PERMEABLE ROAD PAVEMENT WITH SUBSURFACE PRECAST MICRO-DETENTION STORAGE: A GREEN PAVEMENT PRACTICE

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PERMEABLE ROAD PAVEMENT WITH SUBSURFACE PRECAST MICRO-DETENTION STORAGE: A GREEN PAVEMENT PRACTICE

ABSTRACT

Green infrastructure practices are uniquely applicable to address the relationship between land use and water resources through the replication of the natural hydrological process within the landscape. Implementation of such practices, especially green pavement can significantly improve the rainfall-runoff responses, and thereby minimise the occurrence of flood hazards, which may lead to uncountable economic losses. Common permeable pavements are typically composed of fine-layered particles attributed to low porosity. In this study, an innovative permeable pavement with a micro-detention pond storage (PPDS) system is proposed. It is a modified type of interlocking block permeable pavement consisting of a hollow cylinder with a hexagonal cover at the top and bottom of the PPDS. The PPDS is designed with a void volume of 70% and a water storage capacity of 0.19 m^3/m^2. The system can serve as an alternative for green pavement application as it meets all the principal criteria, particularly integrating the permeable and porous pavement with void spaces to store and recycle stormwater, attenuate the peak discharge, etc. A rainfall simulator is used to test the profile of the hydrological pavement, such as the storage capacity, detention period, permeability rates and infiltration performance over various storm events. The system performance is verified via simulation of storm water management model (SWMM), a product of US environmental protection agency (USEPA). The observed performances indicate that the PPDS has met the basic hydrological design considerations, like those in the typical permeable pavement, from the perspective of permeability rates, infiltration capacity, storage and detention capability. A case study is then developed to assess the hydrological impacts of PPDS and compared it with the

conventional road pavement and other types of permeable pavements, such as pervious concrete (PC) and permeable interlocking concrete pavers (PICP). The PPDS results in higher runoff reduction, the lowest runoff coefficients, and peak flowrate. It also demonstrates faster infiltration of rainfall into ground with a higher rate of infiltration loss in comparison to those recorded for PC and PICP. These results demonstrate the effectiveness of PPDS as a permeable pavement with the presence of subsurface micro-detention storage. Hence, it is concluded that PPDS is a better practice in minimising runoff for stormwater management.

Keywords: Green Infrastructure, Hydrological Performance, Permeable pavement, Rainfall Simulator, SWMM LID practice.

JALAN RAYA TELAP AIR DENGAN PENGGUNAAN PRA TUANG PENYIMPANAN SUBPERMUKAAN TANGKI MIKRO: AMALAN PRAKTIS HIJAU

ABSTRAK

Amalan infrastruktur hijau adalah unik digunakan bagi menangani hubungan di antara penggunaan tanah dan sumber air melalui replikasi proses hidrologi semula jadi di dalam landskap. Pelaksanaan amalan sedemikian, terutama jalan raya hijau boleh meningkatkan tindak balas hujan dan air larian, dengan itu mengurangkan kejadian banjir yang boleh membawa kepada kerugian dari segi ekonomi. Jalan raya telap air yang biasanya digunakan adalah berbentuk lapisan partikel berongga halus yang menyumbang kepada keliangan yang rendah. Dalam kajian ini, satu inovasi telah dicadangkan, iaitu jalan raya telap air yang menggunakan sistem penyimpanan sub-permukaan tangki mikro (PPDS). Pengubahsuaian adalah bentuk silinder yang mempunyai tangki simpanan air dalam skala mikro dan juga terdiri daripada penutup atas dan bawah berbentuk heksagon yang terkunci sesama sendiri. PPDS telah direkabentuk dengan jumlah kapasiti simpanan sebanyak 70% dan isipadu air berjumlah 0.19 m^3/m^2. Sistem ini dijadikan alternatif untuk teknologi hijau iaitu jalan raya telap air kerana ia memenuhi semua kriteria utama, terutamanya mengintegrasikan laluan yang boleh telap dan mempunyai liang rongga, iaitu silinder dengan tangki air untuk menyimpan dan mengitar semula air ribut, mengalirkan ribut pada pelepasan puncak, dan sebagainya. Rumah hujan digunakan untuk melaksanakan ujikaji profil dan parameter hidrologi seperti kapasiti simpanan, tempoh masa tahanan, kadar penyusupan dan penyerapan bagi pelbagai kondisi ribut. Prestasi sistem disahkan melalui simulasi model pengurusan air ribut (SWMM), sebuah produk daripada agensi perlindungan

alam sekitar, US (USEPA). Keputusan ujian menunjukkan bahawa PPDS telah memenuhi pertimbangan reka bentuk hidrologi asas, seperti yang terdapat di dalam jalan raya telap air yang sedia ada, dari perspektif kadar penyerapan dan penyusupan, kapasiti penyimpanan dan masa tahanan. Satu kajian kes kemudian dilakukan untuk menilai impak hidrologi PPDS dan dibandingkan dengan jalan raya sedia ada dan jalan raya telap air jenis lain seperti konkrit telap air (PC) dan konkrit pratuang terkunci (PICP). PPDS menghasilkan pengurangan air larian yang lebih tinggi, pekali air larian dan kadar larian puncak terendah,. Keputusan ini menunjukkan keberkesanan PPDS sebagai jalan raya telap air dengan kehadiran tempat penyimpanan kosong berskala mikro pada sub-permukaan jalan. Oleh itu, disimpulkan bahawa PPDS merupakan amalan yang baik dalam mengurangkan air larian untuk pengurusan air ribut.

Keywords: Infrastruktur hijau, prestasi hidrologi, jalan raya telap air, rumah hujan, SWMM.

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LIST OF SYMBOLS

a	:	Decay coefficient
d_1	:	Depth of ponded surface water
d_2	:	Depth of water in storage layer
f	:	Infiltration rate
f_i	:	Initial infiltration rate
f_1	:	Surface infiltration rate
f_2	:	Soil percolation rate
f_3	:	Soil infiltration rate
i	:	Rate of precipitation
$I(t)$	:	Inflow rate
$O(t)$	:	Outflow rate
q	:	Runoff rate
q_0	:	Externally supplied surface runon
q_1	:	Surface runoff flow rate
R^2	:	Coefficient of determination
t	:	Time
t_c	:	Time of concentration
$\Delta s(t)$	:	Change of storage capacity
x, n, $\bar{x}$	:	Depth, number and average of the rainfall measurements
Y_i^{obs}	:	Observed discharge at i-th time
Y_i^{sim}		Simulated discharge at i-th time step
Y_i^{mean}		Mean observed discharge at i-th time step

LIST OF ABBREVIATIONS

ACPA	:	American Concrete Paving Association
AP	:	Asphalt Pavement
ARI	:	Average Recurrence Interval
BMP	:	Best Management Practice
CN	:	Curve Number
CU	:	Christiansen Uniformity Coefficient
CGP	:	Concrete Grid Paver
DID	:	Department of Irrigation and Drainage
ICPI	:	Interlocking Concrete Pavement Institute
LID	:	Low Impact Development
NSE	:	Nash-Sutcliffe efficiency
PA	:	Porous Asphalt
PC	:	Pervious Concrete
PICP	:	Permeable Interlocking Concrete Pavement
PP	:	Permeable Pavement
PPDS	:	Permeable Pavement with micro-Detention Storage
RM	:	Rational Method
RMSE	:	Root Mean Squared Error
RPD	:	Relative Percentage Difference
RS	:	Rainfall Simulator
SUD	:	Sustainable Urban Drainage
SWMM	:	Stormwater Management Manual
USWM	:	Urban Stormwater Management
US EPA	:	United States Environment Protection Agency

WSUD : Water Sensitive Urban Design

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

1.1 Introduction

Stormwater management is important to achieve sustainable development, which balances the elements, such as environmental protection, economic growth and social consideration, while planning for a development project. One of the major source control measures in stormwater management is the application of green infrastructure. From the aspect of hydrological function, it can be categorised into the infiltration-based and retention-based system. Infiltration-based systems include permeable pavements, swales, infiltration trenches, basins and unlined biofiltration systems, which have the ability to infiltrate and retain runoff. Meanwhile, retention-based systems consist of detention ponds, tanks, lined biofiltration systems, green roofs and wetlands, which play the role of runoff volume reduction through retention (Szota et al., 2019). Nonetheless, the integration of both practices is imperative to enhance the overall effectiveness (Li et al., 2019). Applications that involved the integration of green infrastructure techniques had been proven to effectively reduce flood, peak discharge and subsurface runoff in comparison with a single facility (Ahiablame & Shakya, 2016; Hoghooghi et al., 2018; Matos et al., 2019; Rodríguez-Sinobas et al., 2018).

In this study, a modified permeable pavement design is introduced as a stormwater management infrastructure. It is a precast honeycomb lightweight-structure, designed for dual function as permeable road pavement and subsurface detention pond. The permeable pavement with micro-detention storage (PPDS) is basically a product of multipurpose road pavement for urban areas that is not only able to accommodate traffic loads, but also to convey the stormwater. The main idea is to utilise the spaces of the road subsurface layer for micro- stormwater detention storage. The permeability of the system is accomplished through the underneath drainage, which acts as a water-holding system to enhance the void capacities, and as subsurface detention storage in micro-scale to retain the water.

The detention storage is a hollow cylinder/vessel residing beneath the subsurface of the pavement. The modified feature consists of micro-detention storage, which is made up of cylindrical hollow container in between (300 mm thick, inner diameter 280 mm) and hexagonal shape at the top surface and bottom plate (75 mm thick, 150 mm of perimeter length). The top cover acts as road pavement, the bottom cover serves as base plate and raft foundation and the hollow cylinder plays a role as micro-detention storage. PPDS is a user and environmental friendly product and designed to be applied at low-speed road especially parking lot, business centre and housing area. The conceptual design of the PPDS road system is illustrated in Figure 1.1 (Bateni et al., 2019).

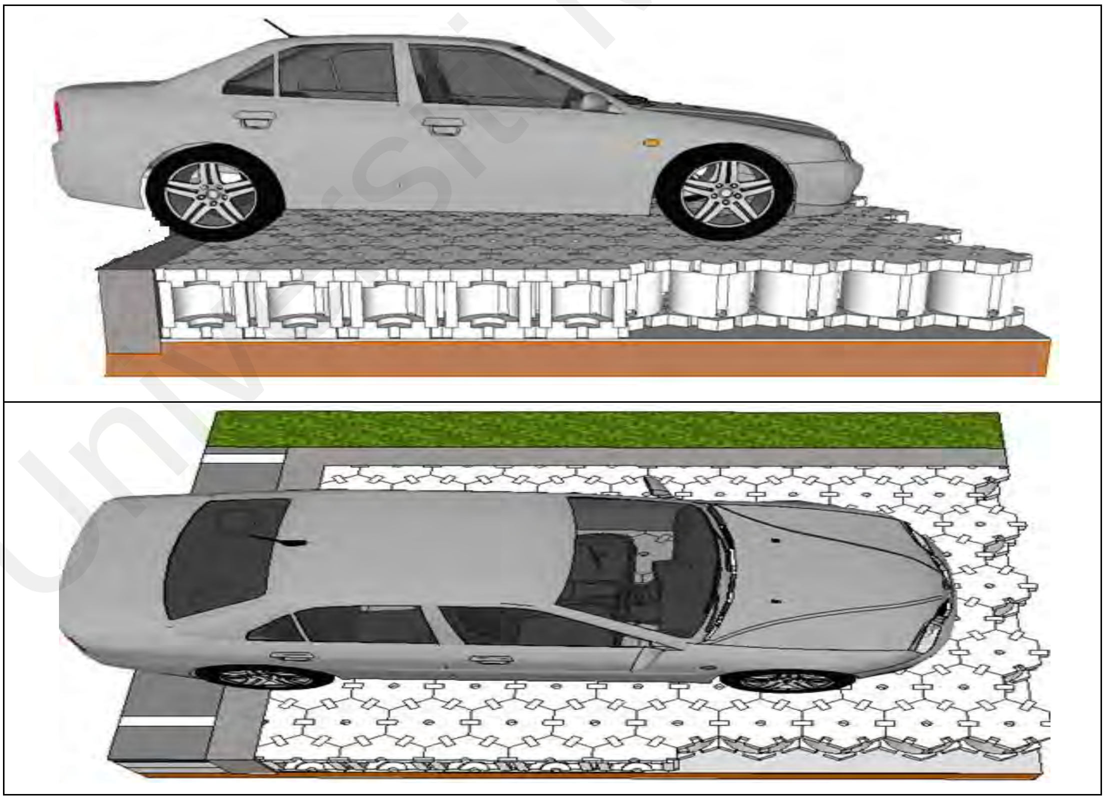


Figure 1.1: Conceptual design of modified stormwater management infrastructure, PPDS with interlocking pavers (Source: Bateni et al., 2019).

1.2 Problem statement

Urbanisation foresees the possibility of the fatal flash flood occurrences, especially in urban areas with higher population density (Ahiablame et al., 2012; Fletcher et al., 2013). As reported by Cohen (2003), the rate of urbanization is predicted to rise from 75% in 2000 to 83% in 2030 in developed countries, whereas in developing countries, it is estimated to reach 56% from the current 40%.

Urbanisation has imposed several negative impacts on hydrological processes due to the reduction of pervious areas, where a higher runoff volume (Eckart et al., 2017; Schütte & Schulze, 2017) and peak flow rate, as well as a lower infiltration rate and groundwater recharge, have been recorded (Dietz, 2007). Urban runoff has been known as a major cause of the fatal flash floods, particularly in high density urbanised city. Therefore, due to the depletion in groundwater recharge associated with the decrease of the pervious surface as a result of rapid development, it may increase the flood events. Hence, it is essential to have proper yet effective mitigation measures for the issue mentioned above (Wong, 2007; Khan & Geiss, 2012; Schütte & Schulze, 2017).

Apart from that, conventional approaches in stormwater management only focus on the peak flow reduction but not the runoff volume. Therefore, it may lead to the occurrence of floods in downstream areas due to excessive runoff. The traditional concrete pavement has a major drawback, where it does not allow infiltration of rainwater into the subsurface and, thereby settles down to the ground due to its impermeability (Hein & Schaus, 2013). Such a condition has disturbed the natural hydrological cycle where infiltration rate to the ground is lesser but runoff volume is higher (Kayhanian et al., 2015).

In fact, to properly maintain watercourses and achieve flood mitigation purposes, the relevant agencies have proposed several ideas, such as urban stormwater management in

Malaysia (Department of Irrigation and Drainage, 2012), low impact development in the United States (US EPA, 2000), water sensitive urban design (WSUD) in Australia, sustainable urban drainage (SUD) in the United Kingdom, etc. for the source quantity control of urban runoff. Stormwater management is crucial to preserve environmental sustainability while reducing the occurrences of disasters. Environmental preservation can be achieved through optimal stormwater collection and storage, thereby reducing the runoff volume.

As the major surface-covered structure, the road system shows great potential to play a significant role in flood mitigation planning. As part of stormwater management, permeable pavement (PP) has been widely used since 1982 in USA and 1990s in Canada, Europe and Japan for stormwater control (Drake, 2013). The PP has been proven effective in infiltrating stormwater (Barszcz, 2015), reducing runoff volume (Lin et al., 2014; Timm et al., 2018) and peak flow (Lee et al., 2010; Hein & Schaus, 2013). Although PP can significantly contribute to environmental sustainability, the main challenge while applying PP is its design. It is highly vulnerable to clogging and periodic maintenance/cleaning is needed to ensure its functionality (Kia et al., 2017). PP is commonly designed with aggregate materials, which are invented with voids to ensure their pervious and porous characteristics. Therefore, it is prone to clog. Due to the blocking of debris and fine particles in the pore spaces, the system can be disconnected easily (Kia et al., 2017; Mishra et al., 2013; Korkealaakso et al., 2014; Marchioni & Becciu, 2015; Xie et al., 2019). Numerous studies have reported that the clogging issue in PP causes the reduction of permeability and infiltration rates (Yong et al., 2010; Coleri et al., 2013; Lucke et al., 2013; Mishra et al., 2013; Brugin et al., 2017; Kamali et al., 2017; Razzaghmanesh & Beecham, 2018; Razzaghmanesh & Borst, 2018; Zhang et al., 2018).

It has become a common trend where PP is designed for multipurpose uses, such as road pavement and detention storage. It is a usual practice to integrate a PP with underground detention to minimise the land use and capture the first flush of rainfall. Many commercial products are available to support this concept, such as Permavoid® (Product of Permavoid Limited, Warrington, UK) or Plaspave® (Product of Plasmor Limited, West Yorkshire, UK), and geo-cellular subbase replacements, SingleTrap® and DoubleTrap® (Product of StormTrap, LLC, US). However, as mentioned in Zhang et al. (2013), the large-scale design of underground detention systems have faced numerous problems associated with the under road systems, such as water supply pipes, sewer pipes, cables and trees roots.

In sum, although the typical permeable pavement had its own unique design and hydrological benefit characteristics, it has several drawbacks. First of all, it faces the clogging issue due to the pores. Second, the large-scale underground detention storage is uneconomical due to the large structure setting up and existing under road systems. Thus, it is of interest to introduce a permeable pavement with an innovative design, equipped with micro-scale on-site detention pond storage and denote by PPDS for the aim to achieve sustainable development.

1.3 Research objectives

This research aims to achieve the following objectives:

i. To construct a rainfall simulator for green pavement application and verify the chosen configuration for replicating natural rainfall.
ii. To evaluate hydrological performance of the PPDS system.

iii. To investigate the hydrological impact of PPDS by comparing with other permeable pavements using software modeling.

1.4 Significance of study

A newly designed permeable pavement with micro-detention pond storage, PPDS, system is proposed and its hydrological performance is investigated. The hydrological parameters such as storage capacity, permeability rate and infiltration capacity are determined to assess the hydrological performance, which is a strong indicator to show the appropriateness of such a system to be considered as one of the components in promoting sustainable development. The system has an empty hollow space, which can reduce the clogging effect, prevent the system disconnection, and thereby enhances its efficiency, while managing the stormwater. The PPDS system, consisting of a precast set and micro-scale detention pond storage, is apparently a more economical choice as it reduces the usages of construction materials and on-site machine. The system can be seen as a green pavement application as it meets all the principal criteria, especially integrating the permeable and porous pavement with void spaces to store and recycle stormwater, attenuate the peak discharge, etc.

1.5 Contribution to knowledge

This section highlights the main contributions of this study, particularly to the development of the permeable pavement. The major contributions are:

i. A new design of the rainfall simulator, which can generate artificial rainfall to mimic the natural rainfall pattern well. The newly developed rainfall simulator consists of:

   a. An area of 3.16 m x 1.47 m with an adjustable height of 1.55 m to 3 m.

b. A green pavement box, which can provide a catchment volume of 3.0 m (width) x 1.305 m (length) x 1.0 m (height), indicating a single lane road section. With such a design, the green pavement box has an adequate design to place 300 mm to 500 mm thick compacted road subgrade (equivalent to 5 to 8.5 tonnes) and 24 units of PPDS with a depth of 450 mm.

c. Three full cone nozzles (Full jet S. S 3/4HH-30WSQ) with 120˚ coverage to produce higher rainfall intensities at a larger scale with reasonable drop size distribution.

ii. An innovative design of permeable pavement equipped with subsurface detention storage and associated hydrological improvement. The proposed system exhibits several modifications in terms of design when compared to the conventional permeable pavement, such as:

a. A void capacity of 70% due to the hollow design of a middle section of PPDS, where most of the design of permeable pavement has only less than 40% void porosity.

b. Micro-scale and lightweight concrete precast set with a weight of 40 kg and 28 kg for cylindrical and hexagonal sections, respectively. The total depth of the proposed PPDS is 450 mm.

The newly designed PPDS has shown an improvement in terms of hydrological performance, for instance, higher infiltration rate, larger storage capacity and better peak reduction.

1.6 Scope of work

Overall, the scope of work can be divided into three major phases. A rainfall simulator is developed as a tool to test the newly designed permeable pavement. It plays a role to ensure the artificial rainfall in the laboratory to represent the real-life natural condition.

The hydrological performance of the PPDS involves two experimental stages, which take into consideration the parameters such as design storm, rainfall depth and runoff from surrounding catchment areas. The hydrological parameters of the PPDS are investigated and compared with the simulated values. Also, the evaluation of the system hydrological performance is conducted for process flow (i.e. underlying soil infiltration rate, volume and storage capacity) and system outflow (i.e. water discharge, rate and volume), respectively. The result is then validated using Storm Water Management Model (SWMM). SWMM is used to assess the hydrological impact of PPDS in a real-life case study by comparing it with the existing conditions and other permeable pavements at low-speed residential suburban area in Kota Samarahan, Sarawak, Malaysia.

1.7 Thesis Outline

This thesis contains five main chapters. Chapter 1: Introduction aims to introduce the background, problem statement, and objectives of the research. Also, it describes the significance and scope of the work.

Chapter 2: Literature review summaries the previous important studies on stormwater management focusing on the permeable pavement. It also reviews the techniques for testing device and stormwater management model simulation.

Chapter 3: Methodology explains the fabrication and calibration of the rainfall simulator as the testing device, the laboratory experimental procedures for subgrade properties and PPDS hydrological performance using a rainfall simulator. Development of the case study application via stormwater management model, SWMM, to assess the hydrological impact of PPDS is also highlighted.

Chapter 4: Results and Discussion analyses the experimental work and reports the observed and simulated results. The results are then discussed and compared with theoretical values and previous findings.

Chapter 5: Conclusion concludes the findings of this study and recommends possible future works.

CHAPTER 2: LITERATURE REVIEW

2.1 Overview

This chapter reviews the studies and published works related to stormwater management. It comprises the hydrological properties and design of the permeable pavement, as well as the application of the testing device, rainfall simulator and SWMM model.

2.2 Stormwater management

Urban development affects land-use changes and thereby influences the natural hydrological cycle (Wheater & Evans, 2009). Hydrological cycle is the largest material cycle on the earth, therefore it is essential to have proper water management (Kuusisto, 2012). Figure 2.1 shows a simple illustration of hydrological cycle in both natural and urban environments. In general, relationship of the processes within the water cycle can be simplified using water balance equation (equation 2.1). The equation is commonly applied to evaluate the importance of different hydrological parameters under a variety of hydrological conditions (Ghandhari & Moghaddam, 2011) and expressed as,

$$P = Q + ET + \Delta S \qquad \text{Equation 2.1}$$

where P is precipitation, Q is discharge or runoff, ET is evapotranspiration, ΔS is changes in storage in the watershed. The domain of water balance equation is based on conservation principle. In this study, the water budget is focused on prominent aspects of hydrological processes (rainfall-runoff).

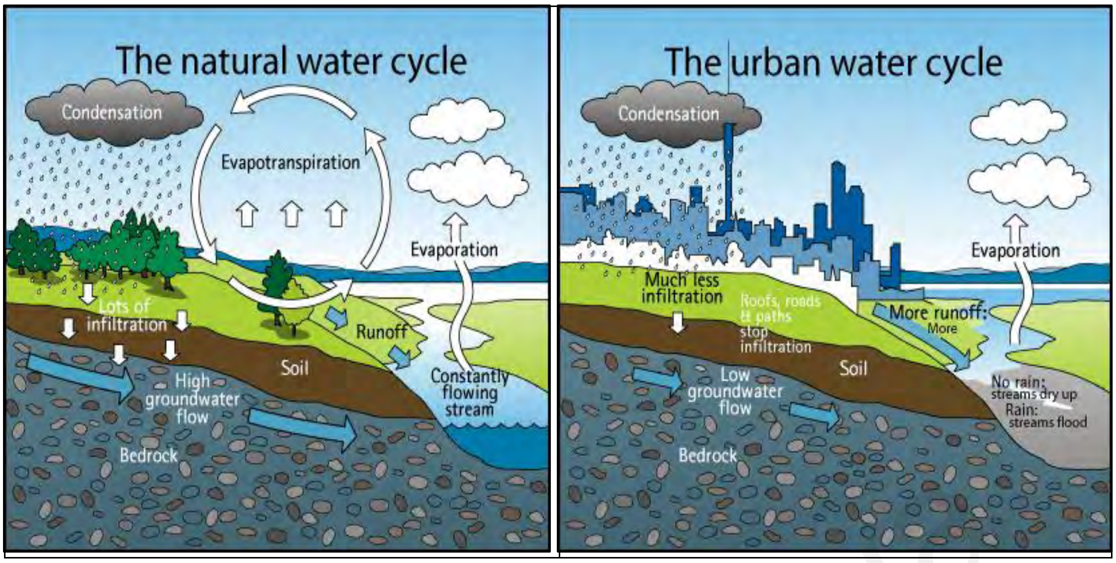


Figure 2.1: Hydrological cycle (Source: http://www.blueplanet.nsw.edu.au)

Percentage of land covered by impervious surfaces varied significantly with the changes of land use (Arnold et al., 1996). In urban areas, due to rapid development projects, the original vegetated covers have been replaced with the concrete impervious surface. As a result, it caused a depletion in groundwater recharge, reduction in infiltration rate, creation of more runoff and thereby increasing the flood events (Li et al., 2019; Zhu et al., 2019).

Surface-water flooding in urban areas has become a critical issue due to the changing of precipitation patterns, congestion of the stormwater drainage system, expanding of urban areas and aging of drainage infrastructure (Webber et al., 2018). The conventional approaches in stormwater management were mainly designed to reduce the peak flow but not the runoff volume. Consequently, it may lead to the occurrence of flood at downstream areas due to excessive runoff. This is primarily a major issue in stormwater conveyance systems. It is normally addressed by enlarging the hydraulic capacity of the systems (Haris et al., 2016) and expanding existing urban drainage systems (Zhu et al., 2019). However, enlargement of the existing system has been proved ineffective in terms of economy and sustainability (Zhu et al., 2019). As a result, sustainability has appeared as the main concern while designing the stormwater management infrastructure since 1990s. Stormwater management system is a mitigation measures to lessen the impact of increasing overland flow, runoff volume and peak discharge (Wong, 2007; Schütte & Schulze, 2017; Webber et al., 2018) through optimal collection and storage of stormwater, which can help to reduce the runoff volume (Eckart et al., 2017). In short, stormwater management is crucial to preserve environmental sustainability, mainly in urban society.

In past, there were numerous attempts to manage stormwater intercourse (US EPA, 2000; Beecham, 2003; DID, 2012; Fletcher et al., 2014). Among the efforts, source control of stormwater with green infrastructure is a promising alternative for flood mitigation. Such an approach has different terms in different countries, such as low impact development (LID) in the United States, water sensitive urban design (WSUD) in Australia, sustainable urban drainage (SUD) in the United Kingdom and urban stormwater management (USWM) in Malaysia. Although the terms are different, they have the same goal, which is to achieve sustainable development (Fletcher et al., 2014). Saraswat et al. (2016) reported the effectiveness of these stormwater management practices through the case studies in Tokyo, Bangkok and Hanoi. According to Castro-fresno et al. (2013), since year 2003, in Spain, a total number of 13 projects were developed using SUD that provided an encouraging output.

From the aspects of hydrological function, green infrastructure can be grouped into infiltration-based and retention-based systems (Szota et al., 2019). Nevertheless, the integration of both practices is imperative to enhance the overall effectiveness (Li et al., 2019). Applications that involved the integration of green infrastructure techniques had been proven to effectively reduce flood, peak discharge and surface runoff in comparison with the single facility (Ahiablame & Shakya, 2016; Hoghooghi et al., 2018; Rodríguez-Sinobas et al., 2018; Matos et al., 2019). Green infrastructure is a promising solution to several problems, such as aging of water infrastructure, urbanisation, climate change and water shortage (Gordon et al., 2018; Mei et al., 2018). The performance of green infrastructure is significantly affected by the size of the storm event, including event duration and peak flow intensity. On the other hand, the reduction efficiency is dependent on the magnitude of rainfall events, regardless of the event duration (Tao et al., 2017). Therefore, the integration of green infrastructure facilities can enhance the reduction effectiveness and show a better performance, particularly for the low intensity and short duration events (Li et al., 2019), it may have a considerable contribution to urban flood control (Zhang et al., 2016).

Green infrastructure practices have been established and widely employed to control stormwater. Barszcz (2015) reported a reduction in runoff depth and peak flow rate, recorded at 50% and 38.5% respectively, in sub-catchment of Służewiecki Stream in Warsaw through their study on the characteristics of surface runoff/outflow with 4 different types of LID structures. Ahiablame and Shakya (2016) found that, under a condition of 50% to 100% permeable pavement and 100% rain, the rate of flood reduction of the garden areas varied from 45.5% to 54.5% for major floods and from 28.8% to 40.8% for action floods. While at the parking lot areas, the flood reduction was 36.4% for major floods and 21.6% for action floods. Rodríguez-Rojas et al. (2018) showed an average water volume reduction of over 41% in a SUD application. Eaton (2018) found a different reduction rate under various conditions, where it reaches 35-55% for individual land uses and 23-42% for the entire watershed of a low-density residential area in New York City. In a recent study conducted by Matos et al. (2019), it was reported a peak discharge reduction of 76% while applying the LID combinations at the university campus with green roofs, as well as at parking lots, sidewalks, secondary roads and primary roads with permeable pavement.

The implementation of green infrastructure practices, especially green pavement, can significantly improve the rainfall-runoff responses and thereby minimise the occurrence of flood hazards, which may lead to uncountable economic losses (Kumar et al., 2016). A case study to simulate the effect of green infrastructure practices on urban flooding reduction was carried out by Li et al. (2019) in a community area located in Haidian district of Beijing. Their findings showed that the runoff volume was reduced by 42.0-46.2% while the peak flow was reduced by 35.7-37.9% under 1-, 2-, 5- and 10-year storm events. In the study, 50% of the impervious surface was converted to the porous brick pavement. The permeable pavement could mitigate the stormwater runoff through infiltration, void spaces storage, and evaporation. The findings are in agreement with other researchers who have found that permeable pavements are extremely effective in infiltrating stormwater (Bean et al., 2005; Barszcz, 2015) and significantly reducing runoff volume (Lin et al., 2014; Timm et al., 2018) and peak flow (Kim et al., 2014).

2.3 Permeable pavement

Porous or pervious concrete, which was known and used for about 50 years ago in Europe and the United States, is a type of concrete that contains little or no fines (i.e. sand). It is mostly composed of aggregate and cement paste. Its history started in the mid of 1940s as simple concrete turf blocks, which are a modular system to address flooding issues in the large cities of the United States. In 1970s, due to the development of the turf blocks in plastic version, which provides the advantage in terms of cost-effectiveness, permeable pavement has become a more and more popular choice (Booth et al. , 1991; Lipman & Najafi, 2014), while drawing the stormwater management strategies since 1980s in the United States, Canada, Europe and Japan. It was mostly applied to parking lots, low-density traffic lanes and pedestrian pathways (Drake, 2013).

Rowe (2012) defined pervious and porous surfaces as "open to passage" and "full of openings (pores)", respectively. The permeable surface was known as "capable of being passed through." In general, the term "pervious" is used to describe permeable concrete as it allows the water passage, while "porous" is used to label permeable asphalt because of the void spaces. Permeable pavement (PP) is a paving system that allows water to infiltrate to the underground. Therefore, it is suitable for a wide variety of residential, commercial and industrial applications. Figure 2.2 shows the permeable pavement systems, which are frequently used nowadays. Figure 2.2a contains a system with canals on the sides of the paving stones with narrow joints filled with a permeable mineral material that allows a rapid water transport. A system, consisting of paving stones within a special porous concrete, with a high level of porosity is illustrated in Figure 2.2b. Figure 2.2c depicts a porous paving stone with greened apertures, where it is an ideal growth environment for grass. Figure 2.2d shows concrete pavers equipped with spacers of large joints. The joints are filled with a substrate to store rainwater for the growth of grass. PP consists of permeable material, normally coarse aggregate, which functions as an aggregate reservoir to provide a storage capacity during rainfall or precipitation events. Pervious concrete is a special concrete with a high porosity attained in an interconnected void content for concrete flatwork applications (Ahmed et al., 2011).

PP can be generally categorised according to the surface type, such as pervious concrete (PC), porous asphalt (PA) and permeable interlocking concrete pavers (PICP). Figures 2.3 and 2.4 illustrate examples of different permeable pavement types. The Interlocking Concrete Pavement Institute (ICPI) provides a comprehensive manual, which covers designs, specifications, constructions and maintenances of the PICP. Figure 2.4 provides some examples of PICP.

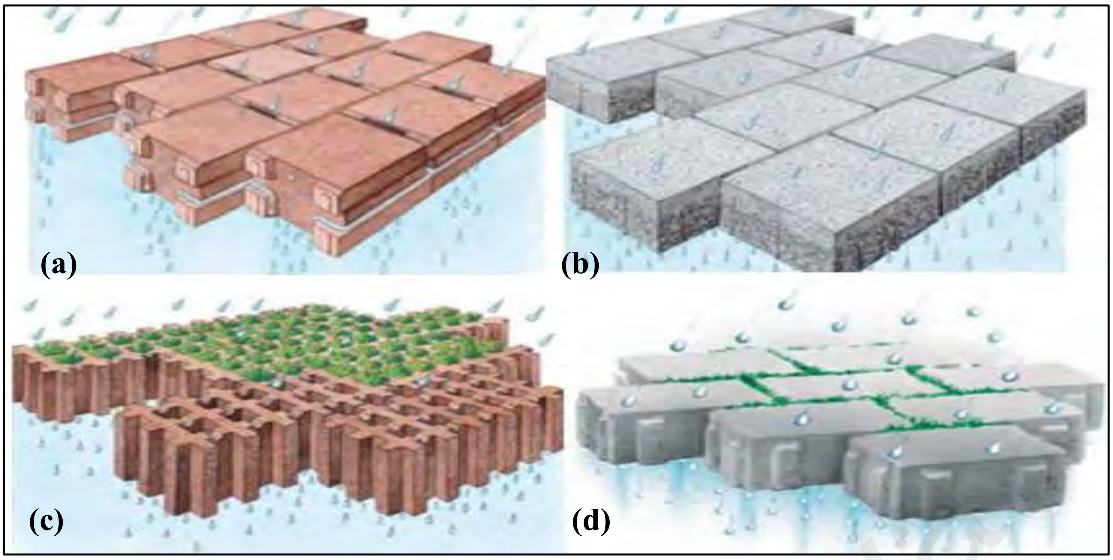


Figure 2.2: Permeable pavement systems: (a) pavers with canals, (b) porous pavers, (c) small apertures, and (d) wide joints (Source: Dierkes et al., 2000, 2002)

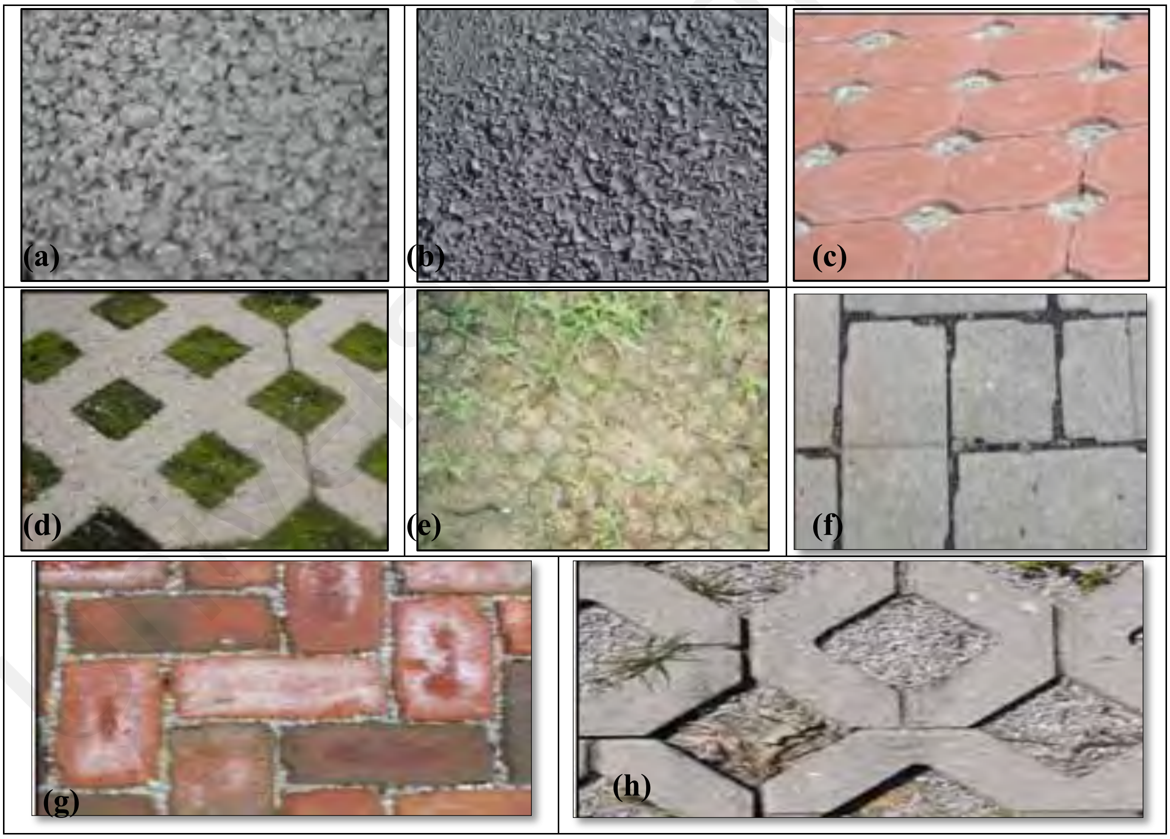


Figure 2.3: Different types of permeable pavement (a) PC, (b) PA, (c) PICP with pea gravel fill, (d) PICP grid with topsoil and grass fill, (e) PICP plastic reinforcement with earth and grass fill (Source: Collins, 2007) and (f) PICP with concrete brick, (g) PICP with clay brick, and (h) PICP concrete grid with gravel fill (Source: Agouridis et al., 2011)

Figure 2.4: Various types of PICP (Source: ICPI, 2013)

Each type of PP has its own functions, environment and aesthetical values. Commonly, the researchers tend to focus on studying the more commercially applied materials, which are PC, PA and PICP. PC and PA are permeable versions of concrete or asphalt where the binding agent coats the aggregate particles without filling the voids between the particles (Tennis et al., 2004). PICP consists of modular units separated by the joints filled with open-graded aggregate (Kuosa et al., 2013).

PC is basically similar to traditional concrete. The main difference is that there are no fine particles in the concrete mix production. This property allows air to remain trapped in the mix when it is poured at the installation site. When the mix becomes hardened, the air will form void spaces, that allow the water movement through the material (Offenberg, 2005). PC is strong enough to be used in applications that have to sustain the heavyload, such as loading docks and roadway curbing, but it is most often to be applied for parking lots, sidewalks, and playgrounds. Tennis et al. (2004) and Wanielista et al. (2007) provided reviews of the hydraulic and structural design characteristics as well as the construction techniques of the PC.

Additionally, Schaefer et al. (2006) and Kevern (2008) conducted studies to investigate the benefits of PC application in stormwater management. Kevern et al.(2012), Kevern et al. (2009) and Hager (2009) found that the use of portland cement pervious concrete (PCPC) is following an increasing trend due to its workability and durability, as it has specially designed combination of aggregate mixture, void capacity and pervious concrete materials. Meanwhile, Meddah et al.(2017) studied the application of PC in hot climate regions with various combinations of natural aggregate.

PA is similar to traditional asphalt, but with the absence of fine particles during the mix production. Therefore, the air can be trapped in the mix and thereby the pore spaces are formed in the cured material, allowing the water movement through the surface. PA is often used in parking lots, driveways, and playgrounds. NAPA (2008) provided detailed literature on the guideline of PA application. In addition Wang & Wang, (2011) presented the modification, case study and application of the PA in their study.

PICP is recognized by federal and state-level stormwater and transportation agencies in some of the countries as a best management practice (BMP) and low impact development (LID) tool to reduce the runoff and water pollution. PICP has seen its increasing application since its introduction to countries like Germany, the United States, etc. from the mid-1990s (Federal Highway Administration (FHWA), 2015). PICP offers a unique design for the sewer overflow in green alley and street, as well as parking lot and pedestrian surface.

The concrete block permeable pavement technology is growing in popularity due to the modularity of precast block design. It is well-established with the provision of design guidelines and various case studies (Smith, 2006; UNI-GROUP, 2008; Interpave, 2010). Interlocking concrete pavers are aesthetically pleasing and practical that are generally used in driveways, parking lots and walkways (Interlocking Concrete Pavement Institute (ICPI), 2013).

Permeable eco-paving, a member of the PICP family, was first developed in Europe more than a decade ago. Eco-paving has seen its application in Olympic Boulevard, Sydney in 1999, Kiama and Smith Street in 1998, and bus terminal in Germany and Austria in 2000. In the United States, eco-paving has been used in port pavements, which are mainly used for carrying heavy containers (Shackel & Pearson, 2004).

In fact, PP also appears in the other forms of modified concrete block, such as precast grid or block-shaped concrete, plastic grid and grid paver as shown in Figure 2.5. According to Imran et al. (2013), a more detailed explanation is given as:

a) Precast grid with open voids is generally used in the permeable pavement for infiltration purposes. Typically, the voids of the block are filled with crushed gravel, stone or topsoil with turf. The installation is either by hand or mechanical process. Several common concrete blocks, such as Turfstone®, UNI Eco-Stone® and Unilock® had been investigated from the perspective of runoff volume. The results indicated that the runoff volume was significantly lower than that of the asphalt driveways.

b) Plastic grid provides more void spaces for filling materials than the concrete block. Concrete block is mostly impervious while plastic grid is mostly pervious. Nevertheless, the voids of the grid are filled in the same way as the concrete block. Grasspave® and Gravelpave® plastic grids were used by Booth & Leavitt (1999) and Brattebo & Booth (2003) to monitor runoff at a site. They reported that plastic grids had recorded less stormwater runoff if compared with the asphalt lots.

c) Grid paver is a modular grid that is made of concrete, plastic or rubber. The grid space may be filled with gravel, grass, or both. Grid paver is often used for overflow parking, emergency vehicle access route or erosion control site, and is not suitable in high-volume traffic areas.

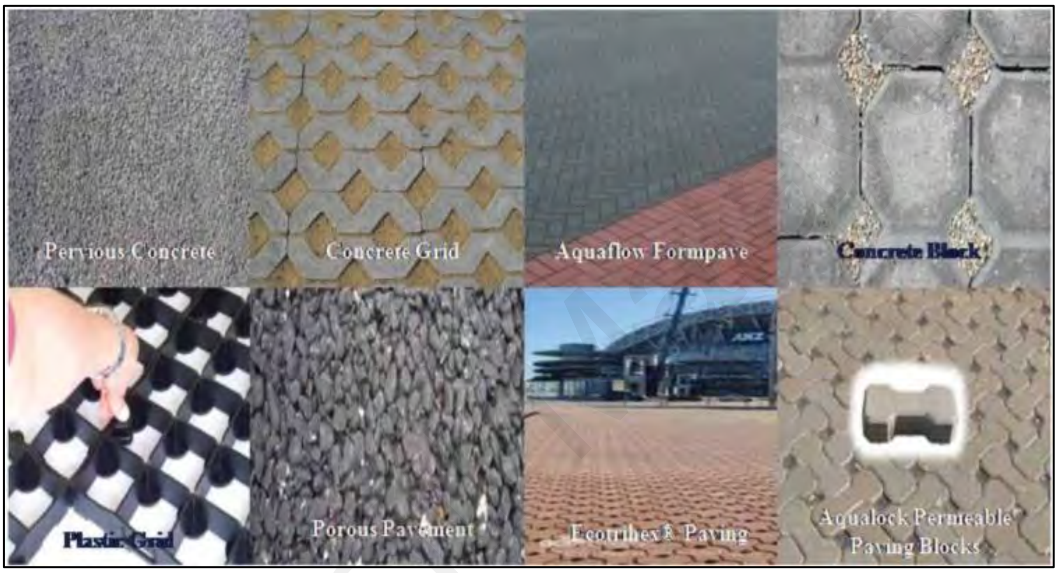


Figure 2.5: Various types of PP system (Source: Imran et al., 2013)

2.4 Hydrological performance

PP has been widely used in stormwater management practices due to its environmental advantages, such as reducing runoff (Scholz & Grabowiecki, 2007; Yong et al., 2008), recharging groundwater (Dietz, 2007), mitigating heat island effect and removing pollutants (Roseen et al., 2012; Drake et al., 2014; Xie et al., 2019). The application is an important initiative towards sustainable development, especially for water quality protection (Ahmed et al., 2011).

Jaffe (2010) reviewed the online economic model developed by the Center for Neighborhood Technology (CNT) through its application on construction costs, maintenance costs and component life spans. They found that the green infrastructures include permeable pavement, provided substantial economic benefits than the gray infrastructures. Moreover, Coupe et al. (2010) revealed that, with the installation of the permeable pavement system, the utility bills could be reduced by 50%. This is because the system provided void spaces for water storage. The stored water was then supplied as non-potable water for a building and used to generate renewable energy. In addition, Lee et al. (2010) also found that porous pavement would be a cost-effective best management practice, BMP, in an urbanised setting.

The potential hydrological benefits of PP were typically focused on quantifying the water balance and measuring the timing and rate of flows. To fully characterise the hydrological behaviour, a PP system must be monitored under a range of conditions (e.g. storm events with a wide range of magnitude, intensity and duration, as well as different antecedents and seasonally-variable conditions). Hydrological performance of a PP system, with respect to outflow volume, rate, timing and frequency, was typically measured and reported its high dependency on an impervious pavement 'control'. Drake (2013) carried out a series of study on PC, PP, PA, concrete grid pavers, plastic geocells and PICP, and identified their effects on runoff or exfiltration hydrograph characteristics. They reported a noticeable volume and peak flow reductions. This is because surface runoff and exfiltrated volume from PP were generally smaller than those from asphalt pavement during the entire monitoring period. The reduction rate of the exfiltrated stormwater volume was at least 30%, while peak flow reduction was recorded at 70% or above. PP normally consists of a base and subbase to allow water to infiltrate during the occurrence of rainfall (Collins et al., 2006). The main idea is to absorb the rainwater rather than repel it. The rainwater either infiltrates into the underlying soil or flows away through the subsurface drain (Yong et al., 2013).

Pratt et al. (1999) and Alsubih et al. (2013) reported the percentage of the retained rainfall in their designed PP as around 55% and 40-92%, respectively. Timm et al. (2018) conducted numerous studies on hydrological balances of PP materials. They found that the concrete paver had a low runoff value ranging from 7% to 42% and a high infiltration rate ranging from 38% to 86%, grass paver showed a low runoff at around 6% and high infiltration with a percentage of 68%, porous asphalt yielded a low runoff at 16% and a medium infiltration at 58%.

The difference in the reported results may be affected by certain factors, such as material condition (e.g. age of the material, slope and climatic conditions) and surface micro-topography. In addition, pervious concrete and permeable paver that are properly designed, installed, and maintained, will have a surface infiltration rate of more than 140 in/h. Weiss et al. (2015) found that the resulting variability on peak runoff and infiltration rate was mainly due to differences in PP, such as construction materials, mix designs, construction techniques, maintenance received, etc. Figure 2.6 summaries the stormwater management benefits of permeable pavement, which are stormwater runoff reduction, infiltration rate enhancement, surface skid resistance improvement, underground water quality amelioration, heat-island effect reduction and traffic noise mitigation.

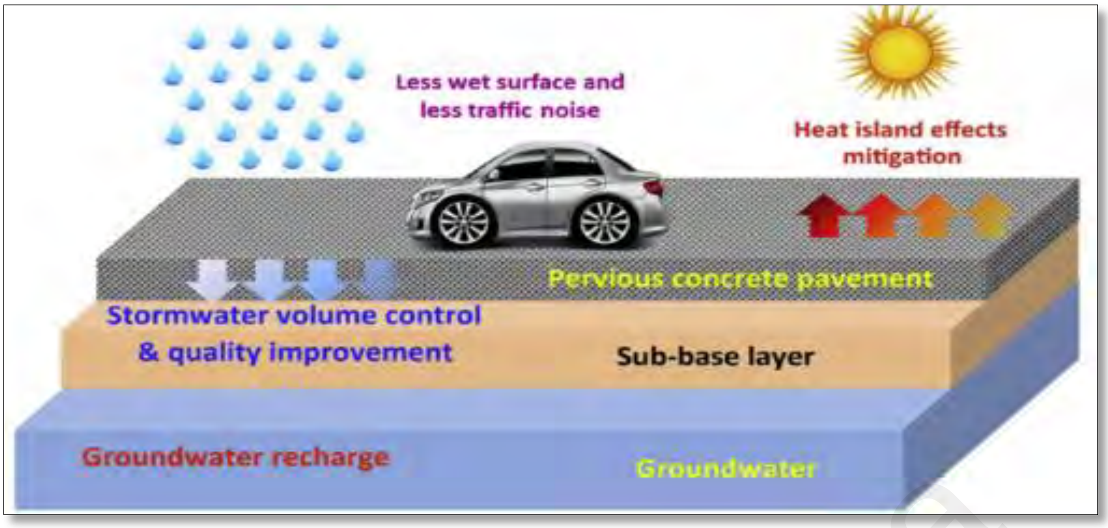


Figure 2.6: Stormwater management benefits while applying permeable pavement (Source: Xie et al., 2019)

Table 2.1 presents some studies on PP and their associated findings. In Table 2.1, the porous pavement had shown its potential to reduce the runoff to more than 40%, decrease the peak to at least 50-90% and improve the infiltration rate from 4-11 cm/h. Almost all studies agreed that permeable pavements, when constructed well and maintained regularly, could have the ability to reduce peak runoff and infiltrate a significant fraction of runoff volume. Ferguson (2009) stated that, if the runoff coefficient that has been measured on the properly built porous pavement is zero, it meant there is no runoff due to the high surface permeability.

Table 2.1: Researches on permeable pavement and the findings

Sources	Objectives	Findings
Dierkes et al. (2000, 2002)	To investigate the pollutant retention capability of four different systems, which are paving stones, pavers with infiltration joints, porous concrete pavers with filter layer, and greened porous pavers.	The greened porous pavers showed the highest efficiency in terms of pollutant retention capacity.
James & Langsdorff (2003)	To determine the relationship between infiltration capacity and other variables of interlocking concrete block pavers.	Infiltration capacity was found to be spatially varied and dependent on the traffic applications.

Table 2.1, continued

Sources	Objectives	Findings
Rankin & Ball (2004)	To study the effect of Rocla-Ecoloc pavers on the residential area with low traffic volume at Smith Street, Australia.	The application of Rocla-Ecoloc pavers resulted in very little runoff if compared to other paver systems.
Bean et al. (2004) Bean et al. (2007),	To evaluate the efficiency on runoff volume reduction and pollutants removal of different sustainable urban drainage applications	A proper yet regular maintenance could improve surface permeability at a confidence level of 99.8%. The average infiltration rate was increased from 5.0 cm/h (existing condition) to 8.0 cm/h (after maintenance). Concrete grid pavers and PICP had relatively high surface infiltration rates under a sandy soil environment.
Dreelin et al. (2006)	To investigate the efficiency of porous pavements for runoff control on clay soil in Athens, Georgia, and United States.	Porous pavement produced a 93% runoff reduction than the asphalt lot and 40-45% than the conventional parking lot. Therefore, porous pavement could be used effectively on clay soil for the control and retention of the stormwater.
Gilbert & Clausen (2006)	To study the effects of different material types, such as asphalt, paver and stone.	The average infiltration rate was 0, 11.2 and 9.0 cm/h for asphalt, paver, and crushed stone driveways, respectively. The paver and crushed stone driveways exhibited a better ability for runoff reduction if compared to an asphalt driveway.
Zhang (2006)	To investigate the hydrological properties and infiltration rate of pervious pavement with block paver.	When the rainfall intensity was less than the saturated hydraulic conductivity, the infiltration rate was equal to the rainfall intensity. However, when the rainfall intensity was greater than the saturated hydraulic conductivity, the infiltration capacity and the cumulative infiltration volume were independent of the rainfall intensity after surface saturation. Infiltration rate reduced with time because of the clogging problem.

Table 2.1, continued

Sources	Objectives	Findings
Fassman, et al. (2007)	To monitor and assess the performance of permeable pavement with impermeable paver blocks and enlarged joint spacing of an active carriageway at North Shore of Auckland.	The onset of runoff was delayed by 2.4 h and the peak flow was decreased by 83%.
Collins (2007)	To monitor a parking lot consisting of PC, concrete grid pavers (CGP) filled with sand, and two PICP with gravel fill at a void space of 12.9 % (PICP1) and 8.5 % (PICP2), respectively.	All permeable pavements significantly reduced the surface runoff volume and peak flow rate. CGP displayed the greatest peak flow reduction and was followed by PICP1.
Straet et al. (2008)	To compare the performance of greened porous pavement and open jointed paving block.	The greened porous pavement was less-performed than the open-jointed paving block under a 10-min rain with an intensity of 114 mm/h. The recovery time of the greened porous pavement is longer after the occurrence of intense rain. Open- jointed paving blocks dried within a few hours while greened porous pavements needed 2 days to dry.
Jayasuriya & Kadurupokune (2008)	To conduct field tests to evaluate the peak discharge and stormwater volume reduction after infiltrating through pervious pavement surface.	C&M Ecotrihex paver and Atlantis turf recorded an average ratio of total runoff to total rainfall at less than 40% and a peak discharge reduction with at least 50%, while comparing to conventional asphalt pavement.
Hou et al. (2008)	To study the effect of different treatment, Treatment A (RA) for PC block paving with a subbase of 20 cm sand; Treatment B (RB) for PC block paving with a subbase of 10 cm thick concrete lacking sand and 15cm thick gravel; Treatment C (RC) for PC block paving with a subbase of 5 cm thick concrete lacking sand and 20cm thick gravel; Treatment D (RD) for impervious surface, on hydrological performance.	A larger porosity, higher infiltration coefficient, thicker sub-base layer and lower subgrade initial water content produced a higher infiltration rate and smaller runoff coefficient.

Table 2.1, continued

Sources	Objectives	Findings
Gomez-Ullate et al. (2010), Gomez-Ullate et al. (2011)	To study the capacity of PP to store stormwater on parking bay with different surface layers, such as aquaflow concrete block with 8 cm of thickness, Montserrat PC block with 10 cm of thickness, porous asphalt with 8 cm of thickness, PC with 8 cm of thickness, combination of grass surface and concrete reinforcement with 9 cm of thickness and plastic cells with similar base and subbase.	There was no significant difference could be observed as all of the pavements showed a relatively good performance in terms of water-storing and water-harvesting.
Carbone et al. (2014)	To investigate the performance of the permeable pavement that served as a parking lot at University of Calabria with an area of about 154 m^2 and a total depth of 0.98 m. The pavement system included a 8cm surface concrete blocks cover, a combination of 5cm thick glass, sand, zeolite and geotextile, 35 cm gravel (ASTM No 57), 45 cm gravel (ASTM No 2), and 5cm sand (ASTM No 8)	No runoff was noticed during the rainfall events. The recorded volume reduction was ranged from 60% to 68%. The pavement exhibited an optimal retention capacity.
Kumar et al. (2016)	To investigate the PPs in terms of their relative physical conditions.	PC had the best physical conditions followed by permeable paver and lastly PA.
Niu et al. (2016)	To evaluate stormwater infiltration and pollutant removal rate at different layers, including surface permeable bricklayer, coarse sand bedding layer with different thickness of 2, 3.5 and 5 cm, and single-graded gravel sub-base layers with the thickness of 15, 20, 25 and 30 cm.	The thickness was the main factor influencing the infiltration and pollutant removal rate. The surface brick layer recorded the highest infiltration rate at 51.0 mm/h, followed by the 5 cm sand bedding layer at 32.3 mm/h, and a 30 cm gravel subbase layer at 42.3 mm/h.
Brugin et al. (2017)	To test the performance of porous asphalt and pervious concrete with different void contents of 15, 20 and 25% under the effect of rainfall intensity and duration, as well as the pavement slope.	The rainfall pattern and pavement slope significantly affected the infiltration capacity of clogged permeable materials. The infiltration capacity became higher after exposing to a long yet intense rainfall event and a low pavement slope. Pervious concrete showed the best performance in terms of infiltration capacity.

Table 2.1, continued

Sources	Objectives	Findings
Alsubih et al. (2017)	To investigate the influence of rainfall intensity on the hydrological responses of permeable pavement.	The hydrological performance varied to rainfall intensity. The total discharge from the permeable pavement ranged from 8% to 60% of the inflow, which indicated that more than 40% of the total rainfall was temporarily detained within the structure.
Ioannidou & Arthur (2018)	To investigate the performance of the specially designed pavement, where the pavement rig was divided into four layers: - Impermeable rectangular concrete modules (Priora) with 80 mm thickness, and 200 mm × 100 mm dimensions; - Bedding course with 50 mm thickness; - Subbase layer with 350 mm thickness; - Subgrade layer with 300 mm thickness. A geotextile with 1 mm thickness was placed between subbase and subgrade layers to prevent the migration of sand into coarse aggregate and over the stainless steel outflow tank.	The amount of water discharged from the pavement ranged from 16.52% to 77.30% of the total rainfall. The permeable pavement reduced the peak concentration time, mitigated stormwater runoff and achieved a good performance under wetter condition.

Table 2.2 lists the research studies on the development of PP from 1990s to 2019. The PP has been widely used since the 1990s in Australia, Europe and Japan, and earlier in the United States in 1984 (Drake, 2013). Most of the studies aimed to investigate the stormwater management benefits of the PP in reducing the peak runoff and its volume, as well as increasing the infiltration rate. The recent development of PP can be divided into three major time periods. In the 1990s, the PP system was introduced to the users. Several prototypes had been constructed for the property and characteristic determinations via laboratory studies and field tests. The main concern of the analyses was the measurement of stormwater management benefits.

Table 2.2: Studies on the development of permeable pavement

Sources	Contents of studies
James et al.(1996)	- Introduction to Stormwater Management Model (SWMM) for the hydrological design of permeable pavement, for example, PC-SWMM for permeable pavement (PCSWMMPP).
Booth & Leavitt (1999), Brattebo & Booth (2003)	- Studies on manufactured permeable pavers, such as grasspave, gravelpave, turfstone and Uni Eco-Stone. - Review of the existing permeable pavements, particularly on their characteristics, on-site hydrological testing (infiltration, durability and water quality) and long term performance. - Reporting on the permeable interlocking concrete pavers (PICPs), which had been in service for over six years, could still infiltrate almost all the rainwater reaching the pavers.
Kipkie & James (2000)	- Review on Laboratory investigations on 2 m by 2 m Uni Eco-Stone using rainfall simulator with different intensities to observe the runoff pattern subjected to different slopes and infiltration capacities. - Review on Field experiments on examining the hydrological responses of modular interlocking concrete block (MICBEC an internal drainage cell type) with different material types, particle sizes and distributions, as well as properties. - Summary of the saturated hydraulic conductivity of different Uni Eco-Stone drainage cell material types, experiments on a porous asphalt pavement (PAP) and its comparison with conventional asphalt pavement, infiltration capacity differences for two Uni Eco-Stones (2 years and 5 years in age respectively), infiltration capacity of Uni Eco-Stone with different combinations of bedding, jointing and drainage cell material.
Dierkes et al. (2000, 2002)	- Presentation on stormwater infiltration techniques, which include infiltration with/without storage of greened permeable paver. - Reporting on clogging and pollutant retention as well as infiltration capacity of the existing permeable pavements. - Verification works via laboratory and field studies to develop a new cleaning device equipped with direct vacuum suction to recover the infiltration capacity.
Kipkie & James(2000), James et al.(2003)	- Investigation on the development of stormwater management model and the code feasibility of the Storm Water Management Model (SWMM) to allow planners and designers to simulate the responses of permeable pavements.
He (2000), Ladd (2004)	- Study on the development of pavement management, networks and projects, particularly on the OPAC 2000, a new pavement design package, which handles the pavement design process in a comprehensive computerised system. - Parameters determination for the computer models to assess the hydrological effectiveness of a porous concrete infiltration basin as an initiative for best management practice (BMP).

Table 2.2, continued

Sources	Contents of studies
Knapton et al. (2002), Adams (2003), Kuennen (2003), Yang & Jiang (2003),	- Study on hydrological properties, design standards, specifications and considerations, costs, and maintenances of pervious concretes for runoff reduction and pollutant removal
James & Langsdorff (2003)	- Investigation on the hydrological performance of permeable concrete pavers with various ages, and the relationship between the infiltration capacity and the ages.
Shackel & Pearson (2004)	- Reporting on the testing, evaluation, design and construction of permeable eco-paving. The main focus is on water infiltration through the eco-pavement surfacing, the structural capacity of the paving and the properties of base materials.
Interlocking Concrete Pavement Institute (ICPI) (2005), Smith (2006)	- A comprehensive study on the permeable interlocking concrete pavement (PICP) includes the criteria for appropriate site selection, basics for storage areas sizing, guidelines for PICP construction and maintenance.
Boomsma & Huurman (2006)	- Comparison of two different permeable paving types of the aquaflow system, one with infiltration system while the other with tank and SC membrane at the bottom depending on the subgrade and the groundwater level to determine their appropriateness to be used as water management practices.
Shackel (2006)	- Review of permeable interlocking concrete pavement (PICP) testing since 1994 in Australia, particularly on the bedding and jointing materials, as well as the hydraulic and structural properties of the paver and bedding courses.
Dreelin et al. (2006)	- Investigation on the efficiency of porous pavements in controlling stormwater runoff on clay soils.
Gilbert & Clausen (2006)	- Comparison of the quality and quantity of runoff from replicated asphalt, permeable paver and crushed-stone driveways.
Collins et al. (2007), Illgen et al. (2007)	- Presentation of hydrological parameters and water quality monitoring, sites clogging studies, and model applications for permeable pavement applications.
Michael (2007)	- Introduction to concrete grid pavers (e.g Monoslab®, Grasscrete®, and Turfstone®), laboratory monitoring on runoff characteristics and pollutant removal, site construction and monitoring, as well as development, construction and field investigation of permeable pavements (e.g. turfstone® (concrete block turf infill),Uni Eco-Stone® (concrete block gravel infill), grasspave® (plastic grid turf infill), gravelpave® (plastic grid gravel infill) and Unilock® pavers)

Table 2.2, continued

Sources	Contents of studies
Jayasuriya et al. (2007), Jayasuriya & Kadurupokune (2008)	- Investigation on the hydrological performance, stormwater quality, and groundwater contamination monitoring of permeable pavements (with permeable surfaces of BORAL, ROCLA or grass subject,as well as porous concrete and asphalt). - Reporting on the determination of the optimal structure materials and thickness, preparation of the synthetic stormwater quality samples and selection of parameters for model verification.
Scholz & Grabowiecki (2007)	- Review on innovative design of permeable pavement, where the addition of materials (e.g. silica fume and superplasticizer) could enhance the compressive strength for higher load; the addition of material (e.g. heat-bonded geotextile) could improve the pollutant removal efficiency; the development of a heating/cooling system within the subbase of the modern permeable pavement.
UNI-GROUP (2008)	- Summary of the researches and studies on the Eco-Stone® family of permeable interlocking concrete pavers.
Kadurupokune (2008)	- Investigation on hydrological balance (rainfall-runoff relationship) and stormwater quality monitoring for both field tests and experimental test rig.
Hou et al. (2008), Straet et al. (2008)	- An overview of hydraulic behavior and rainfall-runoff relation for the porous pavement with different materials.
Yong, et al. (2008)	- Laboratory investigation on the clogging behaviour of monolithic porous asphalt (PA), permapave (PP), and modular hydrapave (HP).
Interpave (2008)	- Reporting on a new guidance document of concrete block permeable paving, which explains the details of different systems and techniques, and their applications.
Swan & Smith (2009)	- Insight on the development of a non-proprietary software called Permeable Design Pro, which integrated the hydrological and structural elements for the design of permeable interlocking concrete pavement.
Rossman (2010b)	- An overview of the manual of SWMM 5.0
Dierks &Associates (2009)	- Presentation on the application of Storm Water Management Model (SWMM) to simulate the measured flows and forecast flows of porous pavers and vegetated swales.
Shackel & Pezzaniti (2009), Shackel (2010)	- Investigation on the case study and application of permeable interlocking concrete pavement (PICP). The PICP was designed by implementing software called PERMPAVE.

Table 2.2, continued

Sources	Contents of studies
Unilock (2011)	- Case study of eco-paving, which were differed in terms of design consideration and shapes, hydrological applications for the purposes of runoff detention, volume control, infiltration enhancement and water quality improvement. 
Hein & Schaus (2013)	- Investigation on numerous stormwater models that could be used to complete the hydrological design for permeable shoulder pavements, and the key design considerations including structural and hydrological conditions.
Imran et al. (2013)	- Study on water quality and pollutant removal and suggestion of combining the permeable pavement and geotextiles as an effective way to remove contaminants from the stormwater.
Nichols et al. (2014)	- Evaluation of two PICP surface infiltration rate measurement methods, which were modified double-ring infiltrometer (DRIT) and specially designed rainfall simulation infiltrometer (RSIT) on their applications under different conditions.
Korkealaakso et al. (2014)	- Review ofpervious pavement dimensioning (both hydrological and structural), which focused on the engineering aspects of different pavement types; computational models that were able to integrate permeable pavement systems into the urban drainage design and could help to size the permeable pavement structures. - Reporting on SWMM and SUSTAIN as two modelling platforms, which were suitable to hydrologically model the stormwater-permeable pavement environment and as site-scaled sizing tools which could be used to complement both hydrological and structural considerations
Federal Highway Administration (FHWA) (2015)	- Technical reporting on the permeable interlocking concrete pavement (PICP), containing the inclusive overview and its applications with the provision of hydrological and structural designs, construction techniques, and maintenance methods.
Kayhanian et al. (2015),Weiss et al. (2015)	- A summary of the current practices and design methods on the application of permeable pavement for highway environment, from the aspects of mixed design, hydrological performance, maintenance, water quality benefits, identified knowledge gaps and unresolved issues.
Marchioni & Becciu (2015)	- Discussion on the roles of permeable pavement in urban drainage by analysing the main result from the full-scale tests, especially regarding the runoff volume reduction and quality improvement.
Xie et al. (2017)	- Reporting on the application of stormwater management model (SWMM) to reasonably conceptualise the study area.

Table 2.2, continued

Sources	Contents of studies
Kumar et al. (2016)	- Performance evaluation on the measured in-situ infiltration rate and reporting the temporal changes of water infiltration in different sections (permeable pavers, permeable concrete and permeable asphalt) of the pavements.
Rossman & Huber (2016)	- Update and revision of the SWMM incorporating low impact development (LID) modelling.
Huang et al. (2016), Brugin et al. (2017), Kia et al. (2017), Kamali et al. (2017), Braswell et al. (2018), , Razzaghmanesh & Borst (2018), Hammes et al. (2018), Razzaghmanesh & Beecham (2018) , Zhang et al. (2018)	- Monitoring of water quality and pollutants by assessing the clogging progression, mechanism and chronological trend, and introducing the current mitigating strategies for the issue.
Kayhanian et al. (2019)	- A review study on the aspects of hydrological performance, surface permeability, clogging issues, and water quality benefits for full depth permeable pavement.
Xie et al. (2019)	- A review study on key environmental benefits of permeable concrete pavement (PCP), in terms of runoff reduction, underground water quality improvement, heat-island effect mitigation, traffic noise reduction and skid resistance improvement.
Timm et al. (2018)	- A review study on the effect of different paving materials on hydrological balance and the process involved.

Towards 2000s, the main focus of most of the research studies was on the applications aspect, which compared the designed PP with the existing road pavement or the pre- and post- conditions for the PP applications. Several modelling tools had been commonly used to assist the studies and applications of PP (James et al., 1996). The permeable pavers, acting as the most successful pervious system had been seen for its wider application. This is because a number of design products, case studies benefits and standard guidance had been established (Smith, 2006; Unilock, 2011).

From 2010s until recently, the main direction has changed to implementation and modification. Different modifications had been introduced, such as the adding of high strength materials with sufficient void to improve both structural and hydrological benefits, the modification of pavers surfaces with unique and aesthetic looks, etc. Nevertheless, no matter how the modifications were implemented, the most important thing was the designed pavement must meet the standards and guidelines, especially to fulfill the structural and hydrological requirements. Of course, the point of view from the aspects of sustainability, economy and society has become more and more important. In addition, the optimal combination of LID practices or green infrastructure techniques has become the main concern in order to achieve the maximum benefit in stormwater management (Liu et al., 2017; Gordon et al., 2018; Li et al., 2019; Matos et al., 2019; Thuy et al., 2019). The chronology of PP development is simplified in Figure 2.7.

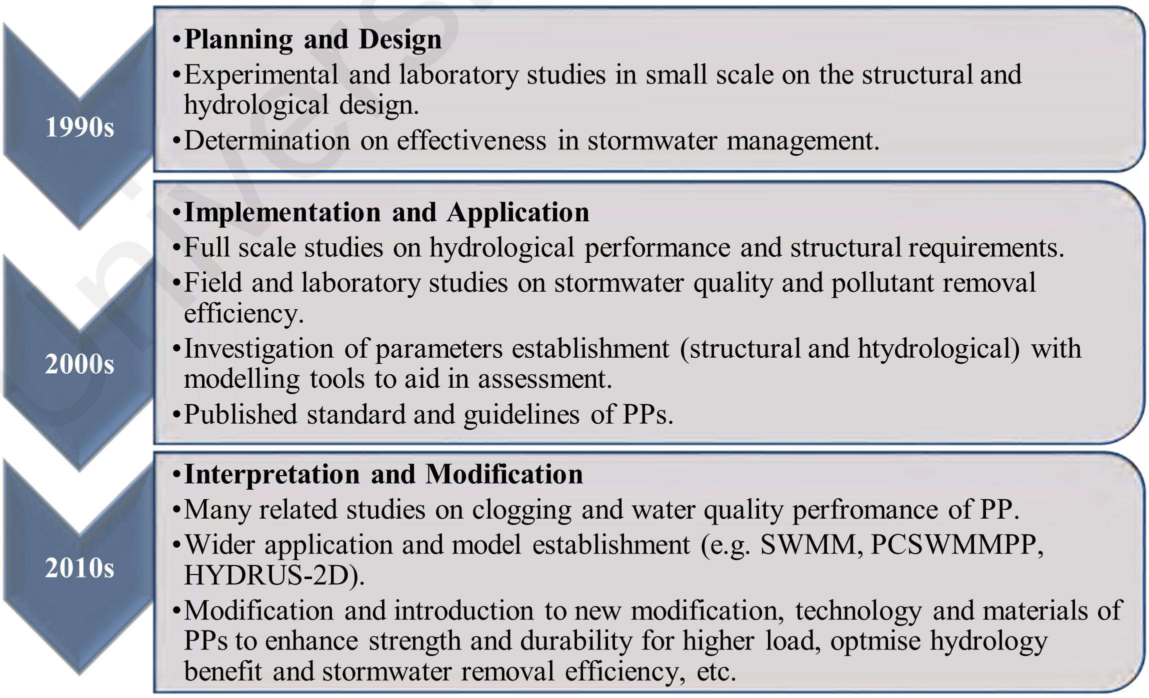


Figure 2.7: Chronology of permeable pavement development

2.5 Hydrological design

Hydrological design is an integral and important aspect for any permeable pavement design to serve as stormwater management infrastructure. According to Kayhanian et al. (2019), specific characteristics that should be exhibited throughout the life of the permeable pavements include (i) adequate subgrade reservoir capacity to capture runoff volume, (ii) surface pavement remain highly permeable and unclogged, (iii) allowing minimum permeability of subgrade soil to infiltrate the captured runoff, and (iv) assuring no adverse impact on underground water. Shackel (2010) reported the design considerations that are (i) the choice of the pavement surfacing, cross-section and materials, especially on the subgrade conditions to manage structural responses to traffic and hydrological requirements, (ii) hydraulic analysis, which is important to determine the appropriate materials thickness to ensure the permeable pavement has sufficient capacity to manage the rainwater, and (iii) structural analysis to identify the suitable pavement thickness, which is strong enough to meet the traffic requirements.

Smith (2006) reported that, in order to perform the hydrological design, several steps should be taken, including (i) preliminary assessment on catchment characteristics, such as underlying soil, watershed and land use, (ii) determination of design storms, total area and percent of imperviousness, as well as (iii) sampling and analysis of soil subgrade. Hydrological design generally relies on the design storms, long-term soil infiltration rate (which could be estimated either from soil samples or field measurement), base/subbase thickness and storage capacity (Smith, 2010; Smith & Hunt 2010). Hein et al. (2010) proposed several design steps, which are (i) performing experiment on native soil infiltration rates for the consideration of full, partial or no filtration, as the natural soils at site are much less permeable, while the system relies on underdrains to convey a significant fraction of infiltrated water downstream, (ii) setting the permeability rates of permeable pavement system to 10 in/h as it is the conservative design value for a maintained permeable interlocking concrete pavement (PICP) system, (iii) determining the maximum allowable storage time for the retention of 24 h to 48 h rainfall, and (iv) identifying the design storm and watershed area to determine the volume of runoff. Their hydrological design steps are illustrated in a flowchart in Figure 2.8.

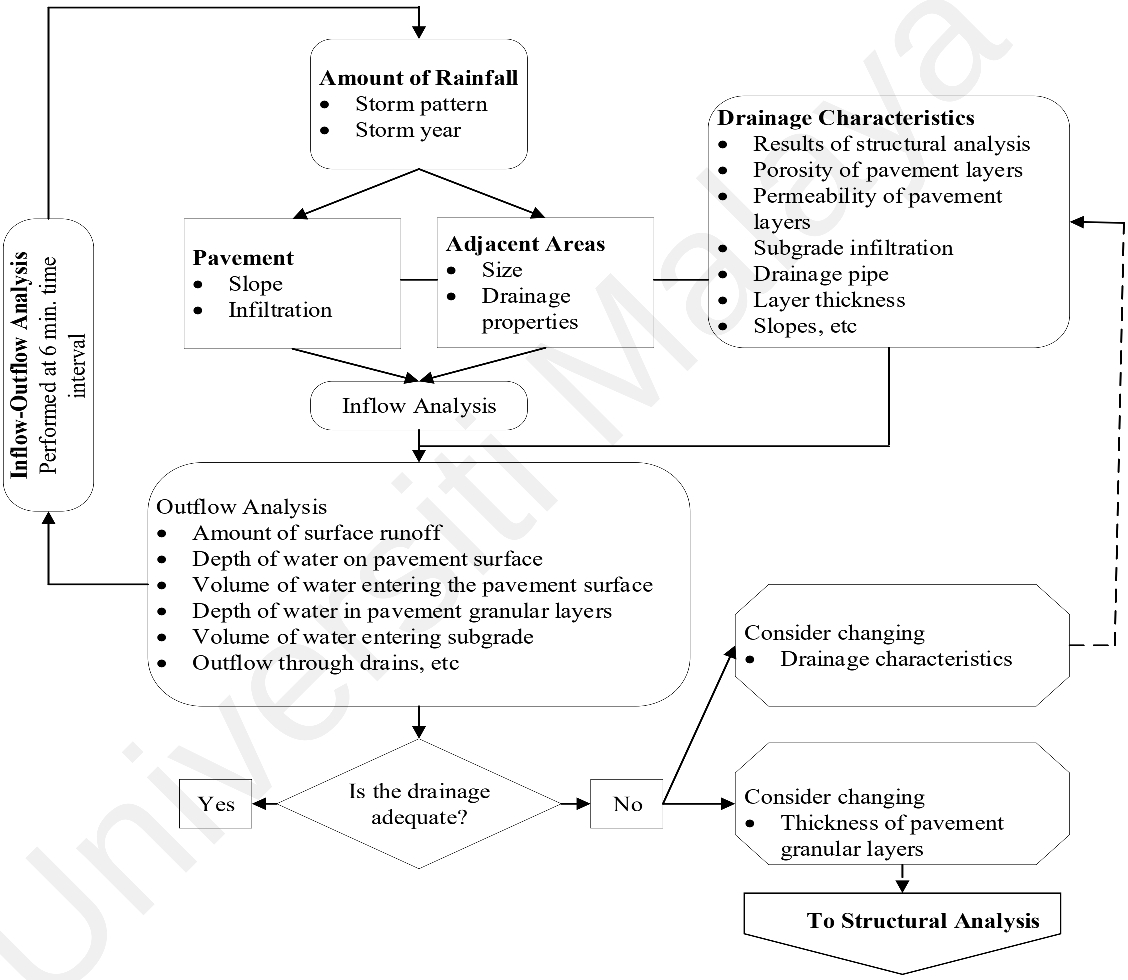


Figure 2.8: Flowchart on hydrological design (Source: Hein et al., 2010)

The flow of stormwater entering the pavement surface was described based on the concept of water balance model as shown in Figure 2.9. According to Swan & Smith (2009), the volume of water in the pavement system could be described as Equation 2.2.

$$Water\ Volume\ (time)\ =\ Initial\ Water\ Level + \int_0^{Time} Inflow(Time) - Outflow\ (Time)$$ Equation 2.2

There are three major components that affect the water volume in the pavement system, which are inflow, infiltration and outflow. Inflow means the entering of water into the pavement, either in the form of precipitation or from the surrounding areas. Infiltration can be described as the process where the inflow water in the system infiltrates through the ground soil. Outflow is the leaving of water from the system via evaporation.

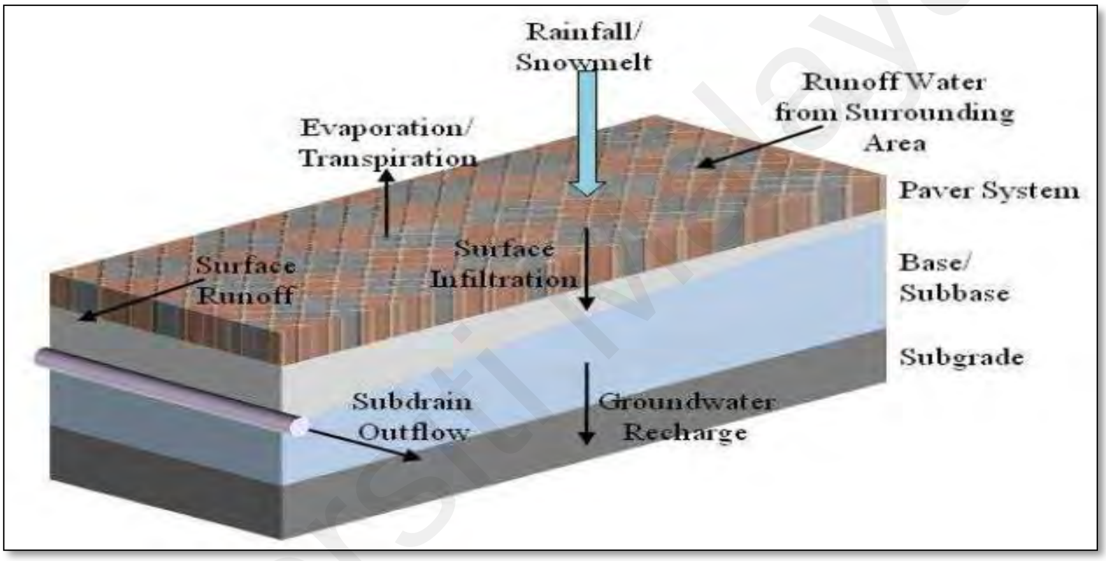


Figure 2.9: Inflow and outflow of water on the permeable pavement (Source: Swan & Smith, 2009)

Beeldens et al. (2009), in the guidelines for hydraulic design of permeable pavements, mentioned that the criteria for optimum design include the soil type, drainage system, choice of pavement block over the material and dimension of the subbase and base layers. The hydrological design is usually presented with a decision tree to provide optimum selection on the hydrological and structural designs as shown in Figure 2.10. In the decision tree, firstly, the drainage system was determined as a function of the soil permeability. Secondly, the thickness of the base layer and type of material were fixed according to the traffic requirements. The thickness of the sub-base layer was then determined to protect the soil against frost or provide the buffering capacity. The larger thickness was always favourable.

Finally, the types of pavement block joint filling material and base layer material were selected. A geotextile was added at the bottom of the structure to prevent the infiltration of fines into the structure. To achieve a similar goal, the pervious lean concrete could be used above the base layer. Overall, application of the pervious paving system is strongly related to the permeability of the soil and traffic on the pavement.

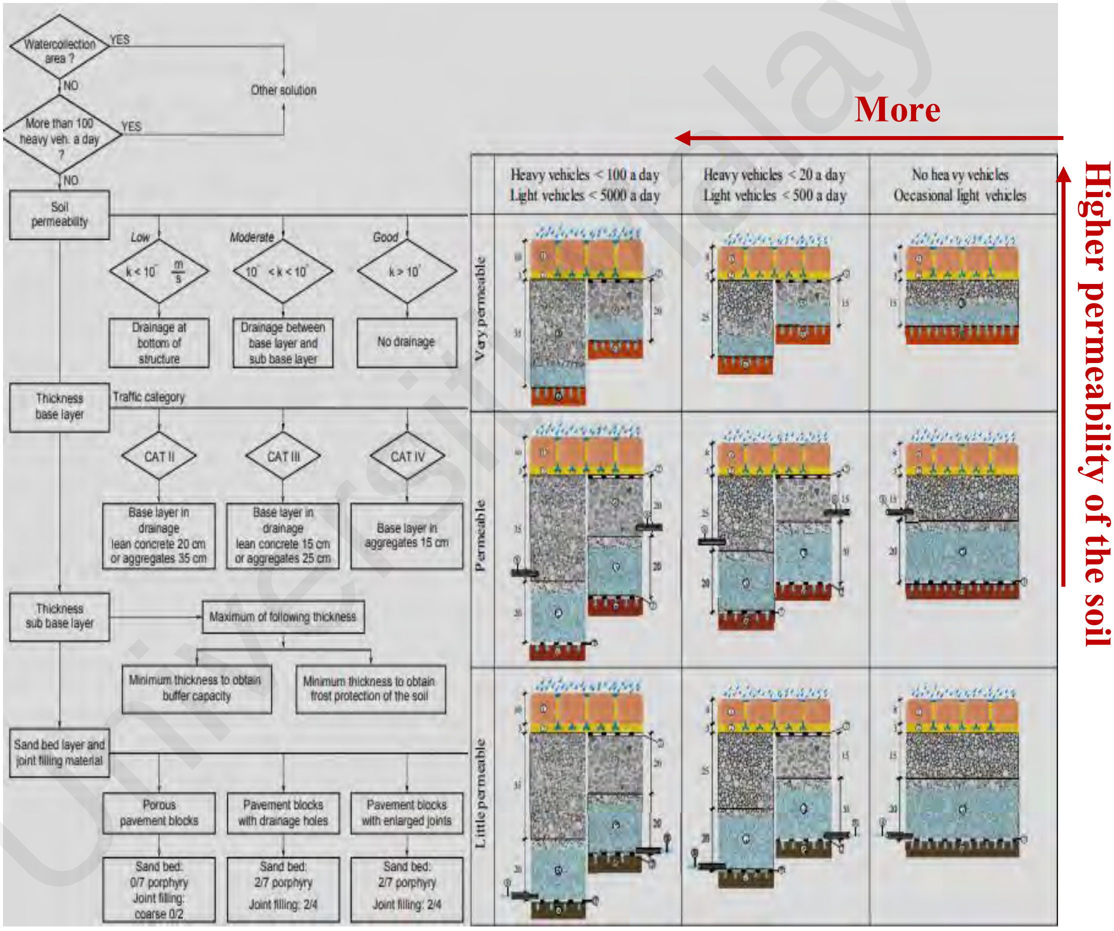


Figure 2.10: The decision tree to design permeable pavement structures and standard structures in relation to soil permeability and traffic, where the soil permeability alternatives in the decision tree are $k<10^{-8}$ m/s, 10^{-8} m/s $<k<10^{-6}$ and $k>10^{-6}$ m/s (Source: Beeldens, 2009).

Storage volume and infiltrating/recharging rate are the two main factors in the hydrological design of permeable pavement. The values can be calculated if the designer knows the maximum amount of stormwater within a certain timeframe (e.g. 2- or 10-yr maximum) of storm events, infiltration capacity of the structure and subbase soil, and recharge rate. The drainage system should be designed to have sufficient thickness of reservoir layer, enough pipes and detention structures, an alternate route that can divert the flows to another detention/conveyance system, and observation wells for maintenance purposes (Ferguson, 2005). The hydrological design should be completed with structural analyses on strength and durability. It is a must to ensure a pavement to have sufficient thickness to support the intended design traffic while protecting the subgrade from permanent deformation. The hydrological design must include all the key elements that determine the infiltration rate of rainwater and surface runoff into the pavement and exhibit the ability to detain and filter the water. An optimal designed permeable pavement is the one that is strong enough to accommodate the design traffic and has the minimum hydrological features for water quantity and quality management (Hein et al., 2010; Smith, 2011).

2.6 Hydrological properties

The hydrological design must be performed carefully in order to determine the hydrological properties, which include an adequate aggregate depth that is large enough to provide the necessary storage capacity for the design runoff volume. Hydrological design is typically based on the storage volume provided for temporarily stormwater runoff storage and release by the pavement structure. A typical cross-section design with an appropriate aggregate mix design suggested by the three leading permeable pavement industries is shown in Figure 2.11. Generally, a cross-section consists of the surface permeable pavement (asphalt, concrete or interlocking pavers) on top, a choker coarse, a stone subbase recharge bed, and an uncompacted subgrade. A non-woven geotextile fabric can also be used to separate the reservoir bed with subgrade soil (Kayhanian et al., 2015). The designated system cross-section in Smith (2011), from top to bottom, consisted of concrete pavers, open-graded bedding course, open-graded base reservoir, open-graded subbase reservoir (with underdrain, if necessary), geotextile fabric (optional), and subgrade soil.

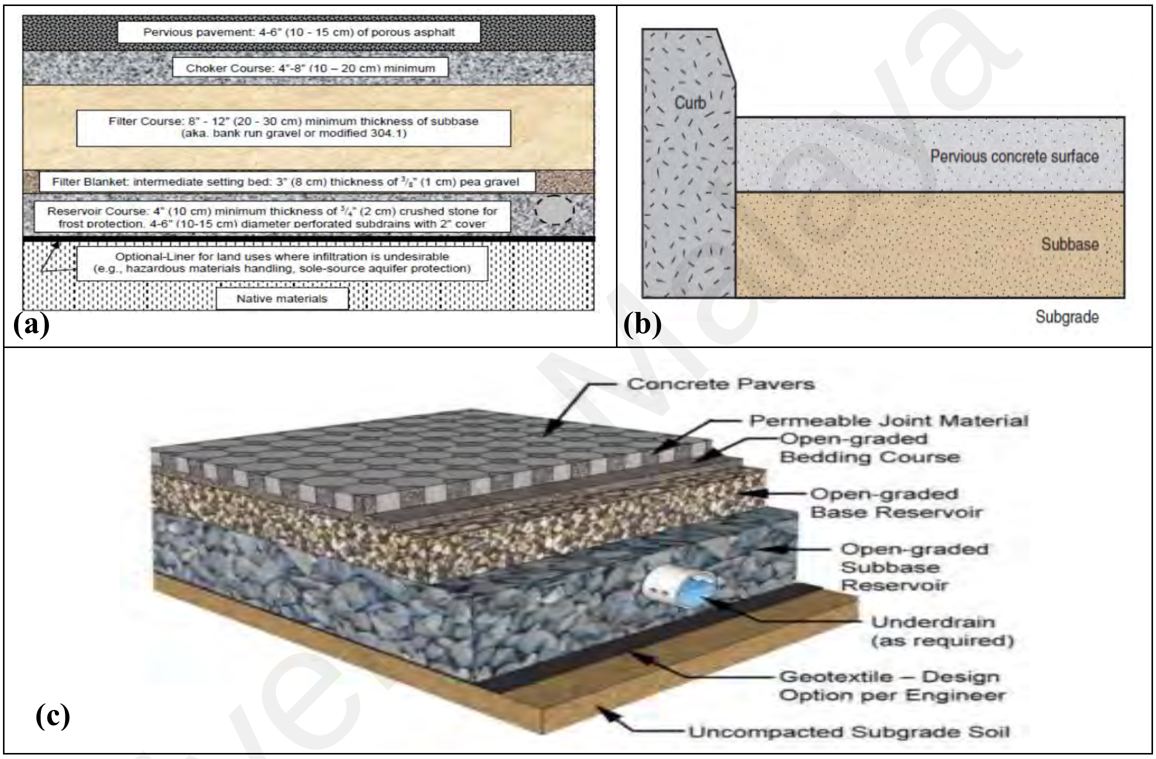


Figure 2.11: Typical cross-section of permeable pavement system (a) porous asphalt pavement (NAPA, 2008), (b) pervious concrete pavement (Source: ACPA, 2009) and (c) permeable interlocking concrete paver system (Source: ICPI, 2013)

In Smith (2006), Federal Highway Administration (FHWA) (2015), Kayhanian et al. (2015) and Hein and Smith (2017), the properties of each layer in the cross-section of permeable pavement system were discussed in detailed the summary of which are given below:

i) Permeable pavement surface: The recommended thickness of permeable pavement surface could be ranged from a minimum value of 60-80 mm. The thickness was generally depended on either pedestrian or vehicular applications. For PICP, the paver normally consisted of a paving unit assembled in certain pattern filling with permeable jointing material that created joints or openings to infiltrate water. For vehicular traffic, the paver basically had an aspect ratio of length to thickness ratio, which was less than or equal to 3:1 and a minimum thickness of 80 mm (3.125 in.). Permeable jointing material was a permeable crushed stone that typically met the requirement for ASTM No. 8, 9 or 89 materials. The joints or openings typically covered about 5% to 15% of the total pavement surface area.

ii) Bedding: Open-graded bedding course was a permeable layer of crushed stone that typically had a thickness of 50 mm (2 in.) and provided a level bed for the paver. It consisted of small-sized and open-graded aggregate, which was typically ASTM No. 8 stone.

iii) Base: The open-graded base reservoir was permeable. It was usually an aggregate layer with a thickness of 100 mm (4 in.), consisting of crushed stones with size ranging from 13 mm (0.5 in.) to 25 mm (1 in.). Besides storing water, this layer provided a gradational transition between the bedding and subbase layers. The stone size was typically ASTM No. 57 or similar sized material.

iv) Subbase: The open-graded subbase reservoir stone had a size larger than the base, primarily between 50 mm (2 in.) and 75 mm (3 in.), equivalent to ASTM No. 2, 3 or 4 stone. Similar to the base layer, water was stored in the space among the stones. The thickness of this layer depended on water storage requirements and traffic loads. A subbase layer might not be required in a pedestrian or residential driveway application. If the native soils underlying PICP system did not provide adequate infiltration, the open-graded subbase reservoir may include a perforated underdrain (as shown in Figure 2.11) to convey water out from the system. In addition, a geotextile fabric might be placed between the open-graded subbase layer and the uncompacted subgrade soil. The purpose of the geotextile layer was to separate the subbase reservoir from the natural soil and prevent the fines from migrating into the layers above.

The thickness and void capacity of different types of permeable pavements were simplified (Smith, 2006; Florida Concrete & Products Association, 2009; Virginia DEQ, 2013; Kayhanian et al., 2015;) as presented in Table 2.3. Overall, the designed thickness of permeable pavement can be more than 200 mm to 600 mm with aggregate sizes of about 2 mm to 76 mm, void capacity of 15% to 40% and pore space between 0.5 mm to 50 mm as shown in Table 2.4.

Therefore, in this study, the newly developed permeable pavement, permeable pavement with micro-detention storage (PPDS) had a total thickness of 500 mm, which consists of top cover of about 75 mm, middle base of micro-detention storage at around 350 mm and bottom cover of 75 mm thickness. The thickness is designed within the range of typical permeable pavement design with consideration of both hydrological and structural factors. The underlying soil, which is normally used as the subgrade, should be carefully evaluated. It should have a minimum field-verified permeability rate of 0.5 in./h less than 5% passing the No. 200 (0.075 mm) sieve, and a percolation rate of 0.5 in./h (12 mm/h). However, a slight difference was reported by Smith (2011), where the soil infiltration rate should be set at 0.52 in/h (3.7 x 10^{-6} m/sec) and considered a factor of safety of 2.

Table 2.3: Common thickness and void capacity of the permeable pavement section

Types	Surface materials properties	Reservoir materials properties
Porous asphalt (PA)	Compacted porous asphalt surface with a thickness of 2.5, 4, or 6 in.	Choker layer (8 in. was preferred), 8 to 12 in. filter course layer of poorly graded sand, 3 in. (minimum thickness) filter blanket (i.e. pea gravel) Thickness: 4 to 8 in. and maximum void ratio: 40%.
Porous concrete (PC)	Concrete surface layer with 15-25% voids	Void ratio of subbase layer: 20-40% Thickness: 3/8 in. and 3/4 in.
Permeable interlocking concrete pavement(PICP) section	Concrete paving units with ASTM C936 Standard Specification for Solid Interlocking Concrete Paving Units. Jointing materials with permeable, small-sized aggregates such as ASTM No. 8, 89 or 9 stone Thickness: minimum of 31/8 in. (80 mm) in vehicular areas and 2 3/8 in. (60 mm) in pedestrian areas. Bedding course: Small-sized, open-graded aggregate, typically ASTM No. 8 stone or similar sized material with Thickness: 2 in. (50 mm)	Base: Crushed stone primarily 1 in. to 1/2 in. (25 mm to 13 mm), ASTM No. 57 or similar sized material. Thickness: 4 in. (100 mm) Subbase: 3 in. down to 2 in. (75 mm down to 50 mm), typically ASTM No. 2, 3 or 4 stone. Thickness: 100-450 mm Minimum void ratio: 40%.

Table 2.4: Summary of the properties of each permeable pavements layer

Layer	Surface course	Bedding	Base	Subbase
Thickness (mm)	20-40	50-100	70-150	100-250
Aggregate size (mm)	2-5	2-10	5-25	50-76
Void content (%)	15-25	15-25	20-40	20-40
Pore space (mm)	0.5-2.5	0.5-5	2-20	25-50

2.7 Hydrological design consideration

Tennis et al. (2004) studied two factors to determine the design thickness of pervious pavements, which were the hydraulic properties, such as permeability and volume of voids, and the mechanical properties, such as strength and stiffness. They stated that the hydrological design had to consider the storms, runoff and ground soil. Runoff is a function of the soil properties; in particular, different infiltration rates and rainfall events may result in different runoff amounts. Therefore, the selection of design storms significantly affects the quantity of runoff. For each rainfall event flowing into a permeable pavement system, only a portion of the rainwater was captured in the depression storage, and the rest was either infiltrated into the soil or intercepted by the ground cover (Korkealaakso et al., 2014). Besides, Federal Highway Administration (FHWA) (2015) had listed the detailed features and hydrological considerations for the design of permeable pavement, which were:

i) Design storm, to determine expected storm duration, frequency, intensity and depth;
ii) Contributing areas of runoff, to determine runoff volume, velocity, etc. from the contributing areas and considered potential sediment loads to be captured before reaching the permeable pavement surface.
iii) Subgrade infiltration, to determine potential infiltration based on the soil type and density. Normally, subgrade compaction is required to support vehicular traffic, but lower compaction is more favourable to provide maximum infiltration capability.
iv) Surface, to determine initial and long-term surface infiltration if it is subjected to sediment loads. The surface slope should be less than 5%, especially while designing the supplemental surface drainage for high-intensity storms.

v) Subgrade, to determine the infiltration rate in the subgrade layer. The slope should be maintained at less than 1%. Underdrains for partial or no infiltration designs, to determine the type, location and need of underdrains and specify the outlet details and cleanout(s).

vi) Geosynthetics (e.g. geotextile, geogrid, geomembrane), to assess the need and benefit of geosynthetics in separation, filtration, containment, reinforcement, etc.

2.7.1 Storage capacity

The storage capacity of the entire permeable pavement system included the capacity within the permeable pavement layer, the capacity within the base course, storage above ground due to curbs and underground storage tanks (Kayhanian et al., 2015). In general, while designing the storage capacity, the main focus is to determine the required thickness for the temporary storage of runoff. In order to achieve that purpose, the design runoff and reservoir capacity must be determined (Weiss et al., 2015). Theoretically, storage capacity can be considered effective in service only if a minimum thickness of 150 mm coarse aggregate is used (Leming et al., 2007). Tennis et al. (2004) stated that pavement with a thickness of 5 in. (125 mm) and 20% void had the ability to store 1 in. (25 mm) of rainwater. The storage could achieve a three times improvement to 3 in. (75 mm) when the thickness was increased to 6 in. (150 mm). According to NAPA (2008), the recharge bed was typically having a depth of 12 to 36 in.

PICP were typically built over an open-graded aggregate base, which normally had an in-situ porosity of at least 32%. A 40% void space meant that the volume of the base was 2.5 times larger than the volume of water that it could store. Nevertheless, the water infiltration capacity of the base was varied with its depth and the percentage of void space (UNI-GROUP, 2008).

The selection of an appropriate return period is important. A 2-yr storm is often considered as the "service load" for the site while a 10-yr storm has traditionally been used in the design of a stormwater collection system (Leming et al., 2007; Tennis et al., 2004). Other storms, such as the 20-yr, 50-yr, and 100-yr storms were only used while analysing larger basins for flood control. According to Smith (2010), the permeable pavement was usually designed to handle the 24 h rainfall for a 2-yr storm. Stormwater that was stored in the stone reservoir should be ideally exfiltrated within 24 h to 48 h following a rainfall event in order to provide sufficient storage for subsequent storm events.

Lin et al. (2014) and Park et al. (2014) studied the storage capacity of different permeable pavements, which were dense graded asphalt (AP), permeable block (PBP), porous concrete (PCP) and porous asphalt (PAP). All of the tested pavement structures had different cross-sections. PBP has a block paver, bedding sand andsubbase with a thickness of 80 mm, 30 mm and 300 mm, respectively. Both the PCP and PAP had a thickness of 100 mm, however, PCP had a subbase of 300 mm thick and PAP had a filter layer of 50 mm thick instead of the subbase. Through the testing, the average maximum storage of each pavement was obtained. It was 40 L/m^2 for PBP, 35 L/m^2 for PCP, and 30 L/m^2 for PAP. Boomsma & Huurman (2006) conducted a study on a permeable block pavement system consisting of a permeable subbase with 35% porosity. The finding showed that it had the capability to store a maximum amount of 140 L/m^2 rainwater. Furthermore, Zhang (2006) showed that storage of 48.2 L/m^2 could be achieved by using 80 mm of Ecoloc surface pavers, 30 mm of bedding material and 200 mm of permeable subbase in a permeable pavement.

While calculating the total runoff volume for hydrological design capacity, different methodologies have been employed, such as Curve Number (CN), Rational Method

(RM), etc. The Curve Number is an appropriate method when the main purpose of the pervious concrete system is to reduce runoff volume (Leming et al., 2007). NAPA (2008) also recommended CN method for porous pavement design. It estimates the total runoff volume, Q, by using Equations 2.3 and 2.4:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.85)}$$
Equation 2.3

$$S = \frac{1000}{(CN - 10)}$$
Equation 2.4

where Q is the total volume of runoff, P is the precipitation, S is the retention area, and CN is the Curve Number. With respect to CN, hydrologic soil groups (HSG) A (sand, loamy sand, or sandy loam) and B (silt loam or loam) are identified as the best suited soil for permeable pavement. However, it was stated that hydrologic soil groups C (sandy clay loam) and D (clay loam, silty clay loam, sandy clay, silty clay, or clay) can also be considered as a choice if and only if a special care measure is taken.

According to Leming et al. (2007), RM can provide an accurate result while estimating the flow rate of the peak runoff in a simple pervious concrete system. However, for a complex pervious pavement system, the estimated value may not be acceptable for the design and analysis purposes since some of the advantages of hydrological features cannot be captured. In RM, the peak flow is estimated using the relationship:

$$Q = CIA$$
Equation 2.5

where Q is the peak run off flow (ft^3/s), A is the area of the watershed (acres), I is the average rainfall intensity for a critical time period (in/h), and C is the runoff coefficient for the surface. While applying RM, the duration of the design storm was recommended to be equal to the time of concentration (T_c). A higher value of C means more runoff was expected. Conventional pavements were typically assigned with a C value of 0.98, indicating that almost all of the rain falling on that pavement would become runoff.

Smith (2011) recommended the use of this method recommended by Interlocking Concrete Pavement Institute (ICPI) (2005) to calculate the runoff volume for a PICP system. The method is basically based on the surface area of PICP that is usually considered 100% pervious. This is because, if functioning properly, all the rainwater that lands on it will infiltrate. For this method, the assumption of the maximum allowable storage time is essential to ensure that the subgrade will not be saturated for a long period of time. With the time limit and final infiltration rate, the maximum allowable base/ subbase depth can be estimated through:

$$d_{max} = \frac{fT_s}{V_r}$$ Equation 2.6

where d_{max} is maximum base/subbase depth, f is final infiltration rate, T_s is maximum storage time, V_r is void ratio of the base/ subbase (typically 0.4).

2.7.2 Permeability

The hydraulic conductivity (or permeability) of a material is a measure of its ability to allow water to move through its porous medium when submitted to a hydraulic gradient (Xie et al., 2019). According to Mishra et al. (2013), the most distinguished feature of permeable pavement was its high permeability, indicating the flow of water through the pore space. The permeability depended on materials, mixtures compaction and placing operation, and was governed by the capillary pores of the permeable pavement layer, where large pores resulted in a high permeability while small pores resulted in low permeability. Coarse aggregates were used instead of fine aggregates for high and good porosity. However, the very large size of aggregates reduced the structural aspects of the permeable pavement, while the use of small aggregates reduced its functional characteristics as a stormwater management infrastructure. Therefore, the integration of both is important in the design of permeable pavement (Mishra et al., 2013).

Tennis et al. (2004) reported the typical flow rates for water passing through pervious concrete that ranged from about 120 L/m^2/min or 2 mm/s to 320 L/m^2/min or 5.4 mm/s, and might probably hike until 700 L/m^2/min or 12 mm/s. Meanwhile, Leming et al. (2007) concluded that, a moderate porosity pervious concrete pavement system would have a permeability of 143 L/m^2/min, which was equivalent to an infiltration rate in excess of 2.4 mm/s (8.6 m/h), and more than 100 times the infiltration rates of most natural saturated sands. On the other hand, PICP had a very high permeability rate, ranging from 500 in./h (10^{-3} m/s) to over 2000 in./h (over 10^{-3} to 10^{-2} m/s), which was far more pervious than any of the existing site soil (UNI-GROUP, 2008). Table 2.5 summaries the hydrological properties such as measurement of storage capacity based on void volume, permeability, required designs storms and detention duration. Nonetheless, according to Leming et al. (2007) and Tennis et al. (2004), permeability, in general, is not a limiting or critical design feature of a permeable pavement structure.

Table 2.5: Hydrological properties consideration for permeable pavement design

Hydrological properties	Standard design
Storage capacity(capacity of pervious concrete + reservoir + optional features; curbs and underground tanks)	Based on design thickness; Surface Pavement layer + Base + Subbase = Total (15%) 80 mm + (30%) 150 mm + (40%) 150 mm = 117 mm
Permeability	143 L/m^2/min or 8600 mm/h
Design storms (return period)	2 years (service load) and 10 years (flood control)
Detention period	Within 24 h to 72 h

2.7.3 Infiltration rate

Infiltration is the process in which water enters the soil and contributes to soil moisture. The amount of water infiltrating the soil surface had a direct effect on the quantity of surface runoff, soil saturation and groundwater recharge (Weiss et al., 2015). Therefore, a thorough soil investigation must be performed to measure if the soil is adequate for the permeable pavement with regards to infiltration rate and capacity. The specifications and guidelines for designing hydrological structures were depended on the amount of stormwater and the infiltration rate of subgrade soil (Hein et al., 2010). The selection of the base structures, layer thicknesses and materials of porous pavement were affected by the native soils. The subgrade soil type had the most significant impact on permeability, while the thickness was selected based on soil permeability.

According to Ferguson (2005), subsoil characteristics and structures were essential in designing porous pavement. Infiltration is strongly depended on soil properties. If there is an impermeable layer near to the bottom of the pavement, the infiltration rate of soil has to be greater to maintain the ability to convey water. If the subsoil is less permeable, additional drainage systems would be required in the storage layer. An acceptable reservoir detention rate is usually two days (48 h) with a soil infiltration rate of at least 1.27 cm/h (0.5 in./h) dependent on the reservoir discharge design (Agouridis et al., 2011; Virginia DEQ, 2013). NAPA (2008) reported that native soil with an infiltration rate of 0.1 to 10 in./h had the best working performance. Table 2.6 shows the range of infiltration rate of Hydrologic Soil Group, HSG, from high porous sand (Group A) to low porous clay (Group D) in National Resources Conservation Services (NRCS) classification system. U.S. Environmental Protection Agency (USEPA) listed 0.27 in./h as the minimum acceptable infiltration rate while designing the permeable pavement. Therefore, soil textures in hydrologic soil groups C and D are not the preference as their minimum infiltration rates are lower than the recommended value.

Table 2.6: Infiltration rates of Hydrologic Soil Group (HSG)

Soil Texture	Hydrologic Soil Group	Minimum Infiltration Rate (in./h)	Minimum Infiltration Rate (mm/h)
Sand	A	8.27	210.06
Loamy sand	A	2.41	61.21
Sandy loam	B	1.02	25.91
Loam	B	0.52	13.21
Silt Loam	C	0.27	6.86
Sandy clay loam	C	0.17	4.32
Clay loam	D	0.09	2.29
Silty clay loam	D	0.06	1.52
Sandy clay	D	0.005	1.27
Silty clay	D	0.04	1.02
Clay	D	0.02	0.51

In fact, different countries have different standards for infiltration capacity. In Germany, the permeable pavement must provide an infiltration capacity of larger or equal to 270 l/s/ha, equivalent to the hydraulic conductivity of $2.7x10^{-5}$ m/s. Due to the existence of air-filled pores in the underground, a decrease of the flow velocity is expected, and thereby a hydraulic conductivity with a minimum value of $5.4x10^{-5}$ m/s is necessary (Dierkes et al., 2000). In Australia, the subgrade soil of a permeable pavement should have a good drainage property and minimum hydraulic conductivity of 0.36 mm/h (Lucke & Beecham, 2011a). In Netherlands, the newly-installed permeable pavement must demonstrate a minimum infiltration capacity of 194 mm/h (540 l/s/ha), whereby once the infiltration falls below 20.8 mm/h, maintenance work should be taken on it (Boogaard et al., 2014). While, in most of the United Kingdom (UK) soil, the maximum exfiltration rate was recorded at 13.32 mm/h (37 l/s/ha). This value should be compared with the 5 yr return period of 64.8 mm/h (180 l/s/ha) in UK rainfall requirement (Kayhanian et al., 2019). Lastly, Shackel (2010), through his study for 7 sites distributed randomly, which had been constructed for around 8 yr to 12 yr, had concluded that the average infiltration rate found in Australia was about 288 mm/h (800 l/s/ha).

The reviews of literature contained in Weiss et al. (2015) reported that the performance of permeable pavements in terms of infiltration rate could reach as high as 4000 cm/h from the lowest of 1 cm/h, where different materials have different infiltration rates and the rate declined with years of service. In a study by Bean et al. (2007) to determine the surface infiltration rate for 3 different pavement types, which were CGP, PICP and PC; found that for CGP, the median value for existing was 4.9 cm/h and maintained was 8.6 cm/h , for PICP and PC, median value for sites affected by fines was 8.0 cm/h and 16 cm/h, respectively, and for sites free from fines was at 2000 cm/h and 4000 cm/h, respectively.

The subgrade reservoir capacity is significantly impacted by the infiltration capacity of on-site native soil. Although a higher infiltration rate is always desirable, the minimum infiltration rates of 1.27 cm/h and 0.25 cm/h were suggested by Leming et al. (2007) and Virginia Department of Environment Quality (DEQ, 2013) , respectively. To ensure the effectiveness of permeable pavement for runoff reduction, several criteria have to be fulfilled that are locating the pavement in a sandy or loamy sand soil without seasonally high water table, well-maintaining the pavement, using proper construction materials and techniques, and ensuring the pavement is essentially flat and away from the disturbed fine soils and does not have excessive structural loads on it (Bean et al., 2007). In addition, depending on the infiltration capacity of the native soil, the permeable pavement system may equip with underdrain located in the aggregate reservoir layer to collect and convey infiltrated water (Kayhanian et al., 2015).

The measurement of surface infiltration rate of permeable pavement is essential to assess its infiltration capability. The surface infiltration test measures the time taken to infiltrate a known volume of water. According to Fernandez-Barrera et al. (2008), the apparatus used for in-situ measurement could be classified into two main types, which were flooding or ring infiltrometer that used a column of water, constant or variable, over the surface, and the infiltrometer that used rain simulation, of any kind, over the test area.

Single-Ring Infiltrometer Test (SRIT) and Double-Ring Infiltrometer Test (DRIT) were used for soil infiltration measurement and adopted to determine the infiltration rate of the permeable surface. Two different methods were generally used to measure the soil infiltration rate, namely constant head and falling head. For the constant head method, a sufficient amount of water was continually added to the ring in order to maintain a constant head. The inflow rate was then measured and converted to a suitable infiltration rate (usually in mm/hr). For the falling head method, the time taken for a certain volume of water within the ring (usually between two predetermined levels) to fully infiltrate into the soil was measured. SRIT and DRIT were used by Bean et al. (2007) to test the infiltration rates of PP. ASTM D 3385 (ASTM 2003b), or known as the "Standard Test Method for Infiltration Rate in Field Soils Using Double-Ring Infiltrometer", was used as a procedural basis to measure the surface infiltration rate. In their study, some of the methods and materials in ASTM D 3385 were modified, for example, sealing the infiltration rings to the surface with plumbing putty and filling it with water. Water level was recorded at a regular interval because the water would drain into the pavement. The falling-head was used to calculate the vertical infiltration rate. The double-ring infiltrometer consisted of two galvanized steel rings. The inner ring had a diameter between 280 mm (11 in.) and 305 mm (12 in.), while the outer ring had a diameter between 760 mm (30 in.) and 910 mm (36 in.) or approximately three times the diameter of the inner ring. On the other hand, the single-ring infiltrometer method had only an inner ring. The SRIT was not as accurate and precise as the DRIT because it did not prevent the horizontal migration of the water once it entered the media (Bean et al., 2007). However, it provided a method for quantifying the surface infiltration rate on highly permeable applications. Thus, the single ring infiltrometer test was generally used for pavements with an infiltration rate, which was too high to maintain a hydraulic head (Lucke & Beecham, 2011b). Single-Ring Infiltrometer Test (SRIT) was used by Lucke, et al. (2015) with a cylindrical ring of 300 mm or larger in diameter that was driven for about 50 mm into the soil to prevent lateral water flow. A pre-wetting process was carried out by pouring 3.6 kg of water into the ring to maintain a constant head between 10-15 mm from the base. The time taken for the water to fully infiltrate through the surface (from the time the water hit the surface to the time it is no longer visible on the surface) was recorded for obtaining the infiltration rate.

Stovring et al. (2013) modified the conventional SRIT into a more advanced test called Constant Head Single Ring Infiltrometer Test (CONSRIT) by combining certain features of the DRIT and SRIT methods. Using the CONSRIT method, a single ring of 300 mm in diameter and 400 mm height was added with a Topaz valve for trough ½" JOBE (max 6 bar, max 150 l/min) and connected to water supply with a ½" water hose connected with a water meter. The infiltration ring was tightened using a rubber band and the constant head was formed at a height of 6~10 cm.

Nichols et al. (2014) studied the infiltration performance of a modified DRIT and a specially designed rainfall simulation infiltrometer test (RSIT). The DRIT normally involved the driving of two rings (an outer ring with 600 mm diameter and an inner ring with 300 mm diameter) to a certain soil depth (usually 150 mm deep for the outer ring and between 50 and 75 mm deep for the inner ring). Two rings were used to prevent or minimise the lateral movement of water during the test. Water was then added to the rings at an appropriate flow rate in order to maintain a constant head in both rings over the test duration. The volume of water added over time was then used to calculate the soil infiltration rate. In Nichols et al. (2014), to enhance the effectiveness of DRIT, they used the falling head method instead of a constant head. The rings were filled with water and the time taken for the water level in the central ring to fall to a certain distance was recorded. The change in water level over time was then used to calculate the infiltration rate.

Meanwhile, Nichols et al. (2014) designed a RSIT with a test rig made up of a square steel frame fixed with a series of PVC pipes on top. The RSIT included an inner and outer "ring" that was separated by 3 mm thick Perspex® sheeting. The area of the inner ring was 0.50 m^2. The outer ring was mainly used to reduce lateral flow effects. The PVC pipes were designed to replicate the water supply of a dual ring system used in the standard DRIT. Rainfall simulation was achieved by supplying water to the RSIT through a series of holes (2.5 mm diameter) drilled into the underside of the pipes 50 mm apart. Water was supplied to the RSIT device using a pump and a water tank mounted on a trailer. The flow of water was controlled via flow meters and valves. In order to visually simulate rainfall droplets, the jets of water flowing from the holes in the PVC pipe were passed through two horizontal wire gauge sheets to break the flow into droplets prior to contacting the pavement surface. During the RSIT, the maximum infiltration capacity of the pavement was identified when the water started visibly ponding on the pavement surface outside the framed area. Once ponding was observed, the flow meter reading was recorded and classified as the maximum infiltration capacity of the site.

Boogaard et al. (2014) developed a full-scale infiltration test to evaluate the infiltration performance of existing permeable pavements in the Netherlands. The procedure required a large volume of water to be discharged onto the tested paving section and to the maximum allowable water level that would not cause overtopping of the roadway kerb and gutter system. It was generally between 50 and 90 mm from the lowest point in the pavement to the top of the gutter. Pressure transducer was used to monitor the water level and transmitted the result to the computer. The study also applied hand measurements, calibrated the underwater camera and time-lapse photographing to measure the difference of water level with time.

Fernandez-Barrera et al. (2008) used LCS Permeameter and Cantabrian Portable Infiltrometer (CP Infiltrometer), which was a specially designed device based on rainfall simulation, for the assessment of the infiltration capacity. LCS Permeameter was a flooding type infiltrometer, which employed a ring with a variable water column inside. Using the apparatus, the time taken for the water level to fall between two marks when water discharged through a small hole was measured. Meanwhile, for CP Infiltrometer, the constant head was applied and simulated at specific rain intensity according to the location and return period. On the other hand, Cox et al. (2018) studied the use of a simple permeameter device, called Mississippi permeameter (MSP), to measure water infiltrated into asphalt pavement regardless of the type of the surface.

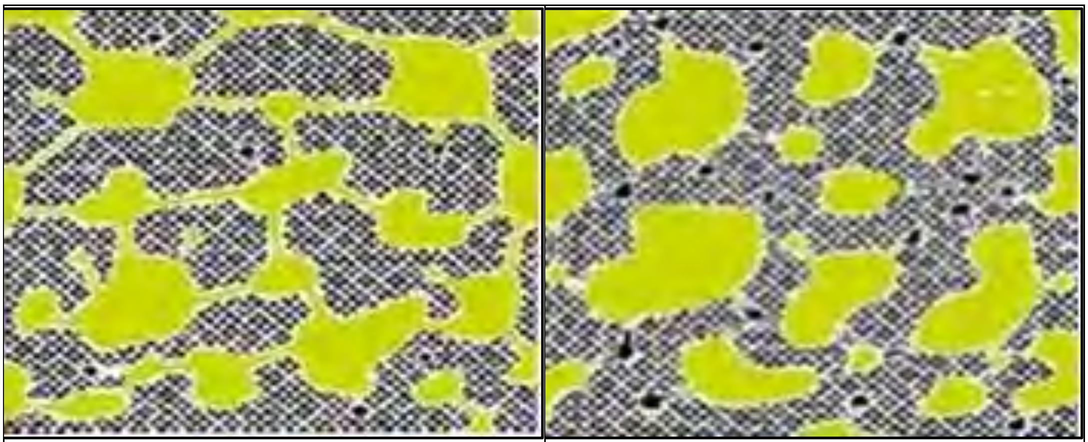
Lucke et al. (2015) introduced a simple, modified and easy method, namely Stormwater Infiltration Field Test (SWIFT). It used a 20 L plastic bucket with a 40 mm diameter hole cut into its base to estimate the PICP infiltration rate. The SWIFT relied on the number of fully wetted bricks and no surface pre-wetting was required. It involved the bucket placement over the surface paver so that the drainage hole was located directly above the centre of the tested paver. The plug was inserted into the bucket drain hole and the bucket was filled with 6 L of water. Then, the plug was removed using the attached chain or rope. The water was allowed to flow out of the bucket and onto the paving surface. Next, the SWIFT device was removed and the number of bricks that were fully-wetted across their entire surface was counted and recorded. The final step was to estimate the average infiltration rate.

Alizadehtazi et al. (2016) applied a Cornell sprinkle infiltrometer to simulate rainfall at predetermined rates onto a control surface and allow the estimation of important hydraulic properties, such as time to run off and field-saturated infiltration rate. The device consisted of a water reservoir with a perforated bottom, which delivered the simulated rainfall onto a 241-mm-diameter area delimited by a metal ring. An outflow tube was fitted in the metal ring and allowed water to run off once surface ponding occurred. When the steady-state in the outflow was achieved, the field-saturated infiltration rate or rate of water intake into the soil under these conditions could be estimated as the difference between the applied rainfall rate and the runoff rate. Contrary to the common ring infiltrometers, the Cornell sprinkle infiltrometer had the advantage of not creating a significant hydraulic head over the surface. Therefore, it is not water-intensive and less susceptible to the errors resulting from soil slaking or the presence of the large downward flow through the macro-pores, which is one of the common problems in ring infiltrometers.

In this research, falling head method is emphasised as it is deemed suitable to measure the infiltration rate in the laboratory. The experimental procedure applied are as in Alizadehtazi et al. (2016). A detail on experimental procedure to measure infiltration rate is in Section 3.4. Overall, the design and construction of permeable pavement, regardless of the type of surface pavement, requires comprehensive structural and hydrological analyses to ensure the functionality of the pavement.

2.8 Permeable pavement drawbacks

A typical permeable pavement is connected through the pore spaces and void interconnection as shown in Figure 2.12a. The pore spaces in the permeable pavement surface allow the water to infiltrate into the pavement during rainfall. Permeable concrete is characterised by highly interconnected porosity, typically ranges from 15% to 40% that allows water to flow rapidly through the pore structure. Water passed through several layers of pervious material, where it is temporarily stored and finally entered the ground. Since water is held within the pores of the soil, the water holding capacity is depended on the capillary action and the size of the pores that existed between particles medium. Large pores spaces allow water to move quickly whereby small pores would hold water tightly. For water to move in the reservoir, the pores between the materials must be connected. Good connections of pore spaces would make water moves freely and transmits easily to the ground as depicted in Figure 2.12a. On the other hand, Figure 2.12b shows a disconnected system due to the clogging of particles and sediments in the system. Clogging refers to a decrease in permeability due to physical, biological and chemical processes (Mishra et al., 2013). While water entered into the pavement, it entered along with many fine and coarse particles and matters. Overall, the clogging process occurred in three stages. In the first stage, particulate matters entered the surface. In the second stage, fine particles flowed through the substrate with water and coarse particles retained on the surface and formed a blanket type of layer, which reduced infiltration. In the third stage, the blanket-like deposition layer became thick and acts as a barrier to prevent most particles from reaching the clogging layer. As a result, the clogging layer reduced the infiltration rate, which led to serious surface ponding (Mishra et al., 2013).



(a) Void content in a PP system with a good connection between the voids for stormwater flow, hence resulted with a high permeability rate.	(b) Void content in a PP system with large pores but no connection between the voids for stormwater flow, hence resulted with a low permeability rate.

Figure 2.12: Permeable pavement with (a) interconnected pores, and (b) loss of connection due to surface clogging

PP ensures water availability to the groundwater. The permeable layers provided void spaces for water to flow through and infiltrate to the ground. Rainfall was conserved whilst runoff and flooding were reduced. These layered characteristics with open-graded materials were opened for particle build-up block, which connected capillary pores, accumulated in void spaces of permeable pavements and clogged the system (Pratt, 1995; Yong et al., 2008; Kia et al., 2017). Moreover, PP invented with voids and porosity properties acts as stormwater management structure prone to clog due to the blocking of debris, sediment and fine particles in the pore spaces, which disconnected the system (Leming et al., 2007; Yong et al., 2010; Kayhanian et al., 2012; Sansalone et al., 2012).

Boogaard et al. (2014) monitored 55 permeable pavements, located in Australia and the Netherlands, with an age ranged of 1-yr to 12-yr. The infiltration capacity of the permeable pavements decreased with pavement age due to cumulative clogging by sedimentation, poor installation and maintenance. The clogging of pores could be caused by dry deposition of particles (i.e. sand, silt, clay, debris), as well as shear stress of vehicles driving and degrading the permeable surfaces (Weiss et al., 2015; Kumar et al., 2016; Kia et al., 2017; Kayhanian et al., 2019). Mishra et al. (2013) found that 70% of clogging issues were caused by suspended solids (SS) and bubbles, 10% by chemical reactions, 15% by microbial growth and the rest 5% by other reasons.

There is an indirect relationship between surface infiltration rate and the age of the pavement (Razzaghmanesh & Beecham, 2018). The measured infiltration rate of PP usually decreased significantly within three years after installation due to clogging (Scholz & Grabowiecki, 2007). Al-Rubaei et al. (2013) observed an infiltration rate, which was 95% lower than the original condition on several porous asphalts, which had been constructed for around 18-yr to 24-yr in Northern Sweden. Kumar et al. (2016) measured the in-situ infiltration performance of a car park, which contained three sections (permeable pavers, permeable concrete and permeable asphalt) for a four-year time since its installation. The infiltration rate was very high at the beginning but started to decline with time due to clogging. Kamali et al. (2017) conducted a study on the capacity of the PP to investigate the chronological clogging trend. They found that the runoff coefficient increased around 15% in the sixth year after installation and boosted up to about 35% in the seventh year, whilst the sediment loadings had a big influence on the age of the permeable pavement. The finding is in agreement with Lucke & Beecham (2011b) who indicated the infiltration rate of PICP system, which had been in service for over eight years, decreased over time from 63.3% to 100%.

Most of the clogging happened near the surface of the PP and thereby the remedial work should be concentrated on the upper layers (Marchioni & Becciu, 2015; Kayhanian et al., 2015). Clogging is generally appeared to be limited to the top layer (50 mm). A lower porosity of the top surface was an indication of clogging (Kayhanian et al., 2019), where most of the penetrated particles accumulated at the bottom of open-graded and the top of the dense-graded layer. Nevertheless, in some of the cases, the clogging occurred on the bedding aggregate at the bottom of the pavers (Yong et al., 2008; Coleri et al., 2013; Lucke, 2014). Coleri et al., (2013) evaluated particle-related clogging by comparing the void content distribution (porosity profile) of open-graded friction course (OGFC) pavement using X-ray CT imaging. The result showed that the highest air-void reduction was concentrated at the bottom of the OGFC layers. Therefore, it is a normal trend to put a geotextile layer between the surface layer and the base layer of PP. This practice could effectively remove the particulate matters, however, contributing to clogging problem above the geotextile and, thereby leading to a reduction of infiltration capacity (Newton, 2005; Yong et al., 2008; Boving et al., 2008; Yong et al., 2010; Kamali et al., 2017).

The most challenging problem with current permeable concrete is its high susceptibility to clogging. Therefore, a periodic maintenance/cleaning is essential to retain its function (Kumar et al., 2016). The clogging issues could be solved through regular vacuum cleaning with a combination of high-pressure washing (Kumar et al., 2016; Kia et al., 2017). Marchioni and Becciu (2015) introduced a maintenance method, which involved the removal of joint material and bedding layer. The other method for maintenance purposes is to remove the entire system, but the frequent replacement is impractical and expensive (Lucke & Dierkes, 2015). Thus, permeable pavement of PICP types becomes the preference, while selecting the type of pavement due to its modular interlocking concrete block characteristic that smoothens the remediation work for clogging, high infiltration rate and ease of installation (Ferguson, 2009; Shackel, 2010). However, even with maintenance work, a degree of clogging of PP systems is still unavoidable (Kia et al., 2017). Hence, the development of PP with less clogging issues has become the priority for both researchers and practitioners (Razzaghmanesh & Beecham, 2018).

Several types of research that focused on different methods to restore the permeability of permeable concrete had been carried out. Nonetheless, the suggested maintenance methods were not particularly effective to remove the clogging particles that accumulate below the surface of the PP system (Kia et al., 2017). Besides, infiltration with integration of retention based systems that consist of a PP with underground detention storage is a large-scale design of stormwater infrastructure. The concept of storing water in an underground carriageway could help to significantly reduce drain size and peak runoff, greywater usage and water harvesting (Zhang et al., 2013). However, it faced numerous problems associated with the under road systems, such as water supply pipes, sewer pipes, cables and trees roots. Furthermore, it might also require big-scaled machinery and equipment for the construction. Therefore, it is of interest to develop an innovative design for a micro-scale on-site detention pond permeable pavement, PPDS, to avoid potential conflict with the existing systems under roads besides having the ability to detain water with minimize clogging and recharge groundwater for sustainability development.

2.9 Testing device for permeable pavement

The testing devices in this study are consisted of laboratory-scaled rainfall simulator and software modelling of Urban Stormwater Management Model (SWMM). An extensive review is included in this section.

2.9.1 Artificial rainfall techniques using laboratory-scaled rainfall simulator

Rainfall simulator (RS) had been extensively used in the study of rainfall, runoff, soil erosion and infiltration (Huang et al., 2013; Kathiravelu et al., 2014; Lora et al., 2016). RS is a device to duplicate the physical characteristics of natural rainfall. One of its advantages is the possibility to vary the system configuration for simulating different scenarios of rainfall field characteristics (Corona et al., 2013). In addition, it encompasses the fact that rainfall can be produced quickly on-demand, wherever necessary without having to wait for natural rain at the intensity and duration required, and thereby eliminating the erratic and unpredictable variability of natural rain (Aksoy et al., 2012), as well as the rapid data collection under relatively uniform conditions (Abudi et al., 2012).

There are two types of rainfall simulators, which are drop former and nozzle simulator. Drop former is a drop-forming type rainfall simulator that simulates the rainfall through a drip tank with uniform arrays of holes. The water flow produces a distribution of drop with an intensity that is controlled by the diameter of the holes and the pressure in the tank. Its limitations are the high dependency of drop size distribution and velocity on the tank height, and impractical for a large area. On the other hand, the nozzle-type rainfall simulator generates drops that force water into the nozzles and produces higher velocity and rainfall intensity at a larger scale with uniform spatial distribution and reasonable drop size distribution (Corona et al., 2013).

Rainfall characteristics that have to be determined in RS include drop size, spatial uniformity and terminal velocity (Meyer, 1994). Besides, the accurate control of rainfall intensity, repeatability of applying the same simulated rainstorms and ease of operation within the research area covered are essential, while applying a rainfall simulator (Clarke & Walsh, 2007). Among the control variables, rainfall intensity was selected according to the study area, where most researchers choose to investigate in an area that is less than 5 m^2. Many rainfall simulators were designed with the nozzle at a height of 3 m or less to replicate the velocity and kinetic energy of natural rain (Humphry et al., 2002). Table 2.7 simplifies the techniques and measurements method of manual techniques reviewed by Kathiravelu et al. (2016) for drop size distribution. This manual technique is the most used due to its simplicity, low cost and availability of material compared to current technique such as high definition digital camera. Based on the review by Kathiravelu et al. (2016), oil immersion is a suitable technique to be used in this study. It is prepared with the mixtures of 2:1, consists of engine oil treatment and mineral oil based on Huang et al., (2013) study. In order to obtain spatial uniformity, Christiansen uniformity coefficient (CU) is applied, where a value higher than 80% is considered a uniform (Aksoy et al., 2012). Christiansen's coefficient of uniformity (CU) is calculated using Equation 2.7

$$CU = 100\left(1 - \frac{\Sigma\left|x - \bar{x}\right|}{n\bar{x}}\right) \qquad \text{Equation 2.7}$$

where, x is the rainfall depth, n is number of measurements and $\bar{x}$ is an average of all the measurements.

Table 2.7: Techniques and users on drop size distribution (Source: Kathiravelu et al., 2016)

Reviewed papers	Techniques	Methodology
14 papers from 1892 - 2012	Stain method: measurement of stains on dyed absorbent paper	Chemically treated paper was used for raindrops size measurement. Rain drops were allowed to fall on a sheet of absorbent paper with a water-soluble dye. Embedded dye reacts with rainfall and leaves permanent marks on paper. The marks was measured and counted for rainfall size distribution.
11 papers from 1940s to 2012	Flour pellet method: measurement of rain drops into finely sieved flour and produce dough pellets	The dough pellets were oven dried. Pellets were sized with sieves and weighed. It was then calibrated by weighing dried pellets produced by drops of a known size.
14 papers from 1937-2016	Oil immersion method: measurement of rain drops in a vessel containing oil.	Raindrops were collected in glass/vessel trough containing mixture of lightly viscous liquids, engine oil treatment and mineral oil. A camera or microscope was used to view the spherical shapes that form by oils, which allowed drop to be counted and measured by microscope or via photograph.

RS model parameterisation is designed and fabricated by designers to provide no limitation on frequency, duration and intensity for the objectives of their research (Fister et al., 2012; Iserloh et al., 2013). The designers made decision based on the specifications and performance characteristics, standard evaluation and test methodology (Grismer, 2011; Aksoy et al., 2012; Nnadi et al., 2012). There is no standard rainfall simulator, which can be applicable for all situations. Thus, the design of each RS is basically developed specific for the aim of the study. Table 2.8 summaries the collection of spatial uniformity in terms of Christiansen's coefficient of uniformity (CU), drop size distribution, types of simulator, range of rainfall intensity, and simulation area covered by various researchers. Some apparent differences are observed between the simulators. For example, drop height of rainfall changes from 0.4 m to 6 m, rainfall intensity varies from 0.5 mm/min to 60 mm/min, median diameter of raindrops ranges from 0.25 mm to 6.5 mm, catchment area changes from less than 1 m^2 to 12 m^2, height to the bottom surface varies from 0.45 m to 5 m.

Table 2.8: Characteristics of rainfall simulators by different researchers

References	Spatial uniformity (Christiansen's coefficient of uniformity, CU, %)	Drop size distribution (mm)	Types: DF-drip former NZ-nozzles	Rainfall intensity (mm/h)	Catchment dimension (width x length x height) , m
Aksoy et al. (2012) from 4 rainfall simulator, RS1 to RS4	RS1: 86 RS2: 87- 91 RS3: 82 & 89 RS4: 95 & 97	RS1: 2.2 RS2: 3.0 RS3: 2.2-3.1 RS4: 1.6	NZ	RS1: 47.5-52.5 RS2: 13 - 178 RS3: 45-105 RS4: 54 & 67	RS1: 2 x 3 x 3 RS2: 0.65 x 0.94 x 3.25 RS3: 6.5 x 1.36 x 1.15 RS4: 0.5 x 0.8 x 4.5
Nnadi et al. (2012)	0.001, 0.007, 3.91, 14.58 & 81.44	0.69-8.97	DF	600	2.30 ×1.801 × 1.60
Corona et al. (2013)	62 to 76	0.25 to 3.3	DF	61.6 and 31	4 × 4 × 2
Huang et al. (2013)	>80%	0.5 to 2	DF	30, 45, 60, 90 & 120	1.5 x 1 x 1.2
Iserloh et al. (2013).	61- 98	0.38 to 6.5	Both	37 to 360	Area (0.05 to 1.5) x Height (0.4 to 3.43)
Lora et al. (2016)	>80%	0.48 to 0.51	NZ	50 to 150	2 x 2 x (0.4-1.2)

The ability to investigate the urbanisation and sustainability awareness leads to the uses of the RS as a tool to evaluate the hydrological performance of green pavement system, such as runoff coefficient, delay effects, infiltration rate and storage capacity (Pratt et al., 1999; Zhang, 2006; Illgen et al., 2007; Hou et al., 2008; Straet et al., 2008; Langhans et al., 2011; Ni et al., 2011; Nnadi et al., 2012; Yong et al., 2013; Park et al.,2014). It was found that the hydrological performance varied according to rainfall intensity (Alsubih et al., 2017). In addition, RS was popularly being used to study the clogging issues of pervious pavement under different conditions, such as pavement slope, rainfall intensity, etc. (Coleri et al., 2013; Brugin et al., 2017; Kamali et al. 2017). Also, RS was seen as an effective tool to evaluates the life efficiency of permeable pavement subjected to sediment loading and pollutant removal (Yazdi et al., 2015; Ioannidou & Arthur, 2018).

2.9.2 Urban stormwater modelling

Basic information on hydrological analyses of stormwater management infrastructure highly relies on the simulation and modeling tools. It is important for the city planners, decision-makers and other stakeholders, to be used for urban planning and governance, especially in urban flood risk management. Simulation of hydrological responses for urban catchments to precipitation has became fundamental to identify the most effective strategy of green infrastructure (Pappalardo et al., 2017).

SWMM has been widely used for planning, analysis and design related to stormwater runoff in urban areas (Shuster & Pappas, 2011; Korkealaakso et al., 2014; Zhang et al., 2018). SWMM 5.1 introduces an additional feature, which enables it to simulate the stormwater management performance of various types of LID practices such as permeable pavements, rain gardens, green roofs, street planters, rain barrels, infiltration trenches, and vegetative swales (Ahiablame et al., 2012; Rossman, 2010a; Saini & Singh, 2016). Figure 2.13 shows the cross-section of LID practices in SWMM. LID practice was represented by a combination of one to four vertical layers: the surface layer, the soil layer, the storage layer, and the underdrain layer (Zhang et al., 2018). First of all, the surface layer received direct rainfall and runoff from upstream land areas, stored excess inflow in depression storage, and generated surface outflow that either entered the drainage system or flow onto downstream land areas. The surface layer page of the LID control editor was used to describe the surface properties of the porous pavement. Secondly, the pavement layer is the layer of porous concrete or asphalt used in continuous porous pavement systems, or in the paver blocks and filler material used in modular systems. Next, the storage layer is a bed of crushed rock or gravel that provided storage in the porous pavement. It received percolation from the soil zone above it and loses water by either infiltration into the underlying natural soil or by outflow through a perforated pipe underdrain system. LID storage layers can include an optional underdrain system that collected stored water from the bottom of the layer and conveys it to a conventional storm drain. The storage layer page of the LID control editor described the properties of the crushed stone or gravel layer porous pavement systems as a bottom storage/drainage layer. Lastly, the underdrain system conveyed water out of the gravel storage layer of porous pavement systems into a common outlet pipe or chamber. In each subcatchment, properties of each layer such as thickness, hydraulic conductivity and height and the LID coverage area were defined (Rossman, 2015). Rossman (2010a) described the modelling of LID in SWMM catered for a path line through the vertical layers as shown in Figure 2.14. The surface and storage layers are presented in Equations 2.8 and 2.9 respectively.

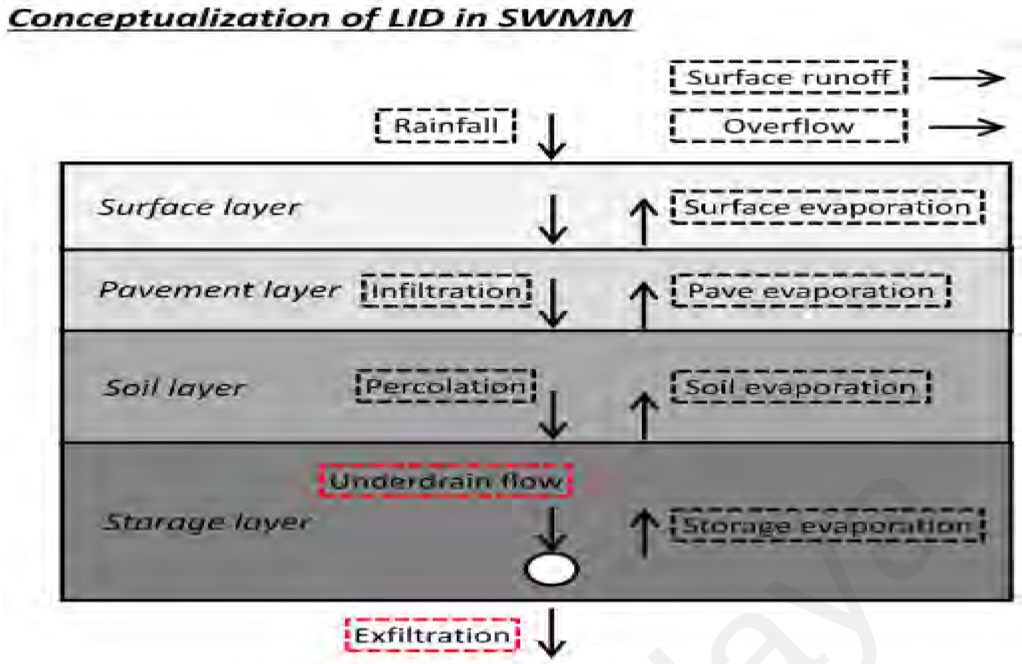


Figure 2.13: Schematic diagram showing the conceptual model of LID practice in SWMM (Source: Zhang et al., 2018)

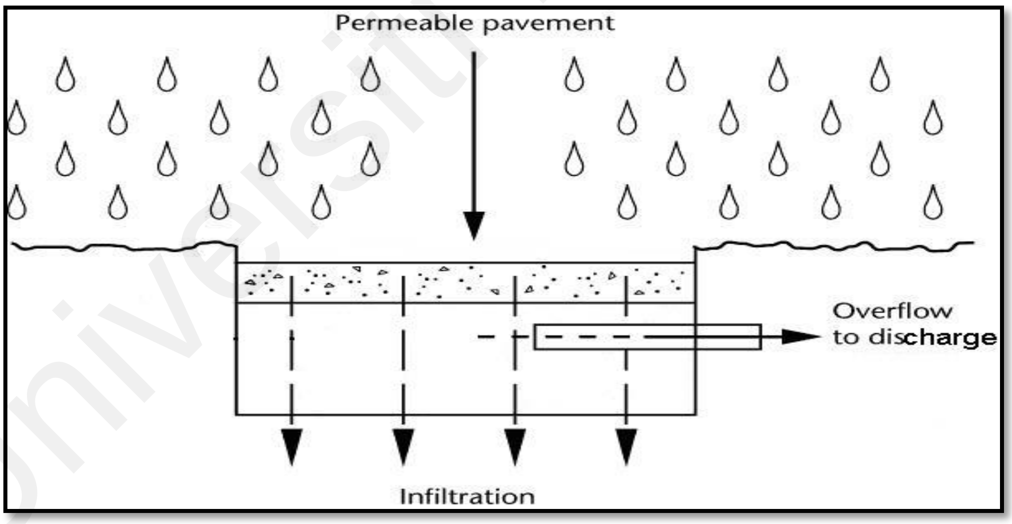


Figure 2.14: Flowpath of the LID structure in SWMM

The equations are as follows;

$$\frac{\partial d_1}{dt} = i + q_0 - e_1 + f_1 - q_1 \qquad \text{Equation 2.8}$$

$$\varphi \frac{\partial d_2}{dt} = f_2 - f_3 - q_1 \qquad \text{Equation 2.9}$$

where d_1 is depth of ponded surface water (m), d_2 is depth of water in storage layer (m), i is externally supplied rate of precipitation (m/s), q_0 is externally supplied surface runon flow rate (m/s), q_1 is surface runoff flowrate (m/s), f_1 is surface infiltration rate (m/s), f_2 is soil percolation rate (m/s), f_3 is native soil infiltration rate (m/s) and φ is known void ratio of the storage layer (m^3/m^3).

From the conservation of mass, the net change in depth, d per unit of time,t is simply the difference between inflow and outflow rates over the subcatchment as in Equation 2.10.

$$\varphi \frac{\partial \mathrm{d}}{\partial t} = i - f - q$$ Equation 2.10

where i is rate of rainfall, f is infiltration rate, and q is runoff rate.

The Horton model provided a reasonable physical description of the infiltration process in SWMM as presented in Equation 2.11.

$$f = f_o - (f_i - f_o)e^{-at}$$ Equation 2.11
1.2

where f is the infiltration rate at any given time t from the start of rainfall (mm/min), f_o is the final infiltration rate (mm/min), f_i is the initial infiltration rate (mm/min), a is the decay coefficient (l/min), and t is time (min).

The surface of the pavement layer was controlled by the following four factors: (i) the available rainwater on the surface of the pavement layer, (ii) the permeability of the pavement layer, (iii) the available void space of the pavement layer, and (iv) the simulation time step (Zhang & Guo, 2014). Results were sensitive to the amount of infiltration modelled. Infiltration achieved by a LID depended upon the filter media, gravel layer and native soil properties such as infiltration rate, porosity and suction head, depth of the filter media and storage layers, and depth of ponding available (Rossman, 2015).

The SWMM is a popular catchment model to simulate the process of urban stormwater runoff (Kim et al., 2014; Guan et al., 2015; Palla & Gnecco, 2015; Rossman, 2015). It is a dynamic hydraulic-hydrology simulation model for single and continuous events that uses physical principles such as the conservation of energy, conservation of momentum, and conservation of mass. The SWMM simulated the infiltration of rainfall and rainfall interception, as well as the routing of overland flow through LID practices. SWMM treated the subcatchment surface as a non-linear reservoir; in other words, surface runoff would occur if the "reservoir" did not have enough depression storage (Rossman, 2010a).

Sponge city in China was a new concept of urban stormwater management (Xie et al., 2017; Thuy et al., 2019). For that application, SWMM was commonly used to model different combinations of LID and case study applications for development of the city such as bio-retention facility, detention basins, swale, green roofs, permeable pavement, and wetlands (Kong et al., 2017; Mei et al., 2018; Li et al., 2019;). Table 2.9 shows some related past studies, which are relevant to simulate using SWMM on the hydrological performance of LID practices. In comparison with other LID practices, permeable pavement has shown the best performance (We et al., 2011; Barszcz, 2015; Chui et al., 2016; Rodríguez-Rojas et al., 2018).

Table 2.9: Hydrological performance of LID simulated using SWMM

LID practice	Study area	Runoff and /or peak flow reduction	Finding	Source
Permeable soil layer, green roof, permeable paved parking lot surface and infiltration trench	Sub-catchment of Służewiecki Stream in Warsaw	50% runoff and 38.5% for peak flow reduction.	Good combination of LID to reduce runoff and peak flow.	Barszcz (2015)

Table 2.9, continued

LID practice	Study area	Runoff and /or peak flow reduction	Finding	Source
Rain barrels and bioretention	Beijing Olympic Village, China	27% runoff and 21% for peak flow reduction.	Optimisation completed on BMP sizes increased storage.	Jia et al. (2012)
Rainwater harvesting, permeable pavement and bioretention	Bronx River Watershed, U.S.	28% for 2-year storm. 14% for 50-year storm runoff and about 8% to 13% peak flow reduction.	Larger reduction for lower intensity precipitation	Zahmatkesh et al. (2015)
Peak flow reduction by installing porous pavement in urban drainage	Downstream of Joong-Rang River	33.4% for both small (2-yr) and large (100-yr) design storms	The peak flow can be reduced below the peak flow of the currently existing condition	Kim et al. (2014)
Green roofs and permeable pavements on the hydrological response of the urban catchment	Colle Ometti, Genoa, Italy	36% runoff reduction	Confirm the role of LID solutions in restoring the critical components of the natural flow regime at the urban catchment scale.	Palla & Gnecco (2015)
Pervious pavement	Little Mill Creek watershed in Lenexa, Kansas, USA	86% to 38.5% runoff reduction	Pervious pavement has great potential in replicating the undeveloped runoff through appropriate size and design	We et al. (2011)
Swale, permeable pavement and green roof	Southwest of Guang-Ming urbanizing catchment in China	Flood volume was reduced by less than 20% with every 50% increase in thickness, void ratio of pavement layer, height, void ratio and conductivity of storage layer	Swales perform best during a storm event at early peak, permeable pavements perform best at middle peak, and green roofs perform best at late peak.	Qin et al. (2013)

Table 2.9, continued

LID practice	Study area	Runoff and /or peak flow reduction	Finding	Source
Porous pavers with swales constructed in the road right-of-way	Easy Street, City of Ann Arbor, Michigan	Reduction of peak flow up to 93% and runoff volume up to 86%.	Doubled porous paver width on either side of the street and positioning the inlet to the storm sewer and elevated above swale and storage basin bottoms.	Dierks & Associates (2009)
Spaced modular, grass grid and gravel grid pavements	Cartuja University, Granada, Spain	Over 70% runoff reduction	Permeable pavements, generates major flow attenuation, slowing and delaying water flow and generating a major reduction in the volumes discharged.	Rodríguez-Rojas et al. (2018)

2.10 Methods of calibration and validation

Model calibration is the process of estimating model parameters by comparing model predictions (output) for a given set of assumed conditions with observed data for the same condition. Model validation involved running a model using input parameters measured or determined during the calibration process (Moriasi et al., 2007). Measurements of goodness-of-fit included Pearson's correlation coefficient (R), the coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE) coefficient, percent bias (PBIAS), and ratio of the root mean square error to the standard deviation of measured data (RSR) (Moriasi et al., 2007).

The NSE is a model performance indicator for evaluating the goodness-of-fit between simulated and observed values (Nash & Sutcliffe, 1970). It is expressed by,

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right)^2}{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{mean} \right) 2} \right] \quad \text{Equation 2.12}$$

where Y_i^{obs} and Y_i^{sim} are the observed and simulated discharges at the i-th time step, respectively; and Y_i^{mean} is the mean observed discharge. The value of NSE varies between $-\infty$ and 1, where a higher value indicates a better performance. Positive value between 0 and 1 is typically considered as an acceptable level of performance, whereas negative value is considered unacceptable as it indicates that the mean value of the observed time series is a better predictor than the model (Moriasi et al., 2007). If NSE value is larger than 0.5, it means the model performance is acceptable and can be labeled as satisfactory (Rosa, 2013; Zhu et al., 2019). NSE was used to validate the hydrological performance of LID on shallow groundwater (Guan et al., 2015; Zhang et al., 2018), quantitatively evaluate the watershed models through the implementation of LIDs with SWMM and assess outflow hydrographs (Kang et al., 2009; Du et al., 2012; Zhang et al., 2018), as well as to study the pollutant behavior of permeable pavement (Ashbolt et al., 2013; Carbone et al., 2014; Guan et al., 2015; Palla & Gnecco, 2015; Ahiablame & Shakya, 2016; Simona et al., 2016; Rodríguez-Rojas et al., 2018; Zhang et al., 2018).

Percent bias (PBIAS) or relative percentage difference (RPD) measured the average tendency of the simulated data to be larger or smaller than their observed counterparts. The optimal value of PBIAS is 0.0. The lower the magnitude of the value, the more accurate is the simulated model. A positive value indicated the occurrence of underestimation while negative value showed overestimation (Gupta et al., 1999; Carbone et al., 2014). RPD is the ratio of the difference between the simulated and the observed values to the observed value for each rainfall event/test and it was used to investigate the model efficiency of SWMM for LID analysis (Palla & Gnecco, 2015).

2.11 Current research related to permeable pavement

As presented in the previous sections, there is the bulk of information related to the hydrological and environmental performance, maintenance requirements and case studies of PP applications. Additionally, the ongoing assessment has been carried out to investigate knowledge gaps and unsolved issues of this technology.

The interesting topics for further research include integration of all aspects to ensure multiple end benefits of permeable pavement (i.e. life cycle analyses containing economic, society, proven maintenance activities and environment), optimisation of materials and mix designs, full long term investigation of permeable pavement life span, improved techniques and methods to study clogging, infiltration rate and maintenance, as well as the uses of modelling software for full permeable pavement investigation. Kayhanian et al. (2019) extended the permeable pavement research on the pavement characteristics to determine the best possible way for optimising the environmental benefit, the ideal maintenance frequency and its best practices, the process flow involved for water quality enhancement and pollutant removal, and the performance of permeable pavement over timeframe with corresponding years of existence. Their main target was to solve the existing issues of permeable pavement so that it can be fully integrated into urban roads and highways of higher speeds and loads.

Numerous studies had been conducted on design materials used for different layers (i.e. surface, base and subbase layer) in permeable pavement system. The main objective was to find out the combinations, which could minimise the clogging issues and optimise the permeability, whilst still can provide a good result in structural strength. Dierkes & Lucke (2015), Lucke & Dierkes (2015) and Lucke (2014) investigated the most effective combination of material to be applied in the joint filling and bedding layer. They proposed a new permeable interlocking concrete paving system (PICP), which comprised a maximum joint width of between 5 mm and 6 mm, two paving stone layers, a typical 10 mm concrete top layer and a 70 mm base layer made of porous concrete (as shown in Figure 2.15a). It was found that such a system took longer period to clog than unmodified pavers. Nonetheless, different aggregate material (especially the one with lower effective diameter) might lead to a different levels of permeability reduction (Koohmishi & Shafabakhsh, 2018). Imran et al. (2013) recommended a special aggregate, consisting of waste materials (i.e. oil palm shell and waste tier chips) to be implemented as an effective supplementary filtering media for a better stormwater treatment (as illustrated in Figure 2.15b). On the other hand, Bentarzi et al. (2015) suggested a new eco-material, comprising a mixture of construction wastes (crushed concrete) and organic matter (compost) to produce permeable pavement. The crushed concrete was mainly for the structural support, while the compost was specifically for the retention and biological treatment of stormwater. Li et al. (2017) used reactive powder concrete (RPC) as the matrix in addition to construct accessible pores with high strength pervious concrete (HSPC) pavement to overcome the issues such as low strength, high likelihood for clogging and inconvenient maintenance (as depicted in Figure 2.15c).

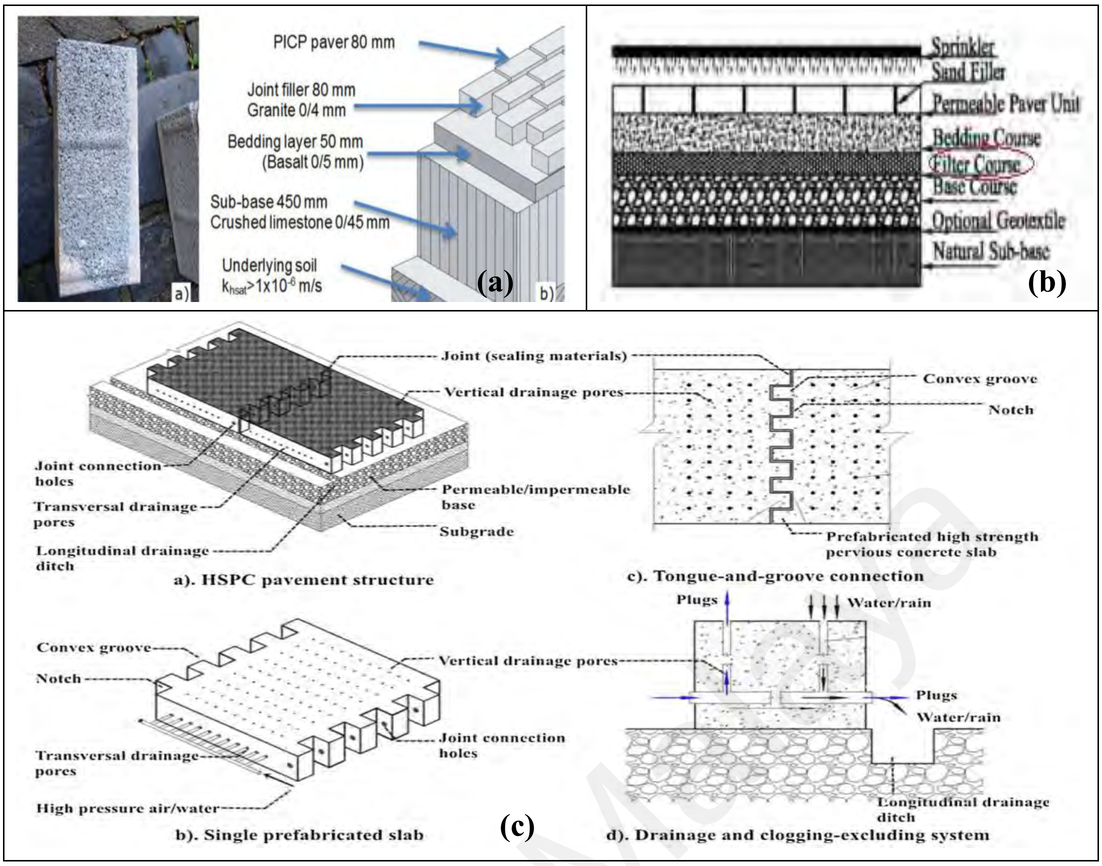


Figure 2.15: New design of permeable pavement proposed by (a) Dierkes & Lucke (2015), Lucke & Dierkes (2015) and Lucke (2014), (b) Imran et al. (2013), and (c) Li et al. (2017)

Kfoury et al. (2015) studied the applicability of permeable pavements in Dubai. They reported that a permeability of 0.005 cm/s, a flexural strength of 3.2 MPa and a compressive strength of 22 MPa could be achieved by applying locally available materials. The additional advantage was the clogging potential of porous concrete due to sand and fine dust exposure was minimal. Tang et al. (2018) evaluated the production processes of the permeable pavement from the perspective of environmental and economic impacts. They suggested that the permeable brick should be more prior than the concrete pavement brick due to its better environmental benefits and cost-effectiveness. Drake (2013) identified optimisation of pollutant retention and minimisation of clogging as the two major problems in the permeable pavement at the watershed-scale. However, to access the problems, it required a full investigation from all aspects in the hydrological cycle, which mainly focused on the mass balance model, particularly the long term infiltration capacity across the various climate and region. On the other hand, Korkealaakso et al. (2014) suggested the possibility to introduce new modules or properties into the established models such as SWMM and SUSTAIN, acting as a platform to model hydrological stormwater-permeable pavement environment to complement hydrological and structural considerations. Hydrological parameters obtaining from laboratory experiments and regular monitoring of field measurements could be seen as important indicators to set standard properties which in turn provided guidelines for implementation.

Figure 2.16 illustrates commercial products by integrating an underground retention and detention such as Permavoid® (Product of Permavoid Limited, Warrington, UK), StormCapture® and PermeCapture™ (Product of Oldcastle Infrastructure, UK), geo-cellular sub-base replacements and SingleTrap® and DoubleTrap® (Product of StormTrap, LLC, US). The products are large underground detention systems for water storage and groundwater recharge.

2.12 Summary

In summary, previous researches on permeable pavement system typically focused on its hydrological performance, the capability of handling traffic volume, materials and mix design, as well as handling, maintenance and safety measures. Nevertheless, among the recent studies that were reviewed in this section, it was found the absence of permeable pavement with a micro-detention pond system.

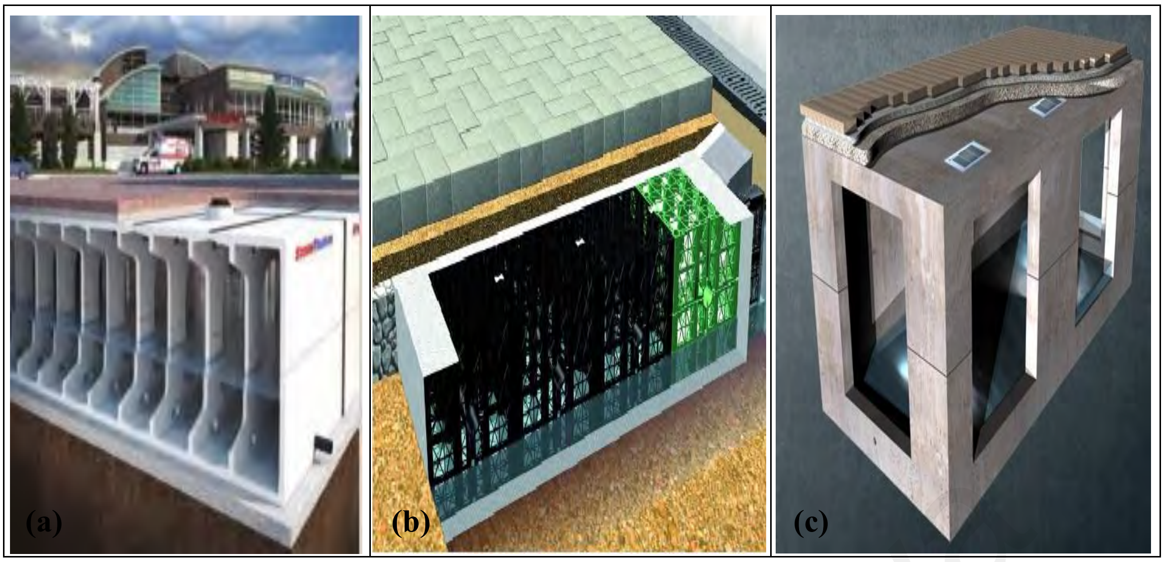


Figure 2.16: Commercial precast underground detention storage product constructed beneath permeable pavement (a) StormTrap, (b) Permavoid®, and (c) PermeCapture™.

The idea is mainly from the PICP design of the modular character, which allows quick and easy installation. To achieve improvement in terms of clogging, the new system eliminates layer characteristics of PICP, where the large precast underground detention structure is replaced with a micro-detention hollow precast system that acted as base and water storage. This empty space enhances void storage for water retention and provides a longer time for infiltration to the ground, especially in the equatorial climate of Malaysia, which receives about 2500 mm to 3000 mm rainwater per year. Figure 2.17 depicts the proposed system with comparison of typical permeable pavement. It is basically a micro-structure, which exhibits the advantages of easy handling and lifting, as well as unique environmental benefits. The system is designed in a shape of hexagon prism, mimicking beehive to gain an interlocking honeycomb frame. The middle part is equipped with a circular shape micro-detention pond, mainly for holding the rainwater to remove the layered characteristics of the permeable pavement. This research concentrates on the evaluation of PPDS design and hydrological performance as a potential solution for reducing runoff, attenuating peak discharge rate and improving land use.

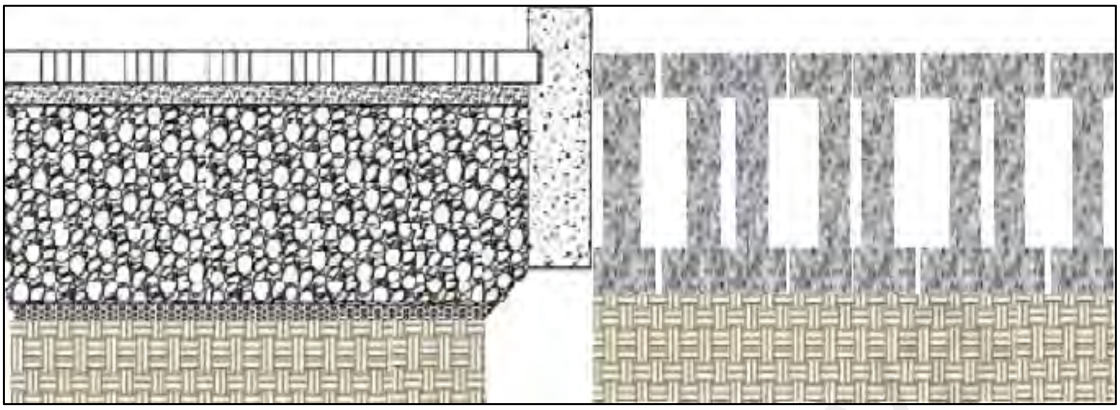


Figure 2.17: Cross-section of, (a) typical PICP pavement structure, and (b) new green pavement design, permeable pavement with micro detention storage (PPDS)

CHAPTER 3: METHODOLOGY

3.1 Introduction

Research methodology is divided into three major parts: (i) development of laboratory-scale rainfall simulator as a device to investigate the permeable pavement with micro-detention pond storage, PPDS, (ii) experimental investigation on the hydrological properties of PPDS using rainfall simulator, and (iii) case study application simulated with Stormwater Management Model, SWMM. The framework is illustrated in Figure 3.1. Firstly, the constructed rainfall simulator is verified with previous studies to ensure the successful duplication of natural rainfall. Secondly, a series of the experimental investigation is performed to obtain hydrological characteristics of PPDS for the assessment of its performance on site. Lastly, a case study is constructed by integrating the proposed system in low impact development (LID) practice through SWMM modelling. The findings are compared with the characteristics exhibited by existing permeable pavement.

Before the hydrological performance evaluation of the PPDS is carried out, its properties and hydrological design are to be determined; these are included in Section 3.2. Next Section 3.3, 3.4 and 3.5 discussed the methodology to achieve objectives one, two and three of the study. The methodology is then concluded in Section 3.6.

1. Development of laboratory-scale rainfall simulator for green pavement test		
a) Specify the design requirements and parameters based on desk study.	b) Construct the rainfall simulator.	c) Calibrate the rainfall simulator to ensure the replication to the natural rainfall characteristics.

2. Evaluation of the PPDS performance using the laboratory-scale rainfall simulator	
a) Hydraulic design performance evaluation of PPDS to include: i) Inflow and outflow efficiency and detention storage capacity. ii) Hydrological design optimisation (with varied detention pond storage volume and void capacity)	b) Hydrological assessments evaluation of PPDS at different design storms and land covers to include: i) Detention storage ii) Permeability rate iii) Infiltration rate

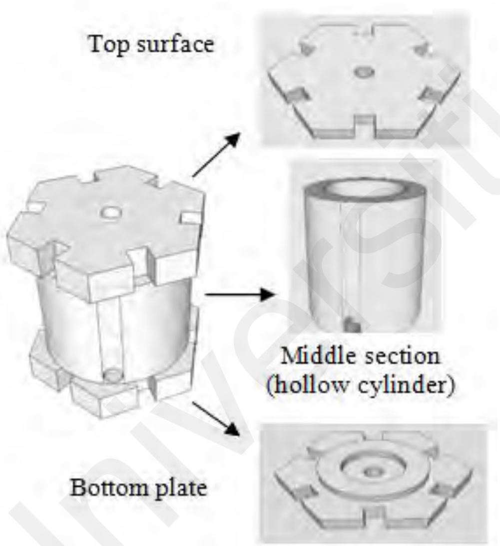
3. Modeling works on case study with SWMM LID practice	
a) Model preparation and preprocessing: i) Construct the LID (PPDS) model in SWMM ii) Simulate the performance of the PPDS with experimental parameter set iii) Validate the model with experimental results and analytical calculations	b) Case study application: i) Construct the case study model ii) Specify the parameters for the case study assessment iii) Simulate the hydrological impact assessment iv) Evaluate the results and make comparison

Figure 3.1: Framework of the study

3.2 Permeable pavement with micro-detention pond storage, PPDS, properties

The single unit of permeable pavement with micro-detention pond storage, PPDS, consists of three pieces of precast concrete block with a top cover, a bottom plate and a unique hydrological feature of a hollow cylinder in the middle section. The top cover acted as road pavement, the bottom plate served as base plate and raft foundation, and the hollow cylinder played a role as micro-detention storage. Basically, the PPDS is made up of three precast solid G-50 concrete structures, forming a single modular unit. It is actually a hollow cylinder covered with the top and bottom plates, reinforced with two layers of steel and optionally covered with a geotextile layer. The system is constructed on the flat subgrade soil and dry-stacked to form an interlocking paver that has the ability to provide structural support and durability, which in turn yielding benefits in terms of permeability in stormwater management. The permeability of the system is accomplished through the under drainage system of the hollow cylinder/vessel residing beneath the subsurface of the pavement.

The design of a single unit of the PPDS system is presented in Figure 3.2 with detailed measurement and physical design properties. Figure 3.3 shows the arrangement of PPDS prototype assembled outside the laboratory and a single unit of PPDS. The proposed PPDS consists of a cylindrical hollow container with a thickness of 300 mm, an inner diameter of 280 mm, and hexagonal shapes at the top surface and bottom (with a thickness of 75 mm and perimeter length of 1500 mm).



Physical characteristics of permeable pavement with micro-detention pond storage	
Height/Thickness (Top and bottom surface with 40 mm diameter hole) Cylinder micro-detention storage	= 75 mm = 350 mm
Total thickness Production type	= 450 mm Full Precast
Width x Length	= 250 x 500 mm
Perimeter length (hexagonal shape)	= 250 mm x 6 side
Number of unit made using 1 m^3 concrete	= 24 units
Area coverage with 24 units	= 4.0m^2 area
Units required for 1 m^2 area	= 6 unit

Figure 3.2: PPDS set with surface top and bottom interlocking and cylinder hollow section and physical characteristics

Figure 3.3: PPDS system: (a) arrangement of PPDS assembled outside the laboratory, and (b) PPDS precast product single unit of a hollow cylinder and cover design

According to Shackel (2010), a paver with dentate shape performed better than the rectangular paver. Thus, the proposed PPDS is designed to have a hexagonal shape in order to achieve better performance from the perspective of hydrological design and structural durability. Acting as the open passage for stormwater inflow and infiltration respectively, both the top and bottom layers comprise a central hole with 40 mm diameter and six grooves as interlocking keys. The concrete interlocking set is reinforced by two layers of steel. With these characteristics, the void capacity of water-holding system is enhanced by about 70% and the detention storage is improved to 0.90 m^3/m^2 (30 L/unit).

The micro-detention storage is made up of the precast honeycomb lightweight-structure, which could percolate the rainwater through the bottom part, thereby recharging the groundwater and reducing the runoff. The system is considered cost-effective; as the precast honeycomb structure is used to enhance self-interlocking and dry-stacked, it stores rainwater through the micro-detention storage structure and allows self-drying through the side and bottom seepage of water. In addition, the system is able to reduce the installation time and save the manpower due to its advantages in modularity, adaptability, portability and self-interlocking. In sum, PPDS is a user-and environmental-friendly product and seen its suitability to be applied at the low-speed roads, especially parking lot, business centre and housing area.

3.2.1 Hydrological design

Both conventional pavement and permeable pavement roadworks are assembled with several layers of pavement materials. Their main differences are the types of surface layer and aggregate material. A flexible pavement basically consists of a fines asphalt course, while permeable pavement generally comprises porous asphalts/concrete aggregates, which meet the requirement of porosity and void capacity. For this study, the innovative idea is to introduce the micro-detention storage structure to replace the layered characteristics. Nevertheless, the design thickness of the proposed PPDS is selected based on the suggested range (for further detailed please refer Section 2.5.2) as shown in Figure 3.4.

The hollow cylindrical feature in PPDS has an empty space of 0.19 m^3/m^2 and about 70% void of the pavement area. It drains the surface water at a rate of 8400 mm/h. In sum, the water could be stored up to a depth of 213 mm in the system. The overall hydrological properties of the PPDS are summarised in Table 3.1.

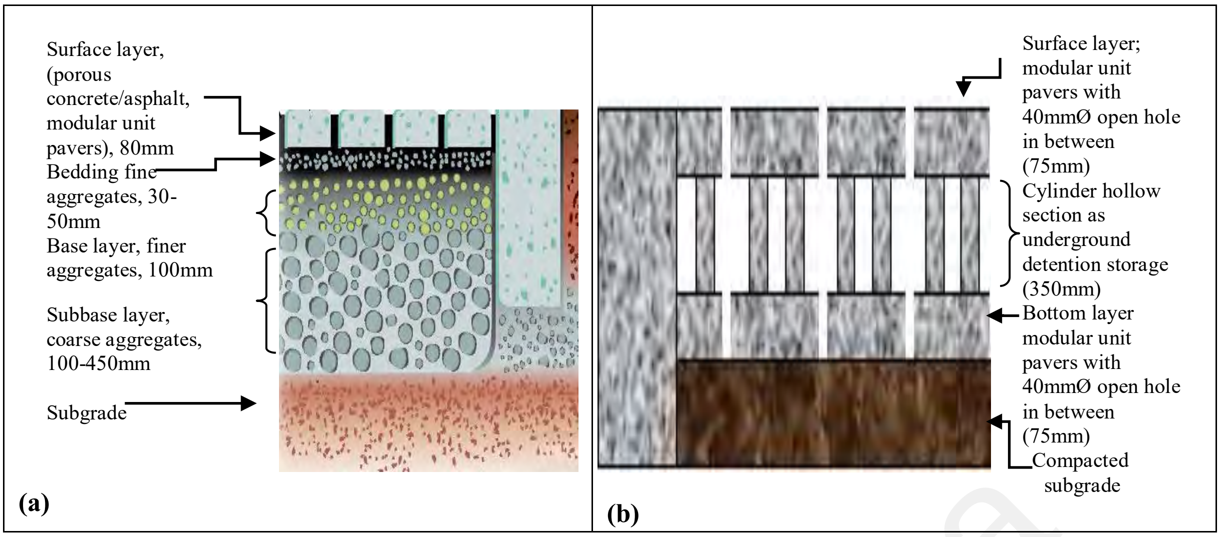


Figure 3.4: Cross-section design of (a) typical permeable pavement, and (b) suggested PPDS

Table 3.1: Hydrological properties of the proposed PPDS

Aspects	**Calculations**
Thickness of top and bottom surface Thickness of cylindrical micro-detention storage	= 75 mm (with 40 mm diameter centre hole) = 300 mm (2 x 40 mm diameter hole close to the bottom for horizontal flow)
Percentage of open surface	= 2%
Flowrate through orifice voids (bottom)	=8400 mm/h or 0.002 m^3/s
Detention volume per metre square	= 0.19 m^3/m^2
Percentage of drainage voids per metre square	= 70%
Storage capacity (capacity of top and bottom precast set + subsurface cylinder hollow empty space)	Based on design thickness; Surface pavement layer (Top cover) + Base + Subbase (Bottom cover) = (2%) x(75 mm x2) + (70%) 300 mm = 213 mm

Additionally, Table 3.2 presents a comparison of the proposed PPDS with a typical permeable pavement, which consists of pervious concrete (PC), porous asphalt (PA) and permeable interlocking concrete paver (PICP) (refer Section 2.3). The additional hollow cylinder feature in PPDS has provided an empty space of 0.19 m^3/m^2 without any layered aggregates. Therefore, it can significantly enhance the infiltration rate and delay the clogging time.

By comparing to the typical permeable pavement, PPDS appears as a more favourable choice in terms of cost-effectiveness. Due to its precast set with mini size, an easy and rapid installation can be expected. This is because it can be lifted manually or by using simple mechanical machines, and hence saving the installation time and manpower. In addition, the estimated production cost is around \$30/ m^2 or \$0.50/ ft^2, which is significantly lower if compared to the normal permeable pavement. However, the proposed system has its own drawback, where its application is limited to low-speed road or garden footpath constructed on the flat ground subgrade.

3.3 Rainfall simulator

In this study, a rainfall simulator is required to produce an artificial rainfall in laboratory-scale for the simulation of green pavement characteristics, infiltration processes and rainfall hydrograph of PPDS (Bateni et al., 2018). The advantage of laboratory investigations in comparison to field measurements is the ability to control the determining factors and concentrate the specific issues to fill the knowledge gaps (Fister et al., 2012). In order to obtain reliable result, a rainfall simulator should exhibit the basic property of producing a wide range of rainfall intensity varying from 40 to 220 mm/h (up to 100-year design storm event), generating an acceptable reproduction of the rain on the plot area, and displaying an adequate design for the green pavement box, in order to place the heavy materials of PPDS, compacted subgrade, and transparent sheet to monitor the storage capacity of the PPDS. The graphical design of a rainfall simulator is presented in Figure 3.5.

Table 3.2: Comparison of the modified permeable pavement, PPDS with conventional permeable pavement

Hydrological design factor	**Conventional permeable pavement**	**PPDS**
Pavement thickness	240-540 mm	450 mm
Aggregate size	2-76 mm	None (Solid concrete) 6 unit/m^2 x 40 mm diameter centre hole and 0.005 mm/unit joint gap @ 2.5% pervious surface area for water by pass
Design permeability	0.6096 m/day (permeable interlocking concrete paver, PICP), 1.8288 m/day (porous asphalt, PA), 3.048 m/day (pervious concrete, PC) Moderate porosity: 143 L/m^2/min or 8.6 m/h	0.002 m^3/s or 1.5 m/day 120 L/m^2/min
Void porosity	15-40%	70%
Pore spaces	0.5–50 mm	Net empty space of 0.19 m^3/m^2
Construction cost	\$ 5.00 to \$ 10.00/ ft^2 (PICP) \$ 0.50 to \$ 1.00/ ft^2(PA) \$ 2.00 to \$ 6.50/ ft^2 (PC)	RM120/ m^2 or \$30/ m^2or \$ 0.50/ ft^2
Minimum batch size	500 ft^2 (PA/PC)	Precast (1 m^3 G50 concrete produce 24 units): 6 units/m^2
Construction properties	No cure period and manual/ mechanical installation of pre-manufactured units, over 5000 sf/day per machine (PICP) Cast in place (PA/PC)	No cure period; manual or simple mechanical lifting device; rapid and simple installation and full precast.
Colour/texture	Wide range of colour, texture and pattern (PICP) Black or dark grey colour (PA) Limited range of colour and texture (PC)	Hexagon shape with beehive interlocking character
Surface clogging	Replace permeable stone jointing material (PICP) Replace paved areas or install drop inlet(PA/PC)	Vacuum sweeping and replace clogging set of PPDS
Applications	Low-speed residential stress, parking lot, sidewalks, road shoulder, foot traffic and light and heavy vehicles (moving & parked)	Low-speed road especially house car porch, parking lot, business centre and housing on flat ground.

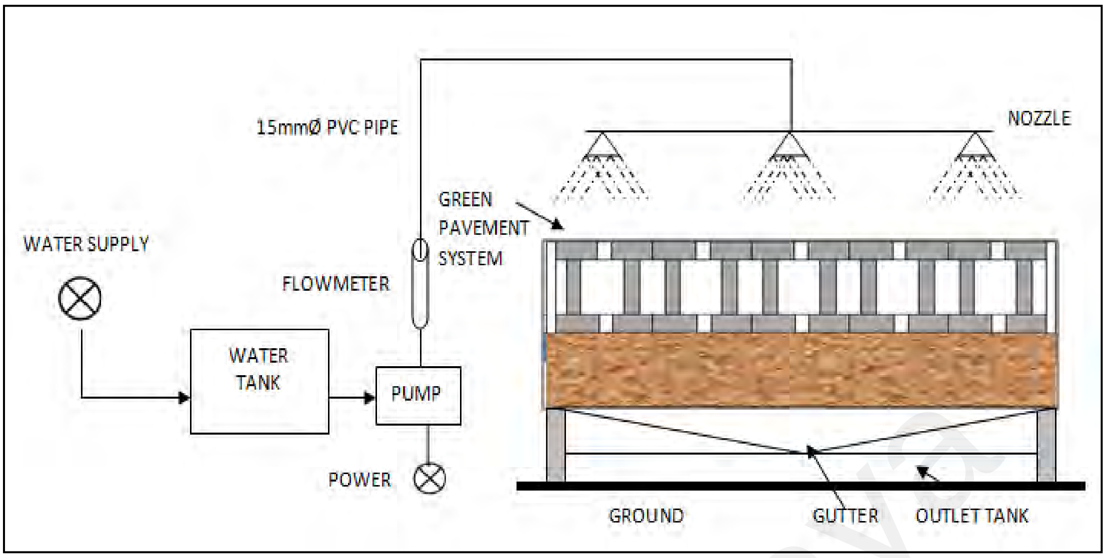


Figure 3.5: Graphical design of the rainfall simulator

3.3.1 Design specifications of the rainfall simulator

In this research, the rainfall simulator is designed to ensure full control of precipitation conditions such as rainfall intensity, frequency and duration. Therefore, important characteristics of the natural rainfall replication are limited to the variation of rainfall intensity (inflow, frequency and duration) and uniformity of distribution to green pavement box. A nozzle-typed rainfall simulator is chosen in this study, due to the advantage as discussed in Section 2.7.1, to produce higher velocity and rainfall intensity at a larger scale with a reasonable drop size distribution (Corona et al., 2013).

The area and size of the rainfall simulator are designed based on recommendations from previous studies as contained in Table 2.9 and Section 2.7.1. Most researchers conducted their studies in an area less than 5 m^2 with a nozzle height of 3 m or less to replicate the velocity and kinetic energy of natural rain (Humphry et al., 2002). For this study, the rainfall simulator is designed with a length of 3.16 m, a width of 1.47 m, and an adjustable height where the maximum height is 3 m from the surface of model box. Such a design offers a variety of height for experiment purposes. The metal frame plays a role as the supporting component for the nozzles and pipes, where solid L shape metals are used as pillars and beams. Meanwhile, PVC plastic cover is fitted around the apparatus to limit the spray and ensure rainwater falls inside the catchment area.

Rainfall dropping from the nozzles is supplied by water tanks as inlet reservoirs. There are 3 sets of water tank. Each tank consists of 3 m x 1 m x 1 m in size with a volume of 3 m^3. The tanks are connected with the pump and piping system to flowmeter and nozzles. The pumping system gives a stable pressure to avoid intensity variation during the simulated rainfall events. The capacity of the pump is within 5 LPM to 35 LPM. The simulator uses three nozzles (Full jet S. S 3/4 HH-30 WSQ) to cover the catchment area of 3 x 1.305 m plot. Full cone nozzle type with 120˚ coverage provides a circular spray pattern to the catchment area. The adjustable valve is attached to the flowmeter to control the flow at a maximum reading of 35 LPM @ 10 GPM. The height of the nozzles from the surface of the green pavement system is set at 1.55 m with nozzles coverage diameter of 1.8 m as depicted in Figure 3.6.

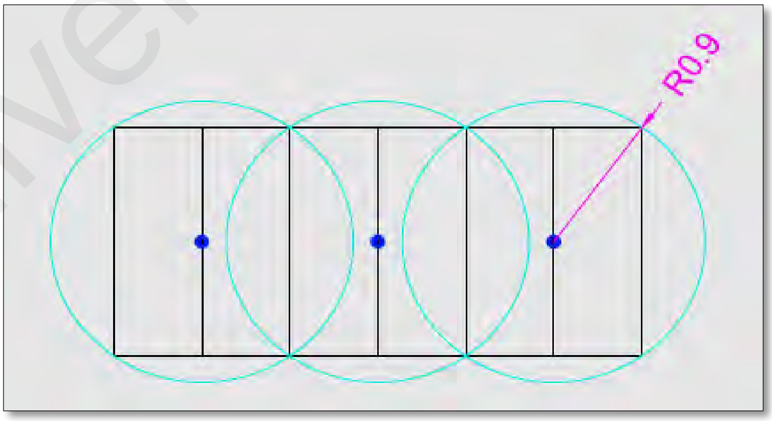


Figure 3.6: Nozzle coverage area of the green pavement box

Green pavement box is another important part of the designed rainfall simulator as illustrated in Figure 3.7. The green pavement box is 3 m x 1.305 m x 0.5 m (height) in size. The 3-m width is chosen as a single lane road width while the 1.305-m length is long enough to put 3 sets of micro-detention storage vertically (Figure 3.7b). In Standard Specification for Road Works, *Jabatan Kerja Raya* (JKR), (1987), the normal depth of the subgrade medium is 300 mm to 500 mm. In this case, the upper limit (0.5 m) is chosen as the green pavement box height. Perspex sheet of 10 mm thick and 450 mm height is extended to the green pavement box for a transparent view.

The bottom catchment is built with a rigid framework, consisting of 30 nos. steel rods and beams with a diameter of 50 mm, and arranged in parallel on the support beams. The designed box could sustain huge loads from the pavement and the subgrade soil (with a total weight of around 5 tonnes). The gutter is attached below the box to collect the discharging water. It is built from a ductile iron of 2 m (width) x 3 m (length), and bent into a triangular shape to direct water to the outlet tank.

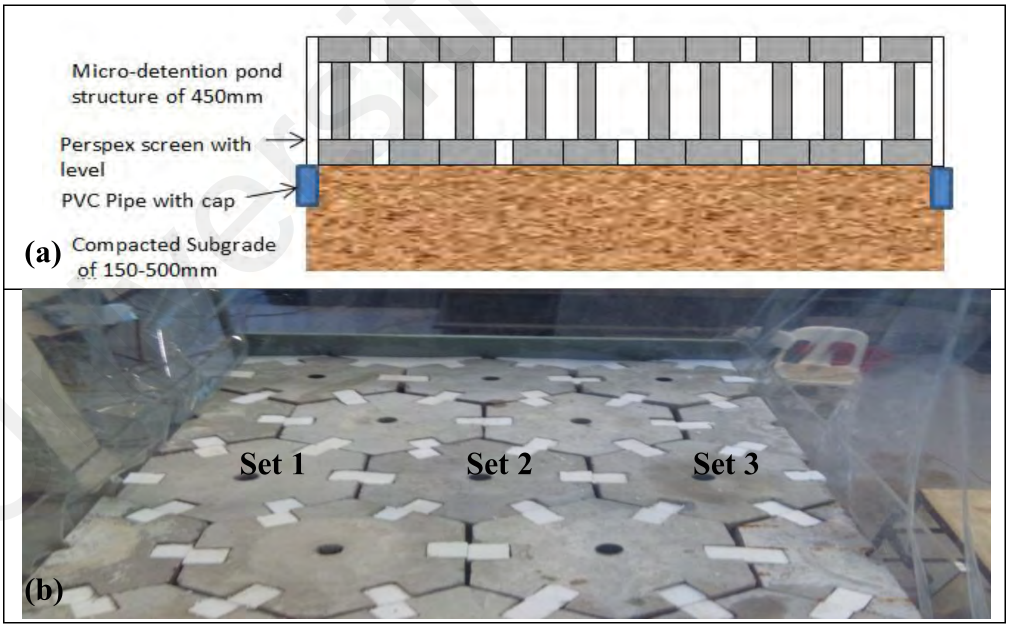
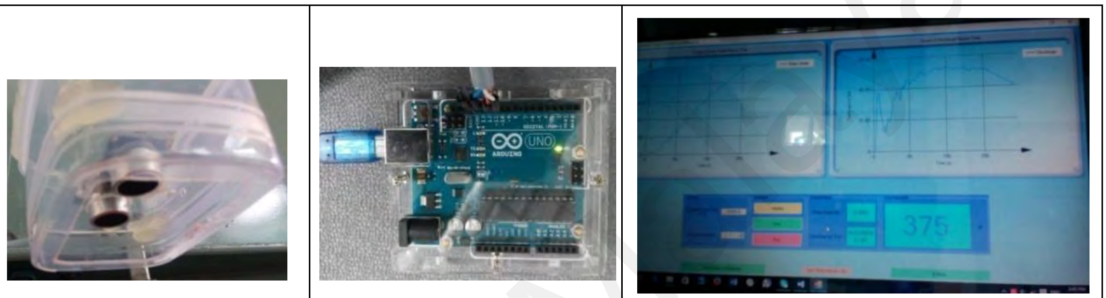


Figure 3.7: Green pavement box: (a) cross-section of PPDS system with subgrade, and (b) PPDS arrangement, with 3 sets per column

The rainfall simulator is equipped with an output device as shown in Figure 3.8. The output device is developed to monitor outlet discharge. The Rainfall Simulator Output Monitoring GUI program detects the depth of discharged water using ultrasonic sensor. The sensor reads the difference of water level every 5 s to 1 min with a maximum of 1 h interval. The reading is then transferred to the micro-controller. It provides the result of the outlet discharge as a unit of hydrograph and presents in an Excel file in tabular form that consists of time, depth and discharge.



(a) Ultrasonic sensor | (b) Micro-controller | (c) Rainfall simulator output recording and monitoring, GUI program

Figure 3.8: Output device for recording and monitoring of outlet discharge

The rainfall simulator is designed to simulate rainfall intensity between 40 mm/h to 220 mm/h for the 100-yr local storm event. Depending on the objectives of the study, simulated rainfall intensity and duration could be varied by controlling the flowmeter and valve. The recorded rainfall intensity is the maximum possible value with the rainfall simulator setup. Nevertheless, a larger water source and different nozzle types could be used to generate a greater intensity.

3.3.2 Development of the rainfall simulator

Rainfall simulator is constructed to generate controllable and repeatable events to access the hydrological performance of the PPDS as illustrated in Figure 3.9. The main goal is to evaluate the storage capacity, permeability and infiltration rate of the PPDS. Prior to the development of the rainfall simulator, extensive desk studies are done to ensure the standards and design requirements; guidelines and hydrological parameters are strictly followed (refer Section 2.7.1). Rainfall simulator is designed with considerations on size appropriateness, pump, flowmeter, pipe network, nozzles, frame, green pavement box, gutter system and outlet discharge. Ultrasonic sensor device is developed to ease the readings of the results obtained. It is installed at the outlet to record outflow discharge. The cross-section and detailed layout on the design specifications of the rainfall simulator are given in Appendices A1, A2 and A3.

Figure 3.9: Rainfall simulator in the hydraulic laboratory for PPDS experimentation

Figure 3.10 illustrates the components of the designed rainfall simulator, which includes: (a) water tank, (b) green pavement box, (c) outlet tank, (d) pump and flow meter, (e) nozzles and (f) ultrasonic sensor device. This rainfall simulator fabrication was commenced in October 2014 and completed in July 2015.

3.3.3 Calibration of the rainfall simulator

Rainfall simulator was calibrated to produce artificial rainfall to ease the experimentation. The rainfall simulator can save time and space with rapid data collection besides performing simulation for various scenarios. In fact, there are no concrete standards for developing a rainfall simulator. However, it is often for the designers to compare the collected experimental data with the previous studies/ on-site measurements. The important parameters should be calibrated based on its performance on inflow and outflow of the water, uniformity of distribution throughout the cover area and nozzles intensity.

(a) Water tanks as inlet

(b) Green pavement box with transparent sheet

(c) Drainage system, gutter

(d) Nozzles system

(e) Nozzle spray and radius

(f) Pumping system and Outlet tank

(g) Rainfall simulator recording and monitoring system including ultrasonic sensor device, microcontroller and recording program.

Figure 3.10: Components of rainfall simulator at the laboratory

The inflow is the quantity of design storm, which was set based on the Intensity-Duration-Frequency (IDF) curve of local rainfall in Kota Samarahan, Sarawak, Malaysia obtained from Department of Irrigation and Drainage (DID). The applied rainfall ranged from 30 mm/h to 220 mm/h is based on the capacity of the flowmeter and the pump. In this case, the rainfall intensity is converted to inflow and controlled by flowmeter to give a steady reading in liter per minute (LPM) (refer Appendix B for rainfall intensity applied in the experiment). The outflow discharge is then recorded.

Several steps were followed to determine the distribution uniformity of the artificial rainfall at the catchment area (the green pavement box). In this study, an oil immersion technique is performed to measure the drop sizes of the rainfall. Three basins with a diameter of 60 cm are placed at the centre of the nozzles. Oil is prepared using the mixing ratio of 2:1, consisting of engine oil treatment and mineral oil (Huang et al., 2013). The readings are taken at three different rainfall intensities of 210 mm/h, 150 mm/h and 80 mm/h, respectively. Water droplets are suspended in the basin due to the viscous oil mixture as presented in Figure 3.11a. The droplets that are trapped on the liquid interface are photographed, measured and recorded.

To check the distribution uniformity of the rainfall simulator over the catchment area, 200 cylinder cups are arranged in the green pavement box as shown in Figure 3.11b. The selected rainfall intensities of 210 mm/h, 150 mm/h and 80 mm/h are simulated for a duration of 7 minutes. Then, the water depth collected in cylinder cups is measured and recorded. Christiansen's coefficient of uniformity, CU, is then calculated.

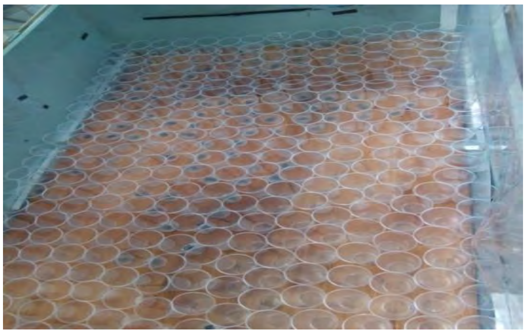
	
(a) Oil immersion technique	(b) Uniformity distribution experiment

Figure 3.11: Calibration of the rainfall simulator: (a) oil immersion technique, and (b) distribution uniformity over the catchment area

Overall, Section 3.3 presents the methodology and procedure to achieve the first research objective of this study. The rainfall simulator is developed to test the hydrological performance of PPDS. Rainfall characteristics, such as rainfall intensity, spatial uniformity, raindrop size and raindrop velocity, are simulated to investigate the accuracy of the rainfall simulator to replicate the natural rainfall. After successfully developing and calibrating the rainfall simulator, the device is applied to investigate and obtain initial hydrology data, which in turn can aid the design of the PPDS prototype to achieve the second research objective of this study. Details on the procedures are explained in the next section, Section 3.4.

3.4 Experiment for PPDS hydrological performance evaluation

Experiments to access hydrological performance normally consist of the measurement of storage capacity, permeability and infiltration rate as reviewed in Sections 2.5.2. In this study, to investigate the hydrological function of the proposed system, the rainfall simulator with a catchment area of almost 4 m^2 was used in the Hydraulic Laboratory to mimic the real-life hydrological cycle (Bateni et al., 2018). Figure 3.12 displays the overall flow path of rainwater in the system. The rainfall falling from the nozzles initially enters the PPDS surface passage opening is detained in the cylinder tanks or between the gap of the structure, and finally distributed laterally through two openings (40 mm in diameter) near the bottom of the cylinder or infiltrates to the subgrade soil.

The water balance model components are closely related to the rainfall amount, surface runoff and the drainage channel outflow. The vertical part of the water balance represents the total inflow and the total storage capacity, while the lateral part refers to the contribution of total outflow from the surface runoff, drainage channel, and subgrade infiltration rate. The other variables of input (i.e. design storm, rainfall depth and, runoff from surrounding catchment areas), process flow (i.e. underlying soil infiltration rate, volume and storage capacity) and system outflow (i.e. water discharge and rate) are also considered. Therefore, the volumes of the input and storage are interpreted as the outflow volume for the PPDS structure, which is expressed using Equation 3.1 (presuming there is no water evaporation).

$$O(t) = I(t) + \Delta s(t) \qquad \text{Equation 3.1}$$

where $I(t)$ is inflow, $O(t)$ is outflow and $\Delta s(t)$ is the change of storage capacity.

The rainfall intensities simulated for this study are based on recent 20-yr statistical data collected from DID, Sarawak, Malaysia. The selected location is Kota Samarahan, Sarawak. Based on the data, Kota Samarahan had an average annual precipitation of approximately 3500 mm, while the highest rainfall recorded is about 500-600 mm, which usually occurred in January. The designed storms are set from 2 average recurrence interval, ARI, to 100 ARI. In other words, the laboratory works are conducted under a range of rainfall intensity from 30 mm/h to 220 mm/h within a catchment area of 3.915 m^2 (see Appendix B for design storms used for the experimentation).

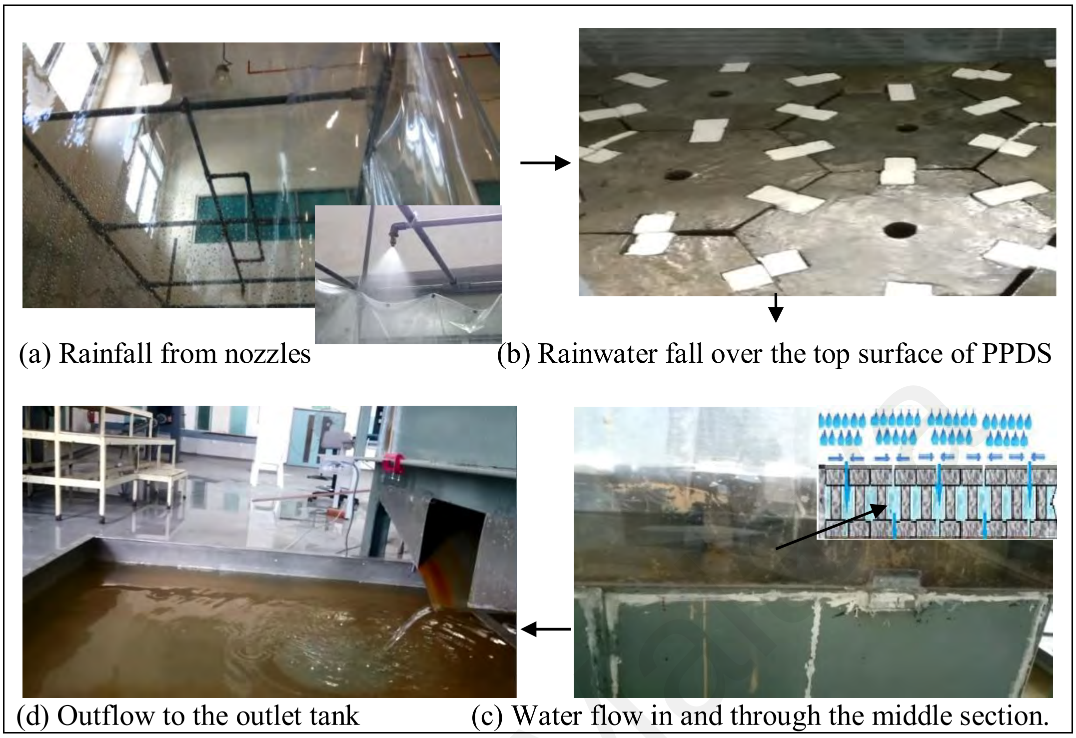


Figure 3.12: Flowpath of the rainfall in the rainfall simulator and through the PPDS system

To evaluate the hydrological performance of the system, which is also the second main objective of this study, three experimental stages are involved. The first stage is to examine the outflow characteristics such as permeability rate, the accumulated volumes of rainfall discharge to outflow tank, water depth in the outflow tank and detention duration of the PPDS system. The second stage is to investigate storage capacity and outflow of the system. This is achieved by first, investigating the relationship of inflow and outflow patterns of the system and the storage capacity (water is prevented to flow out from the system). The third stage investigates the infiltration rate and detention duration within the subgrade soils. The infiltration rate is calculated as the difference in accumulated flow depth over the difference in time.

The outflow data (detention time, depth and discharge) are recorded using a data logger, which is then transferred to a software application via the rainfall simulator graphical user interface (RS GUI). For a more detailed explanation, please refer to Section 3.3.1 and Figure 3.8.

The experiment is set up to test the permeability rate and the effectiveness to discharge the water from the system (permeability rate), as illustrated in Figure 3.13. The first set up is the arrangement of bottom hexagonal cover, middle section (cylindrical hollow), and top hexagonal cover. In this experiment, rainfall flows through the system and discharges at the outlet tank, as shown in Figure 3.12.

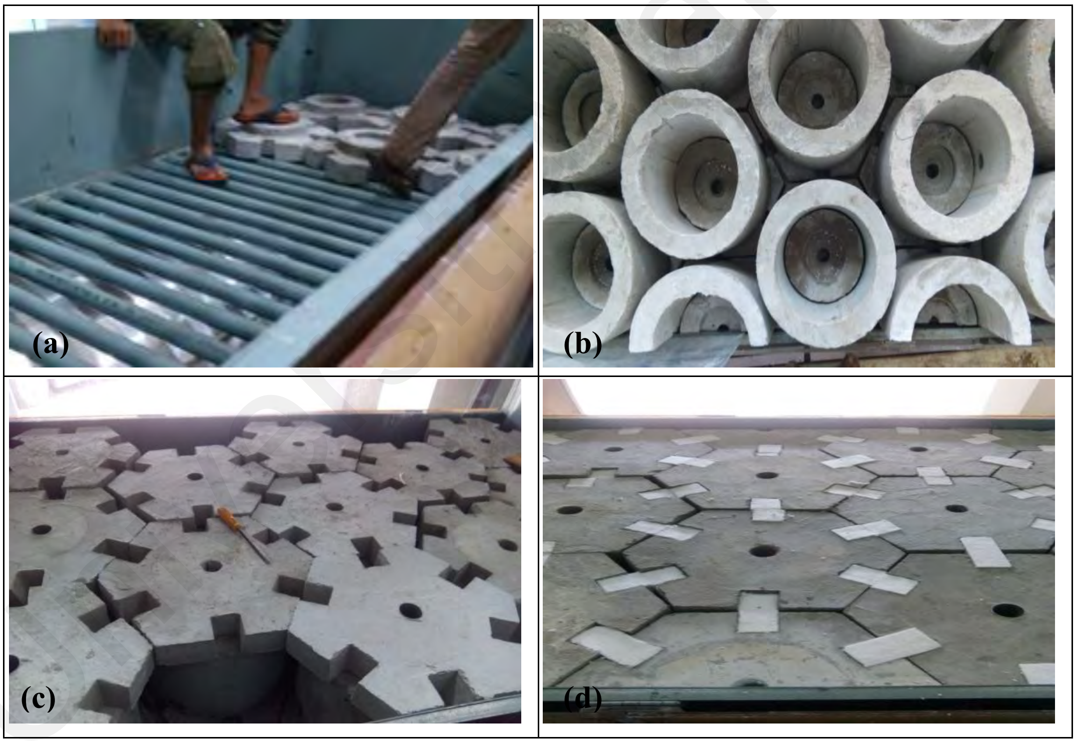


Figure 3.13: Experimental set up to investigate permeability rate of PPDS system

The second experimental set up is to test the water-holding capability (storage capacity) of the PPDS system (Figure 3.14). In this experiment, the rainwater is initially prevented to flow out from the system. To serve that purpose, a polyester waterproof mat is placed and sealed at the base of the green pavement box (Figure 3.14a). The

PPDS sets are then arranged in the green pavement box. First is to arrange bottom cover, followed by middle cylindrical hollow and, finally, the top cover (Figure 3.14b-d).

Figure 3.14: Experimental set up to investigate storage capacity of PPDS system

The third stage of the experimental set up is contained in Figure 3.15, which aims to determine the infiltration rate of the PPDS within the compacted subgrade layer. The bottom catchment of the green pavement box, which is steel rods and beams is closed with a fine nylon mesh. A brown fabric is attached underneath the fine nylon mesh to prevent soil sedimentation.

Measurement of the subgrade is an important design consideration since subgrade soil that cannot infiltrate water at a prescribed rate or higher could significantly reduce the effectiveness of the permeable pavement (Ferguson, 2005; Weiss et al., 2015). The PPDS is placed above the soil, which acts as subgrade and foundation for road-based (Figure 3.15a). Before commencing the laboratory testing, soil samples are first collected from the highway roadside of Kota Samarahan, Sarawak, Malaysia.

Figure 3.15: Experimental set up to investigate storage capacity and infiltration rate of PPDS system

Figure 3.16 shows the preparation of soils for compaction and infiltration rate test. Two types of soils are prepared, which are common subgrade soil (Figure 3.16a & b) and local sand (Figure 3.16c & d). According to soil classification, the common subgrade soil of Kota Samarahan highway is categorised as sandy loam. The local sand is also used as a subgrade medium to investigate the performances of PPDS under different infiltration rates due to different soil types.

According to Kayhanian et al. (2015), there are two common methods to measure the subgrade compaction rate of permeable pavement that are Standard Proctor Maximum Dry Density and Modified Proctor Maximum Density. In this study, the first approach is applied. Standard Proctor test indicates that the moisture content-density relationship of the common subgrade soil at a 95% compaction rate is 1.63 mg/m^3 (or equivalent to 16.63%). The sand moisture content-density relationship at a 95% compaction rate is

1.55 mg/m^3 (or equivalent to 19.95%). The soil is prepared with the additional amount of water to a known weight to achieve the compaction degree with desired moisture content. For the experimentation, the depth of subgrade soil is 300 mm.

Figure 3.16: Preparation of subgrade soils

The soil is compacted with 50 kg of solid concrete roller compacter, applying a minimum of 20 passes with a plate square compactor (10 kg) at the side and corner of the catchment (Figure 3.15b and Figure 3.16d). After that, the soil is filled into three layers in order to achieve the required compaction according to the Proctor test (BS 1377-4:1990) of 100 mm per layer. A geotextile is laid out and installed in the prepared subgrade area to separate the detention storage from the natural soil and prevent fines from migrating into the layers above (Figure 3.14b).

In this research, the experiments are designed to test the hydrological performance of PPDS, to measure the hydrological design properties in terms of permeability and storage capacity. For that purpose, different scenarios and conditions are selected, for instance, a series of designed rainfall events from 2-yr to 100-yr and different types of subgrade medium (sand and sandy loam). The optimum storage volume under various rainfall intensities and percolation rates of the PPDS are determined.

3.5 SWMM for the simulation of PPDS hydrological performance

SWMM version 5.1 is applied to achieve the third objective of this study, which is the assessment and evaluation of hydrological impacts of PPDS application and its case study. To achieve such a goal, two main stages are involved. The first stage is the model preparation and pre-processing steps: (i) to develop the low impact development (LID) model in SWMM containing PPDS properties and parameter settings, (ii) to simulate the hydrological performance of the LID model of PPDS, with designed properties and parameters in the laboratory experimental investigation, and (iii) to validate the model development, with experimental results and analytical calculations with goodness-of-fit measurements. The second stage is the hydrological impact assessment of PPDS field application.

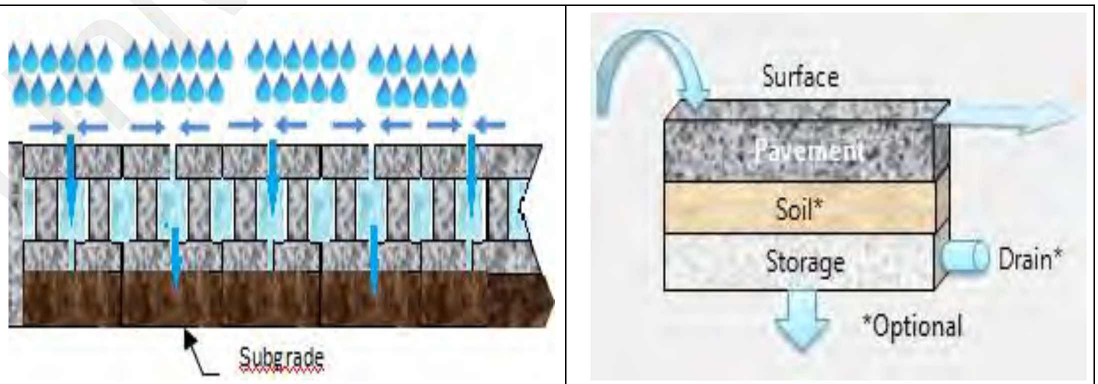
According to Rossman (2015), the procedures in SWMM 5.1 are described as: (i) to construct the case study model and specify the parameters for model assessment, which involves the identification of specific items in default set and object properties to be used in the modeled study area, the choice of properties to construct network and conveyance system, and the selection of the analysis options of such as process models, infiltration model, routing model, etc., (ii) to run the model simulation to access the hydrological impacts of the constructed model for case study, and (iii) to evaluate the assessment results that were obtained from the developed model.

Mah (2016) applied SWMM for the performance assessment of subsurface micro-detention storage, but excluded the infiltration rate capacity of the PPDS system, where it is not a recommended practice for LID module in SWMM. However, if the developed model is correctly calibrated and validated under controlled conditions (events basis) in the laboratory, it could be implemented to study the hydrological responses of a small urban catchment and provided a result with a considerably high level of accuracy (Palla & Gnecco, 2015).

3.5.1 SWMM validation with laboratory experimentation

In this study, the SWMM is developed based on the experimental conditions. Figure 3.17 illustrates the flow path of rainfall in PPDS and SWMM. In SWMM LID module, the surface layer receives direct rainfall and runoff from other areas, the storage layer accepts permeation from the pavement layer above it and the water loses via the infiltration/ evapotranspiration, outflow through the perforated pipe underdrain system or overflow (Rossman, 2010b).

In SWMM, catchment is modelled as a regular pervious subcatchment with its depression storage representing the stormwater retention capacity of the permeable pavement. The applied rain gauge is based on time series with continuous and similar rainfall intensity at a predetermined duration.



a) PPDS b) SWMM LID

Figure 3.17: Schematic diagram of the rainfall route in the system

The performance of the LID is reflected in terms of the overall runoff, infiltration, and evaporation rate. The chronological order is presented in Figure 3.18. First of all, rainwater falls to the subcatchment, flows in the storage and infiltrates to the subgrade. The resulting discharge is collected in the outfall. The rate of runoff is controlled by the rate of inflow and the area, width, slope, and roughness of the pervious subarea.

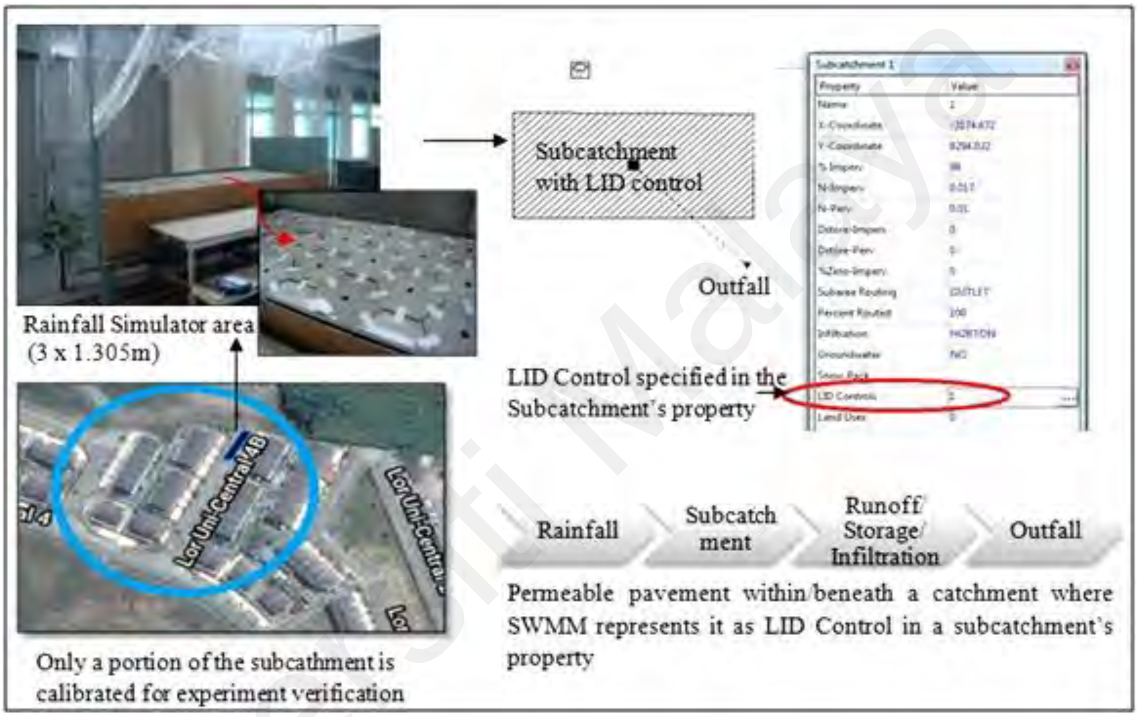


Figure 3.18: Permeable pavement within/beneath a catchment where SWMM represented it as LID Control in a subcatchment's property

Meanwhile, Horton's method is chosen to model the normal infiltration rate. This method is based on the empirical observations, showing that the infiltration rate decreased exponentially from an initial maximum rate over the duration of a long rainfall event. Input parameters required by this method include the maximum and minimum infiltration rates, a decay coefficient that describes how fast the rate decreases over time, and the time taken for a fully saturated soil to completely dry. Tables 3.3 and 3.4 list the data used for the model development.

The rainfall is expected to be detented, if the rainfall rate is larger than the infiltration rate. The tests are performed under various design storm events (i.e. from 80 to 200 mm/h) at a constant rainfall intensity continuously for 15 minutes to 3 h duration.

Table 3.3: Parameters applied in the SWMM 5.1 module

Subcatchment		**Horton Infiltration**	
Subcatchment area (acres)	0.0003915	Initial capacity (in./h) or mm/h	300
Characteristic width (m) (physical width of overland flow)	0.250	Final Capacity (in./h) or mm/h	20
Percent slope	0	Decay Coefficient (h^{-1})	1.5
Percentage of impervious (%)	98	**Design Storm**	
Impervious area roughness (by Yen, 2001)	0.017	Duration (h)	15 min to 3 h designed storm
Pervious area roughness	0.01	Total Depth (mm)	30-200
Impervious area depression storage	0, no depression storage as the surface is totally solid	Time-to-Peak / Duration	constant rainfall
Pervious area depression storage	0		
Percentage of impervious area without depression storage	0		

Table 3.4: LID control parameters

LID Control (at subcatchment) (Permeable pavement-PPDS)	
Area of each unit (m^2)	0.16
Number of units	24
Percentage of subcatchment occupied	100
Surface width per unit (m)	0.250
Percentage of initially saturated area	0
Percentage of treated impervious area	0

The return period of the proposed permeable pavement is designed as 2-yr, while the flood control for the empirical work is set at 10-yr. Additionally, the 100-yr scenario is also calibrated to analyse the hydrological performance in the worst-case scenario. The experimental work is verified with the SWMM model simulation using the Nash-Sutcliffe Efficiency (NSE) index and Relative Percentage Difference (RPD).

3.5.2 SWMM for case study comparison on PPDS hydrological impacts assessment

A case study is developed to assess the hydrological impact of PPDS and compared the performance with the common permeable pavements using SWMM. The analysis considers local soil conditions, slope, land cover and meteorological data.

The study area is located at Lorong Uni Central 4B, Unigarden, Kota Samarahan, Sarawak (Figure 3.19). It has been classified as Class U3 Urban Road with speed control below 60 km/hr (JKR, 1987). The location is moderately sloped at a three-percent grade with an imperviousness of 60%. The soils are characterised as hydrologic soil groups of B with medium infiltration rate. The site covers the whole residential lot, occupying an area of 7272 m^2 (0.7272 ha). The permeable pavement with an area of 933 m^2 (0.0933 ha) is used to replace the asphalt road pavement during the simulation process.

The tropical climate of Kota Samarahan receives annual precipitation of approximately 3000 mm to 3500 mm, where 60% of it occurs during the wet season (from October to March). The designed storms are obtained based on the rainfall intensity-duration-frequency (IDF) curves of Kota Samarahan, Sarawak. It applies the average recurrence interval, ARI, of 10-yr (minor system) and 100-yr (major system) periods. The applied duration is set at 15 minutes (for short-duration events) and 3 h (for long-duration events). The 3 h period is selected as the local rainfall of 2 h to 3 h duration for 10-yr ARI is the common cause of flash flood in Malaysia (Abdullah, 2004).

Figure 3.19: Case study area, where the residential area was pointed with a blue mark

Table 3.5 presents the details of land-use characteristics of the selected study area. The residential area covers a total area of 0.6339 ha, with an impervious area of about 55% to 60%. The depression storage capacity at the site is about 25 mm. The area is divided into three subcatchments, where north wing residential, road pavement and south wing residential, which is labelled as S1, S2 and S3, respectively. S2 is basically a road pavement that receives runoff from S1 and S3 and routes to the outlet or infiltrates to ground. The above-mentioned subcatchments are illustrated in Figure 3.20.

For the model simulation, S2 is run with several scenarios, which consisted of Scenario 1- existing asphalt bituminous pavement and permeable pavement, Scenario 2 - Porous concrete (PC), Scenario 3- Permeable interlocking concrete pavement (PICP), and Scenario 4 - Permeable pavement micro-detention storage (PPDS). Since S2 plays the role of permeable pavement in this case, the depression depth in this area could be referred as the storage depth of each type of the permeable pavement.

Table 3.5: Land-use characteristics of the selected study area

Land use	Surface area (ha)	Width (m)	Impervious area (%)	Depression storage (mm)
Residential, S1	0.3088	14.21	60	25
Residential, S3	0.3251	12.56	55	25
Existing Asphalt pavement, AP, S2	0.0933	3	100	0
PC, S2	0.0933	3	82	162
PICP, S2	0.0933	0.23/ unit	85	132
PPDS, S2	0.0933	0.25/ unit	88	188

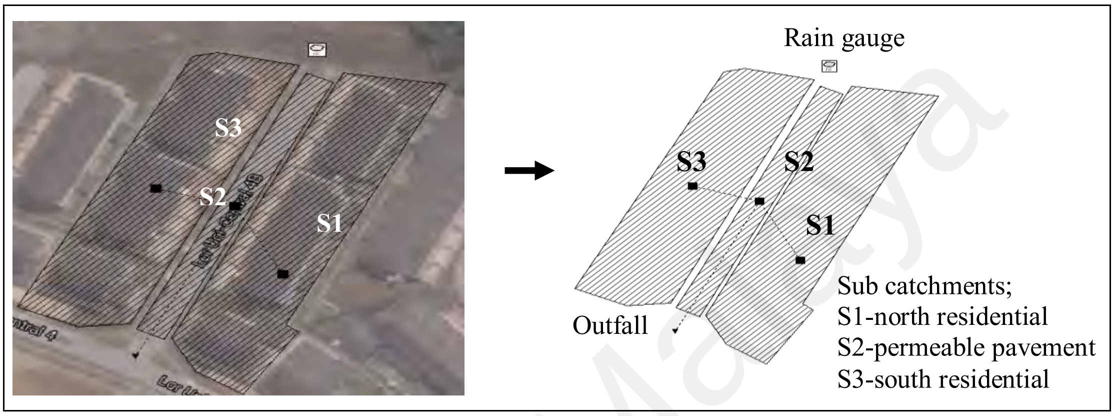


Figure 3.20: Subcatchments, consisting of S1 (north residential), S2-permeable pavement, and S3 (south residential)

Table 3.6 lists the parameters used for each scenario. In Scenario 1, it is the existing study area, consisting of an asphalt bituminous pavement road with drainage at the side as a conveyance system to the outlet. Scenario 2 refers to a simulation of the developed study area with permeable pavement that is controlled using pervious pavement comprising of perforated concrete slab units underlain with gravel (Sun et al., 2014; We et al., 2011). Scenario 3 embeds PICP manufactured by UNI-GROUP U.S.A (UNI-GROUP, 2008) containing a number of paver units. In scenario 4, the proposed PPDS system is applied.

Table 3.6: Parameters for each scenario

Parameters	PC	PICP	PPDS
Surface Layer			
Surface (m^2)	933	0.93/unit	1.6/unit
Vegetation volume fraction	0	0	0
Surface roughness	0.017	0.03	0.017
Surface slope (%)	1	3	0
Pavement layer			
Thickness (mm)	80	203	75
Void ratio (Voids/ Solids)	0.15	0.18	0.11
Impervious surface fraction	0.85	0.82	0.88
Permeability (mm/h)	200	127	220
Clogging factor	0	0	0
Storage Layer			
Thickness (mm)	300	314	300
Void ratio	0.4	0.4	0.7
Seepage rate (mm/h)	20	20	20

Figure 3.21 simplifies the design considerations in the case study. First, the catchment characteristics are investigated (refer Tables 3.4 and 3.5). Next, the hydrology and hydraulic design of the LID module (refer Section 3.2, Table 3.3 and 3.6), as well as the system analysis and the list of design requirements are determined (refer Section 2.5). Lastly, the output results are analysed as presented in Section 4.4.

1. Define catchment characteristics;
- Impervious/pervious area
- Land use
- Drained area

↓

2. Design assessments and considerations

a) System Analysis (Performance);
- Short, very high intensity, thunderstorm-type event
- Infiltration capacity (native soil types)
- Runoff determination; Volume and Discharge (Q_{pre} and Q_{post})
- Depression storage size and Detention time (time for the storage to empty)
- Lag time /Flow Routing

b) Design Selection Criteria;
- Site Characteristics; Area, Soil Type (Infiltration potential), Land use,
- Hydraulic; Hydrology parameter (Rainfall Intensity, Runoff), Acceptable flood water level, System performance (Storage capacity and permeability)

c) Hydraulic Design Consideration
- check sufficient storage capacity
- determine infiltration rate plus factor of safety (FoS) (1.5-10)
- determine design storm
- check time to empty the depression storage

d) Hydrological Analysis
- design approaches for the assessment of development runoff rates and volumes
- Hydrological functions considered when investigating the effectiveness of LID practices such as, runoff curve number (CN), time of concentration, retention and detention duration.

↓

3. System Output
- Runoff reduction, attenuation, storage
- Infiltration suitability, capacity and time

Figure 3.21: Design assessments and considerations for case study application

Figure 3.22 summaries the procedure of applying SWMM in this study. First of all, the properties and parameters are determined and set. The developed model is then verified by the hydrological data, precipitation data of local rainfall (i.e. return period and duration), as well as boundary condition and network distribution. The performance of PPDS is assessed using the developed SWMM via a series of statistical analysis consisting of NSE index and RPD and R^2. If the obtaining output closely matched to the experimental results, the model could be used for the following study. If not, the preset parameter has to be revised. After the model verification process, the developed

SWMM is used to specify the properties of LID practices simulate the case studies. In this study, 4 different scenarios are simulated, where Scenario 1 (existing condition with asphalt bituminous pavement road, AP), Scenario 2 (permeable pavement with previous concrete, PC), Scenario 3 (permeable interlocking concrete pavement, PICP) and Scenario 4 (permeable pavement with micro-detention pond storage, PPDS). After building up all the scenarios, the following step is the evaluation of the simulated results in terms of runoff generation, hydrological changes and impacts on the study area.

3.6 Summary

Chapter 3 provided the procedures to evaluate the hydrological performance of the proposed PPDS. The construction of the rainfall simulator at hydraulic laboratory, to investigate the PPDS hydrological properties took almost one year to complete (from October 2014 to August 2015). Despite encountering several challenges, it is successfully built to achieve the designed objectives of the research study. The rainfall simulator calibration was performed to ensure the occurrence of a nearly continuous and uniform artificial rainfall over the catchment area, so that it can allow the selection of rainfall under a varying duration and intensity.

The laboratory works were conducted to test the hydrological properties of the developed PPDS. The experimentation involved the investigation on the hydrological performance, particularly on the storage capacity and permeability rate. Performance in terms of infiltration rate was another important aspect to be studied. It examined with two types of compacted subgrade soils. The analyses performed with the equations of water balance model and the continuity equation as the basis.

The modelling process using SWMM was executed to analyse the overall performance in field applications. This study analysed an urbanised residential area of Kota

Samarahan, Sarawak to compare the hydrological performance of the existing condition, conventional permeable pavement and proposed PPSD. The flowchart, as shown in Figure 3.22 summarised the overall procedures of the SWMM application in this study.

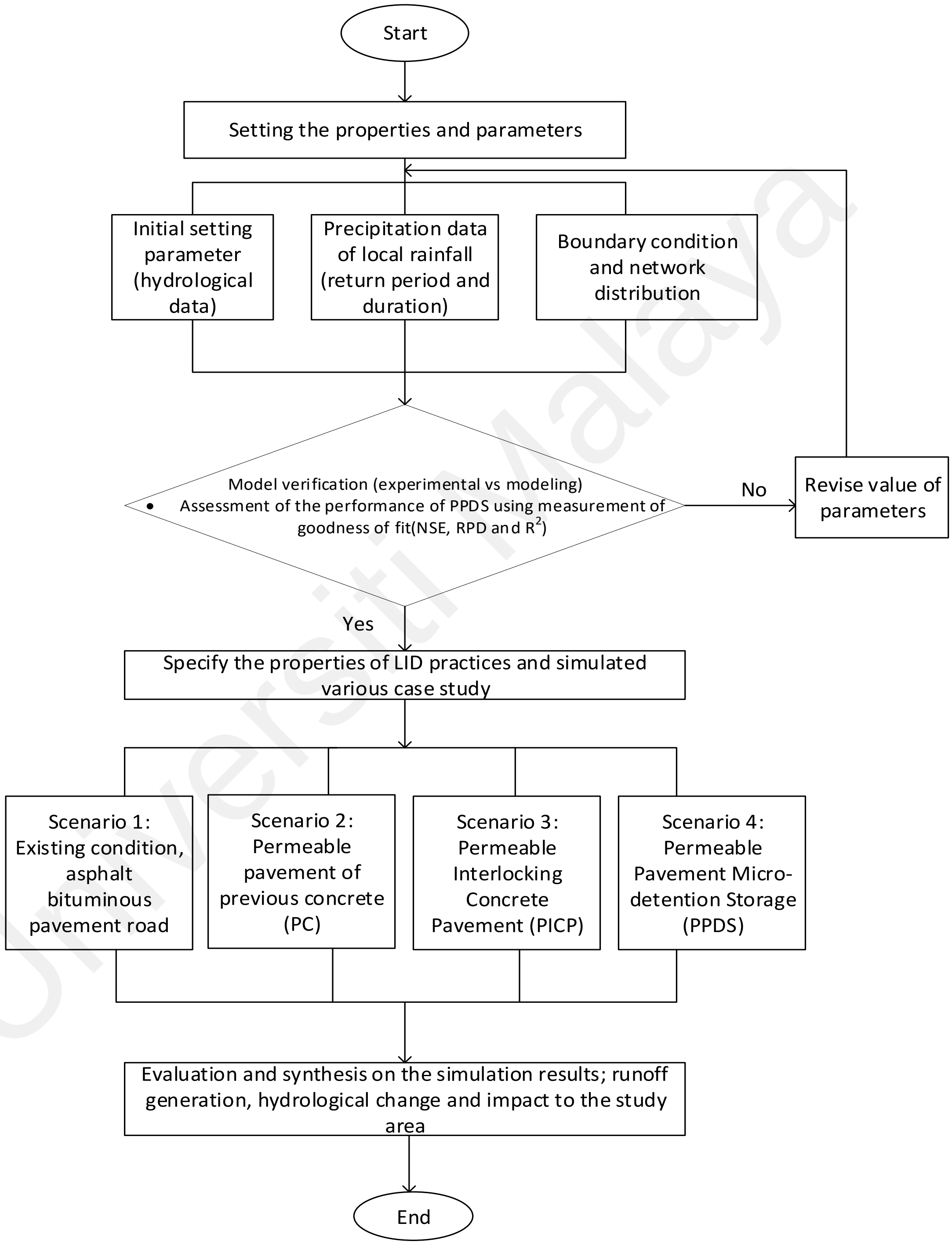


Figure 3.22: Overview of the process involved in SWMM

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents analyses and findings, obtaining obtained from the laboratory works and model simulation. The results are highlighted and discussed. The main objective of this chapter is to demonstrate that the permeable road pavement with micro detention pond storage, PPDS, can perform as green pavement infrastructure in relation of its hydrological benefit and fulfilling the sustainability development requirements.

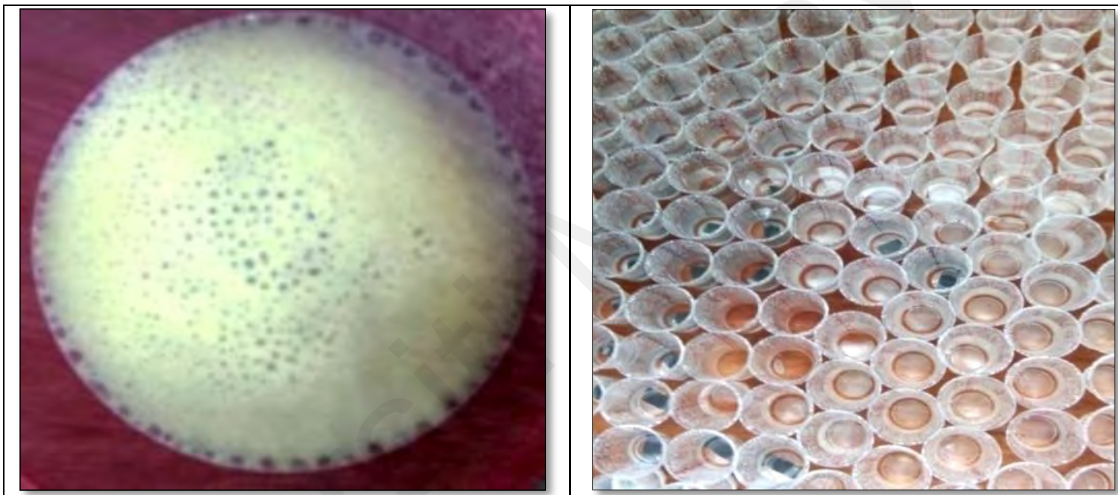
4.2 Rainfall simulator performance

The rainfall simulator's performance is compared with those aspects suggested by previous studies as contained in Table 2.8 under Section 2.7.1. First of all, Table 4.1 shows the performance of the inflow and outflow of the simulated rainfall at 15 min duration. The unit of rainfall intensity obtained through the local IDF curve is converted from mm/h to L/min so that it can be tallied with the unit of flowmeter measurement. The outflow discharge is calculated using Equation 3.1 as presented in Section 3.4. The average percentage of outflow is recorded at around 98%, showing the effectiveness of the system in nearly perfectly following the law of continuity equation.

Table 4.1: Inflow and outflow capacities of the designed rainfall simulator with respect to 6 different ARIs

ARIs	2	5	10	20	50	100
Rainfall intensity (mm/h)	155	170	175	180	200	210
Inflow (L/min)	10	11	11.5	12	13	14
Inflow volume (m^3)	0.150	0.165	0.168	0.180	0.195	0.210
Outflow discharge (m^3)	0.145	0.159	0.163	0.179	0.194	0.205
Outflow (%)	97	96	97	99	99	98

Furthermore, rainfall drop sizes are measured using oil immersion technique. Three ranges of rainfall intensities; from high intensity, short duration to lower intensity, longer duration, at 210 mm/h (15 min 100 ARI), 150 mm/h (60 min 100 ARI) and 80 mm/h (180 min 100 ARI) are applied in this research. The drop sizes are recorded as an image (Figure 4.1a). The drop size distribution ranges from 2 mm to 5 mm within the velocities of 0.5 m/s to 15 m/s. The resulting distribution is in agreement with previous studies as it was reported that the drop size for a nozzle with 3 m height was recorded around 1.6 mm to 6.5 mm.



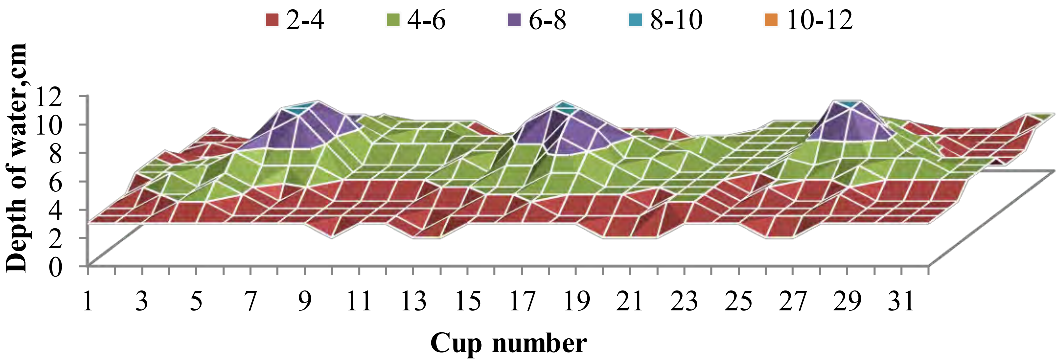
(a) Drops distribution (b) Distribution uniformity

Figure 4.1: Calibration on (a) drop sizes, and (b) distribution uniformity.

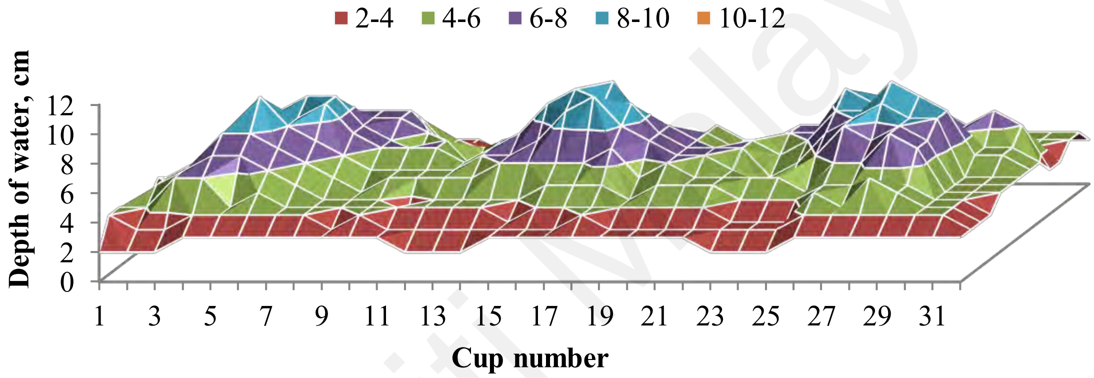
In addition, the size of natural rainfall droplets basically showed a variation from 1.5 mm to 2.5 mm for the rainfall intensity ranged from 50 mm/h to 150 mm/h (Abudi et al., 2012; Lora et al., 2016). Therefore, the experimental results indicate that the droplets size of the generated rainfall falls within the range of previously designed rainfall simulator (refer Section 2.7.1). Figure 4.1b shows the rainfall water collection in the plastic cups. The water depth is measured and used as the input of Christiansen's coefficient of uniformity (CU) to investigate the spatial uniformity. Figure 4.2 shows the distribution of the collected rainfall for the three selected rainfall intensities (80 mm/h, 150 mm/h and finally 210 mm/h). The peaks show the highest depth recorded from measured data of each scenario and their corresponding mesh surface interpolated in excel graph. The recorded depths from the examined rainfall intensities are following ascending order from 2-4 cm to 8- 10 cm to form an uneven layer that provides general performance features for each scenario. The rainfall intensity of 210 mm/h results in more significant depth if compared to the other two scenarios (Figure 4.2a). The result is in agreement with Knasiak et al. (2007), where a higher degree of spray overlapping can be expected for a higher rainfall intensity in the same coverage area, showing a more significant peak. For the rainfall intensities of 210 mm/h, 150 mm/h and 80 mm/h, the recorded CU value is 97%, 95% and 93%, respectively. The closer the CU value to 100%, the more uniform is the rainfall pattern. Normally, rainfall can be considered as uniform when CU value is higher than 80% (Aksoy et al., 2012). In sum, the rainfall that generated by the rainfall simulator exhibit reasonably even pattern; present CU values ranging from 93% to 97% and within the required drop size range. Therefore, it can be concluded that the designed rainfall simulator has shown its ability to produce artificial rainfall, which can mimic the natural rainfall phenomenon well. It is also expected that the developed rainfall simulator is capable to help monitoring the performance of green pavement systems in terms of infiltration rate, permeability and storage capacity.

4.3 Laboratory evaluation of PPDS hydrological system design

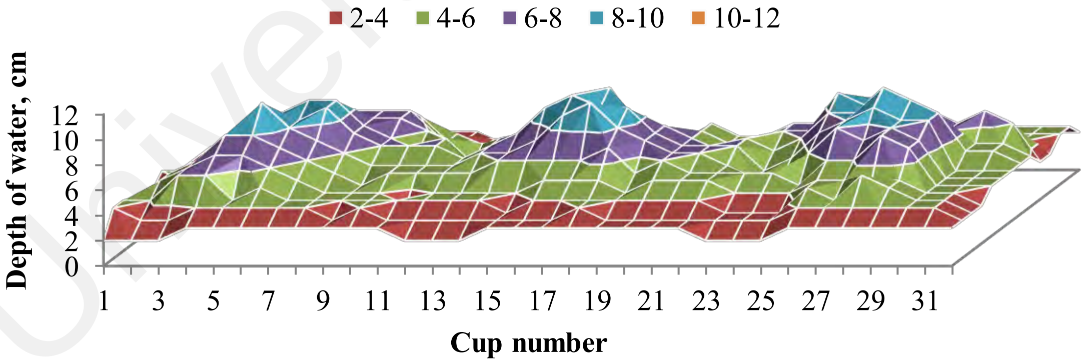
This section provides the analyses and discussion on the laboratory outputs, focusing on the performance, especially on permeability rate and water detention ability as well as the infiltration capacity, of the PPDS. The main aim is to prove that the developed PPDS can serve as a better alternative to conventional permeable pavement.



(a) Spatial uniformity distribution at rainfall intensity 210 mm/h



(b) Spatial uniformity distribution at rainfall intensity 150 mm/h



(c) Spatial uniformity distribution at rainfall intensity 80 mm/h

Figure 4.2: Uniformity distribution of rainfall intensity at 210 mm/h, 150 mm/h and 80 mm/h

4.3.1 Permeability rate of PPDS

Figure 4.3 shows the relationship between inflow and outflow from the perspective of depth, volume and discharge of the proposed PPDS under several rainfall intensities, ranging from 30 mm/h to 220 mm/h at continuously for about 3 h. It is essential to investigate such kinds of relationship as the PPDS is specially designed for enhancing the permeability rate with hollow criteria and more detention storage. In general, the graphs, for outflow depth versus inflow depth (Figure 4.3a) and outflow volume versus inflow volume (Figure 4.3b), exhibit a linear relationship regardless of the variation of rainfall intensity. Using the results and applying the water balance equation, a small change in storage of about 7% is calculated. Figure 4.3c shows the relationship between the inflow discharge rate and outflow discharge rate of the PPDS system for rainfall intensities ranging from 30 mm/h to 220 mm/h. A coefficient of determination (R^2) value of 0.993, which is near to 1, indicates a strong positive linear relationship between the inflow discharge rate and outflow discharge rate, where both the inflow rate and outflow rate show an almost similar value.

Figure 4.3 proves the effectiveness of the proposed PPDS in terms of diverting the water out from the system. The inflow and outflow rate shows a changes of 7%, which is considered as small and the linear trend lines indicate that the PPDS has an almost 100% of draining and conveying efficiency. In addition, the findings are in agreement with previous studies (Brown et al., 2012; Alizadehtazi et al., 2016), where the application of a permeable pavement can minimise the excessive runoff through its rainfall capturing and infiltration based property. Overall, PPDS (consisting of a hollow cylinder micro-detention pond structure) shows a better efficiency of about 93% if compared to 77% of the conventional permeable pavement (Ioannidou & Arthur, 2018).

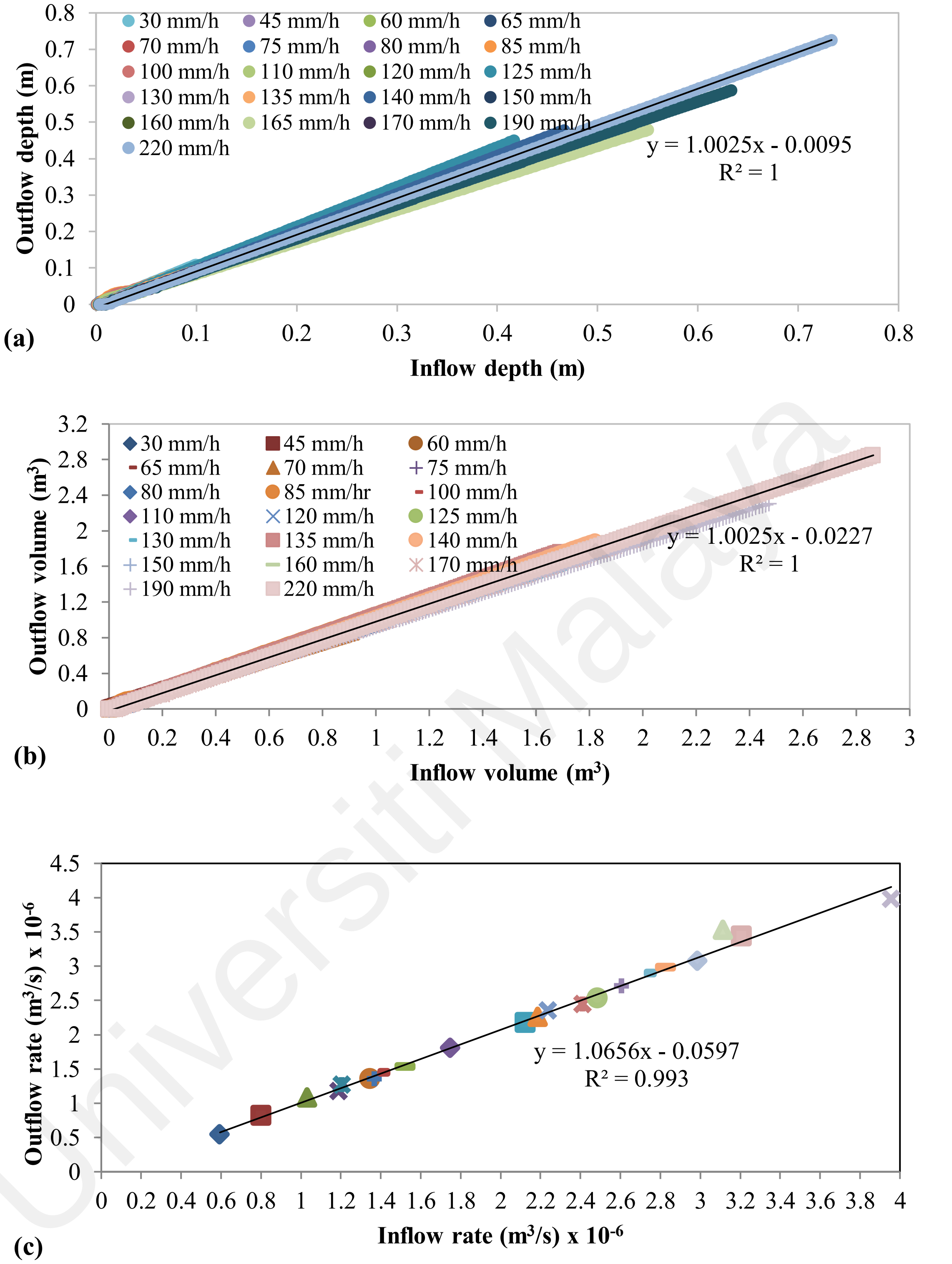


Figure 4.3: Relationship between inflow and outflow in terms of (a) water depth, (b) volume, and (c) discharge

Figure 4.4 depicts the flowrate over time of the proposed PPDS subjected to different rainfall intensities and durations. The rainfall intensities are applied with the duration ranging between 15 minutes and 180 minutes for various design storms ranging from 2

ARI to 100 ARI (see Appendix B). An important thing to be noted is there is no observable surface runoff generated from the simulated storms. This is mainly due to the high permeability rate of the system and there is no subgrade soil underneath the PPDS. The flow through the permeable pavement structure depends on the pavement design and subgrade soil types. At the starting stage, the flowrate depicts a significant increment within a very short period (15 minutes or less), where such a phenomenon generally occurs in the urban basin due to the hydrological response times. After that, the flowrate declines to an equilibrium rate, which is similar to the applied rainfall intensity. The outflow stops once the rainfall ceases.

This finding suggests that the proposed PPDS shows its capability to provide a high permeability rate and by-pass water immediately to the ground. Besides, the permeability rate of the proposed PPDS is designed at 120 L/m^2/min (equivalent to a flowrate of 8400 mm/h or 0.002m^3/s) as presented in Table 3.1. The designed value is higher than the value reported by Fletcher et al. (2008) and Boogaard et al. (2014), which is recorded at 4600 mm/h and 194 mm/h, respectively. In contrast, Leming et al. (2007) suggested a higher permeability rate (8600 mm/h), while designing the moderate porosity permeable pavement.

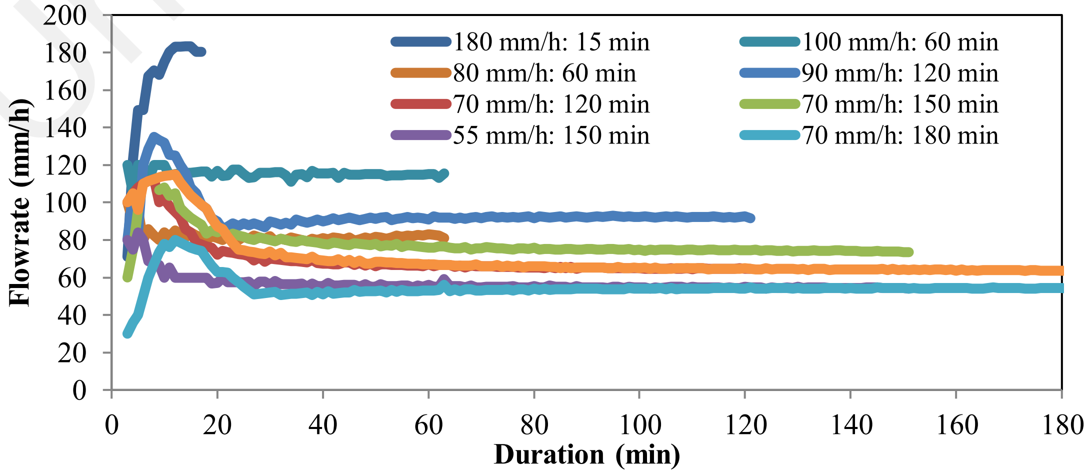


Figure 4.4: Flow pattern in PPDS with duration, at various rainfall intensities

Nevertheless, at current designed void volume (70%), it is proven that the PPDS is able to completely release and discharge the inflow. Therefore, there is no any detained water can that be detected in the system. Theoretically, the discharge rate of the system can be calculated using the fluid flow through cylindrical vessel using Torricelli's formula. For the examined system, the calculated value is recorded at 0.00198 m^3/s ($\approx$ 0.002 m^3/s). It shows that the proposed PPDS is designed according to the theory. Meanwhile, from the laboratory measurement, the discharge rate is measured at 0.0015 m^3/s ($\approx$0.002 m^3/s). An almost similar theoretical and experimental discharge rate provides a strong support on the applicability of the designed system to the real-life situation.

4.3.2 Detention storage capacity of PPDS

Figure 4.5 illustrates the change of storage capacity with respect to the depth of water and time in the proposed PPDS. In this experiment, the rainfall intensities are applied at various design storms ranging from 2 ARI to 100 ARI (see Appendix B). The increase in water depth in the system would increase the storage volume to show the linear trend line (Figure 4.5a). The graph as shown in Figure 4.5a can be applied to investigate the change in water depth in the PPDS corresponding to the change in storage volume.

From Figure 4.5a, by applying the designed water depth in $y = 0.99x$, depression storage of the PPDS can be determined. Based on the designed void porosity, the allowable water depth of the system is 0.2 m (Table 3.1), and the linear equation resulted in almost similar storage volume (0.2 m^3/m^2). The obtained value indicates that the PPDS has the ability to provide a maximum storage capacity of around 0.19 $m^3/m^2 \approx$ 0.2 (equivalent to 190 L/m^2).

Moreover, Figure 4.5b shows that the designed PPDS has great potential to provide benefits in terms of depression storage for a wide range of rainfall intensity. Since the time of concentration (t_c) for most of the small and urban watersheds falls within 15 min to 30 minutes (Leming et al., 2007), particularly observed 15 minutes in the plot, the storage required is 0.15 m^3/m^2, which is less than the designed storage capacity (0.19 m^3/m^2). Based on the evaluations on storage capacity, the PPDS provides sufficient capacity within a variety of rainfall intensity. The storage capacity is sufficient to store a design storm for heavy rainfall up to 220 mm/h, which is almost equivalent to rainfall event at the 15-minutes duration of 100-yr storm (210 mm/h).

Several studies have been conducted to investigate the relationship between the allowable water depth and the maximum storage capacity. Park et al., (2014) reported that a maximum water volume of 40 L/m^2 could be retained in the permeable pavement with a void ratio of 30%. Boomsma and Huurman (2006) found that water storage could reach as high as 140 L/m^2 for permeable pavement designed with a porosity ratio of 35% and thickness of 400 mm. Zhang (2006) showed a block pavement structure with 30% of void capacity displayed an ability to create a maximum storage capacity of 48.2 L/m^2. In sum, a significant improvement is achieved by the proposed PPDS as it can provide a higher depression storage capacity (70% with storing capacity 190 L/m^2). This is mainly because, although its thickness is similar to the typical permeable pavement, the system is designed with a higher void ratio.

Figure 4.6 presents the storage capacity over time of the PPDS for the 5-yr to 100-yr events at Kota Samarahan. Under the condition of 15 minutes short duration continuous rainfalls, the PPDS shows its ability to capture and detain the first flush of rainfall for the rainfall event up to 100-yr ARI (Figure 4.6a). The results support the findings as reported by Pratt et al. (1999), where the permeable pavement can attenuate the first flush of stormwater. However, if the continuous rainfall lasts for at least 90 minutes, the system will reach its storage limit of 0.19 m^3/m^2 within 40 minutes (for both 5-yr and

10-yr ARI events) on average (Figure 4.6b). Nevertheless, Korkealaakso et al. (2014) recommended that the storage capacity of the permeable pavement should be designed based on the specific rainfall events along with the consideration of the soil infiltration.

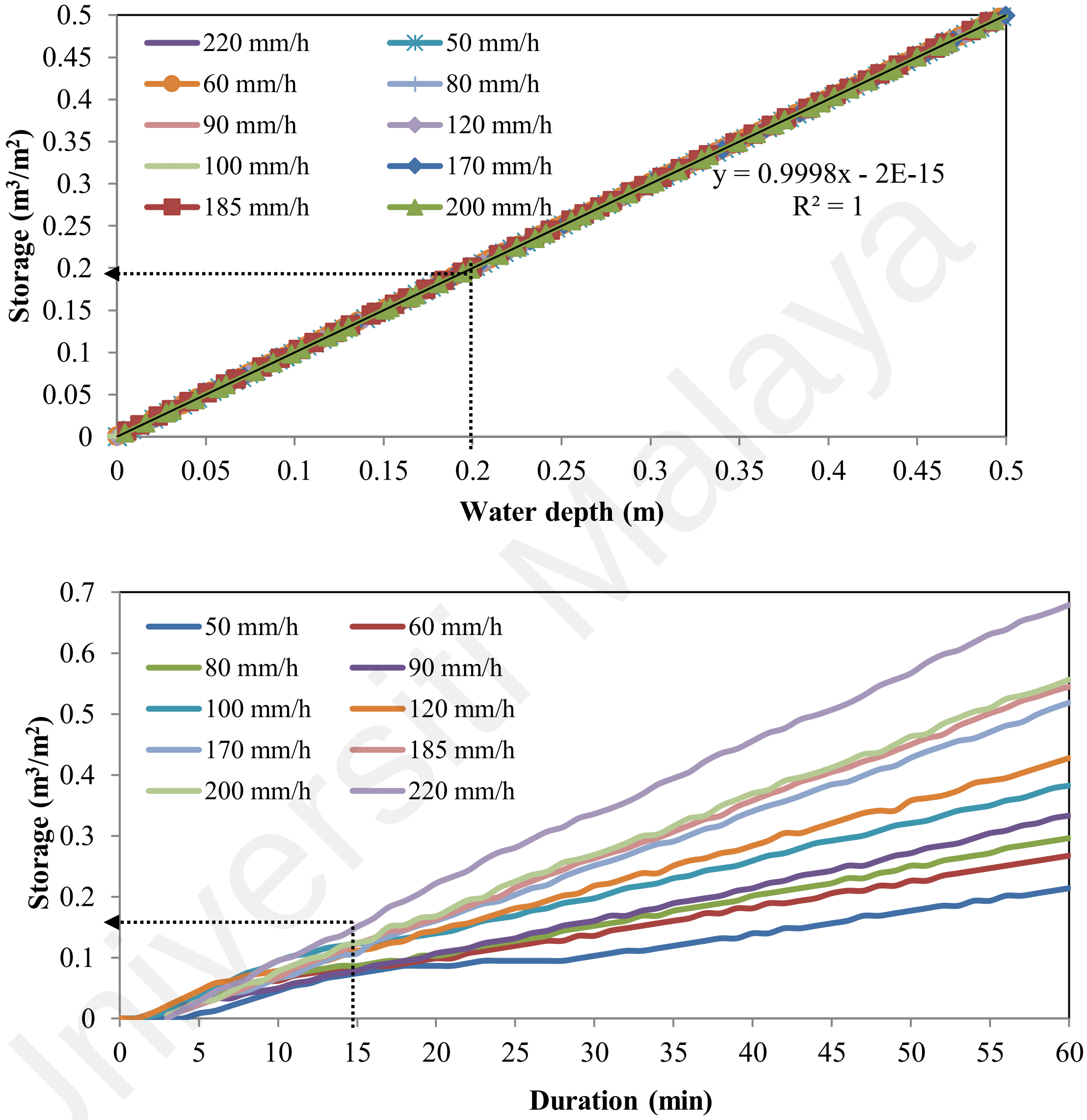


Figure 4.5: Detention storage of PPDS with water depth and duration at various rainfall intensities, (a) water depth-storage curve relationship for rainfall intensities and (b) time-storage curve for various rainfall intensities

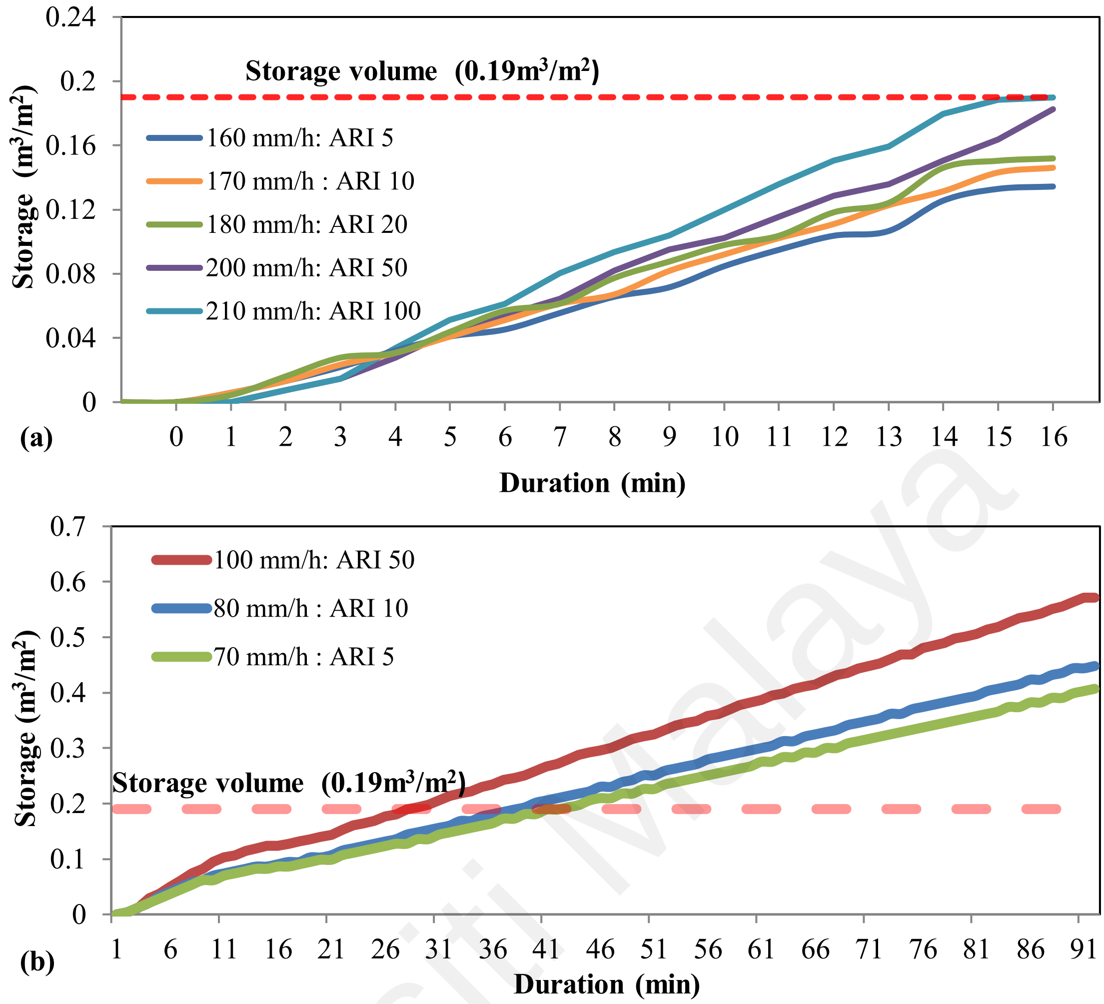


Figure 4.6: Storage volume of PPDS with duration at various rainfall intensity for (a) 15-minutes rainfall duration, and (b) 90-minutes rainfall duration

To assess the performance of water depth and storage volume versus rainfall duration, Figure 4.7 is plotted. An important note is that the proposed PPDS is designed to have a service load of 2-yr ARI and stormwater collection of 10-yr ARI. Figure 4.7a shows the performance in terms of water depth for the investigated rainfalls ranging from an intensity of 56 mm/h to 175 mm/h for a fixed duration of 3 h. Since the total height of the PPDS is 0.45 m (consisting of 300 mm micro-detention storage and 150 mm of top and bottom surfaces), the system shows its ability to fully capture a rainfall with an intensity of less than 80 mm/h for a continuous 3 h duration (equivalent to almost 2-yr ARI, 24 h rainfall event). This finding is comparable with that presented in Smith

(2011) who reported that the permeable pavement can store at least 0.089 m rainfall inside a 250 mm thick base layer under a rainfall event of 2-yr ARI for 24 h duration. Meanwhile, the PPDS captures about 0.21 m rainfall inside the 300 mm height hollow cylinder under the same rainfall pattern. Therefore, it can be concluded that the PPDS has ability to provide better performance in terms of storage capacity if compared to the conventional permeable pavement.

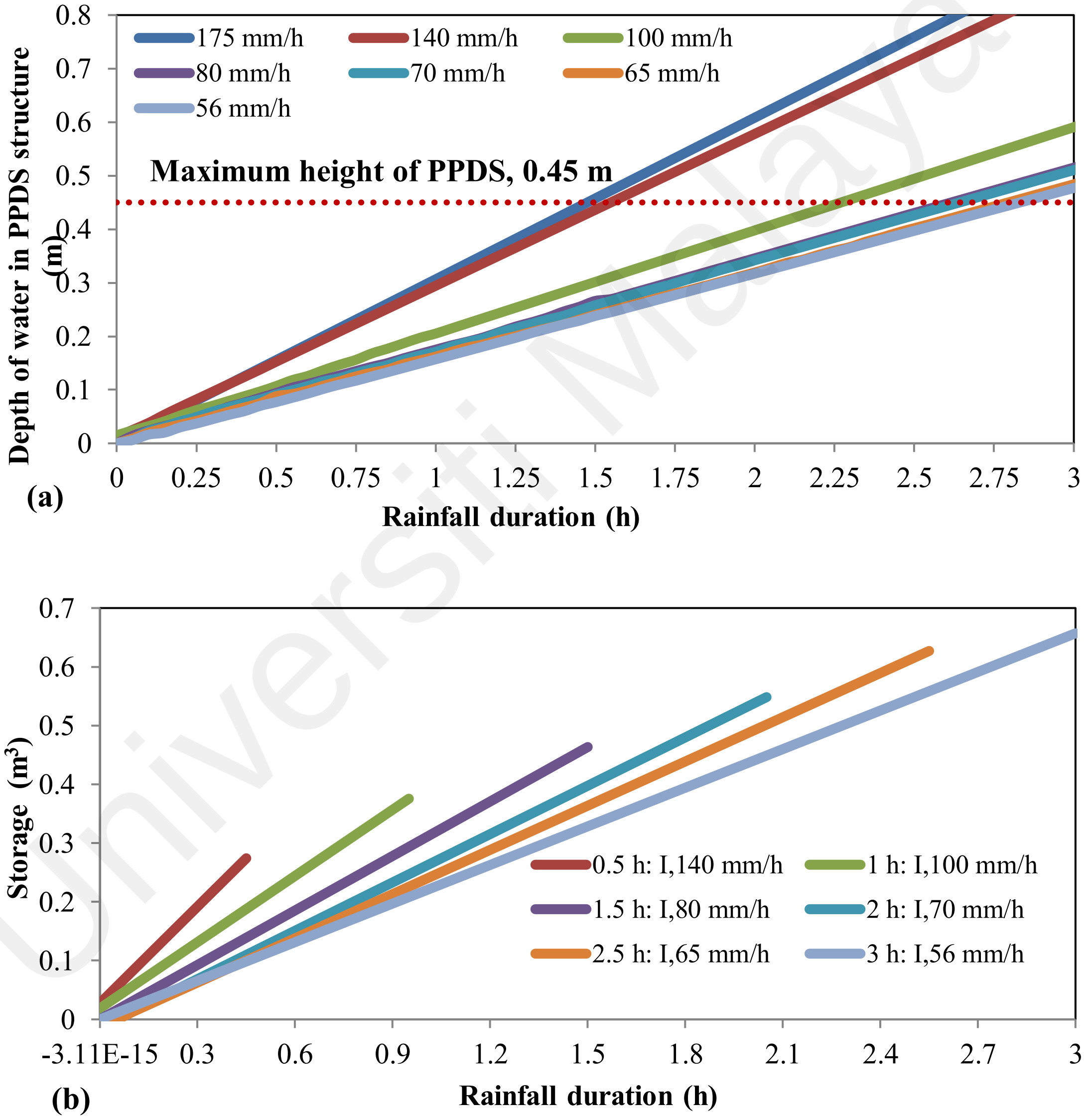
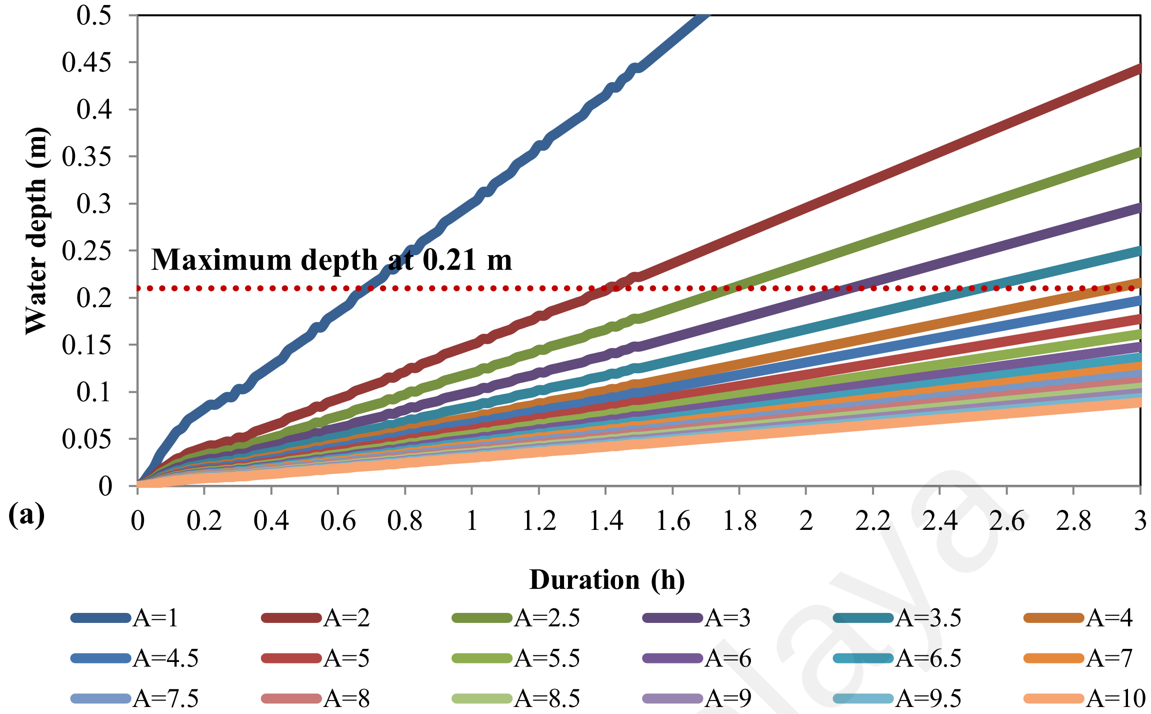


Figure 4.7: Changes in (a) water depth and, (b) volume capacity in PPDS with rainfall duration for different rainfall intensities at 10-year ARI.

Figure 4.7b demonstrates the volume of water that is collected for each examined rainfall intensity in 10-yr ARI at the specified duration within the range of 0.5 hr to 3 hr. It is noticed that for all of the cases the collected water volume does not exceed the maximum allowable capacity of the PPDS, which is 0.76 m^3 (0.19 m^3/m^2 times catchment area of 4 m^2). In sum, it can be deduced that the PPDS meets the volume requirement with only a little overflow at the road surface and satisfies the design requirement in terms of the hydrological design for the 2-yr and 10-yr ARI.

Next, Figure 4.8 exhibits the relationship of water depth with time and depression storage of the PPDS for different coverage areas for a rainfall event with an intensity of 100 mm/h for 3 h duration. The designed rainfall can produce a total rainfall amount of 300 mm, which is almost similar to the average monthly rainfall of Kota Samarahan. The designed capacity of underground micro-detention pond storage of PPDS is 210 mm (with a void porosity of 70% and an empty space of 0.19 m^3/m^2). The horizontal line represents the maximum level of storage for the system (0.21 m). In general, with a constant depth and similar amount of rainwater, large coverage area results in larger storage capacity.

Furthermore, it shows that the proposed PPDS can provide sufficient storage for an area larger than 4 m^2 according to the maximum designed depth of 0.21 m. In other words, the PPDS has the ability to perform well for an area larger than 4 m^2. Such a condition proves the applicability of the designed PPDS in low-speed roads, such as car park and housing area as the total coverage of a car park in the residential area is normally more than 10 m^2, which is larger than 4 m^2 (Tennis et al., 2004).



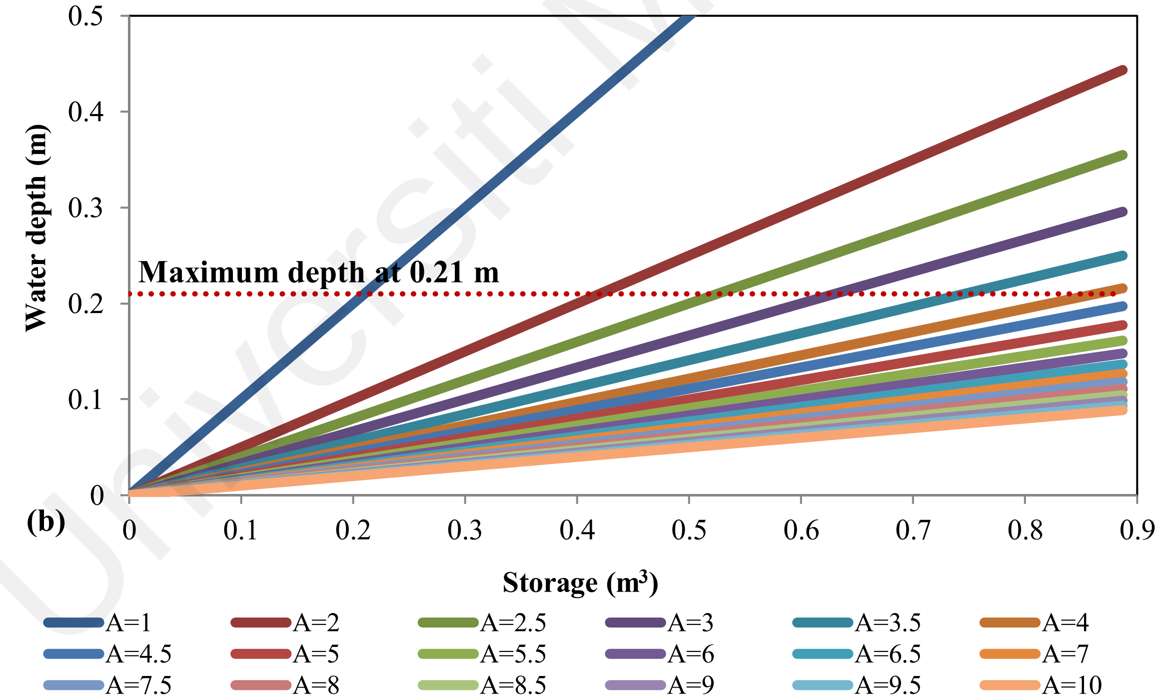


Figure 4.8: Relationship between (a) water depth and duration, and (b) water depth and storage capacity for different coverage areas

An ideal PPDS, acting as a green pavement system, should take all the hydrological perspectives into consideration during the design process, especially the storage capacity. Commonly, the storage capacity of the conventional permeable pavement is considerably effective due to its porous structure (Korkealaakso et al., 2014). As a modified structure to the traditional permeable pavement, the alternative design of PPDS is presented via Figure 4.9, which illustrates the relationships between several parameters including storage capacity, water depth, void porosity and structure thickness. The reported findings can be used as a reference while designing the PPDS to ensure its strength and durability well-suiting to the designed purposes, so that it can efficiently perform its role under different climate conditions.

Basically, the PPDS thickness can be increased to accommodate water storage requirement; however, according to Agouridis et al. (2011), the thickness significantly depends on the structural requirements. As shown in Figure 4.9a, the three presented components are correlated, where an increase in void capacity results in the increase of both storage and water depth in the PPDS. The designed PPDS has a thickness of 450 mm with a void ratio of 70%, and thereby it can achieve a water storage of 0.19 m^3/m^2. However, if the void porosity increases to 80%, the system will be able to detent about 0.22 m^3/m^2 of rainwater under the same structure thickness at water depth of 0.24 m. Figure 4.9b depicts the relationship among the PPDS structure thickness, storage and water depth. Fixing the designed void capacity at 70%, through altering the thickness of the cylindrical component in the PPDS, it is clearly observed that the changes of structure thickness may influence the storage. For example, with a thickness of 0.9 m, the system can provide a storing capacity of 0.6 m^3/m^2 at a water depth of 0.63 m.

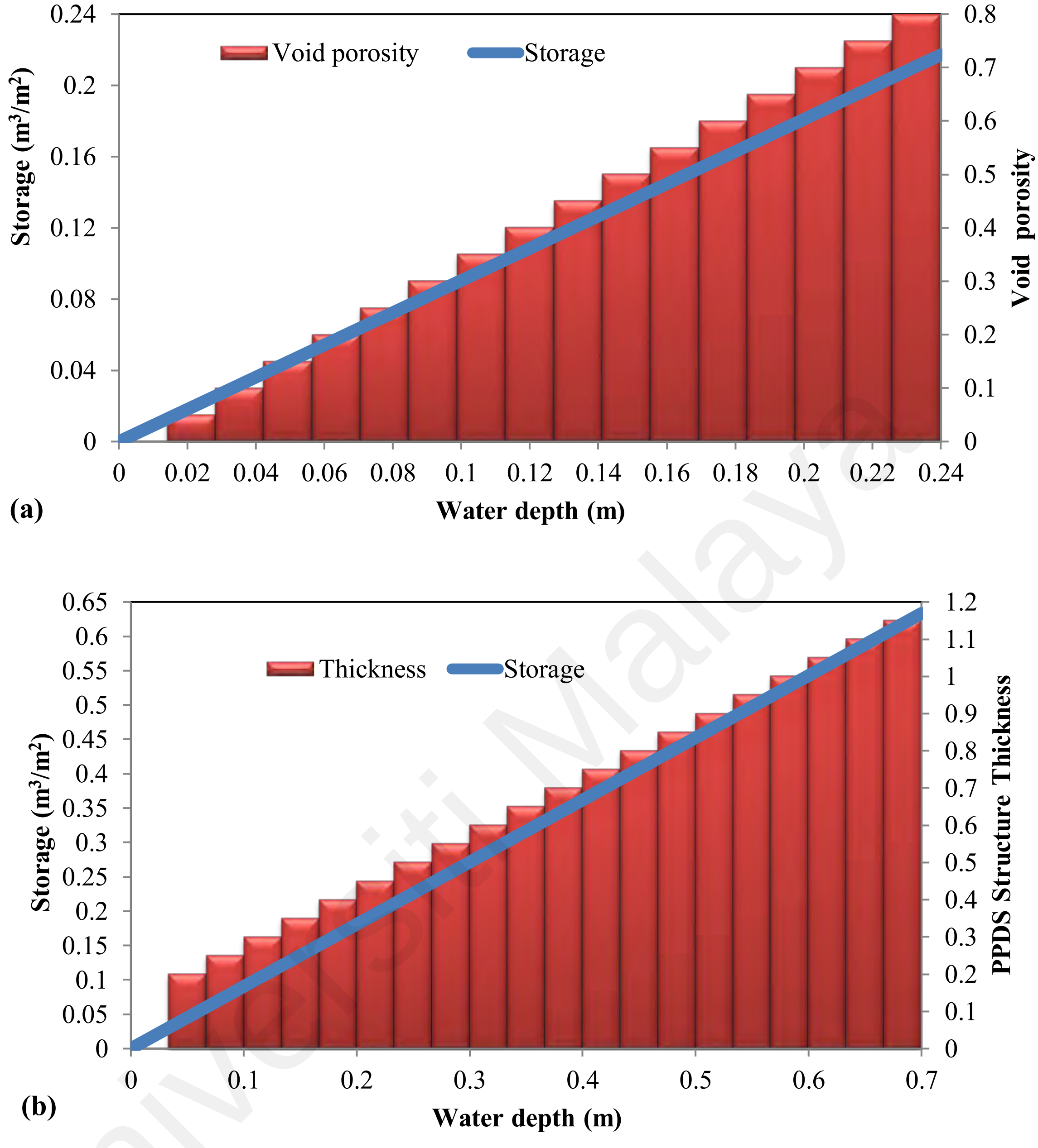


Figure 4.9: Various designed size and volume corresponding to (a) various void capacities with existing designed thickness of 450 mm, and (b) different PPDS structure thickness with a fixed 70% void capacity

In sum, the relevant hydrology information, such as total rainfall events and total rainfall runoff that will be received from the impervious catchment, are essential to determine the inflow amount of stormwater while designing a PPDS, so that the system can function in an optimised manner.

4.3.3 Infiltration rate of PPDS

Both the permeability and infiltration rates play a significant role while designing a permeable pavement (Tennis et al., 2004; Leming et al., 2007). Hence, this section discusses the hydrological performance of the proposed PPDS from the above-mentioned aspects.

Figure 4.10a presents the flowrate pattern within PPDS using common subgrade soil of Kota Samarahan highway, under the 10 yr-ARI rainfall events with a wide variety of intensity for a certain duration. In general, the flowrate increases from the beginning of the rainfall event until achieving its peak and then reduces to the uniform level at an equilibrium depth. For the cases of rainfall with higher intensity, but shorter duration (i.e. 185 mm/h for 15 minutes and 140 mm/h for 30 minutes), the flowrate takes about 2 h to 2.5 h to reach equilibrium. For the other conditions, the flowrate reaches equilibrium within a longer period ranging from 3 h to 7 h.

During the experiment, no overflow is observed on the PPDS surface (Figure 4.10b) while applying the continuous rainfall with intensities of 210 mm/h, 160 mm/h and 80 mm/h. This is because both the inflow and outflow rates reach the equilibrium state. In other words, the PPDS can cater for 100-yr ARI rainfall events of 210 mm/h for 15-minutes duration, which generates no runoff, if it receives only the direct rainfall. On the other hand, a constant water depth is found at about 0.425 m from the bottom surface of PPDS. Based on the balance law, the inflow rate is equivalent to the outflow rate under this circumstance.

The time required to reach constant depth for rainfall intensities of 210 mm/h, 160 mm/h and 80 mm/h are 2.7 h, 3.2 h and 6.8 h, respectively. In short, it can be concluded that the PPDS with the compacted common local subgrade soil has the ability to provide detention storage and release water within a period of 3 h to 7 h. Thus, it meets the standard as reported by Woods-Ballard et al. (2011), stating that it is a must to ensure the permeable pavement system has an emptying time of 12 h in order to provide storage for the subsequent storms. Meanwhile, Hein et al. (2010) suggested the values should be about 24 h to 48 h.

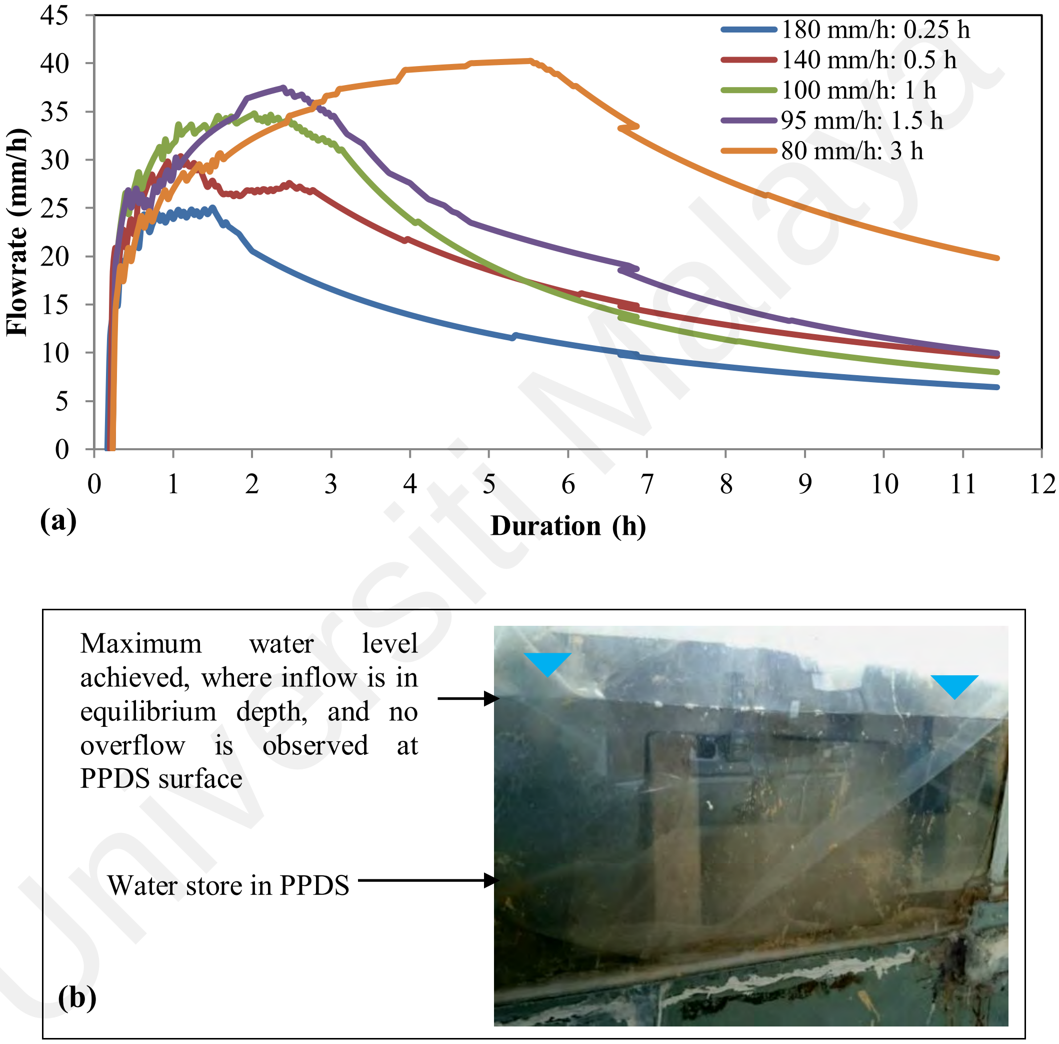


Figure 4.10: PPDS performance assessment in terms of (a) flowrate pattern against duration with respect to different rainfall intensities and durations, (b) depth of water level under continuous and high-intensity conditions

The recorded time and depth once the rainfall stops to achieve its equilibrium state (a condition where there is no rise in depth and stormwater completely flows out of the system) for rainfall events of 5-yr and 10-yr ARI are tabulated in Table 4.2. The infiltration rates of the common subgrade soil and local sand are found at 41.67 mm/h and 62.99 mm/h, respectively. Meanwhile, Wanielista et al. (2007) reported that the pervious pavement with subsoil consisting of hydrologic soil group A, displayed an infiltration rate of 1.67 in/h (42.4 mm/h), which is quite similar to the recorded value as presented in this study.

For the examined rainfall events, the time taken for the system to reach constant depth and completely infiltrate the rainwater falls within a range of 1.3 h to 4.6 h, which meets drainage time of the design manual published by New Jersey Department of Environmental Protection (2016). Accordingly, the drainage time of a pervious paving system is determined by the designed permeability of the subsoil and must be within a maximum design storm volume of 72 h.

Further analysis is summarised as shown in Figure 4.11, where it shows the comparison of the calculated time to infiltrate the soils along with resulted infiltration capacities, T_f with the observed infiltration time. From the findings, as shown in Figure 4.11a, the Relative Percentage Difference (RPD) is less than 12%, whereas, as shown in Figure 4.11b, it is less than 10%. Such a low RPD value indicates the model exhibits a relatively high accuracy of observed infiltration duration with inflow depth and calculated infiltration time corresponding to the infiltration rate of the soils.

Table 4.2: Infiltration capacity and duration subjected to detention storage

Storm duration; subgrade	Rainfall intensity, Return period	Depth at equilibrium, D_e (mm)	Drain time, T_d (h)	Depth at stop of nozzles, D_n (mm)	Infiltration rate, f(mm/h)	Time taken to infiltrate with f, T_f, $[(D_e-D_n)/f]$ (hr)	Time to infiltrate the Depression storage, T $(T=T_d-T_n)$ (hr) *T_n, Time at stop of nozzles
0.25 h, local subgrade	170 mm/h, 5-yr ARI	54.29	1.33	12.53	41.76	1.00	1.08
	180 mm/h, 10-yr ARI	57.08	1.40	13.92	41.76	1.03	1.15
1.5 h, local subgrade	80 mm/h, 5-yr ARI	150.34	3.00	76.56	41.76	1.77	1.47
	100 mm/h, 10-yr ARI	153.129	4.00	55.68	41.76	2.33	2.57
3 h, local subgrade	60 mm/h, 5-yr ARI	215.77	4.50	146.17	41.76	1.67	1.47
	80 mm/h, 10-yr ARI	263.10	4.60	197.68	41.76	1.57	1.63
1.5 h, sand	60 mm/h, 5-yr ARI	99.74	1.70	92.39	62.99	0.12	0.18
	80 mm/h, 10-year ARI	116.54	1.80	103.94	62.99	0.20	0.27
2.5 h, sand	80 mm/h, 5-year ARI	157.48	2.75	145.94	62.99	0.18	0.25
	100 mm/h, 10-year ARI	183.24	2.80	170.09	62.99	0.21	0.32

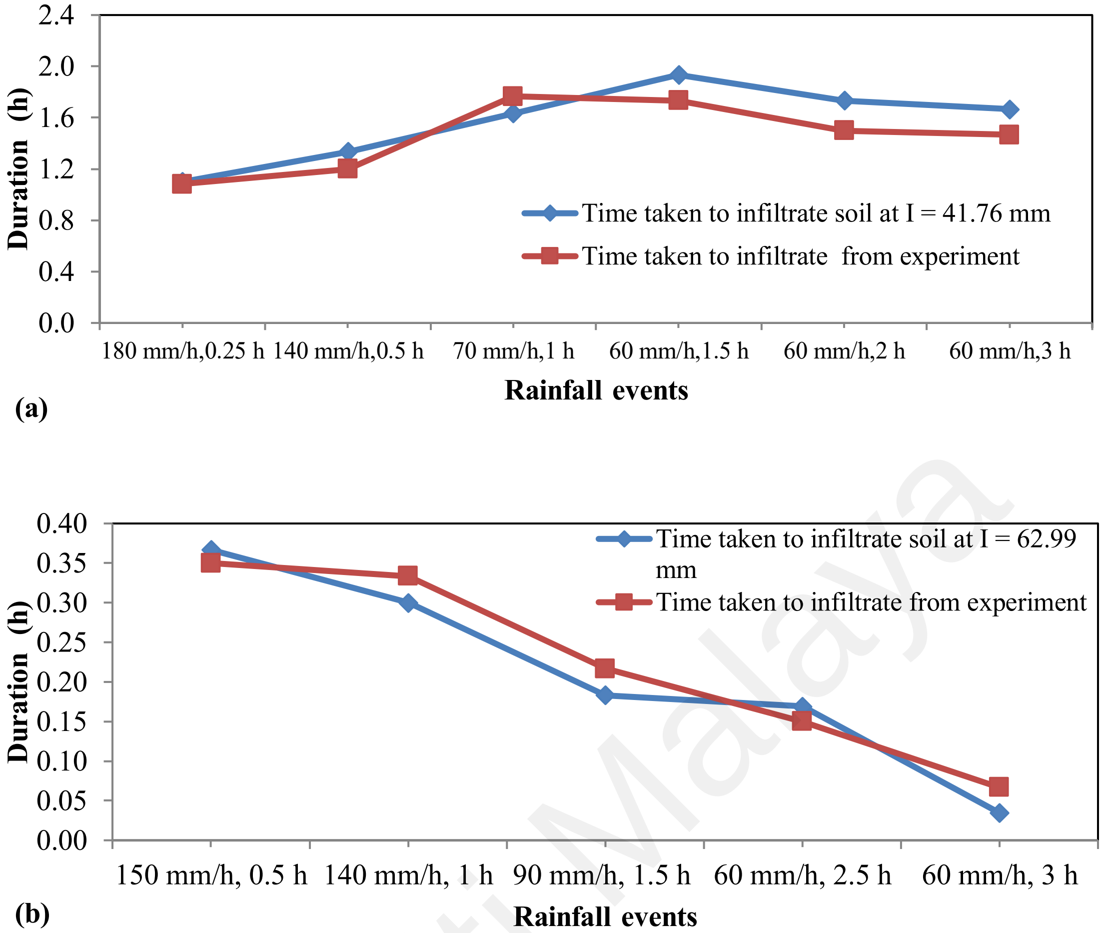


Figure 4.11: Comparison of time to infiltrate the detention storage and time based on experimental infiltration rate (a) with local subgrade soil (sandy loam) at I = 41.76 mm and (b) with sand as subgrade at I = 62.99 mm

It is suggested that the duration to infiltrate water in the detention storage area of the PPDS is reliant upon the infiltration capacity of the subgrade soils. The results are in agreement with Ferguson (2005) and Zhang (2006) where infiltration strongly depended on soil properties. Besides, Kayhanian et al. (2019) claimed the infiltration capacity was a limiting rate of permeable pavement performance evaluation (refer to Section 2.4.1.3).

Table 4.2 and Figure 4.11 provide the summary of the PPDS performances with subgrade soils. The depth of inflow in the system is correlated with the infiltration rate of the subgrade soils. It is attributed to duration taken to infiltrate through the PPDS system that fit the linear regression lines as presented in Figure 4.12. Figure 4.12 depicts the relationship between flow depth in the PPDS and duration under several infiltration rates ranging from 10 mm/h to 70 mm/h. According to Smith (2006) and Leming et al. (2007), hydrologic soil groups, HSG, A and B are listed as best-suited soils for permeable pavement as they are able to provide a wide range of infiltration rate from 13 mm/h to 210 mm/h. In addition, the soils can also detain the rainfall event with continuous 24 h to 72 h.

In Kota Samarahan, Sarawak, the highest rainfall for 10-yr ARI event can be recorded at 0.7 m. Through this research, it is found that the subgrade soil with different infiltration rates has different infiltration durations. The smaller the infiltration rate, the longer is the duration. For example, to infiltrate a rainfall depth of 0.7 m, it needs 70 h, 47 h and 35 h (which fall within 72 h) for the infiltration rates of 10 mm/h, 15 mm/h and 20 mm/h, respectively. Therefore, the results prove that PPDS can be used for the soil with an infiltration rate, which is larger than 10 mm/h to accommodate flood control. It can provide a detention period between 24 h and 72 h for storm events of 10-yr ARI.

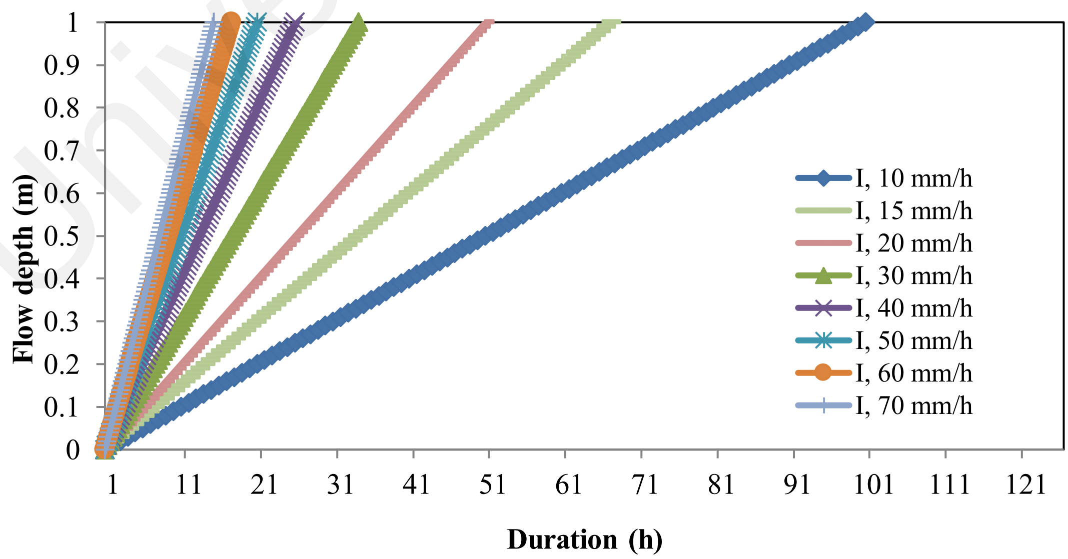


Figure 4.12: Permeability performance of PPDS with respect to the different infiltration rates

4.4 SWMM application for PPDS hydrological assessment

The PPDS is further evaluated using SWMM as a low impact development (LID) practice. The simulated results are compared with experimental results. Then, the field study is conducted to compare the proposed PPDS with the existing pavement condition and common permeable pavement.

4.4.1 Comparison between observed values and simulated results

Figure 4.13 illustrates the comparison between the simulated outcomes and the experimental findings in terms of flowrate. Generally, the observed and the simulated findings display a similar pattern, showing that the developed SWMM model can mimic the performance of PPDS well. In addition, the above statement is supported by the calculated NSE values, where in most cases the value is recorded below 0.5 (an indicator to show the performance is acceptable) (Moriasi et al., 2007).

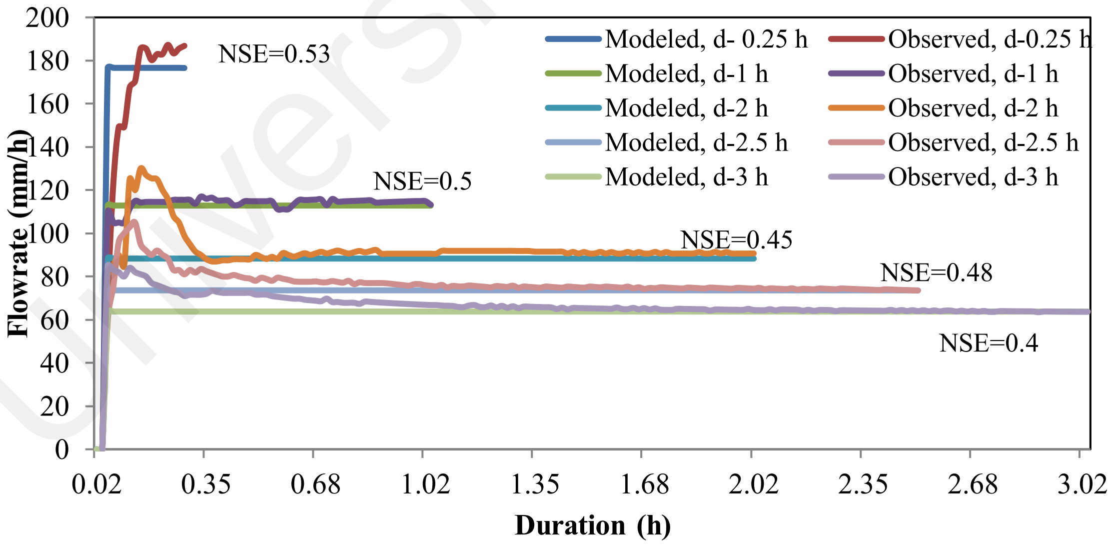


Figure 4.13: Flow pattern and the calculated NSE value for the investigation rainfall events

On the other hand, Table 4.3 presents the outputs of the other type of statistical analysis, which is the relative percentage difference, RPD, to assess the performance of the developed model. The value is controlled below 14% and 10% in average for both infiltration loss and drying time, which means that the developed model has the ability to reach relatively high level of accuracy. Hence, it reveals that the SWMM can model the PPDS well through its LID control module.

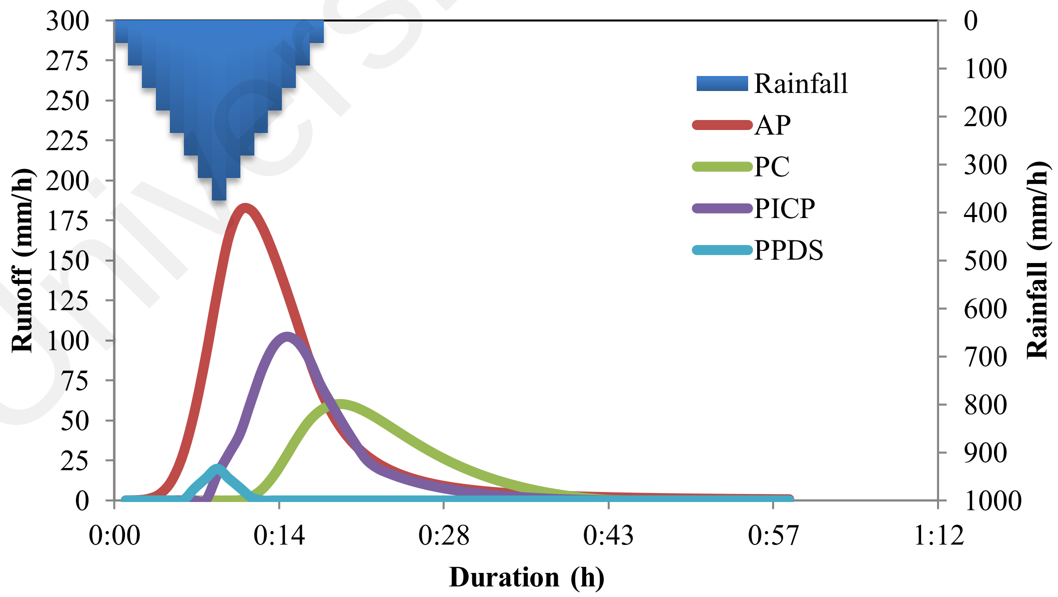
Table 4.3: Statistical analysis in terms of relative percentage difference of the observed and modelled conditions

Precipitation (mm)	Infiltration loss (mm)			Time of infiltration (h)		
	Observed	Modelled	RPD (%)	Observed	Modelled	RPD (%)
45	44.70	44.13	1	1.3	1.2	9
70	69.95	68.69	2	1.9	1.7	11
95	91.53	89.75	2	2.5	2.2	11
190	152.26	131.43	14	3.5	3.2	8
200	165.68	151.59	9	4.4	3.8	14
240	195.07	172.13	12	4.6	4.2	8

4.4.2 Comparison of PPDS with the existing pavement condition and common permeable pavements

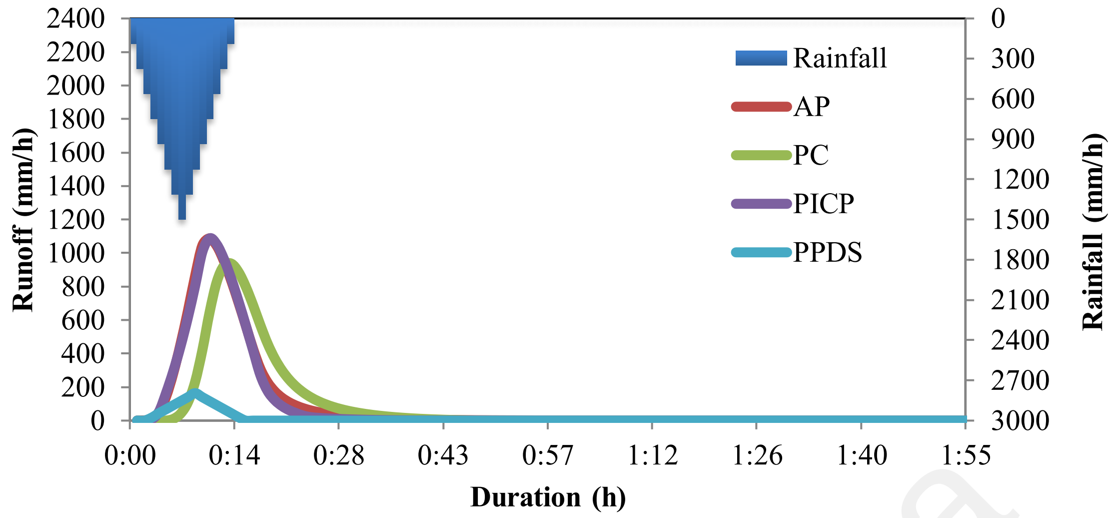
Figure 4.14 illustrates the runoff responses of four different simulated scenarios; AP is asphalt pavement, PC is pervious concrete, PICP is permeable interlocking concrete pavement and PPDS is permeable pavement with micro-detention storage at different rainfall conditions. Under the existing condition, which is AP, the runoff appears immediately after rainfall starts because such a design is not equipped with any depression storage. Meanwhile, a different observation can be investigated for the other three scenarios. The runoff appearance is delayed due to the depression storage feature in the applied systems. In the pervious area, there is no runoff for the first 7 minutes to 12 minutes of the rainfall event, as the designed depression storage and infiltration capacity are sufficient to capture all rainfall during this period. In general, the peak runoff and total runoff volume of the permeable pavements (PC, PICP and PPDS) are smaller than that of existing pavement, AP. The findings are in line with Barszcz (2015) and Kim et al. (2014), where the permeable pavement has a better infiltration rate than the asphalt pavement, which in turn can infiltrate larger runoff amount into the ground.

As reported in Wang et al. (2018), the effect of the permeable pavement applications on urbanisation is more noticeable, especially for small and moderate events with a longer return period. By applying PC and PICP, the resulted runoff is reduced by about 40% for smaller events (e.g. 10-yr ARI with 15-minutes duration) and 10% for larger events. Furthermore, Eckart et al. (2017) has raised up the concern that the LID practice may become less effective for the large rainfall events. Therefore, such an issue is highlighted in this study for the PPDS application. In contrast to the conventional permeable pavements, less than 15% of runoff is generated under a short-duration high-intensity rainfall (e.g. 100-yr ARI for 15-minutes duration) and such a percentage is reduced to only 5% while applying larger events.

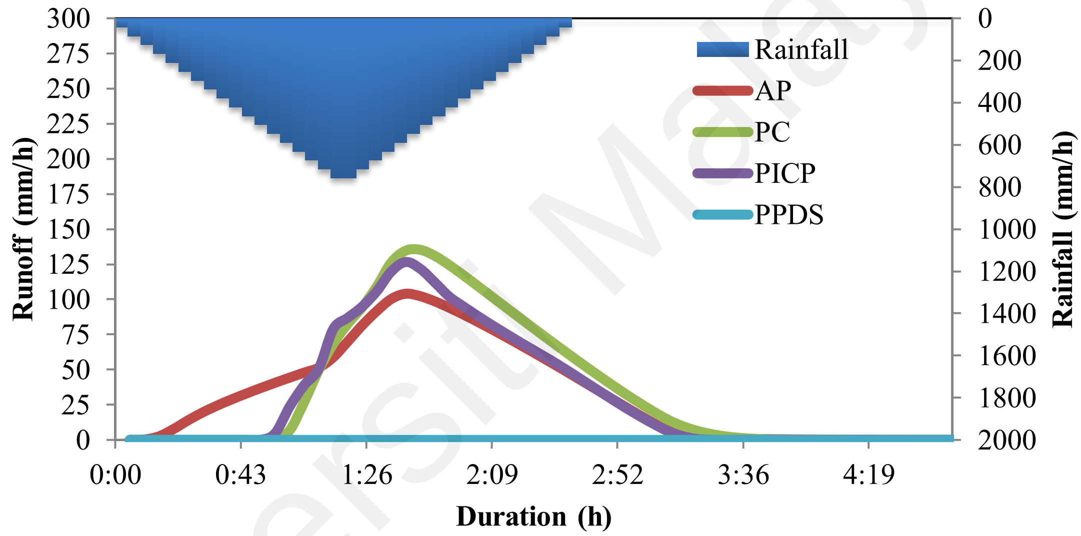


(a) Runoff responses for 15 minutes, 10 yr storm event

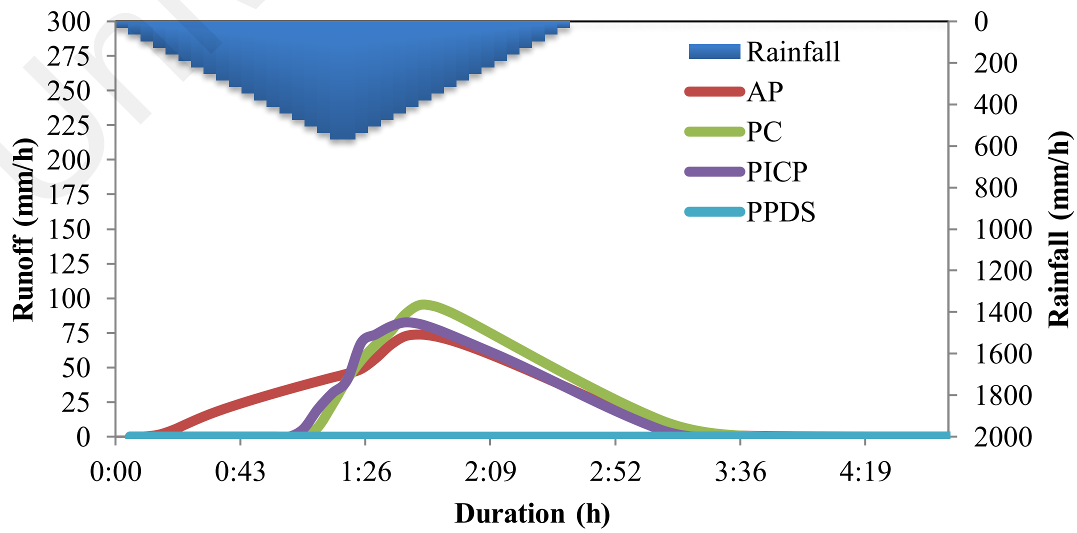
Figure 4.14: Runoff hydrograph for four different scenarios based on 10-yr and 100-yr ARI



(b) Runoff responses for 15 minutes, 100 yr storm event



(c) Runoff responses for 3 h, 10 yr storm event



(d) Runoff responses for 3 h, 100 yr storm event

Figure 4.15, continued

Additionally, the runoff reduction rate is recorded at about 60% for the events of 10-year ARI for 15-min duration. Nevertheless, the rate increases to almost 70% for a larger event. Hence, the PPDS has shown its ability to provide good performance for the large rainfall event because its special hollow cylinder feature allows it to hold more water than the conventional permeable pavements and thus minimizing the stormwater runoff.

Figure 4.15 portrays the runoff coefficient and peak flowrate of the four simulated pavements. For the case of AP, the runoff coefficient is 1.0 under all the rainfall conditions. However, for the remaining three scenarios, the runoff coefficient shows an increment from 10-yr ARI events to 100-yr ARI event, where the value ranges from 0.5 to 0.88 for PC, 0.61 to 0.90 for PICP and 0.04 to 0.074 for PPDS. The results are in agreement with Kim et al. (2014), Barszcz (2015), Elga et al. (2015) and Chui et al. (2016), who reported that the permeable pavement can be an effective approach in stormwater management planning as it exhibits a considerably low runoff coefficient. On the other hand, the heavy rainfall with a short duration (100-yr ARI, 15-minutes duration) produces a very high peak flow for the cases of AP, PC and PICP. The observation is in agreement with Qin et al. (2013) and Elga et al. (2015), who concluded that the permeable pavement is more influential for the rainfall events with low intensity, while its impact is marginal during the heavy rainfall events. Nonetheless, with the presence of hollow detention storage, PPDS provides an exceptional result where the peak flow has significantly reduced and the recorded value is much smaller than that for AP, PC and PICP under similar rainfall condition. Hence, it shows the improvement of PPDS in terms of peak flow reduction to the other conventional permeable pavements.

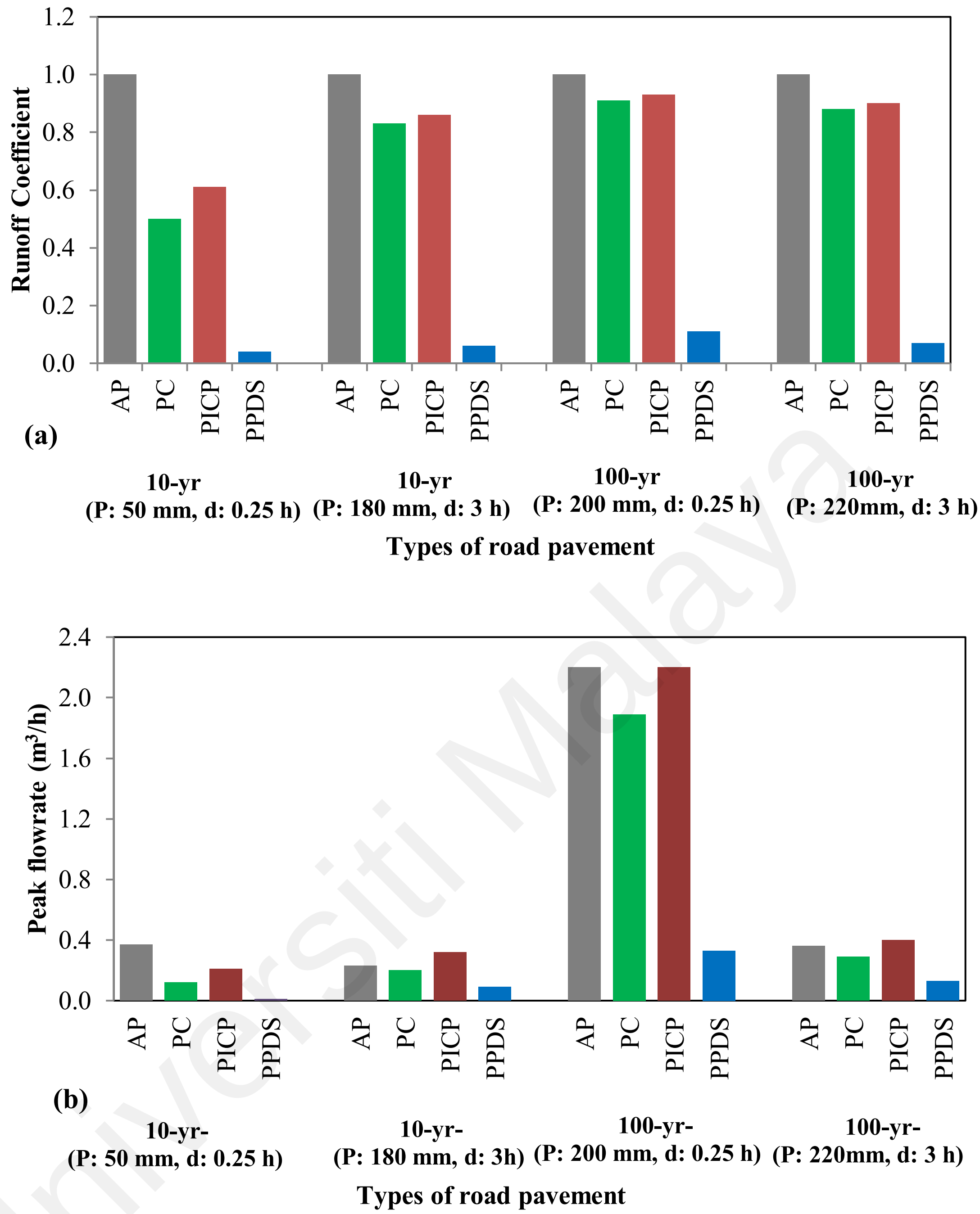


Figure 4.16: Performances in terms of (a) runoff coefficients and (b) peak flow for each simulated pavement under rainfall events of 10-yr and 100-yr ARI

Table 4.4 shows the infiltration time and infiltration loss for PC, PICP, and PPDS. The steady infiltration rate is set at 20 mm/h. Under the dry soil (unsaturated) condition, infiltration starts immediately. For the 15 minutes short-duration rainfall, it takes less time of about 2 h to 5 h to infiltrate to the ground. Meanwhile, for 3 h long-duration rainfall, it needs about 6 h to 8 h. An interesting observation is that the PPDS exhibits the shortest time for the infiltration processes, and it is followed by PICP and PC. Overall, the PPDS has the ability to infiltrate the collected rainfall about 1 hr faster than that of PC and PICP. Meanwhile, from the aspect of infiltration loss, PPDS shows the highest percentage at around 90% while for both PC and PICP, the percentage ranges from about 20% to 70%. This is mainly because the PPDS has a bigger retention capacity/ depression storage which is 30% larger than the conventional permeable pavements. The findings are in agreement with previous studies. Palla and Gnecco (2015) suggested that the performance of a LID unit can be improved by changing the retention. Furthermore, Zhang and Guo (2014) claimed that the actual infiltration rate of permeable pavement is controlled by the depression storage and void capacity. Damodaram and Zechman (2013) found that the storage-based (detention pond) LID measures exhibit a better performance in terms of effectiveness for the larger rainfall events if compared to that of infiltration-based. In sum, the PPDS displays a shorter infiltration time and greater infiltration loss, showing its effectiveness in infiltrating stormwater, and fulfill one of the main criteria to be served as a permeable paver.

Table 4.4: Infiltration loss and infiltration time of the simulated permeable pavements

Rainfall duration, ARI	Rainfall intensity (mm/h)	Time of infiltration (h)			Infiltration loss		
		PC	PICP	PPDS	PC	PICP	PPDS
15-min, 10-yr	50	5.15	4.11	2.07	73%	67%	98%
15-min, 100-yr	200	5.29	4.46	2.45	19%	17%	91%
3-h, 10-yr	180	8.25	7.45	5.35	36%	35%	95%
3-h, 100-yr	240	8.3	7.45	6.2	27%	26%	94%

4.5 Summary

This section mainly consists of three major parts, which are calibration of rainfall simulator, laboratory experiments using rainfall simulator, as well as the development of SWMM models and comparison of different scenarios. Firstly, a rainfall simulator was constructed in the laboratory to ease the experimental studies of the proposed PPDS and to provide continuously artificial rainfall supply during laboratory tests. The developed rainfall simulator has shown a good performance while applying to generate the designed artificial rain in terms of drop sizes, intensity and duration.

The rainfall simulator was then used to test the designed hydrological parameters of the PPDS. The resulting performance indicated that the PPDS has met the basic hydrological design considerations, from the perspective of permeability, infiltration rate, and storage/ detention capacity. Also, the hydrological performance was evaluated via the SWMM. The reporting outcomes of the SWMM were well-matched with that from laboratory works. A case study was then developed to assess and compare the hydrological impact imposed by PPDS with the existing condition and other conventional permeable pavements including PC and PICP. According to the resulting outputs, the PPDS exhibited the best hydrological performance from the aspects of runoff coefficient, peak flow reduction, infiltration time and infiltration loss among the examined scenarios. Hence, it can conclude that the PPDS was indeed practical in minimising runoff, reducing peak flow and increasing infiltration rate to achieve better stormwater management.

CHAPTER 5: CONCLUSION

5.1 Conclusion

Green pavement practices have become the main intention in most of the urban areas, as it plays a significant role in stormwater management to mitigate or prevent flooding issue caused by the rainwater.

The first objective, which was to construct a rainfall simulator for green pavement application and verify the chosen configuration for the natural rainfall replication, was successfully achieved. The overall performance of the rainfall characteristics including its spatial uniformity, raindrop size and velocities, indicated that the produced artificial rainfall can mimic the natural rainfall conditions very well, and thereby suitable to be used to test the performance of the proposed permeable pavement with micro-detention pond storage, PPDS.

The second objective of this study was to measure the optimal hydrological performance of the proposed PPDS. First of all, the reporting results showed that the proposed PPDS, with detention storage of 190 L/m^2 or 0.19 m^3/m^2 and a void ratio of 70%, achieved a minimal storage change of about 7%. This is because the system can release the stored water immediately to the underground, and thereby neither filling up of the depression storage nor generation of the runoff can be seen. In particular, the PPDS can accommodate the short duration (within 15 minutes) rainfall event up to 100-yr ARI, or those events with less than an intensity of 80 mm/h for a continuous 3 h duration. It reached its maximum limit (0.19 m^3/m^2) after receiving a continuous 40 minutes rainfall for an average of 5-yr to 10-yr average recurrence interval, ARI. In short, the PPDS met the hydrological design requirements for the events of 2-yr and 10-yr ARI. Furthermore, it was also found that the proposed PPDS can provide sufficient storage for an area that was larger than 4 m^2.

Nevertheless, with a constant depth and a similar amount of receiving water, an increase in both coverage area and thickness resulted in the increase in depression storage capacity.

The PPDS with the compacted common local subgrade soil has the ability to provide detention storage and release water for a period of fewer than 7 hr, indicating that the system can detain and release stormwater within a duration of 72 hr. In addition, the PPDS, applying as road pavement, can utilise subgrade soil of hydrologic soil groups, HSG, A and B to control the flood for the rainfall events of 10-yr ARI by providing a detention period of 24 h to 72 h. In general, to achieve a good performance, the PPDS should be designed properly from both the hydrological and structural aspects. In this case, based on the experimental results, the proposed PPDS with current design can provide a promising result in terms of storage capacity and infiltration rate. Hence, it can be concluded that the PPDS appears as an alternative as a sustainable green pavement approach, which can serve as a component in the road system and stormwater management.

The third objective was achieved where the hydrological impact of the proposed PPDS, was inspected by comparing it with the other permeable pavements using a software known as stormwater management model, SWMM. The software showed its ability to accurately describe the hydrological performance of PPDS through the statistical analyses in terms of relative percentage difference, RPD, and Nash-Sutcliffe efficiency, NSE, index. The SWMM was used to assess and compare the hydrological impact of PPDS and other road pavements (asphalt pavement-AP, pervious concrete-PC and permeable interlocking concrete pavement-PICP).

The observed results showed that, among the investigated scenarios, PPDS showed the best runoff reduction as well as the lowest runoff coefficient and peak flowrate. The

PPDS also demonstrated the fastest time taken for the infiltration process with the highest rate of infiltration loss. The results proved that with the presence of the subsurface micro-detention storage structure, PPDS as a modified permeable pavement showed an enhancement in terms of effectiveness to the conventional types.

5.2 Recommendations

This study can be further extended by focusing on the pre- and post-development conditions, particularly on the runoff responses, attenuation and storage, detailed construction, structural and stress analyses. To achieve the above-mentioned purpose, it is recommended that to have a detailed yet comprehensive field pilot study to investigate the full performance of the proposed PPDS.

Through this study, although the proposed system is ready for commercial use; however, there still have some specific issues, which require further research efforts, such as pollutants removal, clogging issues, maintenance approaches and frequencies, and designed lifespan. Proper maintenance is essential for PPDS to solve the clogging issue, regain its effectiveness in terms of infiltration and finally extend its lifespan. Another important issue that should be concerned is, based on the current PPDS design, the micro-detention storage although having a high void content and acting as a reservoir, it contributes to a reduction in terms of mechanical strength. Also, it is suggested that the future study can concentrate on the analyses of topographical features, identification of appropriate drainage areas, and determination of runoff coefficient by conducting land use/land cover analyses of the flood-prone areas.

On the other hand, the modelling works can be extended based on the data collected from this study in order to provide a better yet deeper understanding of the proposed PPDS, such as its initial clogging and sedimentation process. Through this, a more accurate prediction on the system performance under different conditions, either normal field condition or with varying inflow patterns can be obtained. Lastly, it is also important to further this study from the perspective of economic and socio-economic aspects. Assessment can be done based on the integrated cost-benefit analyses of the proposed PPDS with the combination of various LID practices. In the context of socio-economic aspects, the acceptance level of the stakeholders and community on this modified permeable pavement will be an interesting research topic. Also, more efforts can be taken to evaluate the related sustainability potential such as damage reduction to provide a stronger fact and support for the application of the proposed PPDS.

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