



Faculty of Engineering

**Application of StormPav Modules as
Alternative Home-Based On-Site Detention System**

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**Doctor of Philosophy
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Alternative Home-Based On-Site Detention System

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A thesis submitted

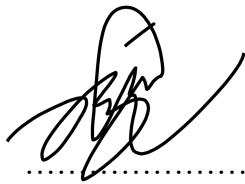
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Faculty of Engineering
UNIVERSITI MALAYSIA SARAWAK
2023

DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.


.....

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ABSTRACT

On-site stormwater detention system within a residential property is meant for an environmental protection device that temporarily stores stormwater within the property lot to mitigate flash flood, particularly during rainy seasons. A field test is constructed in a real-life terrace house's car porch with a 4.40 m (W) x 4.70 m (L) x 0.45 m (D) tank filled with precast-concrete modular units (StormPav) with an effective storage volume of 3.97 m³. Inflow downpipe is installed to the detention tank and connected to the roof gutter which receives rainwater from the house roof; while a pipeline is installed to discharge outflow from the tank to the house perimeter drain. It has recorded sixteen observed storm events coincided with the 2019/2020 Northeast Monsoon that consist of rainfall depth categories ranging from 0-20 mm, 20-30 mm, 30-40 mm, 40-50 mm rainfall depths. Another four historical storm events that coincided with Northeast Monsoon seasons from 2015-2017 are sourced to augment the analysis. The Kolmogorov-Smirnov goodness of fit tests between the observed and modelled cumulative distributions have produced 0.01-0.14 maximum vertical distances that are lower than the 0.41-0.68 critical values which indicating close matches. Outcomes from the validated model have suggested to use an outlet size of 0.055 m. By combining the analyses from the field test and SWMM model, it is found the home-based system is able to contain all stormwaters of the rainfall depths mentioned above. Collected field data from a 95m² roof catchment is used to model an OSD system with 50m² and 150m² roof catchments. The 150m² roof catchment had steep line graphs and the OSD system could handle up to 30mm rainfall, but had the highest water detention and attenuation rate (65%). The 50m² roof catchment had the lowest attenuation rate (15%) due to limited detention.

Keywords: Field test, orifice, rainfall, StormPav, SWMM.

**Ujikaji Lapangan Penahanan Di Tapak Berasaskan Rumah Menggunakan Sistem
"StormPav Green Pavement"**

ABSTRAK

Kajian ini meneroka sistem penahanan air hujan di tapak harta perumahan yang bertujuan melindungi alam sekitar dengan menyimpan air hujan secara sementara untuk mengurangkan banjir kilat semasa musim hujan. Ujian lapangan telah dibina di tepi rumah teres sebenar dengan tangki 4,40 m (W) x 4,70 m (L) x 0,45 m (D) yang diisi dengan unit modular konkrit pracetak (StormPav) dengan jumlah simpanan yang berkesan 3.97m³. Saluran air masuk dan keluar disambungkan untuk menerima air hujan dari bumbung rumah dan mengalirkan air keluar dari tangki ke longkang perimeter rumah. Sebanyak enam belas peristiwa hujan dirakam semasa Musim Timur Laut 2019/2020 dalam kategori kedalaman hujan 0-20 mm, 20-30 mm, 30-40 mm, dan 40-50 mm. Empat lagi peristiwa hujan bersejarah dari tahun 2015-2017 yang bertepatan dengan Musim Timur Laut juga digunakan untuk analisis tambahan. Ujian kesesuaian keseragaman Kolmogorov-Smirnov antara taburan kumulatif yang diperhatikan dan model yang dimodelkan telah menghasilkan jarak maksimum 0.01-0.14 yang lebih rendah daripada nilai kritis 0.41-0.68 yang menunjukkan kesesuaian yang rapat. Melalui gabungan analisis dari ujian lapangan dan model SWMM, didapati sistem berdasarkan rumah mampu memuat semua air hujan pada kedalaman yang disebutkan di atas. Data lapangan yang dikumpulkan daripada kawasan penampungan bumbung seluas 95m² digunakan untuk memodelkan sistem OSD dengan kawasan penampungan bumbung seluas 50m² dan 150m². Kawasan penampungan bumbung seluas 150m² menunjukkan graf garisan yang curam dan sistem OSD mampu menangani hujan pada kedalaman 30mm, tetapi mempunyai kadar penahanan air dan pengurangan yang tertinggi (65%). Kawasan penampungan bumbung seluas 50m²

menunjukkan kadar penahanan yang paling rendah (15%) kerana had penahanan yang terhad.

Kata kunci: *Ujian lapangan, orifis, hujan, StormPav, SWMM.*

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LIST OF ABBREVIATIONS

ARI	Average Recurrent Interval
CFD	Computational Fluid Dynamics
DID	Department of Irrigation and Drainage
MSMA	Manual Saliran Mesra Alam
OSD	On-site Stormwater Detention
SWMM	Storm Water Management Model
WSUD	Water Sensitive Urban Design

CHAPTER 1

INTRODUCTION

1.1 Background

As a piece of land experiences urbanization, the surface of the land changes from forest to physical infrastructures like buildings and roads. Referring to Figure 1.1, a land in its natural form, which is covered with vegetation, 50% of the rainwater is being infiltrated into the soil layer and parts of the rainfall is taken up by the plant roots. As such, surface runoff from forested land is as low as 10%. However, as the vegetation is replaced with physical structures, the rainwater is blocked by the buildings and roads to get into the soil layer. Instead, 55% of the rainwater accumulates on the ground surface. In this case, the surface runoff due to physical development is high (Saraswat et al., 2016).

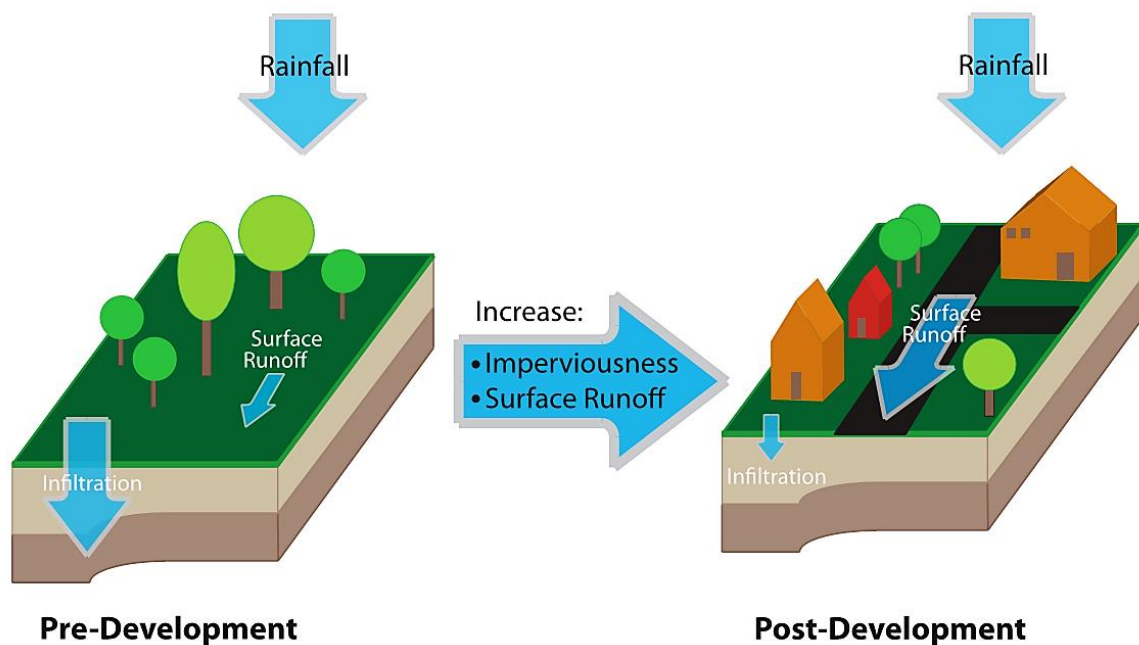


Figure 1.1: Impacts of Urbanization (Avenue Consultants, 2019)

High amount of surface runoff may lead to environmental problems, such as flash flood, erosion, and pollution. There is a need to contain the high amount of surface runoff. Engineers are trying to direct the accumulated surface runoff on ground surface to structures mimicking the functions of natural soil layer and plant roots. With parts of water being captured by the intended structures, the amount of surface runoff is proven to reduce to near pre-development condition (Hou et al., 2022). Many types of structures have been tried on which these are further described in Chapter 2.

On-Site Detention (OSD) is one of the measures creating man-made structures in the urban environment to control stormwater surface runoff. OSD plays a role to detain a portion of the surface runoff, as mentioned above, so that the surface runoff at one time could be reduced by lowering the peak runoff. The design and structure of OSD changes over time, in which big structures are favored in the early days, and then later smaller structures are introduced. Another problem arises in the construction of these structures as the availability of open land is increasingly difficult to come by (Muangsri et al., 2022). The trend nowadays leans towards the concept of sponge city which small pockets of water detention structures are scattered along the stormwater flow paths (Fu et al., 2023). These structures are small and designed to merge with urban infrastructures. In another word, the structures are designed to be multi-purpose. Take the focus of this study, a residential car porch is a structure for housing vehicles, and at the same time, tried for water detention structure underneath it.

In the case of a housing estate, if each house could detain a portion of stormwater from the premise, the accumulated effect from the whole housing estate would have an effective reduction of urban runoff. StormPav Green Pavement System, or in short,

StormPav, could function as a form of OSD as reported in Mah et al (2014). The concrete pieces that make up the StormPav, provide empty spaces in between the pieces to store water (Figure 1.2). It has three layers, in which the top and bottom layers are hexagonal plates with service inlets; while the middle layer is packed with hollow cylinders. In line with the concept of OSD, the middle layer plays a major role in allowing stormwater from the ground surface to be stored within this layer and to be discharged at a slow rate through an outlet structure.

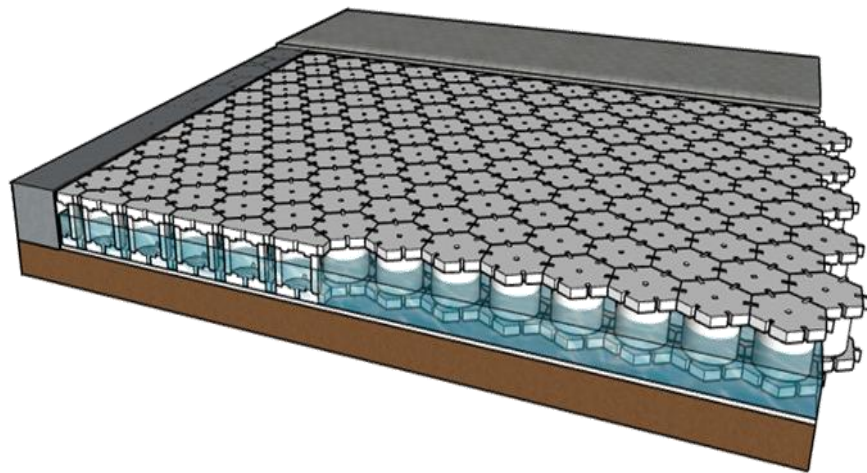


Figure 1.2: StormPav Green Pavement System (Liow et al., 2019b)

OSD could appear in different forms. Apart from road, StormPav could be applied as home-based OSD. The idea is to make use the space provided by residential car porch. Mah and Ngu (2017) reported that a sizable car porch area in each single home could be put into good use by having an underground OSD to detain stormwater from residential roof. An example of such a system is depicted in Figure 1.3. A surface area of 4.6m x 4.3m was identified as the optimum size fitting two cars most commonly found among malaysian residential houses. It was concluded that the use of StormPav as the underground OSD is practical for managing urban stormwater.

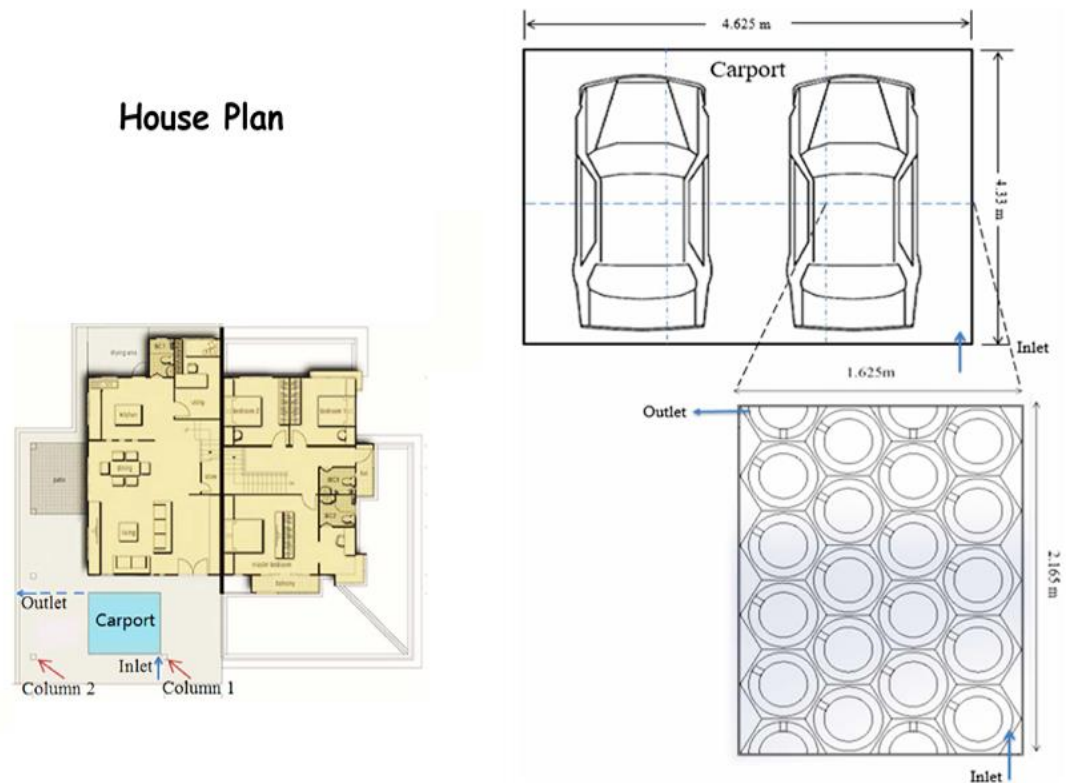


Figure 1.3: StormPav as Home-Based OSD (Mah and Ngu, 2017)

The home-based OSD mentioned above had been studied on the basis of computer simulations using Storm Water Management Model (SWMM). The computer model could not provide a successful quantitative result if it could not correspond directly to reality (Kamphuis, 2010). It was followed by a small-scaled physical model that was one sixth (2.2m x 1.6m) in relation to the full tank (4.6m x 4.3m) (Figure 1.3). Both studies were tested based on design rainfall. It was a process involving statistical analysis and probability of historical rainfall to classes of rainfall intensity. Only 10-year Average Recurrent Interval (ARI) was considered for minor system in residential area. The system was designed to withstand 15 minutes of continuous rainfall under the said ARI (Mah, 2016). However, the system had not been tested under actual rainfall, particularly during the rainy season.

1.2 Problem Statement

While there have been studies on StormPav as an underground on-site stormwater detention (OSD) system, there is limited research on its practical application as a home-based OSD solution in residential settings under actual rainfall conditions. Previous investigations have mostly relied on computer simulations and small-scale lab data, leaving a gap in understanding StormPav's real-world performance and effectiveness in mitigating stormwater runoff in car porch of residential houses. Hence, this research is exploring StormPav as a home-based OSD system in residential settings under actual rainfall conditions. The hypotheses put forward are:

- a) Field testing could better describe the actual performance of StormPav than the numerical and small-scale lab data from the previous studies;
- b) With field measurement, validation of the SWMM model is able to be performed to determine the degree to which the SWMM model is an accurate representation of the real world.

By conducting field tests and computer modelling, this research shall provide practical insights into StormPav's performance and its potential application in mitigating stormwater runoff (Landahl and Mollo-Christensen, 1992; Sargent, 2013). The results will contribute to the existing knowledge of stormwater management and offer valuable guidance for future sustainable urban development. The following shortcomings of the system are identified:

- a) How the system responses to actual rainfall events, is unknown;

- b) The stormwater characteristics, due to actual rainfall from catchment area to the multiple-chamber detention storage provided by StormPav, are unknown;
- c) The flow mechanism due to actual rainfall among the StormPav modular units, in terms of its flow and water level in tight spaces, is unknown;
- d) While the system had been modelled to reduce urban runoff, performance of the system due to actual rainfall is yet to be validated.

1.3 Objectives

The aim of this study is to characterize the stormwater detention under residential car porch by using a field test. The field test is set up in a house using StormPav Green Pavement System to collect first-hand data on rainfall, flow and water level acting upon the said system. This is followed by a computer modelling of the system to better describe the system's behaviour. The objectives of this study are:

- a) To analyse the responses of system to actual rainfall events;
- b) To analyse the catchment area to detention storage characteristics;
- c) To analyse the relationships of flow and water level within the system;
- d) To evaluate the performance of urban runoff reduction.

1.4 Scopes of Work

This study covers:

- a) Rainfall patterns are highly influenced by geographical location and climate condition. As the selected area is located at Samarahan, Sarawak, the rainfall patterns

are expected to have characteristics of coastal zone under equatorial climate, in which Northeast Monsoon is significant to bring in high amount of rainfall;

- b) Catchment sizes that intercepted the rainfall, determine the sizes of stormwater storage facilities. A single unit of a terrace house has limited catchment and storage sizes which are explored on its relationships. Key hydrologic parameters, including rainfall depth (mm), stormwater flow (m^3/s), and water level (m), are included in the field testing and data collection process;
- c) In a short-term monitoring, collected hydrological data may be limited. The computer model developed using SWMM version 5.0 could be validated with the collected data and further simulations using the model could augment the analyses.

1.5 Structure of Thesis

The thesis is divided into five chapters. Chapter 1 gives brief introduction of the study, problem statement, objectives, and scopes of the study. Chapter 2 gives reviews from the literature on the OSD, concept of StormPav Green Pavement as an OSD, past studies of StormPav as well as case studies of hydrological and hydraulic properties of OSD. Chapter 3 gives the methodology used in the current study, field test set up, as well as the sensors set up. Chapter 4 presents the results obtained from field testing, stormwater characteristics and performance of urban runoff reduction. Chapter 5 concludes the findings and presents recommendations of the future works.

CHAPTER 2

LITERATURE REVIEW

2.1 On-Site Detention

Naturally, soil layers absorb much of the stormwater. However, physical development brought by human civilization has reduced the natural function of soil layers when more and more land surfaces are covered with impervious land covers (Konrad, 2003; Gregory et al., 2006; Singer, 2006; Scalenghe and Marsan, 2009; McGrane, 2016). As such, the stormwater that could not be infiltrated to the ground is causing environmental problems (He et al. 2011; Jacobson, 2011; Proenca and Ghisi, 2013; Peter et al., 2013; Farmani and Butler, 2014) like flash flooding and erosion. Furthermore, with more and more rain predicted in the tropical region due to climate change (Sun et al., 2014; Xie et al., 2014; Lo et al., 2015), the volume of stormwater is expected to rise in the years to come (Bacmeister et al., 2018; Fix et al., 2018). As a way to combat the deterioration of this issue, manmade structure is introduced in the urban environments to mimic the water storing capacity of natural soil layers (Lawrence et al., 1996; Mascararenhas et al., 2005).

OSD is a stormwater management practice that is most often employed in urban stormwater drainage systems to control the runoff discharge rate of development sites (Weiss et al., 2006; Ronalds et al., 2019). It is generally designed to have a storage with a flow control device to control the discharge to an acceptable rate (DID, 2000). The amount of stormwater leaving the site is not reduced but released gradually when downstream drainage capacity becomes available.

OSD is one of the most effective solutions to manage stormwater runoff (Weiss et al, 2006; Ronalds and Zhang, 2019). It is first introduced and widely implemented in country like Australia as to provide solution to the consequences of urbanization and industrialization (Phillips, 1987; O'Loughlin et al., 1995; Phillips, 1995). Since the introduction of 'Best Management Practices' (BMPs) and 'Sustainable Cities and Development' (Urbanos and Stahre, 1993; Butler and Parkinson, 1997; Hamel et al., 2013), OSD has emerged as a popular research topic. Today, drainage engineers tend to design localized control structure (Niemczynowiz, 1999; Petrucci et al., 2012), for example OSD (Lawrence et al., 1996; DID, 2012) than centralized large size storage structures such as detention basins (Vorogusshyn et al., 2012), and wet ponds (Ahmad et al., 2014) which are popular in the past. The shifting to localized control structure is due to the fact that, it is not possible to progressively augment drainage system while resources of empty land is limited particularly in urban compounds.

OSD can be configured as above ground storage, below ground storage or a combination of both as depicted in Figure 2.1 (DID, 2000). The selection of the type of storage is based on site condition as well as requests from clients. Both types of storages present respective pros and cons.

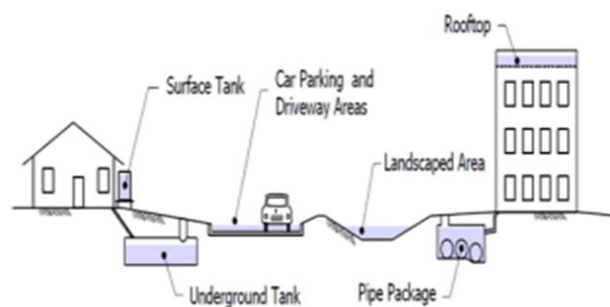


Figure 2.1: Above and Below Ground OSD Facilities (DID, 2000)

OSD facilities can also be classified as on-line storage, off-line storage or conveyance storage. On-line storage (Figure 2.2(a)) is a facility that the stormwater drains directly within the detention tank via a structural control facility. Off-line storage (Figure 2.2(b)) is a facility that diverts the stormwater from the detention tank. Apart from that, conveyance storage can also provide detention characteristics. In this case, slow-flowing conveyance caused by rougher channels or flatter slopes can significantly retard the build-up of flood peaks (DID, 2000).

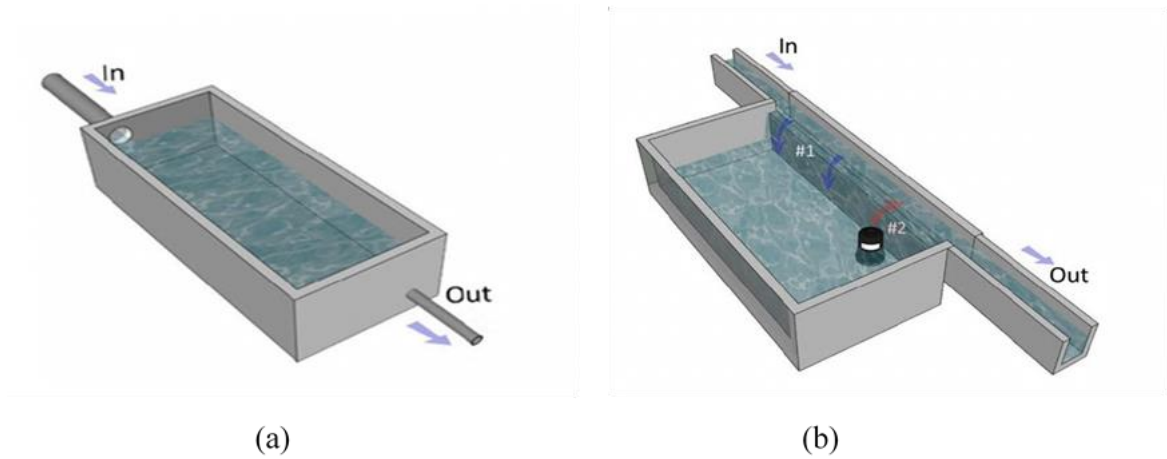


Figure 2.2: (a) Online Detention System, (b) Offline Detention System (PUB, 2021)

The discharge flows out of the detention system can be performed either by gravity or through pumping. Pump is used when the head difference is not feasible due to the site constraints to allow water flow by gravity. In this current study, StormPav as an OSD is categorized as below ground storage and on-line storage that discharges stormwater by gravity. Further details of the OSD are elaborated in the next section. The general OSD design is presented in Section 2.2.

2.2 StormPav Green Pavement

StormPav is an Industrialized Building System (IBS) product patented by Mannan et al (2016). A single unit is made up of three layers, namely two plates for the top and bottom

layers; a cylinder in the middle layer as shown in Figure 2.3. The detailed dimensions of the StormPav unit are illustrated in Figure 2.4. Top layer consists of a plate 75mm in thickness to support vehicle load. A cylinder 280mm (dia) x 300mm (h) stores water at a capacity of $0.19\text{m}^3/\text{m}^2$ of pavement area (Mah, 2016). Each cylinder is characterized with three side inlets to allow water to flow in and out of the cylinder. Whilst, bottom layer consists of a plate 75mm in thickness. Similar to the top layer, a 40mm service inlet on the plate allows infiltration into the soil beneath it. When multiple units of StormPav are put together and bordered them with ground beams, it forms a subsurface OSD to detain stormwater. The spaces provided between StormPav also contribute to additional volume to store stormwater. Each unit of StormPav has the capability to support up to 10 tons of load compared to the required 4 tons for normal practice (Mah et al., 2018c).

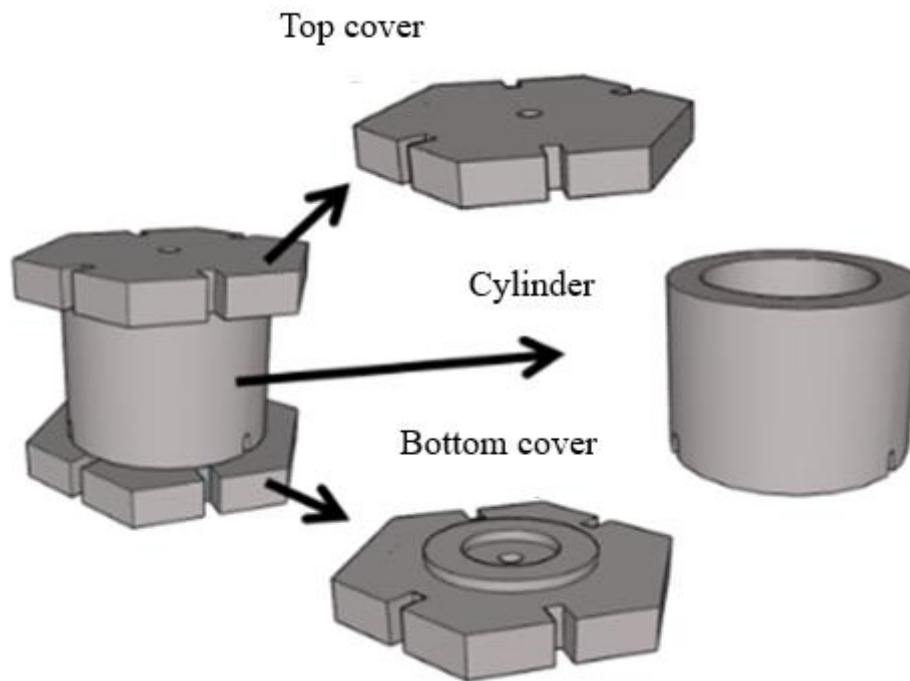


Figure 2.3: Component of a single StormPav model

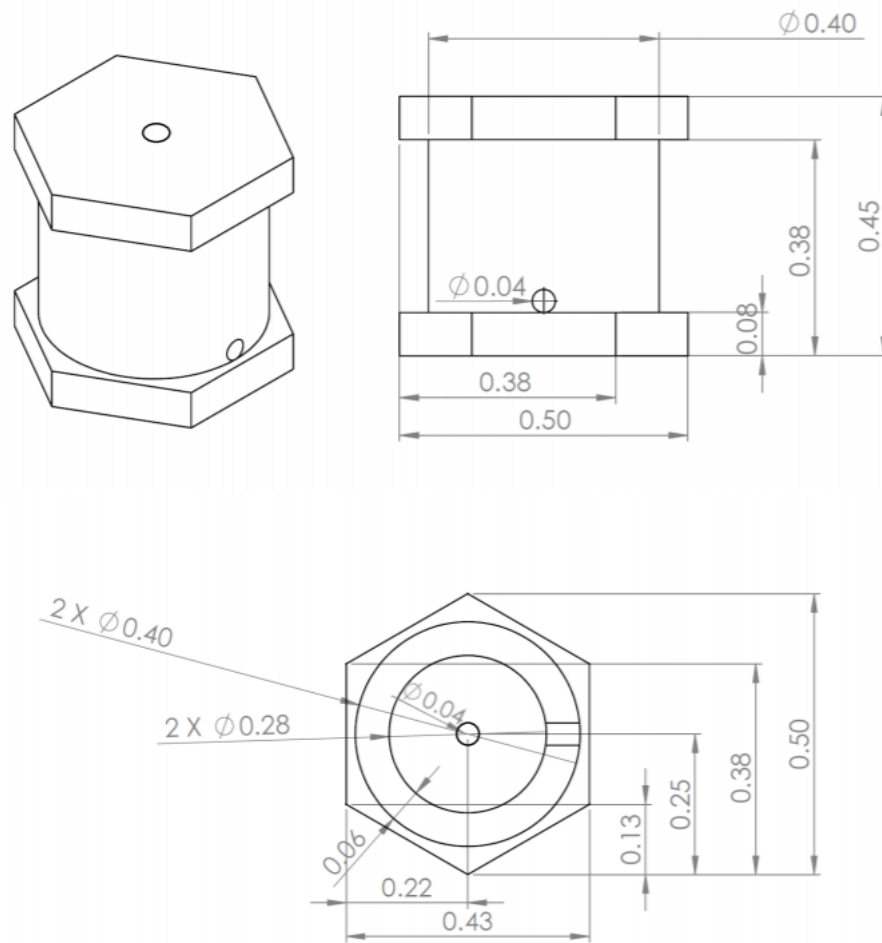


Figure 2.4: Technical Drawing of StormPav Unit

StormPav design revolves based on the way in which OSD stores stormwater runoff from its surrounding drainage catchments. The way of stormwater flows in and out of the system is literally based on the intended implemented purpose for a project/study (Section 2.2.1). In this current project, StormPav as the home-based OSD, the design of the OSD is further explained in Chapter 3. The following section presents the past studies of StormPav.

2.2.1 Past Studies of StormPav

To date, past studies of StormPav are divided into two main applications, namely, road-based and home-based applications. Generally, the concept of StormPav as road-based

application and its water balance equation are showed in Figure 2.5 and Equation 2.1 respectively.

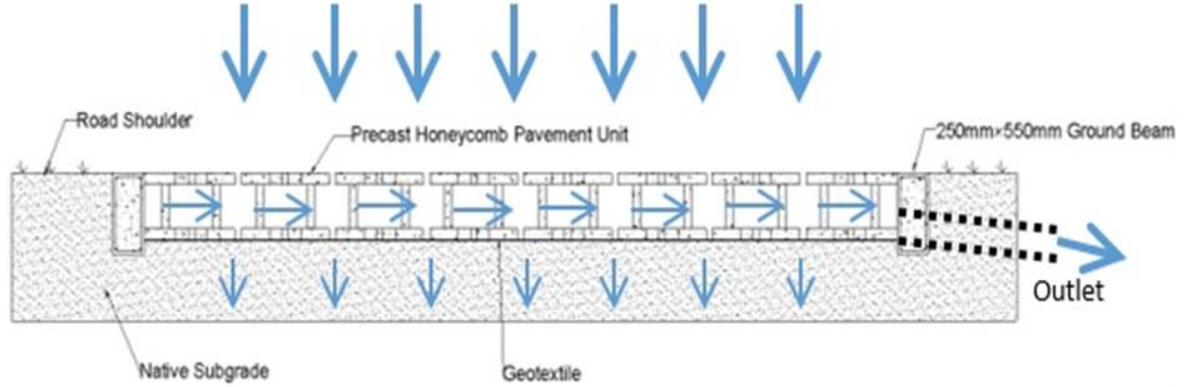


Figure 2.5: Concept of StormPav as Road-Based Application

$$\frac{dp_1}{dt} = P - I - Q - E \quad \text{Equation 2.1}$$

where

p_1 = depth of water in storage layer (m);

P = surface permeation rate (m^3/s);

I = native soil infiltration rate (m^3/s);

Q = outflow rate (m^3/s);

E = surface evapotranspiration rate (m^3/s).

Generally, flow mechanism of road-based application includes the stormwater permeates into the system through service inlets on the top plates, and for certain cases, additional stormwater flows into the system through a connection of inlet structure. Horizontal and vertical flow are involved within the system. Stormwater is expected to detain within the system before being discharged out of the system either by infiltration, evapotranspiration and/or a primary outlet structure.

Potential of road subsurface OSD by Mah (2016) presented the origination of StormPav as an OSD. StormPav was successfully applied through a system using SWMM. It was confined to a road catchment of 3m wide and 1.3m long as showed in Figure 2.6. It was reported that the storage height of 0.3m as the middle part was able to fully capture 3 hours continuously 10-year ARI design rainfall. The SWMM model was then retested with past storm events, and it proved that the model was able to fully detain the subjected rainfalls with slight surface ponding predicted.

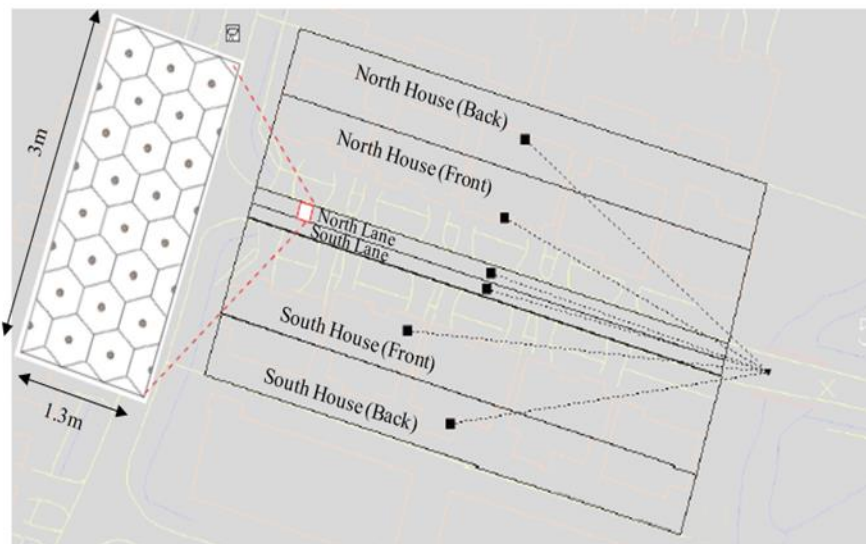


Figure 2.6: Disconnected System Model (Mah, 2016)

Study was also conducted to augment drainage system in the old town of Kuching, Sarawak (Mah et al., 2018a). This study focused on a solution to improve the inability to manage urban runoff at Padungan area, Kuching City. Critical flash floods frequently happened in Padungan area due to old drainage system. Due to land space constraint, the proposed solution was to utilize the backstreet of the shophouse (Figure 2.7) to place the StormPav.

Stormwater runoff of the surrounding area was directed to the StormPav by perimeter drains while runoff on the StormPav permeated into the system through service inlets on the

top plates. SWMM simulation (Figure 2.8) was performed using 15-minute, 10-year ARI design rainfall and it was found that the modelling of existing drain gave an estimation of peak discharge of $0.975\text{m}^3/\text{s}$. On the other hand, by installation of StormPav Green Pavement as an OSD with a controlled discharge rate of $0.088\text{m}^3/\text{s}$, the peak discharge was reduced by 30%. Thus, from the analysis, applying OSD in the form of permeable road was practical to solve the issue.



Figure 2.7: Proposed StormPav at Back Street of Shophouse (Mah et al., 2018a)

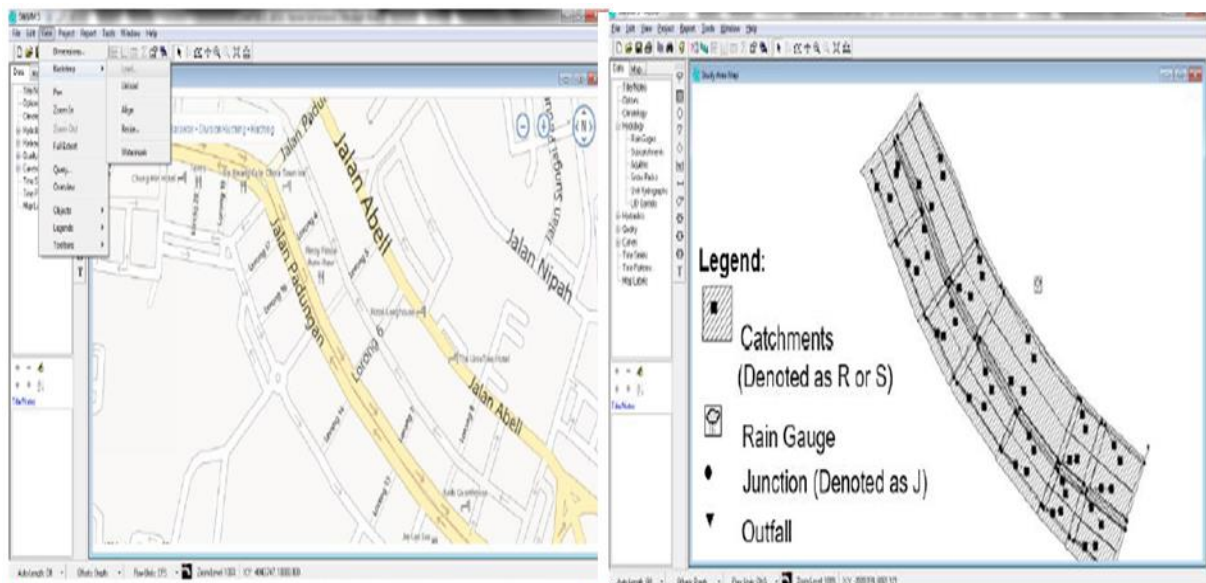


Figure 2.8: Conveyance Network with Drainage System (Mah et al., 2018a)

Pilot Project Road

Apart from that, a small-scale pilot study of StormPav (Mah et al., 2018c) was carried out after StormPav had been tested using computer simulation and laboratory observation. A 10m x 4m rural road was constructed on shallow peat in Kampung Mang, Sarawak in collaboration with JKR Sarawak. The idea was to have a permeable road surface to allow stormwater to store water, meanwhile, to provide shallow inundation to conserve peat. Stormwater runoff left the system through infiltration into the under-laying peat soil.

This pilot study reported the construction process (Figure 2.9), first hand observation of its stormwater impact, and road subsidence for four months. Cracks were observed at the flanges of the top hexagonal plates due to the facts that the concrete pieces were casted by hand which created uneven surfaces on the plates. However, no cracks observed in the middle and bottom layers. As such, as a way to improve the concrete pieces is to have an automated machine to fabricate better quality pieces.

In terms of stormwater impact, results showed that the stormwater runoff was well captured within the system and discharged away via the surrounding peat. No stagnant pool of water was found on the next day that could invite breeding ground for mosquito. In terms of road subsidence, it was found that the compaction happened during the first 7 days; then, the road and peat system seemed to stabilize. During the observation days, fluctuations of StormPav road levels were remarked below $\pm 1\text{cm}$ which were within the allowable limit.



Figure 2.9: Assembling of StormPav Road, (a) Levelling of Soil Level, (b) Arranging of Bottom Plates, (c) Arranging of Cylinders, (d) Arranging of Top Plates (Mah et al., 2018c)

Commercial Area

The StormPav was then explored of conveyance properties as an added value to it. A road made of StormPav was not only designed for road transportation and stormwater detention but also for conveyance. Stormwater perimeter drains around property could be replaced by StormPav. A case study (Figure 2.10) of a typical commercial area (0.399ha) was modelled to determine the conceptual model. 1D (SWMM) and 3D (SolidWorks Flow Simulations) modelling were incorporated in this study. Stormwater from roof flowed into

the StormPav through downpipes and stormwater on the pavement itself permeated into the system through service inlets of the top plates. Stormwater flowed out of the system through a primary outlet structure which was designed at the end of the structure. In such a case, additional parameter of inflow rate from downpipes shall be added to water balance equation. With appropriate inlet and outlet design, results concluded that adding conveyance properties to the StormPav was possible. The StormPav was successfully modelled with 10-year ARI design rainfall with storm durations up to 3 hours and attenuation of discharge at the outfall was reported.

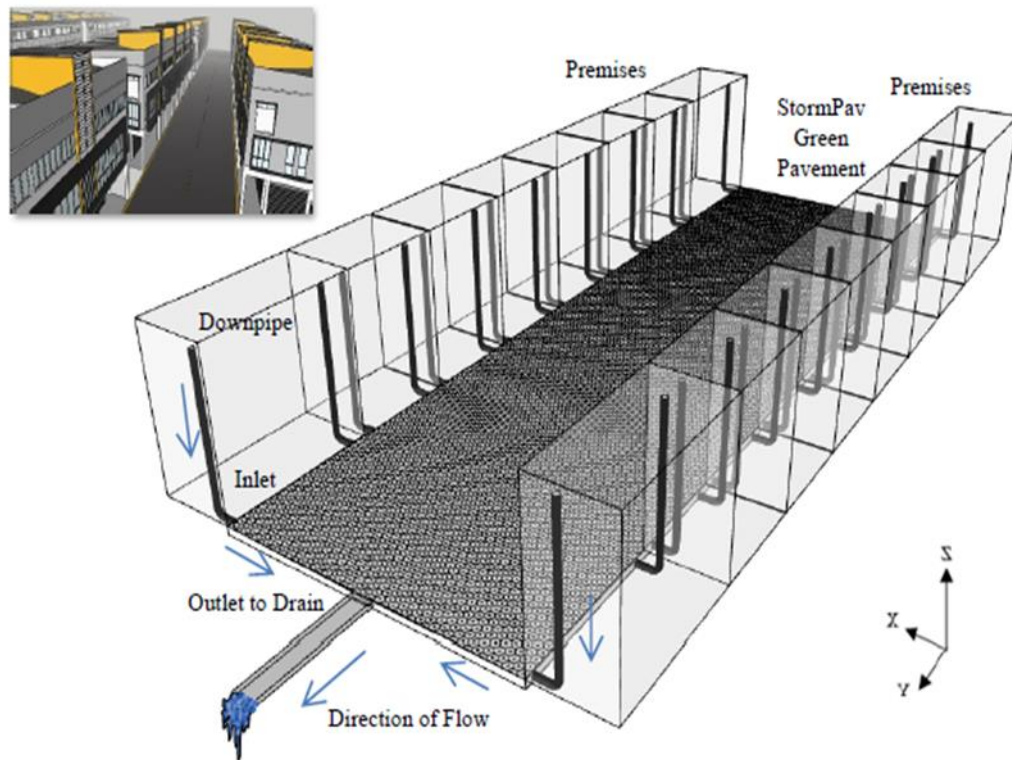


Figure 2.10: Conceptual Design of StormPav in “A Road that Flows Stormwater” Study (Liow et al., 2019a)

Besides that, a study on stormwater detention in road shoulder using StormPav was carried out by Lui et al. (2019). StormPav system as combined road shoulder and stormwater detention structure was studied using SolidWorks Flow Simulation. A road shoulder of 1.5m x 6m dimension in a typical residential compound was taken as case study (Figure 2.11).

This application was tested by simulating flow through the multiple chambers within the StormPav system via road curb opening inlet and outlet. Distance of inlet and outlet was simulated and analyzed for 5-minute, 10-year ARI design rainfall. Results reported that incorporating StormPav to a road shoulder to detain stormwater was possible. The apart the distance between inlet and outlet, the more the distributed flow could be achieved.

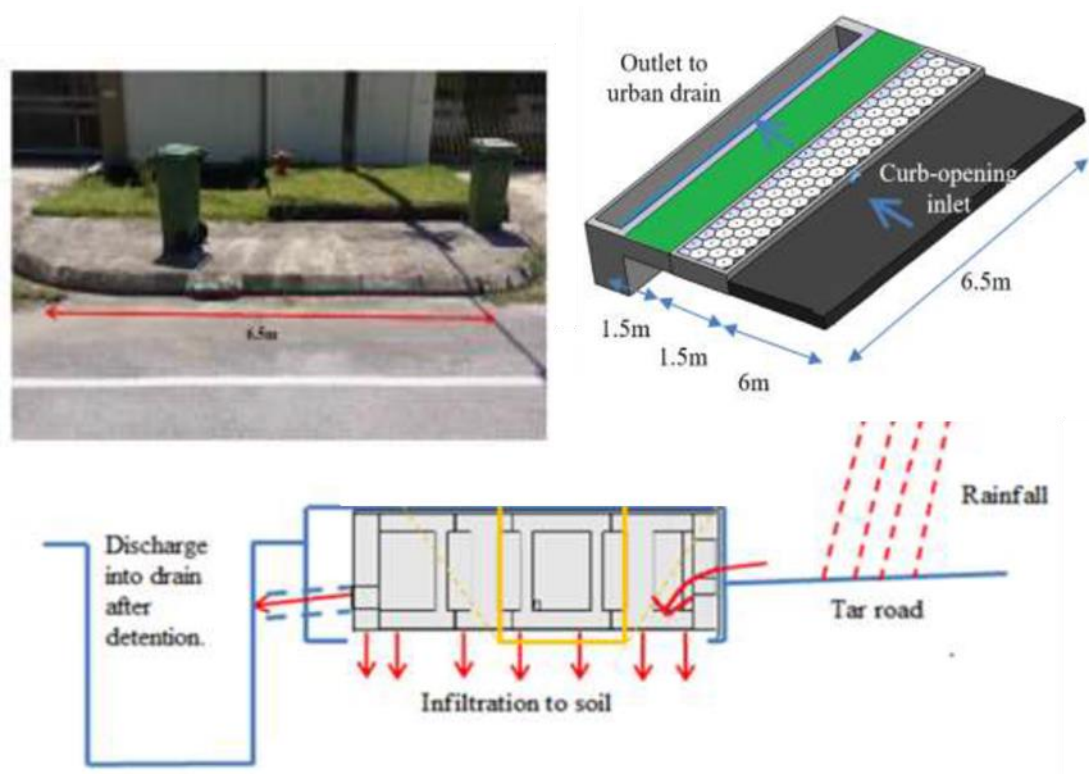


Figure 2.11: StormPav as Road Shoulder (Lui et al., 2019)

Home Based

In an effort to diversify the application of StormPav, the research team explores on home-based application. General concept of StormPav as home-based application and its water balance equation are shown in Figure 2.12 and Equation 2.2 respectively.

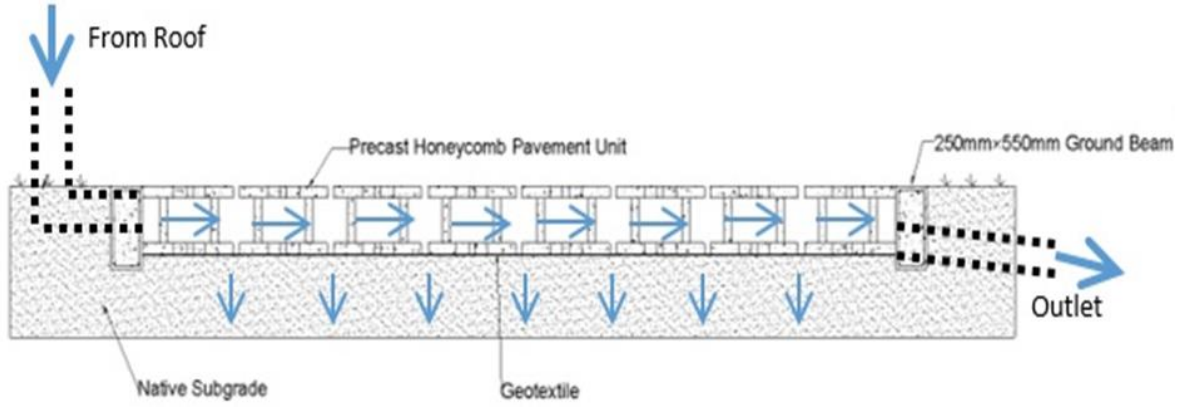


Figure 2.12: Concept of StormPav as Home-Based Application

$$\frac{dp_2}{dt} = D - I - Q - E \quad \text{Equation 2.2}$$

where

p_2 = depth of water in storage layer (m)

D = inflow rate from through downpipes (m^3/s)

I = native soil infiltration rate (m^3/s)

Q = outflow rate (m^3/s)

E = surface evapotranspiration rate (m^3/s)

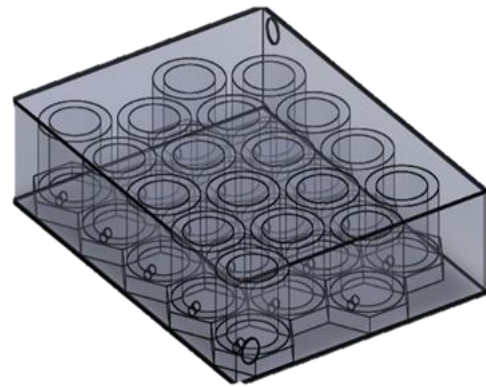
The flow mechanism is modified compared to road-based application, which includes the stormwater flows into the system through a connection of inlet structure (downpipe). Stormwater is expected to detain within the system before being discharged out of the system either by infiltration, evapotranspiration and/or a primary outlet structure.

A study on individual lot on-site stormwater detention underneath residential car porch was done by Ngu et al. (2016). In this study, a laboratory study (Figure 2.13(a)) and CFD simulation (Figure 2.13(b)) were carried out to analyze the flow characteristics of

stormwater directing from 95m² roof catchment to the StormPav system through downpipe. The characteristics of multi-unit chambers provided by StormPav was designed as a subsurface OSD underneath residential car porch to overcome the hollowness in the middle section of a long span OSD tank. Meanwhile, it supported loads atop. The OSD was designed to fully capture 15-minute, 10-year ARI design rainfall from roof catchment. With the effort of simulation, Figure 2.14 depicts how the water changed its pattern from turbulent to laminar flow. The turbulence in OSD was concentrated in the first 433mm. Findings reported that, the OSD was safe to store stormwater from the roof catchment, congestions at the inlet regions were short lived and overflowing from the system were absent in all situations.



(a)



(b)

Figure 2.13: (a) Laboratory Study (b) Simulation Study (Ngu et al., 2016)

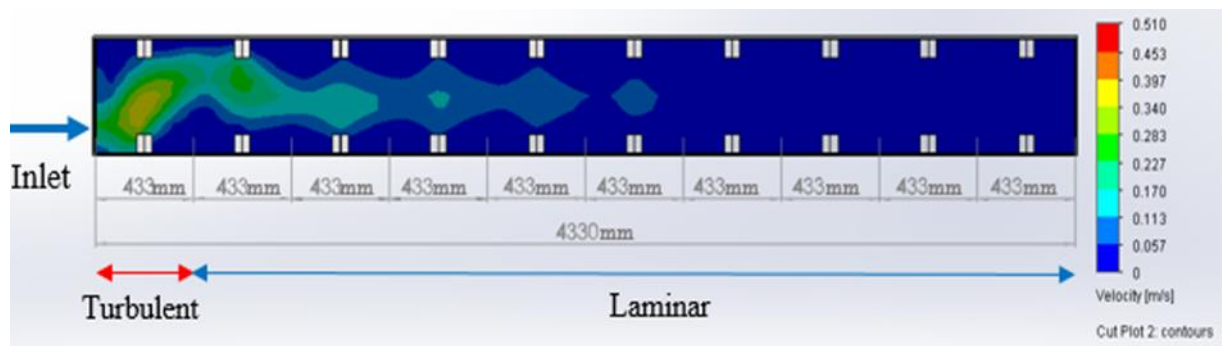


Figure 2.14: Front Cut Plot of The StormPav (Ngu et al., 2016)

Summary

The past studies of StormPav are summarized with its applications in **Table 2.1**.

Table 2.1: Summary of Past Studies of StormPav

Road-based application	Studies	Rainfall	Catchment	OSD	Tool	Remarks
	Mah (2016)	3-hour 10-year ARI design rainfall	3m x 1.3m road catchment in a housing estate	3m x 1.3m under the road	SWMM	StormPav could capture fully the 3-hour 10-year ARI design rainfall from road catchment
	Mah et al. (2018a)	15-minute 10-year ARI design rainfall	m ² of road catchment, m ² of roof catchment in the city centre	280m x 3.6m x 0.3m at the backstreet	SWMM	StormPav could reduce the peak flood by 30% from road and roof catchments.
	Mah et al. (2018c)	Observation over actual rainfall	10m x 4m of rural road catchment	10m x 4m x 0.3m OSD under the road	Pilot Study/ Field Study	StormPav performed as designed stormwater detention from road catchment.

Table 2.1 continued

Home-based application	Liow et al. (2019a; 2019b; 2019c; 2019d)	3-hour 10-year ARI design rainfall	918 m ² of road catchment, 2160 m ² of roof catchment in a commercial area	17m x 54m x 0.3m under the front street of shop-lots	SWMM & SolidWorks Flow Simulation	StormPav could store and flow stormwater at the same time from both road and roof catchments.
	Lui et al. (2019)	5-minute 10-year ARI design rainfall	39 m ² of road catchment in a housing estate	1.5m x 6m x 0.3m under the road shoulder/foot path	SolidWorks Flow Simulation	StormPav could store stormwater at the roadside structure from road catchment.
	Ngu et al. (2016)	15-minute 10-year ARI design rainfall	95 m ² of roof catchment of a typical Malaysia terrace house	2.2m x 1.6m x 0.3m under the car porch. 1/6 of a full-scale model	Laboratory and SolidWorks Flow Simulation	StormPav could diminish the turbulent flow from roof catchment.

Study Gap

The study of Ngu et al. (2016) of home-based application reported a small-scale StormPav that was tested in laboratory. The flow was based on design rainfall derived from statistical analysis and probability of historical rainfalls, which was a common industrial practice. Thus, it poses two limitations. It has not been tested under actual rainfall in the field, particularly during rainy season and validation of the actual performance of the system is still lacking. Furthermore, the study was made small-scale in nature due to limitation in the laboratory. The area (2.2m x 1.6m) was 1/6 of a supposedly two-car parking area. With that, a full-scale model (4.625m x 4.33m) subjected to actual rainfall is envisioned to fill up the limitations of the previous study.

2.3 OSD Design

The author compares four guidelines regarding to OSD design. References are made to Table 2.1 for discussion. As this project is steered towards home-based application, discussion of OSD design is focused on building the system within a property than other open spaces. The guidelines are:

- i. Chapter 5. On-Site Detention, Manual Saliran Mesra Alam (DID, 2012);
- ii. Chapter 6. Guidelines Detention / Retention Ponds, Sarawak Urban Stormwater Management (SUStoM) Guideline (DID, 2016);
- iii. Chapter 3. Design of Detention Tank System, Technical Guide for On-Site Stormwater Detention Tank Systems (PUB, 2021); and
- iv. On-Site Stormwater Detention Guide (Sydney Water, 2014).

There are five design considerations extracted from the guidelines:

2.3.1 Rainfall

Both the Malaysian (DID, 2012) and Singaporean (PUB, 2021) guidelines suggest the use of 10-year ARI design rainfall for OSD design. However, the Australian (Sydney Water, 2014) is suggesting 100-year ARI. The neighbouring Malaysia and Singapore are located in the equatorial region, and as such, the 10-year ARI mark is more reasonable in Sarawak. It is evidence in Table 2.1, StormPav designs are based on 10-year ARI. The rainfall durations, on the other hand, differ due to the size of drainage catchment and its associated time of concentration. The ARI and rainfall duration decide the intensity of design rainfall, usually denoted as I (mm/hr), or the rainfall depth, denoted as P (mm).

2.3.2 Catchment

Drainage catchment area results in the amount of runoff generated, and its characteristics influence the runoff flow rate, that may appear high or low in its peak discharge. DID (2012) suggests that individual OSD is suitable for catchment area below 1000m^2 , in which most property lots fall under this category. In fact, referring to Table 2.1, those past studies also have catchment areas within the mentioned range.

In order to determine the peak discharge, DID (2012) suggests the use of Rational Method:

$$Q = \frac{CIA}{360} \quad \text{Equation 2.3}$$

where

Q = Peak discharge at the point of design (m^3/s);

C = Runoff coefficient;

I = Average rainfall intensity (mm/hr);

A = Catchment area (ha).

The runoff coefficient (C) of a site depends on its land uses. PUB (2021) recommends 0.45 for pervious areas that allow water to infiltrate to the ground; while 1.0 for impervious areas like roads, buildings, and pavement. All the studies in Table 2.1 use C equals to 1.0 in the design, except the pilot study that reported in-field observation.

2.3.3 OSD Sizing

There is no specific size and shape for OSD. PUB (2021), DID (2012) and Sydney Water (2014) maintain that the OSD sizing should be able to fully contain the amount of runoff resulted from the design rainfall. PUB (2021) introduces a method in Figure 2.15 to estimate the stormwater storage volume.

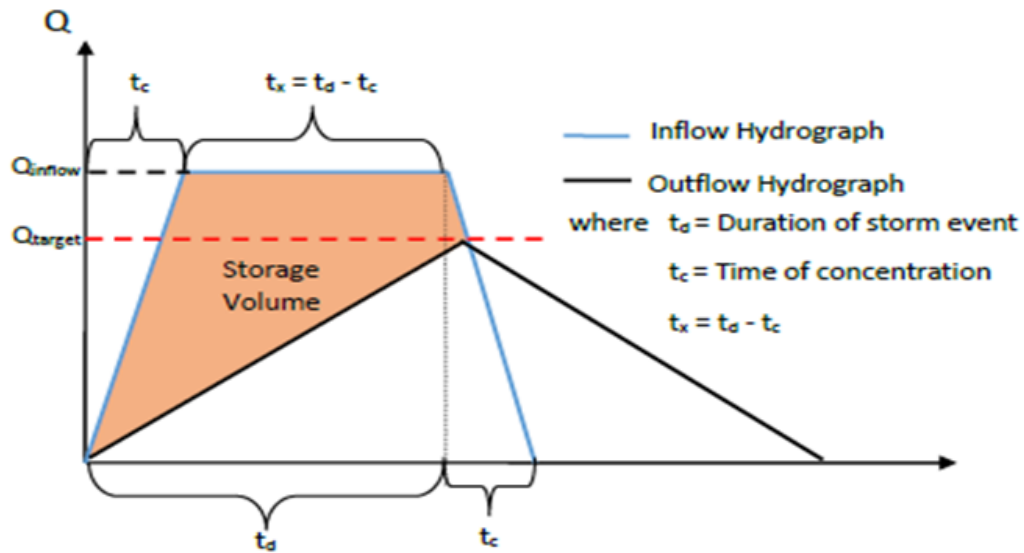


Figure 2.15: Example of Inflow and Outflow Hydrographs for Online Gravity Controlled Detention System (PUB, 2021)

The sizing of the inlet and outlet of the OSD could be determined. PUB (2021) recommends the following Equation 2.4 and Figure 2.16.

$$Q_o = C_o A_o \sqrt{2gH_o} \quad \text{Equation 2.4}$$

where

Q_o = Orifice discharge rate (m^3/s);

C_o = Discharge coefficient (m^2);

A_o = Area of orifice (m^2);

g = Acceleration due to gravity ($9.81 \text{ m}^2/\text{s}$);

H_o = Maximum head to the centre of the orifice (m).

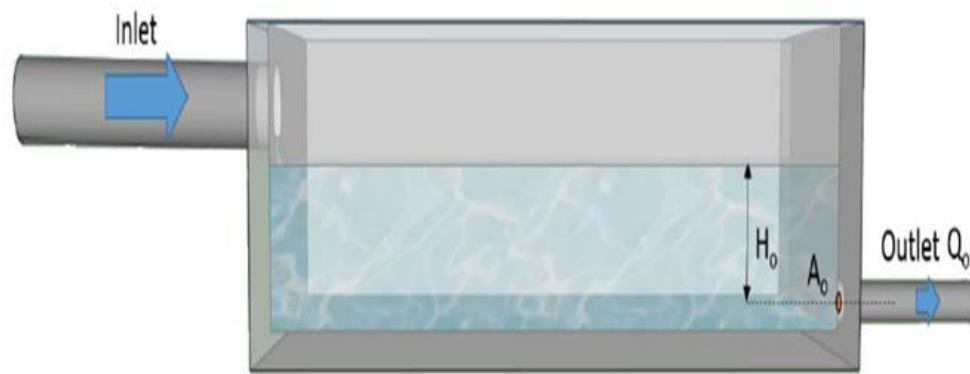


Figure 2.16: Diagram on Orifice Discharge Parameters (PUB, 2021)

The effective depth of OSD, H_o could be determined by considering the inlet invert level and the outlet invert level. For below ground storage, no specific effective storage depth is mentioned in any of the guidelines. Referring to Table 2.1, StormPav OSD has a storage depth of 0.3m.

2.3.4 Impact

To obtain Q_{target} , the OSD must meet two key requirements, namely:

i. Permissible Site Discharge (PSD)

PSD is the maximum rate of discharge for a site that the existing downstream stormwater system can handle.

ii. Site Storage Requirement (SSR)

SSR is the minimum storage volume that is needed to temporarily store and offset the excess stormwater runoff due to the development.

In another word, PSD is indeed the Q_{target} . PSD and SSR are stressed in PUB (2021).

In the developed countries like Australia, Sydney Water (2014) has its jurisdiction area divided into regions. Each of the region has been studied of its stormwater systems' limitations. It is no surprise that by pinpointing an exact location, a specific PSD catering for a project site could be provided. Meanwhile in Malaysia, DID (2012) divides the Peninsular Malaysia into five design regions, and general PSD values for major towns are available for reference. However, Sabah and Sarawak are excluded. DID (2016) is developed to cater for Sarawak, in which PSD and SSR are not spelled out but stresses on a requirement to have peak discharge $Q_{\text{post-development}}$ lower or same as $Q_{\text{pre-development}}$. In another word, Sarawak side is adopting $Q_{\text{pre-development}}$ as Q_{target} . Therefore, the studies in Table 2.1 that are carried out in Sarawak did not mention about PSD and SSR.

2.3.5 Tool

PUB (2021) describes tools for hydraulic and hydrological modelling of drainage system which include US EPA SWMM and MIKE II. SWMM is repeatedly stated in Table

2.1. It is a one-dimensional model for drainage modelling. MIKE II is another one-dimensional model under a different brand. These are computer software that assist in accelerating the engineering design process, a common industry practice.

2.4 Field Testing

Testing of an existing stormwater facility on-site or building a new stormwater facility at a selected site for testing purposes, is termed a field test. It is expensive. Researchers may not opt for field tests due to the costs of acquiring equipment, construction or manpower to carry out the tests. Those researchers who afford field tests have reported tremendous benefits of the approach to determine the adequacy of stormwater facility under study (Hunt and Winston, 2011; Drapper and Hornbuckle, 2015). Most stormwater field tests are programs that involve scheduled field sampling, in which water samples from a stormwater system are collected, analyzed and monitored from time to time (NCHRP, 2019). However, water quality transport in stormwater facility is triggered by rainfall and/ or water level fluctuation over a specified time duration. Therefore, past field tests have demonstrated water quality and quantity are always inter-related. As this study is not intended for water quality, the ensuing writing is focused on water quantity. Law et al. (2008) had suggested a list of critical parameters for stormwater field test set up and these are outlined on the left of Table 2.2.

Table 2.2: Field Test Parameters

Law et al. (2008) (p.8) Recommendation	Author's comments
a) Contributing drainage area	Only roof catchment is involved.
b) Hydrologic characteristics	Rain gauge is needed to record the rainfall depth.

Table 2.2 continued

c) Runoff volume	Flowmeter is needed to measure the flow volume.
d) Land use	Roof is 100% impervious surface.
e) Drainage infrastructure	In this case, an OSD with one inlet and one outlet.
f) Any effect to flow/ loading	Water proofing is needed to cut down unrecorded water.

2.5 Simulation and Verification

Simulation and verification are important components of model development and testing. Simulation involves creating a model that represents a real-world system, while verification involves testing the model to ensure it accurately reflects the system it represents (Gallagher et al., 2019). One method of verifying a model is through the use of statistical tests, such as the K-S test. The Kolmogorov-Smirnov (K-S) test is a non-parametric statistical tool used to compare a sample of data with a reference distribution or to compare two samples of data to determine if they are drawn from the same distribution (Draper & Smith, 2014; Montgomery et al., 2017). In the context of model validation, the K-S test is used to evaluate how well a model fits the data. The test involves sorting the data in ascending order, calculating the empirical distribution function (ECDF), and calculating the cumulative distribution function (CDF) of the model's predicted values. The K-S test statistic is then calculated as the maximum absolute difference between the two CDFs (Hastie et al., 2017).

The null hypothesis of the K-S test is that the two distributions are the same, while the alternative hypothesis is that the two distributions are different. The significance level is usually set at 0.05, and if the p-value associated with the K-S test statistic is less than this

value, the null hypothesis is rejected, and it is concluded that the model does not fit the data well (Draper & Smith, 2014).

The K-S test has been applied in various fields, including hydrology, where it is used to validate models of streamflow and other water-related variables (Sahin & Kisi, 2018; Xu et al., 2018). In particular, the K-S test is commonly used in machine learning and predictive modelling to evaluate the goodness-of-fit of models to data (Hastie et al., 2017).

One application of the K-S test is in the validation of Storm Water Management Model (SWMM) models. SWMM is a widely used software for simulating the hydrology and hydraulics of urban and suburban areas, including the analysis of stormwater runoff, combined sewer overflow, and other water-related issues. In SWMM modelling, the K-S test can be used to evaluate the goodness-of-fit of the simulated results against observed data.

In a study by Sharif et al. (2018), the authors used the K-S test to validate a SWMM model developed to simulate the hydrologic response of a watershed to different land use scenarios. They collected observed data from four rain gauges located within the study area and compared the simulated results with the observed data using the K-S test.

The results of the K-S test indicated that the simulated results were in good agreement with the observed data, suggesting that the model was capable of accurately predicting the hydrologic response of the watershed to different land use scenarios. According to Sharif et al. (2018), their proposed methodology for SWMM model development can effectively simulate the hydrologic response of urban watersheds, indicating its potential usefulness in informing stormwater management decisions. This example highlights the application of the K-S test in the validation of SWMM models, which

can provide important insights into the hydrologic response of urban watersheds and inform management decisions related to stormwater management.

Hence, simulation and verification are critical aspects of model development, and the K-S test is a powerful tool for validating models and determining whether a data set follows a specific distribution. Its non-parametric nature makes it a useful tool for validating models with unknown distributions or for which parametric tests are not appropriate. Its application in SWMM modelling provides important insights into the hydrologic response of urban watersheds and can inform management decisions related to stormwater management. By using statistical tests like the K-S test, modelers can ensure that their models accurately represent real-world systems and can be used to make informed decisions and predictions.

2.6 Detention Storage Characteristics

This section describes the past studies concerning the design of detention storages.

2.6.1 Rainfall

It is found that the design step of having rainfall as input to detention systems, to date, still relying on artificial rainfall data. It is evident in the studies of Chin (2023), Jayathilake et al. (2023) and Wang et al. (2023). Artificial rainfall data are continued to be used by scientists and engineers alike to support the design of detention storages.

There are also another group of scientists and engineers who press for actual rainfall. Qiu et al. (2023) argued that natural rainfall-runoff provide better environmental protection measures in stormwater systems, particularly good linear relationships are derived for control of COD and SS concentrations. Besides, Yazdi (2019) and Scheibes et al. (2022) had

reinstated that actual rainfall gives optimum rates underlying any significant flood loads entering a detention system.

Both of the method, be it artificial or actual rainfall, are still relevant in stormwater detention design. However, it is desirable to have actual rainfall for a more realistic performance of a system than the idealized artificial rainfall, as reported in Mergen et al. (2021).

An example of past study on rainfall is presented below. Alam et al. (2019a) had documented a study on actual rainfall on storage volume and outflow for Porous Concrete Pavement (PCP) as permeable pavement (Figure 2.17).

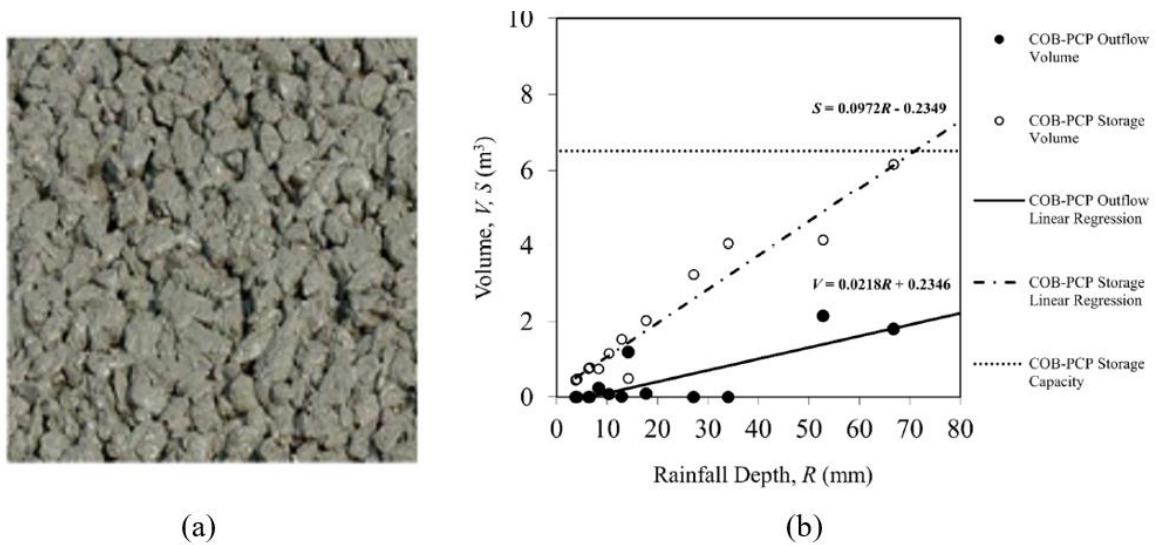


Figure 2.17: Responses to Actual Rainfall for (a) Porous Concrete Pavement and (b) Plot of Rainfall, storage volume and Outflow (Alam et al., 2019a)

According to Alam et al. (2019a), the storage volumes presented in the graph were derived from inflow values entering the system. Therefore, inflow and storage volume were closely related. The outflow line was always on the bottom of the graph. It was due to the restrictions of the outlet to enable water detention in the PCP detention system.

2.6.2 Catchment to Detention Storage

A catchment itself influences the stormwater characteristics for water flowing over an area of interest. An example is presented by Rodriguez-Rojas et al. (2020) (Figure 2.18).

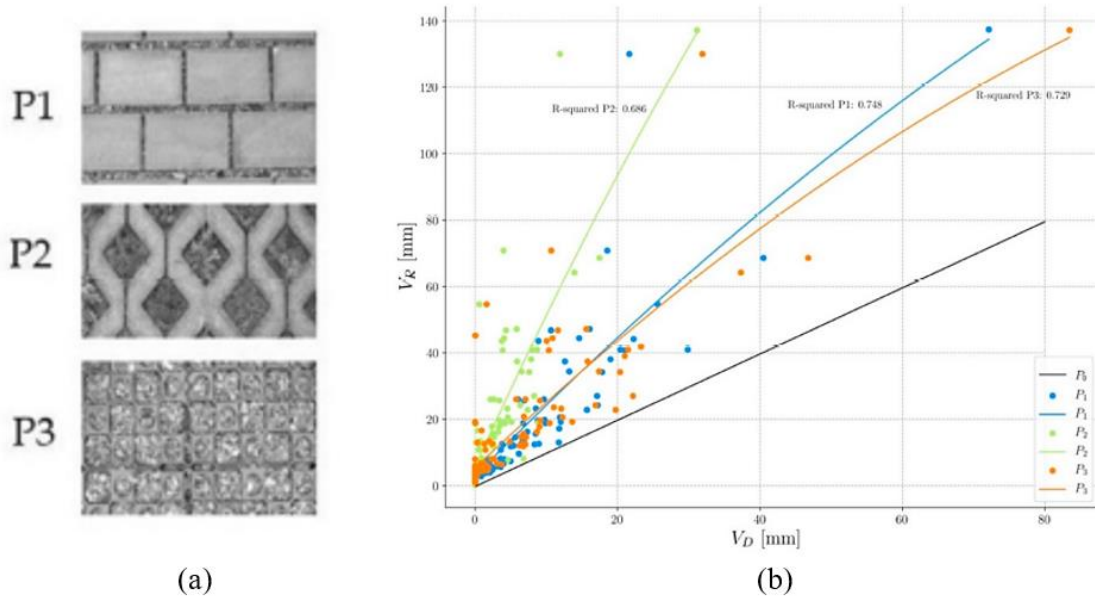


Figure 2.18: Catchment to Detention Storage Relationships for (a) Types of Pavers and (b) Plot of Rainfall Volume (VR) and Drainage Volume (VD) (Rodriguez-Rojas et al., 2020)

This study indicated that the natures of the catchment generated different flows. Three types of pavers (P1, P2 and P3) were highlighted in Figure 2.18(a) and were compared to a theoretical conventional tar surface (P_0). In this case, the surfaces covered by the pavers functioned as the catchment. A car parking area of 813m^2 was installed with the three pavers and these were subjected to the form of rainfall volume and the associated drainage volume generated from the mentioned car parking area equally divided into three sections are presented in Figure 2.18(b).

The impervious tar surface, P_0 generated the highest amount of drainage volume. From the graph, 40mm of rainfall generated 40mm of drainage volume. The three pavers generated lesser drainage volume under the same 40mm of rainfall. P2 generated the least,

8mm of drainage volume. P1 and P3 generated 17mm of drainage volume. These happened because the paver, P2 was found to infiltrate the most stormwater to soil layer. P2 could be seen in Figure 2.18(a). The other two pavers were found to infiltrate stormwater less. Their structures could be observed in the figure as well. In short, each of the pavers portrayed unique characteristics than the others.

The next example is using artificial rainfall. Bateni et al. (2021) had carried out a laboratory-based testing on StormPav (Figure 2.19).

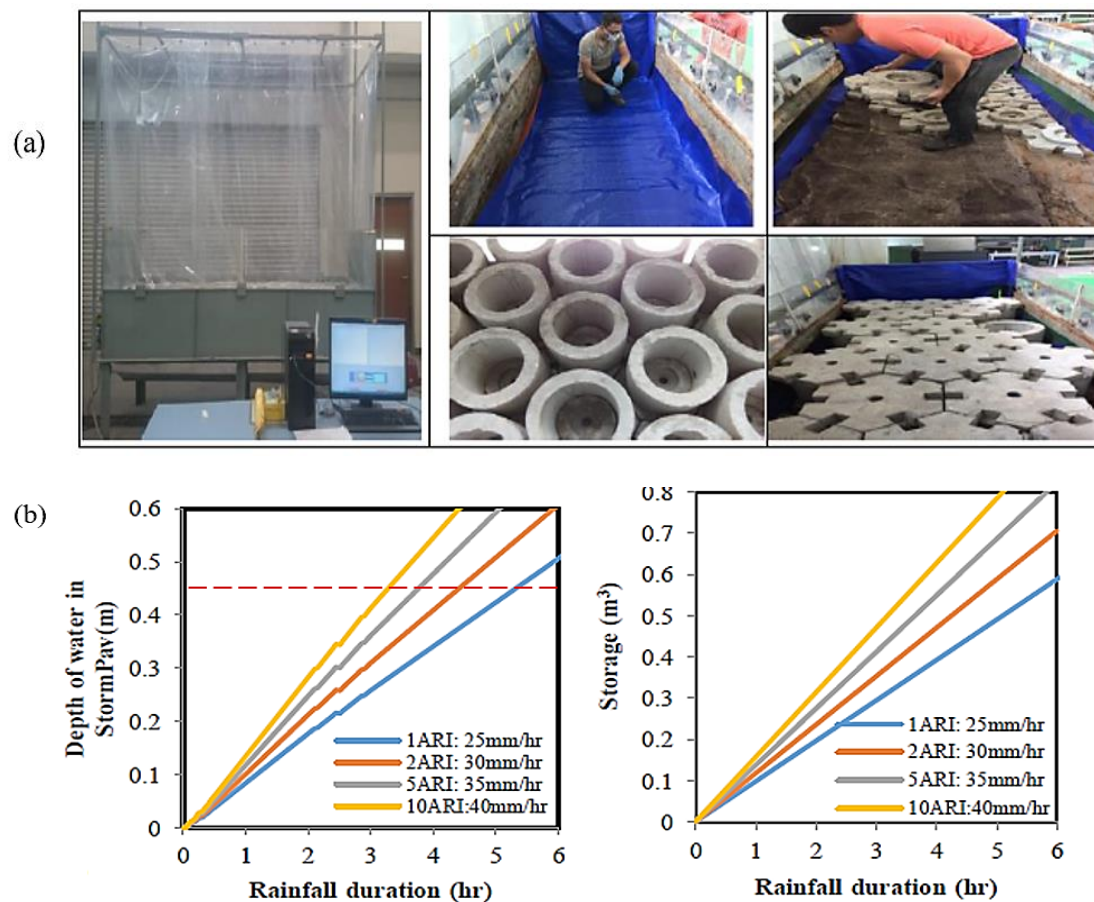


Figure 2.19: Catchment to Detention Storage Relationships for (a) Laboratory-based Testing (Rainfall Simulator) on StormPav and (b) Plot of Rainfall, Water Level and Storage Volume (Bateni et al., 2021)

The study involved a self-fabricated rainfall simulator. Calculated design rainfall values were produced by controlling a pump and the sprinkle design. The rain drops

produced by the combination of pump and sprinkles were controlled to have a constant rate. StormPav modular units (3.2m^2) were laid within the rainfall simulator. In this case, the StormPav surface layer functioned as the catchment. Bateni et al. (2021) presented their findings in water levels and storage volume in the storage layer of StormPav modular units. With the maximum height of StormPav (0.45m), it was found that the laboratory setting ($3.2\text{m}^2 \times 0.45\text{m}$) could withstand 3 hours storm under 1-year ARI, 3.5 hours storm under 2-year ARI, 4 hours storm under 5-year ARI and 5 hours storm under 10-year ARI.

2.6.3 Flow and Water Level

Flow and water level relationships are generally known as rating curves in hydrology. Most of the time, flow is comparatively more difficult to measure compared to water level. Once the relationships of the flow-water level are known, then the flow values could be determined from the water level values. The mentioned relationships are obtained by conducting synchronized measurement of flow and water level. In the case of stormwater structure, it is generally accepted the structure as a form of hydraulic structure, in which both the flow and water level readings could be taken from (Sarvarinezhad et al., 2022).

An example of flow-water level rating curve is presented in Mohammad Nezhad et al. (2022). The study computed the flow-water level relationships of a smooth triangular-shaped channel (Figure 2.20).

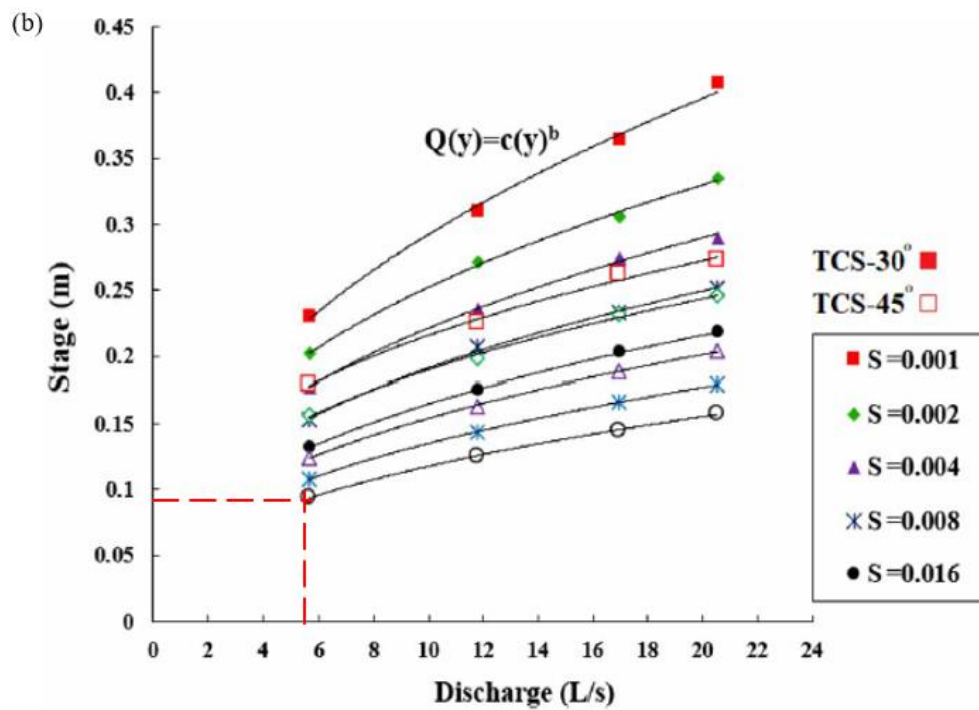
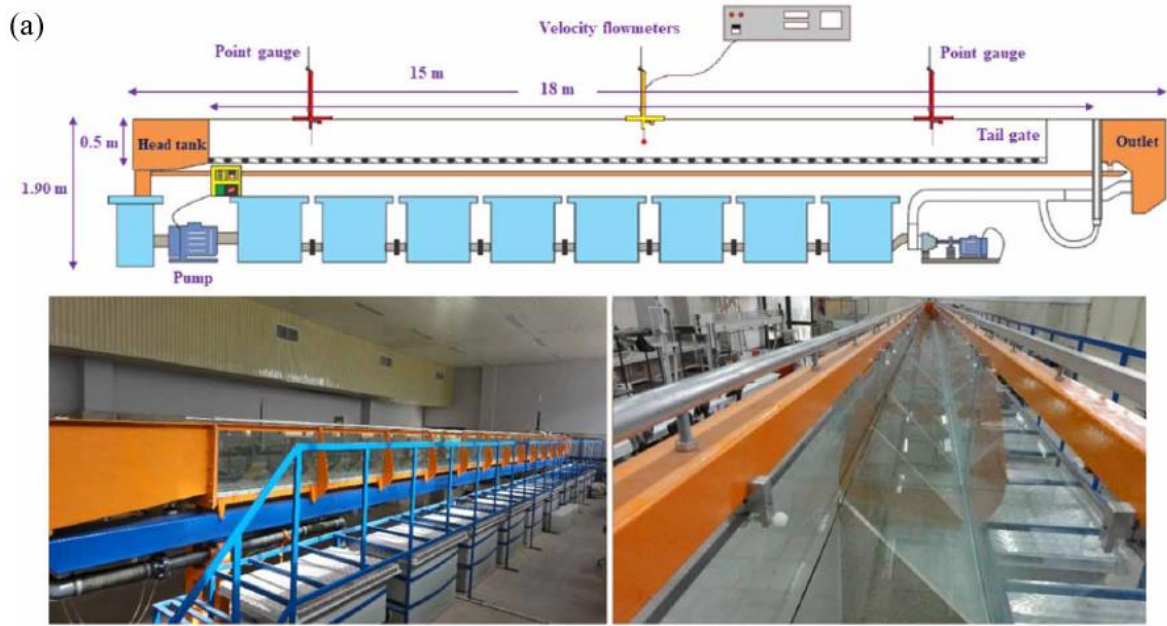


Figure 2.20: Flow and Water Level Relationships via (a) Laboratory Setting for Smooth Triangular-shaped Channel and (b) Rating Curves according to Different Channel Bed Slopes (Mohammad Nezhad et al., 2022)

An example of flow-water level rating curve is presented in Mohammad Nezhad et al. (2022). The study computed the flow-water level relationships of a smooth triangular-shaped channel (Figure 2.20). Mohammad Nezhad et al. (2022) was using the terms stage

(which is synonymous to water level) and discharge (which is synonymous with water flow). Referring to Figure 2.20(b), pinpointed with dotted lines, it is shown that 0.09m of water level was corresponding with 5.7L/s of flow for the cross section triangular cross section (TCS) 45° with channel bed slope, $S=0.016$. The laboratory setting helped to collect a series of flow-water level datasets.

2.6.4 Surface Runoff Reduction

Runoff reduction is the ultimate goal of most stormwater system. The most common practices are efforts being carried out to lower the peak runoff. An example of Yuan et al. (2022) is presented in Figure 2.21.

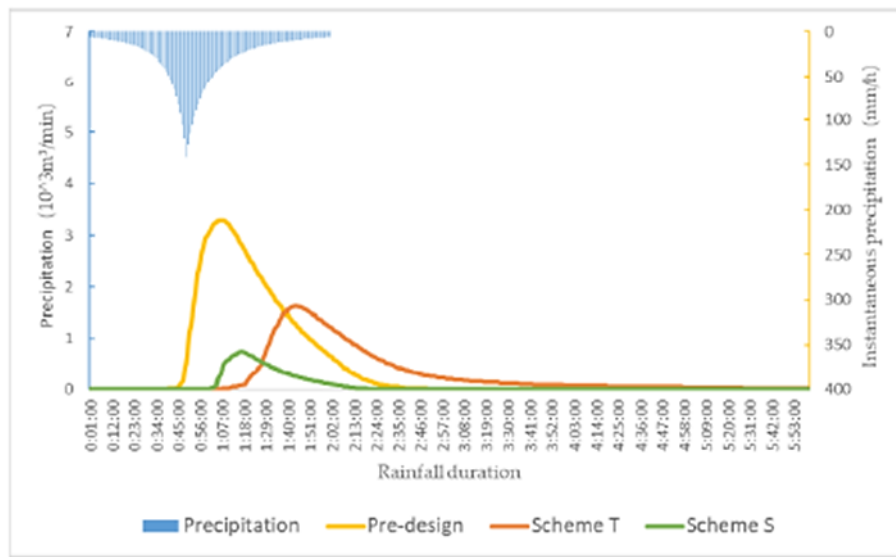


Figure 2.21: Rainfall and Runoff Relationships at Outflows in a 2-year Return Period (Yuan et al., 2022)

There are three hydrographs in the figure, in which the pre-design (equipment to post-development condition without intervention) had the highest peak runoff value. When Scheme T and Scheme S were introduced, the peak runoffs produced due to the schemes reduced significantly. Generally, the differences between the peak of pre-design and Scheme T or Scheme S were measured as the reduction.

Different stormwater systems are reported with a variety of reduction rates. Hamouz et al. (2020) reported on green and grey roof, in which it was found with 11% of the roof area converted into green or grey roof, the maximum flow out of the roof was reduced by 17%.

Alam et al. (2019b) reported the use of interlocking block pavement with gravel (IBPG) as permeable pavement. The 789.03m² area was having 210.33m² covered with the pavement. It was found that runoff reduction ranges were up to 60mm when subjected to 56 flow monitoring events (Figure 2.22).

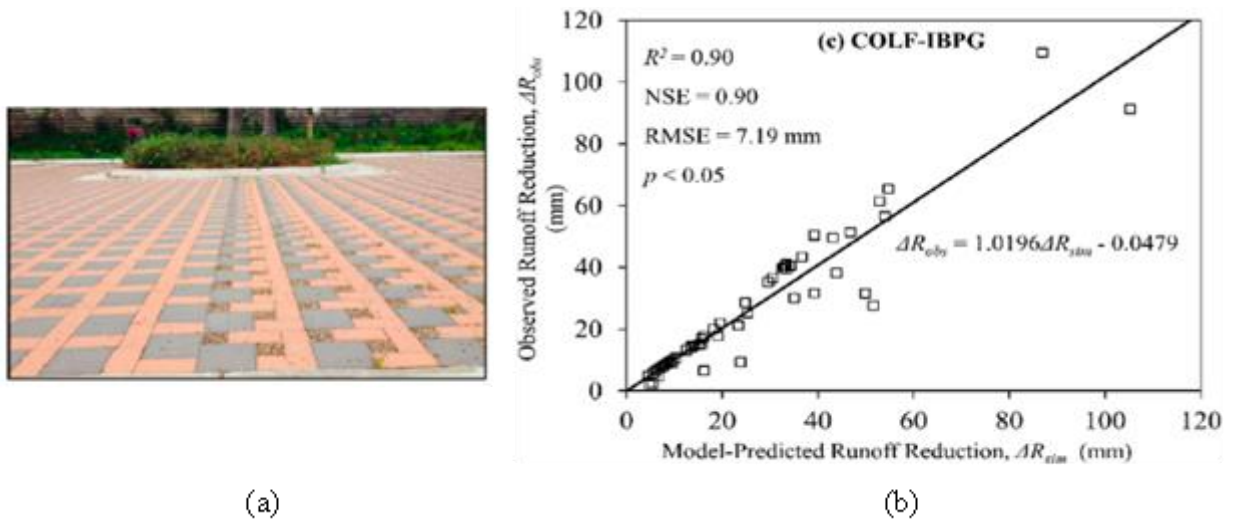


Figure 2.22: Runoff Reduction for (a) Interlocking Block Pavement with Gravel (IBPG) and (b) Plot of Observed and Model-Predicted Runoff Reduction (Alam et al., 2019b)

Bonane et al. (2022) carried a study of OSD in individual lot, in which the study was concluded with 21-35% reduction in flow rates from the study sites. de Paula Drumond et al. (2022) reported that two OSDs monitored in Belo Horizonte, Brazil which the structures were reducing peak runoff more than 50%. In another study of Maseri et al. (2020), OSD was reported to reduce runoff up to 77% of the total rainfall volume. In short, a range of 17-

77% runoff reduction was found in the studies. It can be said that stormwater structures are able to reduce the urban runoff when detention is introduced.

2.6.5 Research Gap

From the descriptions in the earlier sub-sections, a stormwater structure functions and produced unique patterns in its flow mechanism. As such, StormPav modular units when intended as a home-based OSD is expected to give specific traits. With a field test in place, the data are a reflection how the system actually behaves which is realistic than laboratory test and computer simulation. Therefore, the research gap put forward in this study is the stormwater detention characteristics unique to StormPav subjected to actual rainfall.

This research addresses the comments on the methodology by providing a comprehensive explanation of the SWMM model. The Storm Water Management Model (SWMM) is an established stormwater modelling software that offers a range of functionality for simulating hydrological processes and assessing stormwater management practices. In this study, the governing equations and analysis conducted using the SWMM model are elaborated, ensuring transparency and clarity in the modelling approach. The advantage of using SWMM lies in its reliability, calibration, and validation capabilities, which ensure accurate representation of stormwater behaviour. However, some limitations, such as complexity, data requirements, and computational intensity, are acknowledged. The contribution of this research lies in its in-depth analysis of the StormPav OSD system, addressing some of the existing model's disadvantages and providing valuable insights into its performance under real-world conditions. By combining field data and validated modelling, the research highlights the system's efficiency and limitations, further supporting the conclusion on the effectiveness of StormPav as an on-site stormwater detention solution.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In order to achieve the objectives of this study, the following steps are needed:

- i. A study area is determined. A specific area must be identified as distribution of rainfall varies from one location to another, and therefore, rainfall pattern is usually taken as location specific;
- ii. A home-based StormPav OSD needs to be constructed as no such system exists in the real world;
- iii. The mechanism of water flowing through the constructed home-based StormPav OSD is measured with appropriate sensors and devices;
- iv. The collected field data are used to validate the afore-mentioned SWMM model; and
- v. A design chart for the home-based StormPav OSD is computed based on the validated SWMM model.

Based on the descriptions above, the current study is divided into five major stages below. A general flowchart is presented in Figure 3.1.

- i. Stage I : Designation of home-based StormPav OSD;
- ii. Stage II : Field test set-up (that in line with objective 1);
- iii. Stage III : Collection and analysis of field data (that in line with objective 2);
- iv. Stage IV : Validation of SWMM model (that in line with objective 3);
- v. Stages V : Design chart (that in line with objective 4).

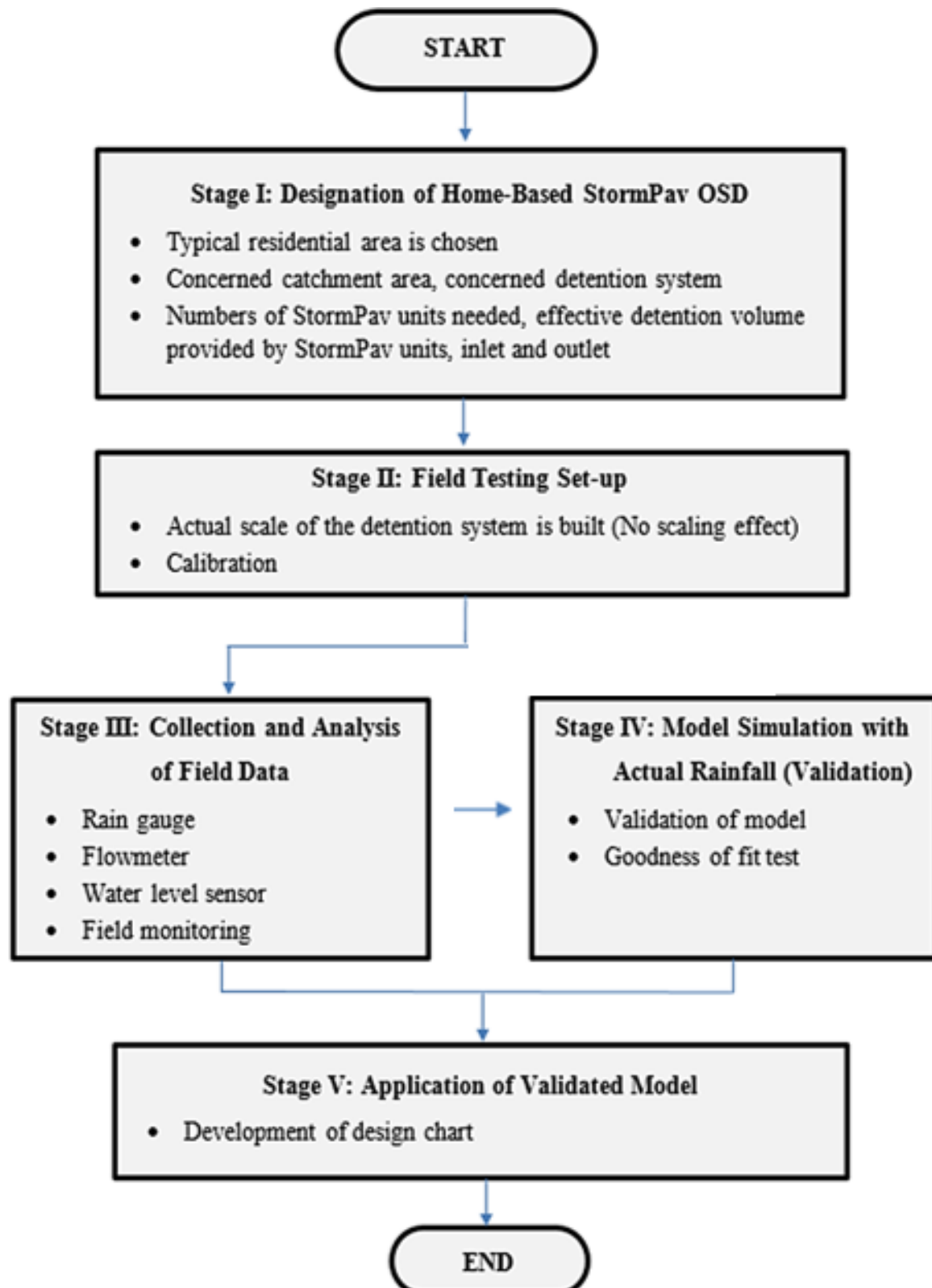


Figure 3.1: Flowchart for Current Study

A SWMM model covers the design rainfall, catchment area, storage unit, orifice outlet and outfall (Figure 3.2). In this case, the roof catchment (95m^2) is modelled to receive the design rainfall of 10-year ARI before channelling the water to an OSD.

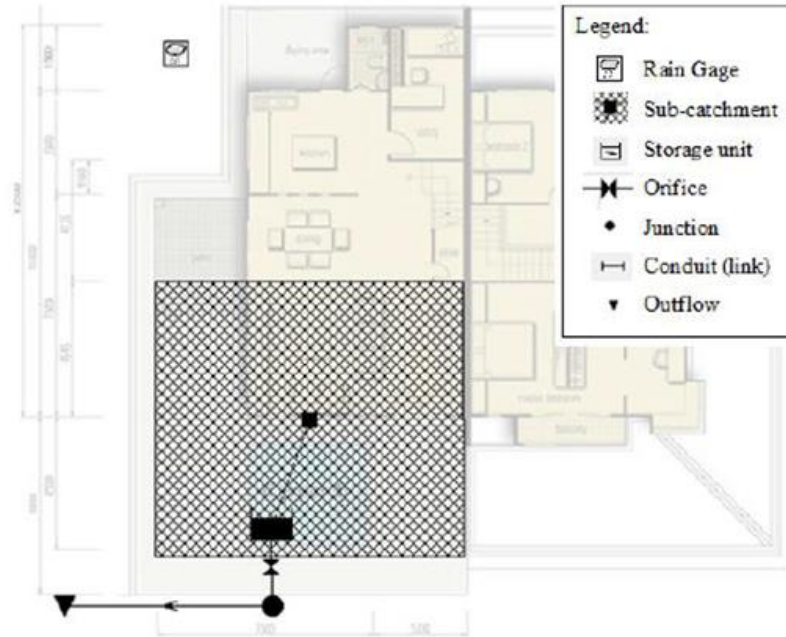


Figure 3.2: Digitization of SWMM Components (Ngu et al., 2019)

A storage unit in Figure 3.2 represents home-based StormPav OSD and its outlet is represented by a 0.05m diameter circular site orifice. The effective storage volume is inputted to the storage unit. This method of applying effective storage volume has been reported in Liow et al. (2019a; 2019b; 2019d) and Mah et al. (2020). The same method is applied here but with the validation of field data in the next chapter.

Calculations of the home-based OSD are summarized in Table 3.1. Referring to the table, the author tests the OSD subjected to 5-, 10-, 15-, 30-, 60-, 120-, and 180-minute design rainfalls under the intensity of 10-year ARI. The computed design hydrographs are presented for comparison with field data.

Table 3.1: Design of On-site Detention

Location		Kota Samarahan, Sarawak						
Residential		Use 10-year ARI Design Rainfall						
Design Rainfall		Use IDF curves of Kota Samarahan, Sarawak						
Storm Duration		5, 10, 15, 20, 30, 60, 120, 180 minutes for 10-year ARI						
Roof Catchment Area		95m ² / 0.0095 ha						
Analysis of Hydrological Parameters for Design Rainfall:								
	10-year ARI Storm Duration							
Minutes	5	10	15	20	30	60	120	180
Intensity (mm/hr)	278	214	183	166	142	95	70	56
Rain Depth (mm)	23	36	46	55	71	95	140	168
Peak Runoff from Roof (m ³ /s)	0.0073	0.0056	0.0048	0.0043	0.0037	0.0025	0.0018	0.0015
Runoff Volume from Roof (m ³)	2.2	3.4	4.4	5.2	6.8	9.0	13.3	16.6
Analysis of StormPav On-site Detention								
Surface area of OSD			4.7m x 4.4m (Size to fit two cars)					
Water Storing Capacity of StormPav			0.19 m ³ / m ² of pavement area					
Expected Water Storage			20.68 x 0.19 = 3.9 m ³					

From Table 3.1 calculation, although the effective storage volume is calculated at 3.9 m³, the roof runoff volume calculated at 4.4 m³ due to 15-min 10-year ARI design rainfall is still able to be captured by the OSD. This is because the OSD is intended as a dynamic system, in which the outlet is allowing free flowing throughout the course of any storm. It is also reported in Ngu et al. (2019) that SWMM modelling of the same-size OSD subjected to

15-min 10-year ARI design rainfall is found without overflowing. Therefore, the OSD could tolerate up to 15-minute design rainfall. It could no longer accommodate the runoff volume beyond the 15-minute design rainfall.

3.2 Study Area

As the StormPav OSD is intended as a home-based application, a residential area is designated as the study area. A detached house at 868, Lorong 7A Merdang Gayam, 94300 Kota Samarahan is selected, in which the property owner has agreed to allow the set up within the property over the course of study. The location of the housing estate lies in Samarahan division. Therefore, the rainfall patterns are referred to the named location that is a flat alluvial plain at the Sarawak southern coastal line facing South China Sea. Samarahan is known to receive ample of rainfall brought about by the Northeast Monsoon between November to February yearly. The general rainfall patterns of Samarahan are presented in Figure 3.3 below. In Figure 3.3, the rainfall patterns of Samarahan are presented by month. It shows the average monthly rainfall in millimeters (mm) for each month of the year. On the other hand, the 10 ARI (Annual Recurrence Interval) Design Rainfall, which is mentioned in Table 3.1, refers to a specific rainfall event that has a 10-year return period. It represents the maximum rainfall intensity that is expected to occur on average once every 10 years.

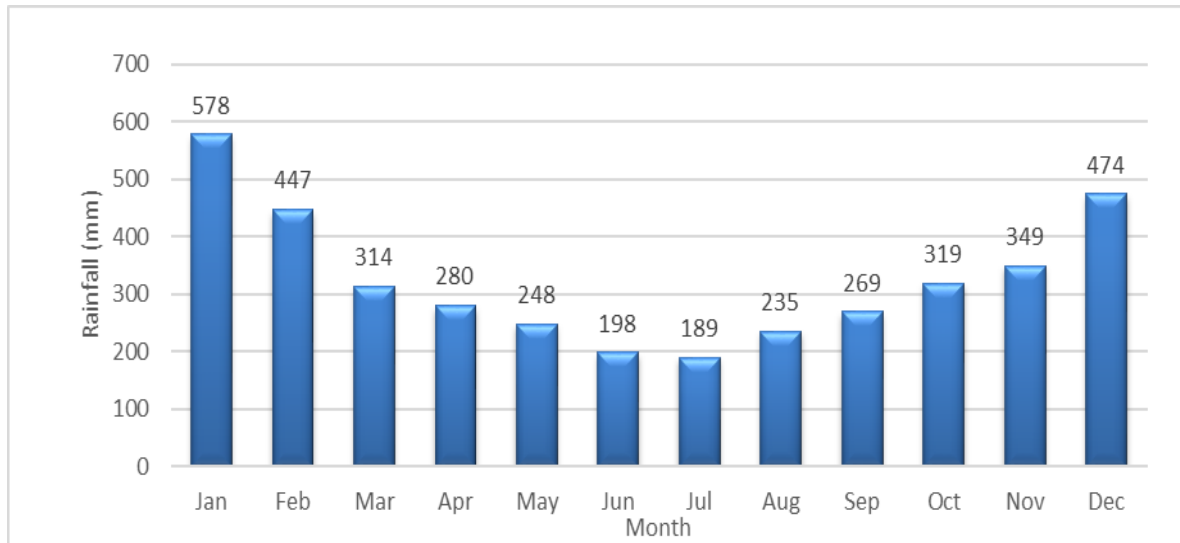


Figure 3.3: Rainfall of Samarahan by Month (Climate-Data. Org., 2020)

Most of the rainfall here falls in January, averaging 578mm. The driest month is July, averaging 189mm. The rainfall varies 389mm between the dries and the wettest months. It can be declared that Samarahan is an area with significant rainfall. Based on the figure above, data collection period of this study is decided between December 2019 to April 2020.

3.3 Field Testing Set Up

For a home-based OSD tank, the sizing as the best size for two cars, limited by the current dimension of StormPav modular units is 4.63m x 4.33m (20.68m²). The two-car fitting is chosen because it is a common and much needed feature in most residential house design nowadays. Having a more than two-car fitting car porch is less common and only available for a handful of luxury housing. The height of OSD is 0.45m. Therefore, the gross volume of the StormPav is 9.31m³, in which 5.16m³ (55%) of it consists of solid concrete and 3.97m³ (45%) is the effective storage volume.

The methodology employed in this study centers on the use of the Storm Water Management Model (SWMM) to simulate and analyze stormwater behaviour in the StormPav on-site stormwater detention (OSD) system. Through a field test conducted at a

real-life terrace house, data on storm events and rainfall depths were collected and compared with the SWMM model's predictions, ensuring its validation and reliability. The SWMM model's governing equations and analysis were thoroughly explained to provide transparency in the modelling approach. The research aims to evaluate the efficiency and performance of StormPav OSD under different storm conditions, providing valuable insights into its ability to mitigate flash floods and manage stormwater runoff. By effectively combining field data and validated modelling, this study presents a comprehensive assessment of the StormPav OSD system's capabilities and limitations. Readers will be eager to delve further into the chapter to discover how StormPav addresses real-world stormwater challenges and the contributions this research makes towards enhancing on-site stormwater detention solutions. A schematic drawing of the set-up is presented below. A flowchart of the field testing set up is presented in Figure 3.5.

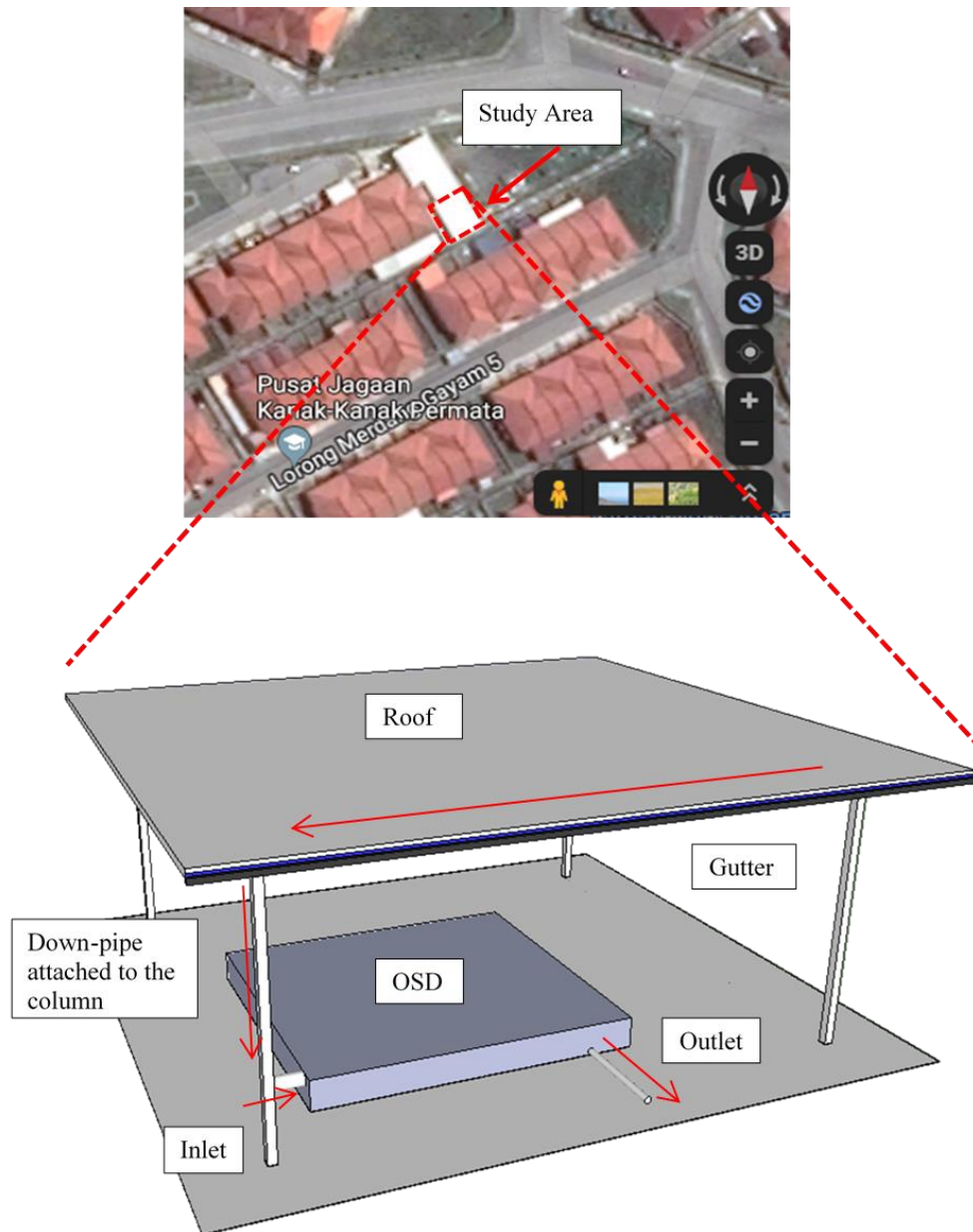


Figure 3.4: Field Testing Set-up

In addition, the StormPav OSD is constructed from the existing ground level, not below the ground level. This is done so that deconstruction of the OSD after the study period could be implemented at ease. Another point is this above-ground setting allows water-proof layer to be applied on the OSD. Having a water proof OSD could ensure a proper water accounting on the volume of water in and out of the OSD by eliminating any possibility of

water losses seeping out of the OSD. Observation and data measurement could be done more efficiently than an underground structure.

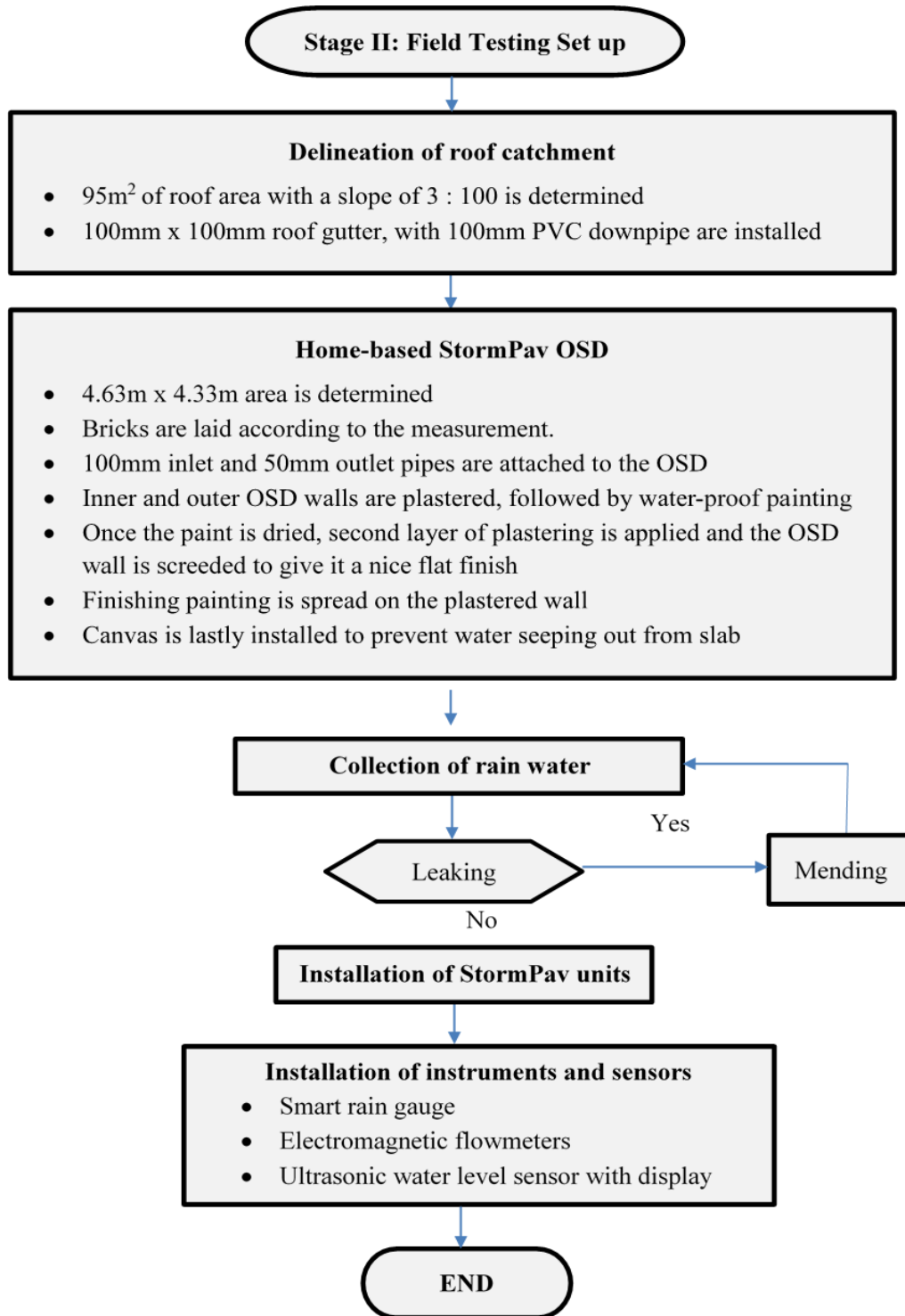


Figure 3.5: Flow chart for Field Testing Set up

A home-based StormPav OSD is constructed at Merdang Gayam, Samarahan. The OSD is set up within a detached house so that it mirrors an actual residential environment. The roof catchment is an actual house roof. The outer OSD is made of layers of brick work encasing the StormPav modular units. Special treatment has been done to make sure the inner wall of the OSD is waterproofed. Figure 3.6 shows the construction stages of the OSD.



Figure 3.6: Construction of Home-Based StormPav OSD, a) Delineation of Roof, Installation of Roof Gutter and Downpipe, b) Brick Layering and c) Water-proof Treatment

Figure 3.7 shows a photo of the empty OSD is filled up with rainwater in November 2019. Careful inspection is carried out to make no water would leak out of the tank. This step is to make sure the water-proofing layer on the inner wall of OSD is functioning well to ensure a proper water auditing of the amount of water being detained in the system.



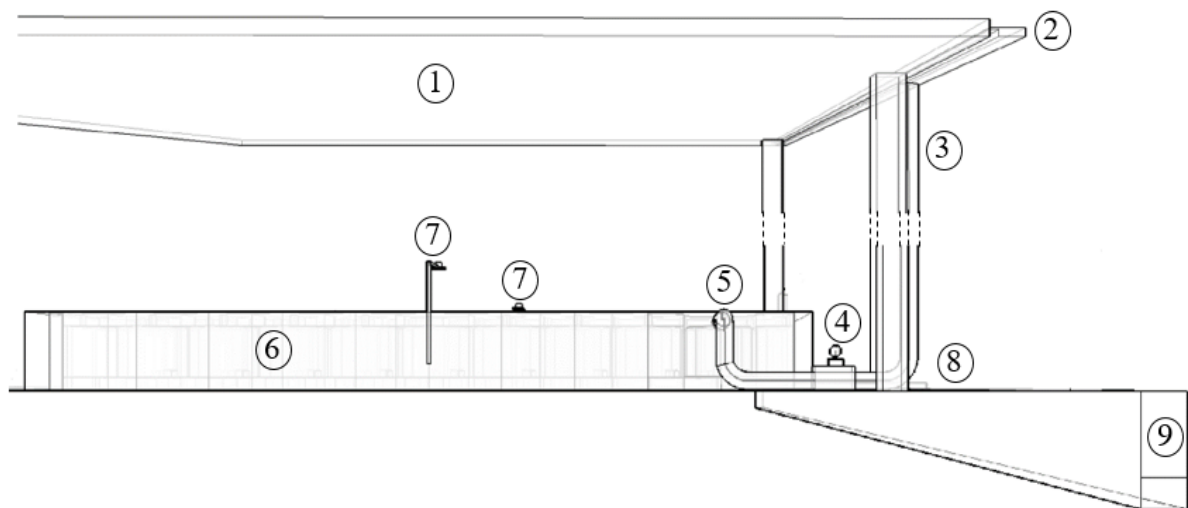
Figure 3.7: Water Leaking Testing of OSD

Figure 3.8 shows the completed StormPav OSD, in which one can observe open spaces on the OSD. The reason to open the cover of some of the modular units is to observe the water level in the OSD. The actual-built OSD is intentionally made slightly larger than is 4.70m x 4.40m as built compared to the planned 4.63m x 4.33m. The difference is only 3.14% that would not have impacted much on the flow patterns. The larger size is a precaution taken to avoid tight fitting of the StormPav modular units. The whole structure consists of 114 of full modular units and 12 of half modular units.



Figure 3.8: Completed Home-Based StormPav OSD

As the photos could not explicitly depict the whole system, AutoCAD drawings are presented in Figure 3.9, Figure 3.10 and Figure 3.11 to illustrate in details of the system being built.



- ① House side canopy, made of spandex, area 95 m², slope 3:100
- ② Roof gutter, made of PVC, 0.1 m x 0.1 m
- ③ Downpipe, made of PVC, 0.1 m in diameter
- ④ Electromagnetic flowmeter
- ⑤ Inlet to tank, 0.1 m in diameter
- ⑥ Stormwater detention tank, 4.40 m x 4.70 m x 0.45 m in size
- ⑦ Ultrasonic water level detector
- ⑧ Outlet pipeline, made of PVC, 0.05 m in diameter
- ⑨ House perimeter drain

Figure 3.9: Side View of Home-Based OSD

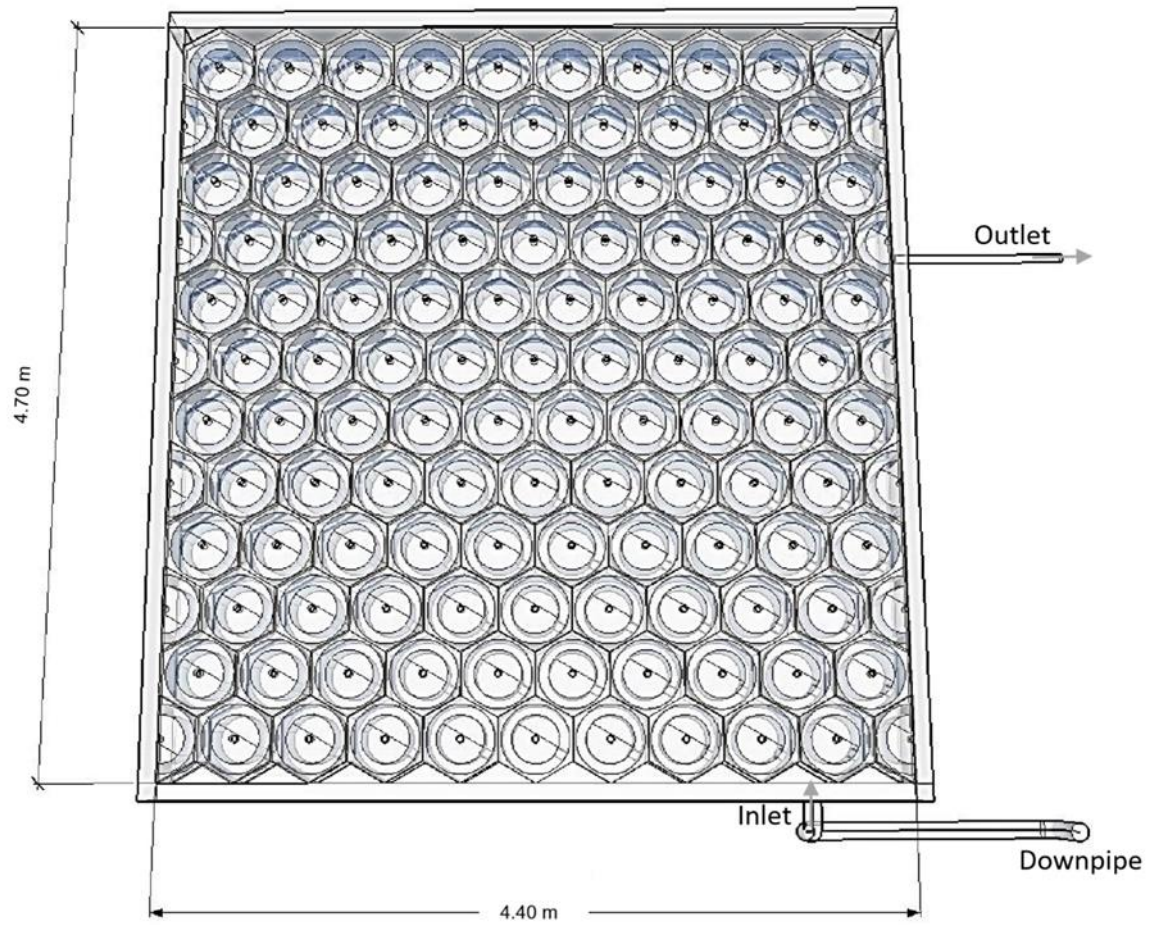


Figure 3.10: Plan View of Home-Based OSD

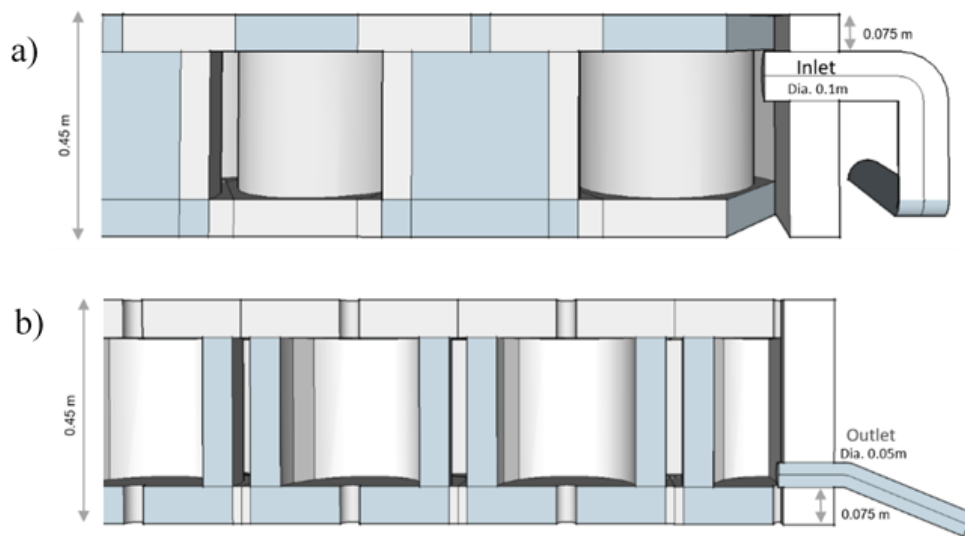


Figure 3.11: Cross-sectional Views for a) Inlet and b) Outlet

3.4 Data Collection and Calibration

Referring to Table 3.1 that shows the design sheet of home-based StormPav OSD, the critical parameters are rainfall and flow data. In order to validate the design parameters, field data of the similar data should be collected. The ensuing writing discusses on collection of rainfall and flow data.

3.4.1 Rainfall

A rain gauge is needed to collect the rainfall depth(mm). A smart rain gauge is obtained (Figure 3.12). It is installed within the compound of the chosen residential house. The device is based on the principle of tipping bucket, in which the data are recorded real time and shall be recorded on a display monitor.



Figure 3.12: Smart Rain Gauge

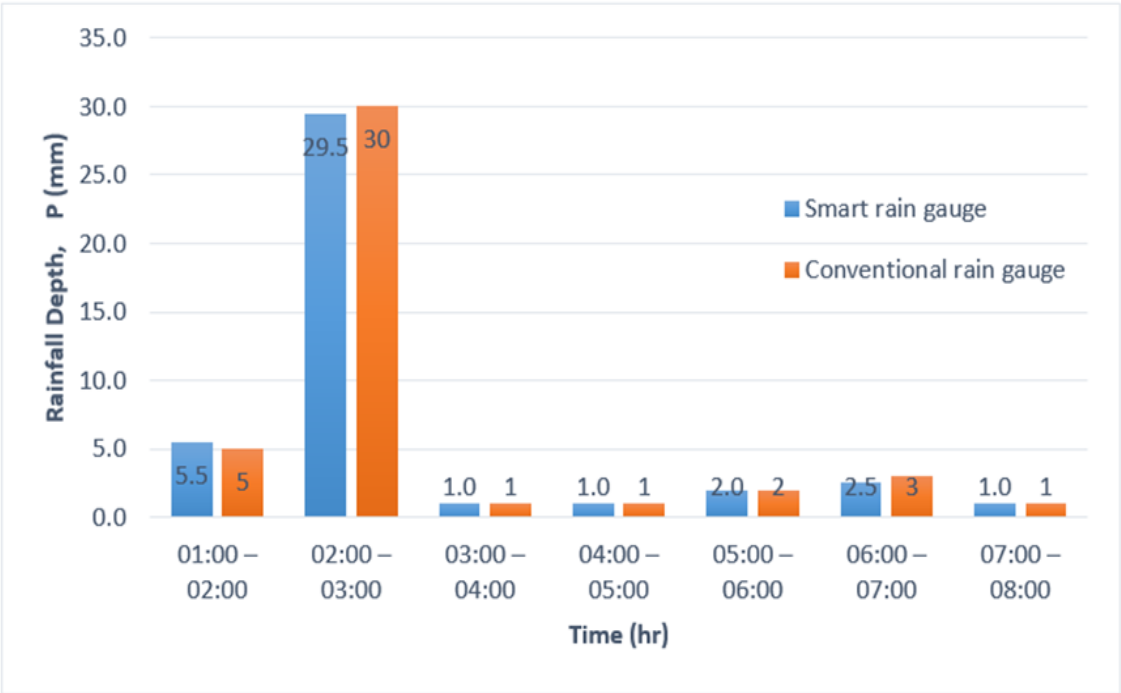
To calibrate the smart rain gauge, a conventional rain gauge (Figure 3.13) is put side by side. Rainwater droplets enter the opening of the device and accumulated within the tube.

The amount of rainwater collected in this device is compared with the previous device. It is expected the rainfall depths collected by both devices to be close with each other.

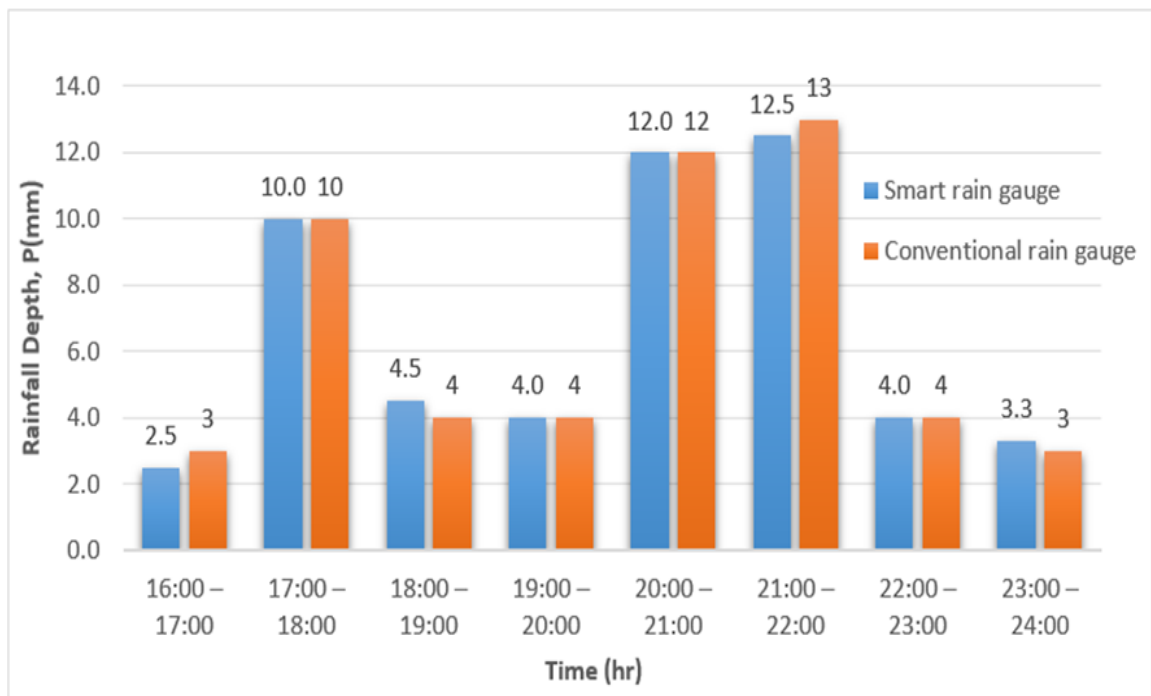


Figure 3.13: Conventional Rain Gauge

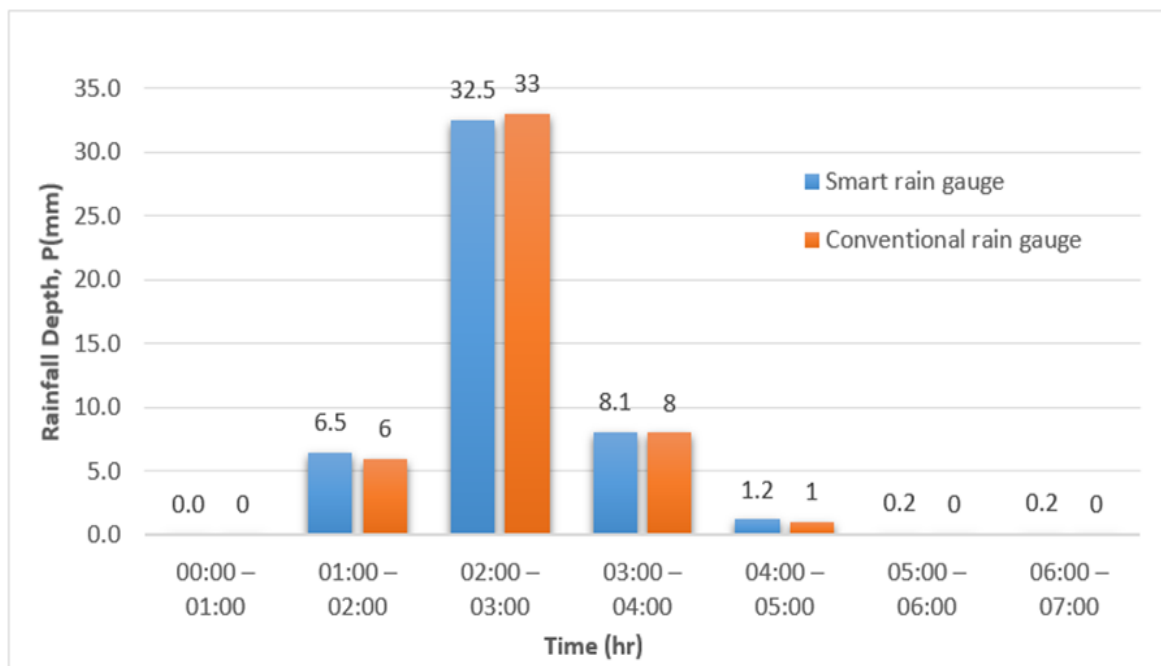
Presented in Figure 3.14, comparison of rainfall depths for three different storm events shows matching rainfall depths from both devices. It indicates the smart rainfall gauge is functioning properly. The detailed calibration data is available in Appendix A.



(a)



(b)



(c)

Figure 3.14: Calibration of Rain Gauge for (a) 1 December 2019, (b) 2 December 2019 and (c) 7 December 2019 Storm Events

3.4.2 Inflow

Referring to Ngu et al. (2016) study, more than 90% of flow inside the StormPav OSD is laminar in nature or the tank is stagnant in most part. Only less than 10% of flow is observed around the inlet and outlet areas. Based on such a report, it can be deduced that measurement of flow, in this case should focus on the inflow and outflow.

The inflow here refers to the roof runoff that is channelled by 0.1m diameter PVC downpipe. An inflow electromagnetic flowmeter (Figure 3.15) is installed on a segment of downpipe before discharging to the StormPav OSD to record the inflow flowrate. To calibrate on the flow data, a flow probe meter (Figure 3.16) is used to obtain the velocity of inflow, and then to calculate its associated flowrate for comparison.

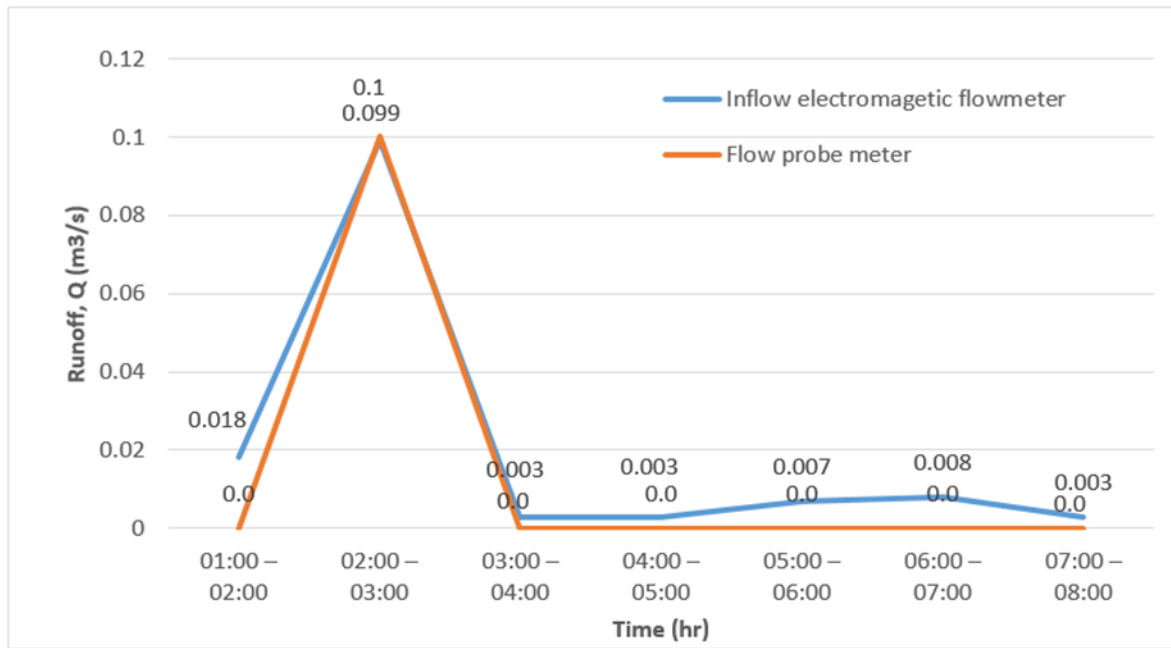


Figure 3.15: Inflow Electromagnetic Flowmeter

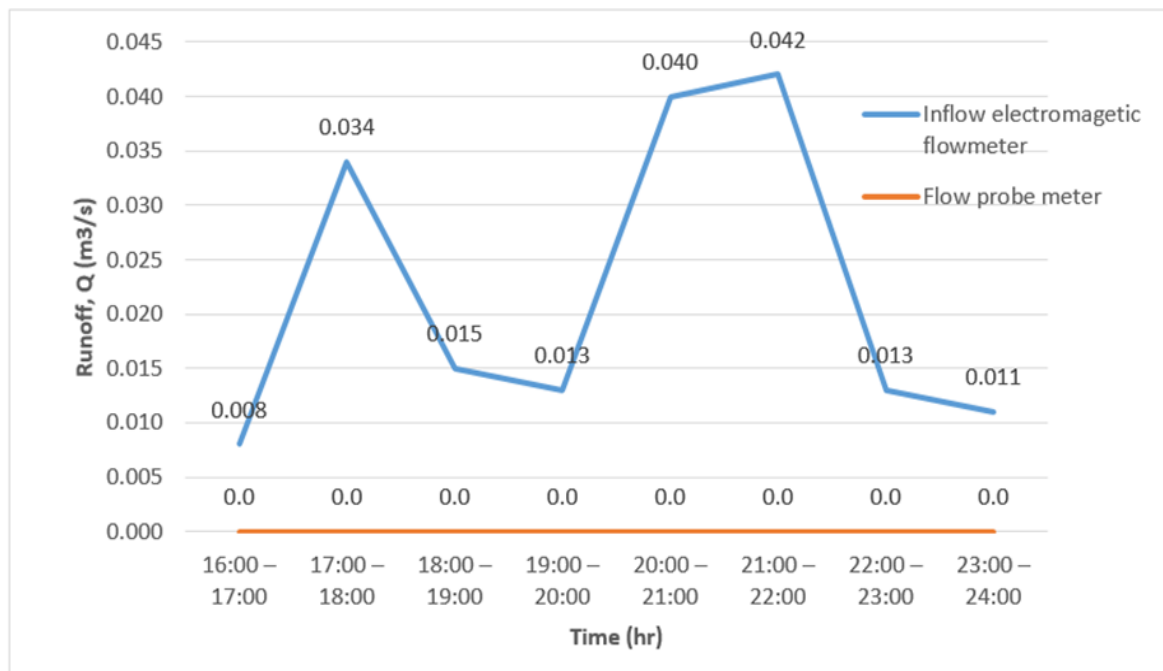


Figure 3.16: Water Flow Probe

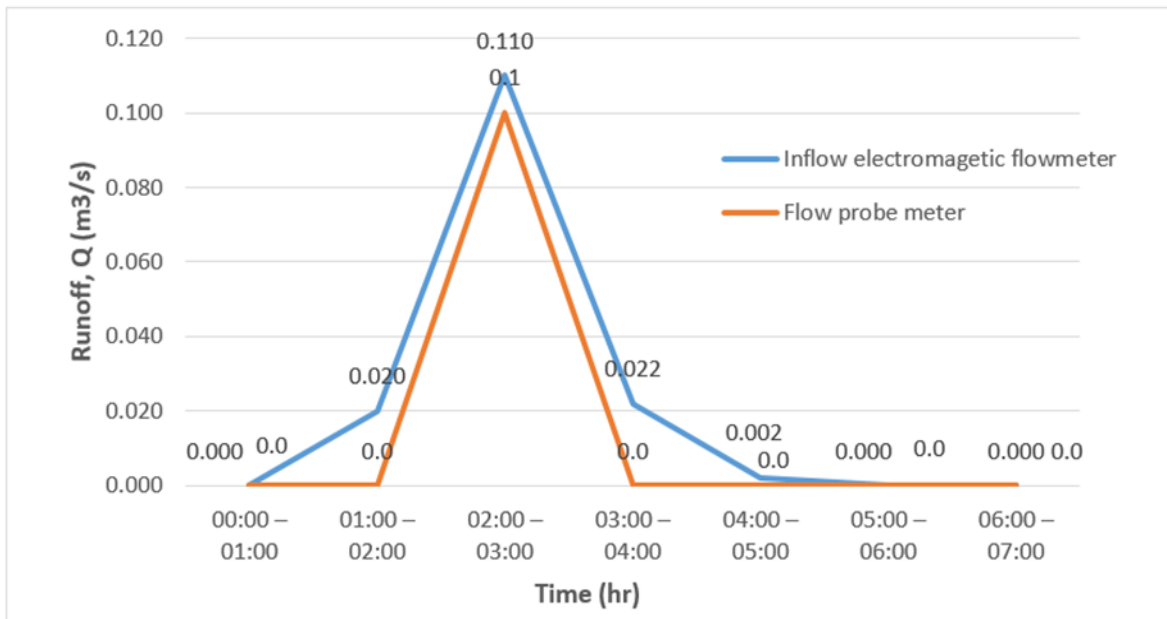
Presented in Figure 3.17, flow hydrographs recorded by the electromagnetic flow meter are compared with the calculated flow hydrographs from the flow probe meter. It is observed that the flow probe meter is less sensitive. For the case of 2 December 2019, the observed flows are below $0.1\text{m}^3/\text{s}$ and these are out-of-the-range of the flow probe. The other two events on 1 December 2019 and 7 December 2019 have observed flows above $0.1\text{m}^3/\text{s}$ and the peak flows and the general hydrograph shapes are found to match. As such, the inflow electromagnetic flowmeter is calibrated to function properly. The detailed calibration data is available in Appendix A.



(a)



(b)



(c)

Figure 3.17: Calibration of Inflow Electromagnetic Flowmeter for (a) 1 December 2019, (b) 2 December 2019 and (c) 7 December 2019 Storm Events

3.4.3 Water Level

On the other hand, the outflow is referred to the discharge through 0.05m diameter PVC outlet pipe that functions as a side orifice. An orifice is always related to the water level before the orifice. Therefore, two ultrasonic water level sensors (Figure 3.18) are obtained to record the water level in the StormPav OSD.

The StormPav modular units are not sealed but are allowed to rest freely. As such, water could seep among the modular units. Referring to Ngu et al. (2016) study, the water levels raise uniformly system wide. Although two units of water level sensor are installed at two different sides of the StormPav OSD, both are expected to return with similar water level reading.

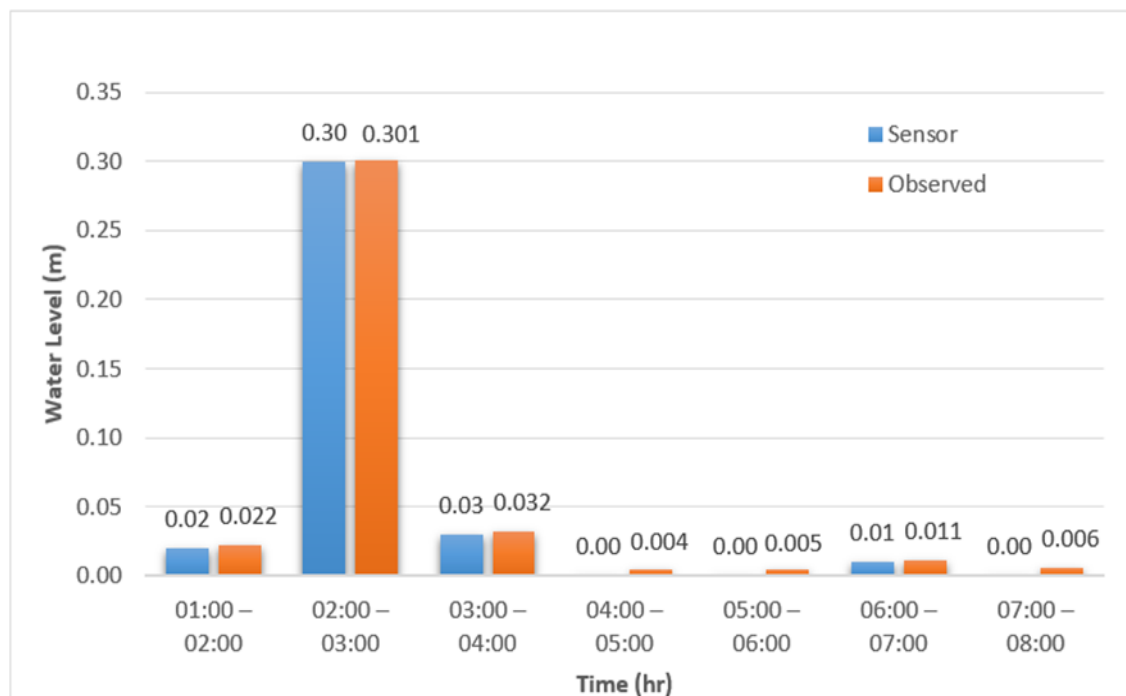


Figure 3.18: Ultrasonic Water Level Detector with Display

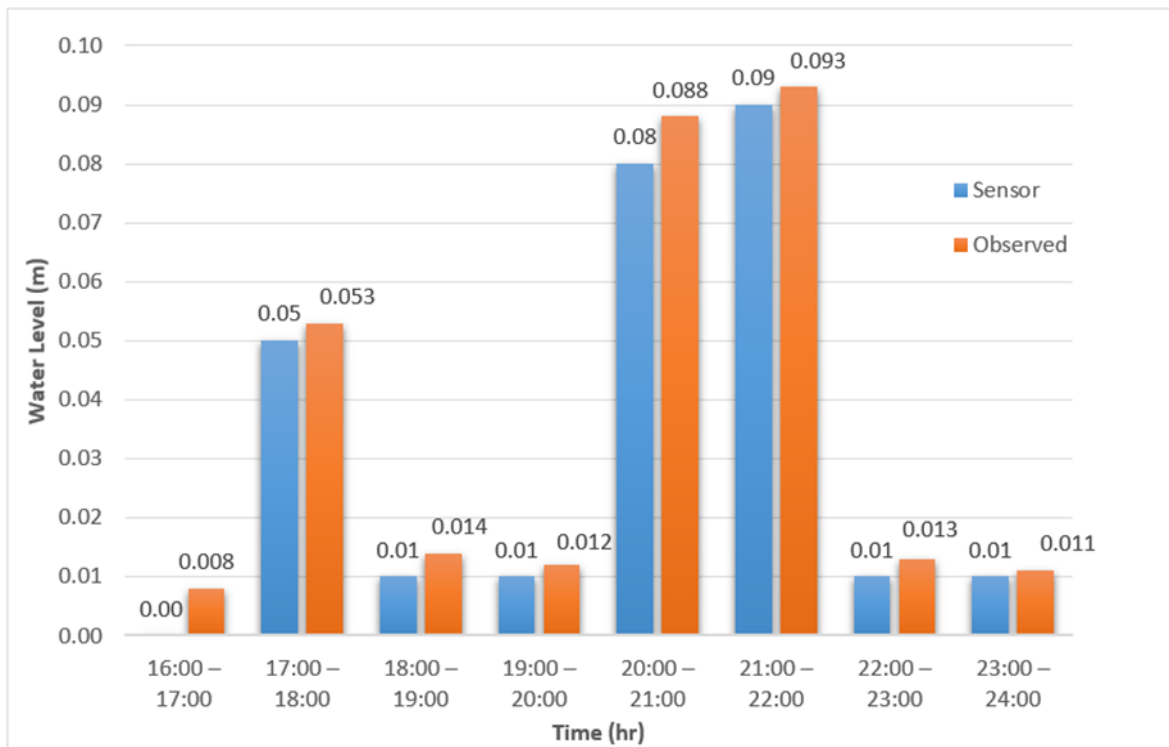
In order to calibrate the readings of the water level sensor, an ordinary ruler is stationed in one of the cylinder unit. The ruler functions as a measuring staff, in which water level could be read and recorded based on the water marking on the ruler (Figure 3.19). Presented in Figure 3.20, comparison between the readings by the water level sensor and observed water level readings is made using bar chart. It is found that both readings match each other. Therefore, the water level sensors are functioning properly. The detailed calibration data is available in Appendix A.



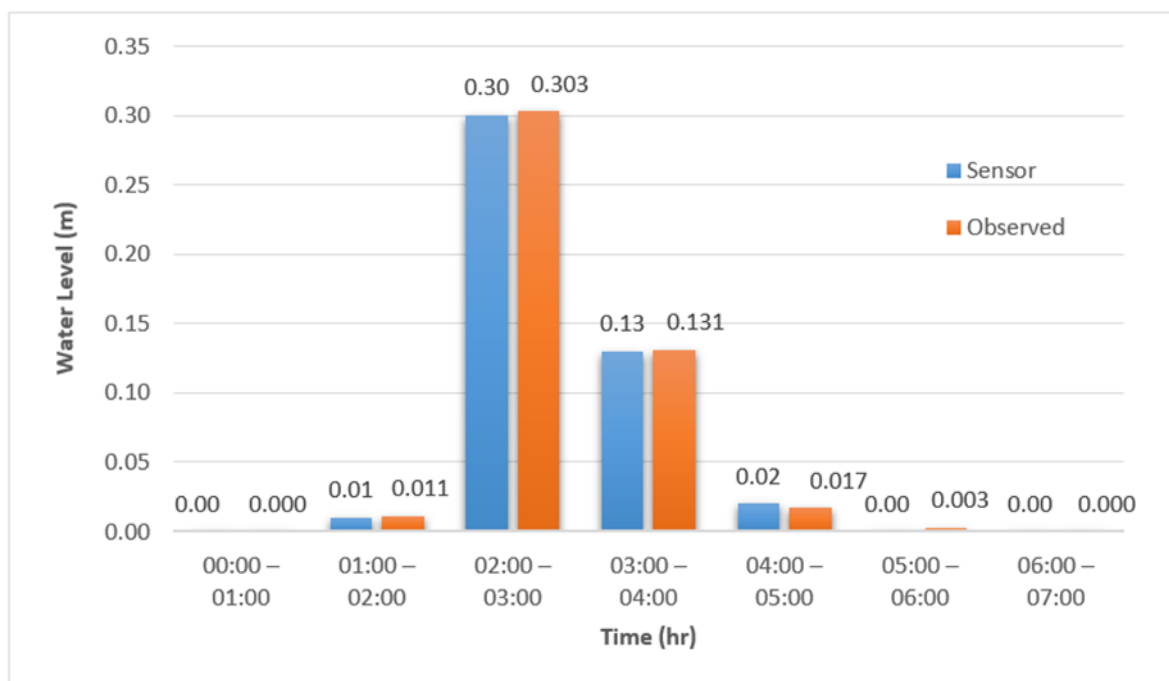
Figure 3.19: Ruler



(a)



(b)



(c)

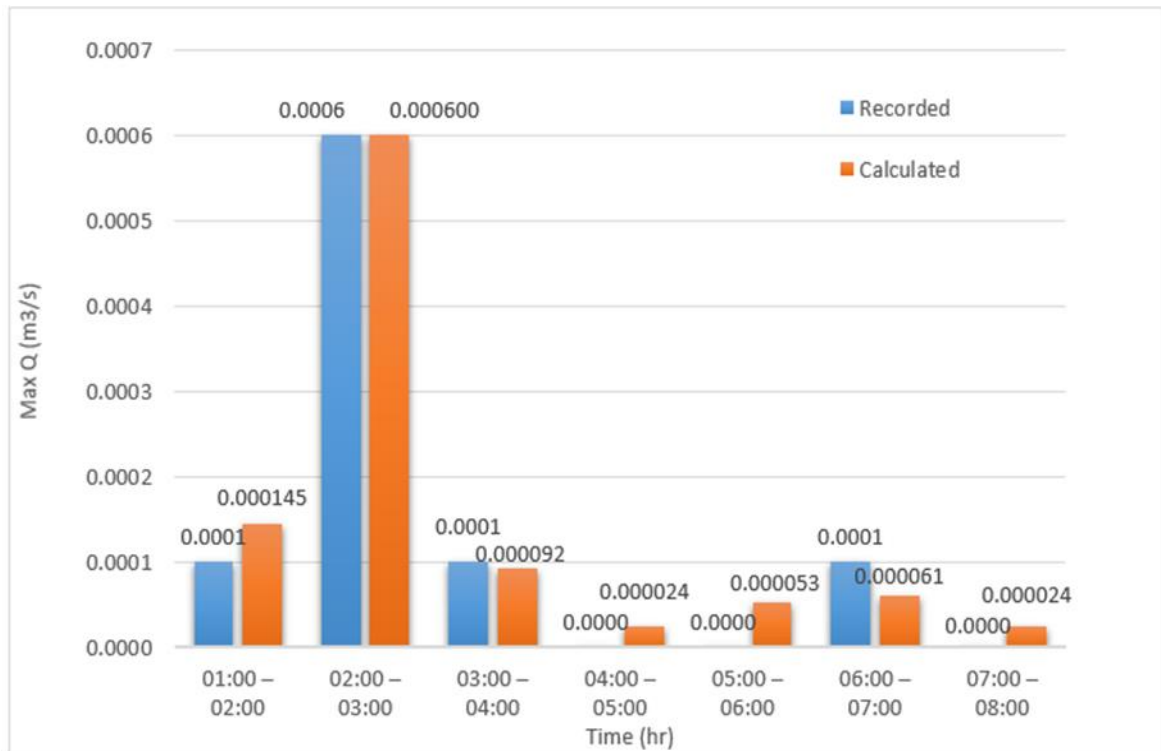
Figure 3.20: Calibration of Ultrasonic Water Level Sensor for (a) 1 December 2019, (b) 2 December 2019 and (c) 7 December 2019 Storm Events

3.4.4 Outflow

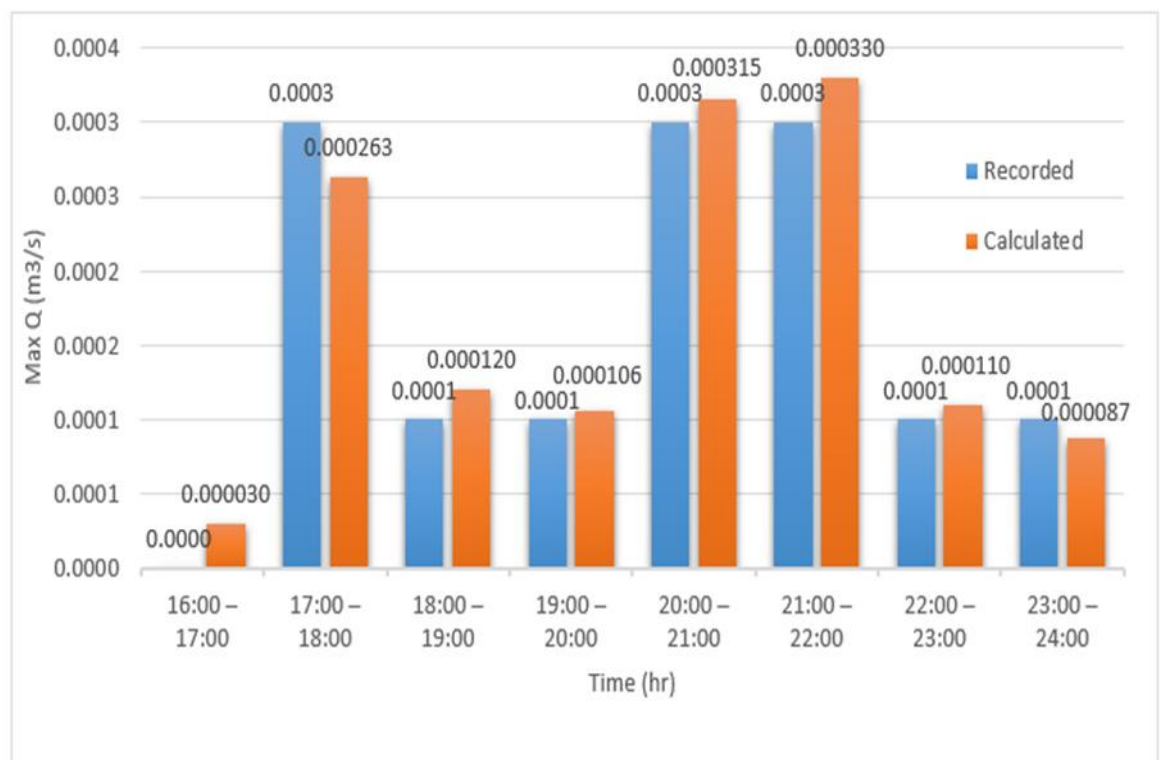
The outlet pipe is also equipped with a 0.05m diameter outflow electromagnetic flowmeter (Figure 3.21). The restricted flow out of the orifice is maintained uniformly depending on the water level before the orifice that provides the head to the water jet. However, the flow probe meter used at the inflow flow meter could not be applied here because the flow value is too small to be recorded by the probe. Calibration could only be done by applying the orifice equation. Comparison of the recorded and calculated orifice flows is presented in Figure 3.22. The results are matching and therefore, the outflow flowmeter is found functioning properly. The detailed calibration data is available in Appendix A.



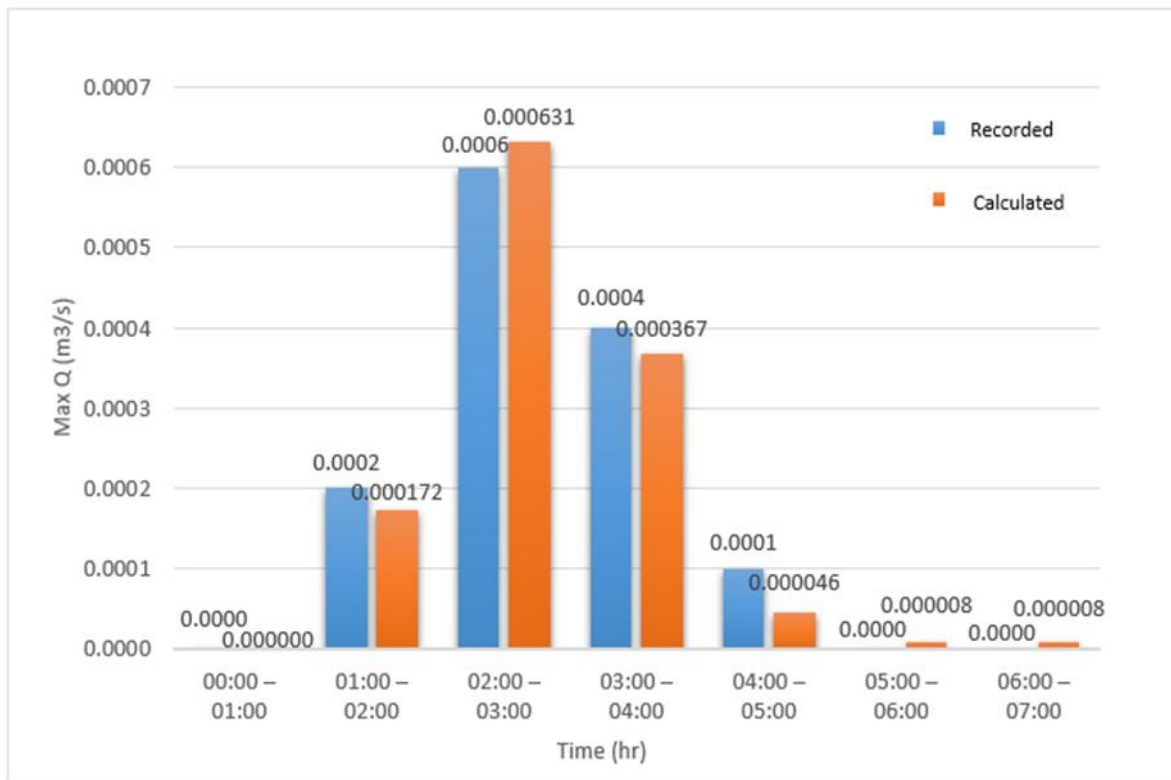
Figure 3.21: Outflow Electromagnetic Flowmeter



(a)



(b)



(c)

Figure 3.22: Calibration of Outflow Electromagnetic Flowmeter for (a) 1 December 2019, (b) 2 December 2019 and (c) 7 December 2019 Storm Events

Schematic diagram of the set-up of the measuring devices is presented in Figure 3.23. Being the field testing, it is a waiting game for the actual rainfall. As the devices are electromagnetic based, the necessary could be automatically detected and started recording. However, it is observed that the devices are less sensitive towards smaller rainfall (below 10mm of depth). Although the study area has significant rainfall throughout the year, it is foreseeing most smaller rainfall events could not be recorded satisfactorily. One of the reasons is being the size of the StormPav OSD result that rainwater could simply flow in and out without any ponding event when the rainfall is low intensity. Therefore, the monsoon months from November – February are the most ideal period to have high intensity rainfall that could fill up the StormPav OSD.

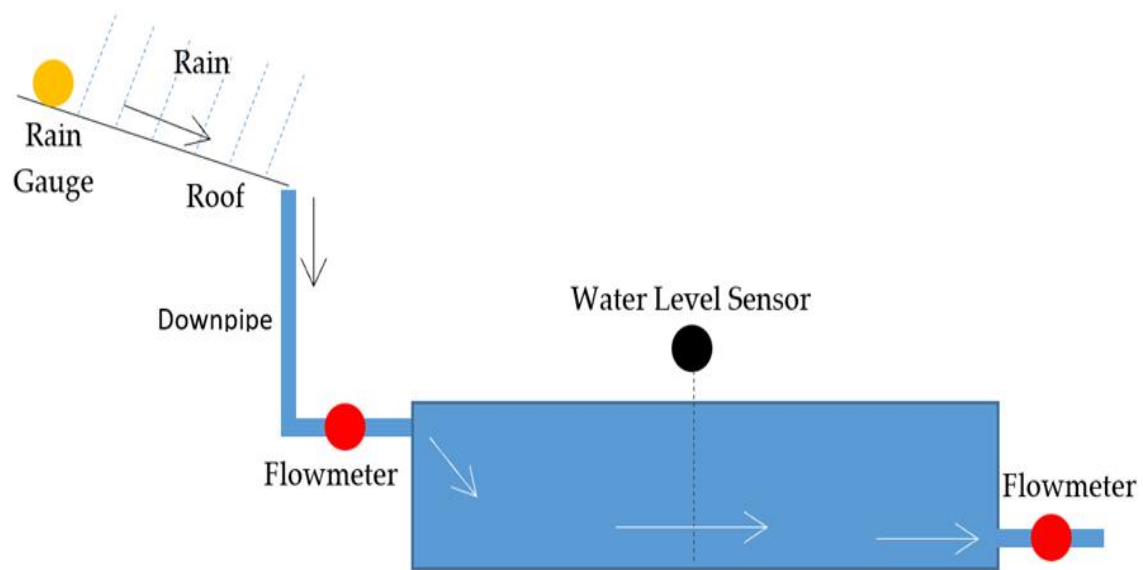


Figure 3.23: Set up of Measuring Devices

3.5 Configuration of Model

3.5.1 Validation

SWMM is used by Ngu et al. (2016) in modelling a StormPav OSD system. It is also evidence that SWMM is an efficient tool to represent stormwater system as listed in Table 2.1. However, it should be noted that StormPav is a multi-compartmental system, in which the arrangement of concrete pieces has created empty spaces to store and convey water. SWMM is not developed for this type of multi-compartmental system. As such, a modification is needed. Previous modelling efforts of StormPav are taking effective storage volume into the modelling. Effective storage volume is calculated by removing the solid concrete parts from the gross storage volume. These are observed in the works of Liow et al. (2019a; 2019b; 2019d) and Mah et al. (2020). These authors verified the developed SWMM models with analytical principles of water balance. With the availability of field data, the following characteristics could be validated in SWMM as the actual representation of StormPav OSD, in terms of:

3.5.2 Inflow Patterns

The flow characteristics from roof to downpipe at the moment entering the OSD could be validated. It represents the water source to the OSD.

3.5.3 Outflow Patterns

The flow characteristics due to the orifice outlet at the moment leaving the OSD could be validated. Orifice flow is important to influence the detention volume and time.

3.5.4 Water Level Patterns

The water level fluctuation within the StormPav OSD could be validated. Water levels are direct representation of detention volume of the system under study. As mentioned before that 90% of the system is laminar in nature, water level is a more dominant parameter than water velocity in the OSD.

3.5.5 Goodness of Fit

How good the match between the field and modelled data is quantitatively measured via a goodness of fit test. This study chooses the Kolmogorov-Smirnov Test (K-S Test) because it could be applied to any distribution and no restriction on sample size. The field data is mostly below 10 hours and consists of small samples. Therefore, the commonly used student's T-Test that needs at least 10 datasets is not suitable in this case.

The K-S Test is a non-parametric test used to compare two datasets and determine whether they follow the same distribution or come from the same population. In the context of this study, the K-S Test is used to evaluate how well the modelled data from the SWMM simulation matches the field data collected during the field testing of the StormPav OSD system.

The K-S Test works by calculating the maximum vertical distance (D) between the cumulative distribution functions (CDF) of the two datasets being compared. The test statistic D is used to determine the level of agreement between the datasets. If D is small and the associated p-value is high, it indicates that the modelled and observed data are likely to come from the same distribution, suggesting a good fit. On the other hand, if D is large and the p-value is low, it indicates a significant difference between the datasets, suggesting a poor fit.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Field Data Analysis

4.1.1 Timeline for Data Collection

After completing the field test and testing of leakage, field data collection is commenced. The data collection period spans for five months that includes the monsoon season and transition period (Table 4.1). The months of October and November are the beginning of Northeast Monsoon. Although not included in the timeline, the author is preparing and setting up the field test during the two months. The said monsoon usually peaks in December and January. Its influence weakens till March and April. After that, the Southeast Monsoon begins in May till September, in which Sarawak is known to experience dry season and the period is excluded from data collection. As such, the author has covered the most rainfall-sensitive period in Sarawak with the identified five months.

Table 4.1: Timeline for Data Collection

December 2019	January 2020	February 2020	March 2020	April 2020
Northeast Monsoon Season			Transition Period	

4.1.2 Frequency of Storm Events

Depicted in Table 4.2, the frequencies of storm duration over the data collection period are tabulated. December 2019 has the highest number of 58 storms with a monthly rainfall of 687.3 mm (mean 4.8 hours, median 2 hours and mode 2 hours). It is followed by January 2020 with 48 storms with a monthly rainfall of 883.4 mm (mean 4.4 hours, median

2 hours and mode 2 hours). The remaining three months are comparatively lowered in terms of storm number and rainfall depths. February 2020 has 30 storms with a monthly rainfall of 499.9 mm (mean 3 hours, median 3 hours and mode 1 hour). March 2020 has 29 storms with a monthly rainfall of 420 mm (mean 4.1 hours, median 3 hours and mode 3 hours). April 2020 has the least number of 21 storms with a monthly rainfall of 231.5mm (mean 3 hours, median 2 hours and mode 2 hours). The details of the collected rainfall data are available in Appendix B.

During the monsoon season, storm durations range from 1 hour to 15 hours. The highest frequency of storm duration is found at 1 hour (23% in Feb 2020), 2 hours (36% in Dec 2019, 37% in Jan 2020 and 33% in Apr 2020), and 3 hours (31% in Mar 2020). It is consistence that throughout the five months, the 1, 2 and 3 hours storms constitute to a strong majority compared to the 4 to 15 hours storms.

Table 4.2: Frequency of Storm Durations for Dec 2019 - Apr 2020

Storm Duration (hr)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
Frequency in Dec 2019	9	21	9	3	5	1	2	2	2	2	1	0	0	0	1	58
Frequency in Jan 2020	5	18	8	4	2	3	1	3	1	1	2	0	0	0	0	48
Frequency in Feb 2020	7	2	6	3	1	2	5	1	1	2	0	0	0	0	0	30
Frequency in Mar 2020	4	7	9	6	1	0	1	0	0	1	0	0	0	0	0	29
Frequency in Apr 2020	5	7	4	3	1	0	1	0	0	0	0	0	0	0	0	21

Table 4.2 continued

Total	3	5	3	1	1	6	1	6	4	6	3	0	0	0	1	186
	0	5	6	9	0		0									

4.1.3 Distribution of Storm Events

Distribution of hourly rainfall plots over the five months are presented in Figure 4.1. A dotted line is drawn across each of the sub-figures at 20 mm. It shows that majority of the storm events, namely 91% for December 2019, 86% for January 2020, 93% for February 2020, 86% for March 2020 and 90% for April 2020 are below the 20 mm mark. This 20 mm mark is selected due to the calculated 23 mm design rainfall depth that is associated with the shortest duration 5-min 10-year ARI design rainfall. The author is going to discuss about this 0-20 mm category in the following paragraphs. It should be noted the observed storm events with rainfall depths between 20-50 mm tally with assumption made in the design storm durations that are suggested for between 5 and 15 minutes. The relationship between these observed storm events and design rainfall lies in their relevance to the design and assessment of stormwater management systems. Storm events are compared to design rainfall to evaluate the system's capacity and performance under different intensities.

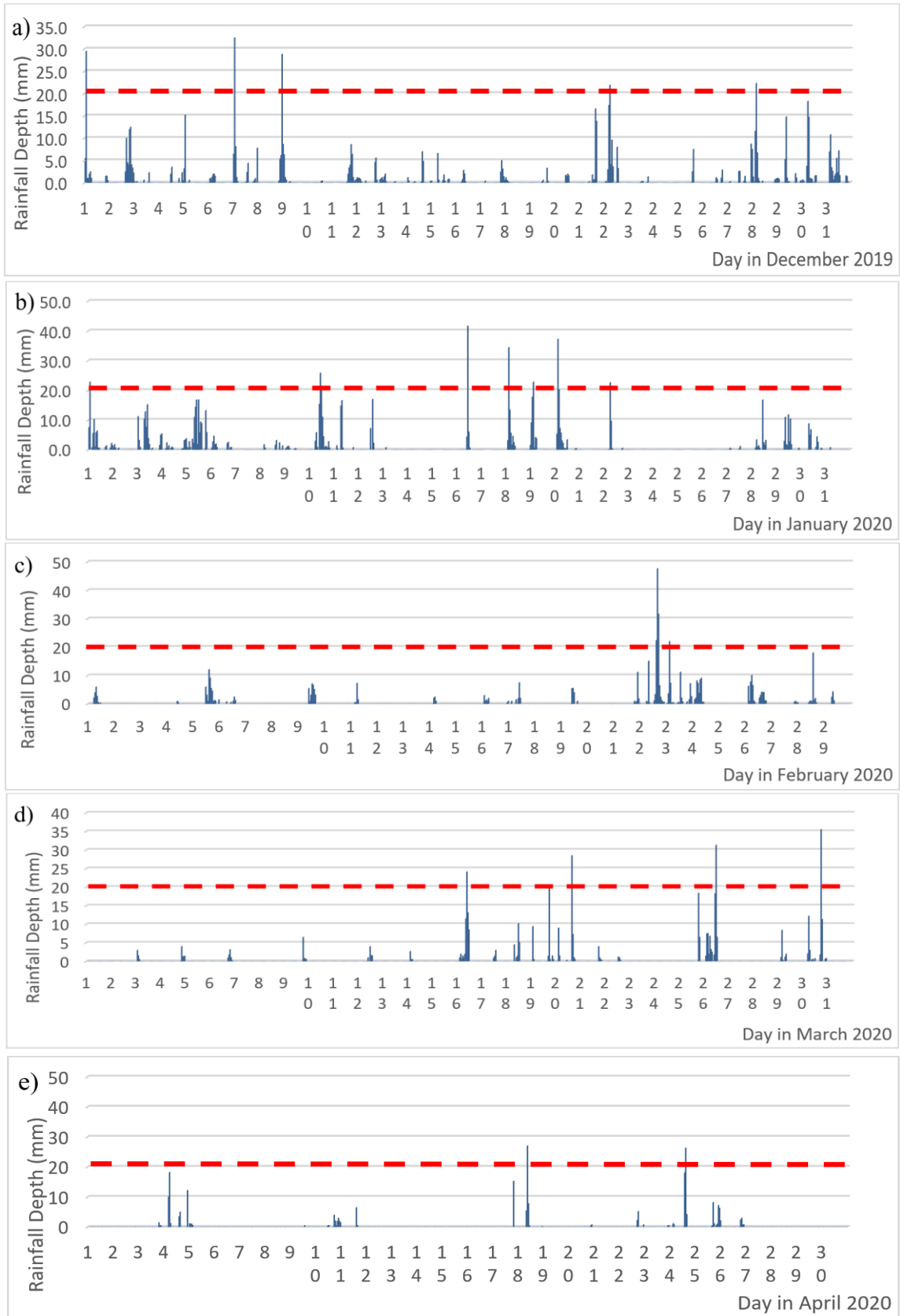


Figure 4.1: Hourly Rainfall Distribution in a) December 2019, b) January 2020, c) February 2020, d) March 2020, and e) April 2020

4.1.4 Classification of Rainfall Depth

A classification of the observed rainfall depths is presented in Table 4.3. The 20-30 mm category is set approximating the 5-min 10-year ARI design rainfall (23 mm). The 30-40 mm category is approximated to the 10-min 10-year ARI design rainfall (36 mm). Similarly, 40-50 mm category is approximated to the 15-min 10-year ARI design rainfall (46 mm). The majority of storm events that fall short of the 20 mm mark are classified as 0-20 mm category. The key difference between the three durations of 5-minute, 10-minute, and 15-minute 10-year design rainfall lies in the amount of rainfall intensity experienced over a specific period. The 5-minute 10-year design rainfall represents an extremely intense and short-duration rainfall event, signifying the maximum rainfall intensity expected to occur in a 5-minute period once in every ten years on average. On the other hand, the 10-minute 10-year design rainfall represents a slightly longer but still intense rainfall event, with the maximum rainfall intensity expected to occur in a 10-minute period once in every ten years on average. Lastly, the 15-minute 10-year design rainfall refers to a longer-duration rainfall event, but with less intensity compared to the previous two durations. It represents the maximum rainfall intensity expected to occur in a 15-minute period once in every ten years on average. These distinct durations play a critical role in understanding and assessing stormwater management strategies and their effectiveness under various rainfall scenarios.

Table 4.3: Rainfall Depths for Dec 2019 - Apr 2020

Rainfall Depth (mm)	Number of Event					Total
	Dec 2019	Jan 2020	Feb 2020	Mar 2020	Apr 2020	
0 - 20	53	41	28	25	19	166
20 – 30	2	4	1	2	2	11

Table 4.3 continued

30 – 40	3	2	0	2	0	7
40 - 50	0	1	1	0	0	2
Total	58	48	30	29	21	186

As summarized in Table 4.4, there are six events in the 20-30 mm category; five events in the 30-40 mm category and two events in the 40-50 mm category. Before the discussion of these three categories, first justifies the 0-20 mm category with three selected storm events.

Table 4.4: Selected Observed Storm Events for Analysis

Category (mm)	Date	Storm Duration (hr)	Peak Rainfall (mm)	Accumulative Rainfall (mm)	Remarks
0- 20	30 Dec 2019	7	18	39.6	Not in the range of Design Rainfall
	2 Dec 2019	8	12.5	52.8	
	11&12 Dec 2019	15	8.6	31.6	
20-30	1 Jan 2020	2	22.8	30.4	Near to 5-min 10-year ARI Design Rainfall
	22 Jan 2020	4	22.6	32.8	
	19 Jan 2020	7	22.8	60	
	22 Dec 2019	8	21.9	60	
	28 Dec 2019	9	22	59.6	

Table 4.4 continued

	10 Jan 2020	11	25.8	84.8	
30-40	7 Dec 2019	5	32.5	48.5	Near to 10-min 10-year ARI Design Rainfall
	1 Dec 2019	7	29.5	42.5	
	8 & 9 Dec 2019	8	28.8	57.6	
	18 Jan 2020	8	34.4	66.4	
	20 Jan 2020	11	37.2	85.6	
40-50	16 Jan 2020	4	41.6	52.6	Near to 15-min 10-year ARI Design Rainfall
	22 Feb 2020	10	47.6	117.5	
	22 Feb 2020	10	47.6	117.5	

4.1.4.1 Rainfall Depth in between 0-20 mm Category

Observed inflow, outflow, and detained water level hydrographs for storm events with 0-20 mm rainfall depth are presented in Figure 4.2. Among the three events, 11 & 12 December 2019 storm has the lowest peak rainfall (8.6 mm) but the storm spans for fifteen hours. However, the resulted inflow and outflow hydrographs are all most similar in hydrograph shape indicating a flow through system. Water flows in and flows out without any detention as it is evidence that water level is not reaching the full size of its orifice outlet. The other two events of 30 Dec 2019 (peak rainfall 18 mm) and 2 Dec 2019 (peak rainfall 12.5 mm) have repeated the flow through system like the former case.

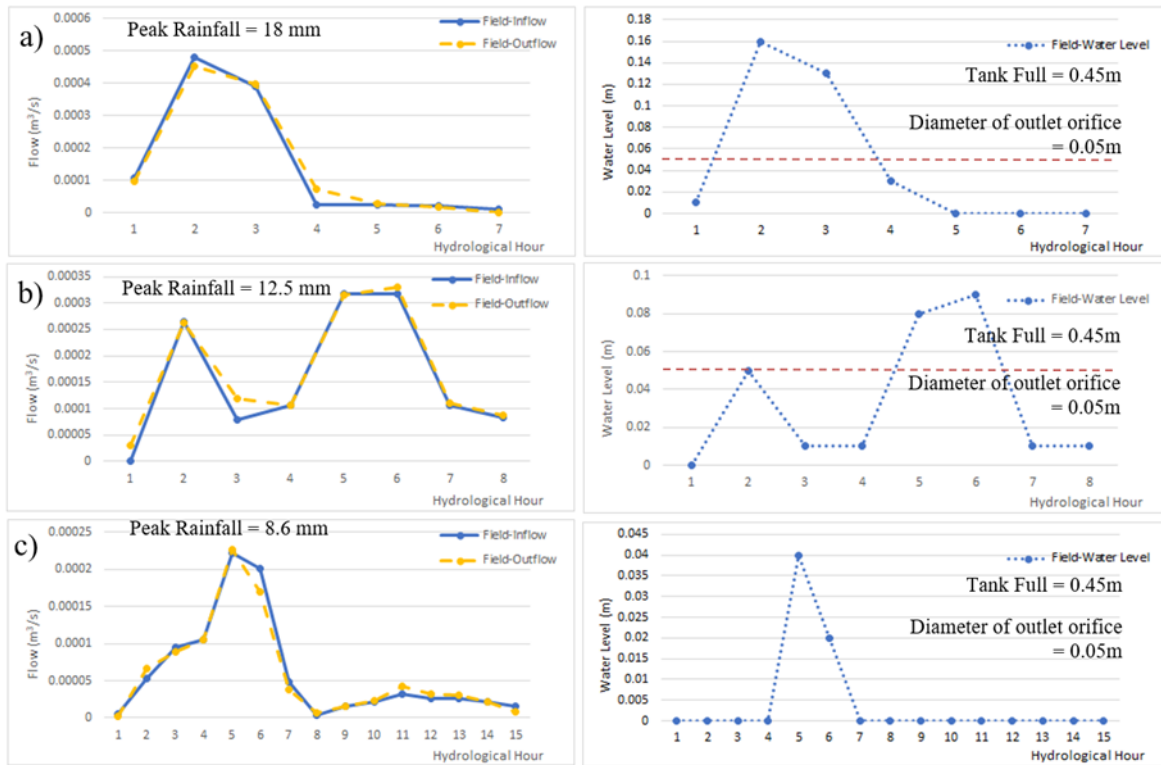


Figure 4.2: Observed Inflow, Outflow and Water Level Hydrographs for a) 30 Dec 2019, b) 2 Dec 2019 and c) 11 & 12 Dec 2019 Storm Events

These three events are selected due to its 7-15 hours long storm durations (as compared to the mean 4-5 hours during December 2019). The author presumes the long duration storms would generate greater water detention, but it is found not happening in the field test. All three events demonstrate flow through characteristics with no detention (for below 10 mm rainfall depth) and little water detention (for above 10 mm rainfall depth).

As such, the same observation could be extended to other shorter duration storms in the same category. The 1-, 2- and 3-hour storms that form the highest frequency events as well as identified as median and mode events from December 2019 to April 2020 are expected to have the similar said characteristics. The author therefore deduces this category as insignificant storm events.

4.1.4.2 Rainfall Depth in between 20-30 mm Category

The selected six storm events under this category have storm durations spanning from 2 to 11 hours, practically the best representing the typical storm duration range (1 to 15 hours) identified in Table 4.2. Peak rainfall values are ranging from 22-25 mm and are taken as near to the 5-min 10-year ARI design rainfall with an estimated 23 mm rainfall depth. In order to assess the design rainfall data against the observed data, the author has presented the design inflow, outflow and detained water level hydrographs in Figure 4.3, along with the observed hydrographs of the six storm events.

Comparison could not be made with the lag time between peak rainfall and peak flow as it is observed the events demonstrate diverse lag times and different from each other; nor with the lag time between peak inflow and peak outflow as it is prevalence both all most peak at the same time in all cases. Similarly, the rising limb, recessing limb and base time are so diversified that the author could not discern a meaningful pattern. However, the attenuation rates, namely the difference between the peak inflow and peak outflow demonstrate a constant pattern throughout the selected storm events. Attenuation rate is a critical parameter, as the more the attenuation is achieved, the more the water is detained in the detention system. The area between the inflow and outflow hydrographs are the volume of detained water.

It should be noted that the design peak inflow in Figure 4.3a has a relatively high flow value of $0.007 \text{ m}^3/\text{s}$ when compared to the six observed events in Figure 4.3b to Figure 4.3g that record only $0.0006\text{-}0.0007 \text{ m}^3/\text{s}$. The difference is starkly about 90%. This could be explained with the computation of the design peak inflow is an assumption that the design rainfall is continuously and consistently falling for 5 minutes over a targeted catchment. In

both Figure 4.3b and Figure 4.3d, the peak rainfall intensity is the same. However, the resulting hydrological outcomes differ significantly due to a crucial factor - the duration of the rainfall.

Due to the difference in design and observed inflows, the attenuation rates are also starkly different. The design approach has estimated an attenuation rate of 93% between the design inflow and outflow peaks. However, the average attenuation rate about 20% is observed from the field data. Individual attenuation rates are 19% for 1 January 2020, 32% for 22 January 2020, 17% for 19 January 2020, 23% for 22 December 2019, 29% for 28 December 2019 and 22% for 10 January 2020.

On the other hand, the design peak outflow estimated at $0.0005 \text{ m}^3/\text{s}$ matches with the observed storm events that record a range of $0.0005\text{-}0.0006 \text{ m}^3/\text{s}$. Outflow data is not influenced by the varied rainfall data but by the characteristics of the detention volume and water level that provide water head to allow free flow through the orifice outlet. The design water level estimated at 0.2 m matches well with the observed water levels of the storm events that are recorded in the range of 0.2-0.25 m.

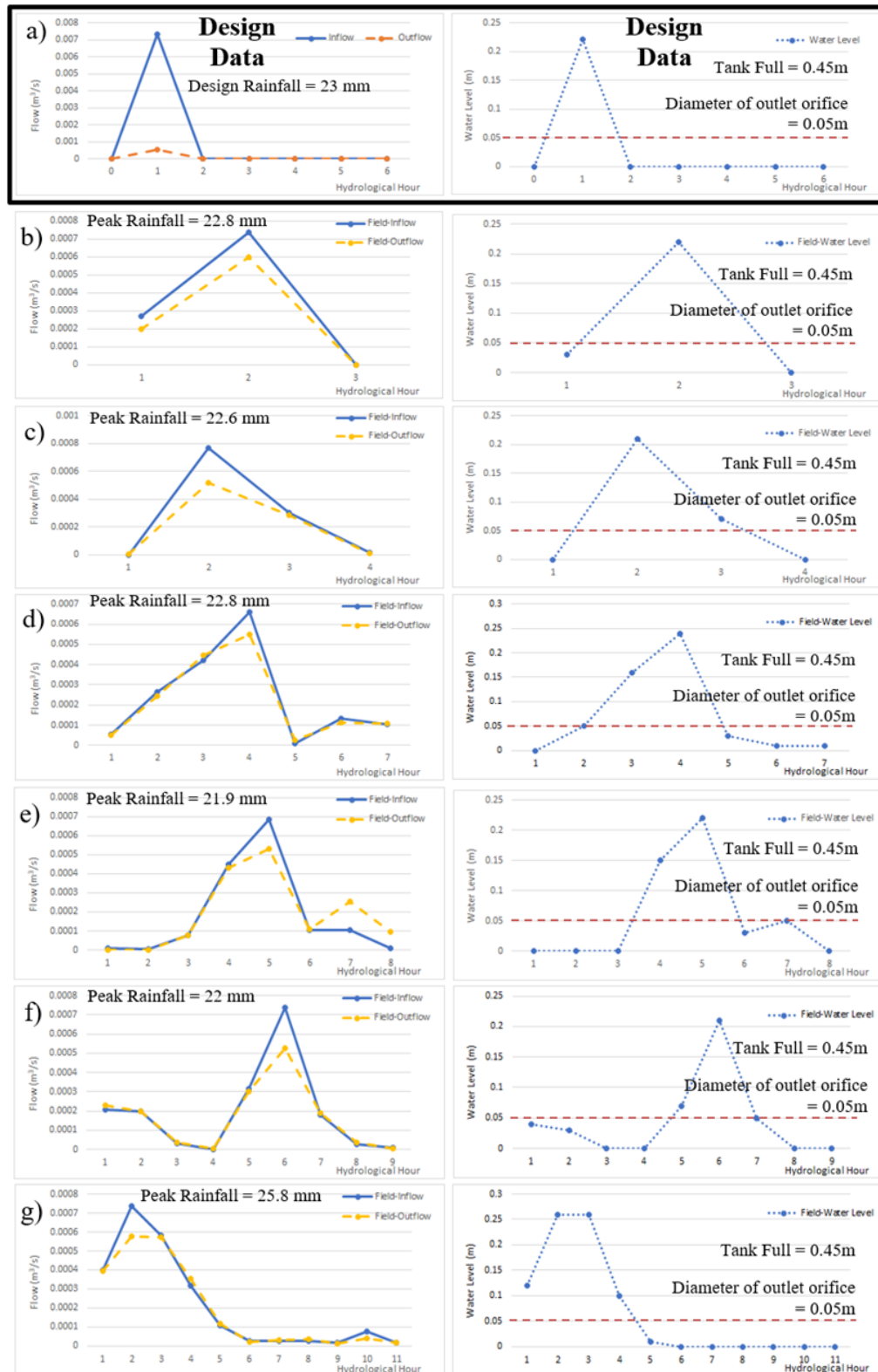


Figure 4.3: Inflow, Outflow and Water Level Hydrographs for a) 5-min Design Rainfall, b) 1 Jan 2020, c) 22 Jan 2019, d) 19 Jan 2020, e) 22 Dec 2019, f) 28 Dec 2019 and g) 10 Jan 2020 Storm Events

4.1.4.3 Rainfall Depth in between 30-40 mm Category

Five storm events are available as representatives of 30-40 mm rainfall depth category. These are near to the 10-min 10-year ARI design rainfall estimated with 36 mm rainfall depth. In terms of storm duration, these events range from 5 to 11 hours. Referring to Table 4.2 that shows the typical storm durations (1-15 hours), this category lacks representatives from the shorter storm events (1-4 hours). In fact, there is none such a short storm recorded with rainfall depth approaching 30 mm during the data collection period.

Out of the five events, two events that are 1 December 2019 and 8 & 9 December 2019 have observed peak rainfall depths of 29.5 mm and 28.8 mm respectively. These two if rounded up, the rainfall depths are close to 30 mm. Furthermore, its observed inflows ($0.0008\text{--}0.001\text{ m}^3/\text{s}$) are out of the range for the inflow in 20-30 mm category ($0.0006\text{--}0.0007\text{ m}^3/\text{s}$). Therefore, the author deduces that these two events are more appropriate in this category instead. As such, the observed rainfall depths of this category range from 28.8 mm to 37.2 mm.

Similar with the previous category, the design data are presented together with the five observed data in Figure 4.4. Significant difference is observed when comparing the design inflow and observed inflows. By design, it is estimated to have a peak design inflow of $0.006\text{ m}^3/\text{s}$. However, the observed inflows come back with values range from 0.0009 to $0.001\text{ m}^3/\text{s}$ that register a difference of 83-85%. The reason has been discussed in the previous sub-section due to the different approaches in design rainfall and actual rainfall.

Attenuation rate comparing the peak inflow and outflow for this category is found repeating the patterns observed in the 20-30 mm rainfall depth category. The design data has estimated an attenuation rate of 89%. However, the observed datasets have stark different

attenuation rate value that averaging at 30%. Individual attenuation rates for each storm are 32% for 7 December 2019, 31% for 1 December 2019, 40% for 8 & 9 December 2019, 29% for 18 January 2020 and 33% for 20 January 2020. However, that needs to be revised.

On the other hand, the observed parameters of outflow and detained water level are found matching with the design data. This observation is also a repeating pattern from the previous category. The design peak outflow estimated at $0.0006 \text{ m}^3/\text{s}$ matches with the observed storm events that record a range of $0.0006\text{-}0.0007 \text{ m}^3/\text{s}$. The design water level estimated at 0.3 m matches well with the observed water levels of the storm events that are recorded in the range of 0.3-0.35 m.

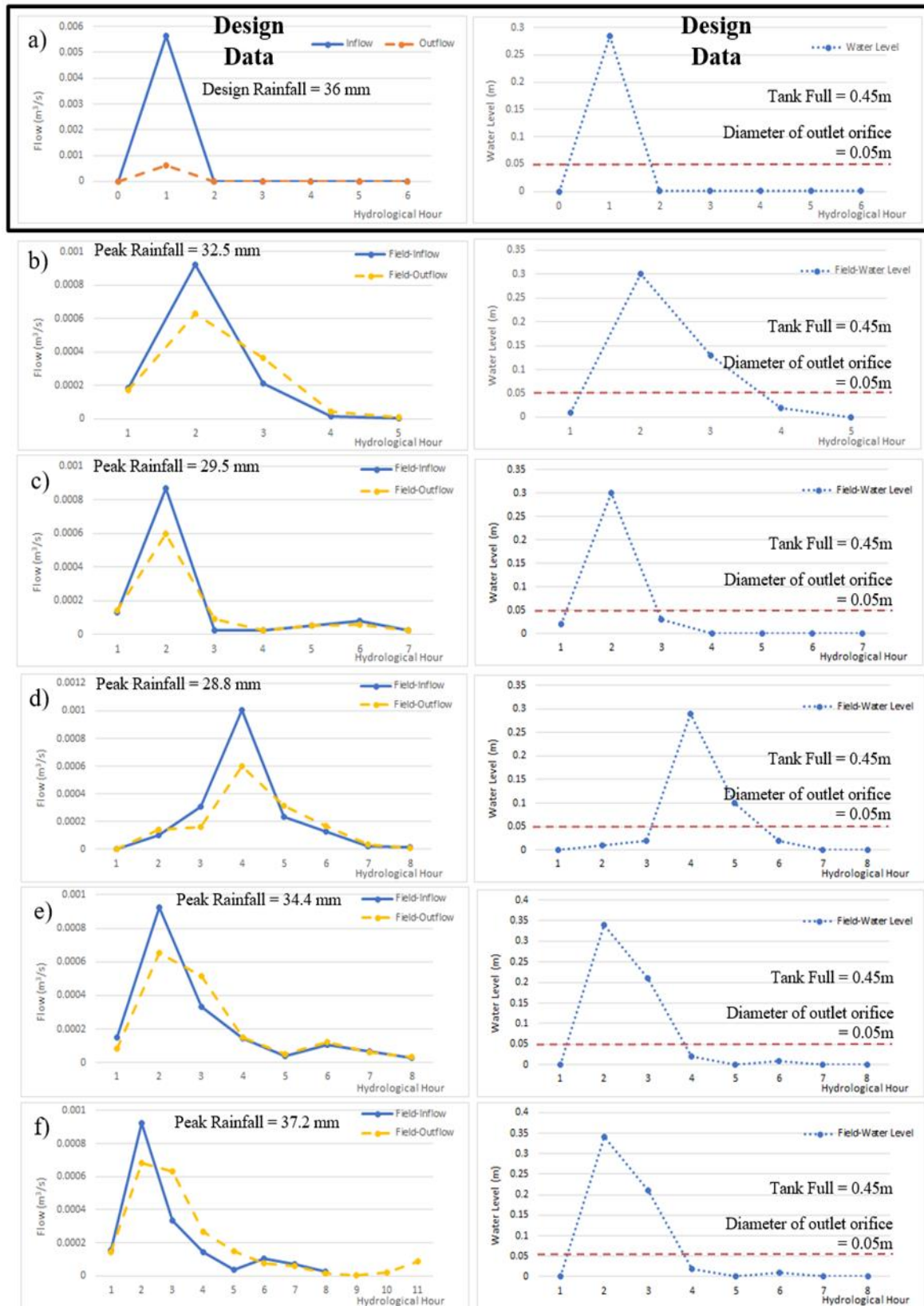


Figure 4.4: Inflow, Outflow and Water Level Hydrographs for a) 10-min Design Rainfall, b) 7 Dec 2019, c) 1 Dec 2019, d) 8 & 9 Dec 2019, e) 18 Jan 2020 and f) 20 Jan 2020 Storm Events

4.1.4.4 Rainfall Depth in between 40-50 mm Category

Storm events approaching 40 mm rainfall depth are rare. Only two events are recorded during the data collection period. The first event happened on 16 January 2020 with a peak rainfall of 41.6 mm. The second event happened on 22 February 2020 with a peak rainfall of 47.6 mm. These storm events have 4- and 10-hour storm durations respectively. Referring to the typical storm duration (1-15 hours), this category lacks representatives of medium length storms between 5-9 hours.

Despite the low number of observed storms and poor representative of typical storm duration, the shortcoming over this category is over-shadowed by the 22 February 2020 event. Flash flooding was reported within the residential area on the day. That made the said storm event an extreme event. Overflowing was observed in the field test and a photo of the StormPav OSD system is captured and presented in Figure 4.5. Although the water level is merely 1-2 cm above the StormPav plates, having the water flowing out of the system has indicated failure. Overflow pipe should be installed for safety purposes.



Figure 4.5: Overflowing due to 22 February 2020 Storm Event

Design and field data for this 40-50 mm rainfall depth category are presented in Figure 4.6. Patterns observed in the previous two categories are reinstated here. Design inflow for 15-min 10-year ARI design rainfall is estimated at $0.005 \text{ m}^3/\text{s}$. However, the field data are recorded otherwise much lower values ranging from $0.001\text{-}0.002 \text{ m}^3/\text{s}$. The difference is as high as 80%. In terms of attenuation rate between the peak inflow and outflow, design data has estimated an attenuation rate of 86%. Both observed storm events have recorded the same attenuation rate of 36%.

On the other hand, the observed parameters of outflow and detained water level are found matching with the design data. This observation is also a repeating pattern from the previous two categories. The design peak outflow estimated at $0.0007 \text{ m}^3/\text{s}$ matches with the observed storm events that record a range of $0.0007\text{-}0.001 \text{ m}^3/\text{s}$. The design water level estimated at 0.35 m matches with the observed water levels of the storm events that are

recorded in the range of 0.4-0.47 m. The maximum difference of the design water level and observed water level is 0.12 m.

From Figure 4.6b about the 16 January 2020 storm event, peak rainfall of 41.6 has caused a maximum water level of 0.4 m in the system, leaving about 0.05 m before overflowing. Next on Figure 4.6c about the 22 February 2020 storm event, peak rainfall of 47.6 mm has caused a maximum water level of 0.47 m, breaching the 0.45 m tank-full mark. If limit this category to a range of 40-50 mm, the former (41.6 mm) is the lower limit, while the latter (47.6 mm) is upper limit. Both indicate the design approach (46 mm rainfall depth) has underestimated the design water level (maximum 0.35 m of water level) in Figure 4.6a. Observed water levels, on the other hand, show risk of nuisance flooding from the home-based OSD.

Previous study has assumed the 15-min 10-year ARI design rainfall or 46 mm rainfall depth as the worst-case scenario, in which the design of StormPav OSD is based on. Procedure wise, this step is appropriate. However, as mentioned in the previous paragraph, the design water level is underestimated based on the newly obtained field data. It is found that the current setup of StormPav OSD poses risk of overflowing for rainfall depth approaching 40-50 mm. But it is safe from overflowing for rainfall depth below 40 mm.

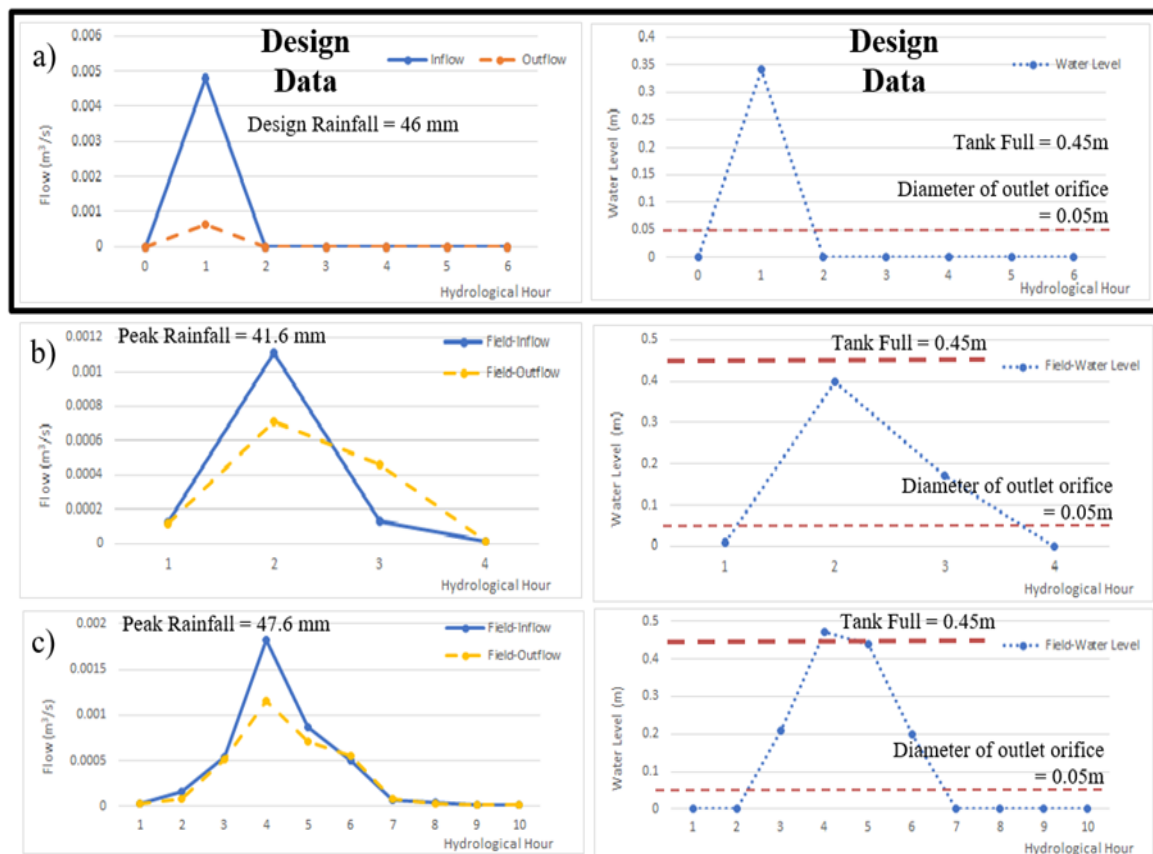


Figure 4.6: Inflow, Outflow and Water Level Hydrographs for a) 15-min Design Rainfall, b) 16 Jan 2020 and c) 22 Feb 2020 Storm Events

4.1.5 Summary

Thirteen significant storm events which are the primary data collected from the field test are analyzed. A summary is tabulated in Table 4.5.

Table 4.5: Summary of Design and Field Data

Category of Rainfall Depth	Inflow (m³/s)		Outflow (m³/s)		Attenuation (%)		Water Level (m)	
	Design	Field	Design	Field	Design	Field	Design	Field
20-30 mm (near 5-min 10-year ARI design rainfall)	0.007	0.0006-0.0007	0.0005	0.0005-0.0006	90	20	0.2	0.2-0.25

Table 4.5 continued

30-40 mm (near 10-min 10-year ARI design rainfall)	0.006	0.0008- 0.001	0.0006	0.0006- 0.0007	89	30	0.3	0.3- 0.35
40 mm & above (near 15- min 10-year ARI design rainfall)	0.005	0.001- 0.002	0.0007	0.0007- 0.001	86	36	0.35	0.4- 0.47*

Note: * indicating risk of flooding

Four repetitive patterns are consistence throughout the three rainfall depth categories:

- i. Observed peak inflows are found 80-90% lower than the design peak inflows due to the different approaches in design rainfall and actual rainfall;
- ii. Due to the differences in the observed peak inflows, the observed attenuation rates are much lowered than the design values, averaging at 20% for 20-30 mm, 30% for 30-40mm and 36% for 40-50 mm categories, in which it has also lowered the anticipated detention volumes;
- iii. Observed peak outflows are found matched with the design peak outflows; and
- iv. Observed detained water levels are matched with the design water levels and yet, the design water level for 40-50 mm category is underestimated and the observed water levels for the same category are posing flooding risk to the household environment.

The current setup of StormPav OSD system is safe from flooding for 20-30 mm and 30-40 mm rainfall depth categories; or in another words, it could accommodate 5- and 10-min 10-year ARI design rainfalls. But, not for the 40-50 mm rainfall depth category, or the

15-min 10-year ARI design rainfall unless improvement is carried out to lower the resultant water level in the OSD.

4.2 Model Validation

4.2.1 Developed SWMM Model

The process flow of simulating a stormwater detention system involves: 1) Rainfall; 2) Interception of rainfall and generation of runoff by a catchment; 3) Flow mechanism into a stormwater structure; 4) Controlled flow at outlet; and 5) Final discharge point. These five stormwater components are represented at the centre of Figure 4.7, along with the finalized parameters applied to each of the components in SWMM adhering to the field test setup.

Stormwater system starts with rainfall. SWMM represents rainfall with “Rain Gauge”, in which modellers input the time series of rainfall data in this component. In this case, the data collected from the field test are inputted as rainfall depth. Secondly, the catchment in this case is referring to the house’s side canopy as a “Subcatchment”. It is defined as 0.0095 ha with a catchment width of 9.5 m, slope of 0.03% and 100% impervious.

After the roof catchment, the generated roof runoff is directed to the roof gutter and downpipe. These are not modelled explicitly. The author has tried out with and without the gutter/downpipe modelling and it is found the flow data is dominant by the catchment characteristics. The roof catchment is large enough to have a strong flow that taken over the restriction of gutter/downpipe. Therefore, it is continued as without gutter/downpipe. Running water enters the StormPav detention system and it is modelled as a “Storage Unit” that is defined as tabular “Storage Curve” outlining the effective storage.

The detained water is leaving via an “Orifice” outlet. It is defined as bottom circular with a diameter of 0.05m and a discharge coefficient of 0.13. Lastly, the final discharge point is represented by an “Outfall” in SWMM. With the exposed of these parameters, the developed SWMM model for StormPav OSD could be duplicated for any future studies by interested parties.

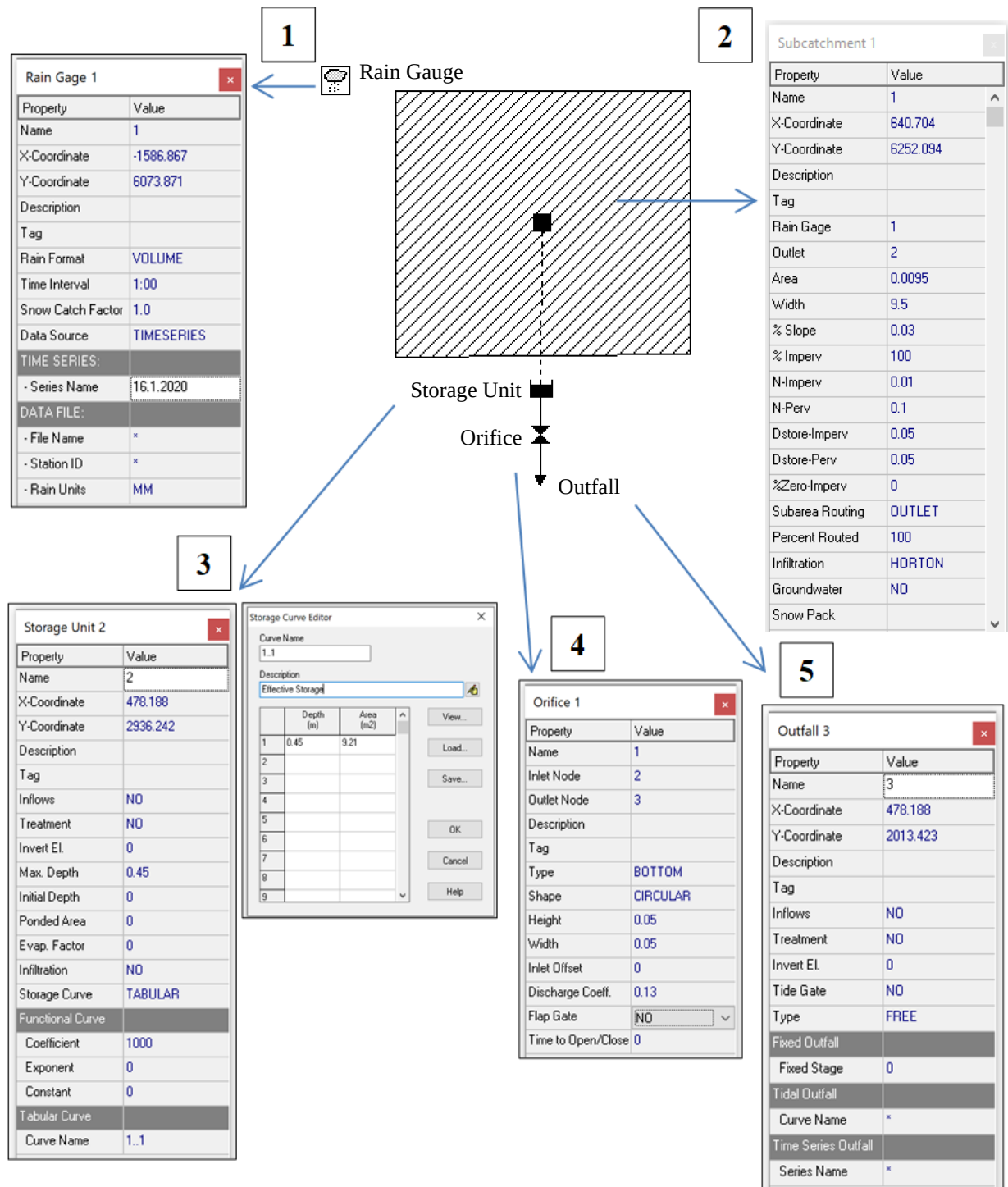


Figure 4.7: Configurations of Developed SWMM Model

4.2.2 Comparison of Field and Model Hydrographs

The purpose of this sub-section is to compare how well SWMM model representing the actual performance of the StormPav OSD. Observed three storm events highlighted in the 0-20 mm rainfall depth category, along with the six storm events in the 20-30 mm category, five storm events in the 30-40 mm category and two storm events in the 40-50 mm category are simulated using the developed SWMM model.

Inflow, outflow and water level hydrographs obtained from the field are plotted against inflow, outflow and water level hydrographs from the SWMM model. These are presented in Figure 4.8 for 0-20 mm category, Figure 4.9 for 20-30 mm category, Figure 4.10 for 30-40 mm category and Figure 4.11 for 40-50 mm category. The field data are plotted in lines with markers, while the model data are with markers only. These figures demonstrate the visual comparison of the two datasets which generally aligned. The details are available in Appendix C. How well match of these plots is quantitatively measured in the next sub-section.

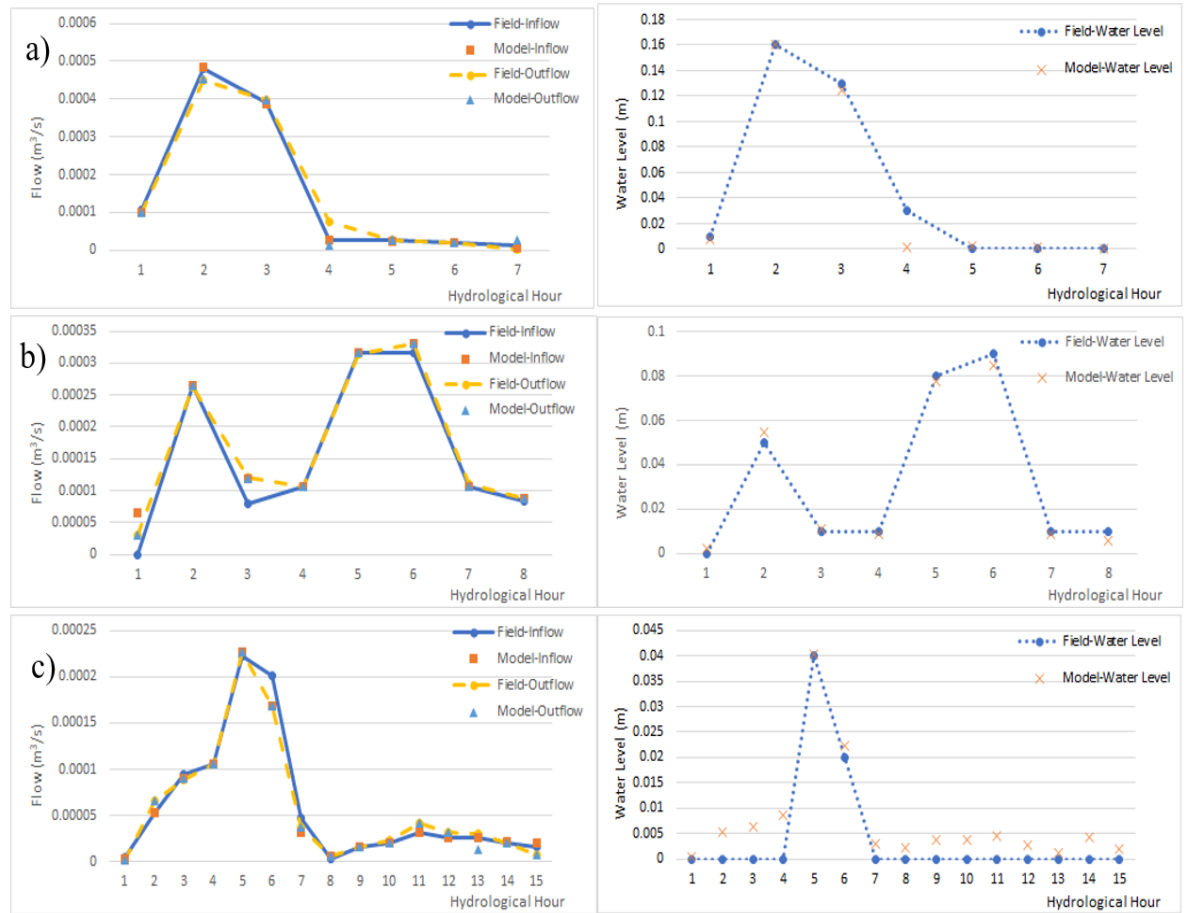


Figure 4.8: Model Validation in between 0-20 mm Rainfall Depth Category, a) 30 Dec 2019, b) 2 Dec 2019 and c) 11 & 12 Dec 2019 Storm Events

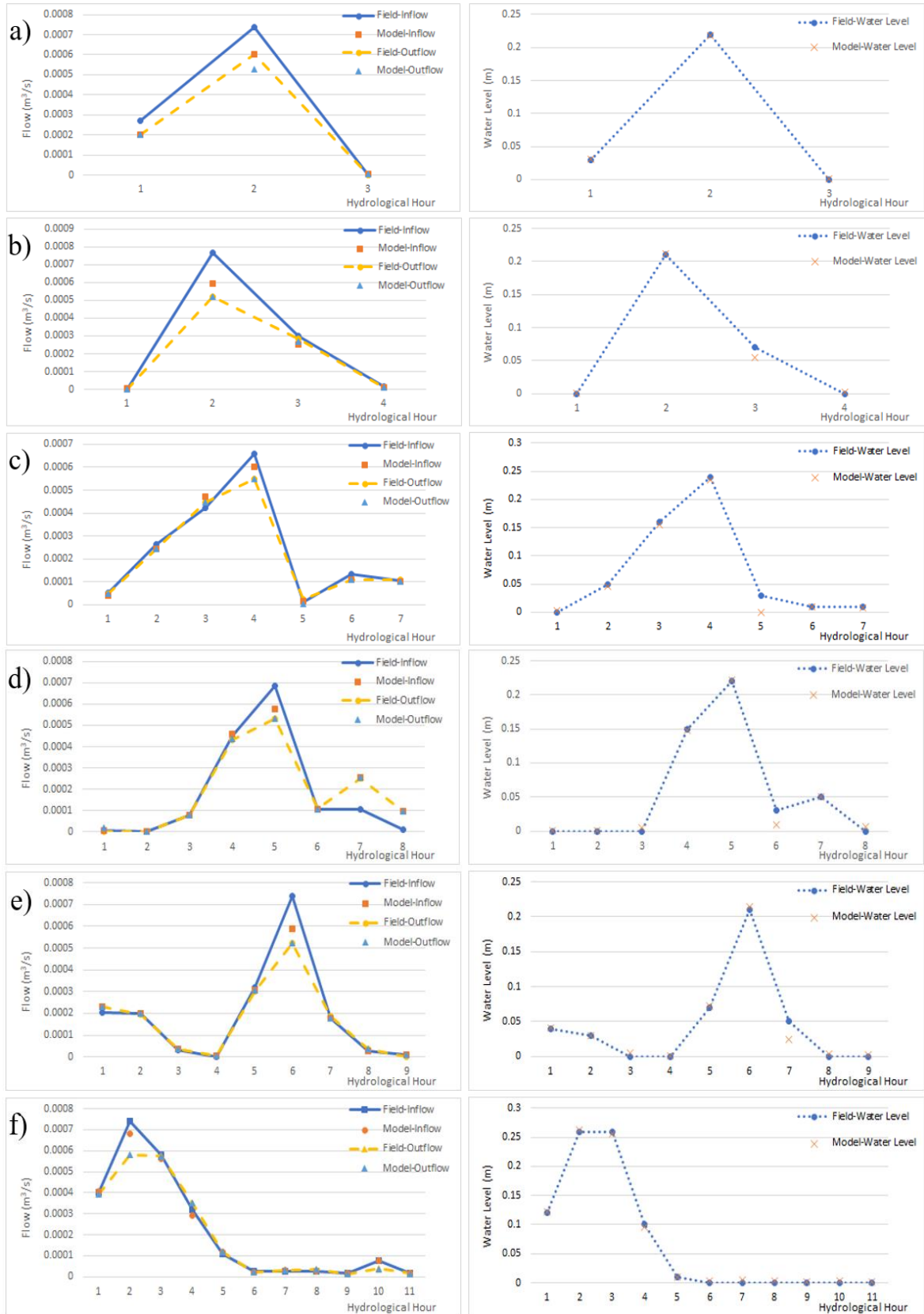


Figure 4.9: Model Validation in between 20-30 mm Rainfall Depth Category, a) 1 Jan 2020, b) 22 Jan 2019, c) 19 Jan 2020, d) 22 Dec 2019, e) 28 Dec 2019 and f) 10 Jan 2020 Storm Events

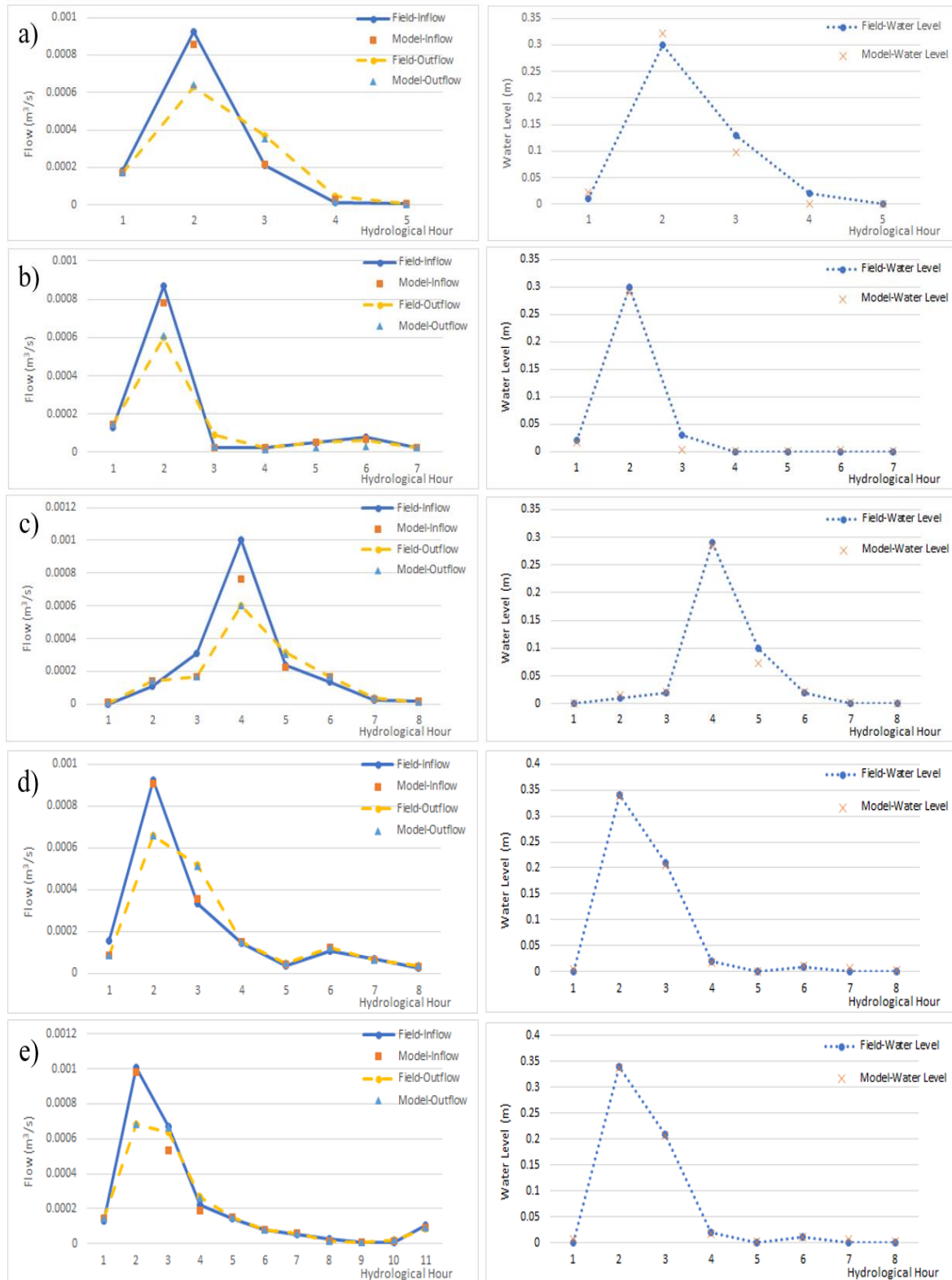


Figure 4.10: Model Validation in between 30-40 mm Rainfall Depth Category, a) 7 Dec 2019, b) 1 Dec 2019, c) 8&9 Dec 2019, d) 18 Jan 2020 and e) 20 Jan 2020 Storm Events

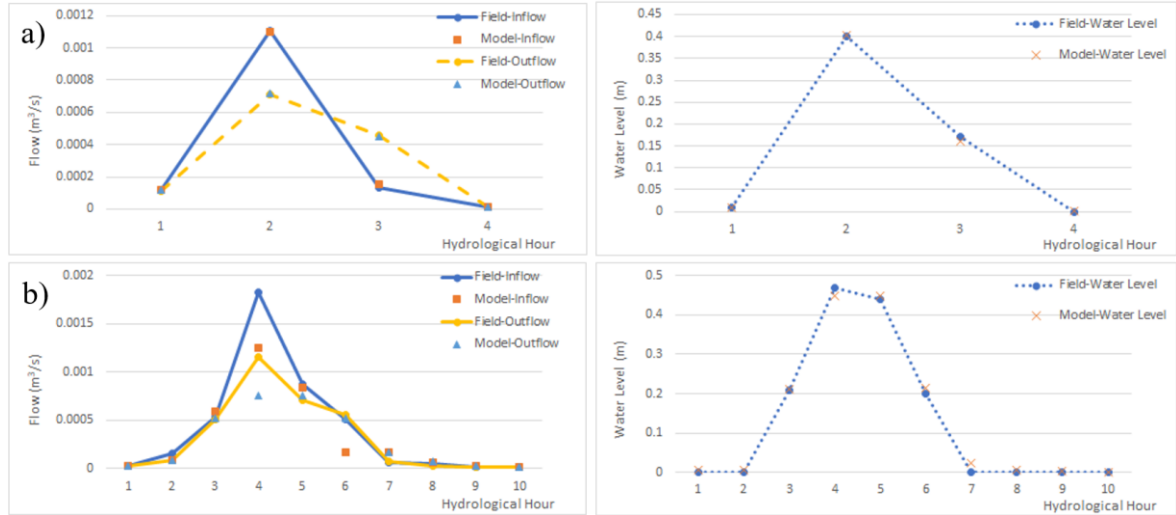


Figure 4.11: Model Validation in between 40-50 mm Rainfall Depth Category, a) 16 Jan 2020 and b) 22 Feb 2020 Storm Events

4.2.3 Goodness of Fit

K-S Test is the statistical tool used to measure the goodness of fit. The outcomes are presented in Figure 4.12 for 0-20 mm category, Figure 4.13 for 20-30 mm category, Figure 4.14 for 30-40 mm category and Figure 4.15 for 40-50 mm category. The details of the analysis are available in Appendix D.

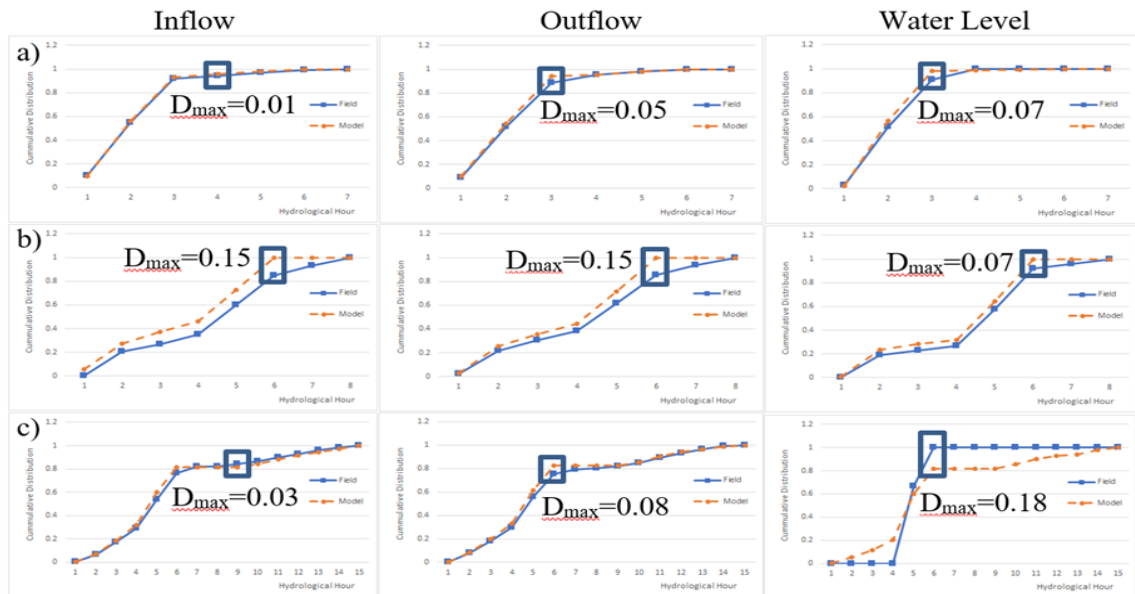


Figure 4.12: K-S Test for 0-20 mm Rainfall Depth Category, a) 30 Dec 2019, b) 2 Dec 2019 and c) 11 & 12 Dec 2019 Storm Events

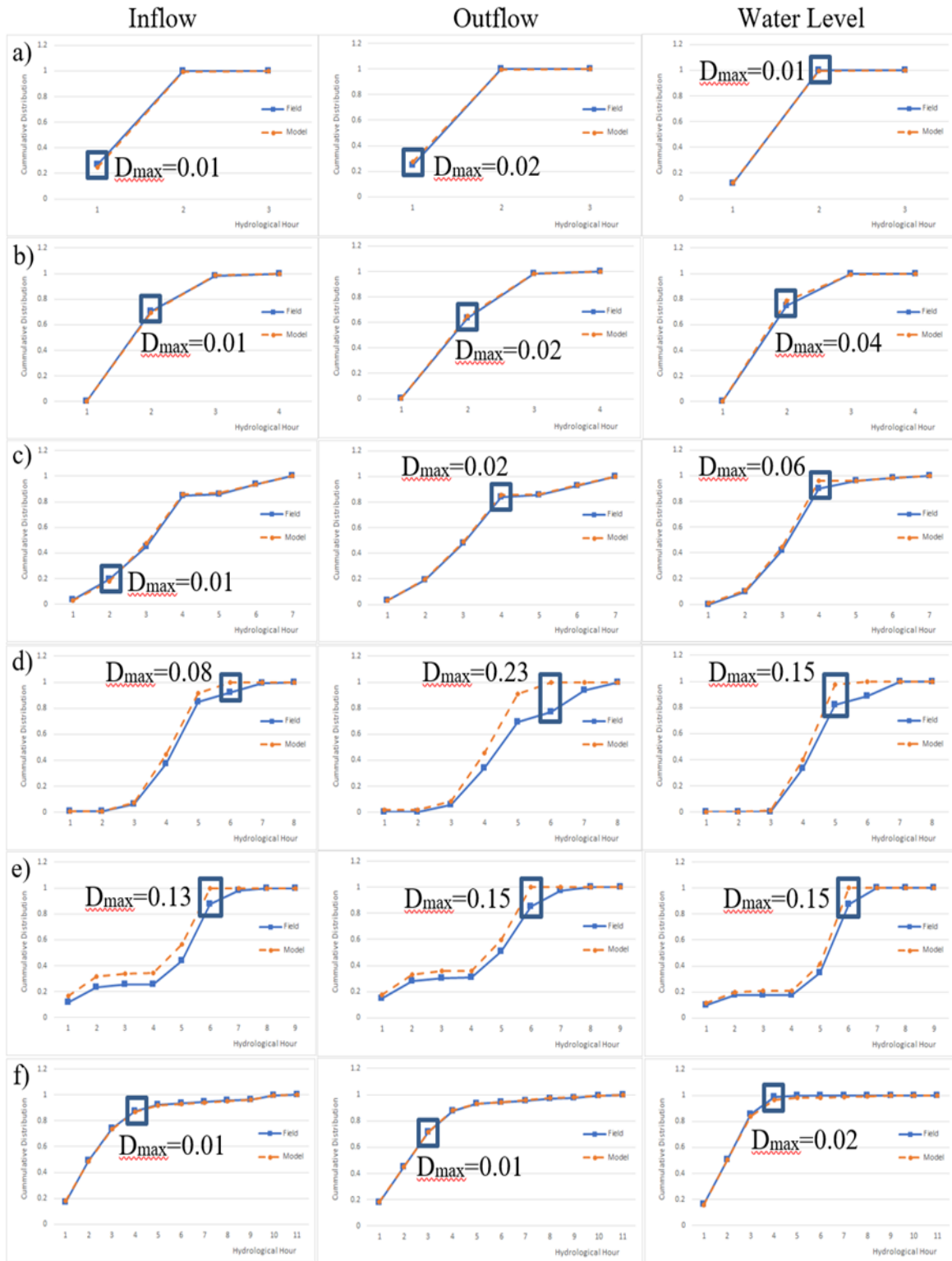


Figure 4.13: K-S Test for 20-30 mm Rainfall Depth Category, a) 1 Jan 2020, b) 22 Jan 2019, c) 19 Jan 2020, d) 22 Dec 2019, e) 28 Dec 2019 and f) 10 Jan 2020 Storm Events

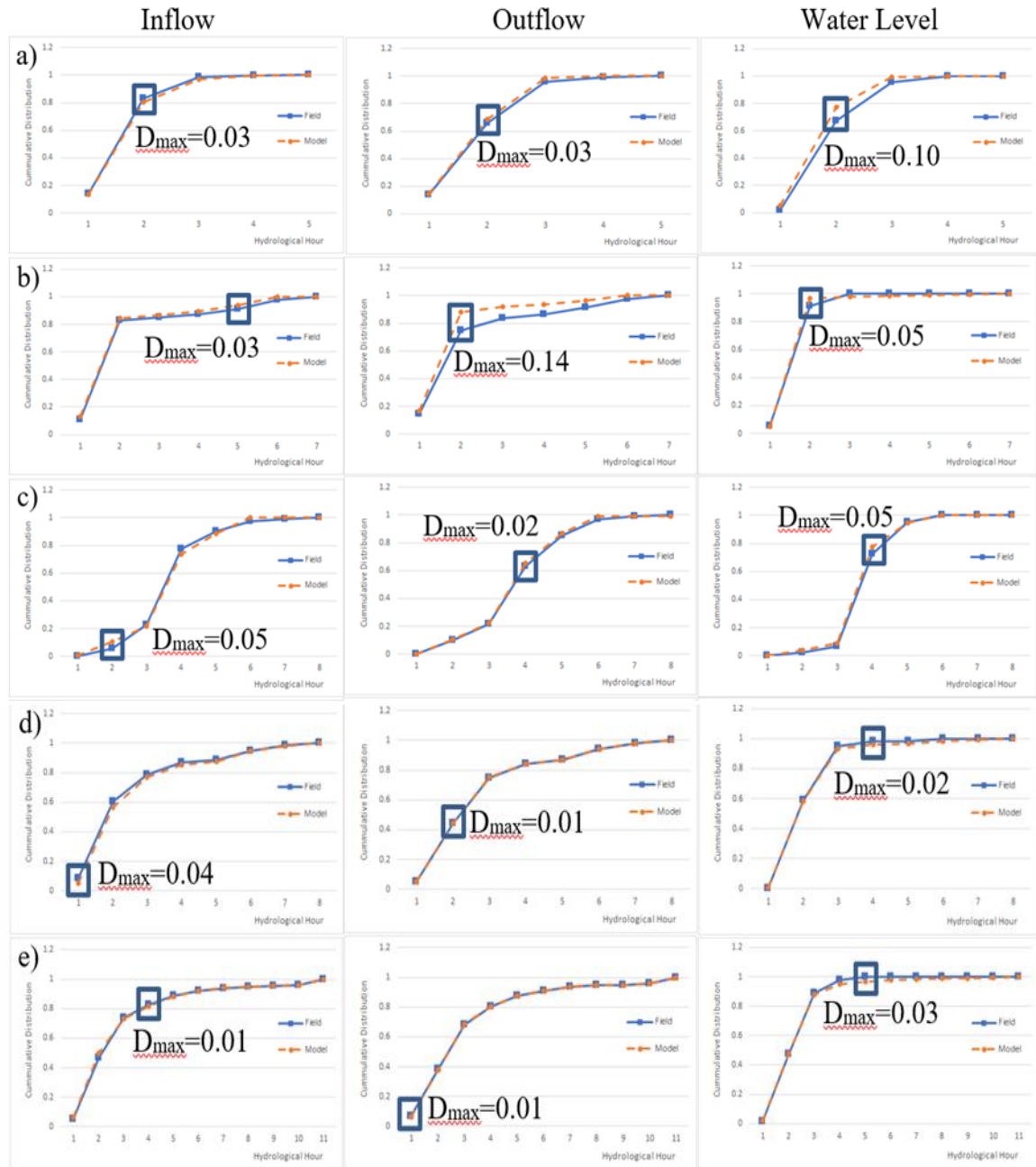


Figure 4.14: K-S Test for 30-40 mm Rainfall Depth Category, a) 7 Dec 2019, b) 1 Dec 2019, c) 8 & 9 Dec 2019, d) 18 Jan 2020 and e) 20 Jan 2020 Storm Events

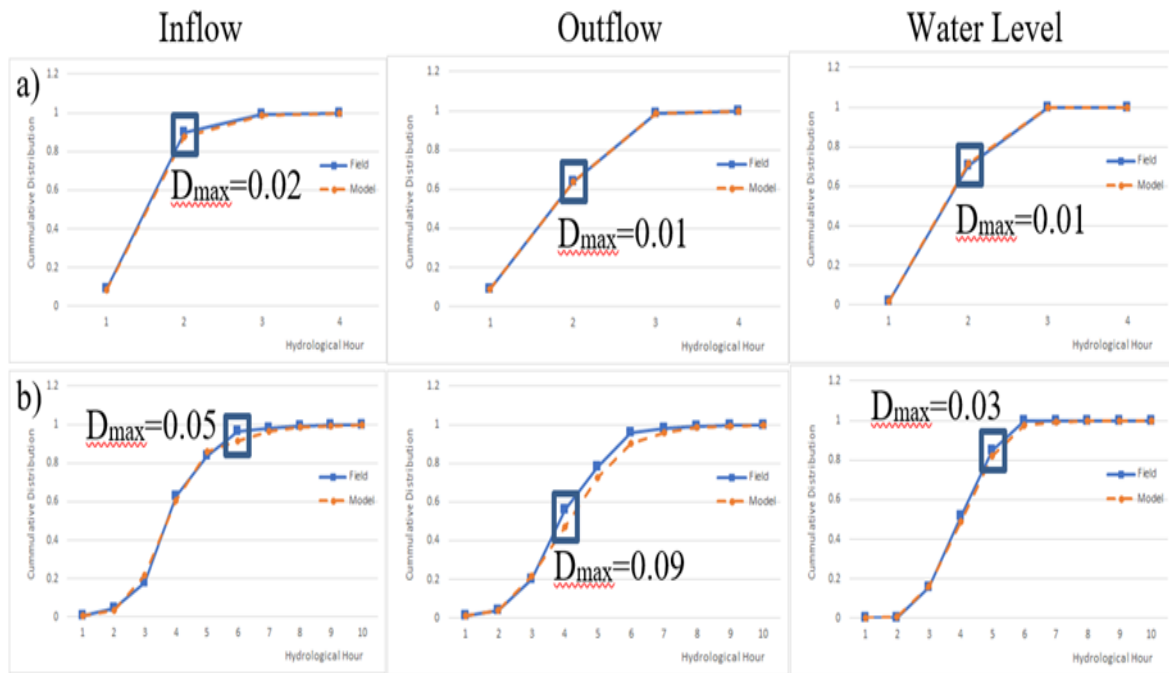


Figure 4.15: K-S Test for 40-50 mm Rainfall Depth Category, a) 16 Jan 2020 and b) 22 Feb 2020 Storm Events

Generally, K-S Tests are carried out for inflow, outflow and water level for each selected storm events. It involves first rationalized each dataset, then data of each points are accumulated and always equal to 1.0. One could observe that there are two lines in each graph, namely the cumulative field distribution and cumulative model distribution. The former is drawn in solid line, while the latter is drawn in dotted line. Comparing the two distributions, the maximum vertical distance ($D_{\max}$) between the two curves could be identified. The smaller the vertical distance, the better the goodness of fit. As demonstrated in the figures, $D_{\max}$ of each graph is pointed out. A summary is tabulated in Table 4.6.

Table 4.6: Summary of $D_{\max}$

Rainfall Depth Category	Storm Event	n, storm duration (Hour)	D_{critical}	$D_{\max}$		
				Inflow	Outflow	Water Level
0-20 mm	30 Dec 2019	7	0.51	0.01	0.05	0.07
	2 Dec 2019	8	0.48	0.15	0.15	0.07
	11 & 12 Dec 2019	15	0.35	0.03	0.08	0.18
20-30 mm	1 Jan 2020	2	0.79	0.01	0.02	0.01
	22 Jan 2020	4	0.68	0.01	0.02	0.04
	19 Jan 2020	7	0.51	0.01	0.02	0.06
	22 Dec 2019	8	0.48	0.08	0.23	0.15
	28 Dec 2019	9	0.45	0.13	0.15	0.15
	10 Jan 2020	11	0.41	0.01	0.01	0.02
30-40 mm	7 Dec 2010	5	0.61	0.03	0.03	0.10
	1 Dec 2019	7	0.51	0.03	0.14	0.05
	8 & 9 Dec 2019	8	0.48	0.05	0.02	0.05
	18 Jan 2020	8	0.48	0.04	0.01	0.02
	20 Jan 2020	11	0.41	0.01	0.01	0.03
40-50 mm	16 Jan 2020	4	0.68	0.02	0.01	0.01
	22 Feb 2020	10	0.43	0.05	0.09	0.03

The null hypothesis (H_0), in this context, is defined as: The difference between the field and model distributions is insignificant. The critical value (D_{critical}) at 5% significance level is usually found from the K-S table, or it could be calculated based the number of samples (n). D_{critical} values as demonstrated in Table 4.6 are varied for each storm events due

to different storm durations. If the $D_{\max}$ values of inflow, outflow and water level for a storm event are less than the critical value, then the null hypothesis is accepted. If the $D_{\max}$ values are greater than the critical value, the null hypothesis is rejected.

Based on Table 4.6, the $D_{\max}$ values range from 0.01 to 0.23. These values across the board are found less than the critical values. As such, the author is accepting the null hypothesis. It also points to close fit of the field and model distributions. A scatter plot of the $D_{\max}$ values is presented in Figure 4.16. It could be observed that 80% of the $D_{\max}$ values are below 0.1. The 0.1 mark is chosen because it is indicating small gap between the field and model distributions and majority of the statistic $D_{\max}$ s are small gaps. Only 20% are above 0.1. These $D_{\max}$ s higher than 0.1 data are highlighted in Table 4.6 for reference. For example, the highest $D_{\max}$ is 0.23 that occurred to outflow on 22 December 2019. However, the value is only half of its associated critical value (0.48) that is far from going overboard the critical value.

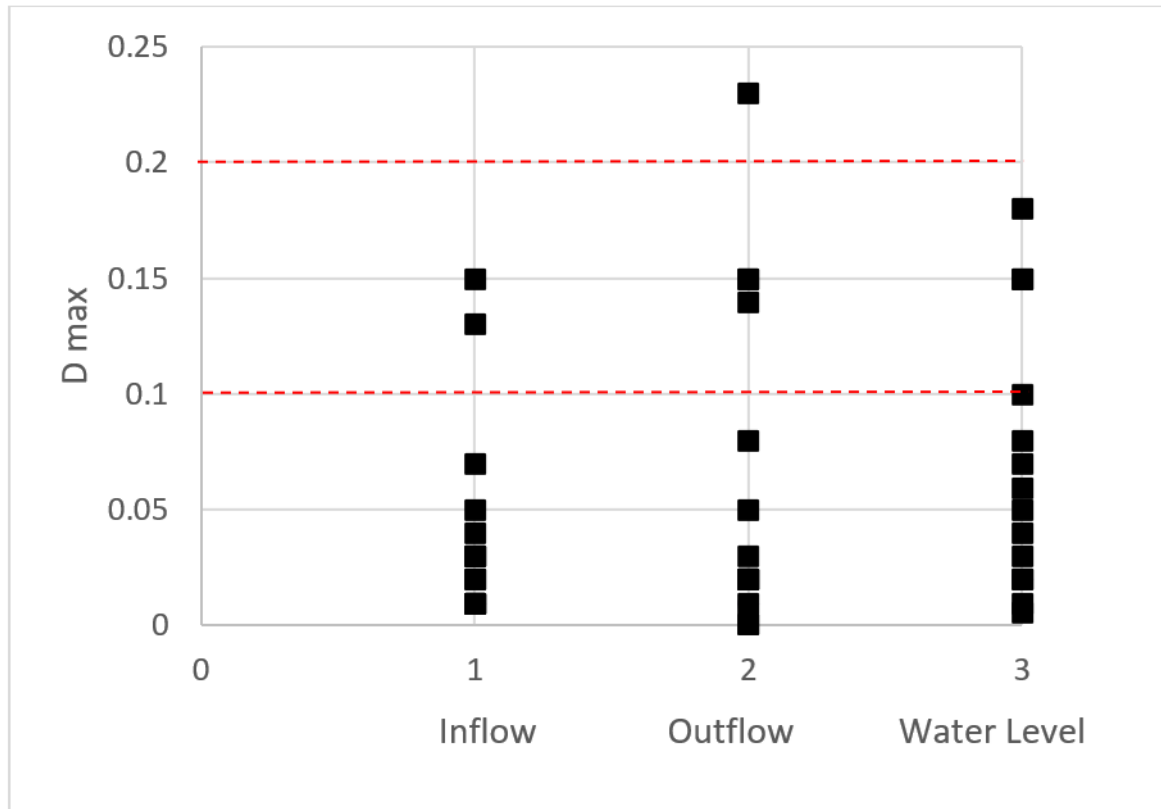


Figure 4.16: Scatter Plot of D_{max}

Based on Figure 4.16, the afore-mentioned highest D_{max} value of 0.23 is the furthest away from other points that could be treated as an outlier. Ignoring the outlier, it is found the three groups are distributed equally. The author could not distinguish one group that is better than the rest of the groups. It is deduced that the inflow, outflow and water level are equally matched. As such, it can be said the developed SWMM model has been validated to represent the actual performance of the StormPav OSD.

4.2.4 Application of Validated Model for Past Extreme Storm Events

This sub-section is meant to compliment the section 4.1 on rainfall depth with 40-50 mm category. The field or primary data only manage to capture two storm events. Two storm events are too little to represent the category. With the availability of the validated SWMM model, secondary data of past extreme storm events could be inputted to the model to provide

further insights. These data are obtained from the Sarawak Department of Irrigation and Drainage.

Figure 4.17 shows three past storm events are sourced. Firstly, the 18 & 19 January 2015 storm event made up of two consecutive storms that spanned 25 hours with a one-hour halt in between, in which 0000-1100 hours event (11 hours) had a peak rainfall of 38.5mm and 1200-0200 hours event (14 hours) had a peak rainfall of 43mm (Figure 4.17a). The former (38.5mm) is close to 40mm, and therefore it is put in this rainfall category. Secondly, the 1 January 2016 storm event spanned for 6 hours with a peak rainfall of 51mm (Figure 4.17b). Thirdly, the 17 & 18 December 2017 storm event spanned for 15 hours with a peak rainfall of 47.5mm (Figure 4.17c). All three events were occurred in the Northeast Monsoon season and were known to cause flooding in Samarahan areas. The details of the analysis are available in Appendix E.

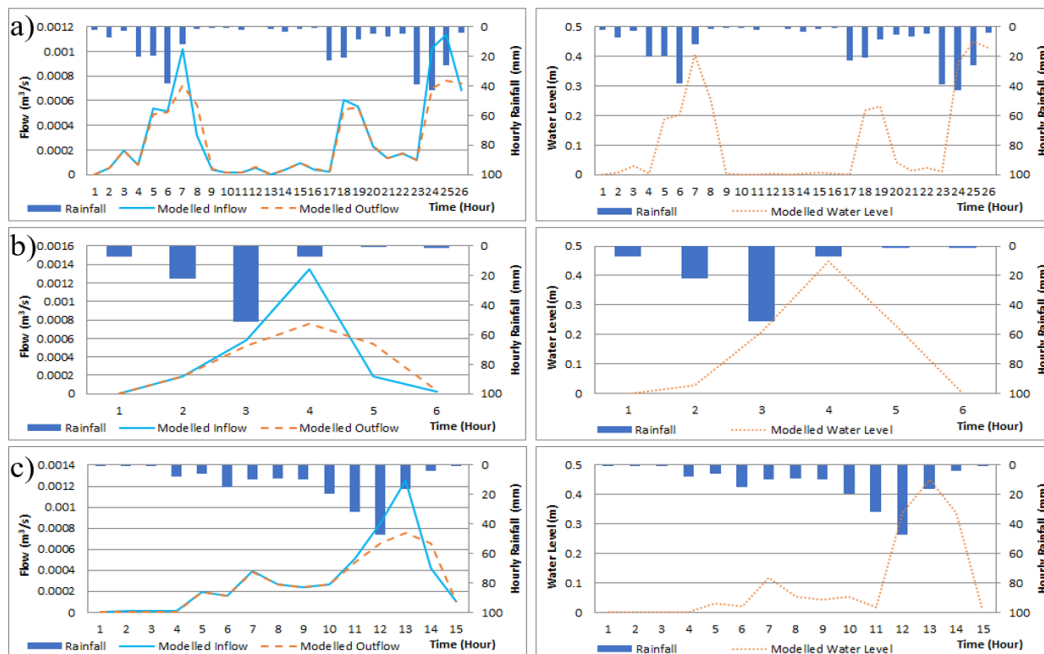


Figure 4.17: Modelling of Past Extreme Storm Events for Inflow, Outflow and Water level on a) 18&19 January 2015, b) 1 January 2016 and c) 17 & 18 December 2017

Together with the two observed events in the 40-50 mm category, the range of storm duration is now 4 to 15 hours (exact distribution as T: {4, 6, 10, 11, 14, 15}) that is a better representation of the typical storm duration (1-15 hours). The range of rainfall depth is now 39 to 51 mm (exact distribution as P: {38.5, 41.6, 43, 47.5, 47.6, 51}). Recalling section 4.1, the observed storm events are reported with inflow values between 0.001-0.002 m³/s. Modelling of the past extreme storm events are found with inflow values between 0.0010-0.0013 m³/s which is tallied with the observed events. The observed events are reported with 36% of attenuation rate. The modelled events are also found to have an average 36% of attenuation rate. Individual attenuation rates are 29% for 18 January 2015, 33% for 18&19 January 2015, 44% for 1 January 2016 and 40% for 17&18 December 2017.

For the modelled outflow, its values are found matching with the observed events. The observed events are reported with outflow values between 0.0007-0.001 m³/s. The modelled events come back with 0.0007 m³/s for all four modelled events. For the modelled water level, same observation is repeated, in which the observed events are reported with 0.4-0.47 m, while the modelled events are found with 0.4-0.45 m.

However, the author would like to point out that the observed 22 February 2020 event has the highest inflow (0.002 m³/s), highest outflow (0.001 m³/s) and highest water level (0.47 m). These values are isolated from the values of other five events. Inflow, outflow and water level values of the other five events are more similar with each other, for example, inflow values in the range of 0.0011-0.0013 m³/s, all outflow values in 0.0007 m³/s and water level values in the range of 0.4-0.45 m. Despite so, the author is still using the 22 February 2020 event as the main benchmark as the said event is of primary data that are superior than the secondary data. Modelled data are treated as secondary supports only.

4.2.5 Application of Validated Model for Improving Orifice Outlet

This sub-section is meant to address the issue identified in section 4.1 on the flood risk due to 16 January 2020 and 22 February 2020 storm events. With the validated SWMM model, investigation into alleviating the flood risk is possible. High water levels approaching the burst-of-tank level (0.45 m) are detected in the field observations. One of the ways to lower the water levels is to enlarge the size of the orifice outlet. Modelling outcomes for the said two storm events under the 40-50 mm category are presented in Figure 4.18. The details of the analysis are available in Appendix F.

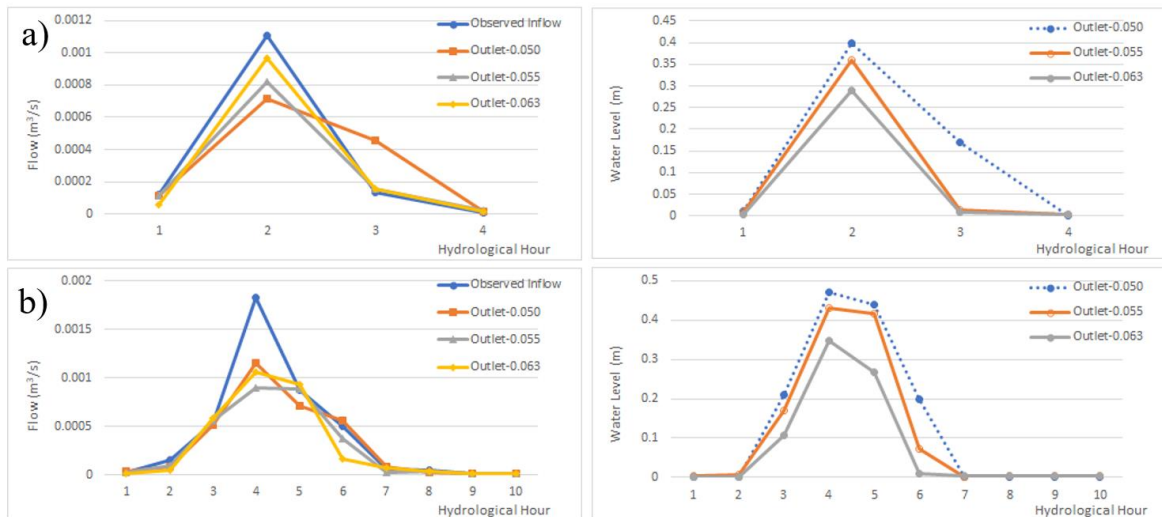


Figure 4.18: Modelling of Orifice Outlets for a) 16 Jan 2020 and b) 22 Feb 2020 Storm Events

There are three orifice outlet sizes, namely the existing size of 0.05 m, along with the newly introduced 0.055 m and 0.063 m. The observed peak outflows and water levels due to 0.05 m orifice outlet remain in the graph for comparison. Circular pipeline sizes available in market that are larger than 0.05 m are 0.063 m, 0.075 m and 0.090 m. The author chooses only the 0.063 m here because the modelling outcomes show this size lowers the water level, but at the same time, it also increases the peak outflow. Take the example of 16 January 2020 storm event with the outlet of 0.063 m, the water level reduces to 0.29 m (compared

with observed 0.4 m) but peak outflow increases to 0.001 m³/s (compared with observed 0.0007 m³/s). This modelled peak outflow is not a favourable outcome.

Due to the above-mentioned observation, the author tries a smaller size of 0.055 m. Such a pipeline size is not available in the market. The 16 January 2020 storm event with the outlet of 0.055 is estimated to reduce the water level to 0.36 m (compared with observed 0.4 m) and increase the peak outflow to 0.0008 m³/s (compared with observed 0.0007 m³/s). Another storm event of 22 February 2020 with the outlet of 0.055 m is estimated to reduce the water level to 0.43 m (compared with observed 0.47 m) but the peak outflow is modelled strangely lowered than the observed value. The outflow is expected to increase but the model predicts otherwise which presents an unsure scenario. More confirmation is needed. Because of this, the author continues to model the extreme storm events from the previous sub-section for second opinion (Figure 4.19).

Based on Figure 4.19, the modelled peak outflow values for the three outlet sizes are consistent that enlarging outlet sizes spike up the peak outflow values. All modelled storm events have the 0.050 m as the lowest peak outflow, followed by the 0.055 m. The 0.063 m has the highest peak outflow values in the four modelling cases. Therefore, it is doubtful for the modelling of peak outflow values for 22 February 2020 event. Double checking on the modelling results remains the same. As mentioned before, the primary data are always being taken as benchmark as the author is confidence of the field data collection.

The modelled 0.055 m outlet has the water level values unchanged for three of out of the four storms. The 18 & 19 January 2015, 1 January 2016 and 17 & 18 December 2017 storm events are estimated to have 0.45 m water level for both 0.050 m and 0.055 m outlet sizes. Referring to 22 February 2020 event, it is estimated to have water level reducing from

0.47 m to 0.43 m. Between 0.43 m and 0.45 m, the mere 0.02 m is not significant, and these could be said the values are closely similar and equally posing flood risk.

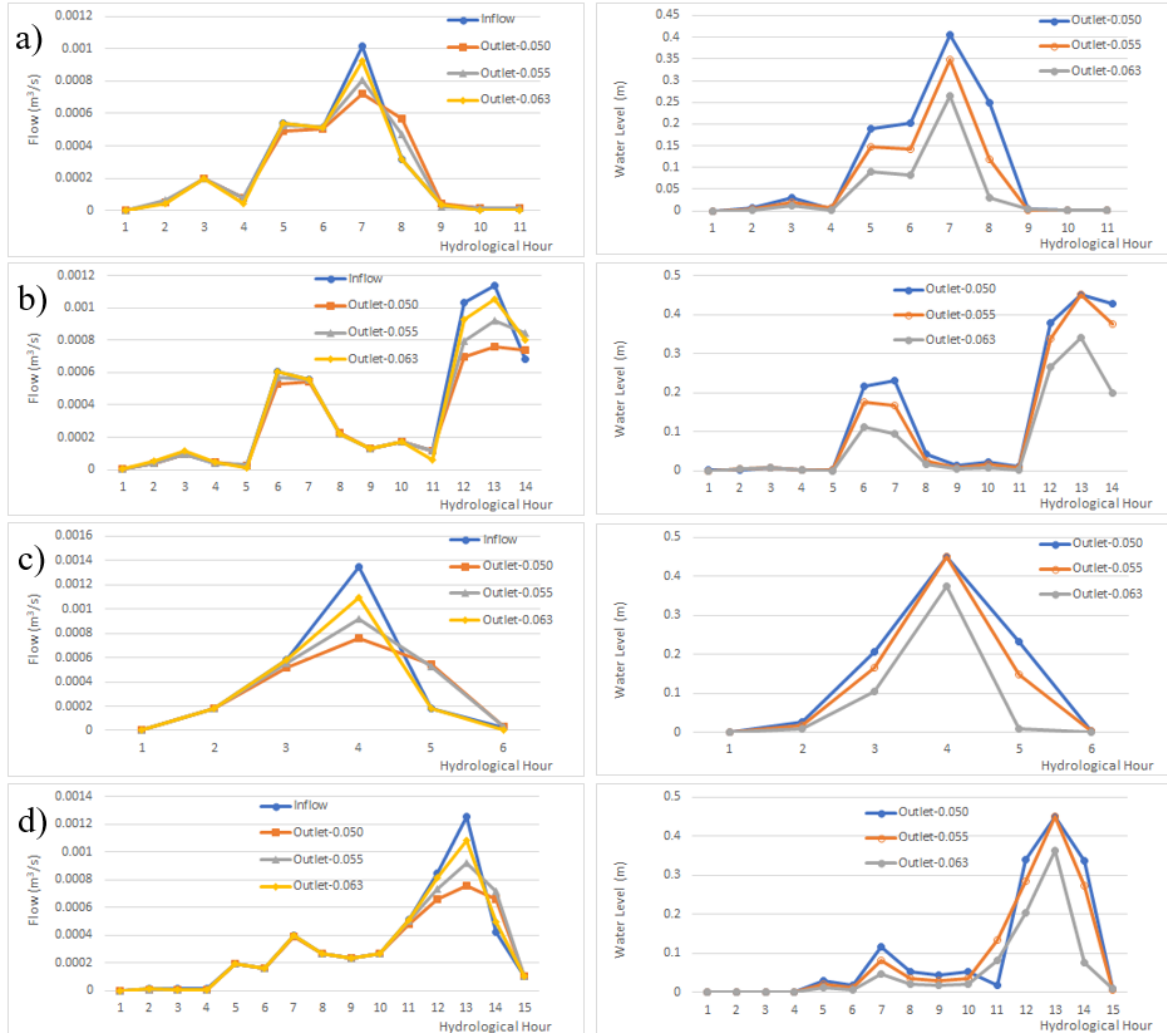


Figure 4.19: Modelling of Orifice Outlets for Extreme Storm Events on a) 18 January 2015, b) 18 & 19 January 2015, c) 1 January 2016 and d) 17 & 18 December 2017

Other storm events are also simulated to weigh the impacts of enlarging the orifice outlet. Figure 4.20 shows the outcomes for 0-20 mm category. By enlarging the orifice outlet to 0.055 m and 0.063 m, the impact on this category is insignificant. The peak outflows for the three storm events appeared similar. The water levels are estimated to decrease as the

orifice sizes increase. However, the flowing through characteristics are even more prevalence than the field test with 0.050 m outlet.

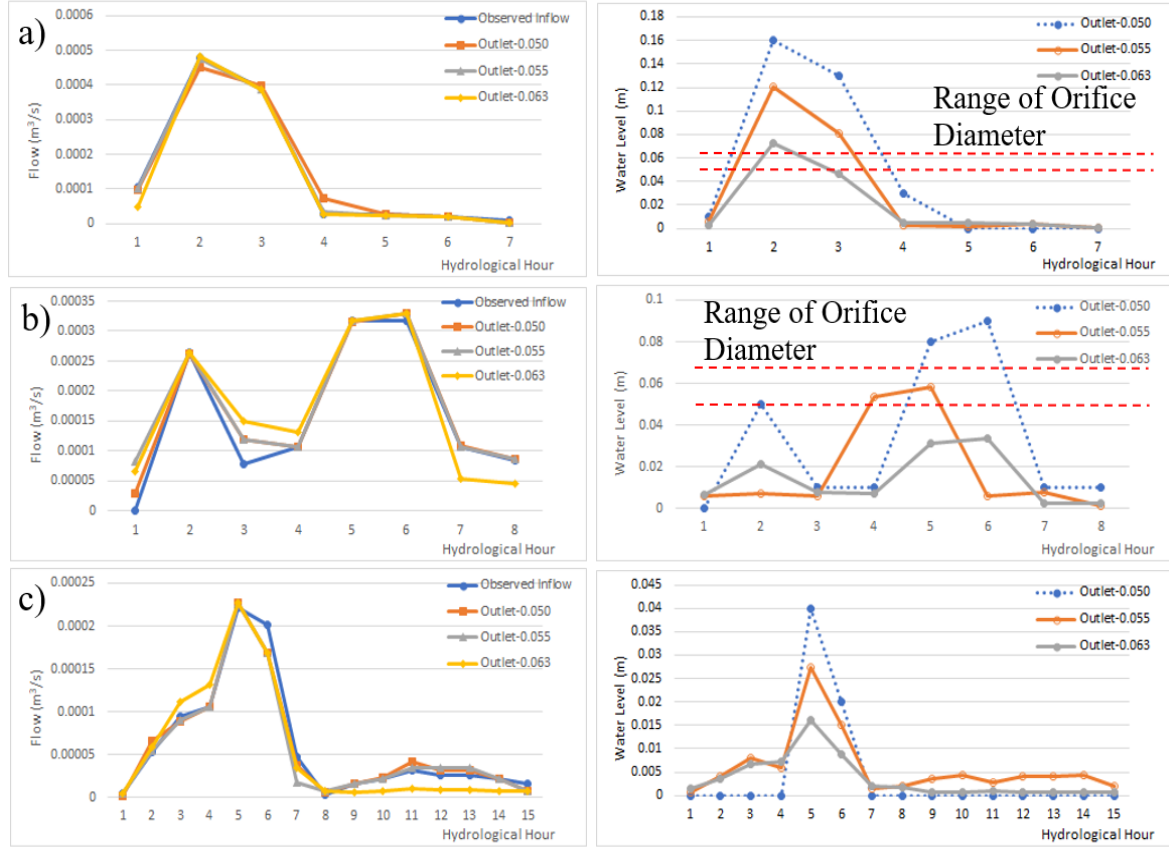


Figure 4.20: Modelling of Orifice Outlets for a) 30 Dec 2019, b) 2 Dec 2019 and c) 11 & 12 Dec 2019 Storm Events

Similar pattern is observed to repeat in the 20-30 mm category. Figure 4.21 shows the outcomes for the said category. The peak outflows are closely knitted. The water levels, on the hand, are estimated to decrease as the orifice sizes increase. It should be noted that the outlet of 0.055 m produces water levels between 0.15-0.2 m, while the outlet of 0.063 m produces between 0.1-0.15 m (compared with the observed water levels of 0.2-0.25 m). In this case, any of the outlet sizes could do as the peak outflows are not changed much. This category is not a good benchmark.

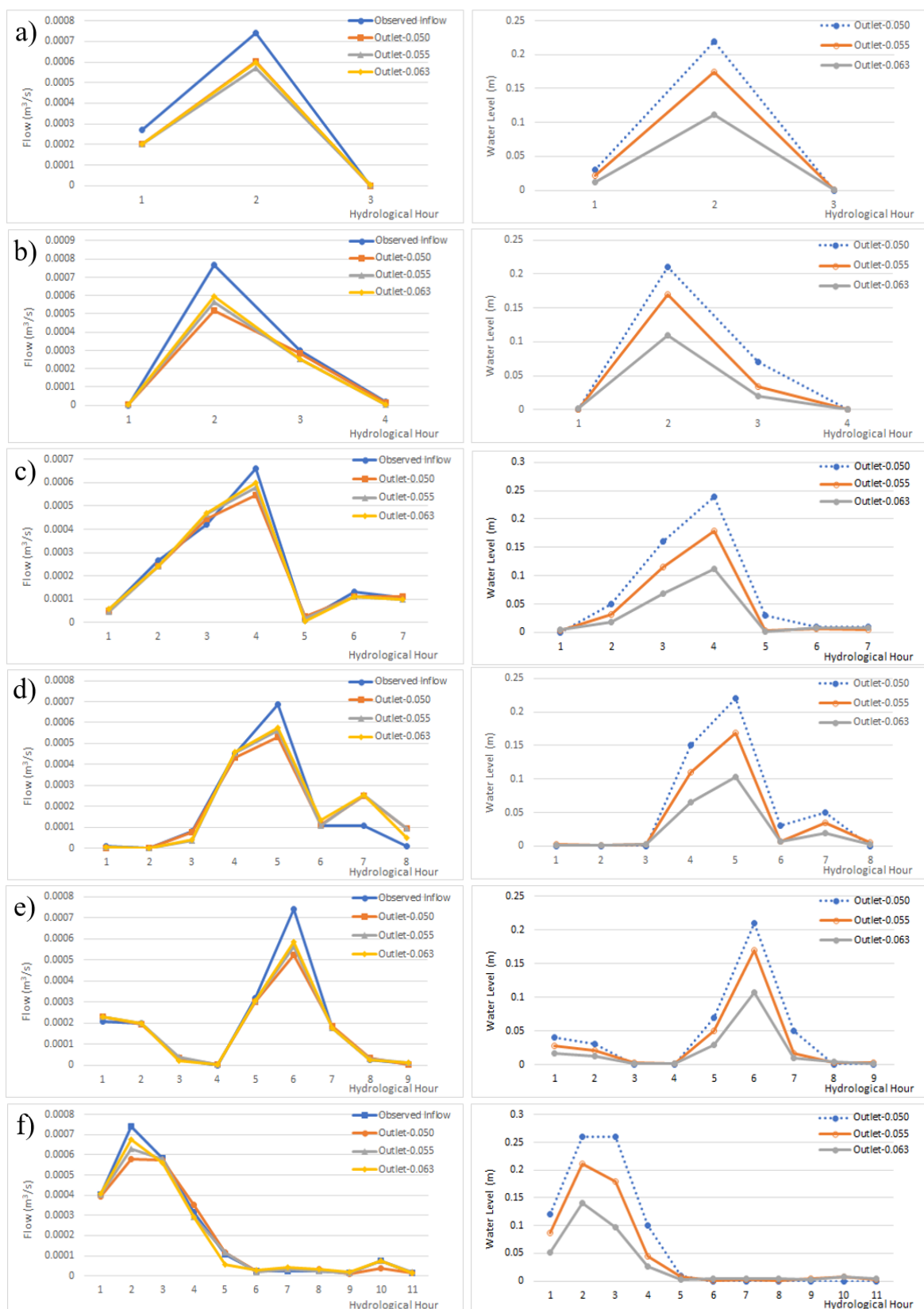


Figure 4.21: Modelling of Orifice Outlets for a) 1 Jan 2020, b) 22 Jan 2019, c) 19 Jan 2020, d) 22 Dec 2019, e) 28 Dec 2019 and f) 10 Jan 2020 Storm Events

Figure 4.22 shows the outcomes of different orifice sizes for 30-40 mm category. The modelled peak outflows of this category show its peak values increase as the orifice sizes increase for all storm events except for 1 December 2019 storm event. This observation is close to the scenario in 40-50 mm category. With the outlet size of 0.063 m, the peak outflows are noted as unfavourable outcomes for approaching the peak inflows, for examples in Figure 4.22d and Figure 4.22e.

By benchmarking the modelling outcomes from 30-40 mm category and 40-50 mm category, the author deduces the orifice outlet size of 0.055 m is more appropriate to lower the flood risk of StormPav OSD without compromising the stormwater detention capacity. With the outlet size of 0.055 m, it produces water levels between 0.25-0.3 m (compared with the observed water levels between 0.3-0.35 m).

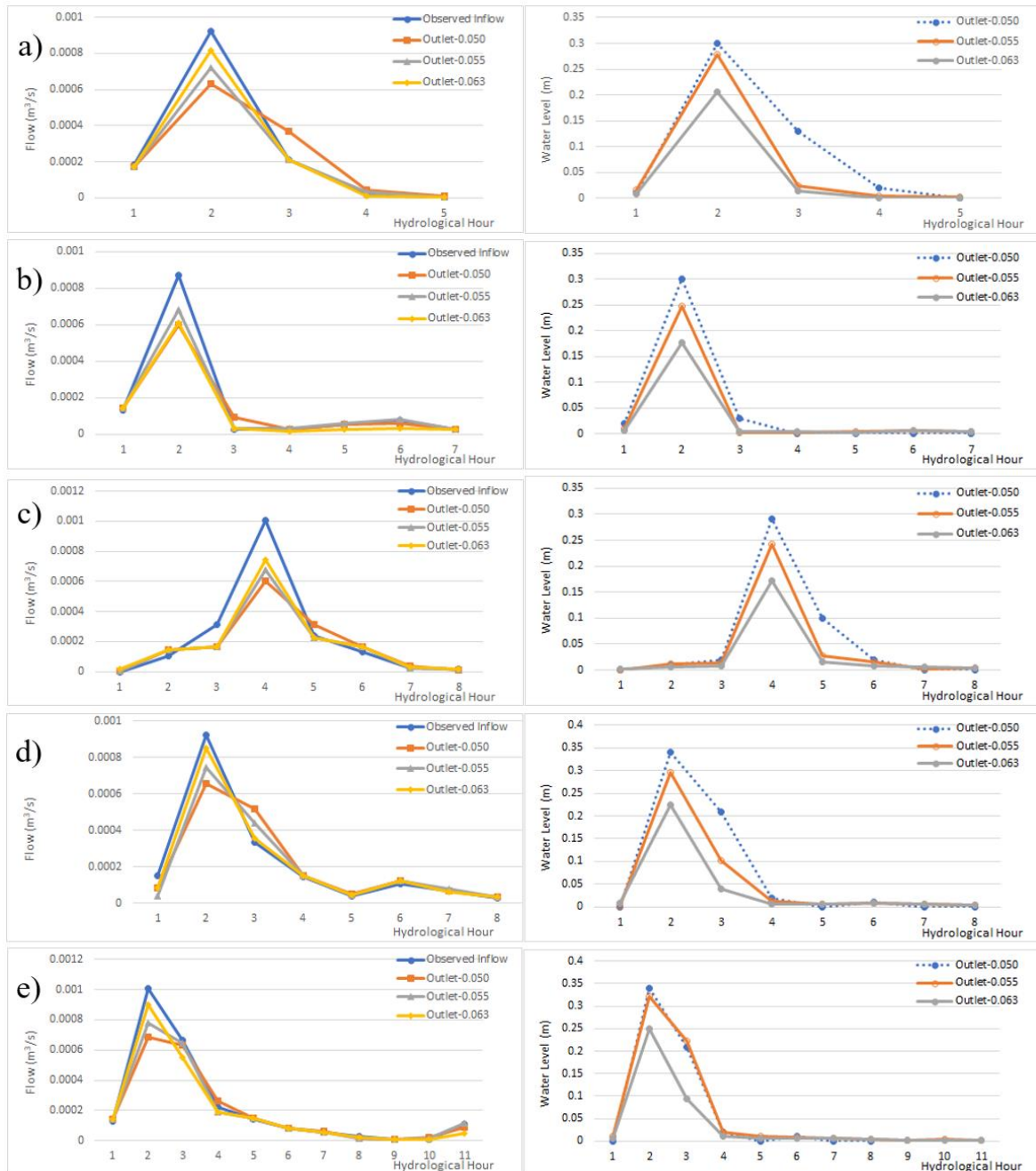


Figure 4.22: Modelling of Orifice Outlets for a) 7 Dec 2019, b) 1 Dec 2019, c) 8 & 9 Dec 2019, d) 18 Jan 2020 and e) 20 Jan 2020 Storm Events

With the investigative improvement being done, a revision could be done to Table 4.5 from section 4.1 and it is presented as Table 4.7 below. The 0-20 mm category is not included in the table for being insignificant to changes in outlet sizes. As mentioned before, theoretically with larger outlet size, the detained water level in the OSD is expected to

decrease due to faster water release via the outlet that could spike up the peak outflow and in return, lower the attenuation rate.

Table 4.7: Summary of Revised StormPav OSD Data

Category of Rainfall Depth	Inflow (m ³ /s)		Outflow (m ³ /s)		Attenuation (%)		Water Level (m)	
	Field Outlet-0.050m	Model Outlet-0.055m	Field Outlet-0.050m	Model Outlet-0.055m	Field Outlet-0.050m	Model Outlet-0.055m	Field Outlet-0.050m	Model Outlet-0.055m
20-30 mm (near 5-min 10-year ARI design rainfall)	0.0006-0.0007	No change in inflow	0.0005-0.0006	No change	20	No change	0.2-0.25	0.15-0.2
30-40 mm (near 10-min 10-year ARI design rainfall)	0.0008-0.001		0.0006-0.0007	0.0007-0.0008	30	25	0.3-0.35	0.25-0.3
40 mm & above (near 15-min 10-year ARI design rainfall)	0.001-0.002		0.0007-0.001	0.0008-0.0009	36	30	0.4-0.47*	0.35-0.45*

Note: * indicating risk of nuisance flooding

In terms of water level, it is found as expected that all categories decrease in water level by 10-20% comparing the outlet size of 0.055 m to 0.050 m. Even so, the newly introduced outlet size of 0.055 m only solves half of the flooding risk in the 40-50 mm category. Limiting the category to a range of 40-50 mm, the lower limit (41.6 mm rainfall depth in 16 January 2020 event) has been estimated with a much-reduced water level to 0.35 m (compared with tank-full 0.45 m). Whilst the upper limit (47.6 mm rainfall depth in 22 February event) is estimated to have a water level of 0.43 m, leaving a 0.02 m space before the tank-full level. The author deduces that the StormPav OSD is safe from overflowing for 40-45 mm rainfall depth but remains as flood risk for 45 mm and beyond.

In terms of peak outflow, the changes within the 20-30 mm category are small that maintain the similar range of peak outflow values; while the 30-40 mm category and 40-50 mm category have decreased peak outflow value by 10-20%.

In terms of attenuation rate between the peak inflow and peak outflow, the 20-30 mm category remains an average 20%. Individual attenuation rates are 23% for 1 January 2020, 26% for 22 January 2020, 12% for 19 January 2020, 18% for 22 December 2019, 24% for 28 December 2019 and 15% for 10 January 2020 storm events. These individual rates are slightly decreased but able to maintain the average value.

For the 30-40 mm category, the average attenuation rate is estimated at 25% with the outlet size of 0.055 m, a drop from the 30% with the outlet size of 0.050 m. Individual attenuation rates are 22% for 7 December 2019, 22% for 1 December 2019, 33% for 8 & 9 December 2019, 20% for 18 January 2020 and 23% for 20 January 2020 storm events.

For the 40-50 mm category, the average attenuation rate is estimated at 30% with the outlet size of 0.055 m. Individual attenuation rates are 26% for 16 January 2020, 51% for 22

February 2020, 21% for 18 January 2015, 19% for 18&19 January 2015, 32% for 1 January 2016 and 27% for 17 & 18 December 2017 storm events.

A summary of the impacts of outlet sizes to water level is presented in Figure 4.23. The author deduces that under the influence of 0.055 m outlet (see the dotted line with triangular markers), the StormPav OSD is safe from overflowing for 40-45 mm rainfall depth but remains as flood risk for 45 mm and beyond. The statement is confirmed while cross-checking with the modelling outcomes of four past extreme storm events.

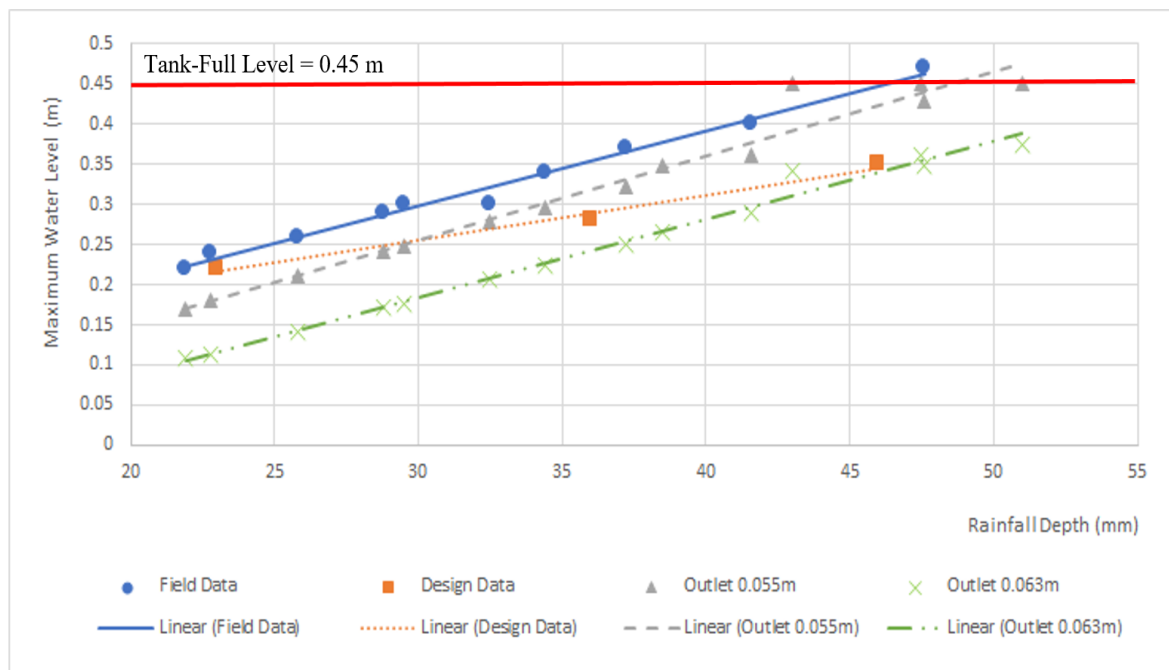


Figure 4.23: Rainfall Depth vs Water Level for Design Data, Field Data, Proposed Outlet Sizes of 0.055 m and 0.063 m

A summary of the implications of enlarging outlet sizes on the attenuation rates is presented in Figure 4.24. Generally, it is observed that the attenuation rates of 0.050 m and 0.055 m are closely ranged between 20-30%. Attenuation rates of 0.063 m are concentrated about 10% only.

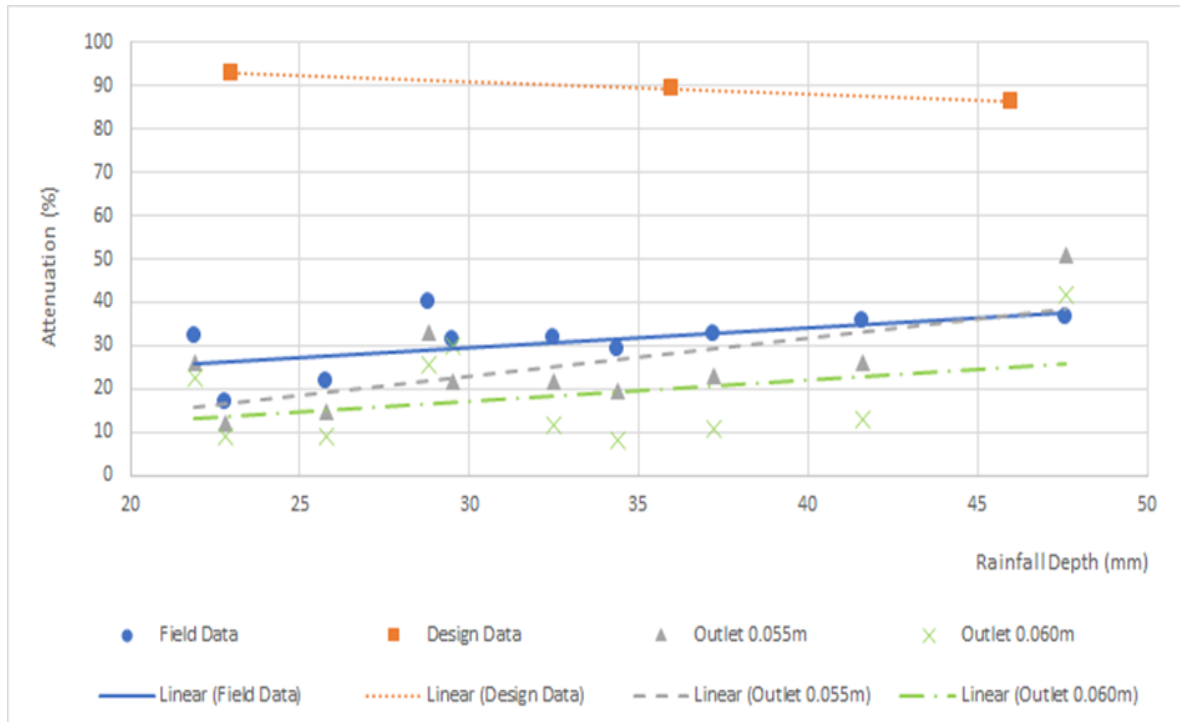


Figure 4.24: Rainfall Depth vs Attenuation for Design Data, Field Data, Proposed Outlet Sizes of 0.055 m and 0.063 m

4.3 Characterization of StormPav Home-Based OSD

Description of this subsection is based on the data extracted from the field data presented in the earlier sub-sections, as well as modelling results from the validated SWMM model. The field data are consequences of 95m² roof catchment carried out on a double-storey terrace house. The modelled data are able to simulate the OSD system with different roof catchment areas, namely 50m² and 150m² roof catchments. The catchment areas come from different house types which 50m², a representation of single-storey terrace house; 150m², a representation of bungalow house.

4.3.1 Responses of System to Actual Rainfall

The effective storage capacity of StormPav OSD is known as 0.19m³/m² of pavement area. For a surface area of 4.6m x 4.3m at the field test, it is calculated to have 19.8m³ of storage volume. On top of that, the system is a flow-through water draining tank, in which

water flows in and out at the same time. How the OSD system could tolerate the actual rainfall depths are presented in Figure 4.25 and Figure 4.26.

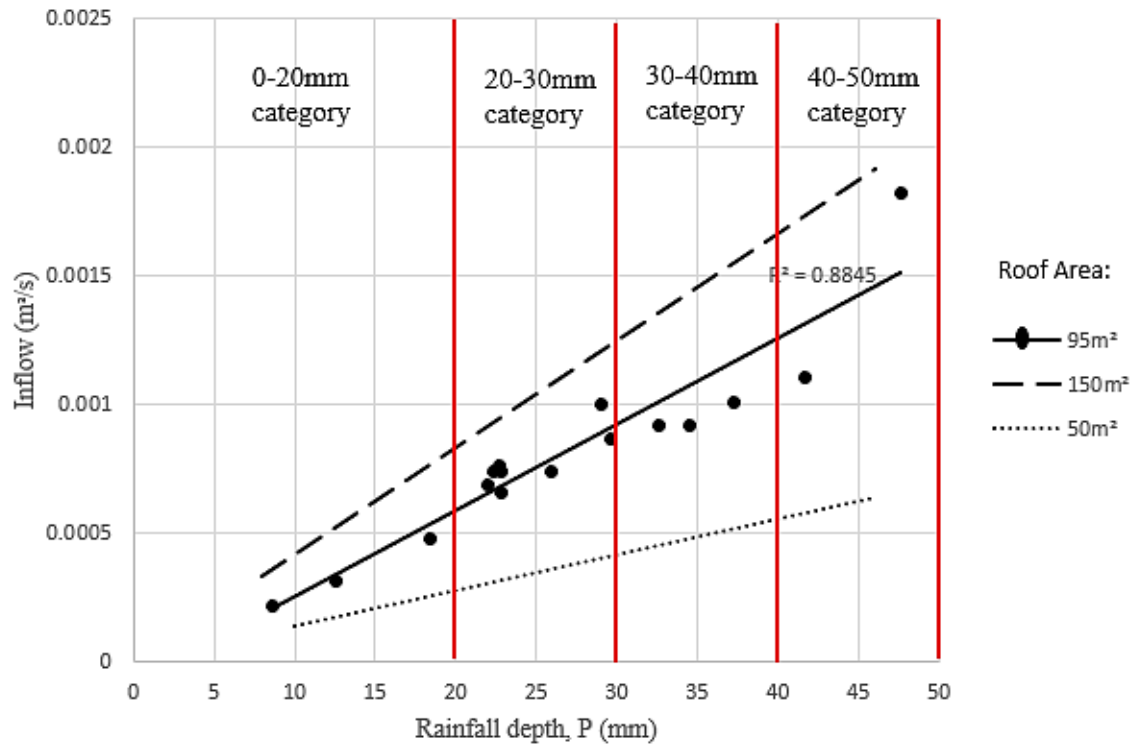


Figure 4.25: Plot of Inflow, Rainfall Depth and Roof Catchment Area

Inflows going into the StormPav OSD are generated from the roof catchment. The three lines on the graph are from the bottom to the top, 50m²; 95m² and 150m² roof areas. The maximum inflow values obtained from the field test are plotted in the middle of the graph and a solid trend line is added. The modelled inflow data are plotted in dotted lines. Generally, the higher the rainfall depth values, the higher the inflow values. The bigger the roof areas, the higher the inflow values as well.

Focusing on the 95m² roof area, inflow values increase linearly with rainfall depth values from 0-20 mm and 20-30 mm categories. Under the 0-20 mm category, the inflow values range from 0.0003-0.0006m³/s. Under the 20-30 mm category, the inflow values

range from 0.0006-0.0008m³/s. However, the field data deviate away from the trend line for 30-40mm, and 40-50 mm category which are lower than the trend line.

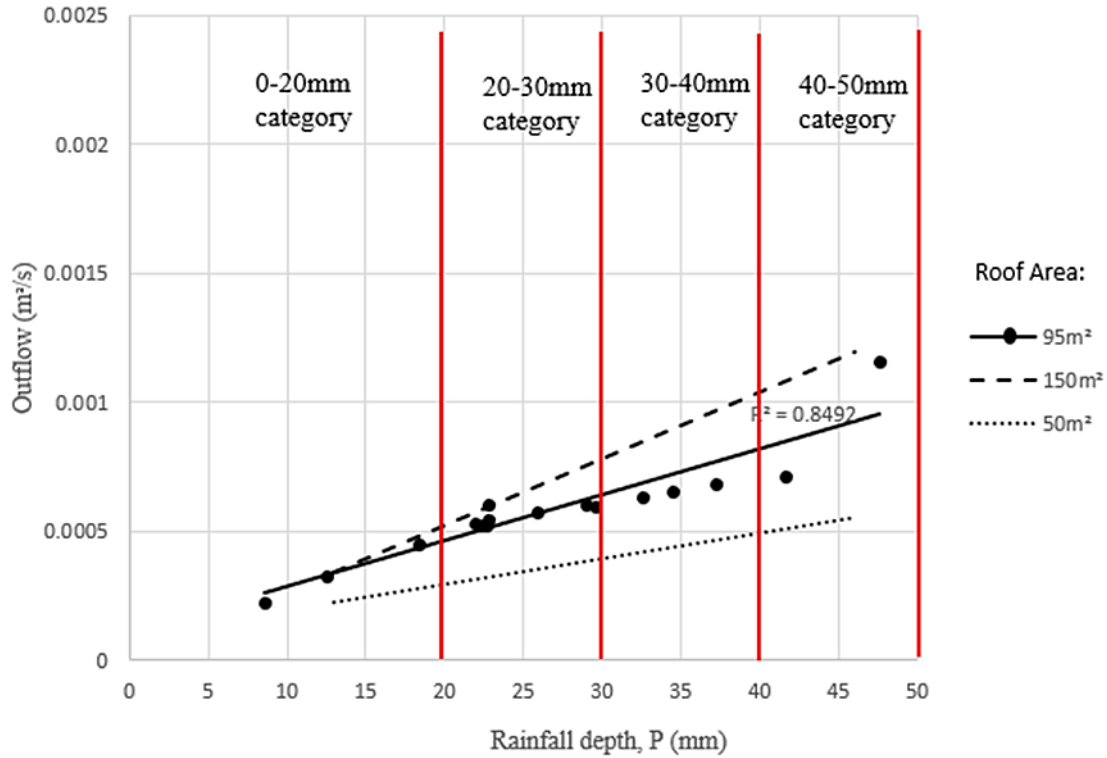


Figure 4.26: Plot of Outflow, Rainfall Depth and Roof Catchment Area

Meanwhile, outflows are leaving the StormPav OSD via orifice outlet. Therefore, the outflows are governed by the orifice. The observations gained from the inflow data are also repeated. Generally, the higher the rainfall depth values, the higher the outflow values. The bigger the roof areas, the higher the outflow values. However, the increment is small, which is in the range of 0.0003-0.0007m³/s. The outflow values increase linearly for 0-20 mm, and 20-30 mm categories; but deviate from the trend line for 30-40 mm, and 40-50 mm categories.

4.3.2 Catchment Area to Storage Detention

Storage capacity of StormPav OSD could be represented with either water level or storage volume. During the field test, the direct measurement of storage capacity was done

via sensor recording the captured water levels in the tank. Therefore, water level is presented here to indicate storage detention. The said storage detention is illustrated in Figure 4.27.

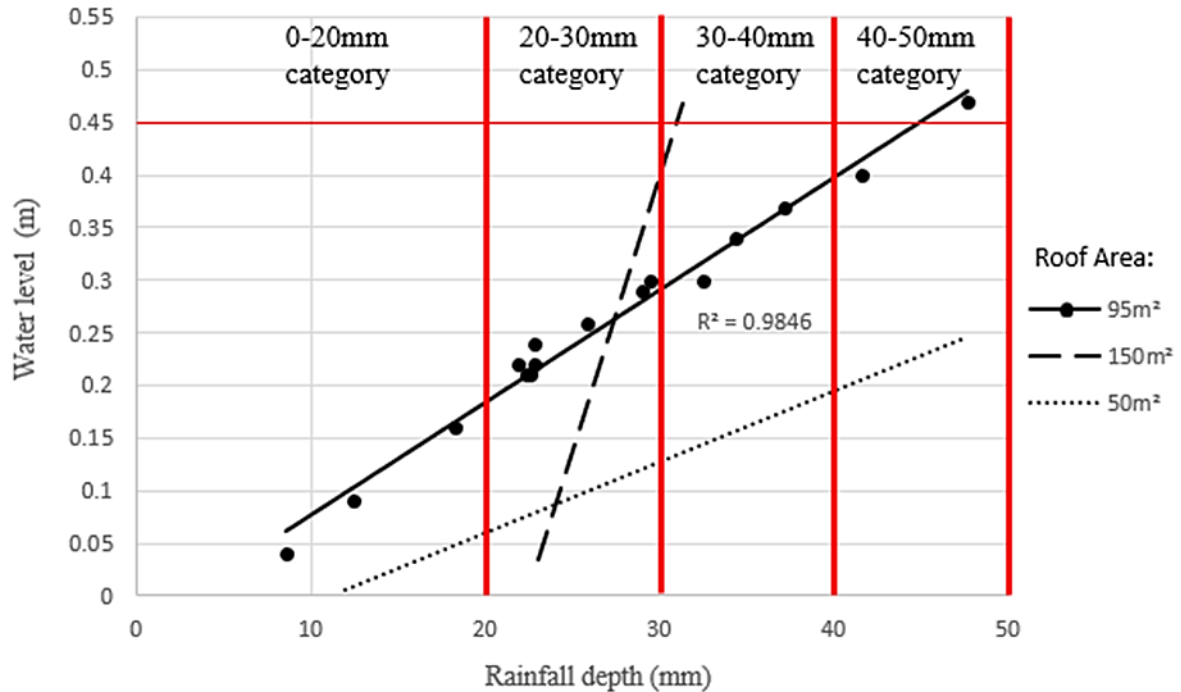


Figure 4.27: Plot of Water Level, Rainfall Depth and Roof Catchment Area

The three lines in the graph represents the roof area. The line for 50m² roof area is at the bottom of the graph. The lines for 95m² and 150m² roof areas intersect at the upper part of the graph. This is due to the slopes of the lines. It appears that the bigger the roof areas, the steeper the slope of the associated line graph. It means that the current OSD setting (4.6m x 4.3m surface area, 0.45m deep and 0.05m diameter orifice outlet) would have faster rising of water levels when the roof area increases.

For the field test, the recorded water levels increase linearly when subjected to different categories of rainfall depths. With the validated SWMM model, 50m² and 150m² roof area with their associated predicted water levels in the OSD are available for comparison. The larger the roof area derived from bungalow house type demonstrates the

steepest slope among the three lines. It shows that the larger roof area is expected to generate higher amount of runoff and to fill up the OSD tank faster than the other two roof areas. The smallest roof area derived from single-storey terrace has a mild slope that observes a gradual fill of the OSD tank.

It can be said that the current OSD setting has limited storage volume. The implication is the OSD responded poorly to 150m² catchment area. The OSD could only accommodate the 20-30mm rainfall category. Exceeding 30mm will indicate overflowing from the OSD, while under 20mm or less, no detention occurs. If the limitation of the current setting is removed, to be specific, the detention surface area is allowed for exploration while the depth of the StormPav maintained, a depiction of a second setting is presented in Figure 4.28.

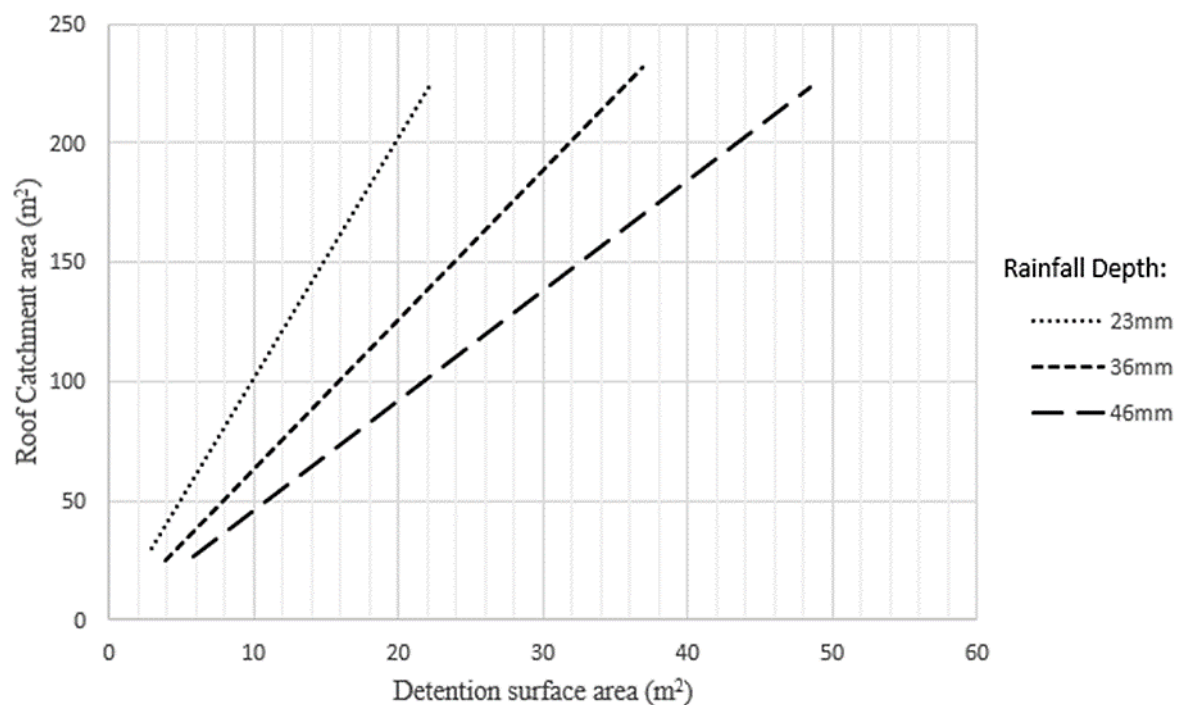


Figure 4.28: Plot of Roof Catchment Area, Detention Surface Area and Rainfall Depth

The mentioned second setting is based on simulation scenarios following the characteristics obtained in the field data. The lines provide choices of detention surface area for different pairing of roof catchment area and rainfall depths, in which the rainfalls represent 5-, 10- and 15-minute 10-year ARI rainfall events.

4.3.3 Flow and Water Level Relationships

Relationships of flow and water level are depicted in Figure 4.29 and Figure 4.30 for inflow and outflow respectively. The water level data here are unique due to StormPav modular units.

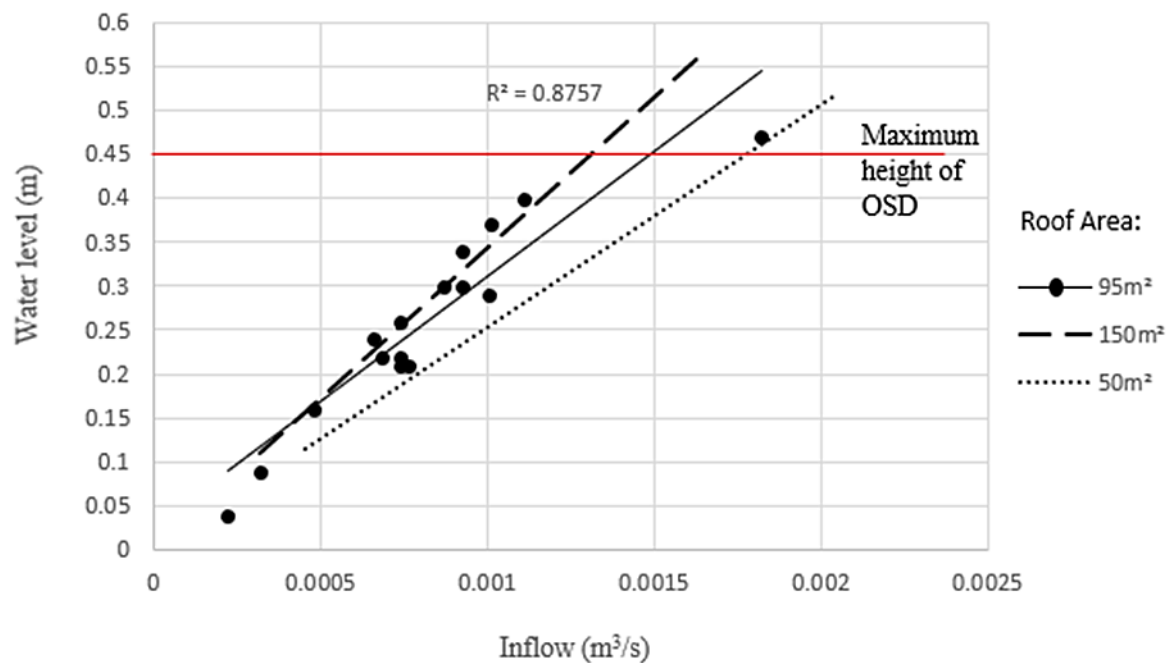


Figure 4.29: Plot of Water Level, Inflow and Roof Catchment Area

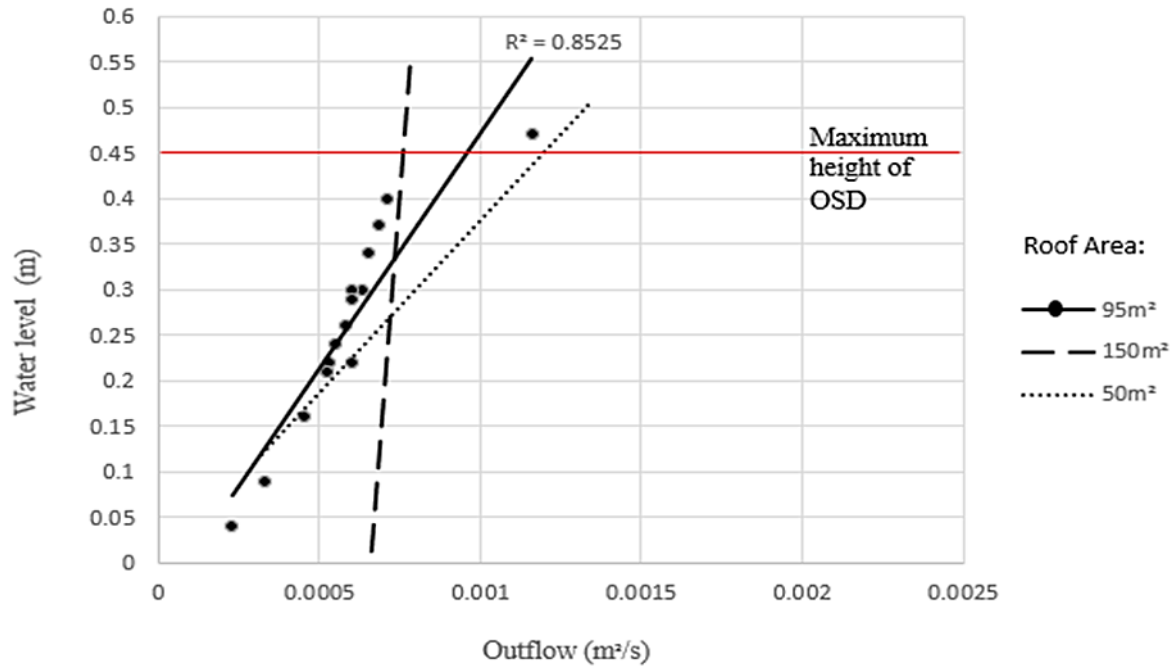


Figure 4.30: Plot of Water Level, Outflow and Roof Catchment Area

The two graphs point to the current OSD setting have a predictable pattern of water level in relation to inflow. It is found that, inflow data concentrate between the range 0.0005-0.001m³/s in response to water level rising from 0.15-0.40m for rainfall depths 0-40mm. It appears that 50, 95 and 150m² share similar trend in inflow.

As mentioned before, the outflow is influenced by the orifice. The latter graph shows that the outflow data concentrate between the range of 0.0003-0.0007m³/s in response to water level rising from 0.15-0.40m for rainfall depths 0-40mm. 50m² and 95m² roof catchment areas share a similar trend in outflow. However, 150m² roof catchment area shows a line different than the other two lines. It reinstates the same observation in the earlier subsection, bigger roof catchment area overwhelms the current OSD setting with high volume of stormwater runoff.

4.3.4 Urban Runoff Reduction

Urban runoff reduction is presented as attenuation, in which it is a measurement in percentage the difference between the peak runoff values with and without StormPav OSD. The attenuation data here are also unique as there are based on field data with StormPav modular units. The graph of attenuation rates is presented in Figure 4.31.

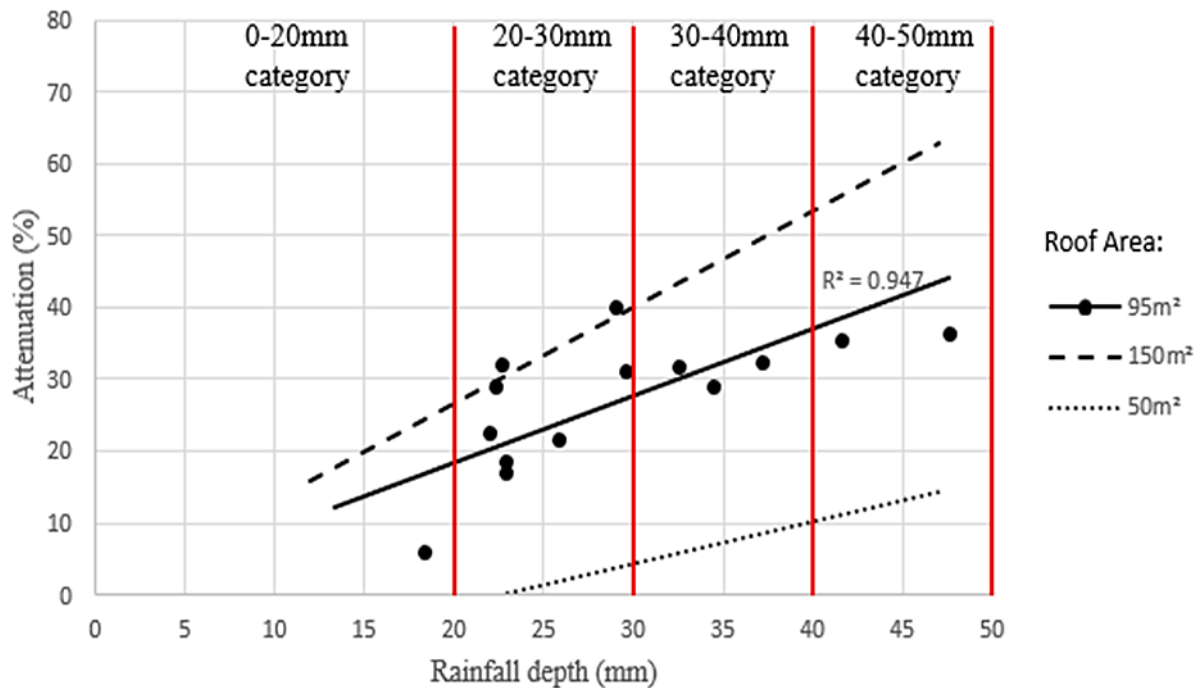


Figure 4.31: Plot of Attenuation, Rainfall Depth and Roof Catchment Area

Referring to the field data scattered in the middle of the graph, attenuation rates range about 20% for 20-30mm rainfall category, 30% for 30-40mm category, and 40% for 40-50 mm category. These mean StormPav OSD is able to reduce the peak runoff by 20%, 30%, and 40% for the mentioned respective rainfall categories. It is found that bigger roof catchment area contributes to higher attenuation rate. The 150m² roof catchment area is estimated to give maximum 65% attenuation. However, it is the opposite for smaller roof catchment area. The 50m² roof catchment area is estimated to give 15% attenuation only.

The most significant peculiarity in the analysis is the steep line graphs observed in Figure 4.27 and Figure 4.30. These two lines come from the 150m² roof catchment area. The current OSD setting could accommodate up to 30mm rainfall depth only. The bigger the roof catchment area promotes higher water level in the OSD tank although the orifice remained a constant outflow rate from the water level. Despite this drawback, the water detention is the highest among the three investigated roof catchment areas. The current orifice outlet size causes higher volume of water remaining in the OSD tank and thus achieving the highest attenuation rate (65%).

The small 50m² roof catchment area is found as unfavourable. It is indicated in Figure 4.31 that the attenuation rate is the lowest (15%). This could be explained by comparing the lines produced by 50m² roof catchment area in Figure 4.25 and Figure 4.26. The inflow line is in the similar range as of the outflow line. It means the water is flowing through the system with little detention achieved for 0-40mm rainfall depth.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The main outcome of this project lies in the reporting of field data analysis collected from the home-based stormwater detention system. Field data of stormwater system are rare. These data represent the actual performances of the system. The superiority of such a database shall exceed the previous studies using computer simulations and laboratory experiments.

With the availability of the field data, previous developed computer model using SWMM5 is validated. The validated model is, in turn, being used for further exploration of the stormwater system to gain more clarity (namely., applying different roof catchment areas to explore the functionality of the OSD under study).

5.1 Conclusions

The field data collected from the field test which has been constructed successfully in Merdang Gayam, a housing estate in Samarahan, Sarawak. The set up involves having an OSD with a surface area of 4.70 m x 4.40 m, a depth of 0.45 m and an effective storage volume of 3.97 m³, constructed under a 95 m² house side canopy. Roof gutter and 0.1 m diameter downpipe is connected to the OSD as inlet and 0.05 m diameter pipe is connected as outlet. To accommodate data collection, one rain gauge is installed at the house fence beside the system, two flowmeters are installed at the downpipe and outlet, as well as two water level sensors are installed at the OSD. The field data collected are similar to the design parameters. Data collection has been successfully carried out for five months, from December 2019 to April 2020 that cover the Northeast monsoon season and monsoon

transition period. Sixteen storm events are selected from the field data for analysis that are classified into four rainfall depth categories, namely 0-20 mm, 20-30 mm, 30-40 mm, 40-50 mm. The 0-20 mm category is considered as insignificant storm events for having no or little detention. The remaining three categories are compared with the design data. It is found that 20-30 mm and 30-40 mm are matching satisfactorily with the design data; while 40-50 mm category has higher observed water levels in OSD than the design data that posing flood risk for the system to counter with rainfall depth above 40 mm.

The developed SWMM model from previous studies is validated using the selected thirteen storm events from the field test. K-S test is the statistical tool used to quantify the goodness of fit, in which analysis from all the thirteen storm events show no significant difference between the field and model distributions. In another word, the model is found to able to mimic the field performances of the OSD well.

5.1.1 Responses to Actual Rainfall

Inflows to the StormPav OSD increase linearly with the increment of rainfall depths from 0-40mm. Outflows, however, are influenced by the captured water levels than the rainfall depths.

5.1.2 Catchment Area to Storage Detention

Small 50m² roof catchment area is found to produce roof runoff flowing through the OSD with little detention. As such, small roof catchment area is unfavourable for OSD purposes.

95m² and 150m² roof catchment area give reasonable detention found at 45% and 65% reduction of peak runoff values, respectively. However, large roof catchment area demonstrated in the 150m², poses threat to overflowing of OSD due to the reason a large

catchment area produces larger amount of runoff that contributes to high water levels in the OSD tank.

5.1.3 Flow and Water Level Relationships

The current OSD setting causes an accumulation of water behind the orifice outlet. This builds up of water also causes higher detention of water in the OSD when the roof catchment area increases.

5.1.4 Urban Runoff Reduction

The current OSD setting had low detention (15%) from small 50m² roof catchment area. However, the runoff reduction, in terms of attenuation rate, increases with the increment of roof catchment area.

5.2 Recommendations for Future Studies

In this thesis, with the availability of the field data, previous developed computer model using SWMM5 is validated. The recommendations for future study in relation to the current study are as follows:

- a) Since the collected rainfall runoff field data are from the roof made of spandex. Thus, in future study, a field test on various types of roof materials is recommended for validation of the model to determine the degree to which a model is an accurate representation of the real-world system;
- b) Further investigation into the various angles of roof which will effect on the discharge runoff and eventually on the size of the OSD;
- c) Further investigation into the number and positioning of the overflow pipe to allow more effective ponding and draining effects.

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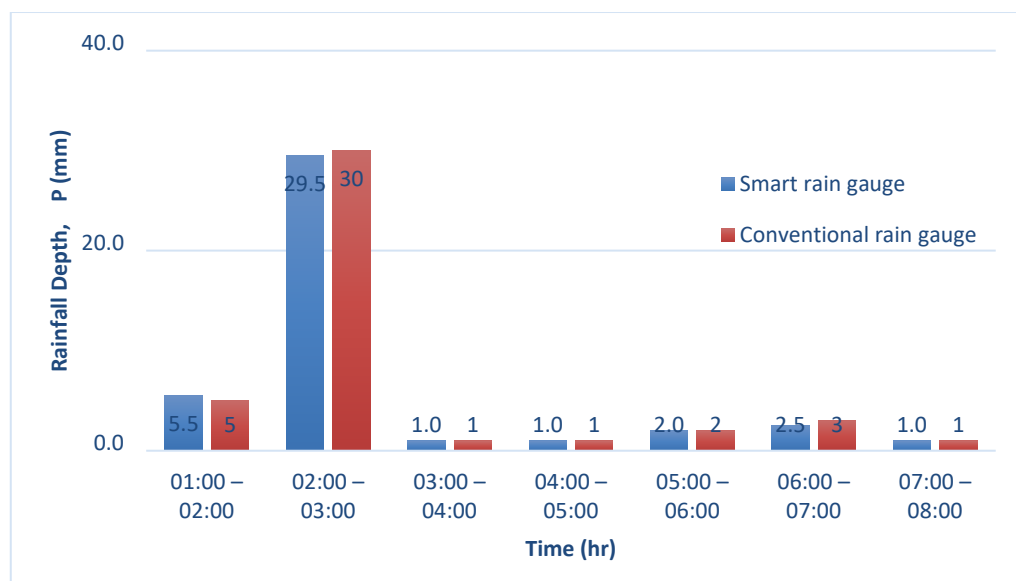
APPENDICES

Appendix A

Equipment Calibration

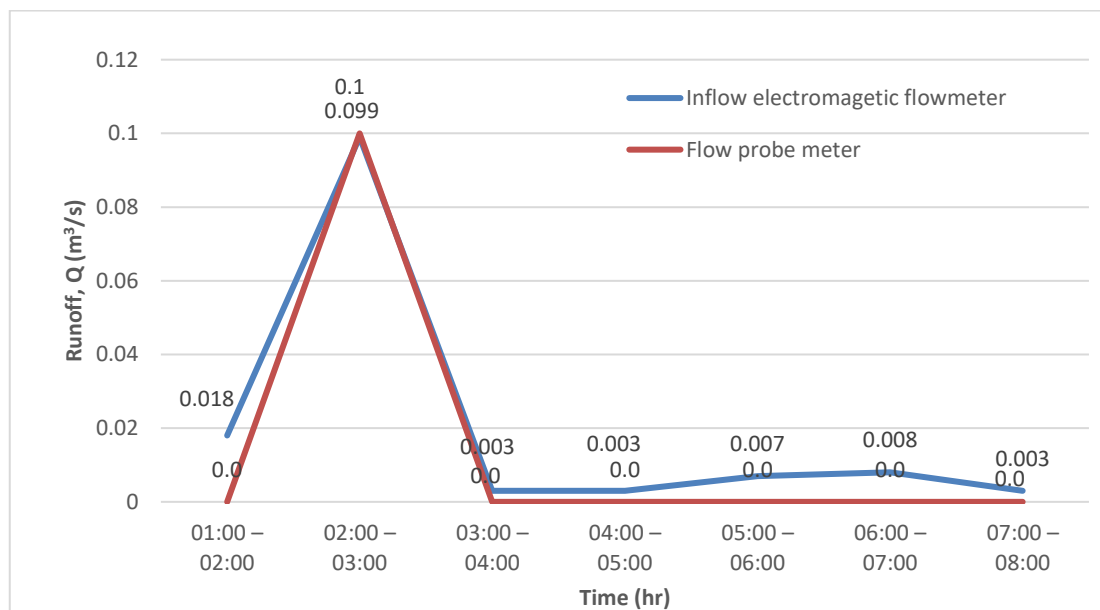
A1(a): Calibration of Intelligent Data Collector Rain Gauge for 1 December 2019

Time	Intelligent data collector rain gauge (mm/hr)	Rainfall gauge plastic dual scale (mm/hr)
01:00 – 02:00	5.5	5
02:00 – 03:00	29.5	30
03:00 – 04:00	1.0	1
04:00 – 05:00	1.0	1
05:00 – 06:00	2.0	2
06:00 – 07:00	2.5	3
07:00 – 08:00	1.0	1



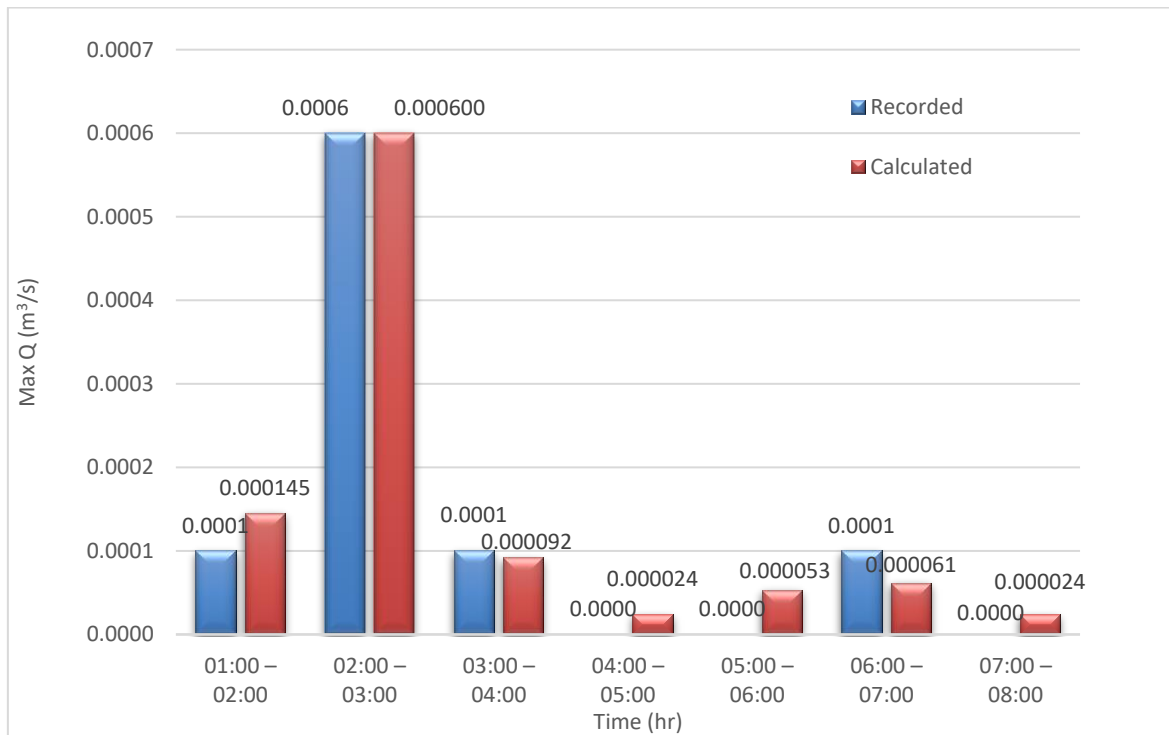
A1(b): Calibration of Intelligent Electromagnetic Flowmeter for 1 December 2019

Time	Intelligent electromagnetic flowmeter (m/s) inflow	Water flow probe (m/s)
01:00 – 02:00	0.018	0.0
02:00 – 03:00	0.099	0.1
03:00 – 04:00	0.003	0.0
04:00 – 05:00	0.003	0.0
05:00 – 06:00	0.007	0.0
06:00 – 07:00	0.008	0.0
07:00 – 08:00	0.003	0.0



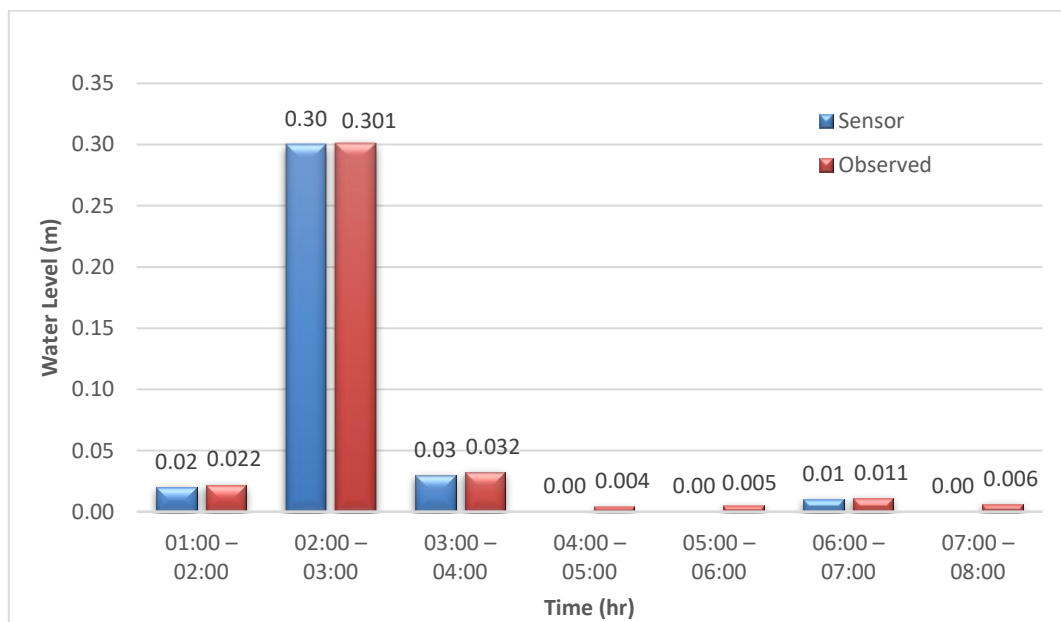
A1(c): Calibration of Intelligent Electromagnetic Flowmeter for 1 December 2019

Time	Intelligent electromagnetic flowmeter (m/s) outflow	Orifice hand calculation (m/s)
01:00 – 02:00	0.0001	0.000145
02:00 – 03:00	0.0006	0.000600
03:00 – 04:00	0.0001	0.000092
04:00 – 05:00	0.0000	0.000024
05:00 – 06:00	0.0000	0.000053
06:00 – 07:00	0.0001	0.000061
07:00 – 08:00	0.0000	0.000024



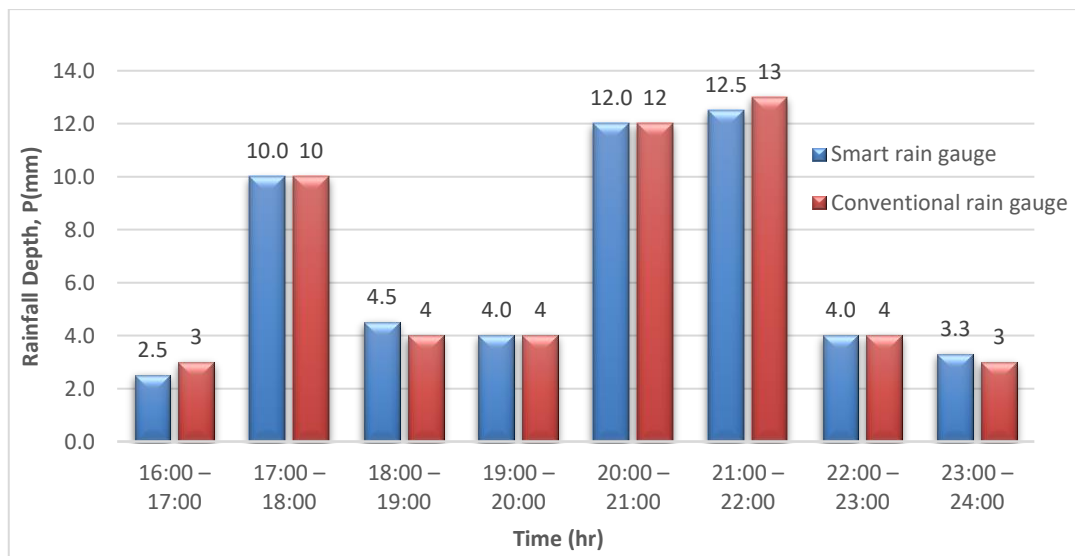
A1(d): Calibration of Ultrasonic Water Level Detector with Display for 1 December 2019

Time	Ultrasonic water level detector with display (m)	Ruler (m)
01:00 – 02:00	0.02	0.022
02:00 – 03:00	0.30	0.301
03:00 – 04:00	0.03	0.032
04:00 – 05:00	0.00	0.004
05:00 – 06:00	0.00	0.005
06:00 – 07:00	0.01	0.011
07:00 – 08:00	0.00	0.006



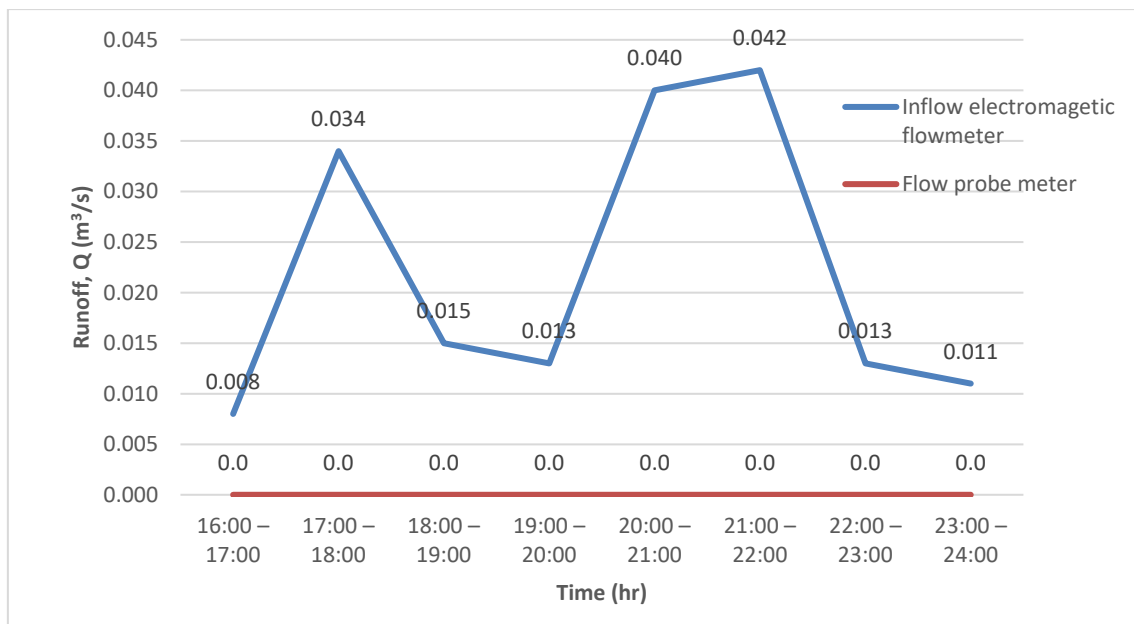
A2(a): Calibration of Intelligent Data Collector Rain Gauge for 2 December 2019

Time	Intelligent data collector rain gauge (mm/hr)	Rainfall gauge plastic dual scale (mm/hr)
16:00 – 17:00	2.5	3
17:00 – 18:00	10.0	10
18:00 – 19:00	4.5	4
19:00 – 20:00	4.0	4
20:00 – 21:00	12.0	12
21:00 – 22:00	12.5	13
22:00 – 23:00	4.0	4
23:00 – 24:00	3.3	3



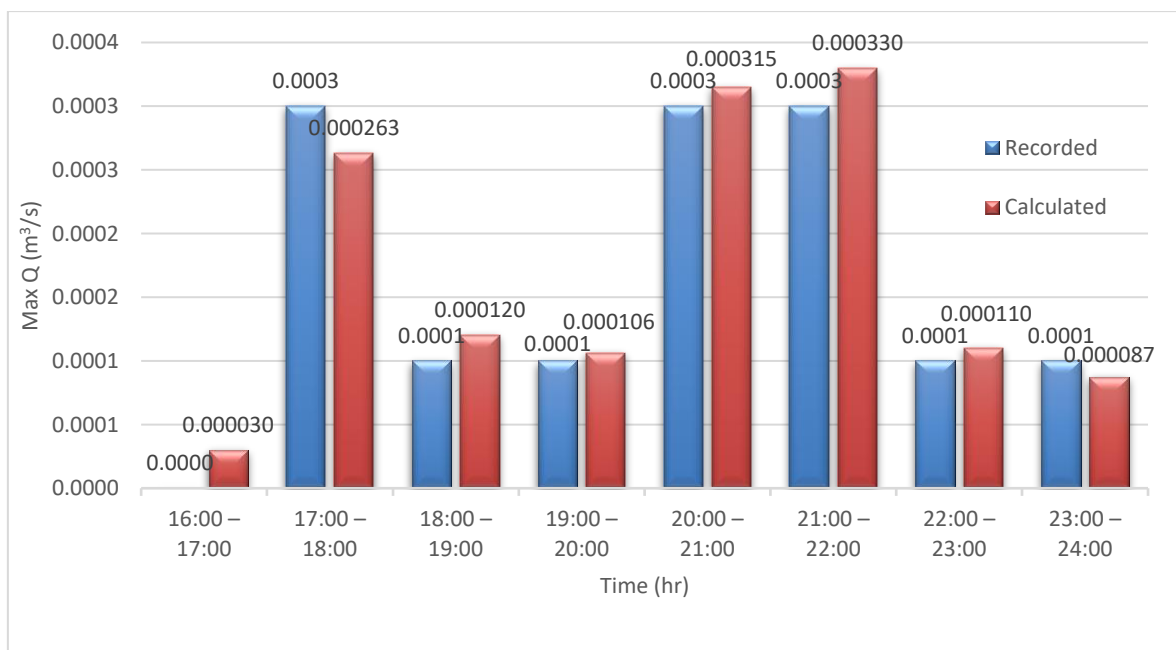
A2(b): Calibration of Intelligent Electromagnetic Flowmeter for 2 December 2019

Time	Intelligent electromagnetic flowmeter (m/s) inflow	Water flow probe (m/s)
16:00 – 17:00	0.008	0.0
17:00 – 18:00	0.034	0.0
18:00 – 19:00	0.015	0.0
19:00 – 20:00	0.013	0.0
20:00 – 21:00	0.040	0.0
21:00 – 22:00	0.042	0.0
22:00 – 23:00	0.013	0.0
23:00 – 24:00	0.011	0.0



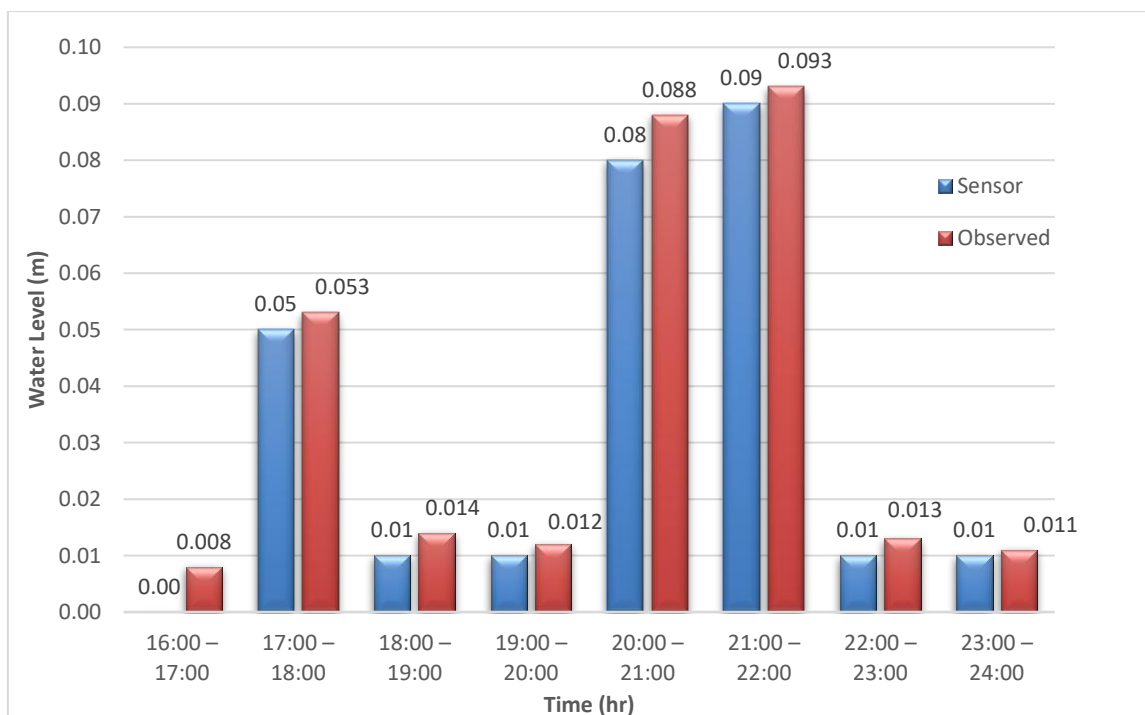
A2(c): Calibration of Intelligent Electromagnetic Flowmeter for 2 December 2019

Time	Intelligent electromagnetic flowmeter (m/s) outflow	Orifice hand calculation (m/s)
16:00 – 17:00	0.0000	0.000030
17:00 – 18:00	0.0003	0.000263
18:00 – 19:00	0.0001	0.000120
19:00 – 20:00	0.0001	0.000106
20:00 – 21:00	0.0003	0.000315
21:00 – 22:00	0.0003	0.000330
22:00 – 23:00	0.0001	0.000110
23:00 – 24:00	0.0001	0.000087



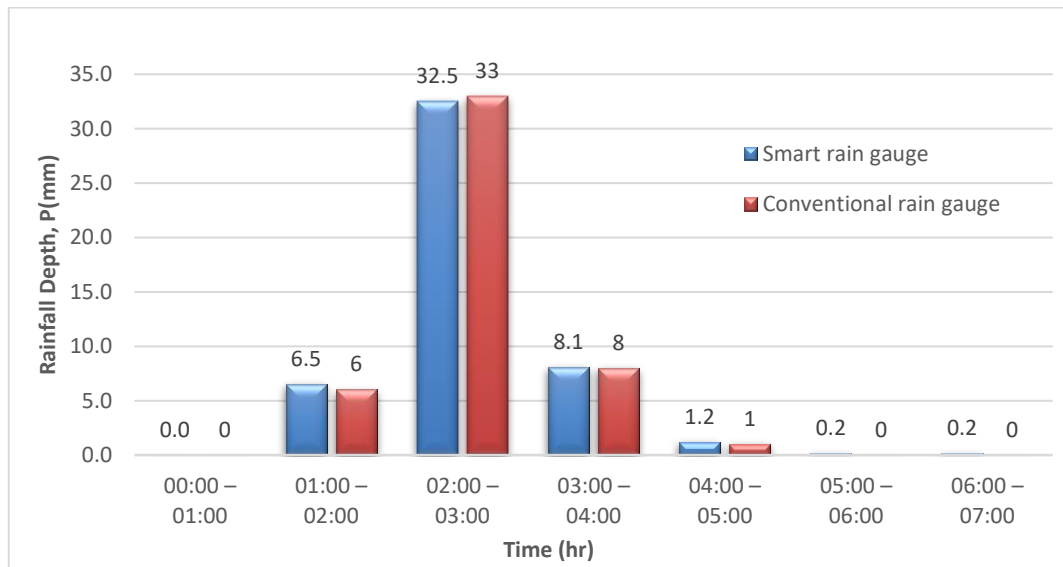
A2(d): Calibration of Ultrasonic Water Level Detector with Display for 2 December 2019

Time	Ultrasonic water level detector with display (m)	Ruler (m)
16:00 – 17:00	0.00	0.008
17:00 – 18:00	0.05	0.053
18:00 – 19:00	0.01	0.014
19:00 – 20:00	0.01	0.012
20:00 – 21:00	0.08	0.088
21:00 – 22:00	0.09	0.093
22:00 – 23:00	0.01	0.013
23:00 – 24:00	0.01	0.011



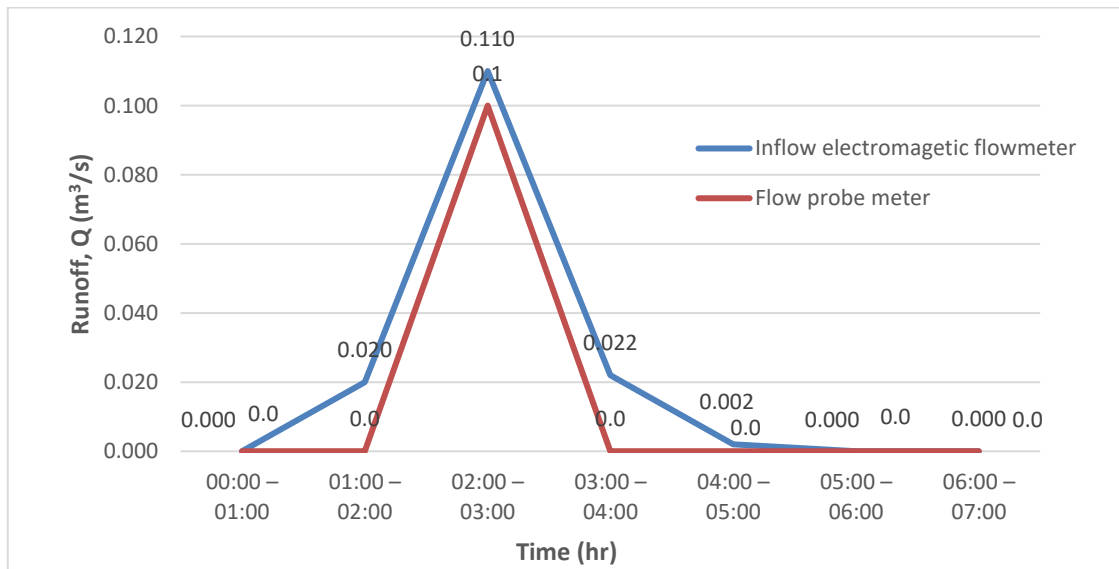
A3(a): Calibration of Intelligent Data Collector Rain Gauge for 7 December 2019

Time	Intelligent data collector rain gauge (mm/hr)	Rainfall gauge plastic dual scale (mm/hr)
00:00 – 01:00	0	0
01:00 – 02:00	6.5	6
02:00 – 03:00	32.5	33
03:00 – 04:00	8.1	8
04:00 – 05:00	1.2	1
05:00 – 06:00	0.2	0
06:00 – 07:00	0.2	0



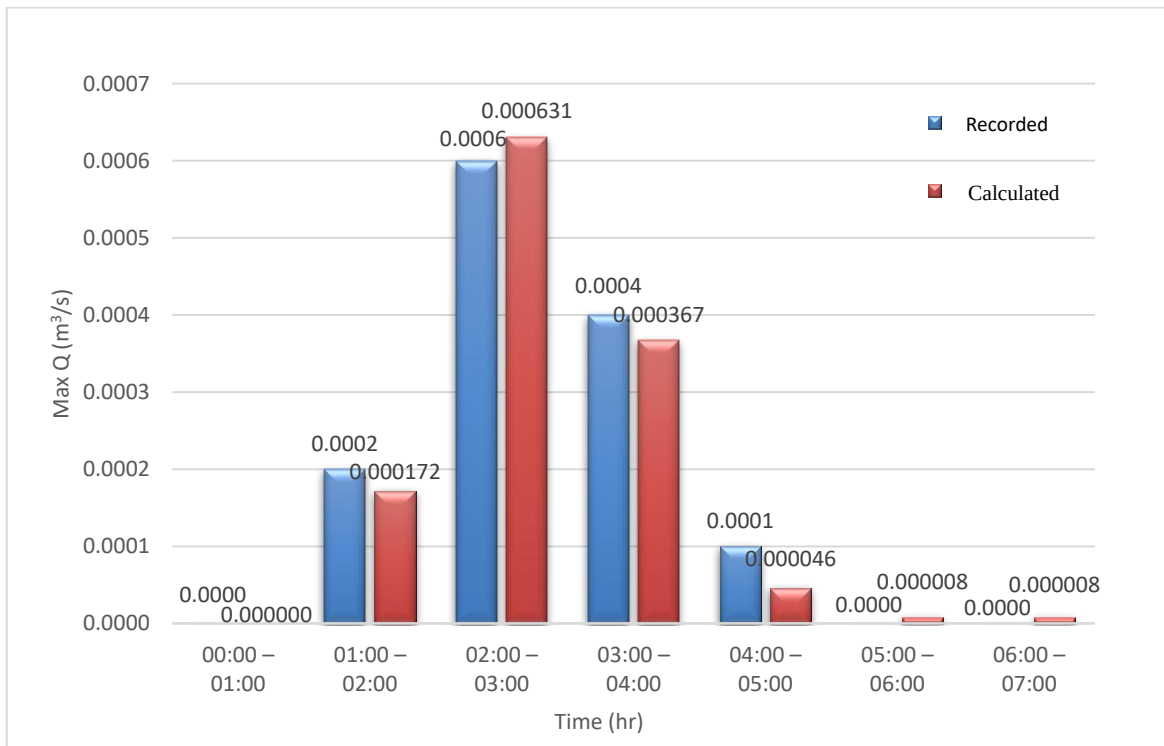
A3(b): Calibration of Intelligent Electromagnetic Flowmeter for 7 December 2019

Time	Intelligent electromagnetic flowmeter (m/s) inflow	Water flow probe (m/s)
00:00 – 01:00	0.000	0.0
01:00 – 02:00	0.020	0.0
02:00 – 03:00	0.110	0.1
03:00 – 04:00	0.022	0.0
04:00 – 05:00	0.002	0.0
05:00 – 06:00	0.000	0.0
06:00 – 07:00	0.000	0.0



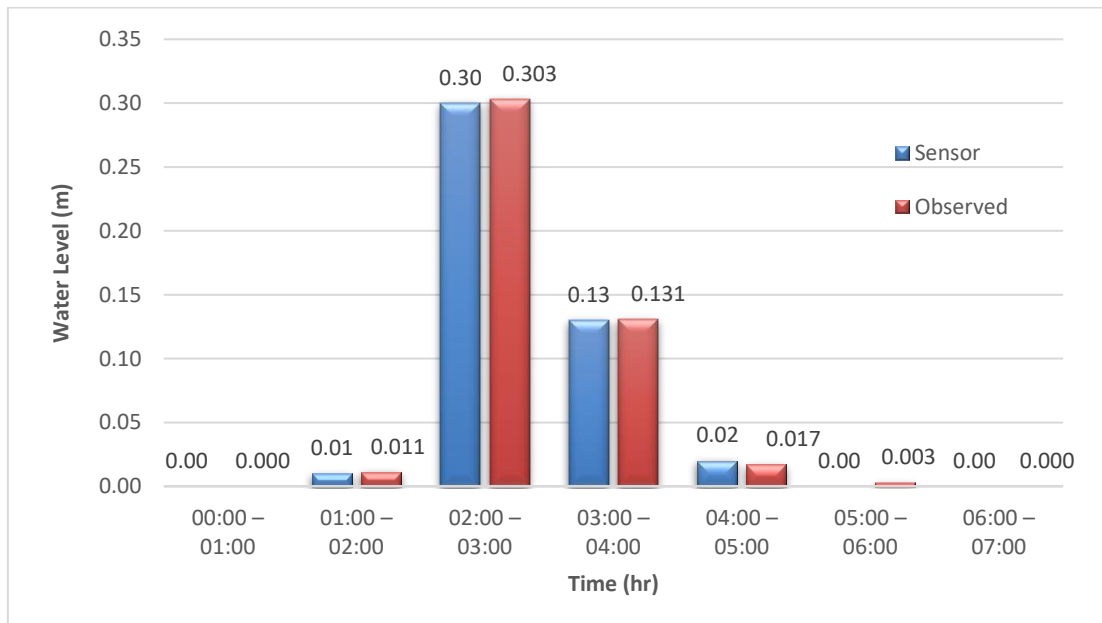
A3(c): Calibration of Intelligent Electromagnetic Flowmeter for 7 December 2019

Time	Intelligent electromagnetic flowmeter (m/s) outflow	Orifice hand calculation (m/s)
00:00 – 01:00	0.0000	0.000000
01:00 – 02:00	0.0002	0.000172
02:00 – 03:00	0.0006	0.000631
03:00 – 04:00	0.0004	0.000367
04:00 – 05:00	0.0001	0.000046
05:00 – 06:00	0.0000	0.000008
06:00 – 07:00	0.0000	0.000008



A3(d): Calibration of Ultrasonic Water Level Detector with Display for 7 December 2019

Time	Ultrasonic water level detector with display (m)	Ruler (m)
00:00 – 01:00	0.00	0.000
01:00 – 02:00	0.01	0.011
02:00 – 03:00	0.30	0.303
03:00 – 04:00	0.13	0.131
04:00 – 05:00	0.02	0.017
05:00 – 06:00	0.00	0.003
06:00 – 07:00	0.00	0.000



Appendix B

Collected Rainfall Data

B1: December 2019

Dec Day / Time	2019																							Max	Total	
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22			23
1		5.5	29.5	1.0	1.0	2.0	2.5	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.5	1.5	0.5	29.5	46.0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.5	10.0	4.5	4.0	12.0	12.5	4.0	3.3	12.5	52.8
3	2.2	0.2	0	0.3	0	0	0	0	0	0	0.6	0	0	0	0	2.3	0	0	0	0	0	0	0	0	2.3	5.6
4	0	0	0	0	0	0	0	0	0	0	0	0	2.0	3.5	0	0	0	0	0	0	1.0	0	0	2.3	3.5	8.8
5	0.5	3.2	15.2	0	0	0	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15.2	19.5
6	0	0	1.0	0.8	1.3	1.9	2.0	1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.0	8.5
7	0	6.5	32.5	8.1	1.2	0.2	0	0	0	0	0	0	0	0.2	2.4	4.4	0	0	0	0	0.2	0.6	1.0	0	32.5	57.3
8	7.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	5.4	6.2	7.8	19.9
9	28.8	8.6	6.3	1.2	0.6	0	0	0.2	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	28.8	45.9
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0.4	0	0	0	0	0	0	0	0	0.4	0.8
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	2.0	3.4	4.0	8.6	6.4	1.2	0.2	0.6	8.6	26.6
12	0.8	1.2	1.0	1.0	0.8	0.2	0	0	0	0.4	0	0	0	0	0	0	0	0	4.6	5.6	0.6	0	0	0.8	5.6	17.0
13	1.0	1.2	0.6	1.4	2.0	0.2	0	0	0	0	0	0	0	0.2	0.2	0	0	0	0	0	0	0	0	0	2.0	6.8
14	0	0	1.2	0.4	0	0	0	0	0.2	0.2	0	0	0	0	0	0.2	7.0	4.8	0	0	0	0	0	0	7.0	14.0
15	0.4	0.4	0	0	0	0	0	6.6	0.6	0	0	0	0.6	1.8	0.4	0	0	0.8	0.8	0	0	0	0	0	6.6	12.4
16	0	0	0	0	0	0	0.2	0.8	2.8	2.0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	2.8	6.0
17	0	0	0	0	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	2.5	5.0	3.1	1.4	5.0	12.4	
18	0.6	1.2	0.6	0.3	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.2	2.8
19	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.6	0	0	0	3.3	0.3	0	0	0	0	0	3.3	4.4
20	0	0	0	0	0	0	0	0	0	0	0	1.7	1.5	2.0	1.6	0	0	0	0	0	0	0	0	0	2.0	6.8
21	0	0	0	0	0	0	0	0	0	0.1	0.3	0	0	1.8	0.6	0.8	16.6	13.8	0	0	0	0	0	0	16.6	34.0
22	0	0	0.3	0.1	3.0	17.4	21.9	4.1	9.6	3.6	0	0	0	8.0	3.2	0	0	0	0	0	0	0	0	0	21.9	71.2
23	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.3	0.3	0	0	0	0.1	1.4	0	0	0	0	1.4	2.3
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.5	7.5	0	0	0	0	0	0	0	0	7.5	10.0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	1.2	0.8	0	0	0	1.1	2.9	0	0	0	0	2.9	6.0
27	0	0	0.2	0.2	0	0	0	0	0	0	0	2.6	2.6	0	0	0	0.4	1.5	0.1	0	0	0	0	8.7	8.7	16.3
28	7.5	1.3	0.1	11.6	22.3	6.7	1	0.3	0	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0.7	0.9	22.3	52.8
29	1	1	0.8	0	0	0	0	0	5.3	15	1.1	0.2	0.2	0	0	0	0	0	2.1	1.1	0	0	0	0.5	14.8	28.1
30	0.4	0.7	0.4	0	0	3.8	18.3	14.7	1	0.9	0.8	0.1	0	1.6	1.6	0	0	0	0	0	0	0	0	0	18.3	44.3
31	0	0	0	7	10.8	3.4	2.6	0.7	1.6	2.1	5.5	2.3	7.2	1.6	0	0	0	0	0	1.6	1.4	0.2	0	0	10.8	48.0
																									687.3	

B2: January 2020

Jan Day / Time	2020																							Max	Total		
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22			23	
1		7.6	22.8	0	0.8	5.6	10.2	1.0	5.8	6.4	0.6	0.6	0	0	0	0	0	1.0	1.4	0	0	0	0.8	2.2	22.8	66.8	
2	1.4	0.8	1.8	0.6	0	0.2	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.8	5.4	
3	0	11.2	3.2	0.8	0	0	0	10.4	12.8	7.6	15.2	3.8	1.8	0	0.2	0.6	0	0	0	0	0	0	1.6	5.0	15.2	74.2	
4	5.4	0	0	0	0.4	2.4	0.6	1.4	0	0.6	1.0	0.6	0	0	0	0	0	0	0	0	0.4	0.4	3.2	3.4	5.4	19.8	
5	3.8	0.8	0.4	2.8	0.8	0	3.6	2.2	11.0	14.4	16.8	1.8	16.8	5.8	9.4	8.8	0	0	0.2	13.2	5.8	0	0	0	16.8	118.4	
6	0	0.8	2.8	4.6	1.8	2.0	0.8	0	0	0	0	0	0	0	0	0	2.2	2.6	0	0.8	0.8	0	0	0	4.6	19.2	
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	
8	0	0	0	0	1.8	0.6	0	0	0	0	0	0	0	0	0	0	1.6	3.2	0	0	2.4	0	0.2	1.4	3.2	11.2	
9	0	0.4	0.8	1.2	1.2	0.4	0	0	0	0	0	0.4	0.4	0	0	0	0	0	0	0	0	0	0	0	1.2	4.8	
10	0	0	0	0	0	0	3.0	5.8	0.8	0	15.4	25.8	21.2	11.0	4.4	0.8	1.2	1.0	0.6	2.8	0.6	0	0	0	25.8	94.4	
11	0	0	0	1.4	0.2	0	0	14.8	16.6	0.6	0	0	0	0	0	0	0	0	0	0.8	0	0	0	0	16.6	34.4	
12	0	0	0	0	0	0	0	0	0	0	0	0	7.2	0	17.0	2.2	0	0	0	0	0	0	0	0	17.0	26.4	
13	0	0	0	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	0.8	
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	
16	0	0	0	0	0	0	0	0	0	0	4.4	41.6	6.0	0.6	0	0	0	0	0	0	0	0	0	0	41.6	52.6	
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	
18	0	0	3.2	34.4	13.4	5.6	1.6	4.6	2.4	1.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	34.4	66.4	
19	1.6	9.2	17.8	22.8	0.6	4.2	3.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22.8	60.0	
20	0	0	5.4	37.2	20.2	7.2	5.6	3.0	2.2	0.6	0.2	0.6	3.4	0	0	0	0	0	0	0	0.4	0.4	0	0	37.2	86.4	
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	
22	0	0	0	0	0	0.2	22.6	9.6	0.4	0	0	0	0	0	0	0	0	0.2	0.6	0	0	0	0	0	22.6	33.6	
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	
27	0	0	0	0.6	0.2	0	0	0	0	0	0	0	0.4	1.2	0	0	0	0	0	0	0	0	0	0	1.2	2.4	
28	0	0	0	0	0.8	3.4	1.0	1.4	0.6	0	0	16.8	2.4	1.6	3.2	0	0	0	0	0	0	0	0	0	16.8	31.2	
29	0	0	0	0	0	0	0	0	3.0	11.0	1.8	1.4	11.8	2.8	10.4	1.8	0	0	0	0	0	0	0	0.6	0.2	11.8	44.8
30	0	0	0	0	0	0	0	0	8.8	5.0	6.8	0	0	0	0	1.0	4.4	2.6	0	0	0.6	0.2	0	0	8.8	29.4	
31	0	0	0	0	0	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	0.8	
																										883.3	

B3: February 2020

Feb Day / Time	2020																								Total	
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23		Max
1	0	0	0	0	0	2.2	4.0	6.0	2.7	0.5	0.2	0.3	0	0	0	0	0	0	0	0	0	0	0	0	6.0	15.9
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0
4	0	0	0	0	0	0	0	0	0	1.0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	1.0	1.5
5	0	0	0	0	0	0	0	0	0	0	0	6.0	3.1	1.0	12.1	9.1	5.5	4.5	1.0	1.3	1.0	0	0	1.5	12.1	46.1
6	0	0	0	0	0	0	0.8	0	0	0	0.6	0	1.0	2.5	1.3	0	0	0	0	0	0	0	0	0	2.5	6.2
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0
9	0	0	0	0	0	0	0	0	0	5.5	1.0	3.2	7.1	6.6	5.1	3.2	0	0	0	0	0	0	0	0	7.1	31.7
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0
11	0	0	0	0.5	0.5	7.3	1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.3	9.8
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0
14	0	0	0	2.1	2.5	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.5	5.6
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0
16	0	3.0	1.0	1.5	1.0	2.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	1.0	3.0	10.0
17	0	0	1.0	0	0	0	1.5	0	2.0	7.5	2.0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.5	14.0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0
19	0	0	0	0	0	0	0	0	0	5.5	5.5	4.0	0	0	1.0	0	0	0	0	0	0	0	0	0	5.5	16.0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.0	0.5	1.0	11.2	1.8	0.1	11.2	15.6
22	0	0	0	0	0	1.0	0.7	15.1	0.3	0	0	0	1.2	3.4	22.4	47.6	31.6	6.4	2.4	1.2	0.7	0.6	0	0	47.6	134.6
23	0.2	3.7	22.0	7.3	0.3	0.5	0.2	0	0	0.2	0.6	0.4	11.2	2.1	0.8	0	0	0	0.8	0	1.6	7.2	2.6	0	22.0	61.7
24	0	1.6	2.2	8.2	7.3	3.8	8.6	9.1	0.7	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9.1	42.1
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0
26	0	0	6.3	1.0	7.8	10.1	6.5	1.1	0.5	0	0	0	2.2	3.1	4.2	4.0	4.1	1.2	1.1	0	0	0	0	0	10.1	53.2
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	1.0	0.5	0.5	0	1.0	2.8
28	0	0	0	0	0	0	0	0	0	0.5	1.0	1.1	0.8	18.0	1.3	2.0	0.4	0	0	0	0	0	0	0	18.0	25.1
29	0	0	0	0	0	0	2.5	4.3	1.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.3	8.0
																										499.3

B4: March 2020

[illegible]

B5: April 2020

[illegible]

Appendix C

Field and Model Data

C1a: (0-20 mm) 30 December 2019

Time (hr)	Rainfall (mm)	Inflow (m ³ /s)		Outflow (m ³ /s)		Water Level (m)	
		Field	Model	Field	Model	Field	Model
0100-0200	3.8	0.000106	0.0001	0.000099	0.0001	0.01	0.0079
0200-0300	18.3	0.00048	0.000483	0.000451	0.000453	0.16	0.1606
0300-0400	14.7	0.000391	0.000388	0.000398	0.000399	0.13	0.1246
0400-0500	1	0.000026	0.000027	0.000074	0.000014	0.03	0.0013
0500-0600	0.9	0.000026	0.000024	0.000027	0.000027	0	0.0021
0600-0700	0.8	0.000021	0.000021	0.000019	0.000019	0	0.0016
0700-0800	0.1	0.000011	0.000004	0.000001	0.000025	0	0.0003
	Mean	0.000151571	0.000149571	0.000152714	0.000148143	0.047142857	0.04262857
	SD	0.000198164	0.00019958	0.000189262	0.000192656	0.068243262	0.06912346
	Pearson		0.999856795		0.990934429		0.9873269

C1b: (0-20 mm) 2 December 2019

Time (hr)	Rainfall (mm)	Inflow (m ³ /s)		Outflow (m ³ /s)		Water Level (m)	
		Field-Inflow	Model-Inflow	Field-Outflow	Model-Outflow	Field-Water Level	Model-Water Level
1600-1700	2.5	0	0.000066	0.00003	0.000031	0	0.0022
1700-1800	10	0.000264	0.000264	0.000263	0.000264	0	0.0544
1800-1900	4.5	0.000079	0.000119	0.00012	0.000119	0.01	0.011
1900-2000	4	0.000106	0.000106	0.000106	0.000106	0.01	0.0087
2000-2100	12	0.000317	0.000317	0.000315	0.000316	0.08	0.0779
2100-2200	12.5	0.000317	0.00033	0.00033	0.00033	0.09	0.0849
2200-2300	4	0.000106	0.000106	0.00011	0.000106	0.01	0.0087
2300-0000	3.3	0.000084	0.000087	0.000087	0.000087	0.01	0.0059
	Mean	0.000159125	0.000174375	0.000170125	0.000169875	0.0325	0.0317125
	SD	0.000121818	0.000109798	0.000114617	0.000115112	0.035757117	0.03485142
	Pearson		0.982578564		0.999903716		0.99626823

C1c: (0-20 mm) 11&12 December 2019

Time (hr)	Rainfall (mm)	Inflow (m ³ /s)		Outflow (m ³ /s)		Water Level (m)	
		Field	Model	Field	Model	Field	Model
1500-1600	0.2	0.000005	0.000004	0.000002	0.000002	0	0.0003
1600-1700	2	0.000053	0.000053	0.000066	0.000066	0	0.0052
1700-1800	3.4	0.000095	0.00009	0.000089	0.00009	0	0.0063
1800-1900	4	0.000106	0.000106	0.000106	0.000106	0	0.0087
1900-2000	8.6	0.000222	0.000227	0.000227	0.000227	0.04	0.0403
2000-2100	6.4	0.000201	0.000169	0.000169	0.000169	0.02	0.0223
2100-2200	1.2	0.000048	0.000032	0.000038	0.000038	0	0.003
2200-2300	0.2	0.000003	0.000006	0.000006	0.000006	0	0.0022
2300-0000	0.6	0.000016	0.000016	0.000016	0.000016	0	0.0037
0000-0100	0.8	0.000021	0.00002	0.000023	0.00002	0	0.0037
0100-0200	1.2	0.000032	0.000032	0.000042	0.000042	0	0.0045
0200-0300	1	0.000026	0.000026	0.000032	0.000032	0	0.0028
0300-0400	1	0.000026	0.000026	0.000031	0.000014	0	0.0013
0400-0500	0.8	0.000021	0.000022	0.000021	0.000021	0	0.0043
0500-0600	0.2	0.000016	0.000021	0.000008	0.000008	0	0.0019
	Mean	5.66667E-05	5.66667E-05	5.71333E-05	5.71333E-05	0	0.00736667
	SD	6.86282E-05	6.49733E-05	6.48997E-05	6.57092E-05	0.011212238	0.01049821
	Pearson		0.991446559		0.997774319		0.98063144

C2a: (20-30 mm) 1 January 2020

Time (hr)	Rainfall (mm)	Inflow (m ³ /s)		Outflow (m ³ /s)		Water Level (m)	
		Field-Inflow	Model-Inflow	Field-Outflow	Model-Outflow	Field-Water Level	Model-Water Level
0100-0200	7.6	0.000269	0.000201	0.0002	0.000201	0.03	0.0314
0200-0300	22.8	0.000739	0.000602	0.000601	0.000528	0.22	0.2176
0300-0400		0	0.000003	0	0.000003	0.00	0.0014
	Mean	0.000336	0.00026867	0.000267	0.000244	0.08333333	0.08346667
	SD	0.00037403	0.00030518	0.00030605	0.00026513	0.11930353	0.11712734
	Pearson		0.99929842		0.99875923		0.99999723

C2b: (20-30 mm) 22 January 2020

Time (hr)	Rainfall (mm)	Inflow (m ³ /s)		Outflow (m ³ /s)		Water Level (m)	
		Field-Inflow	Model-Inflow	Field-Outflow	Model-Outflow	Field-Water Level	Model-Water Level
0500-0600	0.2	0	0.000004	0.000003	0.000002	0	0.0003
0600-0700	22.6	0.000765	0.000596	0.00052	0.000521	0.21	0.2119
0700-0800	9.6	0.000301	0.000253	0.000286	0.000266	0.07	0.0552
0800-0900	0.4	0.000018	0.000012	0.000012	0.000012	0.00	0.0018
	Mean	0.000271	0.00021625	0.00020525	0.00020025	0.07	0.0673
	SD	0.00035702	0.00027829	0.00024755	0.00024627	0.09899495	0.09972432
	Pearson		0.99944589		0.99918777		0.99670415

C2c: (20-30 mm) 19 January 2020

Time (hr)	Rainfall (mm)	Inflow (m ³ /s)		Outflow (m ³ /s)		Water Level (m)	
		Field	Model	Field	Model	Field	Model
0000-0100	1.6	0.000053	0.000042	0.000049	0.000049	0	0.0033
0100-0200	9.2	0.000264	0.000243	0.000243	0.000243	0.05	0.0461
0200-0300	17.8	0.000422	0.00047	0.000446	0.000446	0.16	0.1557
0300-0400	22.8	0.00066	0.000602	0.000548	0.000547	0.24	0.2339
0400-0500	0.6	0.000011	0.000015	0.000025	0.000005	0.03	0.0006
0500-0600	4.2	0.000132	0.000111	0.000111	0.000111	0.01	0.0096
0600-0700	3.8	0.000106	0.0001	0.00011	0.0001	0.01	0.0079
	Mean	0.00023543	0.00022614	0.00021886	0.00021443	0.07142857	0.0653
	SD	0.00023345	0.00022682	0.0002043	0.00020819	0.09227289	0.09255098
	Pearson		0.99078403		0.99946562		0.99329279

C2d: (20-30 mm) 22 December 2019

Time (hr)	Rainfall (mm)	Inflow (m ³ /s)		Outflow (m ³ /s)		Water Level (m)	
		Field-Inflow	Model-Inflow	Field-Outflow	Model-Outflow	Field-Water Level	Model-Water Level
0200-0300	0.3	0.000008	0.000007	0.000002	0.000002	0	0.0004
0300-0400	0.1	0.000003	0.000003	0.000001	0.000001	0	0.0003
0400-0500	3	0.000079	0.000079	0.000078	0.000079	0	0.0049
0500-0600	17.4	0.000449	0.000459	0.000431	0.000436	0.15	0.1487
0600-0700	21.9	0.000686	0.000578	0.000531	0.000532	0.22	0.2212
0700-0800	4.1	0.000106	0.000108	0.000111	0.000108	0.03	0.0092
0800-0900	9.6	0.000106	0.000253	0.000252	0.000253	0.05	0.0502
0900-1000	3.6	0.000011	0.000095	0.000096	0.000095	0	0.0071
	Mean	0.000181	0.00019775	0.00018775	0.0001905	0.05625	0.05525
	SD	0.00025043	0.00021478	0.00019887	0.0001979	0.08365533	0.08392172
	Pearson		0.96110033		0.99946492		0.99489268

C2e: (20-30 mm) 28 December 2019

Time (hr)	Rainfall (mm)	Inflow (m ³ /s)		Outflow (m ³ /s)		Water Level (m)	
		Field	Model	Field	Model	Field	Model
2300-0000	8.7	0.000206	0.00023	0.000229	0.00023	0.04	0.0412
0000-0100	7.5	0.000198	0.000199	0.000197	0.000198	0.03	0.0306
0100-0200	1.3	0.000032	0.000035	0.000036	0.000035	0	0.0048
0200-0300	0.1	0	0.000004	0.000005	0.000005	0	0.0007
0300-0400	11.6	0.000317	0.000306	0.000303	0.000305	0.07	0.0728
0400-0500	22.3	0.000739	0.000589	0.000524	0.000524	0.21	0.2144
0500-0600	6.7	0.000179	0.000177	0.000187	0.000177	0.05	0.0244
0600-0700	1	0.000026	0.000027	0.000036	0.000035	0	0.004
0700-0800	0.3	0.000008	0.000008	0.000003	0.000008	0	0.0027
Mean		0.000175	0.000175	0.00016856	0.00016856	0.04395556	0.04395556
SD		0.00023427	0.00019066	0.00017267	0.00017244	0.06728876	0.06814907
Pearson			0.99141693		0.99972383		0.99014445

C2f: (20-30 mm) 10 January 2019

Time (hr)	Rainfall (mm)	Inflow (m ³ /s)		Outflow (m ³ /s)		Water Level (m)	
		Field	Model	Field	Model	Field	Model
1000-1100	15.4	0.000401	0.000406	0.000393	0.000394	0.12	0.1215
1100-1200	25.8	0.000739	0.000681	0.000578	0.000578	0.26	0.2626
1200-1300	21.2	0.000581	0.00056	0.000574	0.000572	0.26	0.2555
1300-1400	11	0.000317	0.00029	0.000353	0.00035	0.1	0.0956
1400-1500	4.4	0.000106	0.000116	0.000117	0.000116	0.01	0.0105
1500-1600	0.8	0.000026	0.000022	0.000022	0.000022	0	0.0029
1600-1700	1.2	0.000026	0.000031	0.000031	0.000031	0	0.0052
1700-1800	1	0.000026	0.000026	0.000033	0.000033	0	0.0035
1800-1900	0.6	0.000016	0.000016	0.000011	0.00001	0	0.001
1900-2000	2.8	0.000074	0.000074	0.000039	0.000035	0	0.0025
2000-2100	0.6	0.000016	0.000016	0.000016	0.000011	0	0.0011
Mean		0.00021164	0.00020345	0.000197	0.00019564	0.06818182	0.06926364
SD		0.00025914	0.00024342	0.00023105	0.00023139	0.10419388	0.10273026
Pearson			0.99881708		0.99996693		0.99966958

C3a: (30-40 mm) 7 December 2019

Time (hr)	Rainfall (mm)	Inflow (m ³ /s)		Outflow (m ³ /s)		Water Level (m)	
		Field-Inflow	Model-Inflow	Field-Outflow	Model-Outflow	Field-Water Level	Model-Water Level
0100-0200	6.5	0.000185	0.000172	0.000172	0.000172	0.01	0.0230
0200-0300	32.5	0.000924	0.000858	0.000631	0.000641	0.30	0.3209
0300-0400	8.1	0.000211	0.000214	0.000367	0.000353	0.13	0.0976
0400-0500	1.2	0.000013	0.000032	0.000046	0.000016	0.02	0.0015
0500-0600	0.2	0.000005	0.000006	0.000008	0.000001	0	0.0009
	Mean	0.0002676	0.0002564	0.0002448	0.0002366	0.092	0.08878
	SD	0.00037903	0.00034781	0.00025738	0.00026713	0.12755391	0.13566981
	Pearson		0.99964907		0.99903895		0.98784097

C3b: (30-40 mm) 1 December 2019

Time (hr)	Rainfall (mm)	Inflow (m ³ /s)		Outflow (m ³ /s)		Water Level (m)	
		Field	Model	Field	Model	Field	Model
0100-0200	5.5	0.000132	0.000145	0.000145	0.000145	0.02	0.0165
0200-0300	29.5	0.000871	0.000779	0.000600	0.00061	0.30	0.2905
0300-0400	1	0.000026	0.000027	0.000092	0.000032	0.03	0.0028
0400-0500	1	0.000026	0.000026	0.000024	0.000014	0	0.0013
0500-0600	2	0.000053	0.000053	0.000053	0.000025	0	0.0020
0600-0700	2.5	0.000079	0.000066	0.000061	0.000031	0	0.0022
0700-0800	1	0.000026	0.000027	0.000024	0.000027	0	0.0013
	Mean	0.00016043	0.00016043	0.00012629	0.00012629	0.04522857	0.04522857
	SD	0.00031009	0.00027598	0.00020599	0.00021795	0.11090537	0.10829219
	Pearson		0.99935125		0.99490431		0.99546064

C3c: (30-40 mm) 8&9 December 2019

Time (hr)	Rainfall (mm)	Inflow (m ³ /s)		Outflow (m ³ /s)		Water Level (m)	
		Field	Model	Field	Model	Field	Model
2100-2200	0.5	0	0.000012	0.000003	0.000004	0	0.0006
2200-2300	5.4	0.000106	0.000143	0.000142	0.000142	0.01	0.0159
2300-0000	6.2	0.000311	0.000164	0.000164	0.000164	0.02	0.0209
0000-0100	29	0.001003	0.000765	0.000602	0.000604	0.29	0.2856
0100-0200	8.6	0.000238	0.000227	0.000314	0.000304	0.1	0.0725
0200-0300	6.3	0.000132	0.000166	0.000167	0.000166	0.02	0.0216
0300-0400	1.2	0.000026	0.000032	0.000038	0.000038	0	0.003
0400-0500	0.6	0.000016	0.000016	0.00001	0.00001	0	0.0011
	Mean	0.000229	0.00019063	0.00018	0.000179	0.055	0.05265
	SD	0.00033154	0.00024564	0.00019939	0.00019895	0.10056981	0.09696404
	Pearson		0.9845237		0.99982597		0.994952

C3d: (30-40 mm) 18 January 2020

Time (hr)	Rainfall (mm)	Inflow (m ³ /s)		Outflow (m ³ /s)		Water Level (m)	
		Field	Model	Field	Model	Field	Model
0200-0300	3.2	0.000153	0.000084	0.000083	0.000084	0	0.0056
0300-0400	34.4	0.000924	0.000908	0.000655	0.000657	0.34	0.3375
0400-0500	13.4	0.000333	0.000354	0.000516	0.000514	0.21	0.2064
0500-0600	5.6	0.000143	0.000148	0.000149	0.000148	0.02	0.0171
0600-0700	1.6	0.000037	0.000042	0.000048	0.000049	0	0.0012
0700-0800	4.6	0.000106	0.000121	0.000121	0.000121	0.01	0.0115
0800-0900	2.4	0.000069	0.000063	0.000064	0.000063	0	0.0068
0900-1000	1.2	0.000026	0.000032	0.000036	0.000036	0	0.0029
	Mean	0.00022388	0.000219	0.000209	0.000209	0.0725	0.073625
	SD	0.00029895	0.00029676	0.00023823	0.00023835	0.12991756	0.12742179
	Pearson		0.99550641		0.99998503		0.99972561

C3e: (30-40 mm) 20 January 2020

Time (hr)	Rainfall (mm)	Inflow (m ³ /s)		Outflow (m ³ /s)		Water Level (m)	
		Field	Model	Field	Model	Field	Model
0200-0300	5.4	0.000132	0.000142	0.000142	0.000142	0.01	0.0159
0300-0400	37.2	0.001008	0.000982	0.000682	0.000683	0.37	0.3643
0400-0500	20.2	0.000668	0.000533	0.000634	0.000663	0.33	0.3131
0500-0600	7.2	0.000222	0.00019	0.000266	0.000264	0.07	0.0543
0600-0700	5.6	0.000143	0.000148	0.000149	0.000148	0.02	0.0171
0700-0800	3	0.000079	0.000079	0.000079	0.000079	0	0.0049
0800-0900	2.2	0.000053	0.000058	0.000059	0.000058	0	0.0064
0900-1000	0.6	0.000026	0.000016	0.000016	0.000016	0	0.0027
1000-1100	0.2	0.000005	0.000006	0.000007	0.000007	0	0.0008
1100-1200	0.6	0.000011	0.000016	0.000021	0.000021	0	0.0032
1200-1300	3.4	0.000106	0.00009	0.000089	0.00009	0	0.0063
Mean		0.000223	0.00020545	0.00019491	0.00019736	0.07272727	0.07172727
SD		0.00031993	0.00029673	0.00024098	0.00024654	0.13893098	0.13333035
Pearson			0.99384241		0.99960115		0.99890419

C4a: (40-50 mm) 16 January 2020

Time (hr)	Rainfall (mm)	Inflow (m ³ /s)		Outflow (m ³ /s)		Water Level (m)	
		Field-Inflow	Model-Inflow	Field-Outflow	Model-Outflow	Field-Water Level	Model-Water Level
1000-1100	4.4	0.000121	0.000116	0.000114	0.000116	0.01	0.0105
1100-1200	41.6	0.001108	0.001098	0.000713	0.000717	0.40	0.4022
1200-1300	6	0.000132	0.000158	0.000457	0.000452	0.17	0.1599
1300-1400	0.6	0.000011	0.000017	0.000017	0.000017	0	0.0025
Mean		0.000343	0.00034725	0.00032525	0.0003255	0.145	0.143775
SD		0.00051292	0.00050398	0.00032008	0.00032059	0.18699376	0.18687282
Pearson			0.9996615		0.99992859		0.99948821

C4b: (40-50 mm) 22 February 2020

Time (hr)	Rainfall (mm)	Inflow (m ³ /s)		Outflow (m ³ /s)		Water Level (m)	
		Field-Inflow	Model-Inflow	Field-Outflow	Model-Outflow	Field-Water Level	Model-Water Level
1200-1300	1.2	0.000028	0.000031	0.000033	0.000031	0	0.0052
1300-1400	3.4	0.000158	0.00009	0.000089	0.00009	0.00	0.0063
1400-1500	22.4	0.000538	0.000591	0.00051	0.00052	0.21	0.2113
1500-1600	47.6	0.001823	0.001256	0.001159	0.000759	0.47	0.45
1600-1700	31.6	0.000871	0.000834	0.000709	0.000759	0.44	0.45
1700-1800	6.4	0.000507	0.000169	0.000555	0.000525	0.2	0.2156
1800-1900	2.4	0.000066	0.000169	0.000079	0.000169	0	0.0223
1900-2000	1.2	0.000048	0.000063	0.000026	0.00008	0	0.0058
2000-2100	0.7	0.000018	0.000032	0.000017	0.000026	0	0.002
2100-2200	0.6	0.000016	0.000019	0.000016	0.000017	0	0.0015
	Mean	0.0004073	0.0003254	0.0003193	0.0002976	0.132	0.137
	SD	0.00057759	0.00042623	0.00039596	0.00030867	0.18984204	0.18530604
	Pearson		0.95885822		0.95394069		0.99855693

Appendix D

K-S Test

D1a: (0-20 mm) 30 December 2019

				Critical D 0.514032								Critical D 0.514031683								Critical D 0.514032			
Inflow-F	Proportion	Cummulati	Inflow-M	Proportion	Cummulati	D(F-M)		Outflow-F	Proportion	Cummulati	Outflow-M	Proportion	Cummulati	D(F-M)		WL-F	Proportion	Cummulati	WL-M	Proportion	Cummulati	D(F-M)	
0.000106	0.099906	0.099906	0.0001	0.095877	0.095877	0.004028		0.000099	0.09261	0.09261	0.0001	0.098814	0.098814	-0.00620431		0.01	0.030303	0.030303	0.0079	0.026501	0.026501	0.003802	
0.00048	0.452403	0.552309	0.000483	0.463087	0.558965	-0.00666		0.000451	0.42189	0.5145	0.000453	0.447628	0.546443	-0.03194316		0.16	0.484848	0.515152	0.1606	0.538745	0.565247	-0.0501	
0.000391	0.36852	0.920829	0.000388	0.372004	0.930968	-0.01014		0.000398	0.372311	0.88681	0.000399	0.394269	0.940711	-0.05390136		0.13	0.393939	0.909091	0.1246	0.417981	0.983227	-0.07414	
0.000026	0.024505	0.945335	0.000027	0.025881	0.956855	-0.01152		0.000074	0.069224	0.956034	0.000074	0.013834	0.954545	0.001488222		0.03	0.090909	1	0.0013	0.004361	0.987588	0.012412	
0.000026	0.024505	0.969884	0.000024	0.023011	0.979866	-0.01003		0.000027	0.025257	0.981291	0.000027	0.02668	0.981225	6.56297E-05		0	0	1	0.0021	0.007045	0.994633	0.005367	
0.000021	0.019793	0.989632	0.000021	0.020134	1	-0.01037		0.000019	0.017774	0.999065	0.000019	0.018775	1	-0.00093545		0	0	1	0.0016	0.005367	1	0	
0.000011	0.010368	1	0	0	1	0		0.000093	0.000935	1	0	0	1	0		0	0	1	0	0	1	0	
0.001061		0.001043						0.001069			0.001012					0.33			0.2981				

D1b: (0-20 mm) 2 December 2019

Critical D 0.480833												Critical D 0.480832611												Critical D 0.480833											
Inflow-F	Proportion	Cummulati	Inflow-M	Proportion	Cummulati	D(F-M)		Outflow-F	Proportion	Cummulati	Outflow-M	Proportion	Cummulati	D(F-M)		WL-F	Proportion	Cummulati	WL-M	Proportion	Cummulati	D(F-M)													
0	0	0	0.000066	0.054908	0.054908	-0.05491		0.000063	0.022043	0.022043	0.000031	0.026587	0.026587	-0.00454401		0	0	0	0.0022	0.009201	0.009201	-0.0092													
0.000264	0.207384	0.207384	0.000264	0.219634	0.274542	-0.06716		0.000263	0.19324	0.215283	0.000264	0.226415	0.253002	-0.03771884		0	0.192308	0.192308	0.0544	0.22752	0.236721	-0.04441													
0.000079	0.062058	0.269442	0.000119	0.099002	0.373544	-0.1041		0.000012	0.08817	0.303453	0.000119	0.102058	0.35506	-0.05160669		0.01	0.038462	0.230769	0.011	0.046006	0.282727	-0.05196													
0.000106	0.083268	0.35271	0.000106	0.088186	0.46173	-0.10902		0.000106	0.077884	0.381337	0.000106	0.090909	0.445969	-0.06463187		0.01	0.038462	0.269231	0.0087	0.036386	0.319113	-0.04988													
0.000037	0.249018	0.601728	0.000037	0.263727	0.725458	-0.12373		0.000035	0.231447	0.617285	0.000306	0.271012	0.716981	-0.10419641		0.06	0.307692	0.576923	0.0779	0.325805	0.644918	-0.068													
0.000037	0.249018	0.850746	0.000031	0.274542	1	-0.14923		0.000031	0.242469	0.855253	0.000033	0.283019	1	-0.14474653		0.09	0.346154	0.923077	0.0849	0.355082	1	-0.07692													
0.000106	0.083268	0.934014	0	0	1	-0.06599		0.000011	0.080823	0.936076	0	0	1	-0.06392359		0.01	0.038462	0.961538	0	0	1	-0.03846													
0.000084	0.065986	1	0	0	1	0		0.000087	0.063924	1	0	0	1	0		0.01	0.038462	1	0	0	1	0													
0.001273		0.001202						0.001361			0.001166					0.26			0.2391																

D1c: (0-20 mm) 11&12 December 2019

				Critical D 0.35115								Critical D 0.35115049										
Inflow-F	Proportion	Cummulati	Inflow-M	Proportion	Cummulati	D(F-M)		Outflow-F	Proportion	Cummulati	Outflow-M	Proportion	Cummulati	D(F-M)		WL-F	Proportion	Cummulati	WL-M	Proportion	Cummulati	D(F-M)
0.000005	0.005612	0.005612	0.000004	0.005025	0.005025	0.000587		0.000002	0.002283	0.002283	0.000002	0.002509	0.002509	-0.00022631		0	0	0	0.0003	0.002953	0.002953	-0.00295
0.000053	0.059484	0.065095	0.000053	0.066583	0.071608	-0.00651		0.000066	0.075342	0.077626	0.000066	0.082811	0.08532	-0.00769438		0	0	0	0.0052	0.051181	0.054134	-0.05413
0.000095	0.106622	0.171717	0.00009	0.113065	0.184673	-0.01296		0.000089	0.101598	0.179224	0.00009	0.112923	0.198243	-0.01901967		0	0	0	0.0063	0.062008	0.116142	-0.11614
0.000106	0.118967	0.290685	0.000106	0.133166	0.317839	-0.02715		0.000106	0.121005	0.300228	0.000106	0.132999	0.331242	-0.03101385		0	0	0	0.0087	0.08563	0.201772	-0.20177
0.000022	0.249158	0.539843	0.000027	0.285176	0.603015	-0.06317		0.000027	0.259132	0.559361	0.000027	0.284818	0.61606	-0.0566995		0.04	0.666667	0.666667	0.0003	0.396654	0.598425	0.068241
0.000021	0.225589	0.765432	0.000169	0.212312	0.815327	-0.04989		0.000169	0.192922	0.752283	0.000169	0.212045	0.828105	-0.07582229		0.02	0.333333	1	0.0023	0.219488	0.817913	-0.182087
0.000048	0.053872	0.819304	0	0	0.815327	0.003978		0.000038	0.043379	0.795662	0	0	0.828105	-0.03244329		0	0	1	0	0	0.817913	0.182087
0.000093	0.003367	0.822671	0	0	0.815327	0.007345		0.000096	0.006849	0.802513	0	0	0.828105	-0.02559398		0	0	1	0	0	0.817913	0.182087
0.000016	0.017957	0.840629	0	0	0.815327	0.025302		0.000016	0.018265	0.820776	0	0	0.828105	-0.00732914		0	0	1	0	0	0.817913	0.182087
0.000021	0.023569	0.864198	0.00002	0.025126	0.840452	0.023745		0.000023	0.026256	0.847032	0.00002	0.025094	0.853199	-0.00616753		0	0	1	0.0037	0.036417	0.854331	0.145669
0.000032	0.035915	0.900112	0.000032	0.040201	0.880653	0.019459		0.000042	0.047945	0.894977	0.000042	0.052698	0.905897	-0.01091995		0	0	1	0.0045	0.044291	0.898622	0.010378
0.000026	0.029181	0.929293	0.000026	0.032663	0.913317	0.015976		0.000032	0.036553	0.931507	0.000032	0.040151	0.946048	-0.01454083		0	0	1	0.0028	0.027559	0.926181	0.073819
0.000026	0.029181	0.958474	0.000026	0.032663	0.945598	0.012494		0.000031	0.035388	0.966895	0.000014	0.017566	0.963614	0.003281426		0	0	1	0.0013	0.012795	0.938976	0.061024
0.000021	0.023569	0.982043	0.000022	0.027638	0.973618	0.008425		0.000021	0.023973	0.990868	0.000021	0.026349	0.989962	0.000905221		0	0	1	0.0043	0.042323	0.981299	0.018701
0.000016	0.017957	1	0.000021	0.026382	1	0		0.000008	0.009132	1	0.000008	0.010038	1	0		0	0	1	0.0019	0.018701	1	0
0.000891		0.000796						0.000876			0.000797					0.06			0.1016			

D2a: (20-30 mm) 1 January 2020

Critical D 0.785196						Critical D 0.785196366						Critical D 0.785196								
Inflow-F	Proportion	Cumulative	Inflow-M	Proportion	Cumulative	D(F-M)	Outflow-F	Proportion	Cumulative	Outflow-M	Proportion	Cumulative	D(F-M)	WL-F	Proportion	Cumulative	WL-M	Proportion	Cumulative	D(F-M)
0.000269	0.266865	0.266865	0.000201	0.24938	0.24938	0.017485	0.0002	0.249688	0.249688	0.000201	0.27459	0.27459	-0.02490227	0.03	0.12	0.12	0.0314	0.125399	0.125399	-0.0054
0.000079	0.733135	1	0.000062	0.746898	0.996278	0.003722	0.000601	0.750312	1	0.000528	0.721311	0.995902	0.004098361	0.22	0.88	1	0.2176	0.86901	0.994409	0.005591
0	0	1	0.000003	0.003722	1	0	0	0	1	0.000003	0.004098	1	0	0.00	0	1	0.0014	0.005591	1	0
0.001008		0.000806					0.000801			0.000732				0.25			0.2504			

D2b: (20-30 mm) 22 January 2020

Critical D 0.68												Critical D 0.480832611												Critical D 0.480833											
Inflow-F	Proportion	Cummulati	Inflow-M	Proportion	Cummulati	D(F-M)		Outflow-F	Proportion	Cummulati	Outflow-M	Proportion	Cummulati	D(F-M)		WL-F	Proportion	Cummulati	WL-M	Proportion	Cummulati	D(F-M)													
0	0	0	0.000004	0.004624	0.004624	-0.00462		0.000003	0.003654	0.003654	0.000002	0.002497	0.002497	0.00157201		0	0	0	0.00003	0.001114	0.001114	-0.00111													
0.000765	0.70572	0.70572	0.000596	0.689017	0.693642	0.012078		0.000652	0.633374	0.637028	0.000521	0.650347	0.652934	-0.0159087		0.21	0.75	0.75	0.2119	0.787147	0.788262	-0.03826													
0.000301	0.277675	0.983395	0.000253	0.292486	0.986127	-0.00273		0.000286	0.348356	0.985384	0.000266	0.332085	0.985019	0.000364952		0.07	0.25	1	0.0552	0.205052	0.993314	0.006686													
0.000018	0.0116605	1	0.000012	0.013873	1	0		0.000012	0.014616	1	0.000012	0.014981	1	0		0.00	0	1	0.0018	0.006686	1	0													
0.001084			0.000865					0.000821			0.000801					0.28			0.2692																

D2c: (20-30 mm) 19 January 2020

				Critical D 0.514032			
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D2d: (20-30 mm) 22 December 2019

Critical D 0.480833														Critical D 0.480832611														Critical D 0.480833													
Inflow-F	Proportion	Cummulati	Inflow-M	Proportion	Cummulati	D(F-M)	Outflow-F	Proportion	Cummulati	Outflow-M	Proportion	Cummulati	D(F-M)	WL-F	Proportion	Cummulati	WL-M	Proportion	Cummulati	D(F-M)	WL-F	Proportion	Cummulati	WL-M	Proportion	Cummulati	D(F-M)														
0.000008	0.005525	0.005525	0.000007	0.005673	0.005673	-0.00015	0.000002	0.001332	0.001332	0.000002	0.017007	0.017007	-0.01567524	0	0	0	0.0004	0.00104	0.00104	-0.00104	0	0	0	0.0003	0.00078	0.00182	-0.00182														
0.000003	0.002072	0.007597	0.000003	0.002431	0.008104	-0.00051	0.000001	0.000666	0.001997	0.000001	0.00085	0.017857	-0.01585981	0	0	0	0	0.00078	0.00182	-0.00182	0	0	0	0.00049	0.012737	0.014557	-0.01456														
0.000079	0.054558	0.062155	0.000079	0.064019	0.072123	-0.00997	0.000079	0.051931	0.053928	0.000079	0.067177	0.085934	-0.03110592	0	0	0	0	0.00078	0.00182	-0.00182	0.15	0.333333	0.333333	0.1487	0.386535	0.401592	-0.06776														
0.000049	0.310083	0.372238	0.000049	0.371961	0.444084	-0.07185	0.000049	0.286951	0.340879	0.000049	0.370748	0.455782	-0.11490348	0.15	0.333333	0.333333	0.1487	0.386535	0.401592	-0.06776	0.22	0.488889	0.822222	0.2212	0.574994	0.976085	-0.15366														
0.000086	0.473757	0.845894	0.000078	0.468395	0.91248	-0.06649	0.000531	0.353529	0.694407	0.000532	0.452381	0.908163	-0.21375581	0.22	0.488889	0.822222	0.2212	0.574994	0.976085	-0.15366	0.03	0.066667	0.888889	0.0092	0.023915	1	-0.11111														
0.000106	0.073204	0.924403	0.000108	0.08752	1	-0.08076	0.000252	0.167776	0.768309	0.000252	0.353529	0.936805	-0.063915	0.05	0.111111	1	0	0	0	1	0	0	0	1	0	0	1	0													
0.000011	0.007597	1	0	0	1	0	0.000096	0.063915	1	0	0	1	0	0	0	1	0	0	1	0	0	0	1	0	0	1	0	0													
0.001448		0.001234					0.001502		0.001176					0.45			0.3847																								

D2e: (20-30 mm) 28 December 2019

Critical D 0.453333										Critical D 0.45333333										Critical D 0.453333									
Inflow-F	Proportion	Cummulati	Inflow-M	Proportion	Cummulati	D(F-M)	Outflow-F	Proportion	Cummulati	Outflow-M	Proportion	Cummulati	D(F-M)	WL-F	Proportion	Cummulati	WL-M	Proportion	Cummulati	D(F-M)	WL-F	Proportion	Cummulati	WL-M	Proportion	Cummulati	D(F-M)		
0.000206	0.120821	0.120821	0.00023	0.168745	0.168745	-0.04792	0.000229	0.150658	0.150658	0.00023	0.177332	0.177332	-0.02667441	0.04	0.1	0.1	0.0412	0.113032	0.113032	-0.01303	0.03	0.075	0.175	0.0306	0.083951	0.196982	-0.02198		
0.000198	0.116129	0.23695	0.000199	0.146001	0.314747	-0.0778	0.000197	0.129605	0.280263	0.000198	0.15266	0.329992	-0.04972913	0.03	0.075	0.175	0.0306	0.083951	0.196982	-0.02198	0	0	0	0.175	0.0048	0.013169	-0.03515		
0.000032	0.018768	0.255718	0.000035	0.025679	0.340426	-0.08471	0.000036	0.023684	0.303947	0.000035	0.026985	0.356978	-0.05303027	0	0	0	0.175	0.0007	0.00192	-0.03707	0	0	0	0.175	0.0007	0.00192	-0.03707		
0	0	0.255718	0.000004	0.002935	0.34336	-0.08764	0.000005	0.003289	0.307237	0.000005	0.003855	0.360833	-0.05359585	0	0	0	0.175	0.0007	0.00192	-0.03707	0.07	0.175	0.35	0.0728	0.199726	0.411797	-0.0618		
0.000171	0.185924	0.441642	0.000196	0.224505	0.567865	-0.12622	0.000183	0.199342	0.506579	0.000183	0.235158	0.595991	-0.08941139	0.21	0.525	0.875	0.2144	0.588203	1	-0.125	0.05	0.125	0	0	0	1	0		
0.000179	0.433431	0.875073	0.000159	0.432135	1	-0.12493	0.000152	0.344737	0.851316	0.000154	0.404009	1	-0.04869423	0	0	1	0	0	1	0	0	0	1	0	0	1	0		
0.000179	0.104985	0.980059	0	0	1	-0.01994	0.000187	0.123026	0.974342	0	0	1	-0.02565789	0	0	1	0	0	1	0	0	0	1	0	0	1	0		
0.000026	0.015249	0.995308	0	0	1	-0.00469	0.000036	0.023684	0.998026	0	0	1	-0.00197368	0	0	1	0	0	1	0	0	0	1	0	0	1	0		
0.000008	0.004692	1	0	0	1	0	0.000003	0.001974	1	0	0	1	0	0	0	1	0	0	1	0	0	0	1	0	0	1	0		
0.001705		0.001363					0.00152		0.001297					0.4			0.3645												

D2f: (20-30 mm) 10 January 2019

Critical D 0.410055										Critical D 0.410055429										Critical D 0.410055									
Inflow-F	Proportion	Cummulati	Inflow-M	Proportion	Cummulati	D(F-M)	Outflow-F	Proportion	Cummulati	Outflow-M	Proportion	Cummulati	D(F-M)	WL-F	Proportion	Cummulati	WL-M	Proportion	Cummulati	D(F-M)	WL-F	Proportion	Cummulati	WL-M	Proportion	Cummulati	D(F-M)		
0.000401	0.172251	0.172251	0.000406	0.181412	0.181412	-0.00916	0.000393	0.181357	0.181357	0.000394	0.183086	0.183086	-0.00172879	0.12	0.16	0.16	0.1215	0.15947	0.15947	-0.00053	0.26	0.346667	0.506667	0.2626	0.344665	0.504134	-0.002532		
0.000079	0.31744	0.489691	0.000081	0.30429	0.485702	-0.003989	0.000078	0.266728	0.448085	0.000078	0.268587	0.451673	-0.00358795	0.26	0.346667	0.506667	0.2626	0.344665	0.504134	-0.002532	0.26	0.346667	0.506667	0.2626	0.344665	0.504134	-0.002532		
0.000081	0.24957	0.739261	0.000056	0.250223	0.735925	-0.003336	0.0000574	0.264882	0.712967	0.0000572	0.265799	0.717472	-0.00405488	0.26	0.346667	0.506667	0.2626	0.344665	0.504134	-0.002532	0.26	0.346667	0.506667	0.2626	0.344665	0.504134	-0.002532		
0.000117	0.136168	0.87543	0.000129	0.129528	0.865505	-0.009925	0.000133	0.162898	0.875865	0.000135	0.162639	0.880112	-0.00424627	0.1	0.133333	0.333333	0.0956	0.125476	0.964956	-0.021711	0.01	0.013333	1	0.0005	0.013781	0.978737	-0.021663		
0.000106	0.045533	0.920962	0.000116	0.051832	0.917337	-0.003625	0.000117	0.053992	0.929857	0.000116	0.053903	0.934015	-0.00415792	0.01	0.013333	1	0.0005	0.013781	0.978737	-0.021663	0	0	0	1	0.0029	0.003806	0.982544	-0.017456	
0.000026	0.011168	0.932131	0.000022	0.00983	0.927167	-0.004963	0.000022	0.010152	0.940969	0.000022	0.010223	0.944238	-0.00422869	0	0	1	0.0029	0.003806	0.982544	-0.017456	0	0	1	0.0052	0.006825	0.989369	-0.010631		
0.000026	0.011168	0.943299	0.000031	0.013852	0.941019	-0.00228	0.000031	0.014305	0.954315	0.000031	0.014405	0.958643	-0.0043284	0	0	1	0.0052	0.006825	0.989369	-0.010631	0	0	1	0.0052	0.006825	0.989369	-0.010631		
0.000026	0.011168	0.954647	0.000026	0.011618	0.952636	-0.001831	0.000023	0.015328	0.969543	0.000023	0.015335	0.973978	-0.00443455	0	0	1	0.0052	0.006825	0.989369	-0.010631	0	0	1	0.0052	0.006825	0.989369	-0.010631		
0.000016	0.006873	0.96134	0.000016	0.007149	0.959786	-0.001555	0.000011	0.005076	0.974619	0.000011	0.004647	0.978625	-0.00400525	0	0	1	0.0025	0.003281	0.985556	-0.004444	0	0	1	0.0025	0.003281	0.985556	-0.004444		
0.000074	0.031787	0.993127	0.000074	0.033065	0.992851	-0.000276	0.000039	0.017997	0.992617	0.000035	0.016264	0.994888	-0.00227196	0	0	1	0.0025	0.003281	0.985556	-0.004444	0	0	1	0.0025	0.003281	0.985556	-0.004444		
0.000016	0.006873	1	0.000016	0.007149	1	0	0.000016	0.007383	1	0.000011	0.005112	1	0	0	0	1	0.0011	0.001444	0.001444	-0.00000	0	0	1	0.0011	0.001444	0.001444	-0.00000		
0.002328		0.002238					0.002167		0.002152					0.75			0.7619												

D3a: (30-40 mm) 7 December 2019

Critical D 0.60821														Critical D 0.60821														Critical D 0.60821													
Inflow-F	Proportion	Cummulati	Inflow-M	Proportion	Cummulati	D(F-M)	Outflow-F	Proportion	Cummulati	Outflow-M	Proportion	Cummulati	D(F-M)	WL-F	Proportion	Cummulati	WL-M	Proportion	Cummulati	D(F-M)	WL-F	Proportion	Cummulati	WL-M	Proportion	Cummulati	D(F-M)														
0.000105	0.138266	0.138266	0.000172	0.134165	0.134165	-0.004101	0.000172	0.140523	0.140523	0.000172	0.145393	0.145393	-0.00487	0.01	0.021739	0.021739	0.0230	0.051813	0.051813	-0.03007	0.01	0.021739	0.021739	0.0230	0.051813	0.051813	-0.03007														
0.000024	0.690583	0.828849	0.000038	0.669267	0.803432	-0.025417	0.000031	0.515523	0.656004	0.000041	0.541843	0.687236	-0.03119	0.30	0.652174	0.673913	0.3209	0.722911	0.774724	-0.10081	0.30	0.652174	0.673913	0.3209	0.722911	0.774724	-0.10081														
0.000011	0.157698	0.986547	0.000014	0.166927	0.970359	-0.016188	0.000007	0.299837	0.955882	0.000007	0.298394	0.98563	-0.02975	0.13	0.282609	0.956522	0.0976	0.219869	0.994593	-0.0307	0.13	0.282609	0.956522	0.0976	0.219869	0.994593	-0.0307														
0.000013	0.007916	0.996263	0.000032	0.024961	0.99532	0.000943	0.000048	0.037582	0.993464	0.000016	0.013525	0.999155	-0.00569	0.02	0.043478	0.995622	0.0015	0.003379	0.999793	0.002027	0.02	0.043478	0.995622	0.0015	0.003379	0.999793	0.002027														
0.000005	0.003737	1	0.000006	0.00468	1	0	0.000008	0.006536	1	0.000001	0.000845	1	0	0	0	1	0.0009	0.002027	1	0	0	0	1	0.0009	0.002027	1	0														
0.001338			0.01282				0.012124		0.01183					0.46			0.4439																								

[illegible]

Inflow-F	Proportion	Cummulati	inflow-M	Critical D		D-F-M	Outflow-F	Proportion	Cummulati	Outflow-M	Proportion	Cummulati	D-F-M	Critical D	D	D-F-M	WL-F	Proportion	Cummulati	WL-M	Proportion	Cummulati	D-F-M	Critical D	D	D-F-M	
				0.410055	0.410055									0.410055	0.410055										0.410055	0.410055	
0.000312	0.053812	0.053812	0.00042	0.052832	0.062832	-0.00902	0.000142	0.066231	0.066231	0.000142	0.065408	0.065408	0.000824	0.051215	0.051215	0.00019	0.01215	0.01215	0.01215	0.01215	0.01215	0.01215	0.01215	0.01215	0.01215	0.01215	-0.00765
0.001008	0.011925	0.064737	0.00082	0.045113	0.049745	-0.00461	0.000682	0.031897	0.036832	0.000682	0.031460	0.031460	0.000419	0.016215	0.016215	0.00019	0.016215	0.016215	0.016215	0.016215	0.016215	0.016215	0.016215	0.016215	0.016215	0.016215	-0.00688
0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000022	0.090501	0.827558	0.00019	0.084071	0.812757	0.010301	0.000266	0.124067	0.874010	0.000266	0.121613	0.870701	-0.00929	0.00017	0.00017	0.00017	0.00017	0.00017	0.00017	0.00017	0.00017	0.00017	0.00017	0.00017	0.00017	0.00017	0.00017
0.000343	0.058296	0.888584	0.00048	0.058467	0.882743	0.000311	0.000149	0.064906	0.840364	0.000148	0.061781	0.875173	-0.00157	0.00023	0.00023	0.00023	0.00023	0.00023	0.00023	0.00023	0.00023	0.00023	0.00023	0.00023	0.00023	0.00023	0.00023
0.000079	0.032205	0.91806	0.000079	0.034956	0.913689	0.000036	0.000079	0.013687	0.910448	0.000078	0.0136389	0.911561	-0.00111	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011
0.000053	0.021606	0.939666	0.000058	0.025664	0.943963	-0.0037	0.000059	0.027519	0.937966	0.000058	0.026716	0.938277	-0.00031	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011	0.00011
0.000026	0.010599	0.956205	0.000016	0.007078	0.950442	-0.00018	0.000016	0.007463	0.954549	0.000016	0.007737	0.945647	-0.00042	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000011	0.004484	0.950768	0.000016	0.007078	0.950442	-0.00018	0.000016	0.007463																			

Critical D = 0.68										Critical D = 0.68											
Inflow-F	Proportion	Cumulative	Inflow-M	Proportion	Cumulative	D(F-M)		Outflow-F	Proportion	Cumulative	Outflow-M	Proportion	Cumulative	D(F-M)	WL-F	Proportion	Cumulative	WL-M	Proportion	Cumulative	D(F-M)
0.000121	0.088192	0.088192	0.000116	0.083513	0.083513	0.004679		0.000114	0.087625	0.087625	0.000116	0.080904	0.080904	-0.00147	0.01	0.017241	0.017241	0.0105	0.018258	0.018258	-0.00102
0.00108	0.80758	0.895773	0.001098	0.790497	0.87401	0.021763		0.000713	0.54804	0.635665	0.000717	0.550691	0.639785	-0.00412	0.40	0.689655	0.706897	0.4022	0.699357	0.717614	-0.01072
0.000132	0.096251	0.991983	0.000158	0.113751	0.987761	0.004222		0.000547	0.351268	0.986933	0.000542	0.347158	0.986943	-1E-05	0.17	0.293103	1	0.1599	0.278039	0.995653	0.004347
0.000111	0.008017	1	0.000107	0.012239	1	0		0.000017	0.013067	1	0.000017	0.013057	1	0	0	0	1	0.0025	0.004347	1	0
0.001372			0.001389					0.001301			0.001302				0.58			0.5751			

Critical D 0.43007										Critical D 0.43007										Critical D 0.43007									
Inflow-F	Proportion Cumulatif	Inflow-F	Proportion Cumulatif	D-F (M)	Outflow-F	Proportion Cumulatif	Outflow-F	Proportion Cumulatif	D-F (M)	W-L-F	Proportion Cumulatif	W-L-M	Proportion Cumulatif	D-F (M)	W-L-F	Proportion Cumulatif	W-L-M	Proportion Cumulatif	D-F (M)										
0.00000	0.006875	0.006875	0.00003	0.009927	0.009927	0.00003	0.010338	0.00003	0.010338	0.00003	0.010417	-8.45	0.00003	0.003796	0.00003	0.003796	0.00003	0.003796	0.00003										
0.00010	0.038792	0.045667	0.00009	0.027658	0.037185	0.000882	0.000089	0.027873	0.038209	0.00009	0.030242	0.040659	-0.0245	0.00009	0.040659	0.00089	0.030242	0.040659	-0.0245										
0.00038	0.132089	0.177756	0.00051	0.181623	0.218808	-0.04105	0.000051	0.159724	0.179933	0.00052	0.174731	0.21539	-0.01746	0.00052	0.174731	0.00051	0.159724	0.179933	-0.04105										
0.00123	0.447582	0.625338	0.001256	0.385686	0.604794	0.20543	0.001159	0.362982	0.560915	0.000759	0.25504	0.47034	0.090484	0.000759	0.25504	0.001256	0.385686	0.604794	0.20543										
0.000871	0.213847	0.839185	0.000834	0.2563	0.861904	-0.02191	0.000709	0.222048	0.782963	0.000759	0.25504	0.72547	0.057492	0.000759	0.25504	0.000834	0.2563	0.861904	-0.02191										
0.000907	0.124478	0.963663	0.000169	0.156306	0.91303	0.050633	0.000555	0.173818	0.95678	0.000525	0.176411	0.901882	0.054899	0.000525	0.176411	0.000169	0.156306	0.91303	0.050633										
0.000866	0.016204	0.979867	0.000019	0.016396	0.964966	0.04901	0.000079	0.024742	0.98152	0.000019	0.056788	0.985669	0.022853	0.000019	0.056788	0.000019	0.016396	0.964966	0.04901										
0.000018	0.021785	0.991636	0.000013	0.021785	0.994213	0.007125	0.000013	0.008143	0.989663	0.000013	0.008143	0.989663	0.00114	0.000013	0.008143	0.000013	0.021785	0.994213	0.007125										
0.000018	0.004419	0.997867	0.000032	0.0009834	0.994161	0.001911	0.000017	0.005524	0.998049	0.000026	0.008737	0.994288	0.000701	0.000017	0.005524	0.000018	0.004419	0.997867	0.000032										
0.000016	0.003928	1	0.000019	0.005839	1	0	0.000016	0.005011	1	0.000017	0.005712	1	0	0.000016	0.005011	0.000016	0.003928	1	0										
0.004073		0.03254					0.003193		0.02976					1.32		1.3700													

Appendix E

Modelling of Extreme Storm Events

E1: 18 &19 January 2015

Time (hr)	Rainfall (mm)	Modelled Inflow (m ³ /s)	Modelled Outflow (m ³ /s)	Modelled Water Level (m)
0000-0100	2	0	0	0
0100-0200	7.5	0.000053	0.000053	0.0061
0200-0300	3	0.000198	0.000198	0.0306
0300-0400	20.5	0.000079	0.000079	0.0049
0400-0500	19.5	0.000541	0.000491	0.1881
0500-0600	38.5	0.000515	0.000508	0.2016
0600-0700	12	0.001016	0.00072	0.4051
0700-0800	1.5	0.000317	0.000566	0.2504
0800-0900	0.5	0.00004	0.000047	0.0033
0900-1000	0.5	0.000014	0.000016	0.002
1000-1100	2	0.000013	0.000017	0.0023
1100-1200	0	0.000053	0.000066	0.0052
1200-1300	1.5	0.000002	0.000001	0.002
1300-1400	3.5	0.000039	0.00004	0.0036
1400-1500	1.5	0.000092	0.000092	0.0067
1500-1600	1	0.00004	0.000045	0.0034
1600-1700	23	0.000026	0.000022	0.0018
1700-1800	21	0.000607	0.000527	0.2172
1800-1900	8.5	0.000554	0.000545	0.2323
1900-2000	5	0.000224	0.000231	0.0419
2000-2100	6.5	0.000132	0.000132	0.0136
2100-2200	4.5	0.000172	0.000172	0.023
2200-2300	39	0.000119	0.000119	0.011
2300-0000	43	0.001029	0.000697	0.3799
0000-0100	26	0.001135	0.000759	0.45
0100-0200	4	0.000686	0.000741	0.4287

E2: 1 January 2016

Time (hr)	Rainfall (mm)	Modelled Inflow (m ³ /s)	Modelled Outflow (m ³ /s)	Modelled Water Level (m)
1600-1700	7	0	0	0
1700-1800	22	0.000185	0.000185	0.0267
1800-1900	51	0.000581	0.000516	0.2078
1900-2000	7	0.001346	0.000759	0.45
2000-2100	1	0.000185	0.000544	0.2316
2100-2200	1.5	0.000027	0.00003	0.0026

E3: 17 & 18 December 2017

Time (hr)	Rainfall (mm)	Modelled Inflow (m ³ /s)	Modelled Outflow (m ³ /s)	Modelled Water Level (m)
1800-1900	0.5	0	0	0
1900-2000	0.5	0.000012	0.000004	0.0006
2000-2100	0.5	0.000013	0.000004	0.0006
2100-2200	7.5	0.000013	0.000004	0.0006
2200-2300	6	0.000198	0.000198	0.0306
2300-0000	15	0.000158	0.000158	0.0196
0000-0100	10	0.000396	0.000388	0.1174
0100-0200	9	0.000264	0.000264	0.0546
0200-0300	10	0.000238	0.000238	0.0441
0300-0400	19.5	0.000264	0.000264	0.0544
0400-0500	32	0.000515	0.000477	0.01782
0500-0600	47.5	0.000845	0.000659	0.3395
0600-0700	16	0.001254	0.000759	0.45
0700-0800	4	0.000422	0.000657	0.3369
0800-0900	0.5	0.000106	0.000106	0.0087

Appendix F

Modelling of Orifice Outlets

F1a: (0-20 mm) 30 December 2019

Time (hr)	Rainfall (mm)	Observed Inflow (m ³ /s)	Outflow (m ³ /s)			Water Level (m)		
			Outlet-0.050	Outlet-0.055	Outlet-0.063	Outlet-0.050	Outlet-0.055	Outlet-0.063
0100-0200	3.8	0.000106	0.000099	0.0001	0.00005	0.01	0.0054	0.0027
0200-0300	18.3	0.00048	0.000451	0.000476	0.000483	0.16	0.1209	0.0723
0300-0400	14.7	0.000391	0.000398	0.000389	0.000388	0.13	0.0809	0.0467
0400-0500	1	0.000026	0.000074	0.000033	0.000027	0.03	0.0024	0.0048
0500-0600	0.9	0.000026	0.000027	0.000023	0.000024	0	0.0017	0.0045
0600-0700	0.8	0.000021	0.000019	0.000021	0.000021	0	0.0043	0.0042
0700-0800	0.1	0.000011	0.000001	0.000002	0.000004	0	0.0003	0.0007

F1b: (0-20 mm) 2 December 2019

Time (hr)	Rainfall (mm)	Observed Inflow (m ³ /s)	Outflow (m ³ /s)			Water Level (m)		
			Outlet-0.050	Outlet-0.055	Outlet-0.063	Outlet-0.050	Outlet-0.055	Outlet-0.063
1600-1700	2.5	0	0.00003	0.000083	0.000066	0	0.0058	0.0064
1700-1800	10	0.000264	0.000263	0.000264	0.000264	0	0.0075	0.0216
1800-1900	4.5	0.000079	0.00012	0.000119	0.000149	0.01	0.006	0.0078
1900-2000	4	0.000106	0.000106	0.000106	0.000132	0.01	0.0535	0.0072
2000-2100	12	0.000317	0.000315	0.000317	0.000317	0.08	0.0581	0.0311
2100-2200	12.5	0.000317	0.00033	0.00033	0.00033	0.09	0.006	0.0338
2200-2300	4	0.000106	0.00011	0.000106	0.000053	0.01	0.0079	0.0028
2300-0000	3.3	0.000084	0.000087	0.000087	0.000045	0.01	0.0012	0.0025

F1c: (0-20 mm) 11 & 12 December 2019

Time (hr)	Rainfall (mm)	Observed Inflow (m ³ /s)	Outflow (m ³ /s)			Water Level (m)		
			Outlet-0.050	Outlet-0.055	Outlet-0.063	Outlet-0.050	Outlet-0.055	Outlet-0.063
1500-1600	0.2	0.000005	0.000002	0.000005	0.000004	0	0.0007	0.0014
1600-1700	2	0.000053	0.000066	0.000054	0.000059	0	0.0041	0.0036
1700-1800	3.4	0.000095	0.000089	0.00009	0.000112	0	0.008	0.0066
1800-1900	4	0.000106	0.000106	0.000106	0.000132	0	0.006	0.0072
1900-2000	8.6	0.000222	0.000227	0.000227	0.000227	0.04	0.0275	0.0160
2000-2100	6.4	0.000201	0.000169	0.000169	0.000169	0.02	0.0152	0.0088
2100-2200	1.2	0.000048	0.000038	0.000017	0.000035	0	0.0014	0.0021
2200-2300	0.2	0.000003	0.000006	0.000008	0.000008	0	0.0019	0.0018
2300-0000	0.6	0.000016	0.000016	0.000016	0.000006	0	0.0037	0.0006
0000-0100	0.8	0.000021	0.000023	0.000021	0.000007	0	0.0043	0.0007
0100-0200	1.2	0.000032	0.000042	0.000035	0.00001	0	0.0028	0.0009
0200-0300	1	0.000026	0.000032	0.000035	0.000009	0	0.004	0.0008
0300-0400	1	0.000026	0.000031	0.000035	0.000009	0	0.0041	0.0008
0400-0500	0.8	0.000021	0.000021	0.000021	0.000007	0	0.0043	0.0007
0500-0600	0.2	0.000016	0.000008	0.000008	0.000007	0	0.0019	0.0007

F2a: (20-30 mm) 1 January 2020

Time (hr)	Rainfall (mm)	Observed Inflow (m ³ /s)	Outflow (m ³ /s)			Water Level (m)		
			Outlet-0.050	Outlet-0.055	Outlet-0.063	Outlet-0.050	Outlet-0.055	Outlet-0.063
0100-0200	7.6	0.000269	0.0002	0.000201	0.000201	0.03	0.0215	0.0125
0200-0300	22.8	0.000739	0.000601	0.000571	0.0006	0.22	0.1742	0.1115
0300-0400		0	0	0.000003	0.000002	0.00	0.0014	0.0003

F2b: (20-30 mm) 22 January 2020

Time (hr)	Rainfall (mm)	Observed Inflow (m ³ /s)	Outflow (m ³ /s)			Water Level (m)		
			Outlet-0.050	Outlet-0.055	Outlet-0.063	Outlet-0.050	Outlet-0.055	Outlet-0.063
0500-0600	0.2	0	0.000003	0.000005	0.000004	0	0.0007	0.0014
0600-0700	22.6	0.000765	0.00052	0.000565	0.000594	0.21	0.1702	0.1095
0700-0800	9.6	0.000301	0.000286	0.000253	0.000253	0.07	0.0343	0.0199
0800-0900	0.4	0.000018	0.000012	0.000004	0.000005	0.00	0.0006	0.0005

F2c: (20-30 mm) 19 January 2020

Time (hr)	Rainfall (mm)	Observed Inflow (m ³ /s)	Outflow (m ³ /s)			Water Level (m)		
			Outlet-0.050	Outlet-0.055	Outlet-0.063	Outlet-0.050	Outlet-0.055	Outlet-0.063
0000-0100	1.6	0.000053	0.000049	0.000047	0.000057	0	0.0033	0.0053
0100-0200	9.2	0.000264	0.000243	0.000243	0.000243	0.05	0.0315	0.0183
0200-0300	17.8	0.000422	0.000446	0.000465	0.00047	0.16	0.1154	0.0684
0300-0400	22.8	0.00066	0.000548	0.00058	0.0006	0.24	0.1795	0.1118
0400-0500	0.6	0.000011	0.000025	0.000017	0.000006	0.03	0.0038	0.0007
0500-0600	4.2	0.000132	0.000111	0.000111	0.000111	0.01	0.0066	0.0087
0600-0700	3.8	0.000106	0.00011	0.0001	0.0001	0.01	0.0054	0.0082

F2d: (20-30 mm) 22 December 2019

Time (hr)	Rainfall (mm)	Observed Inflow (m ³ /s)	Outflow (m ³ /s)			Water Level (m)		
			Outlet-0.050	Outlet-0.055	Outlet-0.063	Outlet-0.050	Outlet-0.055	Outlet-0.063
0200-0300	0.3	0.000008	0.000002	0.000007	0.000007	0	0.0023	0.0019
0300-0400	0.1	0.000003	0.000001	0.000003	0.000003	0	0.0013	0.0012
0400-0500	3	0.000079	0.000078	0.000038	0.000041	0	0.0024	0.0023
0500-0600	17.4	0.000449	0.000431	0.000455	0.000459	0.15	0.1103	0.0654
0600-0700	21.9	0.000686	0.000531	0.000561	0.000577	0.22	0.1682	0.1034
0700-0800	4.1	0.000106	0.000111	0.000108	0.000136	0.03	0.0063	0.0074
0800-0900	9.6	0.000106	0.000252	0.000253	0.000253	0.05	0.0343	0.0199
0900-1000	3.6	0.000011	0.000096	0.000095	0.000048	0	0.0048	0.0026

F2e: (20-30 mm) 28 & 29 December 2019

Time (hr)	Rainfall (mm)	Observed Inflow (m ³ /s)	Outflow (m ³ /s)			Water Level (m)		
			Outlet-0.050	Outlet-0.055	Outlet-0.063	Outlet-0.050	Outlet-0.055	Outlet-0.063
2300-0000	8.7	0.000206	0.000229	0.00023	0.00023	0.04	0.0281	0.0164
0000-0100	7.5	0.000198	0.000197	0.000198	0.000198	0.03	0.0209	0.0122
0100-0200	1.3	0.000032	0.000036	0.000039	0.00002	0	0.0028	0.0014
0200-0300	0.1	0	0.000005	0.000006	0.000004	0	0.0016	0.0014
0300-0400	11.6	0.000317	0.000303	0.000306	0.000306	0.07	0.0500	0.0291
0400-0500	22.3	0.000739	0.000524	0.000563	0.000587	0.21	0.1693	0.1069
0500-0600	6.7	0.000179	0.000187	0.000177	0.000177	0.05	0.0167	0.0097
0600-0700	1	0.000026	0.000036	0.000032	0.000027	0	0.0032	0.0048
0700-0800	0.3	0.000008	0.000003	0.000011	0.000011	0	0.0023	0.0022

F2f: (20-30 mm) 10 January 2020

Time (hr)	Rainfall (mm)	Observed Inflow (m ³ /s)	Outflow (m ³ /s)			Water Level (m)		
			Outlet-0.050	Outlet-0.055	Outlet-0.063	Outlet-0.050	Outlet-0.055	Outlet-0.063
1000-1100	15.4	0.000401	0.000393	0.000405	0.000406	0.12	0.0875	0.0512
1100-1200	25.8	0.000739	0.000578	0.000630	0.000674	0.26	0.2118	0.1409
1200-1300	21.2	0.000581	0.000574	0.000579	0.000561	0.26	0.1792	0.0976
1300-1400	11	0.000317	0.000353	0.00029	0.00029	0.1	0.045	0.0261
1400-1500	4.4	0.000106	0.000117	0.000116	0.000057	0.01	0.0072	0.0029
1500-1600	0.8	0.000026	0.000022	0.000021	0.000029	0	0.0016	0.0037
1600-1700	1.2	0.000026	0.000031	0.000035	0.000042	0	0.0028	0.0045
1700-1800	1	0.000026	0.000033	0.000022	0.000035	0	0.0017	0.0041
1800-1900	0.6	0.000016	0.000011	0.000016	0.000021	0	0.0037	0.0031
1900-2000	2.8	0.000074	0.000039	0.000074	0.000074	0	0.0072	0.0069
2000-2100	0.6	0.000016	0.000016	0.000019	0.000016	0	0.0023	0.0036

F3a: (30-40 mm) 7 December 2019

Time (hr)	Rainfall (mm)	Observed Inflow (m ³ /s)	Outflow (m ³ /s)			Water Level (m)		
			Outlet-0.050	Outlet-0.055	Outlet-0.063	Outlet-0.050	Outlet-0.055	Outlet-0.063
0100-0200	6.5	0.000185	0.000172	0.000172	0.000172	0.01	0.0157	0.0091
0200-0300	32.5	0.000924	0.000631	0.000722	0.000815	0.30	0.2780	0.2062
0300-0400	8.1	0.000211	0.000367	0.000214	0.000214	0.13	0.0244	0.0142
0400-0500	1.2	0.000013	0.000046	0.000032	0.00001	0.02	0.0049	0.0009
0500-0600	0.2	0.000005	0.000008	0.000006	0.000003	0	0.0022	0.0004

F3b: (30-40 mm) 1 December 2019

Time (hr)	Rainfall (mm)	Observed Inflow (m ³ /s)	Outflow (m ³ /s)			Water Level (m)		
			Outlet-0.050	Outlet-0.055	Outlet-0.063	Outlet-0.050	Outlet-0.055	Outlet-0.063
0100-0200	5.5	0.000132	0.000145	0.000145	0.000145	0.02	0.0112	0.0065
0200-0300	29.5	0.000871	0.000600	0.000681	0.00061	0.30	0.2473	0.1768
0300-0400	1	0.000026	0.000092	0.00003	0.000032	0.03	0.0028	0.0048
0400-0500	1	0.000026	0.000024	0.000033	0.000014	0	0.0036	0.0047
0500-0600	2	0.000053	0.000053	0.000059	0.000025	0	0.0038	0.0023
0600-0700	2.5	0.000079	0.000061	0.000083	0.000031	0	0.0058	0.0065
0700-0800	1	0.000026	0.000024	0.000027	0.000027	0	0.0047	0.0041

F3c: (30-40 mm) 8&9 December 2019

Time (hr)	Rainfall (mm)	Observed Inflow (m ³ /s)	Outflow (m ³ /s)			Water Level (m)		
			Outlet-0.050	Outlet-0.055	Outlet-0.063	Outlet-0.050	Outlet-0.055	Outlet-0.063
2100-2200	0.5	0	0.000003	0.000004	0.000014	0	0.0006	0.0012
2200-2300	5.4	0.000106	0.000142	0.000143	0.000143	0.01	0.0108	0.0063
2300-0000	6.2	0.000311	0.000164	0.000164	0.000164	0.02	0.0143	0.0083
0000-0100	29	0.001003	0.000602	0.000674	0.000745	0.29	0.2423	0.1719
0100-0200	8.6	0.000238	0.000314	0.000227	0.000227	0.1	0.0275	0.016
0200-0300	6.3	0.000132	0.000167	0.000166	0.000166	0.02	0.0148	0.0086
0300-0400	1.2	0.000026	0.000038	0.000025	0.000032	0	0.0018	0.0053
0400-0500	0.6	0.000016	0.00001	0.000016	0.000016	0	0.0037	0.0036

F3d: (30-40 mm) 18 January 2020

Time (hr)	Rainfall (mm)	Observed Inflow (m ³ /s)	Outflow (m ³ /s)			Water Level (m)		
			Outlet-0.050	Outlet-0.055	Outlet-0.063	Outlet-0.050	Outlet-0.055	Outlet-0.063
0200-0300	3.2	0.000153	0.000083	0.00004	0.000084	0	0.0025	0.0075
0300-0400	34.4	0.000924	0.000655	0.000744	0.00085	0.34	0.2954	0.2239
0400-0500	13.4	0.000333	0.000516	0.000438	0.000354	0.21	0.1025	0.0388
0500-0600	5.6	0.000143	0.000149	0.000148	0.000148	0.02	0.0117	0.0068
0600-0700	1.6	0.000037	0.000048	0.000042	0.000042	0	0.0053	0.0051
0700-0800	4.6	0.000106	0.000121	0.000121	0.000121	0.01	0.0079	0.0092
0800-0900	2.4	0.000069	0.000064	0.000079	0.000063	0	0.0056	0.0063
0900-1000	1.2	0.000026	0.000036	0.000036	0.000032	0	0.0026	0.0041

F3e: (30-40 mm) 20 January 2020

Time (hr)	Rainfall (mm)	Observed Inflow (m ³ /s)	Outflow (m ³ /s)			Water Level (m)		
			Outlet-0.050	Outlet-0.055	Outlet-0.063	Outlet-0.050	Outlet-0.055	Outlet-0.063
0200-0300	5.4	0.000132	0.000142	0.000142	0.000142	0.01	0.0108	0.0063
0300-0400	37.2	0.001008	0.000682	0.000777	0.000899	0.37	0.3224	0.2505
0400-0500	20.2	0.000668	0.000634	0.000646	0.000553	0.33	0.2226	0.0948
0500-0600	7.2	0.000222	0.000266	0.00019	0.00019	0.07	0.0193	0.0112
0600-0700	5.6	0.000143	0.000149	0.000148	0.000148	0.02	0.0117	0.0068
0700-0800	3	0.000079	0.000079	0.000079	0.000079	0	0.0075	0.0072
0800-0900	2.2	0.000053	0.000059	0.000058	0.000058	0	0.0063	0.006
0900-1000	0.6	0.000026	0.000016	0.000016	0.000021	0	0.0037	0.0032
1000-1100	0.2	0.000005	0.000007	0.000008	0.000007	0	0.0018	0.0009
1100-1200	0.6	0.000011	0.000021	0.000016	0.000006	0	0.0037	0.0006
1200-1300	3.4	0.000106	0.000089	0.000113	0.000046	0	0.0018	0.0025

F4a: (40-50 mm) 16 January 2020

Time (hr)	Rainfall (mm)	Observed Inflow (m ³ /s)	Outflow (m ³ /s)			Water Level (m)		
			Outlet-0.05	Outlet-0.055	Outlet-0.063	Outlet-0.050	Outlet-0.055	Outlet-0.063
1000-1100	4.4	0.000121	0.000114	0.000116	0.000057	0.01	0.0072	0.0029
1100-1200	41.6	0.001108	0.000713	0.000822	0.000967	0.40	0.3612	0.2898
1200-1300	6	0.000132	0.000457	0.000156	0.000158	0.17	0.013	0.0078
1300-1400	0.6	0.000011	0.000017	0.000022	0.000017	0	0.0033	0.0037

F4b: (40-50 mm) 22 February 2020

Time (hr)	Rainfall (mm)	Observed Inflow (m ³ /s)	Outflow (m ³ /s)			Water Level (m)		
			Outlet-0.050	Outlet-0.055	Outlet-0.063	Outlet-0.050	Outlet-0.055	Outlet-0.063
1200-1300	1.2	0.000028	0.000033	0.000031	0.00001	0	0.0044	0.0009
1300-1400	3.4	0.000158	0.000089	0.00009	0.000046	0.00	0.008	0.0025
1400-1500	22.4	0.000538	0.00051	0.000562	0.000589	0.21	0.1688	0.1077
1500-1600	47.6	0.001823	0.001159	0.000897	0.001059	0.47	0.4299	0.3476
1600-1700	31.6	0.000871	0.000709	0.000883	0.000931	0.44	0.4161	0.2686
1700-1800	6.4	0.000507	0.000555	0.000371	0.000169	0.2	0.0734	0.0088
1800-1900	2.4	0.000066	0.000079	0.000031	0.000078	0	0.0021	0.0054
1900-2000	1.2	0.000048	0.000026	0.000032	0.000032	0	0.0033	0.0053
2000-2100	0.7	0.000018	0.000017	0.000019	0.000019	0	0.004	0.0039
2100-2200	0.6	0.000016	0.000016	0.000016	0.000016	0	0.0037	0.0036

F4c: (40-50 mm) 18&19 January 2015

Time (hr)	Rainfall (mm)	Modelled Inflow (m ³ /s)	Modelled Outflow (m ³ /s)			Modelled Water Level (m)		
			Outlet-0.05	Outlet-0.055	Outlet-0.063	Outlet-0.050	Outlet-0.055	Outlet-0.063
0000-0100	2	0	0	0	0	0	0	0
0100-0200	7.5	0.000053	0.000053	0.000062	0.000041	0.0061	0.0038	0.0023
0200-0300	3	0.000198	0.000198	0.000198	0.000198	0.0306	0.0209	0.0122
0300-0400	20.5	0.000079	0.000079	0.000079	0.000041	0.0049	0.0075	0.0023
0400-0500	19.5	0.000541	0.000491	0.000524	0.000541	0.1881	0.1466	0.0906
0500-0600	38.5	0.000515	0.000508	0.000516	0.000515	0.2016	0.1423	0.0822
0600-0700	12	0.001016	0.00072	0.000807	0.000926	0.4051	0.3474	0.266
0700-0800	1.5	0.000317	0.000566	0.000471	0.000317	0.2504	0.1183	0.0311
0800-0900	0.5	0.00004	0.000047	0.00002	0.00004	0.0033	0.0016	0.0043
0900-1000	0.5	0.000014	0.000016	0.000018	0.000005	0.002	0.0029	0.0006
1000-1100	2	0.000013	0.000017	0.000018	0.000005	0.0023	0.0029	0.0006
1100-1200	0	0.000053	0.000066	0.000026	0.000065	0.0052	0.0019	0.0049
1200-1300	1.5	0.000002	0.000001	0.000003	0.000001	0.002	0.0005	0.0002
1300-1400	3.5	0.000039	0.00004	0.000039	0.000053	0.0036	0.0051	0.0051
1400-1500	1.5	0.000092	0.000092	0.000092	0.000115	0.0067	0.0081	0.0067
1500-1600	1	0.00004	0.000045	0.00004	0.000044	0.0034	0.0036	0.003
1600-1700	23	0.000026	0.000022	0.000032	0.000009	0.0018	0.0027	0.0008
1700-1800	21	0.000607	0.000527	0.000573	0.000604	0.2172	0.1751	0.1132
1800-1900	8.5	0.000554	0.000545	0.000559	0.000555	0.2323	0.1667	0.0954
1900-2000	5	0.000224	0.000231	0.000224	0.000224	0.0419	0.0269	0.0156
2000-2100	6.5	0.000132	0.000132	0.000132	0.000132	0.0136	0.0093	0.0054
2100-2200	4.5	0.000172	0.000172	0.000172	0.000172	0.023	0.0157	0.0091
2200-2300	39	0.000119	0.000119	0.000119	0.000058	0.011	0.0075	0.0029
2300-0000	43	0.001029	0.000697	0.000796	0.000927	0.3799	0.3384	0.2667
0000-0100	26	0.001135	0.000759	0.000918	0.00105	0.45	0.45	0.342
0100-0200	4	0.000686	0.000741	0.00084	0.000804	0.4287	0.3764	0.2006

F4d: (40-50 mm) 1 January 2016

Time (hr)	Rainfall (mm)	Modelled Inflow (m ³ /s)	Modelled Outflow (m ³ /s)			Modelled Water Level (m)		
			Outlet-0.05	Outlet-0.055	Outlet-0.063	Outlet-0.050	Outlet-0.055	Outlet-0.063
1600-1700	7	0	0	0	0	0	0	0
1700-1800	22	0.000185	0.000185	0.000185	0.000185	0.0267	0.0182	0.0106
1800-1900	51	0.000581	0.000516	0.000556	0.000579	0.2078	0.1648	0.1041
1900-2000	7	0.001346	0.000759	0.000918	0.001099	0.45	0.45	0.3748
2000-2100	1	0.000185	0.000544	0.000529	0.000185	0.2316	0.1495	0.0106
2100-2200	1.5	0.000027	0.00003	0.000035	0.000009	0.0026	0.004	0.0008

F4e: (40-50 mm) 17&18 December 2017

Time (hr)	Rainfall (mm)	Modelled Inflow (m ³ /s)	Modelled Outflow (m ³ /s)			Modelled Water Level (m)		
			Outlet-0.05	Outlet-0.055	Outlet-0.063	Outlet-0.050	Outlet-0.055	Outlet-0.063
1800-1900	0.5	0	0	0	0	0	0	0
1900-2000	0.5	0.000012	0.000004	0.000004	0.000014	0.0006	0.0006	0.0012
2000-2100	0.5	0.000013	0.000004	0.000004	0.000005	0.0006	0.0006	0.0006
2100-2200	7.5	0.000013	0.000004	0.000004	0.000005	0.0006	0.0006	0.0006
2200-2300	6	0.000198	0.000198	0.000198	0.000198	0.0306	0.0209	0.0122
2300-0000	15	0.000158	0.000158	0.000158	0.000158	0.0196	0.0134	0.0078
0000-0100	10	0.000396	0.000388	0.000395	0.000396	0.1174	0.0834	0.0486
0100-0200	9	0.000264	0.000264	0.000264	0.000264	0.0546	0.0372	0.0216
0200-0300	10	0.000238	0.000238	0.000238	0.000238	0.0441	0.0301	0.0175
0300-0400	19.5	0.000264	0.000264	0.000264	0.000264	0.0544	0.0372	0.0216
0400-0500	32	0.000515	0.000477	0.000504	0.000514	0.01782	0.1357	0.0821
0500-0600	47.5	0.000845	0.000659	0.00073	0.000811	0.3395	0.2843	0.2038
0600-0700	16	0.001254	0.000759	0.000918	0.001081	0.45	0.45	0.3622
0700-0800	4	0.000422	0.000657	0.000717	0.000498	0.3369	0.2747	0.0769
0800-0900	0.5	0.000106	0.000106	0.000106	0.000106	0.0087	0.006	0.0085