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Modelling for Climate Adaptation in Urban Drain Design with Orifice Flow Restrictor

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ABSTRACT

Due to the increasing stormwater runoff in urban areas, stormwater infrastructure requires modification to address the flash flooding issues. Occurrences of floodwater overflowing the urban drain have urged drainage engineers to re-look its design. Conventionally, the urban drain is designed to free flow following the provided drain slope. This paper is challenging the old design by introducing orifices into the drain. The lesser-known stormwater characteristics restricted by orifices in open drains were investigated. In this case, twenty-four units of terrace houses were selected as the study area with special attention to the 170 m front drain with a dimension of 0.5 m x 0.55 m. The drain was inserted with one to three orifices of 0.45 m diameter separating the drain into one or more compartments. Three scenarios were formulated, namely S1 with one orifice plate at 170 m, S2 with two orifice plates at 86 and 170 m, and S3 with three orifices at 50, 110 and 170 m, from the starting point. Storm Water Management Model version 5.0 (SWMM5) was utilized to simulate and represent the unique characteristics of the three scenarios subjected to a 5-minute, 10-year average recurrent interval design storm. The analysis found that S1 had similar patterns with the existing condition and therefore, was insignificant. However, S2 and S3 demonstrated improved regulation of flow and water level along the drain. Between the two scenarios, S3 repeatedly displayed the most stable patterns, for example, S3 had a tight range of water levels between 0.30-0.34 m (compared to existing condition with fluctuating water levels between 0.32-0.50 m) and a tight range of flows between 0.01-0.08 m^3/s (compared to existing condition with wider range of flows between 0.01-0.18 m^3/s). The flows in S3 were reduced by half by introducing these series of orifices. These results point to an important finding that orifices were not worsening flood flushing in open drain but capable to regulate the flow and water level better than existing condition without any orifice. The capability of orifices to lower water levels allowing more spaces within the drain channel to accommodate climate-induced floodwater.

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1. Introduction

Generally, urban drainage system in Malaysia is designed as an open drain under its hot and humid tropical climate. During rainy seasons, heavy rainfall causes urban drains to overflow. As such, urban flooding has become a regular problem. Due to the high amount of rainfall experienced in this region, wider and deeper open drains are constructed to accommodate the high volume of stormwater runoff being discharged to the drain [1,2].

On top of that, climate change in the equatorial region is projected to bring more rainfall in the years to come [3]. The weather patterns could lead to even more stormwater runoff volume going into urban drains [4,5]. In line with the current situation, stormwater infrastructure is requiring climate adaptation to solve the urban flooding issues.

A flow restrictor is rarely installed to interrupt the running water. Contrary to normal practices, this paper describes a series of orifice flow restrictors being tried as a way of climate adaptation strategy to regulate stormwater runoff. Orifice flow restrictor is also known as simply orifice or orifice plate. A modification could be done to a stretch of open drain by inserting thin plates with an orifice on each plate and thus creating one or more compartments to detain stormwater, as indicated in Figure 1. Investigation is carried out to check on its flow patterns when stormwater runoff is slowed down at the upper and middle stretches of the drain. This is envisaged to prevent water congestion at the downstream stretch.

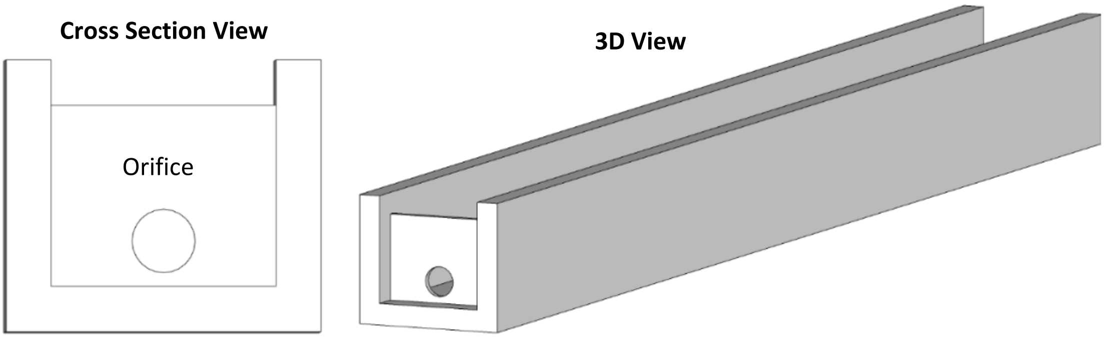


Fig. 1. Orifice flow restrictor in open drain

An orifice is an opening, usually circular in shape. It could be installed in a pipe, open channel and tank. It is used to restrict water pressure or flow volume [6]. When water is flowing through the circular orifice, there is a contraction from a larger to a smaller cross-sectional flow area [7,8]. The restriction of flow due to the orifice plate causes the water level, H, upstream of orifice to rise [9]. Referring to Figure 2(b), the flow out of the orifice is a function of the water level from water surface to the centre of orifice, H_o. The higher the H_o, the higher the orifice flow, Q_o, which is defined in Eq. (1)

$$Q_o = C_o A_o \sqrt{2gH_o} \tag{1}$$

where
Q_o = flow rate produced by orifice (m^3/s);
C_o = contraction coefficient (unitless);
A_o = cross sectional area of orifice (m^2);
g = gravity force (m/s^2);
H_o = water level (m).

In most parts of the drain channel, the Manning equation is applied which is defined in Eq. (2). Water entering the drain is a function of the channel's geometry, wall surface characteristics and slope [10]. As depicted in Figure 2(a), it is a condition allowing the water flowing according to the channel slope. With the same volume of water, the height of water produced in the free-flowing condition is expected to be relatively lower and uniform compared to the orifice-restricted condition.

$$Q_m = \frac{1}{n} A R^{\frac{2}{3}} S^{\frac{1}{2}} \tag{2}$$

where
Q_m = flow rate in the drain (m^3/s);
n = roughness coefficient (unitless);
A = cross-sectional flow area (m^2);
R = hydraulic radius (m);
S = longitudinal slope of drain (m/m).

Having more than one orifice in an urban drain is uncommon, like the one depicted in Figure 2(c). Going through the literature, it is found that the application of multiple orifices is common in a closed pipe system. Due to its closed condition, the pipe is a pressurized system. Inserting multiple orifices in the closed pipe, flowing through any of the orifices due to the contraction of flow area produces higher velocities immediately after the orifices. According to Bernoulli's principle, high-velocity results in low pressure [11]. As such, a gradual dropping of pipe pressure could be achieved along the flow path [12,13].

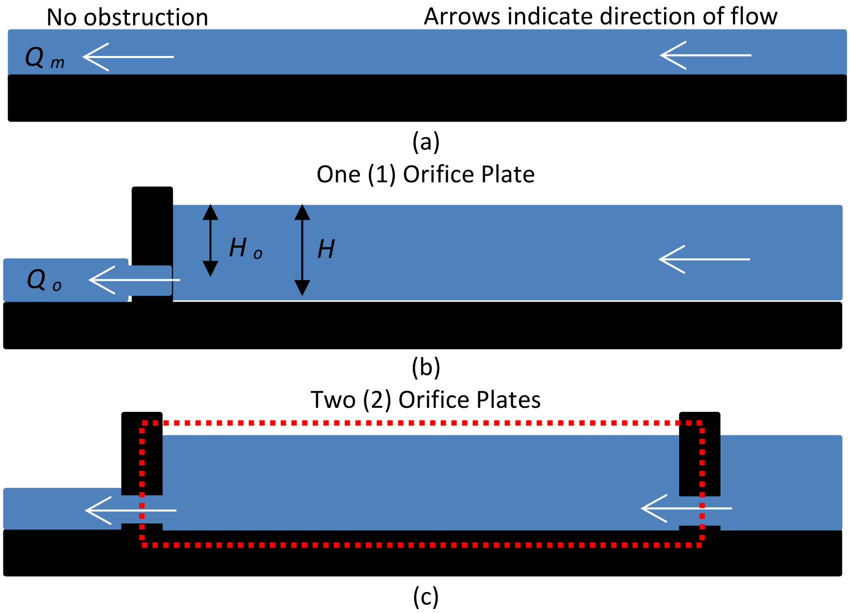


Fig. 2. Longitudinal water profiles, (a) Free flowing, (b) Flow through single orifice, (c) Flow through two orifices in series which the orifice plates create a compartment in the channel as highlighted by the dotted rectangular inset

On the other hand, urban drain as open channel is exposed to the atmospheric pressure. As such, the above-mentioned pressure dropping, which comes from high velocity created by orifices in the closed pipe system, is not repeated in the drain. In contrast, a single orifice in open channel is used to slow down the running water [14]. Reverse flow near the vicinity of the orifice has been observed in previous studies [15,16]. Referring to Figure 2(c), the part of drain encased in between two orifice plates (dotted rectangular inset) no longer functions as a normal drain, instead, it functions similar to a water draining tank. This study aims to characterise water pattern in the above-mentioned modified drain which has not been established in previous studies.

2. Methodology

Open channel and orifice subjects are parts of long-standing textbook materials of fluid mechanics. This study introduces a new concept that involves multiple orifices in an open channel which fills a critical gap in understanding and potential applications that have yet to be explored. The existing formulas pertaining to open channel and orifice are well established. Thus, running the related formulas with the aid of a computer could have reasonable water patterns through open channel and orifice being computed with high confident level [17].

A modelling software, named Storm Water Management Model version 5.0 (SWMM5), developed by the United States Environmental Protection Agency (US EPA), is a model combining hydrological and hydraulic processes, particularly through the network of urban drainage systems [18]. SWMM5 was utilised to simulate the above-mentioned water patterns. In this case, open channel and orifice were applied to build a concept of urban drainage model depicted in Figure 3. Six components are shown in the figure, and each is described in the following sub-sections.

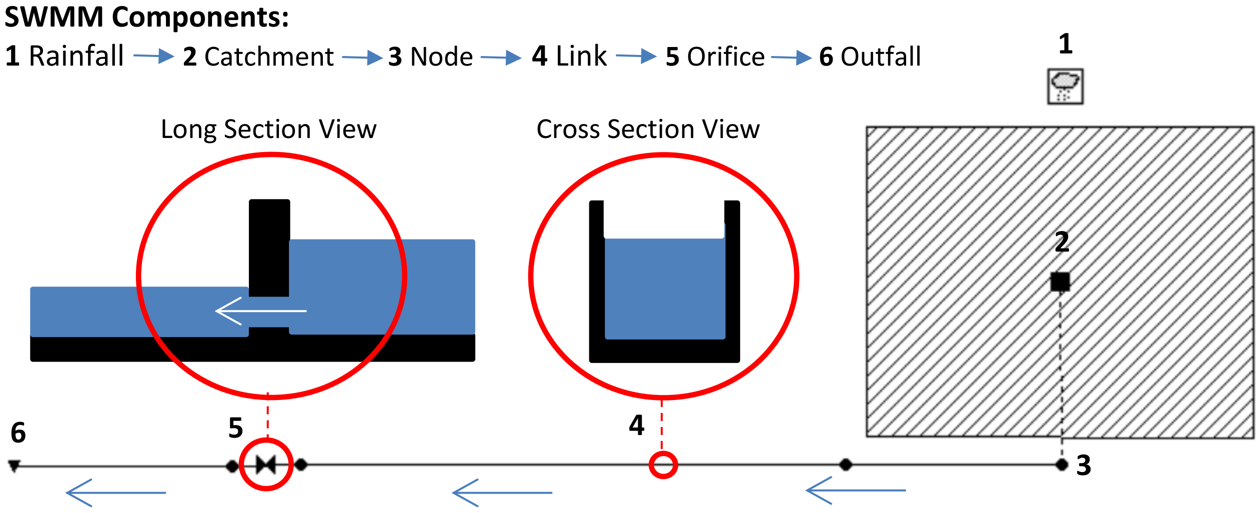


Fig. 3. SWMM model building

2.1 Rainfall

Rainfall data, stated as Component 1 in the figure, is critical to ensure a performing urban drainage system. In this case, the Malaysian and Singaporean guidelines were referred, as these neighbouring countries share similar weather patterns [19,20]. A design storm, designed to a magnitude of 10-year average recurrent interval (ARI) over a storm duration of 5 minutes, was recommended. It was estimated at 278 mm/hr in intensity or 23 mm in depth derived from local hydrological data.

2.2 Catchment

Catchment which stated as Component 2, is an area that receives the rainfall. Having a study area allows a realistic catchment condition than a hypothetical site [21]. An anonymous housing estate without any geographical significance was selected. A row of residential houses was particularly of interest that made up of two blocks of houses, twelve (12) units in each block. Measurement and observation of the site conditions were carried out that covered catchment area, width and slope, dimension of drain & its slope, materials & its possible roughness coefficients and direction of flow.

Catchments, in this case, considered the roof of each house with the front roof received and directed rainwater to the front drain while the back roof, to the back drain. The catchments also include parts of the front road and back lane that received and directed rainwater to the drains as well.

The total catchment area (twenty-four houses, front road, and back lane) was estimated at 4,945 m^2. Roof, road and drain designs are common features in a housing estate. However, the variations of these designs are different from site to site. For example, there are several roof types to choose from. Specific to the study area, the house has a gable roof measuring 6.7 m x 10.2 m that separated the front and back roofs equally. The front road was measured to have a width of 3.46 m. Meanwhile, the front and back drains were made of precast concrete pieces (with a Manning's n roughness coefficient of 0.014), measured to have a dimension of 0.5 m x 0.55 m and a drain slope of 0.1% (1 in 1000 m/m).

2.3 Drainage System

SWMM components 3 to 6 referred to as node, link, orifice and outfall, respectively, comprised of the drainage network [22]. Nodes and links are typically used to represent the stretches of urban drain. Nodes define the location, invert level and changes in the drain while links define the dimension of drain. The study area has one long urban drain in front of the selected row of residential houses, which is measured as 170 m in length. Water from the roof and road catchments were connected to nodes, as entry points to the drain. A link connected an upstream node to a downstream node, allowing the routing of water flow from node to node, until the water reached a final point, labelled as outfall. This condition could be simulated using the dynamic wave algorithm, which was conducted with a time step of 30 s using Eq. (3)

$$Q_D = \frac{\delta A}{\delta t} + \alpha m A^{(m-1)} \frac{\delta A}{\delta x} \tag{3}$$

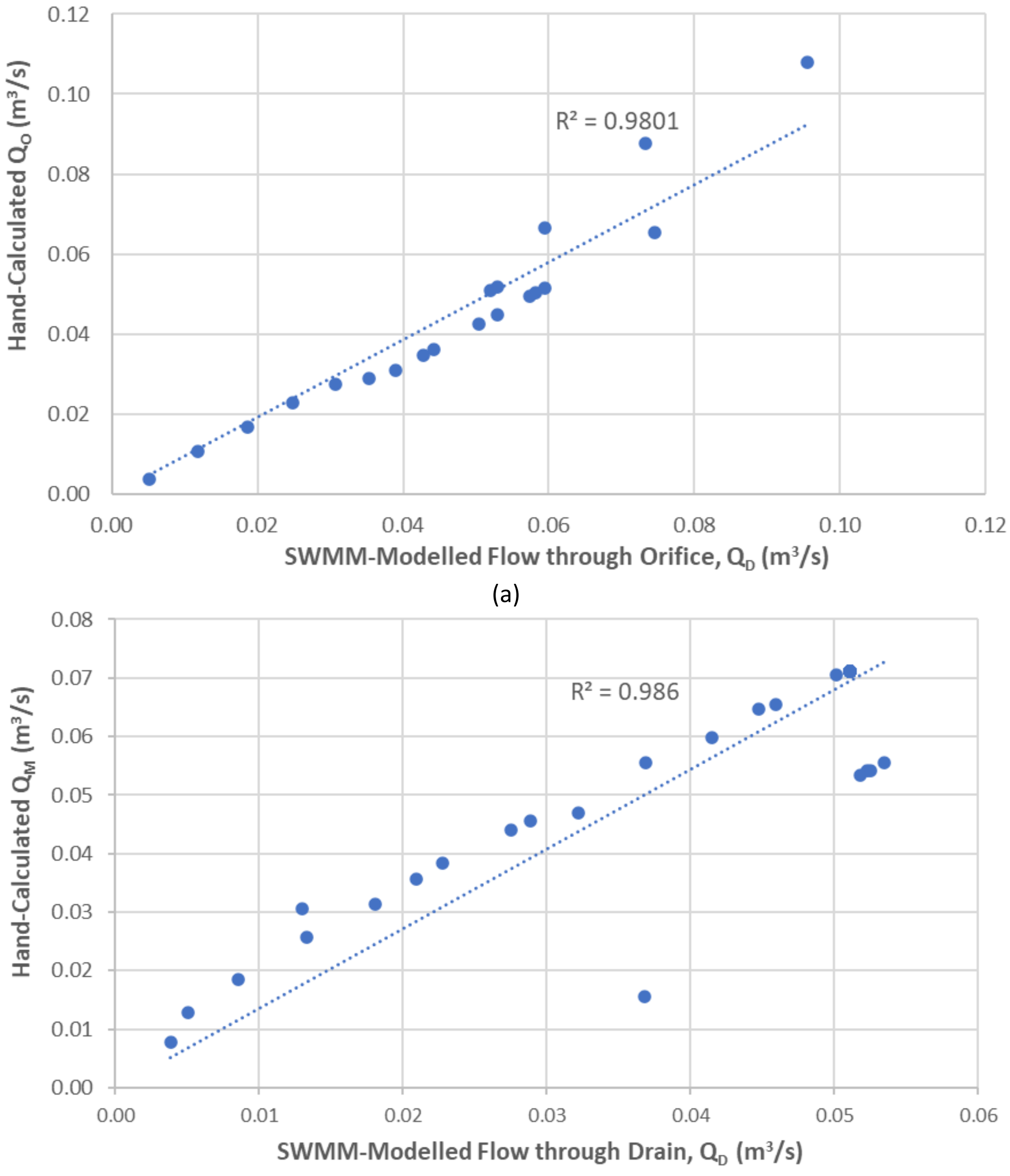
where
Q_D = Drain flow (m^3/s);
A = Cross sectional area of drain (m^2);
δt = Time step (s);
x = Distance between upstream and downstream nodes (m);
α = Flow geometry (unitless);
m = Surface roughness of drain (unitless).

Orifice, in other hand, is commonly attached to a storage unit/tank as its outlet by connecting the storage unit/tank to a downstream node. In contrary, the orifice in this study was inserted in between the nodes and links. It was achieved by connecting two nodes at the intended location instead of attaching it to a storage unit/tank. The flow routing was applying Eq. (3) as well.

The orifice applied here had a diameter of 0.45 m and a contraction coefficient of 0.65. Placement of orifice in the drain had created three scenarios, namely Scenario 1 (S1) with one (1) orifice plate was placed at the downstream end of the selected stretch of drain, Scenario 2 (S2) with two (2) orifice plates placed in the middle and end, and Scenario 3 (S3) with three (3) orifice plates placed at the downstream end of three equal-length of the selected drain. The existing condition (without orifice) was also simulated as a control.

2.4 Model Verification

Three (3) equations were presented in the previous sub-sections. SWMM simulation engine applied Eq. (3) for routing flow along the orifice and drain. Eq. (1) and Eq. (2) are the basic theories for flow through orifice and drain, respectively. These two equations were used here to verify the output of SWMM model. Plots of hand-calculated data over SWMM-modelled data are presented in Figure 4.



(a)

(b)

Fig. 4. Model verification, (a) Flow through orifice, and (b) Flow through drain

In Figure 4(a), the model exhibits a tendency to generate higher values for orifice flow. However, the scattered plots are close to the theoretical data sets. Figure 4(b) illustrates an overestimation of drain flow by the Manning equation. This was expected as the equation did not consider how the flow is affected by the orifices. The few outliers in Figure 4(b) were water patterns around the orifices that produced abrupt higher flow rates than other stretches. Nevertheless, the coefficient of determination, R^2 values derived from both the flow through orifice and drain surpassed 0.9, demonstrating the model's capacity to provide reasonable estimations for both orifice and drain flow rates [23].

3. Results

This section discusses the findings obtained from the SWMM modelling. It is sub-divided into three sub-sections which are water profiles, water level and flow along the length of drain, and water level and flow relationships.

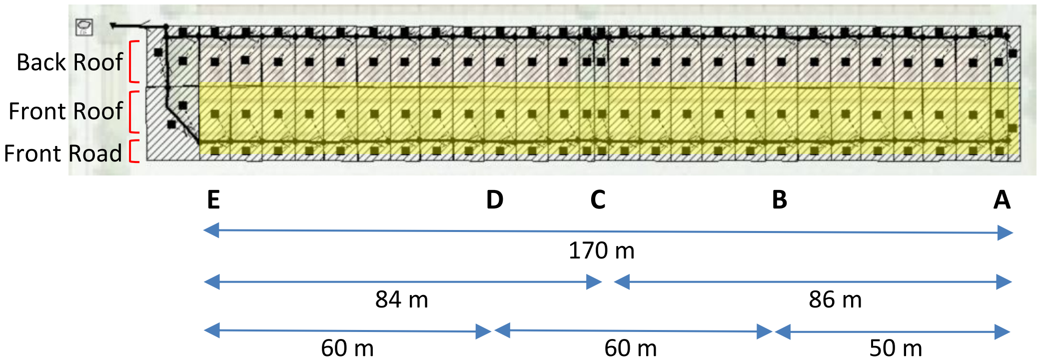
3.1 Water Profiles

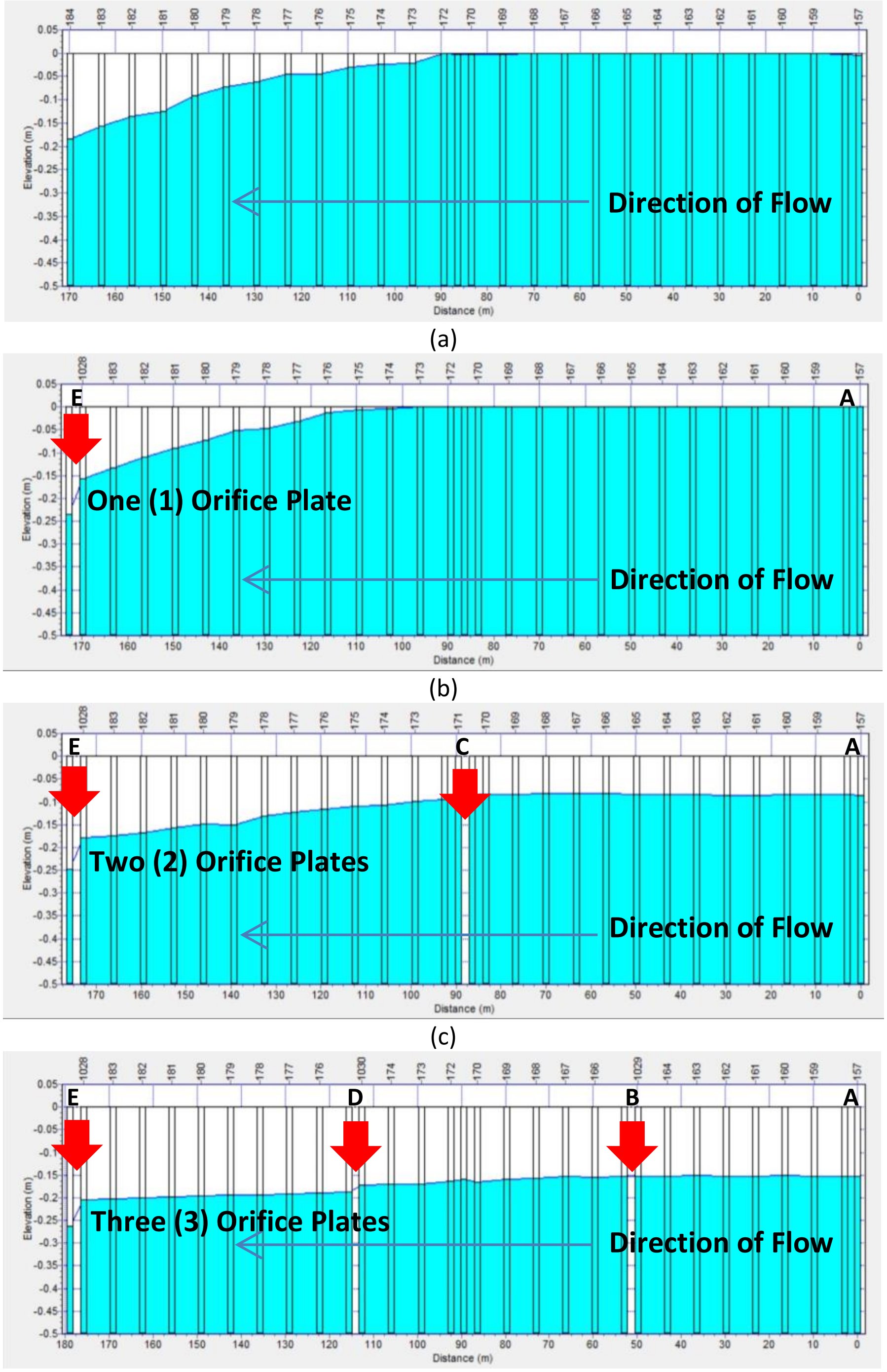
Multiple orifice plates in the drain created a series of tank-like channel compartments which received and drained water simultaneously. The positions of A, B, C, D and E are marked in Figure 5 where water was modelled to flow from point A to point E. Point E was the last point of investigation before the bend. It is also pointed that the water profiles depicted in the subsequent sub-figures were all produced from the same design storm. The water profiles reveal different performances when water passed through different orifices as in S1, S2 and S3 compared to existing condition.

The control scenario is depicted in Figure 5(a), whereby the drain was designed to contain the floodwater from the 5-min, 10-year ARI design storm. The drain had been filled to minimum 0.32 m, maximum 0.5 m depth, leaving only 0.05 m of safe board.

S1 (Figure 5(b)) produced water profile similar to existing condition, however, when checked with the combined water level plots (Figure 6(a)), the orifice plate inserted at point E raised the water levels immediately before the orifice higher than the existing condition. This scenario worsened the drain flow. Water depths of minimum 0.34 m and maximum 0.50 m were observed. Backwater effect was significant in the downstream half of the drain.

The next two scenarios were found to produce lower water profiles compared to the existing condition. Water depths of Scenario 2 (Figure 5(c)) were between 0.32 m to 0.34 m, while Scenario 3 (Figure 5(d)) had water depths between 0.30 m and 0.34 m. It suggests that having at least two orifices in the drain improved the distribution of water more efficiently throughout the length of drain. Further explanation is available in the following subsection.





(a)

(b)

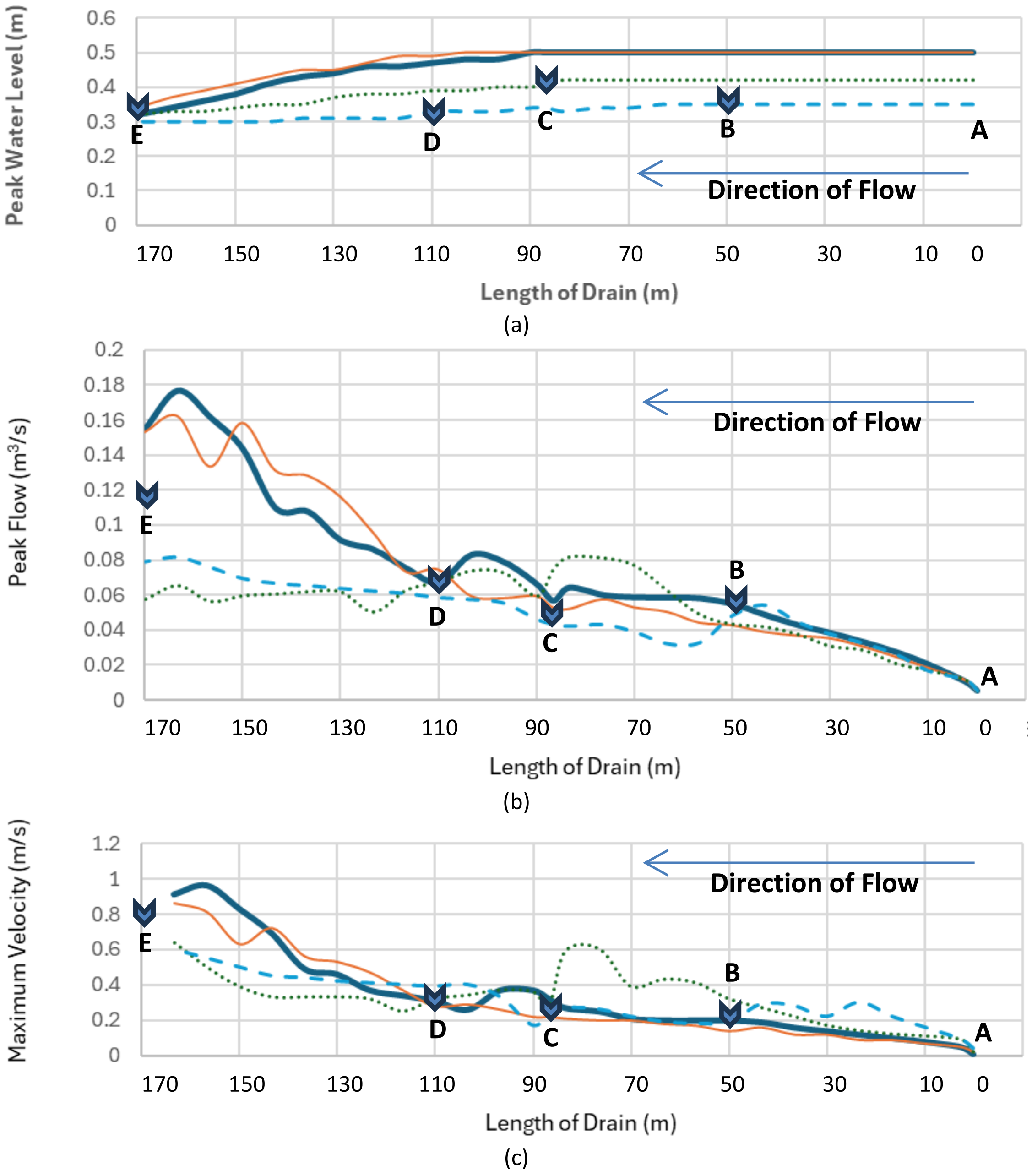
(c)

(d)

Fig. 5. Developed SWMM model with pinpointed positions of A, B, C, D and E with corresponding distances. Simulated peak water profiles for: (a) Existing condition (control), (b) Scenario 1, (c) Scenario 2, and (d) Scenario 3

3.2 Water Level and Flow Along the Length of Drain

The peak water level data extracted from the water profiles, along with the corresponding flow data at various points along the drain are illustrated in Figure 6. The two floodwater attributes, namely the water level and flow, were observed to demonstrate contrasting traits. As water travelled from point A to point E, it gained momentum leading to water flowing faster downstream. This is evident in Figure 6(b), as the flows were higher downstream, particularly the stretch C-D-E, compared to the upstream stretch of A-B-C. In contrast, the water level plots in Figure 6(a) indicate that the water levels were higher upstream than downstream. The highest water level estimated was at 0.5 m, was observed at stretch A-B-C. The lowest water level was estimated at 0.30 m, was observed at point E.



(a)

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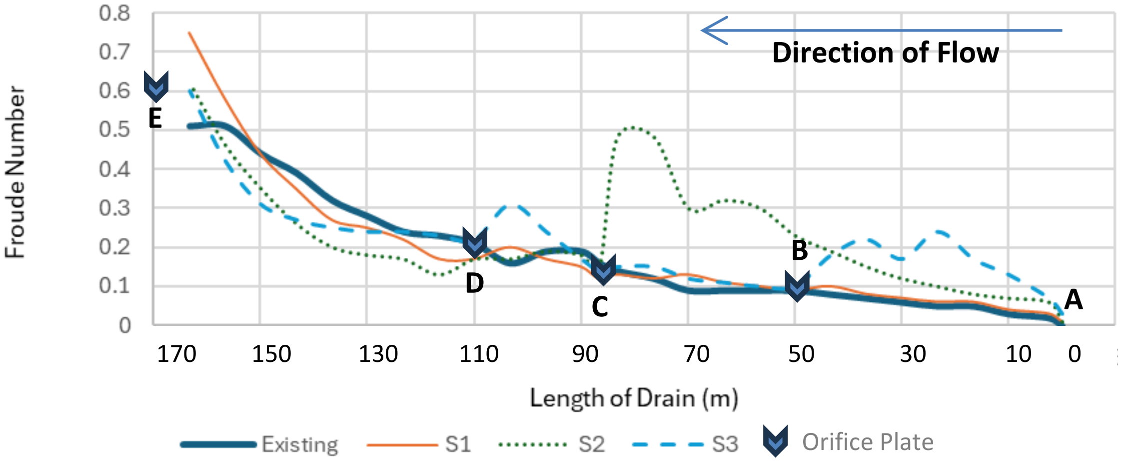

(d)

Fig. 6. Plots along the selected length of drain, (a) Peak water level, (b) Peak flow, (c) Maximum velocity, and (d) Froude number associated with maximum velocity

Following the principles of continuity in fluid mechanics, whereby Q = VA (Q as flow, V as velocity and A as flow area), the higher the Q, the higher the associated V will be. As Q is constant, therefore when V increases, A decreases, and vice versa. The decreasing A is reflected with the lowering of water level. This explains the water level and flow patterns mentioned in the previous paragraph. The plots of maximum velocity in Figure 6(c) and its associated Froude number in Figure 6(d) reinforced the theory.

Orifice plates are inserted in the Figure 5(b) to Figure 5(d). The results of having one to three orifices obstructing the water flow were explored. There are four lines in Figure 6, in which the thick solid line represents the existing condition, the thin solid line represents S1, the rounded dotted line represents S2, and the dashed line represents S3. Theoretically, once an obstruction placed amid the water course, the water level upstream of the obstruction will rise. In Figure 6(a), the peak water levels for all scenarios appeared to be smooth lines. Fluctuation of water level was not observed. However, fluctuations of peak flow were more evident, as shown in Figure 6(b). The orifice plates were observed to decelerate the flow.

The subsequent writing is flipping in between water level (top sub-figure) and flow (bottom sub-figure). In S1 (thin line), the flow before the orifice plate at point E dropped compared to Existing Condition (thick line), in which this decrease in flow (Figure 6(b)) resulted in the increase of water level (Figure 6(a)). The more interesting findings were on the next two scenarios.

Referring to S2 (round dotted line), the first encountered orifice plate at point C had dampened the flow graph to continue rising compared to Existing Condition (thick line), in which the flow graph after the orifice dropped, even lower than S3. This decrease in flow lower than S3 (Figure 6(b)) had resulted in higher water level than S3 (Figure 6(a)).

Referring to S3 (dashed line), the first encountered orifice plate at point B had dampened the flow graph similar to S2. However, under this scenario, water continued to the second orifice at point D and the third orifice at point E. The resulted flow graph was the most stable compared to the other flow scenarios (Figure 6(b)). This was also reflected in the water level graph (Figure 6(a)).

3.3 Water Level and Flow Relationships

Combining the water level and flow in Figure 7, the relationships of pairing water level to flow are visible. The scattered plots could be divided into three clusters. On top, the clusters of square and round markers show that the Existing Condition and S1 had water levels in the range of 0.32 – 0.50 m in corresponding with flows up to 0.176 m^3/s.

In the middle of the graph, the second cluster of diamond-shaped markers shows that S2 had caused water levels in the range of 0.32 – 0.42 m in corresponding with flows in the range of 0.01 – 0.08 m^3/s. S2 reduced the flows by half compared to Existing Condition and S1. However, in the figure, the water levels fluctuated when the flows reached between 0.05 – 0.08 m^3/s.

The triangular markers for S3 are at the bottom of the three clusters of scattered plots. S3 had the tightest range of water levels between 0.30 – 0.34 m. Similar to S2, this cluster had its flows in the range between 0.01 – 0.08 m^3/s, in which the flows were half of the Existing Condition and S1. Again, S3 was demonstrated as the most stable water pattern.

The implication of the findings, particularly S3 which three orifices were being placed in the drain, would be a possible solution to climate change. The modelling effort shows that orifices could regulate better the acceleration of flows when the water being drained from upstream to downstream stretch, and at the same time, lower the water levels along the way. The capability of orifices which was proven here to lower water level, allows more spaces within the drain channel to accommodate more floodwater coming from climate-induced events.

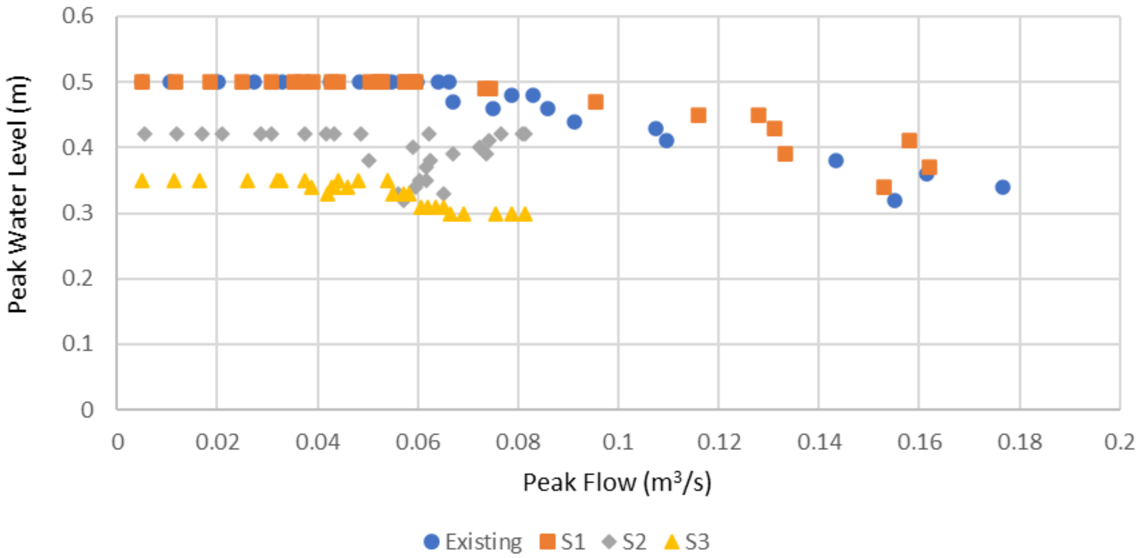

Fig. 7. Peak water level and peak flow relationships

4. Conclusions

Scenarios of having orifices in the open drain were simulated using the US EPA SWMM5. Contrary to common believe, the simulated scenarios came back to clear the misunderstanding that an obstruction like orifice in the water course would worsen the flushing of floodwater. Instead, the modelling efforts discovered a hidden function of orifices, in which the placement of two, even three orifices in the drain regulated the flows better, in this case, up to 50% lower flow rate than the case without orifice.

Besides, the modelling efforts also indicated that the orifices could lower the water levels. As such, spaces within the drain channel, in which by design was expected to be filled by floodwater, were now recovered. These spaces could accommodate more floodwater going into the drain. Thus, the water carrying capacity of the existing drain could be enhanced.

Acknowledgement

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