of the pond in the computer simulation environment [8], which was described in the subsequent sections.

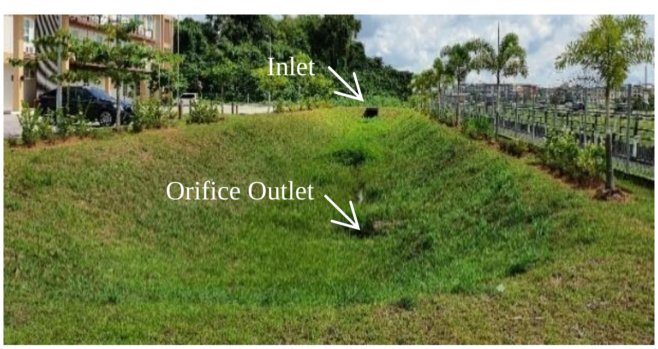


Fig. 3 Selected stormwater detention pond as study area

The pond, as depicted in Figure 3, had a dimension of 80 m in length, 10 m in top width and 1.98 m in depth. It was designed with a storage volume of 1,050 m^3 to receive runoff from a catchment of 27,800 m^2. The time of concentration, t_c, which was the time needed for the runoff to travel from the furthest point to the pond, was calculated as 30 minutes. This was the reason the afore-mentioned design rainfall depths were based on storm duration of 30 minutes.

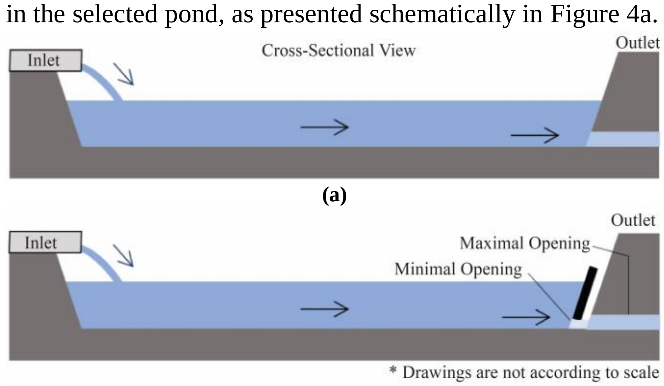
2.3. Pond Outlet Design

Outlet of the stormwater detention pond is usually designed as orifice, which is installed at the bottom of the outlet. This is meant to release all the captured runoff so that the pond would remain dry after a storm. It could be calculated using Bernoulli's principle [9], as in Equation 1:

$$Q_o = C_d A_o \sqrt{2gH_o} \quad (1)$$

Where,
Q_o = flow rate after orifice (m^3/s);
C_d = discharge coefficient (unitless)(0.65);
A_o = area of orifice opening (m^2);
g = standard acceleration (m/s^2)(9.81 m/s^2);
H_o = depth from water surface to the centroid of orifice (m).

When subjected to 96.3 mm (30-minute, 100-year ARI) design storm, to meet the required PSD of 0.4 m^3/s which the value was substituted as Q_o, the orifice diameter was calculated at 0.45 m. This was the existing size of orifice outlet in the selected pond, as presented schematically in Figure 4a.



(b)

Fig. 4 Schematic drawings of stormwater detention pond, its inlet and outlet, a) existing design and b) proposed outlet design.

Refer to the local study, all the 58 storm events which were recorded up to 40 mm only shall have its runoff flowed through the 0.45 m orifice unbothered. As such, a smaller diameter could help to detain the resulting runoff.

The intensity of 10-year ARI design storm was the standard benchmark for minor urban stormwater design. When subjected to a 62.8 mm (30-minute, 10-year ARI) design storm, the orifice diameter to sustain this storm was calculated at 0.1 m, which was arranged in front of the existing orifice, as in Figure 4b.

2.4. Model Building

SWMM version 5, or SWMM5, was developed by the United States Environmental Protection Agency (US EPA). The software was repeatedly proven for its performance in simulating urban stormwater systems [10].

The developed model simulating the campus of *Institut Kemajuan Desa* and its 80 m long detention pond is presented in Figure 5.

There were six SWMM5 components involved. Component 1, Rainfall, was the interface which design storm data was input. The rainfall was applied on Component 2, Catchment, to imitate the process of runoff generation. SWMM applied a nonlinear differential equation of sheet flow based on catchment characteristics [11], as in Equation 2:

$$Q_c = W \frac{1.49}{n} (d - d_p)^{5/3} S_c^{\,1/2} \qquad (2)$$

where,
Q_c = flow rate from catchment (m^3/s);
W = catchment width (m);
d = depth of water over the catchment (m);
d_p = maximum depression storage (m);
S_c = catchment slope (m/m).

The runoff from each catchment was injected to the nearest Component 3, Node. The nodes were connected by Component 4, Link to form a drainage network.

The runoff was routed from node to node until it reached Component 6, Outfall via dynamic wave approximation [12], as in Equation 3:

$$Q_r = \frac{\partial A_c}{\partial t} + \alpha m A_c^{(m-1)} \frac{\partial A_c}{\partial x} \qquad (3)$$

Where,
Q_r = routed flow rate (m^3/s);
A_c = cross-sectional area of the conduit (m^2);
x = distance along the flow path (m);
∂t = time step (s);
α = flow geometry due to the conduit (unitless);
m = surface roughness of conduit (unitless).

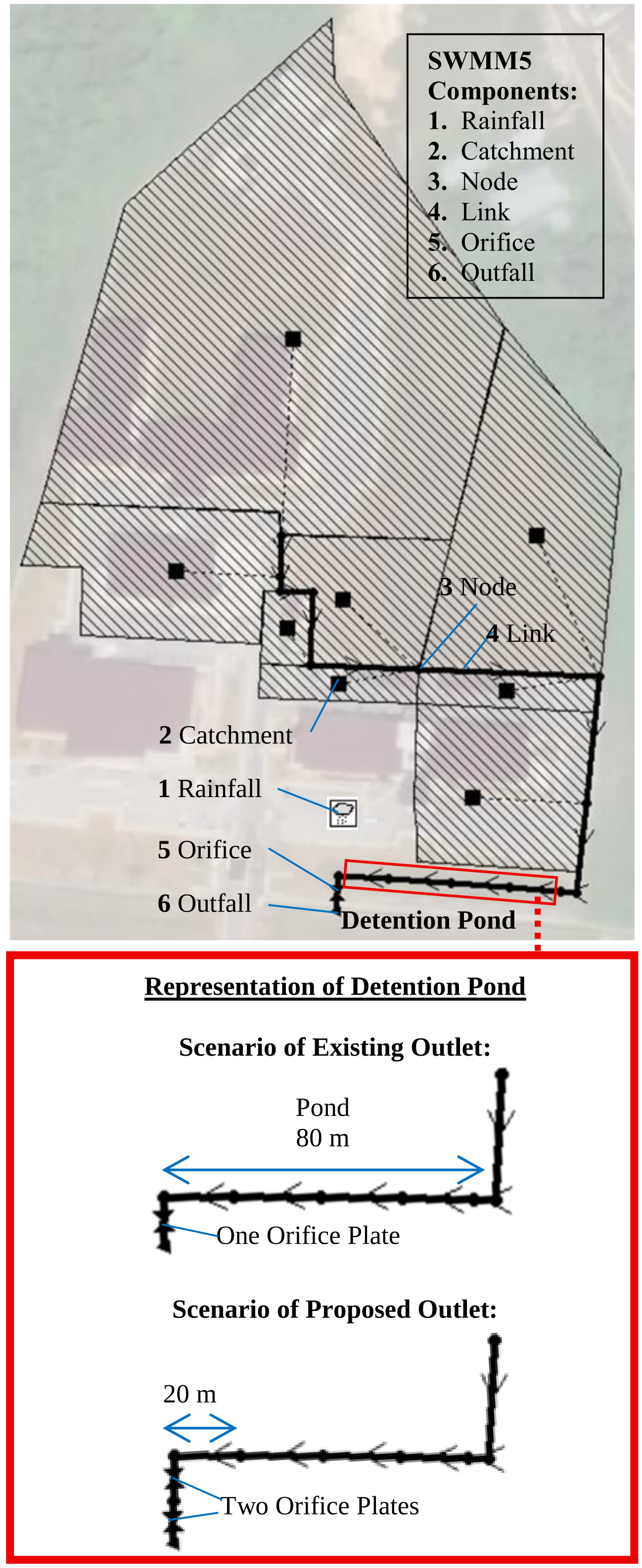


Fig. 5 Developed SWMM5 model for stormwater detention pond with scenarios of one and two orifice plates.

Due to the nature the selected detention pond appeared like long earth trench, the pond was modelled as nodes and links. There were two scenarios of pond outlet which one followed the existing design with one orifice plate with 0.45 m diameter opening, and another represented the proposed outlet with a new orifice plate of 0.1 m diameter opening in front of the existing opening.

2.5. Consistency Check

The modelled flow rates, especially those after the orifice were checked for its consistency. SWMM5 model applied the stated dynamic wave approximation in Equation 3, to route the flow hydrographs through the 0.1 m diameter orifice opening. The modelled flow data was compared to calculated flow data from Equation 1. The scattered plot of modelled and calculated flows is presented in Figure 6.

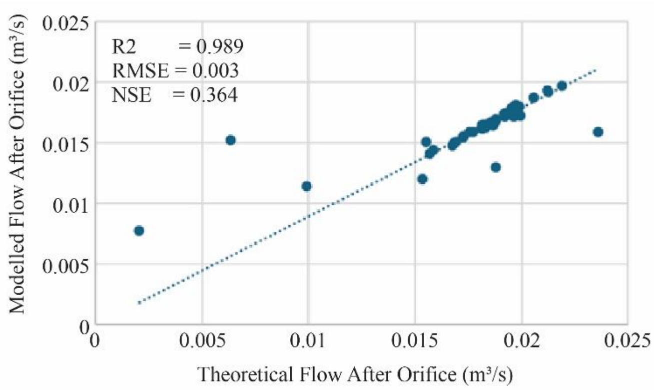


Fig. 6 Consistency check on modelled flow data

Three statistical indices were used to evaluate the matching of datasets, namely coefficient of determination, R^2, Root Mean Square Error (RMSE) and Nash Sutcliffe Efficiency (NSE). Both R^2 and NSE values, which equal to 1, indicated a perfect fit [13, 14]. Contradictorily, an RMSE value equals to 0 indicated perfect fit [15].

The datasets of modelled and calculated flow data produced R^2 of 0.989, which indicated strong linear relationship as demonstrated by the data points above 0.015 m^3/s lied very near the regression line. RMSE was found at 0.003, which represented the average distance between the data points with a range of 0.002 to 0.023 m^3/s.

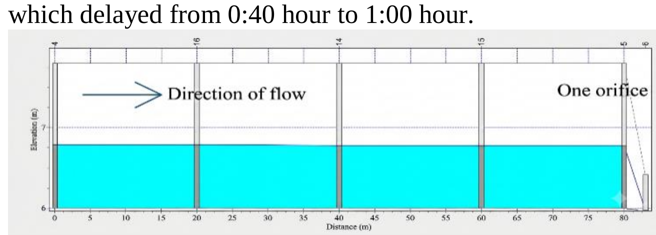
NSE was 0.364, which classified as unsatisfactory due to outliers for flow below 0.015 m^3/s. These happened when the pond stage readings were slightly above 0.1 m high, while the orifice opening diameter was 0.1 m, which caused the bias.

3. Results and Discussion

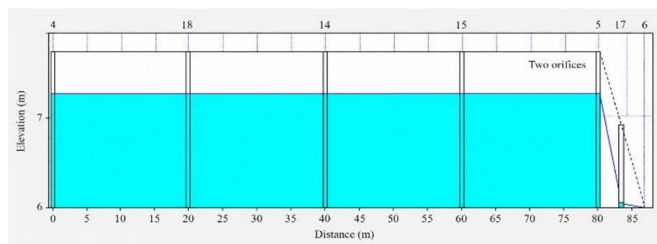
Only the 10-year ARI design storm was run for 6 hours through the developed SWMM5 model with existing and proposed outlet designs. The resulting water profiles, stage and flow hydrographs which associated with the detention pond in response to the two scenarios of pond outlet, were compared.

3.1. Longitudinal Water Profiles

With the orifice, the hydraulic structure would cause a hike of pond stage upstream of the orifice. This phenomenon was simulated in the longitudinal water profiles of the selected pond, as presented in Figure 7. The existing outlet, with 0.45 m diameter orifice opening, caused 0.79 m of peak pond stage, which occurred at 0:40 hour. Its water profile is depicted in Figure 7a. The next scenario, with a proposed 0.1 m diameter orifice opening before the existing outlet, the runoff was directed to flow through the smaller outlet dominantly. It was found to cause 1.29 m of peak pond stage, which occurred at 1:00 hour. The resulted water profile is depicted in Figure 7b. Compared to the existing outlet, the new outlet increased the pond stage by 59%, indicating that a larger volume of runoff was detained in the pond. It was evident in the time to peak, which delayed from 0:40 hour to 1:00 hour.



(a)

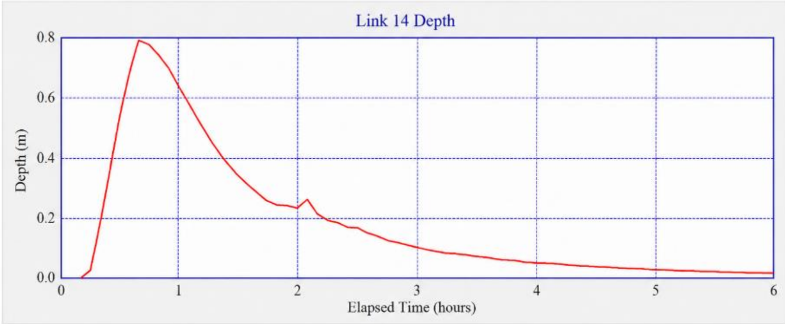


(b)

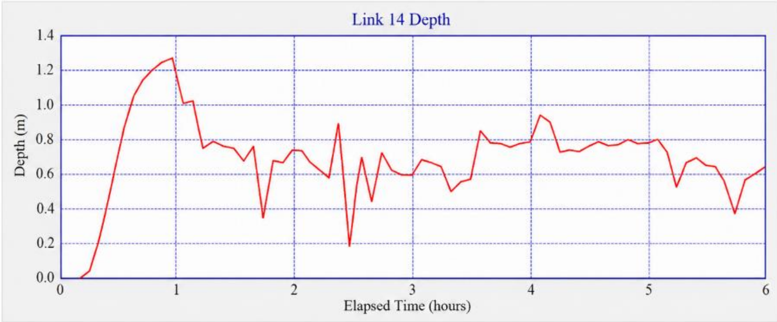
Fig. 7 Peak water profiles in the detention pond when subjected to 10-year ARI design storm, restricted by (a) existing one orifice opening (0.45 m) and (b) two orifice openings (0.1 m, followed by 0.45 m).

3.2. Pond Stage Hydrographs

Other than the water profiles, the associated pond stage hydrographs could reflect the characteristics of water filling and draining in the pond. These are presented in Figure 8. In the scenario of existing outlet, the pond stage hydrograph before the orifice, as depicted in Figure 8a, had a smooth bell-shaped hydrograph. The lag time was 25 minutes (design storm peaked at 15 minutes while, in this case, the stage hydrograph peaked at 40 minutes). The hydrograph base was spanning for 6 hours. In the next scenario, when the 0.1 m diameter orifice opening was imposed, the resulted pond stage hydrograph appeared differently than the previous scenario, as depicted in Figure 8b. The restriction of the 0.1 m diameter orifice, not only hiked up the peak pond stage, also increased the lag time to 45 minutes (design storm peaked at 15 minutes, while, in this case, the stage hydrograph peaked at 60 minutes). The hydrograph base was spanning for 12 hours. The falling limb of the stage hydrograph appeared with pro-long zigzag patterns, which signified variable storage releases induced by the head-depending orifice flows.



(a)



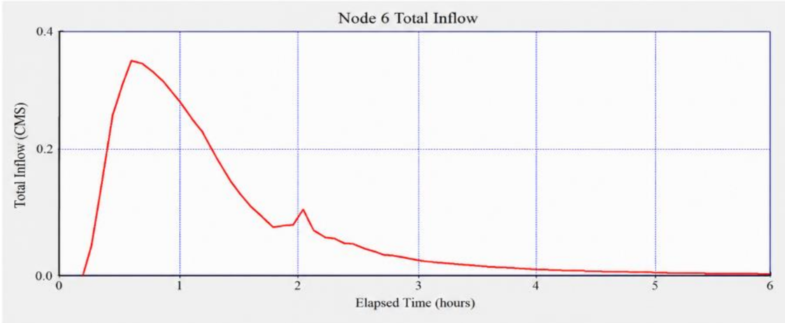
(b)

Fig. 8 Stage hydrographs before outlet for 6 hours after 10-year ARI design storm, restricted by, a) existing one orifice opening (0.45 m), and b) two orifice openings (0.1 m, followed by 0.45 m).

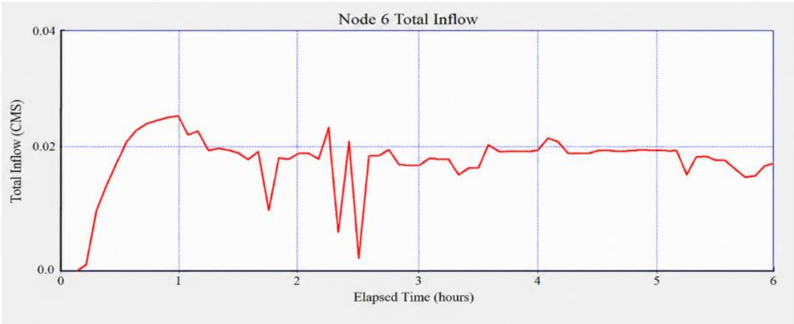
3.3. Flow Hydrograph at Outfall

The outflow hydrographs are presented here to illustrate the system-wide detention performances. The outflow patterns are presented in Figure 9.

It should be noted the detention pond was placed there to meet the objective of stormwater quantity control with a target PSD of 0.4 m^3/s.



(a)



(b)

Fig. 9 Flow hydrographs at outfall for 6 hours after 10-year ARI design storm, restricted by (a) Existing one orifice opening (0.45 m) and (b) Two orifice openings (0.1 m, followed by 0.45 m).

The outflow hydrograph due to the existing outlet, as depicted in Figure 9a, was having a peak flow of 0.35 m^3/s, which occurred at 0:40 hour, spanned for 6 hours. Another outflow hydrograph due to the proposed outlet, as depicted in Figure 9b, was having even lower peak flow of 0.03 m^3/s, which occurred at 1:00 hour, spanned for 12 hours. This reduction was a staggering ten times lower than the existing outlet. Although the 0.1 m and 0.45 m orifice plates were placed side-by-side in the modelling scenario, it was obvious the 0.1 m diameter orifice opening was dominant in the shaping of outflow hydrograph in this case.

3.4. Discussion

Sizing of orifice opening has strong influence in the efficiency and practicality of stormwater storage operations [16, 17]. Comparing the two outflow hydrographs in Figure 9, a pro-long falling limb signified water storage, which such a characteristic happened only in Figure 9b, suggesting the 0.1 m orifice opening enforced stronger degree of detention than the existing orifice opening. Although the size was catering for 62.8 mm of rainfall depth (30-minute, 10-year ARI), it could detain 40–60 mm rainfall depths better. Else, with the existing orifice opening catered for 96.3 mm of rainfall depth (30-minute, 100-year ARI), the orifice could be insufficient to contain any rainfall depth below 60 mm. The existing outlet design can be adjusted [18], and the suggestion demonstrated here is to augment with another smaller orifice opening.

3.5. Limitation

The proposed outlet comes with a spill, as in Figure 4b. Should the pond stage continue to rise, the pond water shall bypass the 0.1 m orifice opening through the spill and drain to the existing 0.45 m orifice opening. Simulating this complex orifice-spill-orifice mechanism was possible, but verifying the data was unconvincing. As such, the current simulation was limited to a 10-year ARI. The next step is to develop a small-scaled prototype for laboratory testing to gather insights to the mentioned flow process.

4. Conclusion

An early investigation of having a new design of detention pond outlet, as subjected to a smaller 10-year ARI design storm, was found with improvement to exert stronger degree of stormwater detention, with prevalent 10 times reduction of peak flow beside delayed time to peak, lag time and hydrograph base time. The existing design was too large to achieve these stormwater objectives for smaller storms.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgment

The authors acknowledge the article processing charge provided by Universiti Malaysia Sarawak.

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