

Short Communication

Modelling of Stormwater Detention Ponds for Water Level, Flow and Velocity Under Future Climate Change

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Abstract - In equatorial countries, drainage engineers are implementing adaptive measures to bolster infrastructure resilience against climate change, particularly on urban stormwater systems, which are among the facilities most vulnerable to increasing rainfall volumes. This paper describes one such effort that proposes the partitioning of a large, single dry pond into two smaller ponds, a rare practice. A case study was conducted using Storm Water Management Model software to model an 80 m long dry pond with orifice plates at the 20, 40, or 60 m points, to produce the 20:60, 40:40, and 60:20 pond designs. The models developed based on the conventional and partitioned ponds were subjected to IPCC 6th Assessment Report's near-, medium-, and long-term scenarios of the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 events. Simulation results for the conventional pond indicate that future climate scenarios significantly increase peak inflow rates and velocities; however, maximum water levels remain within capacity, with no predicted overflows. The partitioned pond simulation findings are encouraging, which cause the water level, flow rate, and velocity in the second pond to decline by nearly 50% regardless of its design, compared to the first pond. The velocity profiles of the three partitioned designs, along the pond length, were compared. Only the 60:20 pond demonstrated the ability to produce a settling velocity <0.1 m/s near the end of the first pond, which suggests that this pond design can treat suspended sediments.

Keywords - Drainage, Flood, Sustainable development, SWMM, Urban runoff.

1. Introduction

This paper further explored a finding by [1], which stated that partitioning a large water storage tank into multiple smaller tanks ensured a better achievement of the various stormwater management objectives by each divided tank. Following this report, a large dry pond was partitioned into two smaller ponds to treat suspended sediments. The modification was minimal, an uncommon practice. Considering climate change, the performance of the selected dry pond was explored, with the objective in achieving optimal settling velocity for suspended particles. The highlighted conventional and newly proposed partitioned ponds were compared.

A detention or dry pond is a type of stormwater pond in which urban surface runoff is directed for quantity and quality control [2]. In terms of quantity control, ponds, such as retention or wet ponds (Figure 1 (a)) and artificially constructed wetlands (Figure 1 (c)), are always filled with water. They also provide additional water storage capacity to accommodate any incoming runoff, minimizing its release into the urban drainage system. However, as dry ponds are

always parched (Figure 1 (b)), they have a large storage volume and can readily receive surface runoff and steadily release it. Ponds can set objectives, such as reducing quality control-associated parameters like nutrients, total suspended solids, and other pollutants [3, 4].

Once generated, surface runoff travels along a particular flow path, with the running water picking up various pollutants. Suspended sediments are one such pollutant, generally composed of solid particles, such as clay, silt, and fine sand, that are uplifted by surface runoff. Their enhanced deposition in a water body reduces clarity, which is detrimental to any aquatic ecosystem.

They naturally sink when a specific settling velocity is achieved. According to the study of [5], settling velocities <0.1 m/s demonstrated the best similarity when comparing the observed values with those predicted utilizing empirical formulas. Lower values have also been reported: ≤ 0.0034 m/s by [6]; ≤ 0.012 m/s by [7]; and ≤ 0.03 m/s by [8]. These values were compared with those obtained from dry ponds in the current study.





(a)



(b)



(c)

Fig. 1 Stormwater ponds, (a) Retention or wet ponds (Taman Desa, Kuala Lumpur, Malaysia; <https://www.thestar.com.my/>), (b) Detention or dry ponds (<https://www.manuelbuilders.com/>), and (c) Constructed wetlands (<https://www.dsfranks.com/>).

A real-world dry pond was selected as the study site (Figure 2). The location housed a training centre for rural development, which had been in operation since 2020. The campus, with an area of 27,800 m², subjected only once to a designed 30-minute-long, 100-year storm event with 96 mm of rainfall, could generate a surface runoff of 2,700 m³. Considering the modifications required in the local stormwater drainage system to tackle such an event, engineers designed a dry pond 80 m long, 10 m wide, 1.98 m deep, with a 0.45 m diameter orifice outlet. The pond was designed to store 1,050 m³ of water at one time. The remaining was discharged into a nearby drain. The post-development peak runoff from the catchment was initially estimated to be 1.5 m³/s. After intervention by constructing a dry pond, the

reduced peak runoff was estimated to be 0.4 m³/s; the second peak indicated the achievement of the pre-development condition.

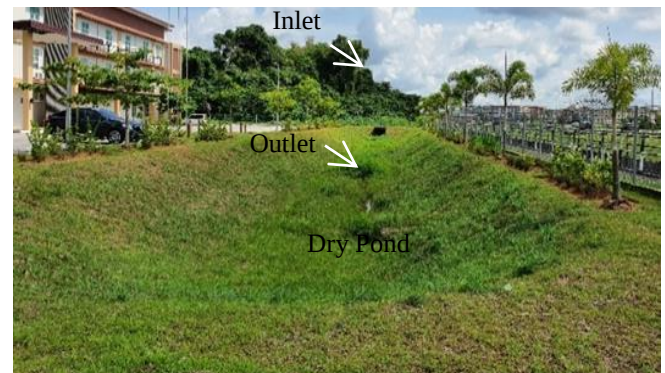
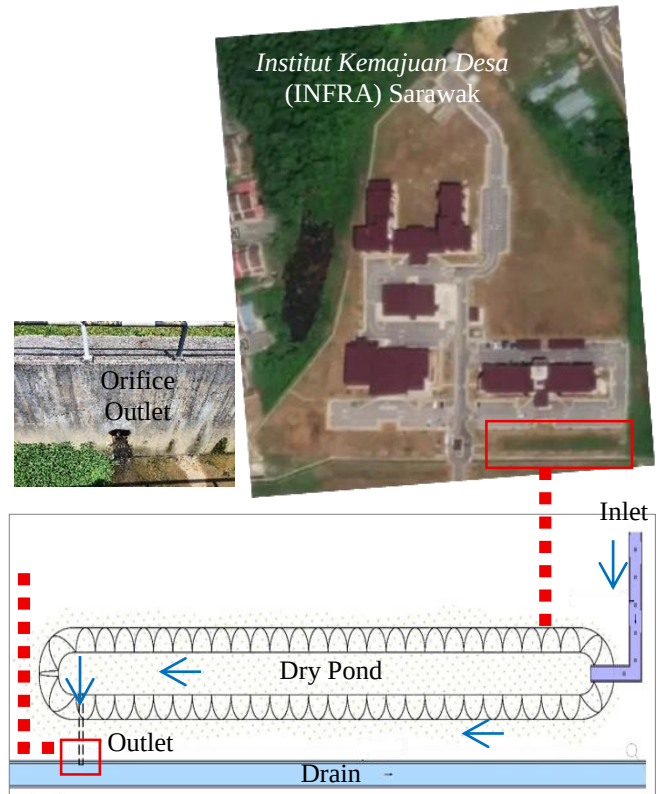
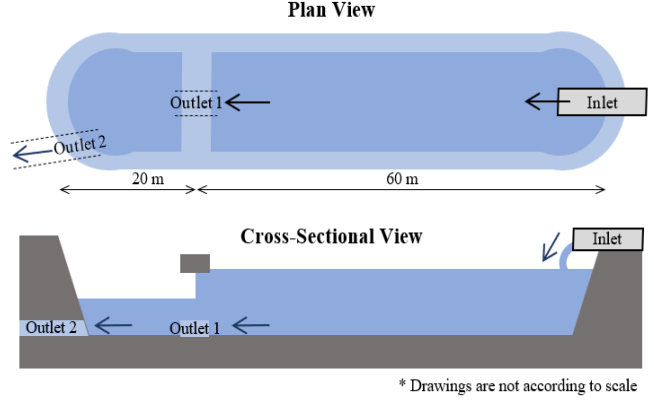
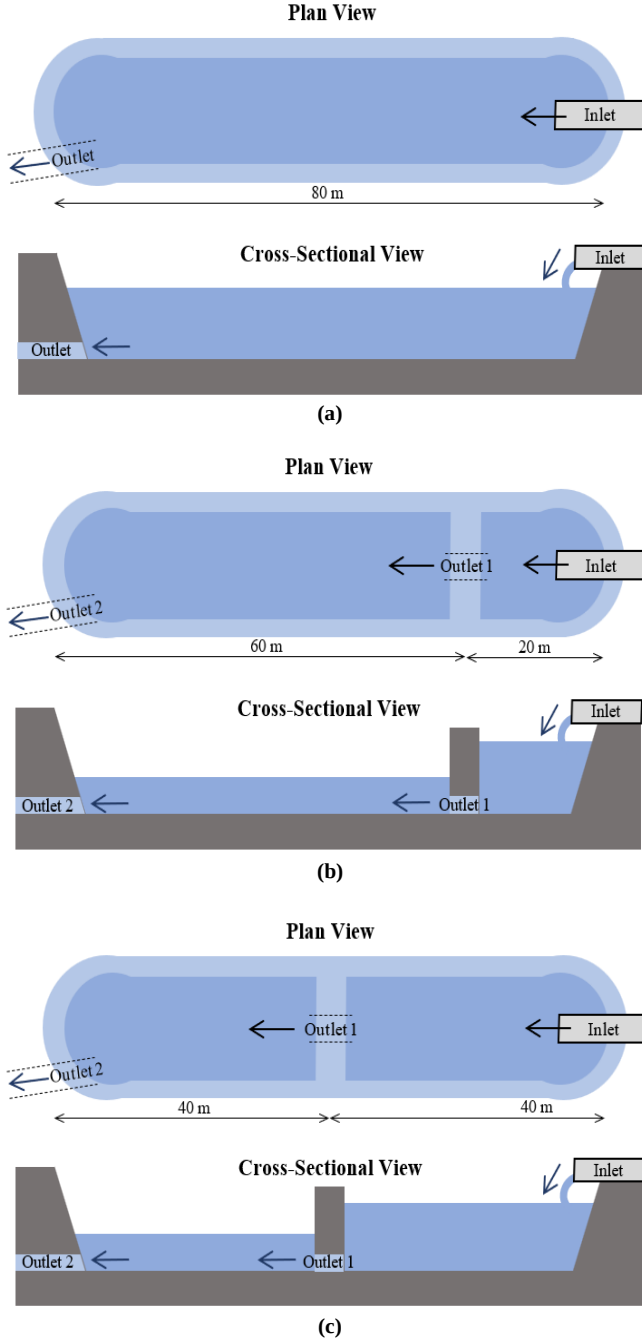


Fig. 2 Study site

The dry pond studied has been in operation for six years (May 2020–May 2026), experiencing six Northeast monsoon seasons. To date, no overflow has been reported from the dry pond. As such, the pond continues to function satisfactorily, due to its design, which was created based on historical hydrological data. However, the pond may be challenged functionally when increased rainfall induced by climate change sets in. Exploring the adaptation of dry pond design to climate change could be performed in the study site. On one hand, the availability of the study site allows field

measurements of the dry pond and its surrounding structures; on the other hand, it provides a realistic representation of the on-site hydrological and hydraulic mechanisms.

The conventional dry pond received inflow via a 1 m × 1 m concrete drain with an invert level above the bank-full water level. The outflow was released at the opposite end of the pond via an orifice outlet with an invert level that follows the bottom slope of the pond (Figure 3 (a)). Thus, the water was discharged completely, and the pond returned to a dry condition after the storm passed.



(d)
Fig. 3 Dry pond design scenarios, (a) A single pond, and the one partitioned into two in the ratios of (b) 20:60m, (c) 40:40m, and (d) 60:20m.

A new partitioned dry pond design was put forward with three different pond scenarios, namely 20:60 m (Figure 3 (b)), 40:40 m (Figure 3 (c)), and 60:20 m (Figure 3 (d)), following the direction of flow and total length of the dry pond. The existing inlet and outlet remained. An additional orifice plate was constructed as a berm separating the previously single pond into two. This orifice plate or berm was inserted at the 20 or 40, or 60 m points from the inlet, respectively, thus creating the above-mentioned pond scenarios. A new orifice outlet, Outlet 1, was added at the bottom of the berm, allowing flow between the two partitioned ponds. The opening size of Outlet 1 followed that of the existing outlet, termed Outlet 2, which had a diameter of 0.45 m.

The foremost point to be considered while designing a dry pond is its storage volume [9]. Essentially, it is the net volume of water remaining after accounting for total inflow and outflow over a specific period [10]. The mentioned balance between the inflow and outflow of water can be calculated using Equation 1:

$$St = \sum_i (Q_i - Q_o) \Delta t_s \quad (1)$$

Where St is defined as the pond's storage capacity (unit: m^3), Q_i is inflow (unit: m^3/s), Q_o is outflow (unit: m^3/s), and t_s is storm duration (unit: s).

As inflow is a function of the catchment area, the catchment-storage characteristics need to be analyzed. Conversely, the outflow is also a function of the outlet, as reflected in Equation 2 [11]:

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

Where Q_o is flow at outfall (unit: m^3/s), C_d is orifice discharge coefficient (unitless), A_o is area of orifice opening (unit: m^2), g is gravitational acceleration (unit: m/s^2), and H_o

is effective head from water surface to the centre of orifice (unit: m).

Another critical parameter is the stage level within the pond, which also corresponds to the storage volume. In practice, as the dimensions of the storage facility are known, a storage curve can be computed to describe the storage–stage relationships.

In the case of the study site, the dry pond was constructed in a way similar to a particular stretch of a channel, and its shape was quite uniform throughout. It transported water from one end to the other. As the channel shape, which is a cross-section, can be delineated, engineers could determine the flow area and hydraulic radius based on the cross-section. The Manning formula could be applied in this case to calculate the flow rate in a channel, as represented in Equation 3 [12]:

$$Q_c = \frac{1}{n} \cdot A_d \cdot R^{2/3} \cdot S_d^{1/2} \quad (3)$$

where Q_c is flow rate in channel (unit: m^3/s), n is Manning's roughness coefficient (unitless), A_d is the drain's flow area (unit: m^2), R is the drain's cross-sectional hydraulic radius (unit: m), and S_d is drain slope (unit: m/m).

The different slopes of the dry pond bottom imply that it is possible to substitute varying slope values into the Manning formula. Such a formula can yield a range of changing flow rates, as well as velocities from upstream to downstream of the dry pond, when the remaining parameters are constant. These are the advantages of the Manning formula over the storage curve.

2. Materials and Methods

A flow chart describing the methods is presented in Figure 4, which starts with the collection of data, followed by model building and model evaluation.

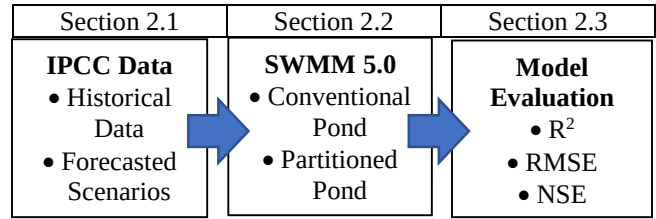


Fig. 4 Flow chart of methods

2.1. IPCC AR6 Scenarios

Rainfall data from the IPCC 6th Assessment Report (AR6) served as primary input for the model [13]. Maximum 1-day precipitation ($R_{x1\text{day}}$) is a critical climate index representing the highest daily rainfall total; in this study, the 95th percentile values for this index ranged from 116 to 131.3 mm (Figure 5). The 100-year design storm for the site (96 mm) was proportioned according to the $R_{x1\text{day}}$ data range to align the design parameters with observed climate extremes. Notably, the AR6 future climate scenarios for the near, medium, and long terms superseded the design data.

To execute the future climate scenarios data for rainfall-runoff simulations estimated at the study site, the $R_{x1\text{day}}$ data assumed water to reach the dry pond in 30 min, following the time of concentration. As presented in Figure 6, each value was fractioned into six blocks of 5-minute duration, and each fraction was added up to a 30-minute duration [14].

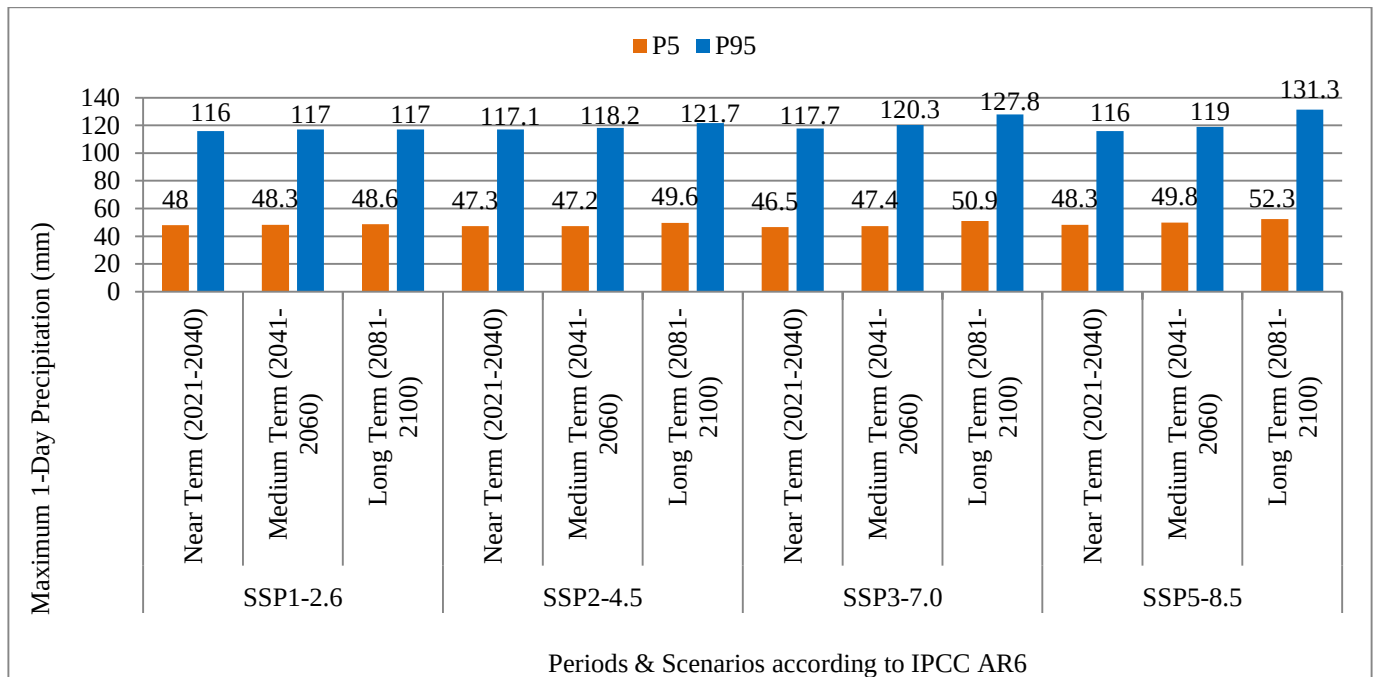


Fig. 5 Maximum 1-day precipitation in the 5th and 95th percentiles according to the AR6 future climate scenarios and periods

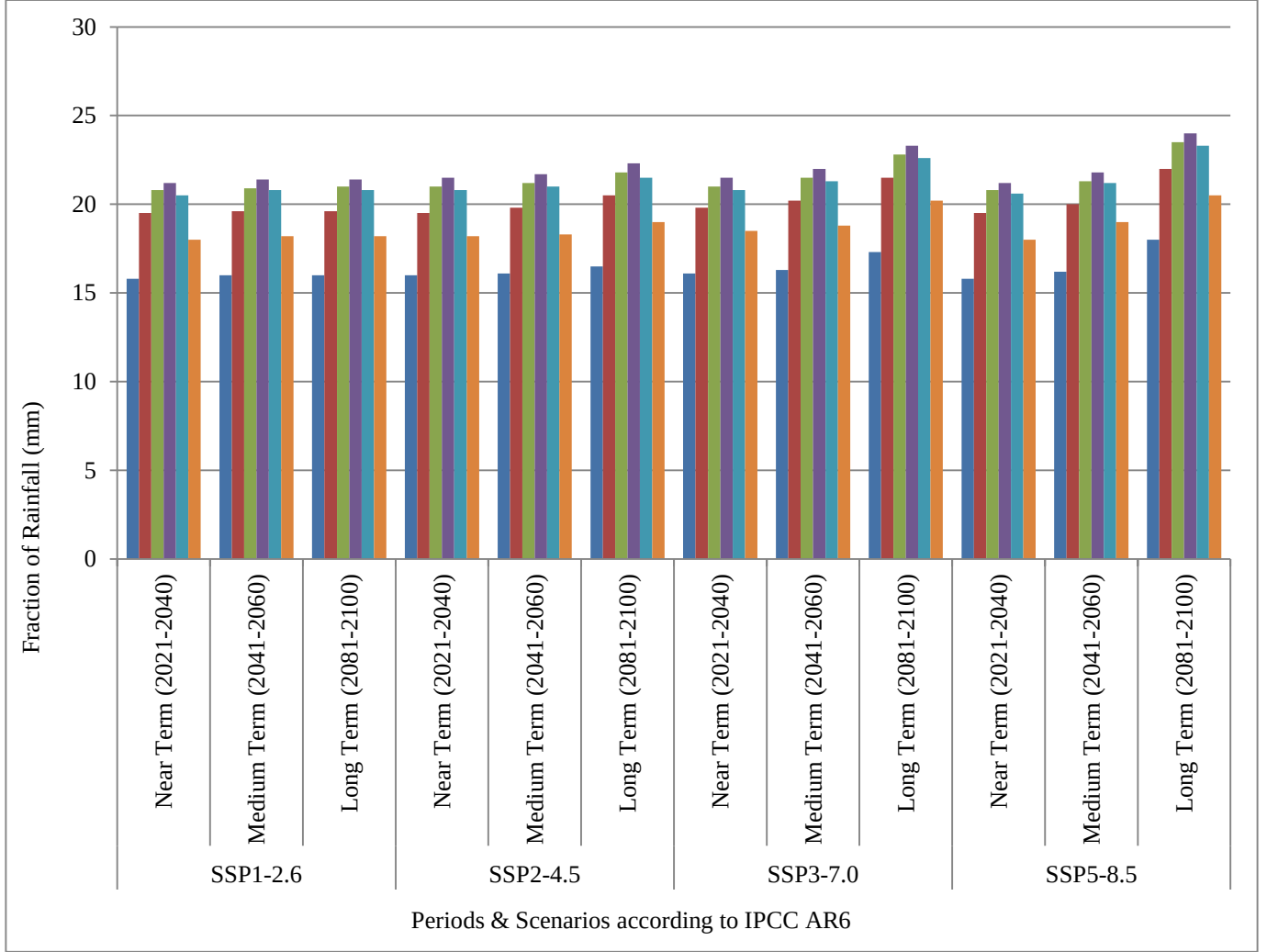


Fig. 6 Fractionation of the maximum 1-day precipitation during a 5-minute storm duration into six blocks (each with a 30-minute storm duration) per the AR6 future climate scenarios and periods

2.2. Drainage Modelling

The pond was modelled using Storm Water Management Model version 5.0 (SWMM 5.0). It covers hydrological and hydraulic simulation for drainage systems. The model developed for the selected dry pond and its connected catchments and upstream drain network is presented in Figure 7. The model components are numbered, with 1–2 covering the hydrological, and the remaining encompassing the hydraulic model.

Surface runoff was calculated by treating the catchment as a nonlinear reservoir, with sheet flow governed by a nonlinear differential equation based on local site characteristics [15]:

$$Q_a = W \frac{1.49}{n} (d - d_p)^{5/3} S_c^{1/2} \quad (4)$$

Where Q_a is sub-catchment flow (unit: m^3/s), W is width of catchment (unit: m), S_c is sub-catchment slope (unit: m), n

is Manning's roughness coefficient (unitless), d_p is maximum depression storage (unit: m), d is depth of water over the catchment (unit: m).

The catchment flows were then directed to the nearest nodes and are injected as inflows at specific points along the drain network. The flows are routed until the outfall, which is the final discharge point. The simulation utilized the dynamic wave routing method [16]:

$$Q_b = \frac{\partial A}{\partial t} + \alpha m A^{(m-1)} \frac{\partial A}{\partial x} \quad (5)$$

Where Q_b is routed drain flow (unit: m^3/s), A is the drain's cross-sectional area (unit: m^2), x is distance along the flow path (unit: m), t is time step (unit: s), α is the drain's flow geometry (unitless), m is the drain's surface roughness (unitless).

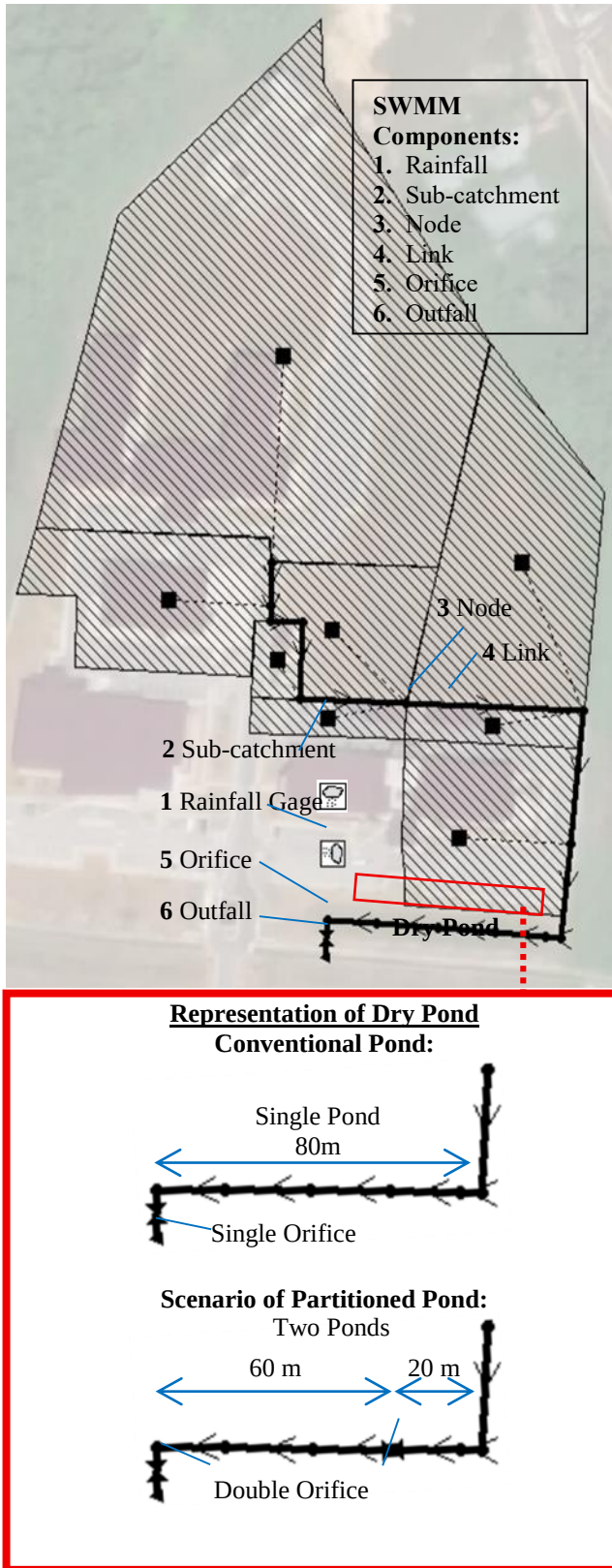


Fig. 7 Drainage model developed with SWMM 5.0 software. Bottom: representations of a conventional dry pond (single pond restricted by one orifice) and a partitioned dry pond (two ponds restricted by two orifices).

2.3. Model Evaluation

The model was validated by comparing the flow routing results from SWMM 5.0 (Equation 5) against theoretical values derived from the Manning formula (Equation 3). The statistical tools used were the coefficient of determination (R^2) [17], Root Mean Square Error (RMSE) [18], and Nash-Sutcliffe Efficiency (NSE) [19].

R^2 values approaching 1.0 indicate a superior fit. Lower RMSE values indicate a smaller deviation between modelled and theoretical data, signifying higher model accuracy. NSE values range from $-\infty$ to 1; an NSE closer to 1 indicates a superior fit between the model predictions and theoretical data. Thus, two plots were created, one for conventional ponds (Figure 8a) and the other for partitioned ponds (Figure 8b). Based on these descriptions, it was observed that the modelled flows in the conventional pond matched better with the Manning formula results, with an R^2 of 0.96, RMSE of 0.06, and NSE of 0.75. When the modelled flows in the partitioned ponds were compared with the Manning formula, the fit of the model performance indicators was downgraded from a high to a moderate level, with an R^2 of 0.61, RMSE of 0.27, and NSE of -0.04 . This effect was due to the flows being sped up after passing through the second orifice, which contradicts the former case, where the flows were relatively slower. This phenomenon is reflected by the presence of more outliers in this case. However, the lower range of flows between 0 and $0.3 \text{ m}^3/\text{s}$ fits well with the trend, indicating that the modelled flows remained acceptable as the sudden surge in flows was short-lived and was diminished by the ponding effect of a filled pond.

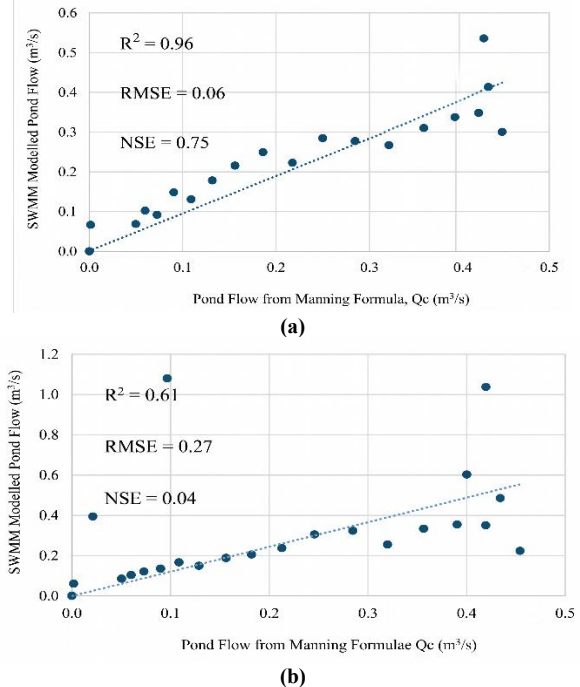


Fig. 8 Model evaluation comparing the modelled and theoretical flow data. (a) Flows in a conventional dry pond design and (b) Flows in a partitioned dry pond design.

3. Results and Discussion

It was mentioned at the beginning that this paper explores the possibility of treating suspended sediments in a dry pond as the topmost major stormwater management objective to control the stormwater volume. As such, the modelling results are presented in terms of water level profile, flow rate, and velocity, followed by insights into the control of suspended sediments.

3.1. Dry Pond Longitudinal Profile

The water profiles were assessed at two time points, 20 and 40 min after the onset of the designed storms. Those of the conventional ponds were constant at these two times (Figure 9 (a)). The orifice restriction increased the water depth upstream and effectively maintained the pond's storage level during the simulation. Regardless of the position of the second orifice plate, this observation was repeated in the partitioned pond designs, in which the water levels were always greater in the upstream than in the downstream ponds (Figure 9 (b), Figure 9 (c) and Figure 9 (d)). At 40 min, the water levels were equally high among the four pond designs. However, those in the downstream ponds reduced markedly in all cases.

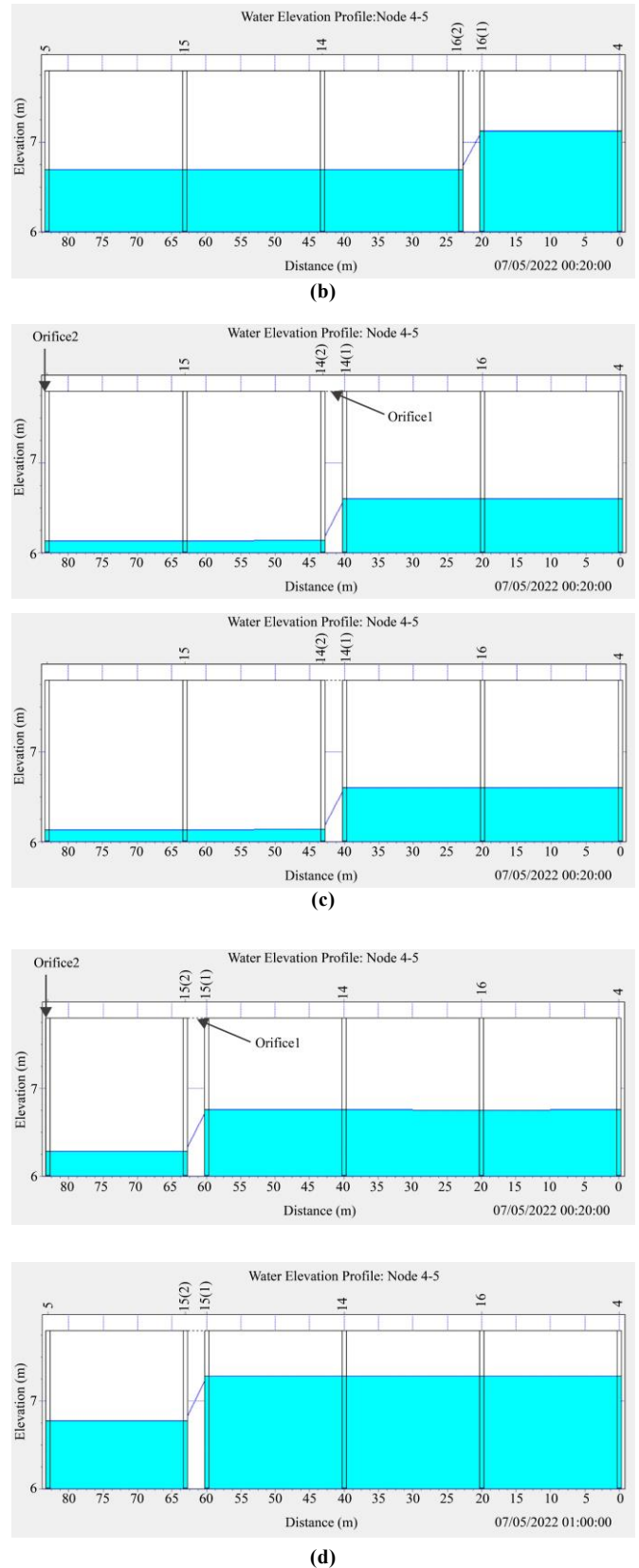
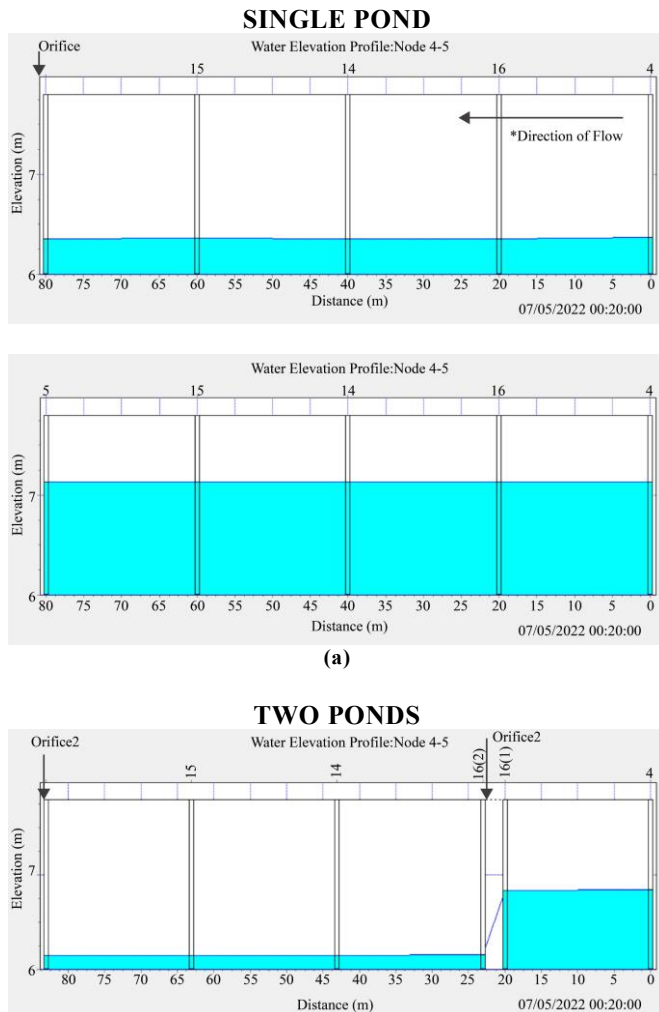


Fig. 9 Longitudinal water profiles of the: (a) Conventional dry, (b) The 20:60, (c) The 40:40, and (d) The 60:20 pond at 20 and 40 min after the onset of the 100-year design storm.

Adding the future climate change scenarios, the peak water levels modelled were plotted as a bar chart based on the four pond designs (Figure 10). The ponds before the orifice plates shared a similar range of water levels at 1.35–1.45 m: 1.36–1.4 for the conventional pond, 1.35–1.36 for the 20:60 pond, 1.38–1.45 for the 40:40 pond, and 1.39–1.43 for the 60:20 pond (Figure 10 (a)). Incorporating orifice plate restrictions reduced pond water levels by approximately 50% compared to the conventional design. The restricted ponds exhibited a narrow range of 0.70–0.78 m, with specific levels of 0.70–0.73 m (20:60 pond), 0.75–0.76 m (40:40 pond), and 0.78 m (60:20 pond), whereas the

conventional pond had much higher levels between 1.36 and 1.40 m (Figure 10 (b)).

3.2. Water Flow

The model, which represents the dry pond as four links (Figure 7), allowed the plotting of four separate hydrographs as the water flowed through the pond. As such, there were four flow hydrographs, indicated in each sub-figure of Figure 11. For demonstration, only “avoid at all costs” SSP5-8.5 scenario was compared with the 100-year storm event.

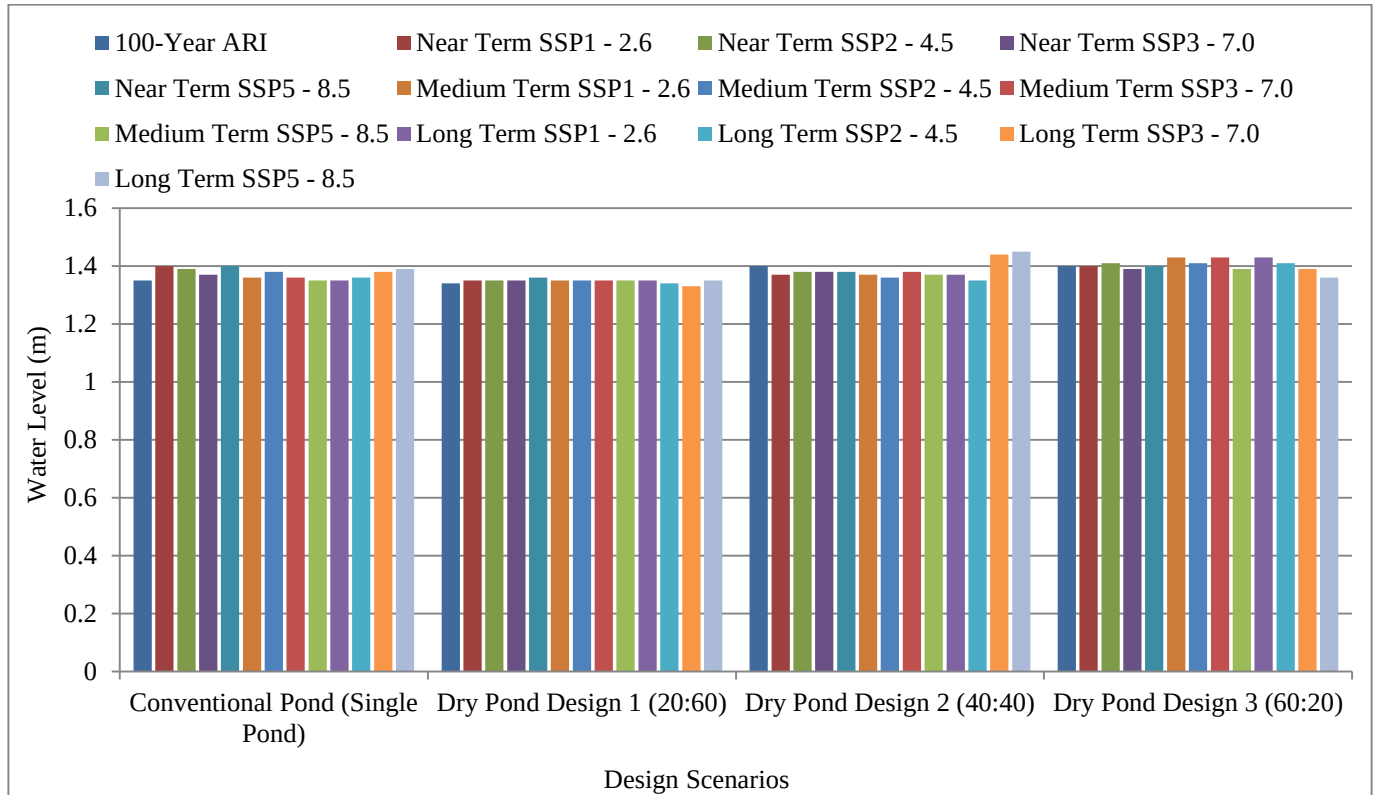
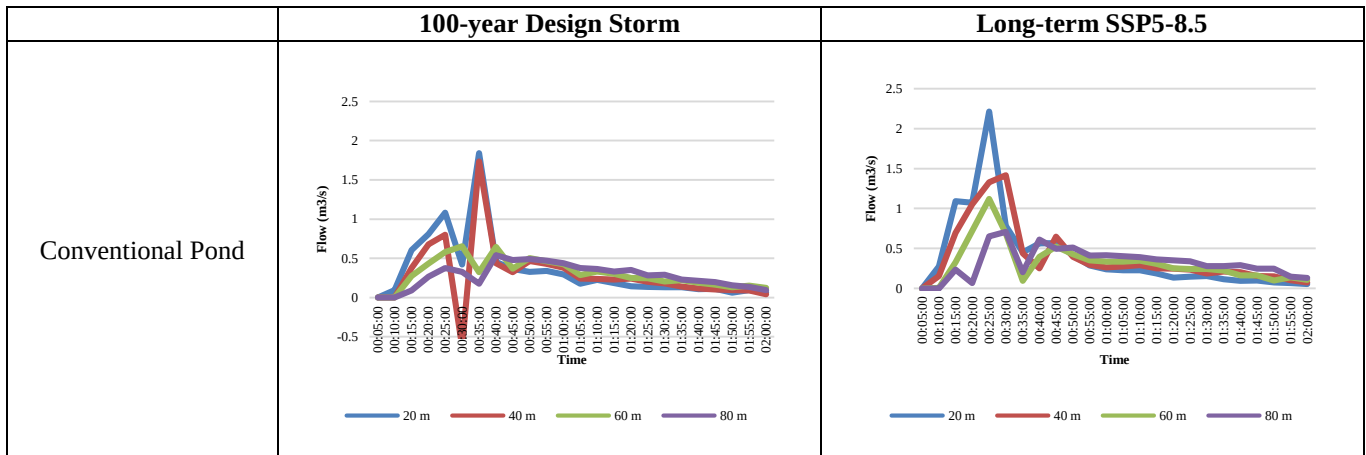


Fig. 10 Peak water levels in the dry pond per the future climate change scenarios, (a) Upstream, and (b) Downstream ponds.



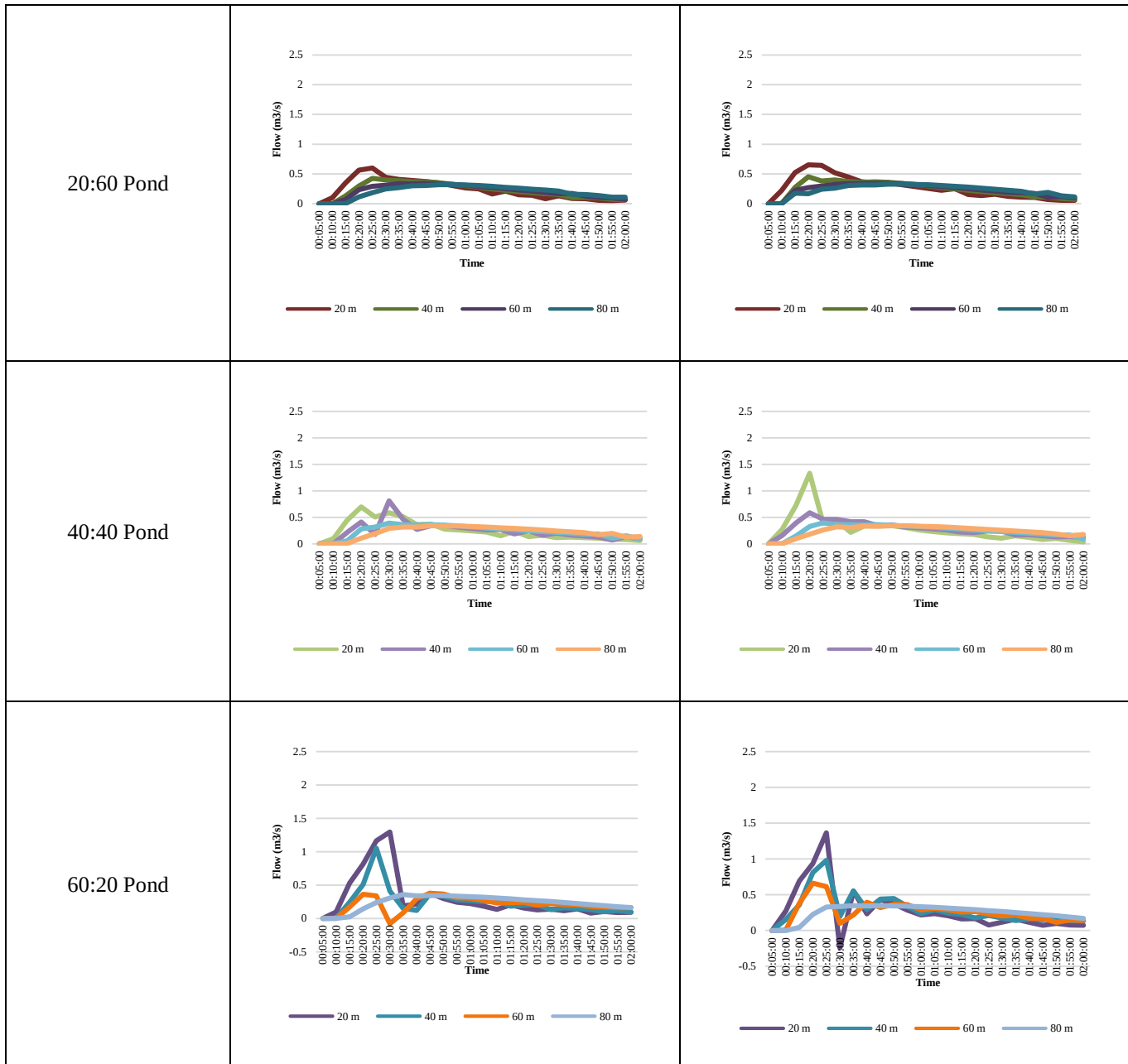


Fig. 11 Time series of the flow hydrographs according to pond designs

The sub-figures indicated that in the conventional pond, the peak flow values increased from 1.7 to 2.2 m³/s when transitioning from the 100-year to the SSP5-8.5 event, particularly in the first 20 m of the pond.

This finding suggests that the conventional pond design received higher inflows from the upper catchment due to increased rainfall in the future. In contrast, peak flow values in the partitioned dry ponds were <1.5 m³/s, indicating a significant reduction compared to the conventional pond. This result suggests that introducing a second orifice plate in the conventional pond could offset the impact of climate change.

Adding the future climate change scenarios, the modelled peak flow rates of the four pond designs were plotted as a bar chart (Figure 12). The ponds before the orifice plates had fluctuating flow rates due to high inflows, in a range between 0.17–1.57 m³/s: 0.45–1.01 for the 20:60 pond, 0.74–1.57 for the 40:40 pond, and 0.17–1.52 for the 60:20 pond, compared to 1.31–2.59 for the conventional pond (Figure 12 (a)). The greatest flow reduction was in the 60:20 pond, followed by the 40:40 pond and the 20:60 pond. After the orifice plates, the ponds demonstrated a reduced range of flow rates, which was between 0.34–0.45 m³/s: 0.39–0.45 for the 20:60 pond, 0.35–0.40 for the 40:40

pond, and 0.34–0.36 for the 60:20 pond vs. 1.31–2.59 m³/s for the conventional pond (Figure 12 (b)). The second orifice plates in all partitioned ponds blocked the high inflows from the upstream pond, and reduced more than 50% flow in the downstream pond.

3.3. Velocity

The velocity hydrographs correlated with the flow hydrographs presented in the previous section for the 100-year and SSP5-8.5 events (Figure 13). While peak flows declined, the peak velocities in the partitioned ponds increased when transitioning from the 100-year to long-term SSP5-8.5.

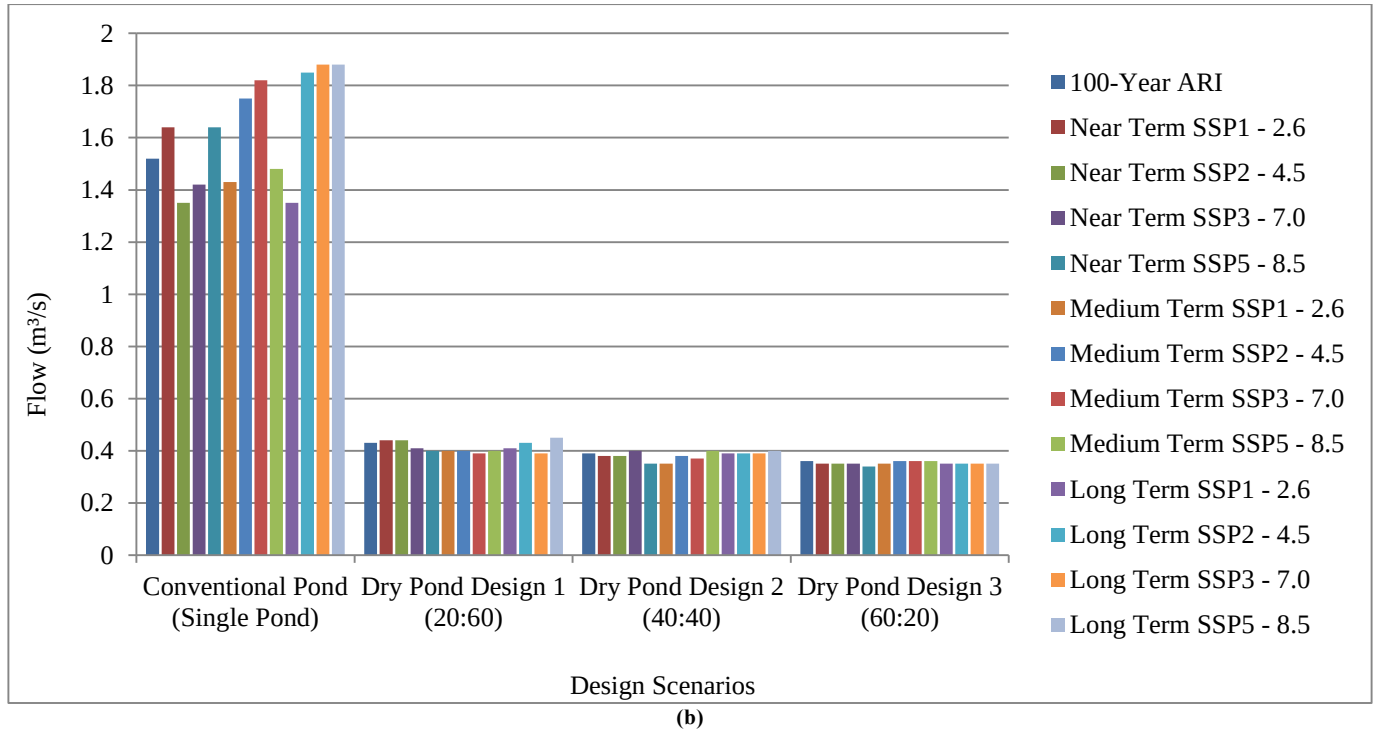
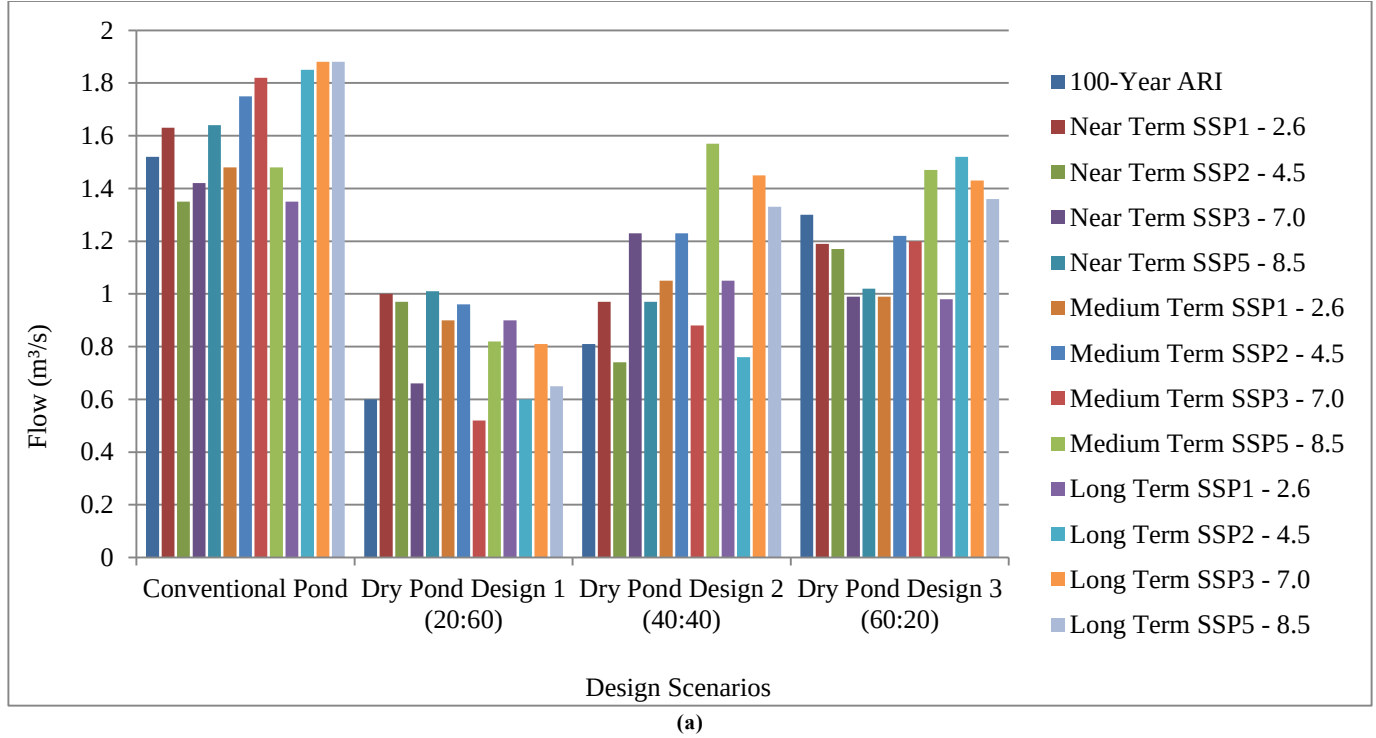
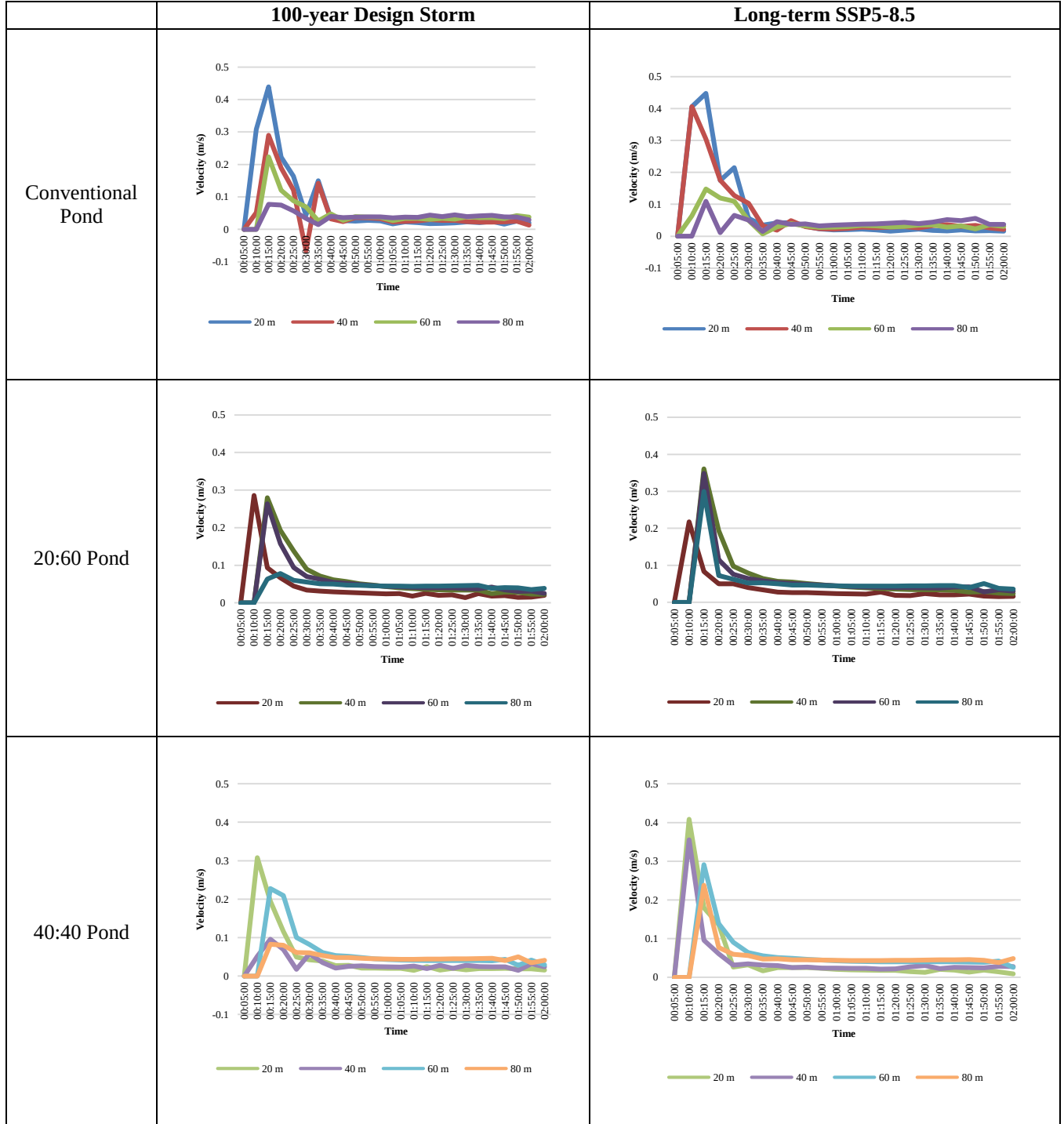


Fig. 12 Peak flow rates in the dry pond according to future climate change scenarios: (a) Upstream, and (b) Downstream ponds.

3.4. Implications on Suspended Sediments

Suspended sediment settling requires a low velocity in the dry pond. As such, the next investigation delves into the velocity profiles along the pond and is presented in Figure 14. The existing design of the conventional pond does not support suspended sediment settling (Figure 14 (a)); not every pond can achieve this stormwater objective. High velocity was

observed in the first 20 m of the pond, as this stretch received high inflows. This observation was also repeated in other pond designs, except for the 20:60 pond. Due to a restriction orifice outlet at the end of the pond, the velocity profiles according to the following 100-year and future climate change scenarios declined along the pond length. This observation was repeated in the other pond designs, except for the 60:20 pond.



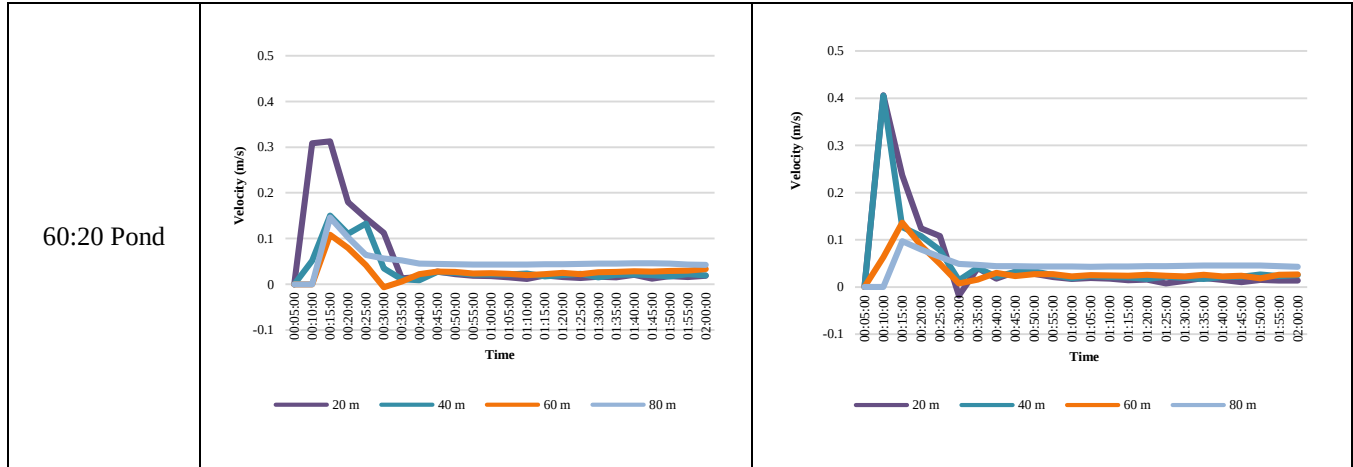
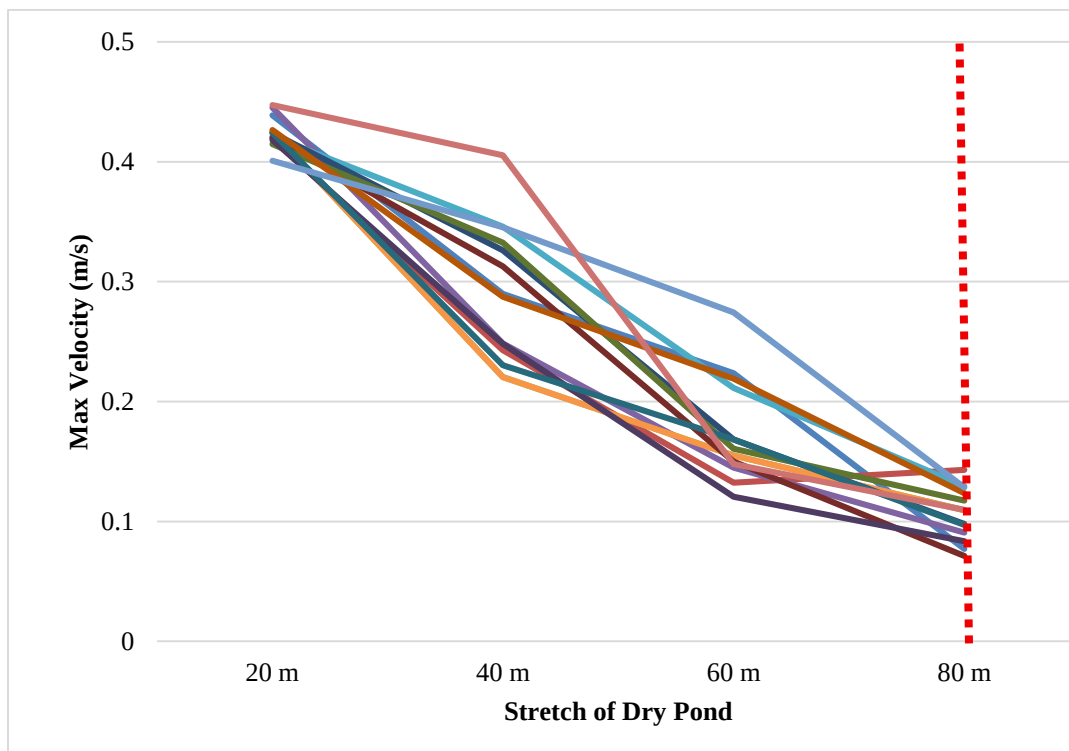


Fig. 13 Time series velocity hydrographs according to pond designs

Among all designs, the 20:60 pond, which demonstrated the maximum reduction in flow rates, revealed the highest hike in velocity (Figure 14 (b)). Its velocity profiles differed from those indicated in the rest of the sub-figures. This sub-figure revealed an upward trend, while the others showed a downward trend. It was devoid of the velocity spike during the first 20 m stretch, but instead had a dip. The pool of water retained by the orifice plate placed at the 20 m point could have simultaneously diminished the flow rate and velocity. However, the velocity of the water passing through the orifice plate increased. This observation was repeated in all partitioned pond designs. Near the end of this pond, the

velocity profiles reduced due to the end-point orifice. This pond design does little to encourage the settling of suspended sediments.

The 40:40 pond had two equally spaced ponds with high velocities in the 20 m stretch (Figure 14 (c)). As the water flowed through the two orifice plates in series, its profiles portrayed lower velocities before and higher velocities after the plates. The velocity profiles due to future climate change scenarios were >0.2 m/s. Such a pond design also did not encourage the settling of suspended sediments.



(a)

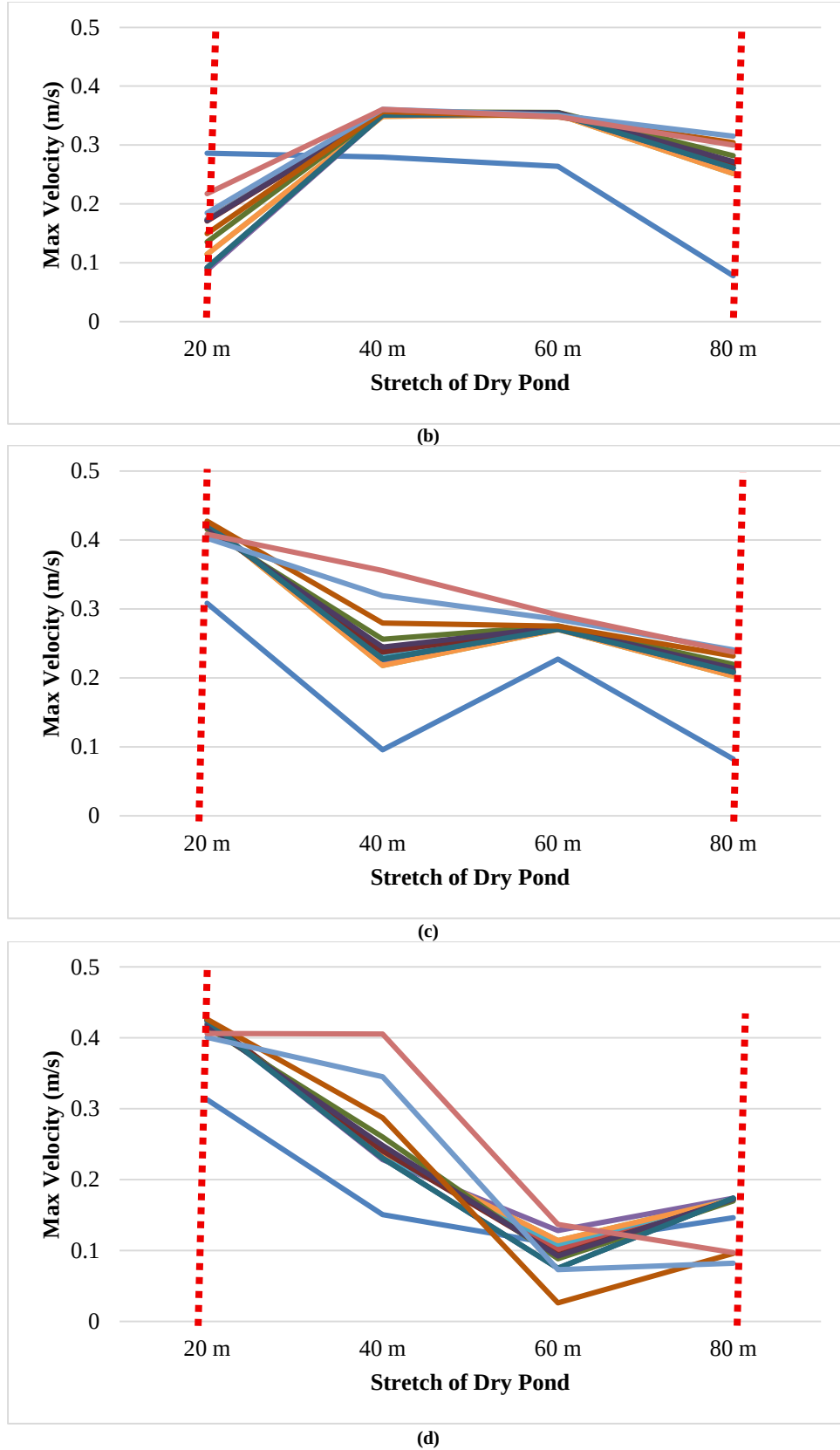


Fig. 14 Maximum velocities at different stretches of the dry pond according to future climate change scenarios: (a) Conventional, (b) The 20:60, (c) The 40:40, and (d) The 60:20 ponds. The red dotted vertical lines indicate the locations of the orifice plates.

In the 60:20 pond, the first 60 m allowed a dissipation of the thrusting stormwater energy (Figure 14 (d)). The remaining 20 m had rising velocity profiles, in contrast to the other pond designs. The design of the 60:20 pond mirrors that of a sedimentation tank. On another note, long-term scenarios were at the top in all sub-figures, indicating that these worst-case scenarios projected unfavourable conditions of fast-running water. The 60:20 pond design was the only one to facilitate high velocities due to long-term SSP2-4.5 and SSP3-7.0, slowing down to <0.1 m/s, which concurs with the settling velocity reported by [5]. Such characteristics signify the potential of the 60:20 pond in settling suspended sediment.

3.5. Practical Impacts

With partitioning, the simulation results indicate that the water levels in the downstream pond in all three partitioned pond design scenarios were reduced by half consistently. This creates additional water storing capacity in the downstream ponds, which could not be provided by the conventional pond. As the threat of climate change is alarming, with adverse weather and unpredicted rainfall patterns, it is demonstrated that the conventional dry pond could be modified with the proposed partitioning instead of building larger and larger structured ponds.

It is also demonstrated that one of the proposed partitioned designs, which is the 60:20 pond, could treat suspended solids better than the other two designs. This design, with the longest upstream pond among the proposed designs, functions like a sedimentation pond, which is proven by the simulated lowest flow rates and velocity profiles.

4. Conclusion

This paper elaborates on a system of dividing a large water tank into multiple smaller ones, which could perform better by assigning each sub-tank a specific objective. It works with complete tanks, as well as large dry ponds partitioned into two smaller ponds with one direction of flow. The three partitioned pond designs were formulated as 20:60, 40:40, and 60:20 and were compared with the conventional pond design. The modelling simulations using SWMM 5.0 showed constant peak water levels throughout the conventional pond with increasing peak flow rates and velocities when extended to future climate change scenarios. Post partition, the second pond produced 50% lower water levels and flow rates compared to the first. The velocity profiles along the pond were predicted to differ based on the pond design. The 60:20 pond was the only design that could slow down the velocities to <0.1 m/s, which promoted sediment settling.

Conflicts of Interest

The authors have no relevant financial or non-financial interests to disclose.

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