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# The Effectiveness of a Cylindrical Detention Pond (CDP) for Runoff Reduction

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Permeable pavements are a key storm water management measure employed both to attenuate surface runoff in urban areas and to filter urban storm water pollutants. Existing permeable pavements (PP) are design with the specific percentage porosity whereby enabling excess rainwater to infiltrate through the system and acting as a depression storage at the same time. Depression storage basically refers to the volume of water trapped in the depression when the precipitation of a storm reaches the ground and fills up all the depression before it can flow over the surface. Cylindrical Detention Pond (CDP) is an alternative paving material that may alleviate many of the hydrological problems caused by urban runoff from developed areas. CDP consist of three basic components: top cover, bottom cover and hollow cylindrical at the centre (300mm thickness). The hollow cylinder has an approximate 50 percent porosity from the total solid of component, which is every 1 inch (25 mm) of pavement depth can hold 0.5 inches (12.5 mm) of rain in theory. In this study, the depression storage rate of CDP was investigated under three different rainfall intensity scenarios which are 77mm/hr (low), 153mm/hr (medium), and 230mm/hr (heavy) respectively, whereby it functions to monitor the analytical trend line. The experiment was conducted in a model box in the laboratory under a fully saturated condition. It found that the CDP can perform to detain the water until 180 min of excess rainfall for all 2 year ARI, 5 year ARI, 10 year ARI, 20 year ARI, 50 year ARI and 100 year ARI with different rates. CDP's are able to reduce the runoff from up to 77% of the total rainfall volume. The result proved that the hollow cylindrical at centre of CDP was very effective in runoff volume reduction according to the different ARI trend line projections.

**Key words:** *Depression Storage, runoff reduction, Cylindrical Detention Pond, Permeable Pavement, Storm Water Management, Fully Saturated.*

## Introduction

In recent years, rapid urbanisation changes the land use by removing vegetation, green cover and replaces pervious areas with increases in impervious surface with proximity to premix roads and concrete (Pennington, Hansel, & Gorchov, 2010). Since the 1970's, the total population who were urban dwellers increased to 30 percent and even more surprisingly in the year 1991, the urbanisation had increase the population up to 50 percent and even kept on increasing from year to year until now. Urban developments will also increase to meet the need of these increasing urban populations. Therefore, the impact of development has become one of the major causes that lead to flooding and the natural hydrologic cycle is disturbed, where the infiltration rate and ground water recharges decreases, changes imposing high peak flows pattern of surface, and river runoff volume increases (Pennington et al., 2010; Zakaria et al., 2004; Humes, 2012)

Moreover, not surprisingly, the rate of flash flooding in urban areas in Malaysia in general is expanding severely from year to year. Many urban cities have also increased the speed of overland flow and the amount of runoff because gray infrastructure has been designed to move water off streets as quickly as possible through gutters, storm drains, sewer pipes and other engineered collection systems, and is discharged into nearby water bodies. Previously in Sarawak, a conventional drainage system has been designed to provide the fastest possible transport of storm water runoff out of the catchment into the receiving water as an effective mitigation of flash flooding (Othman & Aminur, 2012). Unfortunately, due to rapid development and high rainfall intensities, the conventional drainage system has led to high potential occurrence of flash flooding downstream of the catchments.

Therefore, permeable pavement (PP) is another alternative approach in stormwater management to replace the conventional impervious concrete and asphalt paver and purposely to prevent physical damage to persons and assets from flooding and to maintain the natural hydrologic cycle, reduce runoff volume, and to decrease peak flow pattern of the surface (Parkinson, 2010). Therefore, the Environmental Protection Agency (EPA) focused on studies more specifically to determine the efficiencies of numerous types of PP's for urban runoff control in the early 1970s. Many researchers have reported that PP's performances show the decrease of peaks flow rate and reduce runoff volume. According to the National Asphalt Pavement Association (NAPA), the concept of PP was suggested to allow percolation, reduce storm sewer loads, reduce floods, raise water tables, and replenish aquifers since the 20$^{th}$ century.

Permeable Pavement are widely suitable for a variety of residential, commercial and industrial applications (Scholz & Grabowiecki, 2007), although it is confined to light duty and infrequent usage; however, the capabilities of these systems allocate for a large extent range of usage and one of the best alternatives used in stormwater management. Researchers started to develop the new idea to produce the portable permeable pavement with a futuristic design, colour, is easy to install and user friendly. There are many variants for each of the PP depending on the design goals such as permeable concrete (PC), permeable asphalt (PA), permeable interlocking concrete pavers (PICP), concrete grid pavers (CGP), and plastic grid pavers (Othman & Aminur, 2012). However, all the existing PP is only to help rainfall water infiltrate into the sub-grade but not designed to store the rainfall water temporaryily at the same time. The major problem for each PP is durability, clogging and depression storage, where it will generate back the flash flooding problem (Weiss, Kayhanian, Khazanovich, & Gulliver, 2015).

PP is one of the active mitigation systems where runoff is able to be treated from other features on-site as well, including buildings, areas paved with conventional impervious concrete, and buffer zones. The total amount of runoff is less than the total rainfall because a portion of the rain is captured in small depressions in the ground (depression storage), some infiltrates into the soil, and some is intercepted by ground cover (California Department of Transportation, 2013). Moreover, Foster et al. (2011) also reported in their studies, that PP with suitable “sub-soiling” (maintenance of a porous layer of soil underneath) is able to reduce runoff volume within 70 to 90 percent and is the best medium with the void space that provides temporary storage. However, the temporary storage only can depend on the depression storage depth. A study showed that the depression storage only can hold back for plenty of rainfall in a limited time. Depression storage basically refers to the volume of water trapped in the depression when the precipitation of a storm reaches the ground and filled up all the depression before it can flow over the surface. Depression storage is a controlling storage part which contributes to most of the retention on a catchment surface area and does not appear as runoff (Mwendera & Feyen, 1992). Every PP has their owned depression storage and normally the depression storage is depending on the thickness of the pavement and the void ratio.

The advantage of depression storage is that the total runoff volume is decreased because a portion of the rain is trapped in small depression areas in the ground (depression storage), and some infiltrates into the subgrade. The size of the depression storage in the PP take a major role in the collection and storage of incoming precipitation, thereby modifying the runoff response of a watershed (Ullah & Dickinson, 1979). Moreover, according to Linsley et al., 1982, the volume of water in depression storage at any time during a precipitation event can be approximated as:

$$V = S_d \left(1 - e^{-kp_e}\right) \quad (1)$$

Where;
V is the volume of water in depression storage,
$S_d$ is the maximum storage capacity of the depression,
$P_e$ is the rainfall excess, and
k is a constant equal to 1/ $S_d$

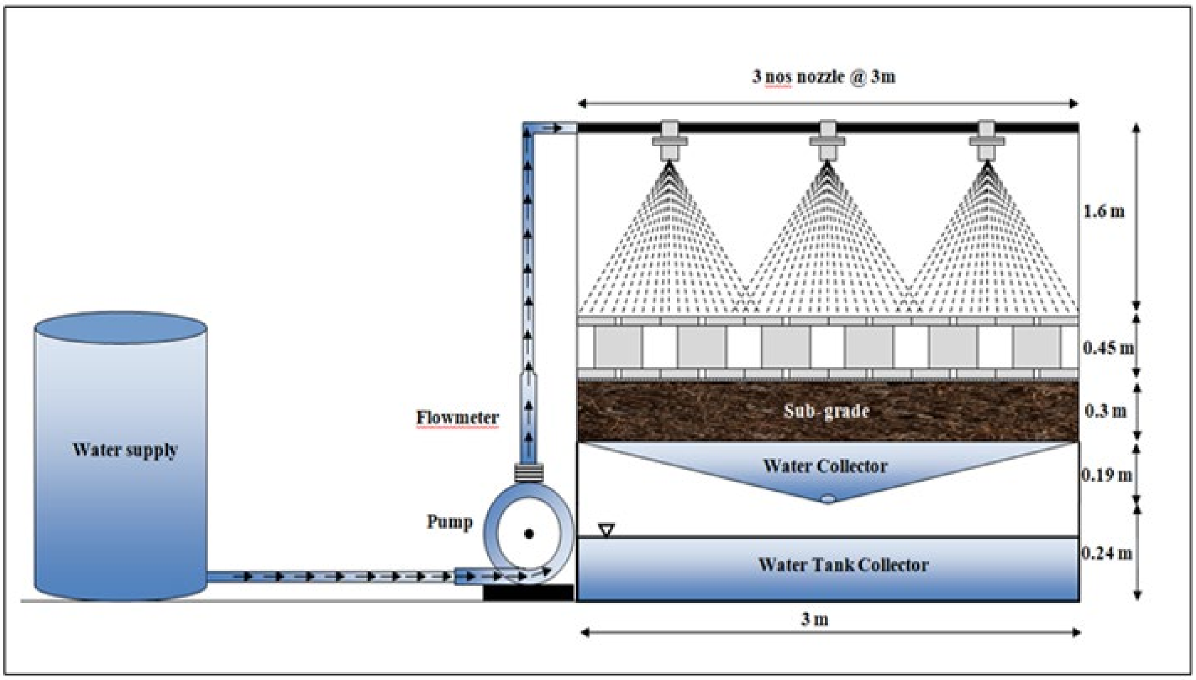
Moreover, the theoretical storage capacity of the PP is based on it's effective porosity which can be filled with rain in service. If the PP has 15 percent effective porosity, then every 1 inch (25 mm) of pavement depth can hold 0.15 inches (4 mm) of rain (Nehls, Menzel, & Wessolek, 2015). The storage capacity of a PP system is typically designed for specific rainfall events, which are dictated by local requirements. Therefore, Mannan, et al.(2015) produced the latest design for permeable pavement which is called a Cylindrical Detention Pond (CDP), where physically it is easy to install, is a small scale size, has high durability and purposely designed for infiltration and as a storage function. CDP acting as permeable pavement which is the concept design, is to allow water to infiltrate and at the same time be detained. The system consists of a hexagon shape at the top and bottom cover while the centre is made in a hollow cylinder shape, which has approximately 50 percent porosity. However, there are insufficiencies of information regarding the hydrological performance for the system and the depression storage rate at the same time of the system as a PP.

With that in mind, the aim of this study is to investigate the performance of the depression storage rate of CDP under a variety of rainfall intensity. The exploration starts by outlining the problem relevant to the PP in relation to the current literature and defining the research direction in line with the current body of knowledge. A comprehensive investigation was carried out under fully saturated conditions.

## Material and Method

The research and experiments were conducted in a laboratory scale setup developed at the Faculty of Engineering, Universiti Malaysia Sarawak. The experimental was set up as shown in Figure 1 below.

**Figure 1.** Schematic Diagram for Experimental Laboratory Setup.




Equipment used to determine the optimum volumes of CDP are, 23 nos. of CDP, Green Pavement Box, and a Pavement Box with the size of 3m (Wide) x 1.305m (Length) x 0.96m (Height) were arranged and installed with 23 nos. of CDP on the peat soil as shown in Figure 2. The CDP was tested under a fully saturated condition in order to determine the optimum volume of the cylinder detention pond under various rainfall intensities using three numbers of full cone nozzle types with the outflow capacity up to 27 Litre Per Minute (LPM) in a circular spray pattern with 3.58mm of orifice diameter and located in a series at a height of 1.6m centre to centre from surface CDP, with the maximum angle distribution up to 103°.

The rainfall intensity was divided into three categories i) Low rainfall intensity (77 mm/hr) ii) Medium rainfall intensity (153 mm/hr) and iii) High rainfall intensity (230 mm/hr). The rainfall intensity was performed up to 3 hours and the water depth and volume discharge were recorded for every 1 minute interval.

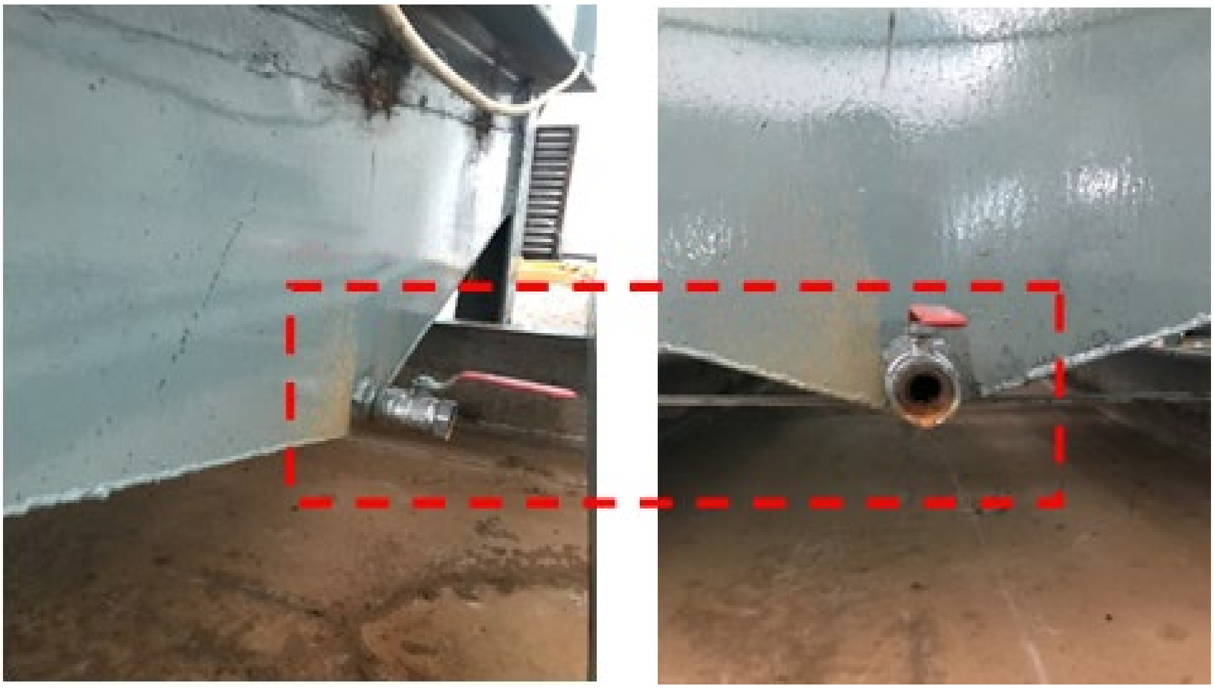
90 percent density compaction of Peat soil as a sub-grade in 350mm thickness was layered below the CDP and soaked into the water for 24 hours to keep it under a fully saturated condition and in part to maintain the water content and degree of saturation, Sr in 100% (Figure 3). Therefore the outlet of the Green Pavement Box was closed and allowed the upward vertical movement of water only, as no infiltration on the sub-grade was allowed (Figure 4). The water table of ground water was set up at the same level of the sub-grade. The incremental of water depth and volume discharge were recorded for every 1 minute interval. The reason to keep the subgrade (peat soil) into fully saturated condition is to ensure that

there are no infiltration processes occurring on the subgrade and to let the rainwater keep on increasing from the bottom of the CDP system to the top.

**Figure 2.** Installation Process of CDP on the Peat Soil.

**Figure 3.** Sub-Grade Soaks into Water for 24 Hour.

**Figure 4.** Outlet Close Panel.



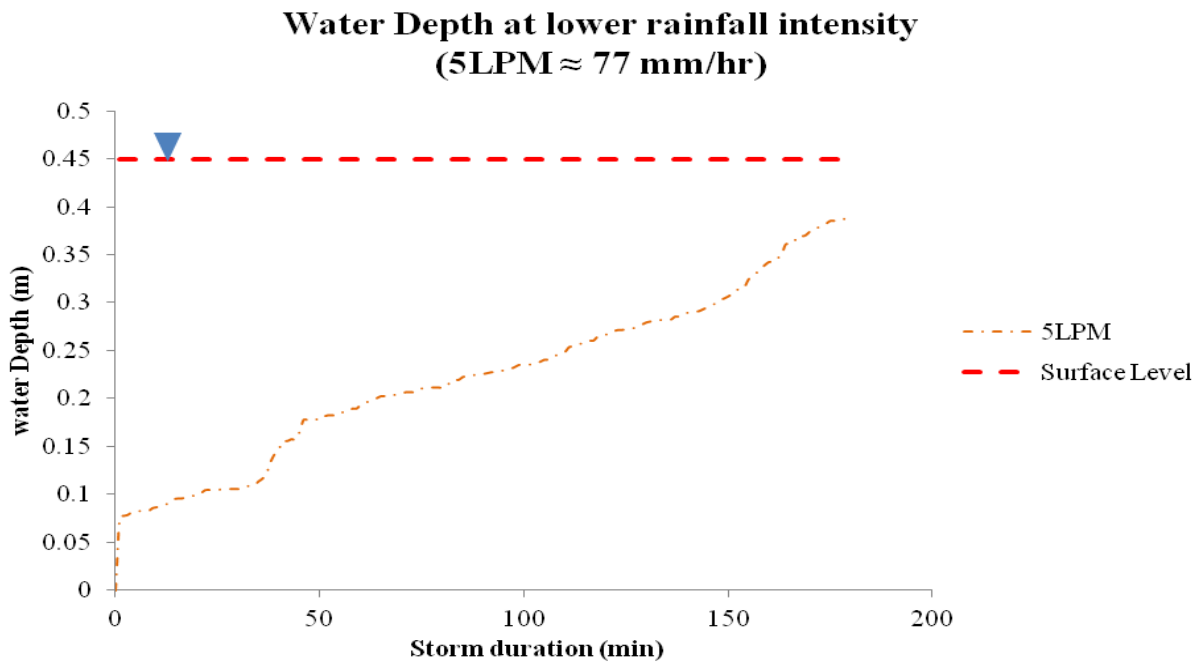
## Results and Findings

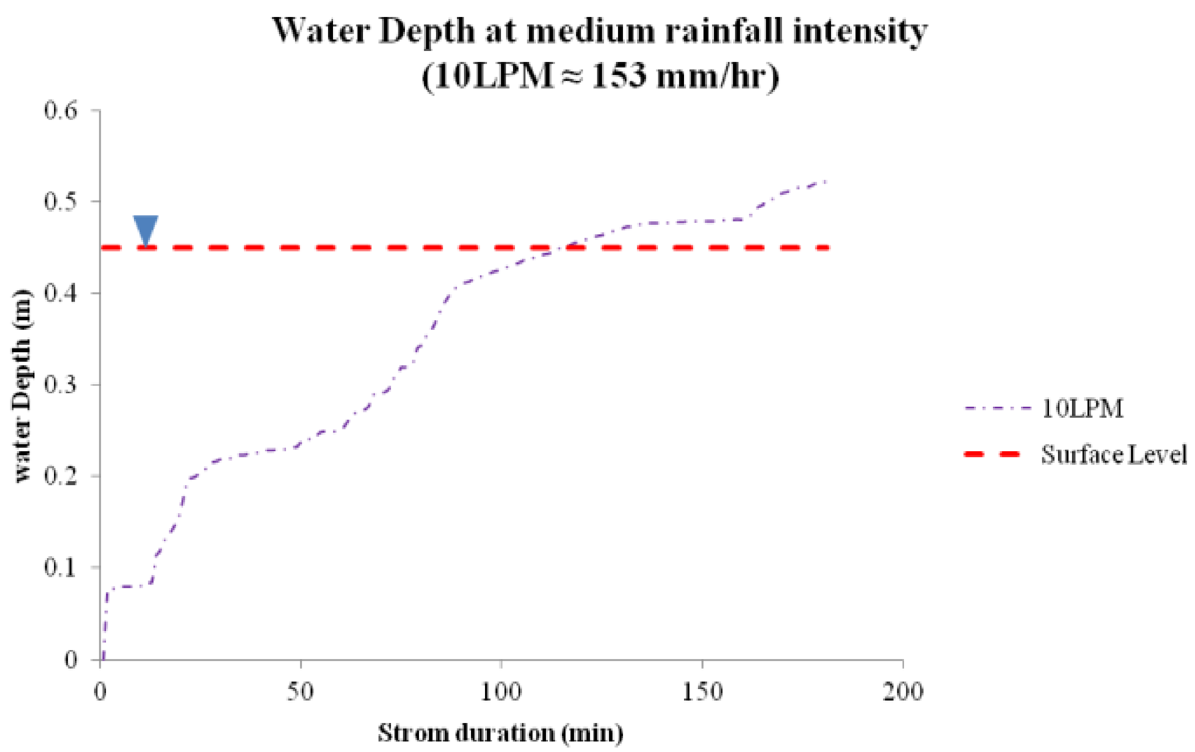
### *Water Depth Versus Storm Duration (Experimental)*

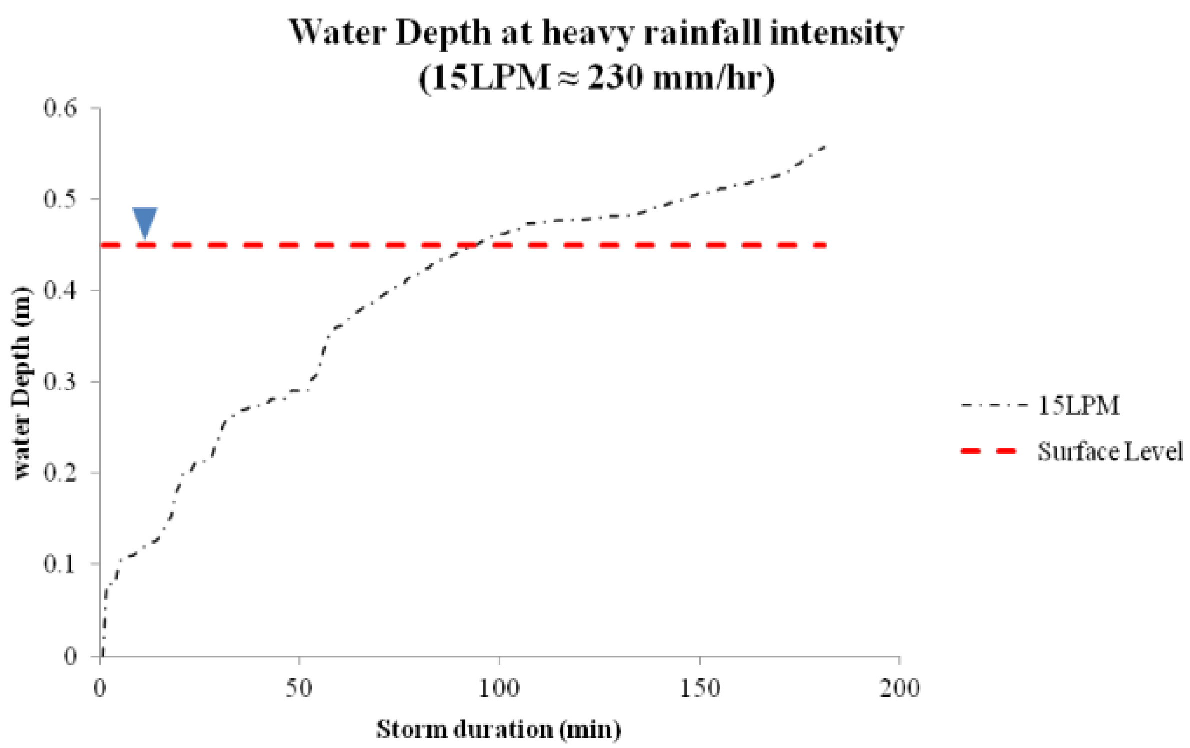
Figure 5 shows the experimental curve for time against water depth for CDP under three different types of rainfall intensity (77 mm/hr, 153 mm/hr and 230 mm/hr). Altogether, it can be seen that water depth increases in direct proportion to the time representing 3 hours duration of rainfall. In the view of the result obtained, water started to overflow on the surface of the CDP system after 110 min and 83 min for 153mm/hr and 230mm/hr rainfall intensity respectively. It is realised that the system is not able to cater for the remaining amount of rainfall for medium and heavy rainfall intensity. However it can be observed that at 77mm/hr rainfall intensity the water depth was still below the surface level.

From the result, this indicated that the CDP system only can cater for the specific amount of volume water based on the size design. Previous study has shown that the existing permeable pavement only allowed water to infiltrate into the groundwater but not function as detention, but the CDP was designed to able allowed water to infiltrate and at the same time to detain the water. However due to the limitation sized design, the CDP only can cater the specific amount of water with the limitation of duration.

**Figure 5.** Experimental Depression Storage Depth at Rainfall Intensity 77 mm/hr, 153 mm/hr, and 230 mm/hr.




Water Depth at medium rainfall intensity
(10LPM ≈ 153 mm/hr)
0.6
0.5
0.4
0.3
0.2
0.1
0
water Depth (m)
0
50
100
150
200
Strom duration (min)
10LPM
Surface Level

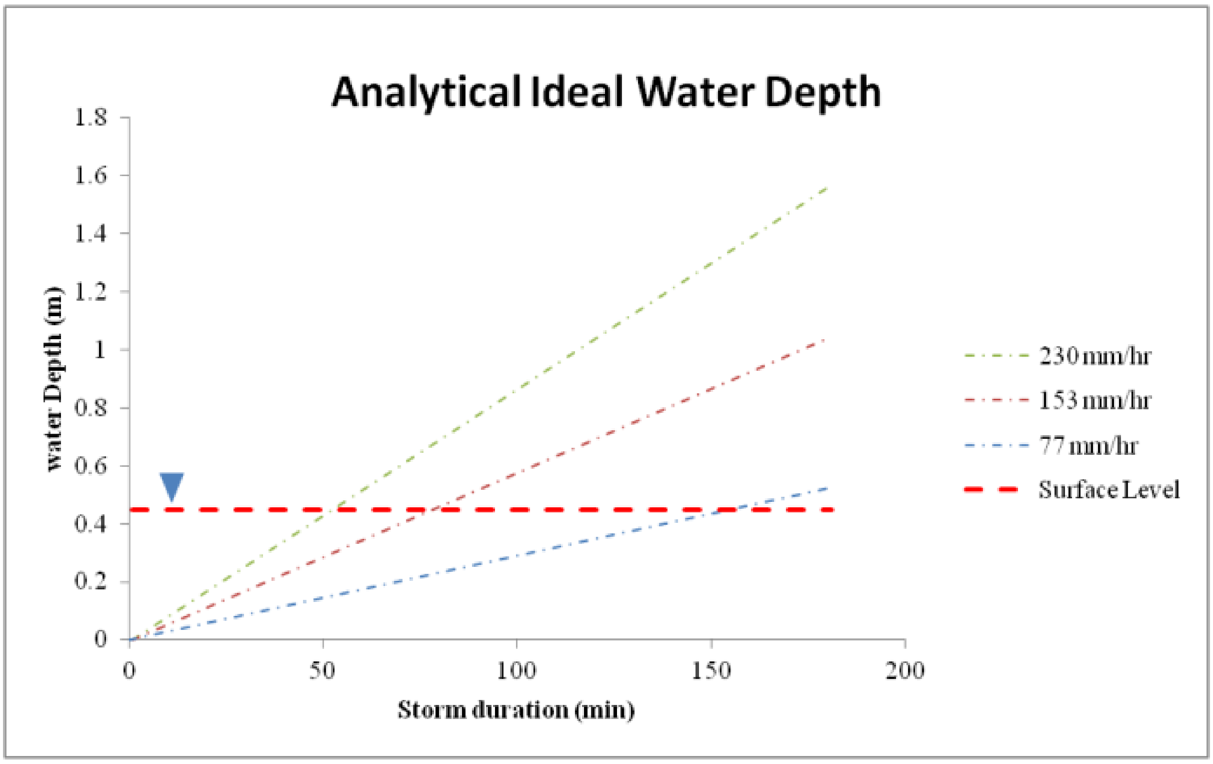

Water Depth at heavy rainfall intensity
(15LPM ≈ 230 mm/hr)
0.6
0.5
0.4
0.3
0.2
0.1
0
water Depth (m)
0
50
100
150
200
Storm duration (min)
15LPM
Surface Level

***Water Depth Versus Storm Duration (Analytical)***

Figure 6 illustrate the estimation of the analytical ideal water depth. The estimation was conducted according to the mathematical formula to determine the increases of water depth in the CDP system against time. As can be seen from the graph the water depth increases linearly proportional when the time increases, until the 180 min storm duration is reached. In contrast, it is apparent that the incremental water to reach the surface level for the three types of rainfall intensity tested is fastest compared to the experimental result. This is subjected to other reasons.

In view of the result obtained, the estimation mathematical formula was conducted in the ideal form in which there are no resistance accesses such as, the cover, and the path of rainfall to reach at the ground of the system compared to the experimental result. Therefore, the water depth increases smoothly without any resistance. As previously discussed the analytical model represents performance in ideal conditions without any resistance. Thus it is believed that the analytical is a platform to monitor the experimental result in order to see the pattern and the trend of the result, which was not out of the boundary. Therefore in order to decrease the range between the experimental and analytical result, the estimation based on these variable should be noted.

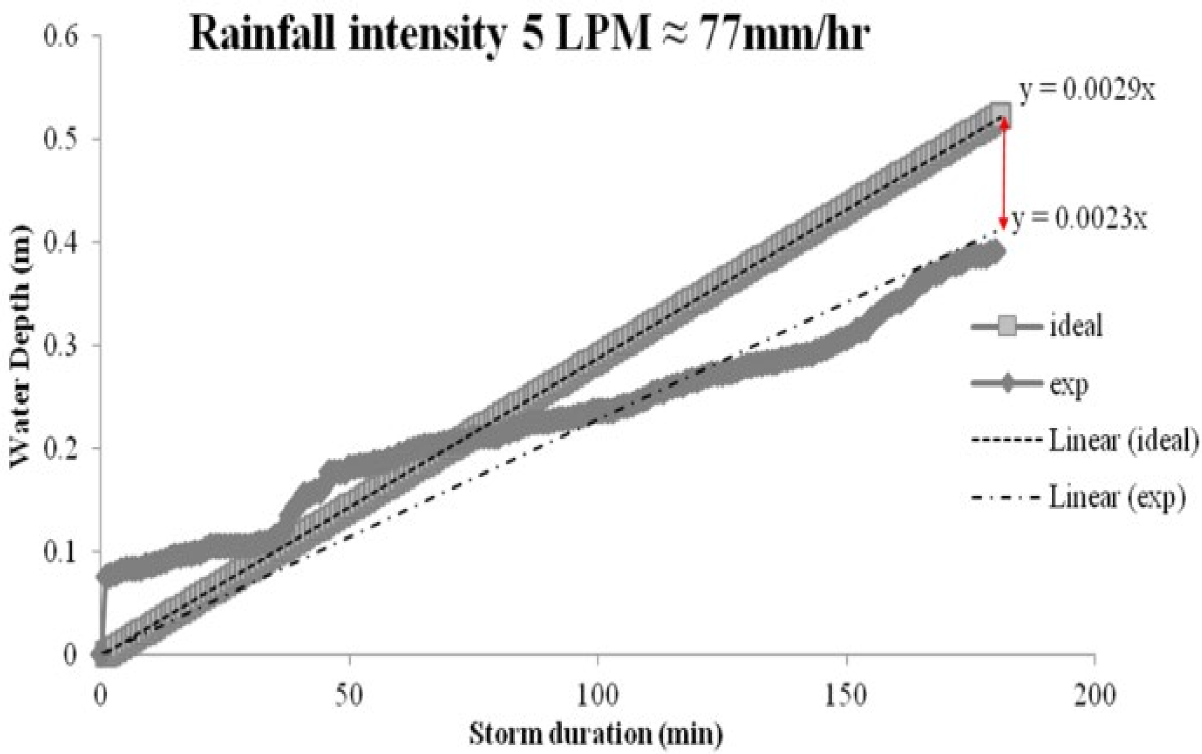
**Figure 6.** Analytical Ideal Depression Storage at Three Different Type of Rainfall Intensity.

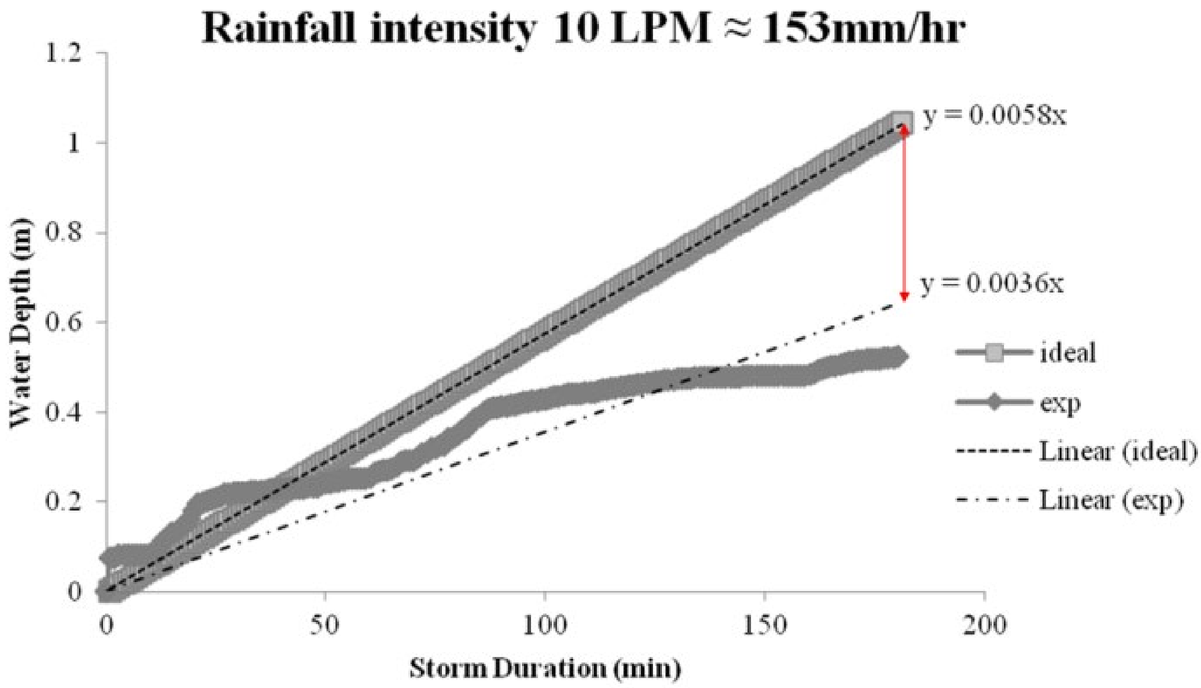


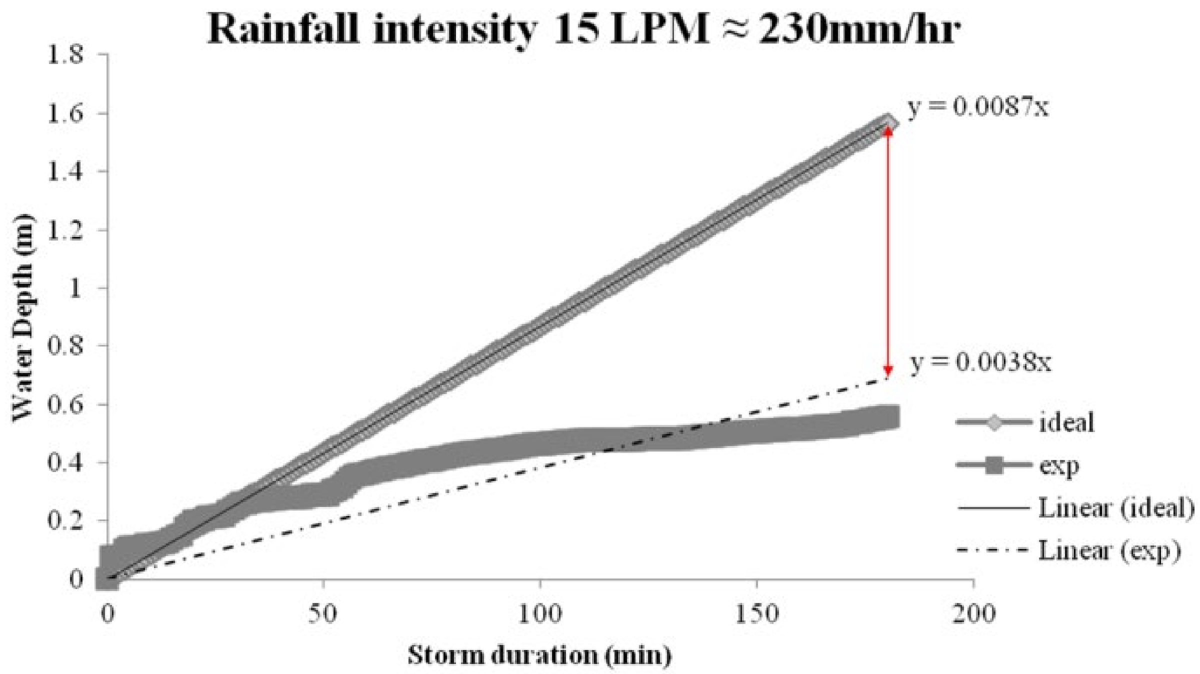
**Comparison between Experimental against Analytical Trend Line (Water Depth Versus Storm Duration)**

Figure 7 shows the trend line between the analytical ideal and experimental data for storm duration against water depth. There was little difference between the analytical and experimental data for all three types rainfall intensity tested. It can seen that the experimental trend line appears at slightly below the analytical trend line. The decreases of the water depth for the experimental were showing the losses of the volume water from the total volume in a 3 hour duration. According to the fully saturated condition, the total amount of output volume should be the same as the amount of input.

**Figure 7.** Comparison Trend Line between Analytical Ideal and Experimental at Rainfall Intensity 77 Mm/hr, 153 Mm/hr and 230mm/Hr






All the processes are deliberately organised to happen in order to see any possibility of water losses. Therefore, three different rainfall intensities are used on the similar CDP system in order to see the movement of water if the subgrade state is not in a fully saturated condition. The water budget concept was applied to this situation.

By referring to the theoretical water budget equation, mass inflow is equal to the mass outflow. However, from the calculation, the total volume after a 3 hour rainfall obtained less compared to the analytical ideal volume. This reduction related to the volume of the collector where it is located below to the sub grade, which is a part of the component in the pavement box. Therefore, from the calculation to verify the reduction of the total amount of water, it was found that the amount of water decreased is equal to the amount of water in the collector and the soil.

**Table 1:** Total Volume Clarification Distribution

| | 5 | 10 | 15 | Unit |
|---|---|---|---|---|
| | LPM | LPM | LPM | |
| Total Volume inflow after 3 hour | 0.9 | 1.8 | 2.7 | $m^3$ |
| Total Rainfall Volume after 3 hour (Experimental) | 0.67 | 0.9 | 0.96 | $m^3$ |
| Total volume infiltrate to collector ($S_g$) | 0.71 | 0.71 | 0.71 | $m^3$ |
| Total volume trapped in the soil ($S_{sm}$) | 0.00 | 0.19 | 1.03 | $m^3$ |

Table 1 above showed the clarification distribution of the water losses. The reduction volume at the experimental data showing that the water was flowing into the collector, which is the amount of volume in the collector, is equal to the amount of volume reduction.

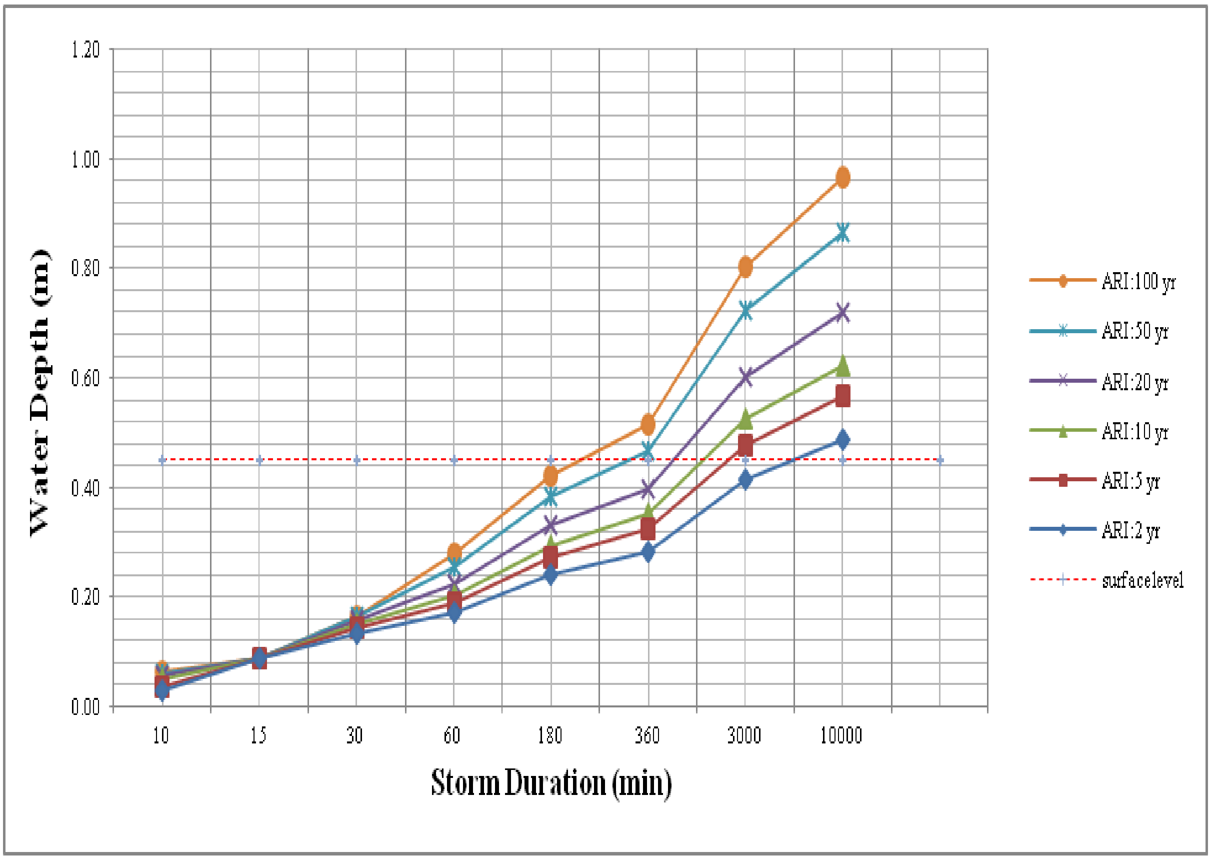
This could be attributed to the water budget equation where the storage, S consisted of three components as surface water storage($S_s$), water storage as soil moisture($S_{sm}$) and water in storage as groundwater($S_g$). Therefore, the reduction volume from the experimental data was showing by infiltration into the groundwater ($S_g$) and in the soil ($S_m$) as remaining. In this case, the groundwater was referred to the water collector while the soil referred to the subgrade component in the pavement box as shown in Figure 7. In addition, the clarification regarding the reduction volume of water outflow was made by proving that using the water budget concept and the amount of water at the collector and in the soil is equal to the amount of reduction.

$$S = S_s + S_{sm} + S_g \quad (2)$$

***CDP Depression Storage Performance under Various ARI's***

Figure 8 shows the water depth of runoff that could be generated on the 3m x 1.305 m experimental project according to different Average Recurrent Intervals (ARIs) and storm durations in Samarahan. It was designed to withstand 3-hours of a continuous 10-year ARI design storm. Moreover, from this trend line, it can give the earlier estimation of the water depth for every single ARI's in designation. Illustrated in the same figure, it shows that the experimental project could capture fully stormwater of less and more frequent storms. Moreover, the CDP able to cater for the number of volume rainfall up to 180 min storm duration at different rainfall intensity according to the ARI's trend line graph. Therefore, according to this experimental project graph below, the CDP applicable to be installed into a large area and still can cater for the volume of rainfall. However this graph was applicable for a design 3m x 1.305m catchment area. Different of size catchment areas will generate a different number of volume rainfalls.

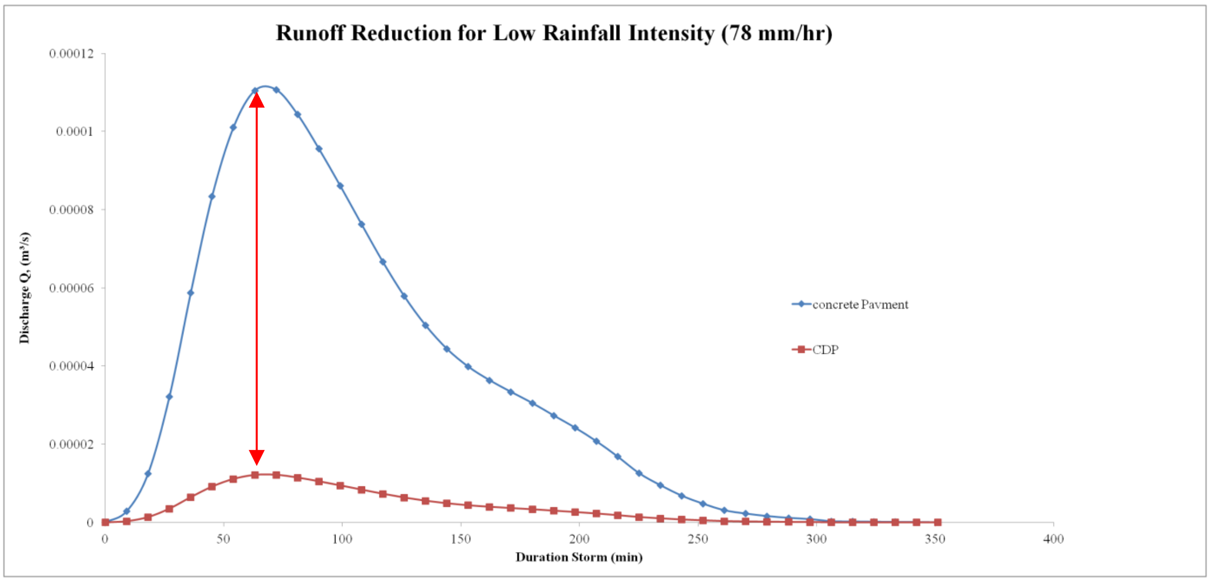
**Figure 8.** Generated Water Depth on the Pavement Box (Laboratory Experimental).

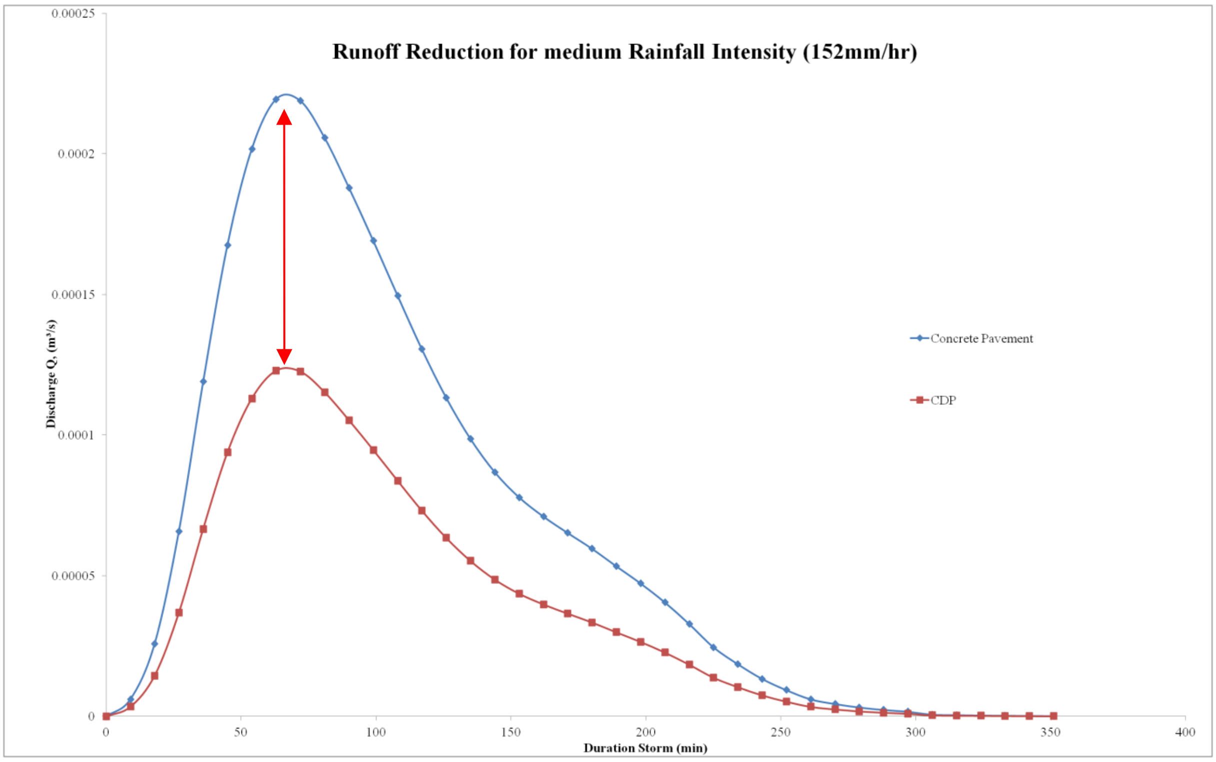


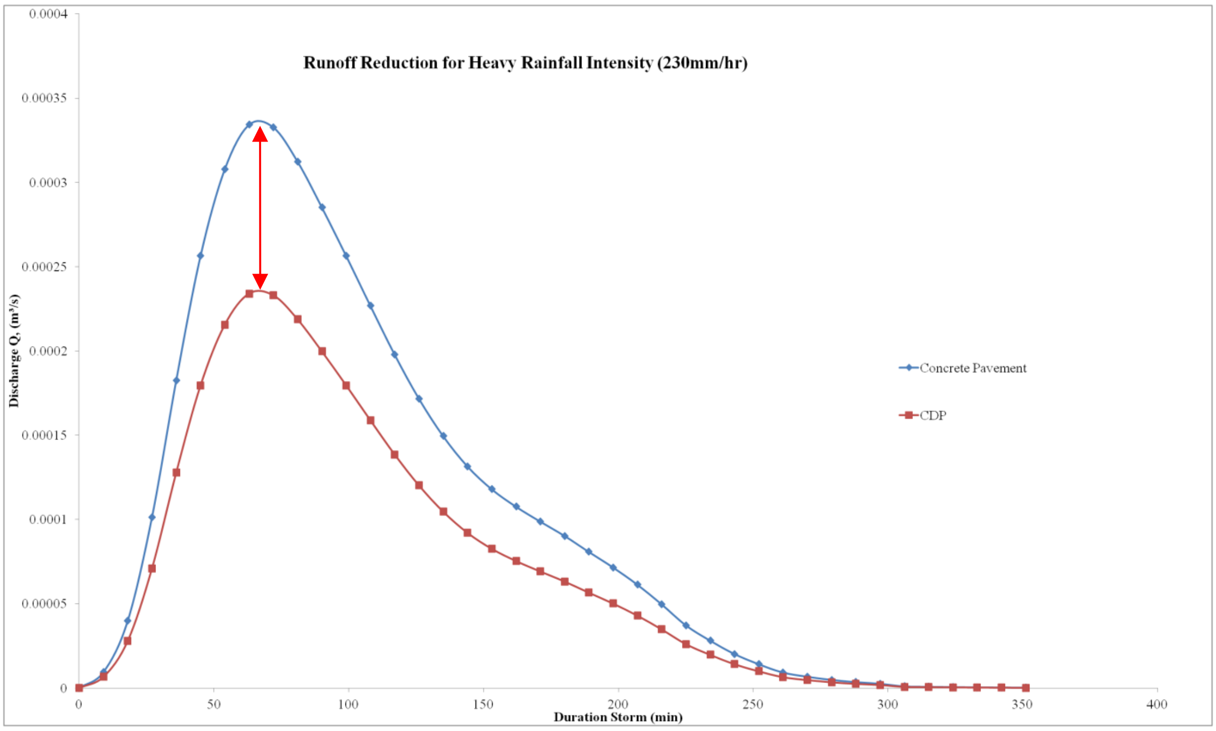
***Runoff Reduction on CDP and Concrete Pavement under a Variety of Rainfall Intensity***

Figure 9 shows the runoff discharge on three various rainfall intensities (Low, Medium and Heavy). The distribution graph shows that the CDP produce a low discharge compared to concrete pavement when both used sub-grade facing under a fully saturated condition. Concrete pavement produced a high distribution discharge on runoff because this component only functioned to allow water infiltrated into the soil stratum through the small void area, while the CDP function allowed the water infiltrated and at the same time stored in temporary duration in the depression storage, and the sub-grade is fully saturated. From the distribution curve runoff below, CDP was able to reduce the runoff up to 77% of the total rainfall volume and the depression storage of CDP was able to detain the water for up to 3 hours under heavy rainfall intensity.

**Figure 9**. Runoff discharge on CDP and concrete pavement under variety rainfall intensity




Runoff Reduction for medium Rainfall Intensity (152mm/hr)
Discharge Q, (m³/s)
Duration Storm (min)
Concrete Pavement
CDP
0.00025
0.0002
0.00015
0.0001
0.00005
0
0
50
100
150
200
250
300
350
400


Runoff Reduction for Heavy Rainfall Intensity (230mm/hr)
Discharge Q, (m³/s)
Duration Storm (min)
Concrete Pavement
CDP
0.0004
0.00035
0.0003
0.00025
0.0002
0.00015
0.0001
0.00005
0
0
50
100
150
200
250
300
350
400

## Conclusion

From the present study, it can be concluded that the CDP system is one of the best alternative in stormwater management as a permeable pavement design. This work was devoted to assess the capability of the CDP to predict the optimum depression storage capacity under a fully saturated condition. This was performed by investigating the variety of rainfall intensity on the effective catchment area. An experiment was carried out to determine the depression storage capacity of CDP on the fully saturated condition. From the projection graphical trend line of ARI, the CDP can detain the rainfall water for up to a 3 hour storm duration without any failure. It found that the depression storage of CDP can perform to cater for the water until 180 min excess rainfall for 2 year ARI, 5 year ARI, 10 year ARI, 20 year ARI, 50 year ARI and 100 year ARI with different rates. Moreover, it was found that CDP had the greatest permeable pavement in stormwater management according to the projection trend line graph.

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