



Faculty of Engineering

**StormPav Green Pavement System as Permeable Road for Detention and
Conveyance of Stormwater**

Liow Ching Vern

**Master of Engineering
2020**

StormPav Green Pavement System as Permeable Road for Detention and Conveyance of Stormwater

Liow Ching Vern

A thesis submitted

In fulfillment of the requirements for the degree of Master of Engineering

(Civil Engineering)

Faculty of Engineering
UNIVERSITI MALAYSIA SARAWAK
2020

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.

.....

Signature

Name: Liow Ching Vern

Matric No.: 18020154

Faculty of Engineering

Universiti Malaysia Sarawak

Date :

ACKNOWLEDGEMENT

I thank God the Almighty for His faithfulness and grace in providing me with the wisdom, strength and health to complete the work. I would like to acknowledge Sarawak Multimedia Authority for providing fund/graduate research assistantship through Digital Sarawak CoE grant scheme. I owe my deepest gratitude to my supervisor, Ir. Dr. Darrien Mah Yau Seng for his guidance and advice, patience and most importantly, unfailing encouragement to cheer me on, especially when I get panicky. His patience and hard work during thesis corrections is so very much appreciated. Besides, I am also thankful to my co-supervisor Professor Dr. Md. Abdul Mannan for sharing his precious experiences, knowledge and advices. I also wish to thank my family for their priceless support throughout this research and thesis writing period. Not to mentions, thanks to all my friends who had kindly helped me in this research works. Their willingness to share their time so generously is appreciated. Last but not least, thanks to anyone that providing moral support that I very much needed to complete this thesis.

ABSTRACT

This study focuses on a value-added function to StormPav Green Pavement System, that is not only designed to store stormwater but to act as a conduit to drain stormwater in a typical commercial environment. This system is a form of permeable road, in which multi-unit small chambers are used to overcome the problem of big stormwater storage structure; and at the same time could provide a greater strength in its interlocking manner for vehicles transportation. This structure is analysed of its capability to store and convey stormwater from roof and road catchments that is subjected to 10-year ARI design rainfall with durations ranging from 5 to 180 minutes. The added function could only be executed when appropriate inlet and outlet design are decided. Computer models are incorporated in this study. Comparison of Storm Water Management Model (SWMM) and SolidWorks Flow Simulation (SWFS) models is performed. Results show that both models are reiterating each other, suggesting that the confidence level of the model verification is enhanced. Visualization of flow within the system is also demonstrated. Results indicate that inlet and outlet design sizes of 100 mm and 190 mm x 700 mm respectively could provide optimum filling, ponding and draining effects. The system is able to reasonably alleviate the peak discharges at the outfall. Besides that, by comparing with conventional drainage system, the discharge reduction after implementing the StormPav system reports the highest reduction in discharge (approximately 80% reduction) occurred for the 5-minute design rainfall duration, while the lowest reduction in discharge (approximately no reduction) occurred for 180-minute design rainfall duration. This means that the structure has reached its limit or range of service. In conclusion, findings show that the StormPav system has demonstrated the capability of conveying and storing stormwater up to 180-minute, 10-year ARI design rainfall.

Keywords: Permeable road, on-site detention, urban drainage, StormPav, SWMM.

Sistem StormPav Green Pavement sebagai Sistem Menakung dan Mengalirkan Air Hujan

ABSTRAK

Kajian ini memfokuskan fungsi nilai tambah kepada sistem StormPav Green Pavement yang bukan sahaja direka untuk menakung air hujan tetapi juga berfungsi sebagai saluran yang mengalirkan air hujan dalam premis komersial. Sistem StormPav dapat diklasifikasikan sebagai jalan telap, di mana pelbagai unit ruang kecil yang diinovasikan untuk mengatasi masalah struktur simpanan air hujan yang besar, dan pada masa yang sama sistem ini dapat menambahkan kekuatan dalam ciri cantuman untuk mengatasi tekanan semasa pengangkutan kenderaan. Struktur ini dianalisa dari segi keupayaan untuk menakung dan mengalirkan air hujan dari kawasan bumbung dan kawasan jalan berdasarkan 10 ulang tahun kejadian (ARI) dalam jangka masa 5 hingga 180 minit. Fungsi tambahan dalam kajian ini hanya dapat dilaksanakan apabila reka bentuk saiz yang sesuai untuk inlet dan outlet diperolehi. Kajian ini melibatkan model komputer. Perbandingan antara model SWMM dan model SW Flow Simulation telah dijalankan. Keputusan menunjukkan bahawa kedua-dua model serasi antara satu sama lain, dan oleh itu, meningkatkan tahap keyakinan pengesahan model. Visualisasi aliran dalam sistem StormPav juga ditunjukkan. Keputusan menunjukkan bahawa saiz 100 mm inlet dan saiz 190 mm x 700 mm outlet dapat memberikan kesan optimum pengisian, penakungan dan pengaliran. Berdasarkan keperluan MSMA, sistem StormPav mampu mengurangkan puncak aliran air di hilir. Sejajar dengan itu, perbandingan antara sistem perparitan konvensional dengan selepas pelaksanaan sistem StormPav menunjukkan pengurangan aliran air dan peratusan pengurangan aliran yang tertinggi ialah ketika reka bentuk hujan untuk tempoh 5 minit, anggaran 80%, manakala tempoh 180 minit memberi pengurangan peratusan yang paling rendah, iaitu hampir tidak ada pengurangan. Hal ini bermakna struktur telah mencapai had perkhidmatan.

Kesimpulannya, kajian menunjukkan bahawa sistem StormPav telah menunjukkan keupayaan penyimpanan dan pengairan air hujan sehingga 180 minit untuk 10 ARI.

Kata kunci: *Jalan telap, detensi di-tapak , saluran air bandar, StormPav, SWMM*

TABLE OF CONTENTS

	Page
DECLARATION	i
ACKNOWLEDGEMENT	ii
ABSTRACT	iii
<i>ABSTRAK</i>	iv
TABLE OF CONTENTS	vi
LIST OF TABLES	ix
LIST OF FIGURES	xi
LIST OF ABBREVIATIONS	xviii
CHAPTER 1: INTRODUCTION	1
1.1 Background	1
1.2 Problem Statement	2
1.3 Objectives	3
1.4 Scopes of Work and Structure of Thesis	4
CHAPTER 2: LITERATURE REVIEW	5
2.1 Introduction	5
2.2 Stormwater Management	6
2.3 Conventional Permeable Road/ Pavement	7
2.4 Latest Development of Permeable Road	11

2.5	StormPav Green Pavement	15
2.6	On-Site Detention (OSD)	20
2.7	Urban Storm Water Management Manual for Malaysia	23
2.8	Design Criteria	24
2.9	Drainage Modelling using SWMM	32
2.10	3-D Flow Modelling using SolidWorks	36
2.11	Summary of Techniques	46
CHAPTER 3: METHODOLOGY		47
3.1	Introduction	47
3.2	Case Study	49
3.3	Proposed Incorporation of StormPav Green Pavement	50
3.4	Design Rainfall	55
3.5	Storm Water Management Model (SWMM)	56
3.5.1	Representation of StormPav Green Pavement	57
3.5.2	Storage Volume Inlet and Outlet	62
3.5.3	MSMA Requirements	62
3.6	SolidWorks Flow Simulation	65
3.7	Summary	70
CHAPTER 4: RESULT AND DISCUSSION		72
4.1	Flow Simulation	72

4.1.1	Velocity	72
4.1.2	Flow Trajectories	78
4.2	Inlet and Outlet of StormPav Green Pavement	84
4.2.1	Inlet Analysis	84
4.2.2	Outlet Analysis	93
4.3	Outfall Analysis	119
4.3.1	Pre-Development Condition	119
4.3.2	Post-development with Conventional Drainage System	120
4.3.3	Post-development with StormPav Green Pavement System	121
4.3.4	Summary	124
CHAPTER 5: CONCLUSION AND RECOMMENDATIONS		127
5.1	Conclusions	127
5.1.1	Computer Models	127
5.1.2	Stormwater Inlet and Outlet	128
5.1.3	The Filling, Ponding and Draining Effects	128
5.2	Recommendations for Future Study	129
REFERENCES		130
APPENDICES		139

LIST OF TABLES

	Page
Table 2.1 Summary of Relevant Case Studies of StormPav Green Pavement	19
Table 2.2 Advantages of Above and Below Ground Storage (DID, 2000)	21
Table 2.3 Summary of Techniques in Previous Studies	46
Table 3.1 Measurement of Study Area	50
Table 3.2 Rainfall Intensities of Different Design Rainfall Duration Under 10- year ARI	56
Table 3.3 Categorization of Observed Rainfall Intensity (https://ihydro.sarawak.gov.my/iHydro/en/datatable/rainfall/hourly-rainfall.jsp)	56
Table 3.4 Design Calculation for StormPav Green Pavement	57
Table 3.5 Dimensions of Cross Section for Conduits	59
Table 3.6 Cross-checking of Surface Runoff for Post-Development	60
Table 3.7 Cross-check of Water Volume Filling the System	61
Table 3.8 Cross-checking of Surface Runoff for Pre-Development	64
Table 3.9 Specifying the Boundary Conditions	69
Table 3.10 Specifications Used in Flow Simulation	70
Table 4.1 Modelled Velocities in Different Design Storm Durations	77
Table 4.2 Maximum Capacity of Varying Inlet Sizes	85
Table 4.3 Summary of Inlet Analysis in Varying Combinations of Inlet and Outlet Sizes for All the Design Rainfall Durations	92
Table 4.4 Summary of Outlet Analysis in Varying Combinations of Inlet and Outlet Sizes for All the Design Rainfall Durations	94
Table 4.5 Outfall Discharge of Three Scenarios in Different Rainfall Durations	124

Table 4.6	Percentage of Discharge Reduction under Different Outlet Orifice Sizes in Rainfall Durations	125
-----------	---	-----

LIST OF FIGURES

	Page
Figure 1.1 Schematics of Conventional Permeable Road	1
Figure 2.1 Effect of Pervious Surfaces and Impervious Surfaces in Rainfall (Chithra et al., 2015)	5
Figure 2.2 Impact of Urbanisation on Infiltration and Runoff (US EPA, 2008)	6
Figure 2.3 Schematics of Conventional Permeable Road Conventional Permeable Road's Cross-Section (ASCE, 2015)	8
Figure 2.4 Types of Permeable Pavements (Hunt & Collins, 2007)	8
Figure 2.5 Design of Q Street Green Alley (District Department of Transportation, 2014)	10
Figure 2.6 Permeable Road of the Q Street Green Alley (Rhodeside & Harwell, n.d.)	10
Figure 2.7 Design of the Bloomingdale Project (District Department of Transportation, 2014)	11
Figure 2.8 Permeable Road of the Bloomingdale Project (District Department of Transportation, 2014)	11
Figure 2.9 SingleTrap Concept Design (StormTrap, 2018)	12
Figure 2.10 DoubleTrap Concept Design (StormTrap, 2018)	13
Figure 2.11 DoubleTrap used in Storrs Center, Village Steet, Mansfield, CT (StormTrap, 2018)	13
Figure 2.12 Design of StormCapture Module (Old Castle Infrastructure, 2018)	14
Figure 2.13 Installation of StormCapture Beneath the Carpark (Old Castle Infrastructure, 2018)	14

Figure 2.14	Installation of Precast StormTraps (Kenter, 2011)	15
Figure 2.15	StormPav Road (Mah et al., 2018b)	17
Figure 2.16	Single Modular Unit of StormPav (Mah et al., 2018b)	18
Figure 2.17	Dimensions of StormPav Modular Unit (Mah, 2016)	18
Figure 2.18	Pilot study of StormPav Green Pavement in Kampung Mang (Mah et al., 2018c)	18
Figure 2.19	Typical OSD (DID, 2000)	20
Figure 2.20	Online Detention System (PUB, 2010)	22
Figure 2.21	Offline Detention System (PUB, 2010)	22
Figure 2.22	Concept of Urban Runoff Control (DID, 2012)	24
Figure 2.23	Non-linear Reservoir Model for A Sub-catchment (Huber & Dickinson, 1988)	29
Figure 2.24	Typical of Inflow and Outflow Hydrographs for Online Gravity Stormwater Detention Storage (PUB, 2010)	30
Figure 2.25	Orifice Discharge System (PUB, 2010)	31
Figure 2.26	Conceptual of Example Drainage Modelling (Rossman, 2015)	33
Figure 2.27	SWMM Model Schematic of Easy Street (Dierks, 2009)	36
Figure 2.28	Processes of CFD (Arokiasamy, 2017)	38
Figure 2.29	Flow Trajectories in Term of Velocity of the Muffler (Priyadarsini et al., 2016)	42
Figure 2.30	Residential Car Porch Used as the Detention Storage (Ngu et al., 2016)	43
Figure 2.31	Velocity Contour in the Individual Lot Stormwater Detention – Result from CFD Simulation.(Ngu et al., 2016)	44

Figure 2.32	CFD Model of StormPav Permeable Road (Mah et al., 2018b)	45
Figure 2.33	Velocity Profile Through Service Inlet for Flows a) 0.1 ℓ/s , b) 0.2 ℓ/s and c) 0.3 ℓ/s (Mah et al., 2018b)	45
Figure 3.1	Flow of Study Approaches	48
Figure 3.2	Typical Outlook of Commercial Area	49
Figure 3.3	Study Area Divided into Sub-Catchments	50
Figure 3.4	StormPav Green Pavement	51
Figure 3.5	Placement of StormPav Green Pavement	52
Figure 3.6	Single Modular Unit of StormPav	52
Figure 3.7	Conceptual Design of StormPav Green Pavement in Commercial Area	53
Figure 3.8	Plan View of StormPav Green Pavement Layout Design	54
Figure 3.9	Section A-A View of StormPav Green Pavement Layout Design	54
Figure 3.10	Section B-B View of StormPav Green Pavement Layout Design	55
Figure 3.11	SWMM Model of StormPav Green Pavement	59
Figure 3.12	SWMM Modeling of Scenario 1	63
Figure 3.13	SWMM Modeling of Scenario 2	65
Figure 3.14	Single Modular Unit of StormPav in SolidWorks	66
Figure 3.15	Schematic of StormPav with Premises	67
Figure 3.16	SolidWorks Flow Simulation in (i) Upper Stretch, (ii) Intermediate Stretch and (iii) Lower Stretch of StormPav Road	68
Figure 3.17	Framework of A Model Credibility (Sargent, 2013)	71
Figure 4.1	Velocity Cut Plot of Stretch i due to 180-minute 10-Year ARI Design Rainfall	73

Figure 4.2	Velocity Cut Plot of Stretch ii due to 180-minute 10-Year ARI Design Rainfall	73
Figure 4.3	Velocity Cut Plot of Stretch iii due to 180-minute 10-Year ARI Design Rainfall	74
Figure 4.4	Velocity Cut Plot of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 120-minute 10-Year ARI Design Rainfall	75
Figure 4.5	Velocity Cut Plot of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 60-minute 10-Year ARI Design Rainfall	75
Figure 4.6	Velocity Cut Plot of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 30-minute 10-Year ARI Design Rainfall	75
Figure 4.7	Velocity Cut Plot of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 20-minute 10-Year ARI Design Rainfall	76
Figure 4.8	Velocity Cut Plot of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 15-minute 10-Year ARI Design Rainfall	76
Figure 4.9	Velocity Cut Plot of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 10-minute 10-Year ARI Design Rainfall	76
Figure 4.10	Velocity Cut Plot of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 5-minute 10-Year ARI Design Rainfall	77
Figure 4.11	Flow Trajectories of Stretch i due to 180-minute 10-Year ARI Design Rainfall	79
Figure 4.12	Flow Trajectories of Stretch ii due to 180-minute 10-Year ARI Design Rainfall	80
Figure 4.13	Flow Trajectories of Stretch iii due to 180-minute 10-Year ARI Design Rainfall	81

Figure 4.14	Flow Trajectories of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 120-minute 10-Year ARI Design Rainfall	82
Figure 4.15	Flow Trajectories of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 60-minute 10-Year ARI Design Rainfall	82
Figure 4.16	Flow Trajectories of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 30-minute 10-Year ARI Design Rainfall	83
Figure 4.17	Flow Trajectories of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 20-minute 10-Year ARI Design Rainfall	83
Figure 4.18	Flow Trajectories of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 15-minute 10-Year ARI Design Rainfall	83
Figure 4.19	Flow Trajectories of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 10-minute 10-Year ARI Design Rainfall	84
Figure 4.20	Flow Trajectories of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 5-minute 10-Year ARI Design Rainfall	84
Figure 4.21	Water Depth at Inlet with Varying Inlet Sizes and ∞ * Outlet Size in Different Design Rainfall Durations at Corner Lot	86
Figure 4.22	Water Depth at Inlet with Varying Inlet Sizes and ∞ * Outlet Size in Different Design Rainfall Durations at Intermediate Lot	86
Figure 4.23	Water Depth at Inlet with Varying Inlet Sizes and 190 mm Outlet Size in Different Design Rainfall Durations at Corner Lot	87
Figure 4.24	Water Depth at Inlet with Varying Inlet Sizes and 190 mm Outlet Size in Different Design Rainfall Durations at Intermediate Lot	87
Figure 4.25	Water Depth at Inlet with Varying Inlet Sizes and 190 mm x 300 mm Outlet Size in Different Design Rainfall Durations at Corner Lot	88

Figure 4.26	Water Depth at Inlet with Varying Inlet Sizes and 190 mm x 300 mm Outlet Size in Different Design Rainfall Durations at Intermediate Lot	88
Figure 4.27	Water Inlet Depth with Varying Inlet Sizes and 190 mm x 500 mm Outlet Size in Different Design Rainfall Durations at Corner Lot	89
Figure 4.28	Water Inlet Depth with Varying Inlet Sizes and 190 mm x 500 mm Outlet Size in Different Design Rainfall Durations at Intermediate Lot	89
Figure 4.29	Water Inlet Depth with Varying Inlet Sizes and 190 mm x 700 mm Outlet Size in Different Design Rainfall Durations at Corner Lot	90
Figure 4.30	Water Inlet Depth with Varying Inlet Sizes and 190 mm x 700 mm Outlet Size in Different Design Rainfall Durations at Intermediate Lot	90
Figure 4.31	Water Inlet Depth with Varying Inlet Sizes and 190 mm x 900 mm Outlet Size in Different Design Rainfall Durations at Corner Lot	91
Figure 4.32	Water Inlet Depth with Varying Inlet Sizes and 190 mm x 900 mm Outlet Size in Different Design Rainfall Durations at Intermediate Lot	91
Figure 4.33	Time Series of Water Depth in StormPav in Varying Rainfall Durations For 190 mm Diameter Circular Orifice Outlet	95
Figure 4.34	Time Series of Water Depth in StormPav in Varying Rainfall Durations For 190 mm x 300 mm Rectangular Orifice Outlet	95
Figure 4.35	Time Series of Water Depth in StormPav in Varying Rainfall Durations For 190 mm x 500 mm Rectangular Orifice Outlet	96
Figure 4.36	Time Series of Water Depth in StormPav in Varying Rainfall Durations For 190 mm x 700 mm Rectangular Orifice Outlet	97
Figure 4.37	Time Series of Water Depth in StormPav in Varying Rainfall Durations For 190 mm x 900 mm Rectangular Orifice Outlet	97

Figure 4.38	Flowing of Stormwater for 190 mm Diameter Circular Orifice Outlet in Different Elapsed Times	98
Figure 4.39	Flowing of Stormwater for 190 mm x 300 mm Rectangular Orifice Outlet in Different Elapsed Times	102
Figure 4.40	Flowing of Stormwater for 190 mm x 500 mm Rectangular Orifice Outlet in Different Elapsed Times	106
Figure 4.41	Flowing of Stormwater for 190 mm x 700 mm Rectangular Orifice Outlet in Different Elapsed Times	110
Figure 4.42	Flowing of Stormwater for 190 mm x 900 mm Rectangular Orifice Outlet in Different Elapsed Times	114
Figure 4.43	Occupied Volume Capacity with Varying Orifice Sizes and Design Rainfall Durations	118
Figure 4.44	Hydrographs at Outfall of Pre-development Condition in Varying Rainfall Durations	120
Figure 4.45	Hydrographs at Outfall of Conventional Drainage System for Varying Rainfall Durations	121
Figure 4.46	Hydrographs at Outfall of 190 mm x 500 mm Outlet Orifice for Varying Rainfall Durations	122
Figure 4.47	Hydrographs at Outfall of 190 mm x 700 mm Outlet Orifice for Varying Rainfall Durations	123
Figure 4.48	Hydrographs at Outfall of 190 mm x 900 mm Outlet Orifice for Varying Rainfall Durations	123

LIST OF ABBREVIATIONS

ARI	Average Recurrent Interval
ASCE	American Society of Civil Engineers
BMP	Best Management Practice
CFD	Computational Fluid Dynamics
DID	Department of Irrigation and Drainage
HDPE	High-density Polyethylene
IBS	Industrialized Building System
LID	Low Impact Development
MSMA	Manual Saliran Mesra Alam
NCSPA	National Corrugated Steel Pipe Association
OSD	On-site Stormwater Detention
PUB	Singapore Public Utility Board
RANS	Reynold-averaged Navier-Stokes
SWMM	Storm Water Management Model
SWFS	SolidWorks Flow Simulation
TxDOT	Texas Department of Transportation
USDC	Underground Stormwater Detention Chamber
US EPA	United State Environmental Protection Agency

CHAPTER 1

INTRODUCTION

1.1 Background

Models of permeable roads are available since 1960s in the hopes of reducing floods, raising water tables and replenishing aquifers. To date, permeable roads are generally designing a subsurface storage to capture portion of stormwater runoffs (Ronalds & Zhang, 2017; Ronalds et al., 2017). A typical permeable road system consists of a surface pavement layer, a thin bedding layer of fine aggregate, an underlying coarse aggregate layer as base course and sometimes, a filter layer or fabric installed at the bottom (Chowdhury et al., 2016). These models are further described in the Chapter 2. Generally, its principle is illustrated in Figure 1.1, in which the detention of water comes first, then followed by a delay discharge through a control at outlet.

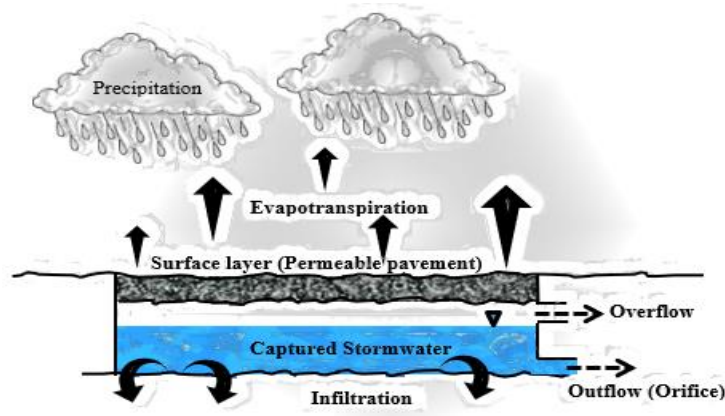


Figure 1.1: Schematics of Conventional Permeable Road

The water balance of the system depicted in Figure 1.1 could be derived as volume of water entering the system equals to volume of water being captured plus losses through infiltration, evapotranspiration, orifice and overflow (Subramanya, 2008; Mah et al., 2018c).

Basically, it follows the water budget equation or hydrologic equation where mass inflow subtracts mass outflow is the change in mass storage.

In normal practice, drainage engineers tend to pay more attention to the storage capacity for safety purposes. They tend to design the volume of storage space equals to potential amount of stormwater runoff plus additional minimum spaces reserved for adverse climates (DID, 2012). As a result, the storage structure could end up as a big structure depending on the size of the contributing upstream catchments.

1.2 Problem Statement

Along with the growing urbanization at a rapid rate, development of permeable road needs to be able to cater for and hold the increasing amount of runoff volume, thus, it is expected that a big storage structure is required. Big storage structure incurs higher cost in terms of construction and the associated safety precaution devices that should come along with the structure. Yet, it is possible to reduce the storage structure without compromising the reduction of stormwater impacts a storage structure could provide. In the case of a permeable road, the subsurface storage could be modified to have a function of stormwater conveyance. The voids within the storage structure provides the ponding effect that attenuates a hydrograph peak (Mah et al., 2014; Mah, 2016). At the same time, manipulating the outlet could allow the captured stormwater to flow (Urbonas & Stahre, 1993; Heiner & MacKenzie, 2015). Meaning, detention of stormwater provided by a storage volume can be released by the outlet structure. This filling and draining effect could reduce the size of the storage structure. Hence, the permeable road not only captures stormwater, but also a conduit to transfer water from one point to another point.

The specific type of permeable road model that this project is investigating, is named StormPav Green Pavement. The details of the product are described in the Chapter 2. This study is investigating an added function of StormPav Green Pavement to transport stormwater runoff on top of it as a stormwater detention structure. To accommodate the investigation of flow mechanism of such permeable road, computer modelling of drainage system is usually applied before an actual road is built. Computer modelling also provides necessary information to assist the construction of the road.

1.3 Objectives

The aim of this study is to focus on the workability of StormPav Green Pavement that flows stormwater underneath its pavement. Benchmarking to the requirement of Urban Storm Water Management Manual for Malaysia (Manual Saliran Mesra Alam or MSMA), post-development peak hydrographs of a development scheme should be lowered with stormwater control measures so that the concept of “saliran mesra alam” could be achieved. StormPav fits in as a new stormwater control measure. By manipulating the inlet and outlet of the system in computer simulation, StormPav Green Pavement will show the capability to store and convey stormwater from premises. As such, the objectives of this study are:

- i. To set up a numerical model that represent StormPav Green Pavement and its flow mechanism;
- ii. To investigate the effect of stormwater inlet and outlet size on the performance of the above mentioned permeable road system to allow ponding, filling and draining effects; and

- iii. To analyse the ponding, filling and draining effects with regards to MSMA requirement.

1.4 Scopes of Work and Structure of Thesis

This study presents on the capability of a permeable road to convey stormwater underneath its pavement in a typical commercial area. This research brings MSMA to another level by combining features so that multipurpose structure is introduced and promoted. In a way, it is also a realization to wise use of expensive land assets. A permeable road that receives and flows stormwater is designed. Computer modelling is done to achieve the objectives of this study. The thesis is organized into five chapters as follows;

- Chapter 1: This Chapter includes the introduction of the study which discusses the general view of the topic, problem statement, objectives as well as the scope of the study;
- Chapter 2: This Chapter includes the literature review, in which necessary information are presented in detail. This involves stormwater management, conventional and latest development of permeable roads, StormPav Green Pavement, design criteria, as well as the modelling of stormwater systems;
- Chapter 3: This chapter includes the methodologies used in the current study;
- Chapter 4: This chapter includes the findings obtained from computer modelling. Tables, graphs, as well as appropriate figures are presented and analyzed to investigate the objectives of the study;
- Chapter 5: This chapter includes the conclusions and research outlook for the future.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Progressive movement from agriculture to industrialized economy has shifted the population into urban centers which it has resulted in conversion of pervious areas to impervious areas. The terms impervious area may refer to roads, parking lots and roof tops which prevent rainfall to infiltrate into ground. Activities such as removal of vegetation from land and construction of impervious surface on it result in changing the surface runoff pattern (Goonetilleke et al., 2005), raising surface runoff volume (Arnold & Gibbons, 1996; Al-Hamati et al., 2010; Barbosa et al., 2012), reducing in runoff lag time (ten Veldhuis & Olsen, 2012; Konrad, 2013); and increasing flood return periods (Hirsch et al., 1990; Hollis, 2010; Houston et al., 2011). As shown in Figure 2.1, when rainfall is on impervious surfaces, it causes zero infiltration; forcing all the water that falls onto them to runoff. Rao et al. (1972) found that an increase in the area of imperviousness from 0 to 40 percent would increase its magnitude of runoff by 90 percent and approximately halve the time to peak discharge.

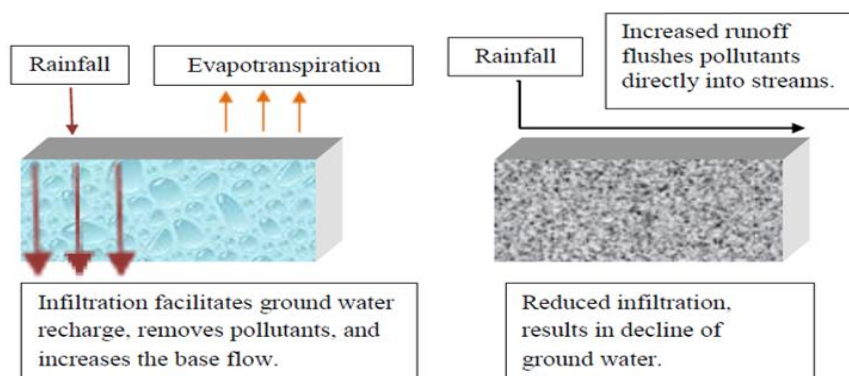


Figure 2.1: Effect of Pervious Surfaces and Impervious Surfaces in Rainfall (Chithra et al., 2015)

Apart from that, according to the Australian Environment, Communications, Information Technology and Arts Legislation Committee (2002), up to 90% of rainfall can be taken up and infiltrated in an undeveloped catchment; while in a developed catchment or built environment, the infiltration can take only as little as 10% of precipitation as shown in Figure 2.2.

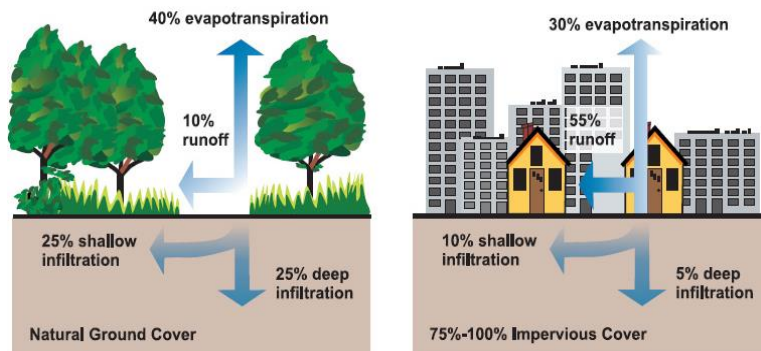


Figure 2.2: Impact of Urbanisation on Infiltration and Runoff (US EPA, 2008)

According to Parkinson and Mark (2005), conventional engineering road is designed in such a way that it is capable to drain runoff as fast as possible from the carriageway in order to minimise damage to the road surface. Consequently, huge amount of runoff is produced and the uncontrolled runoff can result in significant environmental problems. Disaster such as flash flood occurs more frequently when existing road drainage systems are insufficient to cater the increased volume of stormwater (Mah et al., 2016).

2.2 Stormwater Management

Stormwater management is the mechanism to manage stormwater runoff. According to Walesh (1989), urban stormwater management can be defined as everything done within a catchment to remedy existing stormwater problems and to prevent the occurrence of new problems.

Best Management Practices (BMPs) are introduced worldwide to assist authorities for the mentioned purposes. BMPs are basically concepts or design techniques used to control stormwater from the aspects of quantity and quality of runoff to attain zero development impact contribution (Sidek et al., 2004; Zakaria et al., 2004).

BMPs can be divided into structural and non-structural BMPs (Pazwash, 2011). Structural BMPs are corrective measures that improve the quality and control the quantity of stormwater. These include detention/retention basins, vegetated systems, pervious pavements, infiltration trenches and rainwater harvesting (Martin et al., 2007). Non-structural BMPs, on the other hand, are those practice measures that tend to reduce the generation of runoff or pollutants in the runoff. Such BMPs are reducing imperviousness, disconnecting impervious area and avoiding excessive use of lawn chemicals (Pazwash, 2011).

Among the BMPs, permeable road and on-site detention are further discussed in this chapter as these are related in the context of this research.

2.3 Conventional Permeable Road/ Pavement

Conventional roads are impervious and result in generation of runoff. Hence, a permeable road with a combination of permeable pavement and detention storage has served as an alternative road. This approach allows stormwater or runoff to percolate to a subsurface detention system where stormwater is infiltrated to the underlying soil and discharged with lower rate to roadside drain. The depth of stone reservoir depends on the stormwater storage needs and load bearing requirement (Agouridis et al., 2011). The permeable road is a form of structural stormwater BMP designed to control the quantity and quality of stormwater runoff (ASCE, 2015). Permeable road can be regarded as an effective tool in giving a

positive hydrological impact as it has high surface infiltration rates, thus reducing runoff quantity and peak runoff rates and delaying peak flow (Pratt et al., 1989; Hunt et al., 2002; Brattebo & Booth, 2003; Bean et al., 2007a; Kwiatkowski et al., 2007; Collins et al., 2008).

A variety of materials can be used to construct a permeable road. A conventional permeable road's cross section is represented in Figure 2.3. The permeable surfaces or pavements (Figure 2.4) are placed over an aggregate subbase storage layer which serves to detain or retain stormwater and support traffic loads (ASCE, 2015).

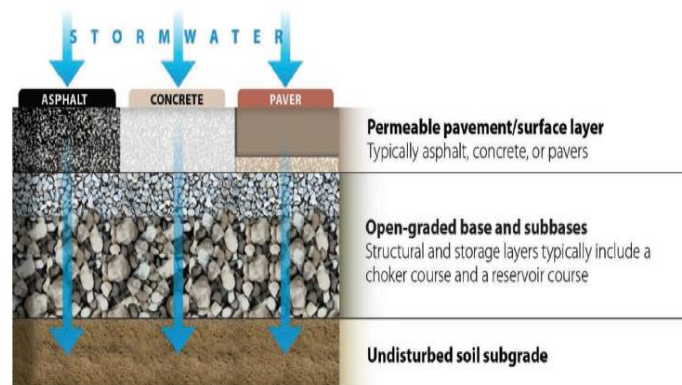


Figure 2.3: Schematics of Conventional Permeable Road Conventional Permeable Road's Cross-Section (ASCE, 2015)



Figure 2.4: Types of Permeable Pavements (Hunt & Collins, 2007)

Different types of permeable pavements have different values of surface permeation. Surface permeation of permeable road works based on the principle of capillary action, where the water seeps through the narrow openings of interconnected voids (Mah et al.,

2018b). According to Ong et al. (2016), the term surface permeation could be defined as “a measure of the water flow through the pore spaces” in the permeable medium. The void content of the pavement type is highly affecting the performance of permeable pavement (Park et al., 2014). However, its application in urban environments has created various maintenance issues (Hill & Beecham, 2018). For example, clogging of permeable pavement has been related to an increased loss of infiltration rate over time (Bean et al., 2007b; Fassman & Blackbourn, 2010; Lucke & Beecham, 2011). Examples of conventional permeable roads are given below.

Q Street Green Alley, Washington, DC, USA

The aim of this project was to convert an existing paved alley in Northwest D.C. into a pedestrian-friendly alley using BMPs such as pervious pavers, porous concrete (in Figure 2.5 and Figure 2.6). The stormwater from the surrounding roads entering the alley was infiltrated through the permeable pavement to reduce volume of stormwater flowing into streams.



Figure 2.5: Design of Q Street Green Alley (District Department of Transportation, 2014)

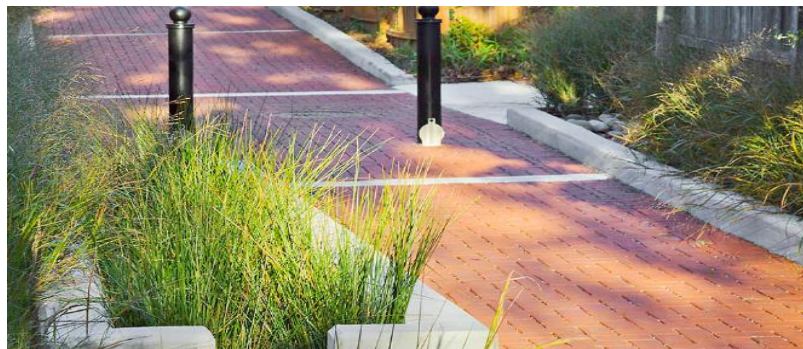


Figure 2.6: Permeable Road of the Q Street Green Alley (Rhodeside & Harwell, n.d.)

Bloomington, Washington, DC, USA

To reduce the likelihood of flooding in the Bloomingdale and LeDroit Park neighbourhoods, District Department of Transportation had implemented green infrastructure (in Figure 2.7 and Figure 2.8). One of them was permeable brick alley. It allowed water to slowly infiltrate into underground storage pipe which then slowly released into the sewer system.



Figure 2.7: Design of the Bloomingdale Project (District Department of Transportation, 2014)



Figure 2.8: Permeable Road of the Bloomingdale Project (District Department of Transportation, 2014)

2.4 Latest Development of Permeable Road

In most applications, conventional permeable pavement manages only the surface over which it covers (Fassman & Blackburn, 2010). Even more so, along with the growing urbanization at a rapid rate, development of permeable road needs to be able to cater for and hold the increasing amount of runoff volume, increasing flood return periods, as well as elevated peak discharge during storm events. Meanwhile, the overall system must also be structurally strong enough to support the load atop it. Precast concrete structures are one of the techniques explored by different countries. A few of the latest development of permeable roads are presented below.

Storrs Center, Village Street, Mansfield, CT, USA

An underground stormwater detention chamber (USDC) called StormTrap was installed under the roadway to mitigate the increase in post-development peak flow rate. StormTrap is a novel technology for the detention and treatment of stormwater runoff (McIntosh, 2015). StormTrap was constructed by precast concrete modules into a configuration that met the project's requirements. StormTrap can be either SingleTrap or DoubleTrap as shown in Figure 2.9 and Figure 2.10. In the case of Storrs Center, DoubleTrap was used due to a tight site condition (see Figure 2.11). The concrete structures were designed to temporarily store stormwater runoff in large underground chambers before being released at a controlled rate. This was a typical example of large storage structure mentioned in the problem statement in Chapter 1.



Figure 2.9: SingleTrap Concept Design (StormTrap, 2018)



Figure 2.10: DoubleTrap Concept Design (StormTrap, 2018)



Figure 2.11: DoubleTrap used in Storrs Center, Village Steet, Mansfield, CT (StormTrap, 2018)

Raymond Elementary School, Washington, USA

A modular underground BMP called StormCapture was used in this project. They were prefabricated concrete components which were easy to install under the paved parking lot. This measure incorporated to hold, filter and discharge clean stormwater. Meaning, StormCapture provided not only volume control with detention, retention and infiltration system but also a treatment approach to address water quality issues. On top of the system structure was covered by earth fill and usually constructed and installed under parking lots as well as roadways as shown in Figure 2.12 and Figure 2.13.

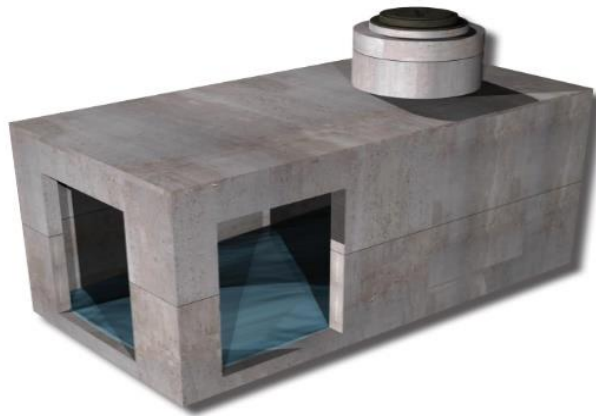


Figure 2.12: Design of StormCapture Module (Old Castle Infrastructure, 2018)



Figure 2.13: Installation of StormCapture Beneath the Carpark (Old Castle Infrastructure, 2018)

Although the above examples are the latest technologies used as to store runoff, one can notice that they are huge concrete structures with chambers. Mobilization and installation of such huge structures require heavy machinery shown in Figure 2.14.



Figure 2.14: Installation of Precast StormTraps (Kenter, 2011)

Yet, author believes that if the structure is divided into smaller hollow compartments, the permeable road would not only carry the same job as water holding, but also could provide a greater strength in interlocking the multiple compartments as an urban road for transportation. According to Mah (2016), dividing a big structure into smaller modular compartments is a wise move as it would allow mass production, easy transportation and assembly. An example can be seen in StormPav Green Pavement in the next section.

2.5 StormPav Green Pavement

StormPav Green Pavement is a patented Industrialized Building System (IBS) product, in which the system employed precast concrete pieces as modular units as shown in Figure 2.15. Three precast concrete pieces (a top cover, a cylinder and a bottom plate) form a single modular unit of StormPav as shown in Figure 2.16. StormPav is originally made for water detention (Mah, 2016). According to Mah et al. (2018b), the single modular unit could withstand crushing load of 100 kN.

Dimension of the modular unit is outlined in Figure 2.17. The surface area of top/bottom plate is 0.1624 m^2 with a service inlet of 0.04 m diameter. StormPav has been

designed to withstand three hours of 10-year Average Recurrence Interval (ARI) design rainfall. It has a hollow cylinder with a height of 0.3 m to act as temporary stormwater storage that can hold water at a capacity of 0.19 m³/m². Besides that, the spaces between each modular also provide detention storage. The surface runoff is permeated through the service inlet as well as the edge gaps of the top plates when assembled together. Meanwhile, the stormwater flows out of the system either by infiltration into native soil through service inlet of bottom plate, edge gaps of the bottom plates when assembled together, evapotranspiration within the system and/or by outflow through an outlet.

Based on a study done by Mah et al. (2018b), the surface permeation rate on StormPav Green Pavement was reported at 18000 to 24000 mm/hr when subjected to 5-minute 10-year ARI design storm. This shows that the StormPav permeable pavement layer via its cover design is effective to drain stormwater that otherwise would have accumulated on the road surfaces.

Apart from that, a pilot study of StormPav road was carried out by Mah et al. (2018c), at Kampung Mang, Samarahan as shown in Figure 2.18. StormPav Green Pavement was assembled on a stretch of 11 m x 4 m rural road over peat soil. This is because, rutting and cracking on the conventional tar roads were observed in Kampung Mang as a result of settlement of drying peat soil. Thus, StormPav permeable pavement was reported to act as a form of floating road that could re-nourish the peat soil from time to time with its stormwater detention ability to alleviate natural peat decay.

Table 2.1 summarizes all the relevant case studies of StormPav Green Pavement according to the research titles and main outcomes of the studies. Author notices that all the past relevant case studies of StormPav have been conducted with its intention to store

stormwater. Yet, based on the field observation by the researchers, the StormPav road not only could store water, but it shows a possibility to transport runoff. This gives confidence to author to work beyond the concept of detention, by further investigating another application of StormPav road to drain water from buildings and roads together. In other words, there is still a lack of information about a combined detention and conveyance functionality of the StormPav Green Pavement.

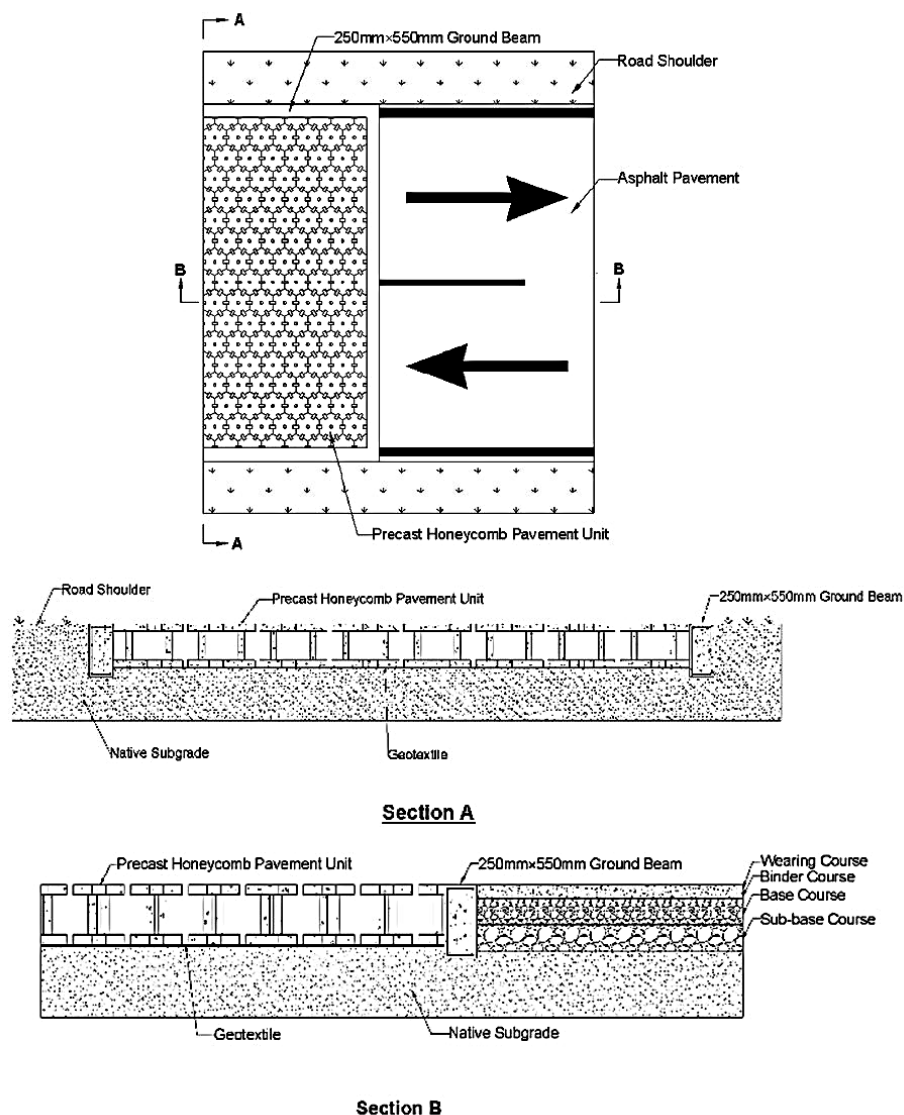


Figure 2.15: StormPav Road (Mah et al., 2018b)



Figure 2.16: Single Modular Unit of StormPav (Mah et al., 2018b)

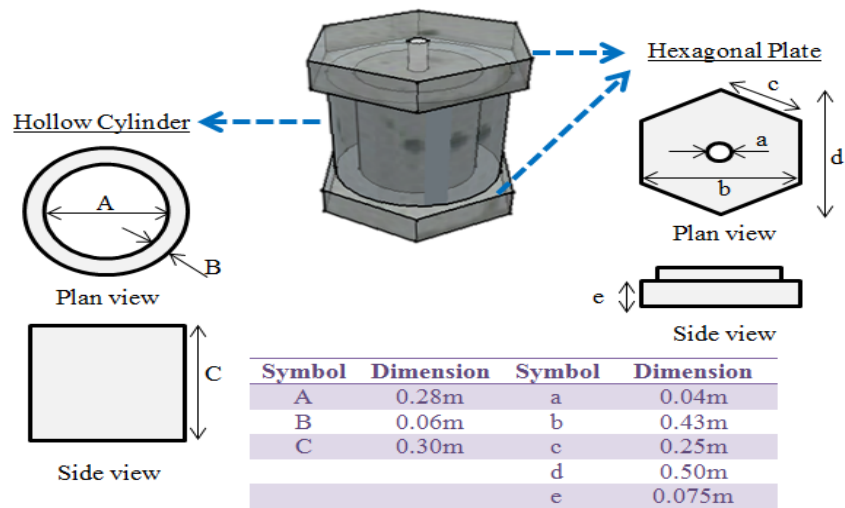


Figure 2.17: Dimensions of StormPav Modular Unit (Mah, 2016)



Figure 2.18: Pilot study of StormPav Green Pavement in Kampung Mang (Mah et al., 2018c)

Table 2.1: Summary of Relevant Case Studies of StormPav Green Pavement

Authors	Research works	Main Outcomes
Mah, 2016	Potential of road subsurface on-site stormwater detention system	Origination of StormPav. Confining to road catchment of 3 m wide and 1.3 m long, on-site detention with a height of 0.3 m provided a volume that enabled it to fully detain 3-hour 10-year ARI design rainfall.
Mah et al., 2018b	Modelling of Surface Permeation in Multiple-orifice permeable road	Both simulation and laboratory work indicated that the StormPav Green Pavement had a permeation rates range from 1800 mm/hr to 2400 mm/hr when subjected to 5-minute 10-year ARI design rainfall.
Mah et al., 2018c	Pilot Study of StormPav Green Pavement System	Reported the construction processes, first hand observations of its stormwater impact and road subsidence on StormPav Green Pavements on peat soil.
Mah et al., 2018a	Augmenting Drainage System in the Old Town of Kuching, Sarawak, Malaysia	This study modelled StormPav Green Pavement along one of the flood-prone backstreets at Padungan area as on-site detention. Result showed that it managed to reduce 30% of peak discharge.

2.6 On-Site Detention (OSD)

In the previous sections (2.3, 2.4 and 2.5), the detention storages within permeable roads are demonstrated to act as On-Site Detentions (OSDs). Storage facilities can be described as any combination or arrangement of detention and retention facilities in a combined sanitary-storm sewer system or a separate stormwater conveyance system (Stahre & Urbonas, 1990).

OSD is first introduced and widely applied in country like Australia as to control the increased stormwater being discharged as a result from urban consolidation projects (O'Loughlin et al., 1995; Phillips, 1995; Scott et al., 1999). OSD becomes an important research topic since the introducing of “Sustainable Cities and Development” and ‘Best Management Practices’ (BMPs) in the mid 1990s and increasing concerns about stormwater quality (Urbanos & Stahre, 1993; Butler & Parkinson, 1997).

OSD as shown in Figure 2.19 can be provided as above ground storages, below-ground storages or a combination of both. The advantages of above and below-ground storages are provided in Table 2.2.

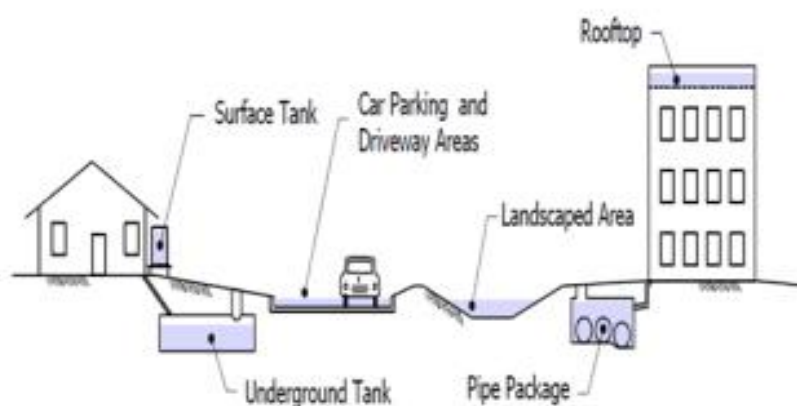


Figure 2.19: Typical OSD (DID, 2000)

Table 2.2: Advantages of Above and Below Ground Storage (DID, 2000)

Types of OSD	Advantages
Above-ground Storage	- Easily incorporated into the site by slight modification to the design of surface features - Relatively inexpensive compared to below ground storages.
Below-ground Storage	- Out of sight - Occupy less physical space - Will not cause any inconvenience with ponding of water.

In the past, centralized large size storage structures were widely applied, such as detention basin (Vorogushyn et al., 2012) and wet ponds (Chang et al., 2013; Ahmad et al., 2014). Yet, problems come when the availability of empty land is getting scarce to obtain especially at the developed areas. Hence, drainage engineers are switching to localized control structures in a distributed manner and below ground storage such as the latest development of permeable roads as discussed early.

Stormwater detention tank systems can be categorized as online or offline according to Singapore Public Utility Board (PUB, 2010). Online storage uses a structural control facility that drains flows directly within a conveyance system, or detention tank via an inlet as depicted in Figure 2.20.

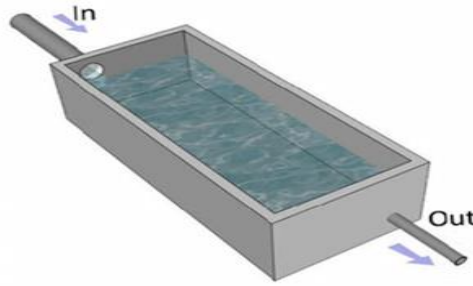


Figure 2.20: Online Detention System (PUB, 2010)

Off-line storage is a separate storage facility to which flow is separated or in parallel to the conveyance system or drain as shown in Figure 2.21. Only excess flow above the level of flow diversion structure such as a side flow weir will drain into the detention tank. Therefore, as compared to online detention system, only a fraction of flow in the drain is conveyed into the detention tank.

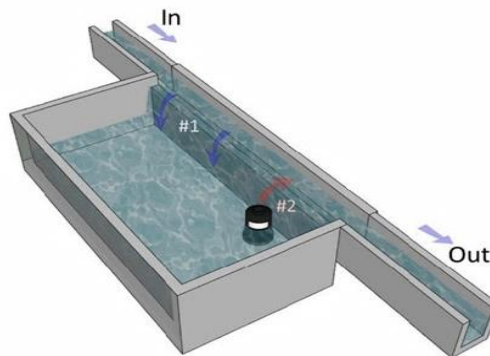


Figure 2.21: Offline Detention System (PUB, 2010)

Generally, the design of offline detention system is more complex due to the sensitivity of the weir levels in relation to the water levels in diversion structure, although its detention volume is smaller compared to online detention system (PUB, 2010). Since they have no moving part or mechanism and remain intact for years (US EPA, 2001), detention storages generally require low maintenance. A condition survey of detention tank was done by National Corrugated Steel Pipe Association (NCSPA, 1999), concluded that the systems

which had been placed for 25 years were well performed and based on observation, the systems would be reasonable to expect to continue in service for a longer period without any repair being necessary.

Apart from that, the Malaysian Department of Irrigation and Drainage (DID) classifies one more facility that is conveyance system. This system provides some extent of detention property, yet, it is an often-neglected form of storage as it is dynamics and requires channel storage routing analysis. Flatter slope and rougher channels can alleviate the build-up of flood peaks and change the time response of the tributaries of a catchment (DID, 2000).

Discharge method of a detention storage can be done either by gravity or through pumping. Discharge of stormwater by gravity makes use of the concept of head difference between the water in the detention tank and the receiving drain. As no complex mechanism involved, this gravity discharge system generally incurs lower operations and maintenance costs compared with pumped discharge system (PUB, 2010). On the other hand, when the concept of head difference is not feasible due to site constraints, pumped discharge system may play a role.

2.7 Urban Storm Water Management Manual for Malaysia

Urban Storm Water Management Manual for Malaysia or better known by Manual Saliran Mesra Alam (MSMA) is introduced and prepared by the Department of Irrigation and Drainage to supersede the old Manual “Planning and Design Procedure No.1: Urban Drainage Design Standard For Peninsular Malaysia, 1975”. This manual provides easy guidance to manage the stormwater instead of draining it away as fast as possible to a more environmentally approach called “control at source” (Zakaria et al., 2004). This approach is indicating any processes which modify the runoff from a given land in which the

modification is close enough to the source of the flow (Sidek et al., 2004). Figure 2.22 shows that the quantity of the runoff from developing area should be maintained to be near pre-development condition.

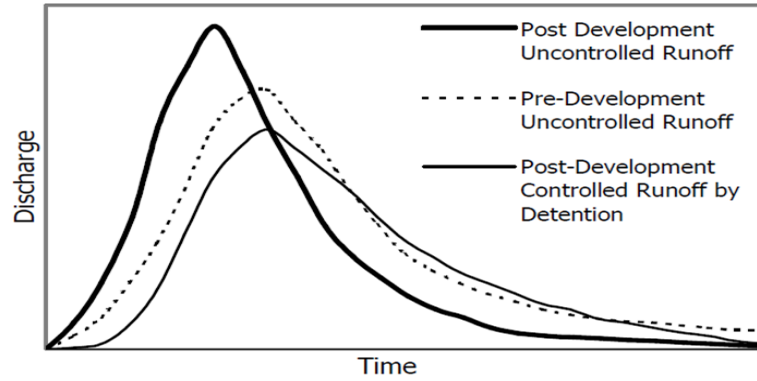


Figure 2.22: Concept of Urban Runoff Control (DID, 2012)

The manual includes various design concepts, criteria and procedures that serve as the basis for developing stormwater management facilities. The design acceptance criteria are mandatory requirements for the planning and design of new and / or upgrading of existing stormwater management system in urban areas (DID, 2012). The criteria are set based on the type of land use, level of protection required, economy, risks of failure, public safety, ecology, aesthetics, etc. One of the more common criteria used in the facility design is the ARI, which is set based on the whole life economy of a facility, the level of protection required and the hazard potentials to the downstream areas.

2.8 Design Criteria

According to MSMA, the storage for OSD should be made of durable material to withstand any deterioration by corrosion or aggressive soil conditions. Expected variable and permanent loads on the storage shall be able to withstand by it. This includes the buoyancy, particularly for lightweight tanks, to make sure that the storage tank is not be lifted up under high groundwater condition. Besides that, it is recommended that the floor

slope of the storage shall not be larger than 10% nor less than 2% in order to permit easy access to all parts of the storage for maintenance and to enable good drainage within the storage.

Design Rainfall

In order to prepare satisfactory drainage and stormwater management projects, design rainfall data is a necessity (DID, 2000). ARI and storm duration are important parameters in this context. ARI is the average length of period between events that have the same magnitude or volume and duration. It may also be referred as the return period. The ARI of design rainfall for urban stormwater systems may refer to MSMA 2, Chapter 1, on Table 1.1 which taking into account of minor and major systems.

The duration of design rainfall may refer to time of concentration on small urban catchment (Bezak et al., 2018). Generally, time of concentration, t_c is the sum of overland flow time, (t_o) and street gutter, drains, or roadside swales flow time, (t_g) and small stream (t_d). In this context, the storm duration equals to t_o represented in Equation 2.1:

$$t_o = \frac{107 \cdot n^* \cdot L^{1/3}}{S^{1/5}} \quad \text{Equation 2.1}$$

where

t_o = Overland sheet flow travel time (minutes);

L = Overland sheet flow path length (m);

n^* = Horton's roughness value for surface;

S = Slope of overland surface (%).

This equation shall only be applied when the length of sheet flow complied as follows:

- For steep slope (>10%), $L \leq 50$ m;
- For moderate slope (<5%), $L \leq 100$ m;
- For mild slope (<1%), $L \leq 200$ m.

Minimum time of concentration for a catchment recommended by MSMA is 5 minutes. Yet, practically, the adoption of design rainfall duration depends on an engineer's judgment based on the catchment size and flow path.

Design rainfall depth, P_d for a given short storm duration and ARI can be determined from Equation 2.2. The short storm duration limit to duration less than 30 minutes. This Equation 2.2 shall only be applied for any ARI within the range of 2 to 100 years:

$$P_d = P_{30} - F_D(P_{60} - P_{30}) \quad \text{Equation 2.2}$$

where

P_{30} , P_{60} are the 30-minute and 60-minute duration rainfall depths respectively which can be obtained through Equation 2.3;

F_D is the adjustment factor for storm duration.

$$\ln (^R I_t) = a + b \ln (t) + c (\ln (t))^2 + d (\ln (t))^3 \quad \text{Equation 2.3}$$

where

$(^R I_t)$ = the average rainfall intensity (mm/hr) for given duration and ARI;

R = average return interval (years);

t = duration (mins);

a, b, c and d are fitting constants dependent on ARI.

Note that the output parameter calculated from Equation 2.3 is in terms of rainfall intensity (mm/hr), not rainfall depth (mm). Their relationship is as shown in Equation 2.4

$$I = \frac{P_d}{d} \quad \text{Equation 2.4}$$

where

I = average rainfall intensity (mm/hr);

P_d = the rainfall depth (mm);

d = the duration (hr).

Meanwhile rainfall intensity of the given ARI and storm duration can be found from using Equation 2.4 with the P_d obtained from Equation 2.2.

Peak Discharge Estimation

Rational Method in Equation 2.5 can be used to estimate peak discharge generated by the design rainfall. This equation is applicable for catchment area less than 80 ha (TxDOT, 2009).

$$Q = \frac{C.I.A}{360} \quad \text{Equation 2.5}$$

where

Q = Peak discharge (m³/s);

C = Runoff coefficient, taking as 1 for imperviousness from road or roof;

I = rainfall intensity (mm/hr);

A = catchment area (ha).

According to MSMA, there are assumptions used in the Rational Method as follows:

- Entire of the catchment area is contributing to the discharge;
- Rainfall intensity is assumed to be uniform over the entire catchment area;
- Time duration equal to the time of concentration.

Apart from Rational Method, another equation which is based on nonlinear reservoir representation can also be used to calculate the surface runoff. Overland flow is generated by treating the sub-catchment as a non-linear reservoir as shown in Figure 2.23.

In this representation, each sub-catchment experiences inflow from rainfall and the runoff from upstream sub-catchment and the losses from infiltration, evaporation and surface runoff. The “reservoir” capacity is the maximum depression storage. Maximum depression storage accounts for initial rainfall abstractions such as interception, ponding and surface wetting. Overland flow takes place when the depth of water, d overreaches the maximum depression storage, d_p and this can be expressed by Manning equation (Equation 2.6).

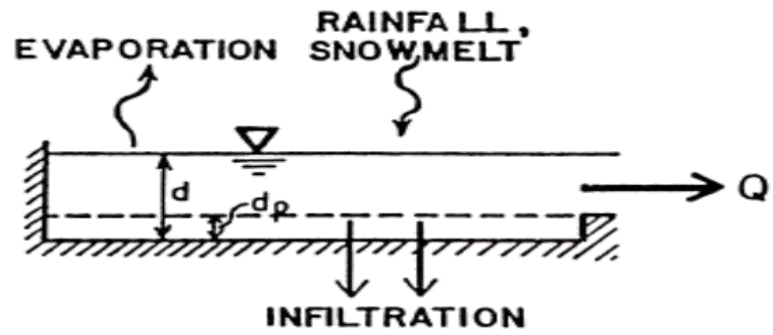


Figure 2.23: Non-linear Reservoir Model for A Sub-catchment
(Huber & Dickinson, 1988)

$$Q = W \frac{1}{n} (d - d_p)^{5/3} S^{1/2} \quad \text{Equation 2.6}$$

where

Q = Discharge (m^3/s);

W = Sub-catchment characteristics width (m);

S = Slope of the catchment (m/m);

n = Manning roughness value;

d = Depth of water in the reservoir (m);

d_p = Maximum depression storage (m).

Detention Volume

According to PUB (2010), for online gravity stormwater detention storage, the shaded area between the outflow and inflow hydrographs is used to represent the storage

volume required for a particular storm event as shown in Figure 2.24. Mathematically, the storage volume can be expressed in Equation 2.7.

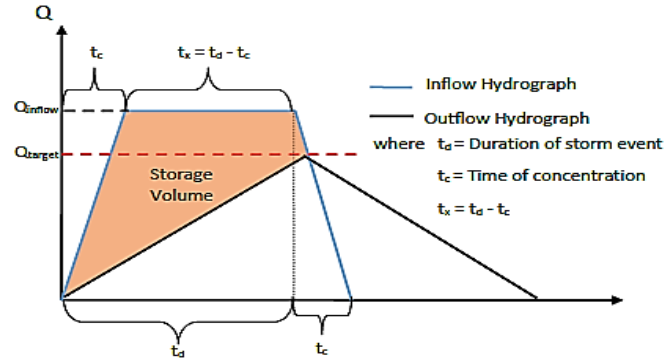


Figure 2.24: Typical of Inflow and Outflow Hydrographs for Online Gravity Stormwater Detention Storage (PUB, 2010)

$$\text{Storage volume, } V_t[m^3] = Q_{inflow}(t_c + t_x) - \frac{1}{2} Q_{target}(2t_c + t_x) \quad \text{Equation 2.7}$$

where

$$Q_{inflow} = \frac{1}{360} C_{post} \left(\frac{8913}{t_d + 36} \right) A;$$

$$Q_{target} = \frac{1}{360} C_{target} \left(\frac{8913}{t_c + 36} \right) A;$$

Q_{inflow} = Inflow rate, (m³/s);

Q_{target} = Target peak discharge rate, m³/s);

C_{post} = Post development runoff coefficient;

C_{target} = Target runoff coefficient;

A = Catchment area, (m²).

Orifice Discharge System

Detention of stormwater is provided by a storage volume that is then released by an outlet structure. This outlet structure is also known as flow regulating structure or device. It is the flow regulating device that determines how efficiently the storage volume is being used. Orifice is one of the examples of flow regulating devices, which is not only used to control the release rate, but also determines the maximum storage depth and volume at the detention site (see Figure 2.25). By knowing the orifice size, the discharge rate by it can be determined by Equation 2.8. In order to apply the Equation 2.8, free flow discharge orifice conditions should be created, hence, the downstream pipe or sump would need to satisfy this condition.



Figure 2.25: Orifice Discharge System (PUB, 2010)

$$Q_o = C_o A_o \sqrt{2gH_o} \quad \text{Equation 2.8}$$

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 m/s^2);

H_0 = Maximum head to the centre of the orifice (m).

2.9 Drainage Modelling using SWMM

Models are generally an accepted tool used for studies of quantity and quality problems associated with urban runoff. Whenever measured data are not feasible, models allow estimates to be made at locations. There are four broad objectives of models: screening, planning, design and operation (Huber & Dickinson, 1988).

Screening models provide a very first estimate of the degree of urban runoff's quantity and quality problem before committing more time and resources into more multiplex computer-based models. Planning models are applied for assessing the urban runoff problem and also for estimating the effectiveness and cost of abatement procedures. Design models, in short, provide for simulating storm events which they come out with descriptions of the flow and pollutant. Operational models are oriented toward producing the actual control decisions during storm events.

The Storm Water Management Model (SWMM) by the United State Environmental Protection Agency (EPA) is a dynamic rainfall-runoff model that is widely used for single event or long-term simulation of runoff quantity and quality from mainly urban study (Rossman, 2009). This model can effectively simulate hydrology, hydraulics and water quality using a series of sub-catchments that takes rainfall to generate the runoff or pollutant (Hsu et al., 2000; Rossman, 2015; Cunha et al., 2016). SWMM was first developed in 1971 and has gone through several major upgrades since then.

In SWMM model, a given catchment can be developed as a set of physical objects including rainfall gauge, sub-catchments, conduits, junctions, outfalls as depicted in Figure 2.26. Rainfall gauge represents the rainfall events. Sub-catchments are hydrological modelling of lands that intercept the rainfall. The surface runoff can infiltrate into the unsaturated soil zone. Three different models of infiltration available in SWMM are Green-Ampt infiltration, Horton infiltration and Curve Number infiltration. The node represents a junction of hydraulic elements where stormwater flows into it. Node junction can model or represent a storage unit such as lake or pond and also a point of change in conduit or channel geometry, a boundary condition in the model, a sewage treatment plant in the transport layer or a watershed in the runoff layer (Rossman, 2015). Links are conduits, pipes or channels that move water from node to node. It also represents pump, weir and orifice flow regulator. To close the hydraulic elements, the stormwater leaves the system in an Outfall.

Figure 2.26: Conceptual of Example Drainage Modelling (Rossman, 2015)

SWMM is a physically based, discrete-time simulation model. It employs principles of conservation of mass, momentum and energy wherever appropriate. The conceptual view of surface runoff used by SWMM as illustrated in Figure 2.23; each subcatchment surface is treated as a nonlinear reservoir. Inflow comes from precipitation and any designated upstream subcatchments. There are several outflows, including infiltration, evaporation, and surface runoff.

In the process of hydraulic simulation, flow routing within a conduit link in SWMM is described by the one-dimensional Saint-Venant equations. Choice on the level of sophistication used to solve these equations as follows,

- Steady flow routing → this routing represents the simplest type of routing possible by assuming that within each computational time step flow is uniform and steady. Thus, it simply translates inflow hydrographs at the upstream end of the conduit to the downstream end, with no delay. This type of routing cannot account for channel storage, backwater effects, entrance/exit losses, flow reversal or pressurized flow.
- Kinematic wave routing → this routing solves the continuity equation along with a simplified form of the momentum equation in each conduit. This routing allows flow and area to vary both spatially and temporally within a conduit, thus, can result in attenuated and delayed outflow hydrographs. However, this form of routing cannot account for backwater effects, entrance/exit losses, flow reversal, or pressurized flow. It can usually maintain numerical stability with moderately large time steps, on the order of 1 to 5 minutes.
- Dynamic wave routing → this routing solves the complete one-dimensional Saint Venant flow equations, and therefore produces the most theoretically accurate results. Dynamic wave routing can account for channel storage, backwater, entrance/exit losses, flow reversal and pressurized flow. This generality comes at a price of having to use much smaller time steps on the order of a thirty seconds or less

Example of SWMM modelling of a permeable road is demonstrated through the case study below.

Easy Street in Ann Arbor, Michigan, US (Dierks, 2009)

This project was carried out in the City of Ann Arbor, Michigan. About 3 ft to 3.5 ft of the outer edges of existing asphalt on Easy Street were replaced with porous pavers. SWMM was used to simulate the existing and proposed conditions. Two Easy Street subwatersheds involved: 1) Buhr Park and 2) Easy Street, labeled with letter B and E respectively as shown in Figure 2.27.

Runoff from the Buhr Park sub-basin was directly contributing to the Easy Street storm sewer. Each street subwatershed was connected to the storm sewer via a bottom orifice. The obtained results shown that based on the 100-year rainfall recorded by the University of Michigan, for 95% of the events happened in Ann Arbor (less than 27 mm in 24 hours), the peak flows and runoff volumes can be lower down to 93% and 86% respectively.

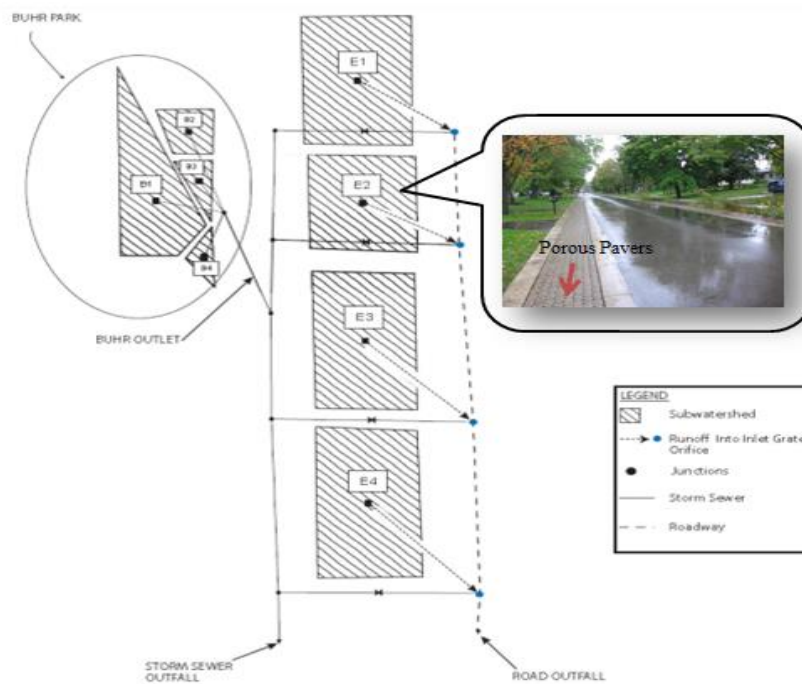


Figure 2.27: SWMM Model Schematic of Easy Street (Dierks, 2009)

2.10 3-D Flow Modelling using SolidWorks

In order to appreciate the relationship between the variables of a system, engineers often anticipate the system behavior. By understanding the behavior of a system, it allows engineers to come up with a better design of systems and optimizing their operations. Generally, method of flow prediction can be obtained by either one of the three approaches by means of experiment, analytics or Computational Fluid Dynamics (CFD) (Arokiasamy, 2017).

By applying the first method (experimental approach), engineers are able to apprehend the system directly or construct mathematical models that represent their systems. This method would provide the most reliable information about the physical phenomena as it involves direct measurements. For instance, full-scale equipment in this approach can be applied to predict how the equipment would operate or behave under different conditions.

Unfortunately, such full-scale tests are, in most situations like this current research, are either difficult to collect data, expensive or impossible to carry out. The alternative is to carry out experiments on small-scale model. Yet, the resulting information must be extrapolated to the full-scale equipment. One should know that, all the features of the full-scale equipment do not usually be simulated in small-scale model. Moreover, none of the measuring instruments are free from errors. Therefore, the usefulness of the test results is reduced and sometimes limited.

Another approach known as analytical approach which requires to construct a mathematical model based on the understanding of the basic physical phenomena that governs its behavior (Sayma, 2009). For physical processes, differential equations are usually mathematically computed. In practice, numerous assumptions and simplifications are involved to allow for the differential equations to be solved. If too many assumptions and simplifications are made, it limits the validity of the outcomes. This approach helps in understanding interpreting experiment results and also verifies the first stage of CFD models.

The third approach is CFD. Due to the advancement of numerical approach and its application in computer technology, complex mathematical models can be solved quickly. The fundamental concept of this approach is to find the values of the flow quantities at a large number of points in the system. These points are usually connected to each other which known as numerical grid or mesh. A series or set of differential equations governing the system concerned could be converted to algebraic equations at discrete points. A digital computer is usually required to solve the outcome of algebraic equations. Therefore, many engineering applications could be solved providing a more complete set of information. As

such, this approach is by popular demand replacing experimental and analytical approach (Sayma, 2009). Generally, the processes of CFD can be illustrated in Figure 2.28.

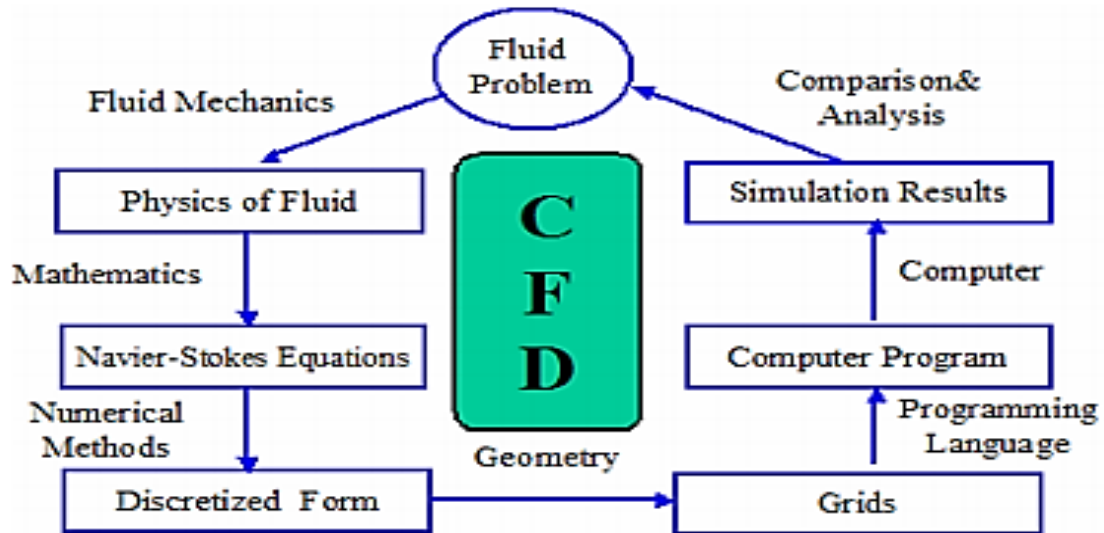


Figure 2.28: Processes of CFD (Arokiasamy, 2017)

All fluid flows are governed by three basic principles (Anderson, 1992; Hjertager, 2001; Veerstedt & Malalasekera, 2007), namely:

- i. Conservation of Mass, in which the mass of fluid is conserved;
- ii. Newton's Second Law, in which the rate of change of momentum equals to the forces on a fluid particle;
- iii. Conservation of Energy also known as First Law of Thermodynamics, in which the rate of change of energy equals to the rate of head addition to and rate of work done on a fluid particle.

Conservation of Mass

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \vec{V} = 0 \quad \text{Equation 2.9}$$

Where

ρ = density of fluid element

t = time

$\nabla \cdot \vec{V}$ = divergence of velocity

$\frac{D}{Dt}$ = substantial derivative in the of rate

The first term on the left is the rate of change of the density following a moving fluid element and the second term is the net flow of mass out of the element across its boundaries.

Newton's Second Law

X-component of the momentum equation:

$$\rho \frac{Du}{Dt} = \frac{\partial(-\rho + \tau_{xx})}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \quad \text{Equation 2.10}$$

Y-component of the momentum equation:

$$\rho \frac{Dv}{Dt} = \frac{\partial(-\rho + \tau_{yy})}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{zy}}{\partial z} + \rho f_y \quad \text{Equation 2.11}$$

Z-component of the momentum equation:

$$\rho \frac{Dw}{Dt} = \frac{\partial(-\rho + \tau_{zz})}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \rho f_z \quad \text{Equation 2.12}$$

Where

ρ = density of fluid element

t = time

u, v, w = velocity components in x-, y-, and z- direction in a fluid respectively

$\tau_{xx}, \tau_{yy}, \tau_{zz}$ = normal stress in x-, y-, and z- direction in a fluid respectively

τ_{yx}, τ_{zx} = shear stress in x- direction on y- and z- plane respectively

τ_{xy}, τ_{zy} = shear stress in y- direction on x- and z- plane respectively

τ_{xz}, τ_{yz} = shear stress in z- direction on x- and y- plane respectively

f_x, f_y, f_z = body force per unit mass acting on the fluid element in x-, y-, and z- component respectively

$\frac{D}{Dt}$ = substantial derivative in the of rate

$\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}$ = local derivative in x-, y- and z- component respectively

The first term on the left represents the rates of increase of x-, y- and z- momentum per unit volume of a fluid particle; the rate of change of mentioned parameters following a moving fluid element, the first three terms on the right are the surface forces (pressure and viscous forces) acted on the fluid particles; the rate of change of the mentioned parameters at a fixed point, the last term on the right is the overall effect of body forces acted on the fluid particles.

Conservation of Energy

$$\begin{aligned}
 & \underline{\underline{\rho \frac{D}{Dt} \left(e + \frac{V^2}{2} \right) =}} \\
 & \begin{array}{l} \downarrow \\ \boxed{\text{I}} \end{array} \quad \underline{\underline{\rho \dot{q} + \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) - \frac{\partial(u\rho)}{\partial x} - \frac{\partial(v\rho)}{\partial y} - \frac{\partial(w\rho)}{\partial z}}} \\
 & \quad \begin{array}{l} \swarrow \\ \boxed{\text{II}} \end{array} \quad + \left\{ \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{yx})}{\partial y} + \frac{\partial(u\tau_{zx})}{\partial z} \right\} + \left\{ \frac{\partial(v\tau_{xy})}{\partial x} + \frac{\partial(v\tau_{yy})}{\partial y} + \frac{\partial(v\tau_{zy})}{\partial z} \right\} \\
 & \quad \quad \begin{array}{l} \swarrow \\ \boxed{\text{III}} \end{array} \quad + \left\{ \frac{\partial(w\tau_{xz})}{\partial x} + \frac{\partial(w\tau_{yz})}{\partial y} + \frac{\partial(w\tau_{zz})}{\partial z} \right\} + \rho \vec{f} \cdot \vec{V}
 \end{aligned}
 \tag{Equation 2.13}$$

Where

e = internal energy per unit mass

$\frac{V^2}{2}$ = kinetic energy per unit mass

$\dot{q}$ = rate of volumetric heat addition per unit mass

T = local temperature

k = thermal conductivity

The first term (I) denotes the rate of change of energy inside the fluid element. The total energy of a moving fluid per unit mass is the sum of its internal energy per unit mass and its kinetic energy per unit mass. The second term (II) denotes the net flux of heat into the element. The third term (III) denotes the rate of working done on the element due to body and surface forces.

Flow simulation solves the Navier-Stokes equations, which are formulation of the above three principles. They are a set of differential equations that describe the behaviors of

a fluid. One should understand that Navier-Stokes equations are used only when Newtonian fluid dynamics is concerned. On the other hand, if a turbulence model is involved, Favre-averaged Navier-Stokes equations are used, where time-averaged effects of the flow turbulence on the flow parameters are considered.

In this study, SolidWorks Flow Simulation is utilized to enhance the confidence level of SWMM model verification. Model verification can be defined as measure to ensure the simulation of the computerized model represents the conceptual model within specified limits of accuracy (Schlesinger et al., 1979; Sargent, 2013). Apart from that, SolidWorks Flow Simulation would be an effective software tool to give the flow visualization. Flow visualization enables us to visually obtain qualitatively and quantitatively flow information. It gives a user a better understanding, as the flow patterns of the study are visible. Among a number of ways to visualize flow pattern, flow trajectories can be created on the flow simulation tool to indicate the direction of flow flowing. It allows users to display as flow streamlines as shown in Figure 2.29. Flow streamline is a curve, at any point of which the flow velocity vector is tangent to that curve.

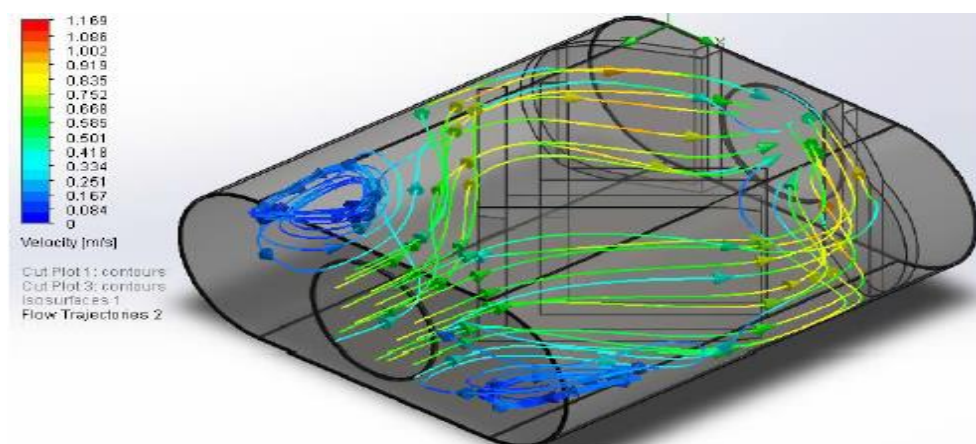


Figure 2.29: Flow Trajectories in Term of Velocity of the Muffler (Priyadarsini et al., 2016)

Example of SolidWorks Flow Simulation modelling applied for StormPav Green Pavement are reported by the two case studies below.

Flow Characteristics of Individual lot Stormwater Detention (Ngu et al., 2016)

A research on individual lot on-site storm water detention underneath residential car porch was done by the research team. In this research, the modular units (StormPav) were used to detain runoff from the roof top with in-built or attached pipe that can direct the rainfall to the storage.

The flow characteristics of stormwater were analyzed upon entering an individual StormPav unit beneath a residential car porch. CFD was done (see Figure 2.31) to do comparison with full-scale model. Results showed that turbulent concentrated near the inlet of the tank and decreased rapidly as getting further from the inlet. In other words, the design of StormPav unit was a wise move considering that flow congestion did not happened. Therefore, the use of StormPav units as the storage beneath the car porch was practical for managing stormwater from roof.

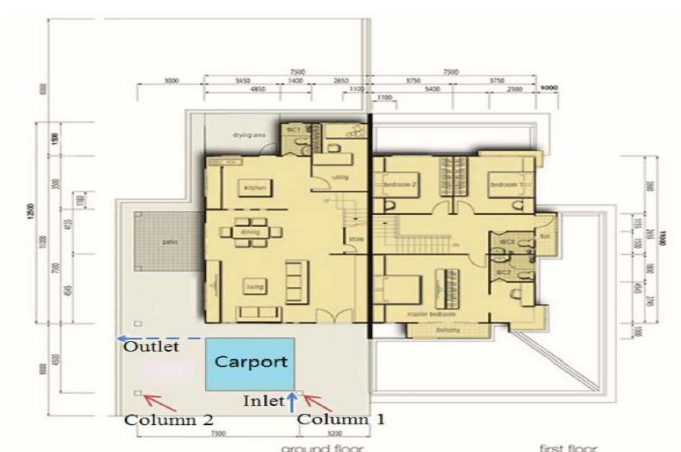


Figure 2.30: Residential Car Porch Used as the Detention Storage (Ngu et al., 2016)

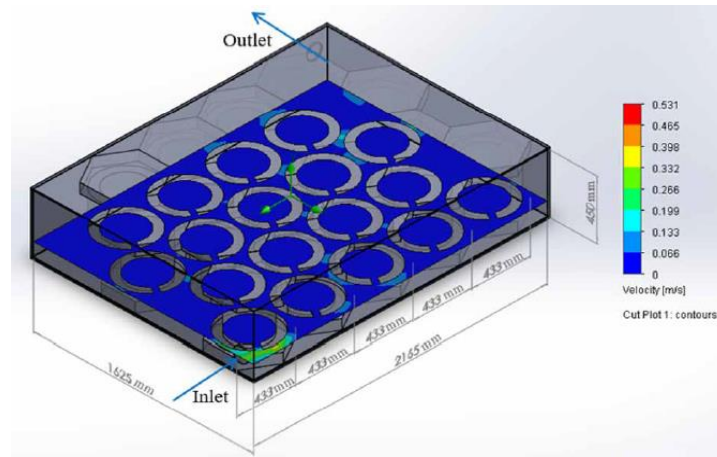


Figure 2.31: Velocity Contour in the Individual Lot Stormwater Detention – Result from CFD Simulation.(Ngu et al., 2016)

Modeling of Surface Permeation in Multiple Orifice Permeable Road (Mah et al., 2018b)

In this study, water draining capability of the StormPav Green Pavement's service inlets was determined. Experimental and CFD approaches were applied to investigate the service inlets of the permeable road. The model of the StormPav system is as shown in Figure 2.32. 15-minute 10-year ARI design rainfall was used in the modelling effort.

The computed flows corresponding with the mentioned time periods were 0.02 ℓ/s , 0.3 ℓ/s and 0.2 ℓ/s respectively as shown in Figure 2.33. The flows through the service inlets in the simulation were consistent in each time period. The results showed that 0.1 ℓ/s , 0.2 ℓ/s and 0.3 ℓ/s gave a permeation rate of 9,000 mm/hr, 12,960 mm/hr and 24,120 mm/hr respectively. Experimental works were used to verify the outcomes of the simulations. Both the approaches showed the StormPav Green Pavement was able to alleviate forming of ponding and flash flood on the roads.

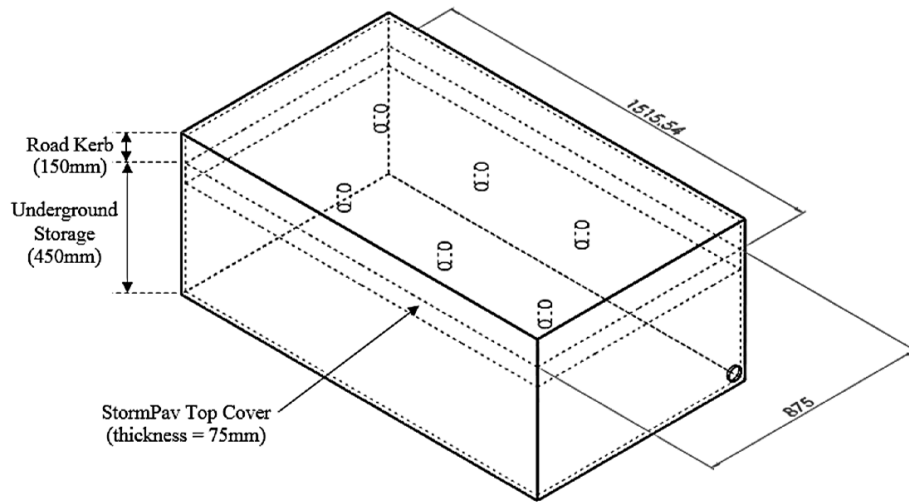


Figure 2.32: CFD Model of StormPav Permeable Road (Mah et al., 2018b)

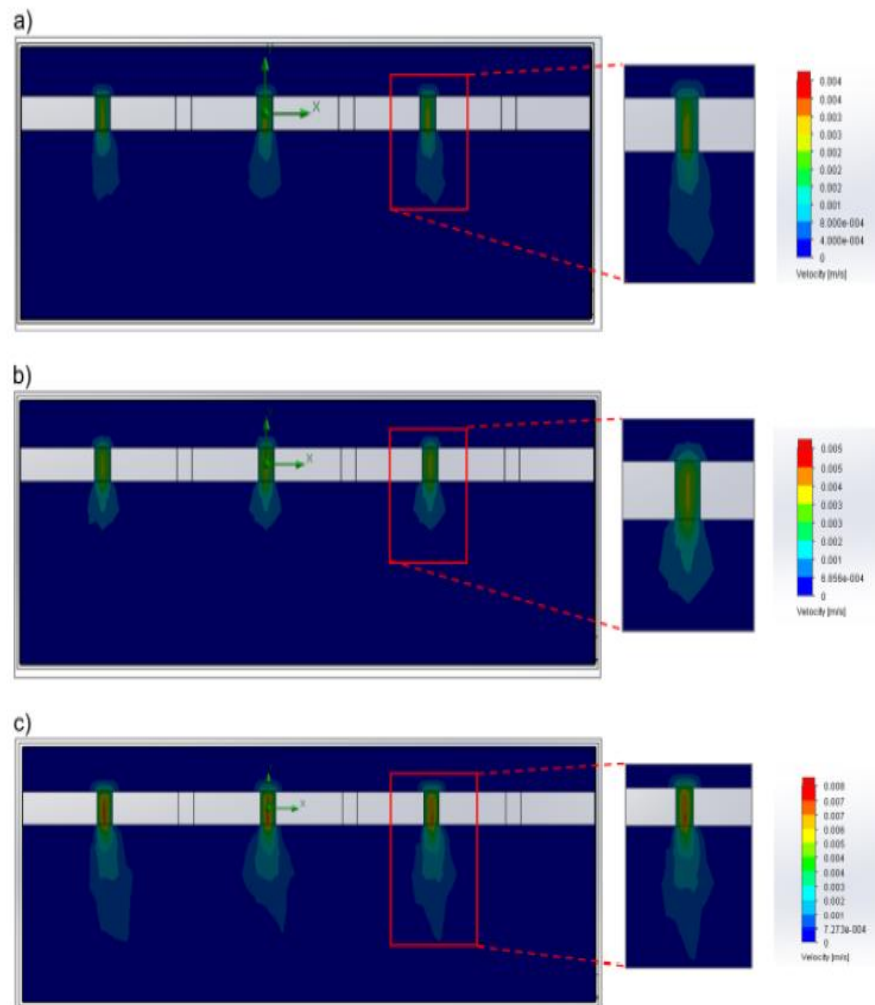


Figure 2.33: Velocity Profile Through Service Inlet for Flows a) 0.1 ℓ/s , b) 0.2 ℓ/s and c) 0.3 ℓ/s (Mah et al., 2018b)

2.11 Summary of Techniques

Table 2.3 summarises the techniques used and the remarks for previous studies which are related to current study.

Table 2.3: Summary of Techniques in Previous Studies

Authors	Method	Remarks
Dierks, 2009	Used LID Control Method in SWMM to simulate the conventional permeable road	This design method is limited to capture surface runoff and provide some combination of detention, infiltration and evapotranspiration to it” (Rossman, 2015)
Mah, 2016	Used Storage Unit Method in SWMM to investigate the detention property of StormPav	The developed SWMM was an initial model to guide the first prototype.
Mah et al., 2018a	Used Storage Unit Method in SWMM to investigate the effectiveness of StormPav along the backstreet of Pandungan area, Kuching, Sarawak.	Take the effective volume by considering the solid volume of the StormPav System.
Ngu et al., 2016; Mah et al., 2018b	Used Storage Unit Method in SWMM and SolidWorks Flow Simulation to investigate the flow characteristics.	Flow data computed from SWMM were fed to SolidWorks Flow Simulation to investigate the objectives of studies. Beside that, it allowed flow visualization.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter discusses the manner of the current study to determine the flow capability of stormwater detention under urban road for conveyance and storage. This study generally is divided into three main stages as outlined in Figure 3.1 which involve hydrology and hydraulic modelling. The first stage involves the hydrology acted upon the StormPav Green Pavement which takes into account the catchment area covered by the StormPav Green Pavement, design rainfalls, amount of surface runoffs generated as well as the storage volume provided by the StormPav. The investigations of the road structure for conveyance and storage are being carried out in second stage, which incorporates the use of Stormwater Management Model (SWMM). Three scenarios are constructed. First scenario is for pre-development, the second for conventional drainage system and the third for inclusion of StormPav Green Pavement. The use of SolidWorks Flow Simulation fits as a tool to visualize the flow within the StormPav Green Pavement and to verify the outcomes from SWMM. With the verified SWMM model, one shall come out with an appropriate inlet and outlet sizes for the StormPav road, runoff hydrographs and percentage of runoff reduction.

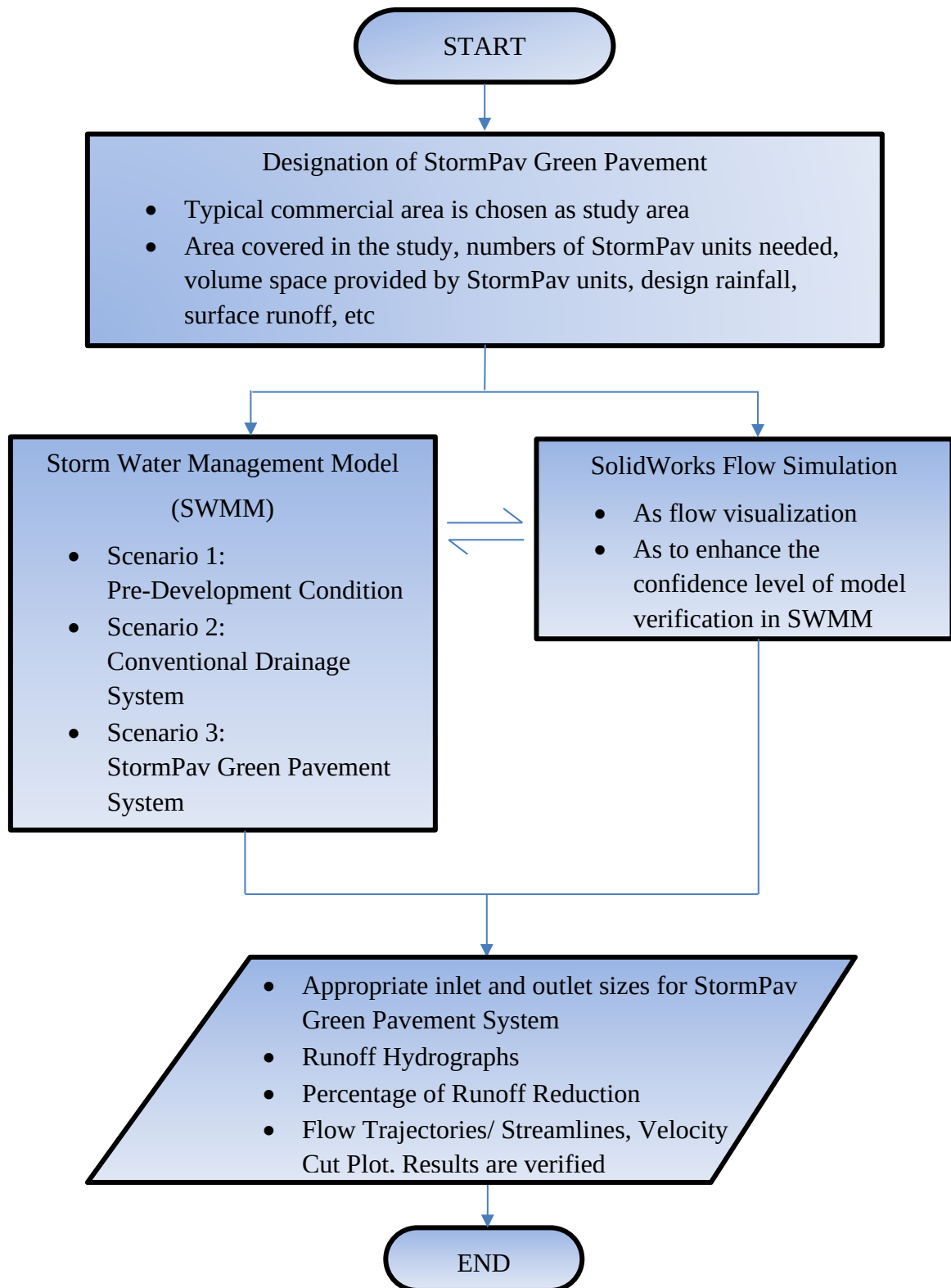


Figure 3.1: Flow of Study Approaches

3.2 Case Study

This study is using a case study as it provides realistic situations to investigate the capability of permeable road to transport water with a minimal cost. Commercial area is selected in the current study because typically, it has a wide road area and the author would like to innovate the usage of existing road; in hoping to integrate the road transportation and road runoff drainage as one structure. A typical commercial area is depicted in Figure 3.2. Two rows of buildings opposite each other and the front street are modelled as a disconnected system, meaning it is independent of the whole commercial area. Disconnected system is focused as to demonstrate the hydrology and hydraulic characteristics from a small urban system. It takes up 3990 m² (0.399 ha) of surface area and divided into catchments as depicted in Figure 3.3 and Table 3.1. As a common feature, shophouses consist of front and back lane drains. Each of the drain is directed to flow to a main drain just beside the main road as in Figure 3.3.



Figure 3.2: Typical Outlook of Commercial Area

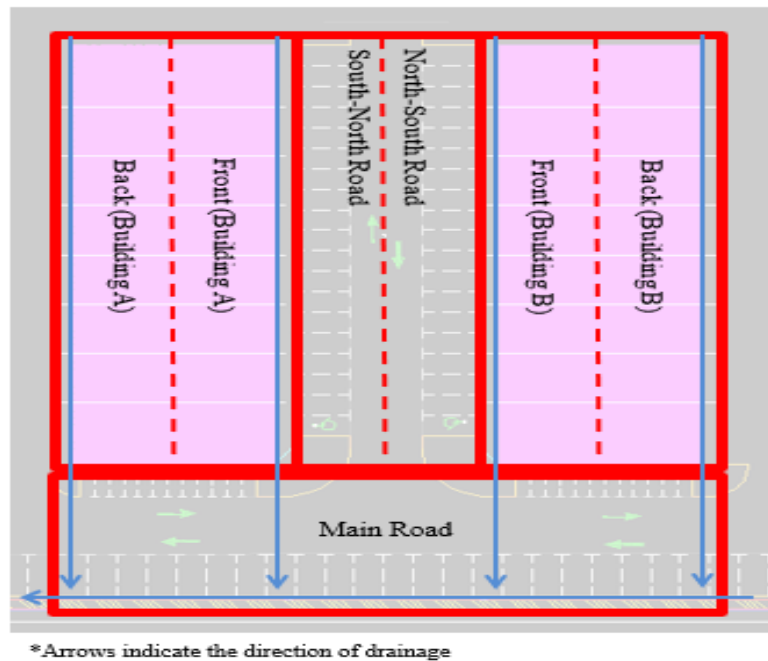


Figure 3.3: Study Area Divided into Sub-Catchments

Table 3.1: Measurement of Study Area

	Building A or B		Roads		
	Front	Back	South-North	North-South	Main Road
Width (m)	10	10	8.5*	8.5*	16*
Length (m)	6 (Intermediate)		54		57
	9 (Corner)				
Area (m²)	1080		918		912

* Inclusive of the carriageway and parking space

3.3 Proposed Incorporation of StormPav Green Pavement

This research is attempting to combine road and stormwater as one structure by manipulating the nature of modularity in Industrial-based Building System (IBS). The mentioned IBS is referring to StormPav Green Pavement (Figure 3.4).

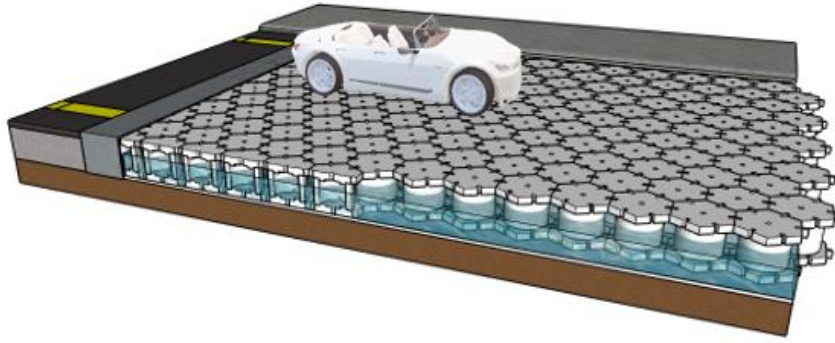


Figure 3.4: StormPav Green Pavement

The road between the two rows of shophouses in the study area, inclusive of its front drains are replaced with StormPav Green Pavement. The back-lane drain is excluded in the modelling, but it could be remained for wastewater disposal particularly for food outlets. The StormPav Green Pavement is designed such a way that is placed in between two rows of premises to provide an optimum surface area for the StormPav as depicted in Figure 3.5. The area of StormPav Green Pavement covered is 918 m². Construction of the latest development of permeable roads (as discussed in Section 2.4) in such a big area which covers $\approx 1000 \text{ m}^2$ is definitely involving heavy machinery, high cost, transport issue and safety issue especially if these are not dealt with properly. Multi-unit IBS StormPav could be the solution to overcome the problem without compromising the function to reduce runoff discharge that could be provided by the permeable road. Figure 3.6 shows the dimensions of a StormPav modular unit. This study area shall have 5584 full units and 46 half units of StormPav.

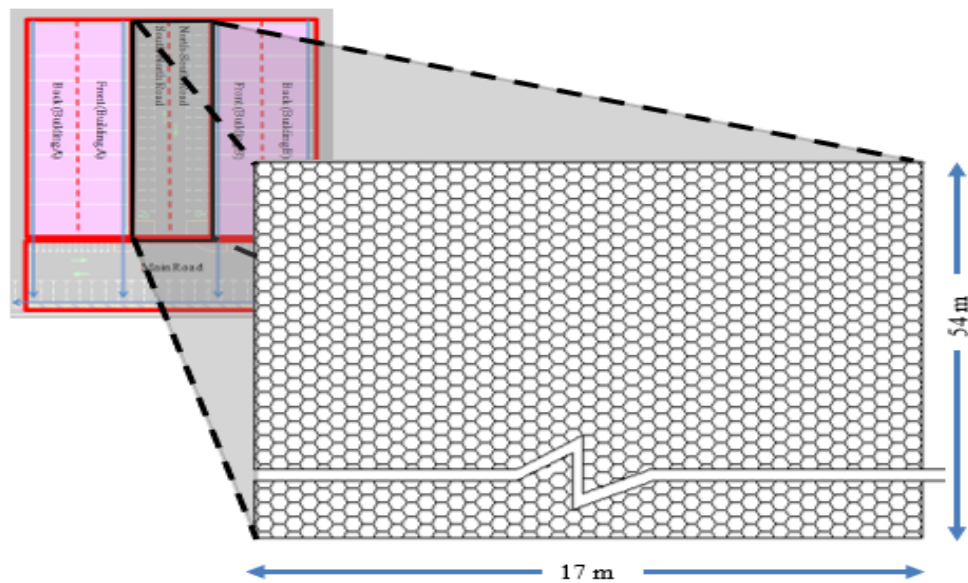


Figure 3.5: Placement of StormPav Green Pavement

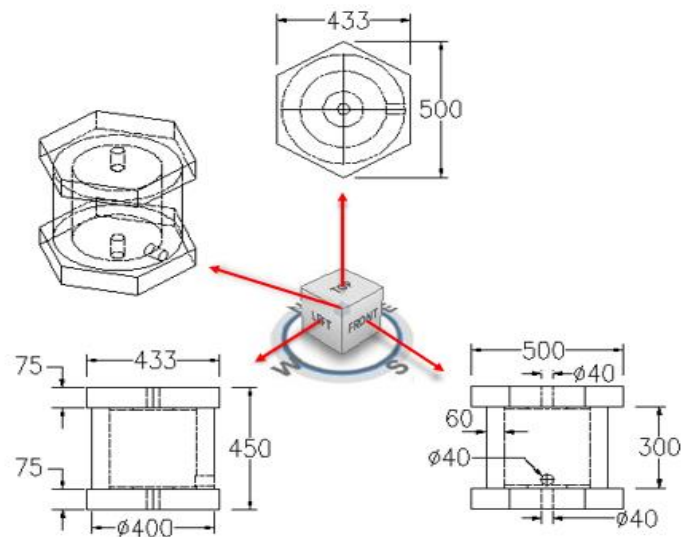


Figure 3.6: Single Modular Unit of StormPav

The concept of utilizing StormPav in a commercial area is depicted in Figure 3.7. The rectangular boxes are representing shophouses. Each box is depicted with two downpipes which are the conduits to drain stormwater from building roof to the StormPav road. These downpipes function as the inlet to the StormPav System. An outlet is to drain stormwater to a nearby waterway.

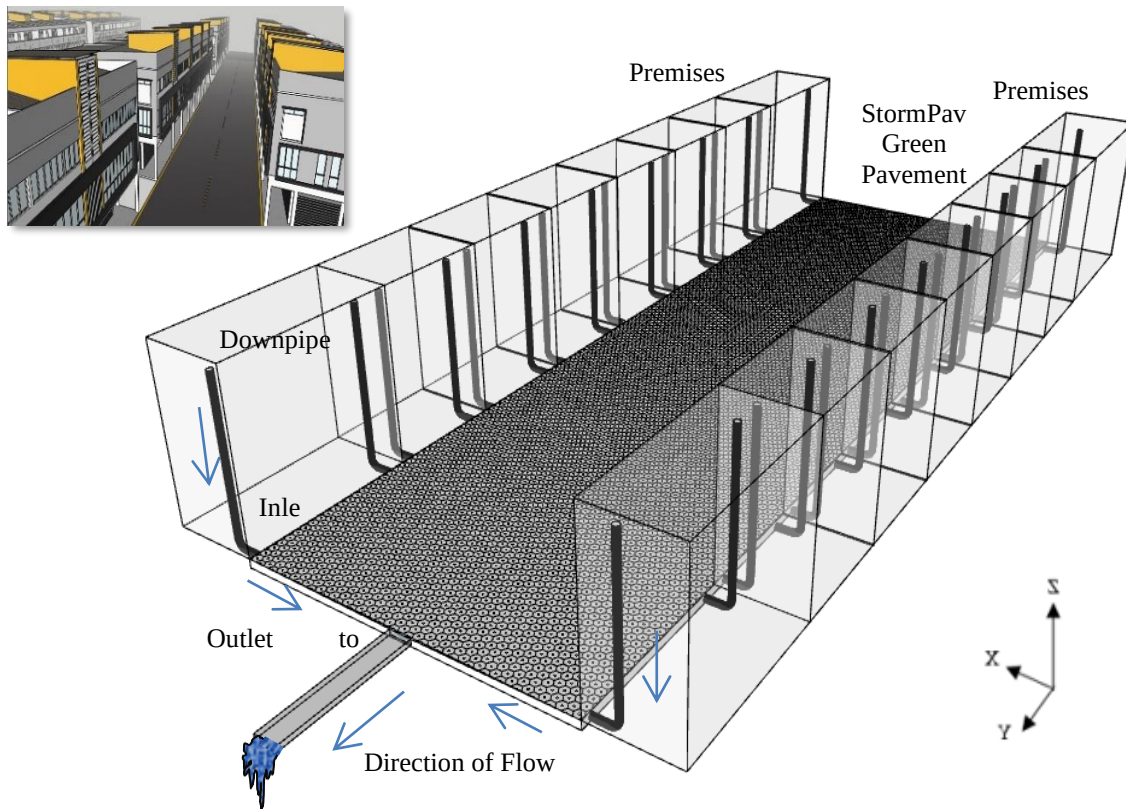


Figure 3.7: Conceptual Design of StormPav Green Pavement in Commercial Area

Referring to the Plan View (Figure 3.8), StormPav Green Pavement is encased with Concrete Beam at four sides and Utility Chambers are constructed along the two sides adjacent to the premises. Stormwaters from premises are drained to StormPav via inlets, stored within the StormPav system and discharged via an outlet at the right-end of the drawing. Surface runoff from the pavement itself is filled into StormPav Green Pavement through the holes provided on the top plates of StormPav.

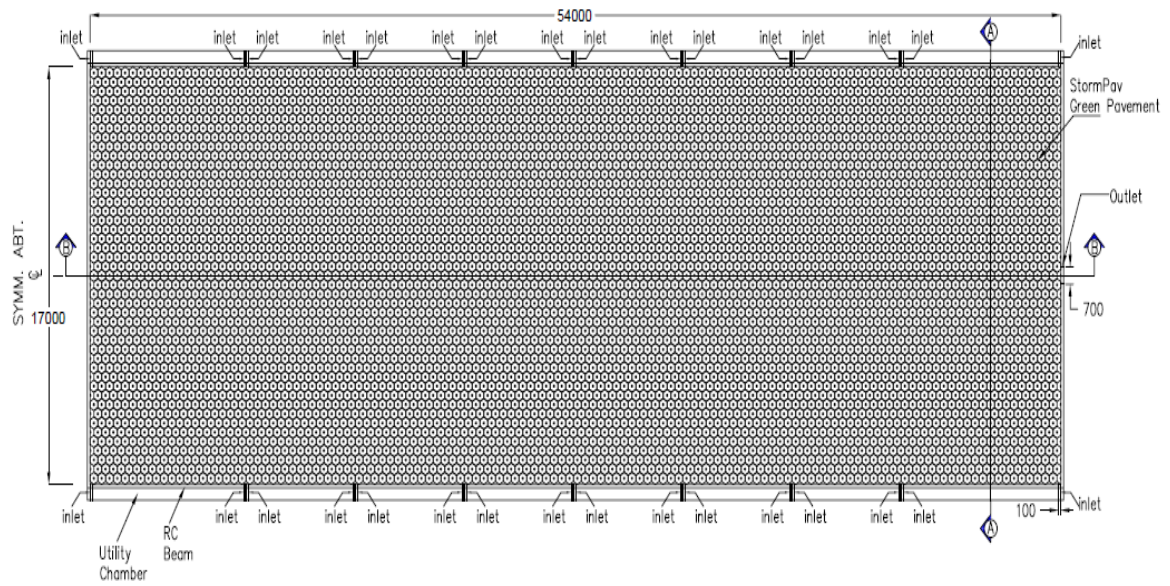


Figure 3.8: Plan View of StormPav Green Pavement Layout Design

Section A-A View (Figure 3.9) shows the detailed design of the inlet to receive water from premises. Downpipes from a premise are channelled through a Utility Chamber, then a Concrete Beam before entering the StormPav system. The whole line of drainage from premise to StormPav is a closed system.

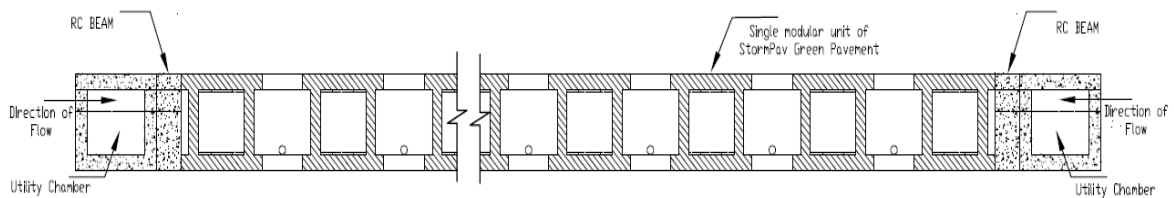


Figure 3.9: Section A-A View of StormPav Green Pavement Layout Design

Section B-B View (Figure 3.10) is the cross section of the StormPav system at its horizontal centre line. It shows the detailed design of its outlet specially tailored to cater for the volume of stormwater resulted from 3-hour 10-year ARI design rainfall from the premises and road surfaces.

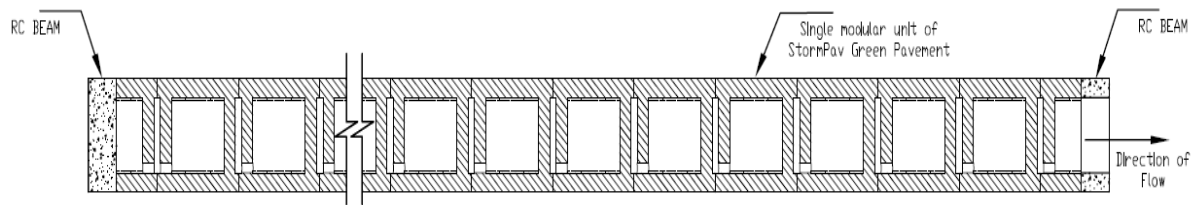


Figure 3.10: Section B-B View of StormPav Green Pavement Layout Design

3.4 Design Rainfall

Under the recommendation of MSMA 2 (DID, 2012), a minor system for commercial area should relate to 10-year ARI design rainfall. In the case of design rainfall duration, different storm durations based on 10-year ARI are incorporated as shown in Table 3.2. Referring to another source of observed rain classification, DID Sarawak has stated that intensities of 60 mm/hr and above as “Very Heavy” Storm (see Table 3.3). Compared to design rainfall data, rainfall intensities listed in Table 3.2 are all “Very Heavy” events. The upper limit shows that 180-minute design rainfall has an intensity of 59.5 mm/hr, a close proximity to the DID’s “Very Heavy” classification. But, the 180-minute design rainfall has the largest rainfall depth of 178.4 mm than other rainfall durations. The lower limit of 5-minute design rainfall has the largest intensity of 210 mm/hr but the smallest rainfall depth of 17.5 mm.

Due to the catchment area of the study area (0.399 ha) is less than 80 ha, rainfall duration of 5 minutes of overland flow are taken as shortest duration for runoff to leave the catchment. PUB (2010), mentioned that 5-minute rainfall duration is recommended for site area of 0.2 to 2 ha. On the other hand, rainfall duration of 180 minutes is taken benchmarked to the “Very Heavy” classification (Mah, 2016). The ranges of 5 to 180 minutes are

considered here, and it believes these ranges could best test the responses of StormPav system for conveyance and storage purposes.

Table 3.2: Rainfall Intensities of Different Design Rainfall Duration Under 10-year ARI

Durations (mins)	Intensities (mm/hr)	Depth (mm)
5	210.0	17.5
10	180.8	30.1
15	161.2	40.3
20	148.2	49.4
30	132.5	66.2
60	101.3	101.3
120	73.4	146.8
180	59.5	178.4

Table 3.3: Categorization of Observed Rainfall Intensity
(<https://ihydro.sarawak.gov.my/iHydro/en/datatable/rainfall/hourly-rainfall.jsp>)

Category	Light	Moderate	Heavy	Very Heavy
Rainfall intensity (mm/hr)	0.5 – 10	11 – 30	31 – 60	>60

3.5 Storm Water Management Model (SWMM)

Computer model is incorporated in this study as it assists researchers to quantify the results, including the possibility of tracking the changes with time in a given design rainfall duration. The intended StormPav road is first modelled using Stormwater Management Model (SWMM). The software as discussed in Chapter 2 is best known and widely applied for modelling of urban water cycle (Jang et al., 2007; Elliott & Trowsdale, 2007; Lee et al.,

2013). SWMM is also able to view the results in the form of statistical reports, tables, profile plots and the most important, graphs in time series plots.

3.5.1 Representation of StormPav Green Pavement

To include close to 5,600 of StormPav units in modelling is arduous. Even more so, SWMM could not represent every single unit chambers of StormPav Green Pavement, thus, a question arises: how to model such StormPav Green Pavement?

The author resorts to take void spaces among the StormPav units as a rectangular tank after the solid spaces of concrete blocks are deducted. The rectangular tank is similar with a rectangular conduit. The input effective dimensions are listed in Table 3.4. For verification of the StormPav Green Pavement model in SWMM, velocities within the system are determined and compared with SolidWorks Flow Simulation that are discussed in Section 3.6.

Table 3.4: Design Calculation for StormPav Green Pavement

Design calculations	
Area covered by StormPav	= 918 m ²
Height of each unit of StormPav	= 0.45 m
Volume of StormPav Green Pavement	= 918 x 0.45 = 413 m ³
Solid volume of each unit of StormPav	= 0.043 m ³
Number of StormPav modular units needed	= 5584 + (46/2) = 5607 units
Total solid volume of the modular units	= 5607 x 0.043 = 241.1 m ³
Effective volume	= 413 – 241.1 = 171.9 m ³

Table 3.4 continued

Effective depth, d	$= (171.9/918) = 0.187 \text{ m}$ $\approx 0.19 \text{ m}$
Effective width, w	$= 17 \text{ m}$
(Full span width of the road)	(Carriageways + parking lots)

The model is depicted in Figure 3.11. The StormPav Green Pavement System is modelled as a replacement of the drains at the front and back of the buildings. In this case, rainfall is intercepted by the surfaces on roof and road. Runoffs generated by the roof catchments are directed to storage structure under the road through downpipes which is modelled as orifice. Runoff generated on the pavement surfaces is allowed to permeate to storage under its permeable pavement layer. Flows out of the storage are controlled by an orifice outlet. In such situation, runoffs are expected to be detained within the StormPav Green Pavement before being released through the orifice outlet. Infiltration and evapotranspiration are excluded in this study, so as to focus solely on the stormwater storage and conveyance purposes. In terms of construction, the orifice could be connected to culvert cutting across the main road to be discharged to the main drain. The cross sections of conduits used are showed in Table 3.5. Nodes J1 to J9 are StormPav Green Pavement. Nodes J9-J12 are the culverts that passing water from StormPav Green Pavement to the main drain. J11-J12-J13-Out1 are the main drain.

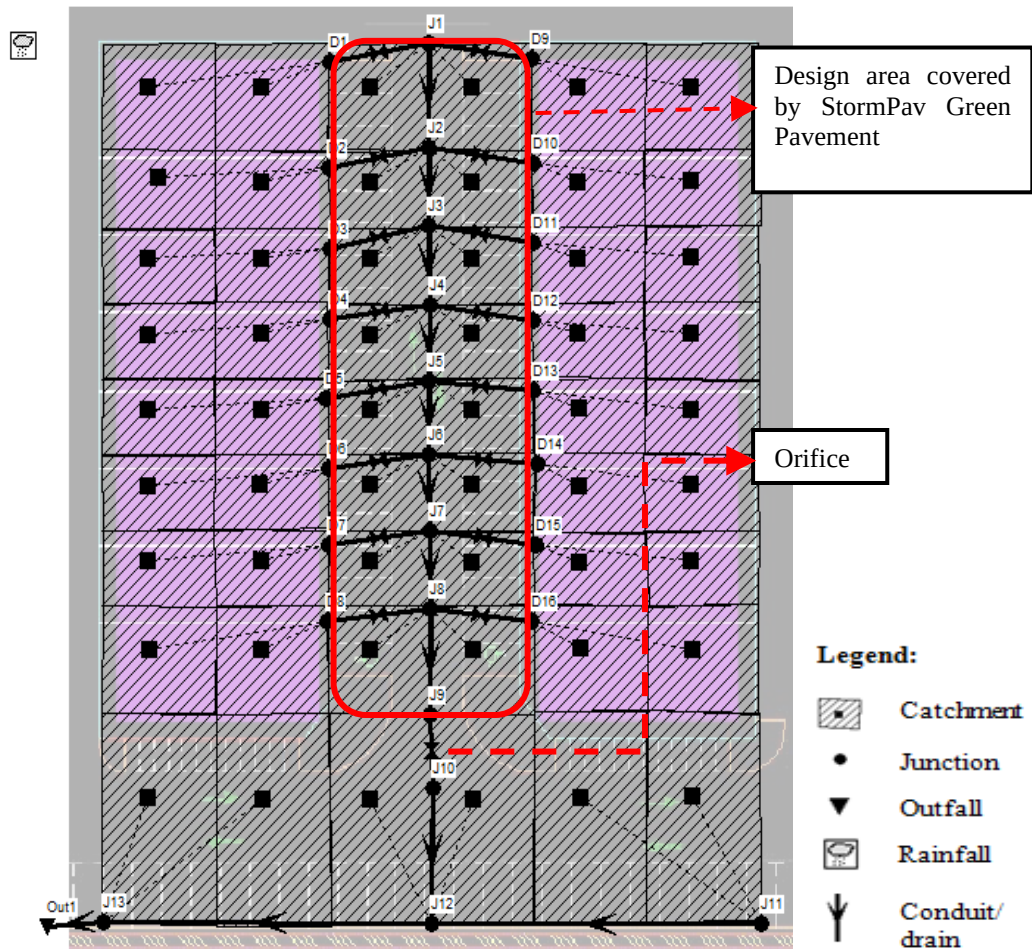


Figure 3.11: SWMM Model of StormPav Green Pavement

Table 3.5: Dimensions of Cross Section for Conduits

Junctions	Dimensions	
	H (m)	W (m)
J1 to J9	0.19	17.0
J9 - J12	0.19	0.70
J11 - J12 - J13 -Out1	1.00	1.00

3.5.1.1 Surface Runoff

As discussed in Section 2.8, both the Equation 2.5 and Equation 2.6 which describe the Rational Method and Nonlinear Reservoir Representation (SWMM) provide the runoff values over a catchment. Thus, the modelled results are cross-checked with analytical calculations to ensure the parameters applied in SWMM are apt. A comparison between the runoff values from the hand calculation using Rational Method and that of values computed by SWMM as presented in Table 3.6. Besides that, the computed runoff coefficient, C values from SWMM are found to be matched with the analytical calculations for each scenario.

Table 3.6: Cross-checking of Surface Runoff for Post-Development

Storm duration (mins)	Land use	Computational step $Q = CIA/360$ (m ³ /s)	Q SWMM (m ³ /s)	Re- mark Q	C SWMM	Re- mark C
5	Road	$1*210*0.183/360 = 0.1068$	0.1068	Match	1.039	Match
	Premise	$1*210*0.216/360 = 0.1260$	0.1260	Match	1.039	Match
10	Road	$1*180.8*0.183/360 = 0.0919$	0.0919	Match	1.022	Match
	Premise	$1*180.8*0.216/360 = 0.1085$	0.1085	Match	1.022	Match
15	Road	$1*161.2*0.183/360 = 0.0819$	0.0819	Match	1.016	Match
	Premise	$1*161.2*0.216/360 = 0.0967$	0.0967	Match	1.016	Match
20	Road	$1*148.2*0.183/360 = 0.0754$	0.0754	Match	1.013	Match
	Premise	$1*148.2*0.216/360 = 0.0889$	0.0889	Match	1.013	Match
30	Road	$1*132.5*0.183/360 = 0.0674$	0.0674	Match	1.009	Match
	Premise	$1*132.5*0.216/360 = 0.0795$	0.0795	Match	1.009	Match
60	Road	$1*101.3*0.183/360 = 0.0515$	0.0515	Match	1.005	Match
	Premise	$1*101.3*0.216/360 = 0.0608$	0.0608	Match	1.005	Match

Table 3.6 continued

120	Road	$1*73.4*0.183/360 = 0.0373$	0.0373	Match	1.003	Match
	Premise	$1*73.4*0.216/360 = 0.0440$	0.0440	Match	1.003	Match
180	Road	$1*59.5*0.183/360 = 0.0302$	0.0302	Match	1.002	Match
	Premise	$1*59.5*0.216/360 = 0.0357$	0.0357	Match	1.002	Match

3.5.1.2 Volume Filling the System

A cross-check is also done by comparing the modelled volume of water filling the system with the analytical calculated volume of generated runoff from the contributing catchments. Table 3.7 deduces that the model output volumes meet the references volume.

Table 3.7: Cross-check of Water Volume Filling the System

Storm duration (mins)	V = Q*t Reference volume (m ³)	SWMM Volume (m ³)	Storm duration (mins)	V = Q*t Reference volume (m ³)	SWMM Volume (m ³)
5	$0.17965*300$ = 53.865	53.870	30	$0.1133*1800$ = 203.918	203.938
10	$0.15456*600$ = 92.735	92.744	60	$0.0866*3600$ = 311.771	311.802
15	$0.13781*900$ = 124.028	124.040	120	$0.06275*7200$ = 451.789	451.836
20	$0.12674*1200$ = 152.088	152.102	180	$0.05087*10800$ = 549.423	549.245

3.5.2 Storage Volume Inlet and Outlet

Inlet and outlet of the system are key elements to allow filling, ponding and draining effects. Stormwater inlets are provided to collect and allow surface runoff from the catchment/s to the system and leaving from the system through an outlet. On the other hand, manipulating the outlet could allow the captured stormwater to flow. This filling and draining effect could reduce the size of the storage structure, meanwhile, allowing runoff to flow from one end to another.

The investigated inlet sizes of the StormPav Green Pavement follow the varying sizes of circular pipes generally used as downpipe connecting the roof of shophouse to the StormPav system. These sizes are chosen based on the diameters of manufactured HDPE pipe available in the market that normally used for downpipe. Whilst, outlet sizes follow the varying sizes of culverts connecting the StormPav system to the main drain. The culverts could be circular or rectangular underground channels. The storage volume inlet StormPav Green Pavement from downpipe is investigated as no congestion (surcharge) just before entering the StormPav Green Pavement system. Same case goes to the opening size of the outlet orifice so that there is no occurrence of flooding or overflowing from the StormPav Green Pavement. Note that, the analysis of size of service inlet on top plate is not focused on this study as the hole size has been determined in Mah et al. (2018b).

3.5.3 MSMA Requirements

MSMA calls for post development peak hydrographs of a development shall be lower or near to the pre-development peak hydrographs. Thus, peak discharges at the outfall of the disconnected system for different scenarios are determined and compared. Three scenarios are simulated in this study. The scenarios are: S1, the pre-development scenario; S2, a

traditional urban development scenario; and S3, an urban development with StormPav Green Pavement.

Modelling of scenario 1 is depicted in Figure 3.12. Taking the pre-development condition of the commercial area as an open space with fully grass cover. Conceptually, rainfall is intercepted by the grass cover, thus this forming the catchment areas to generate surface runoff. Under recommendation of MSMA 2, the runoff coefficient, C for fully grass cover shall be taken as 0.4. The catchments are represented as the diagonal-filled polygons. Generated runoff leaves the system at an exit point or outfall represented by a black triangle as shown in Figure 3.12. The model is cross-checked as shown in Table 3.8.

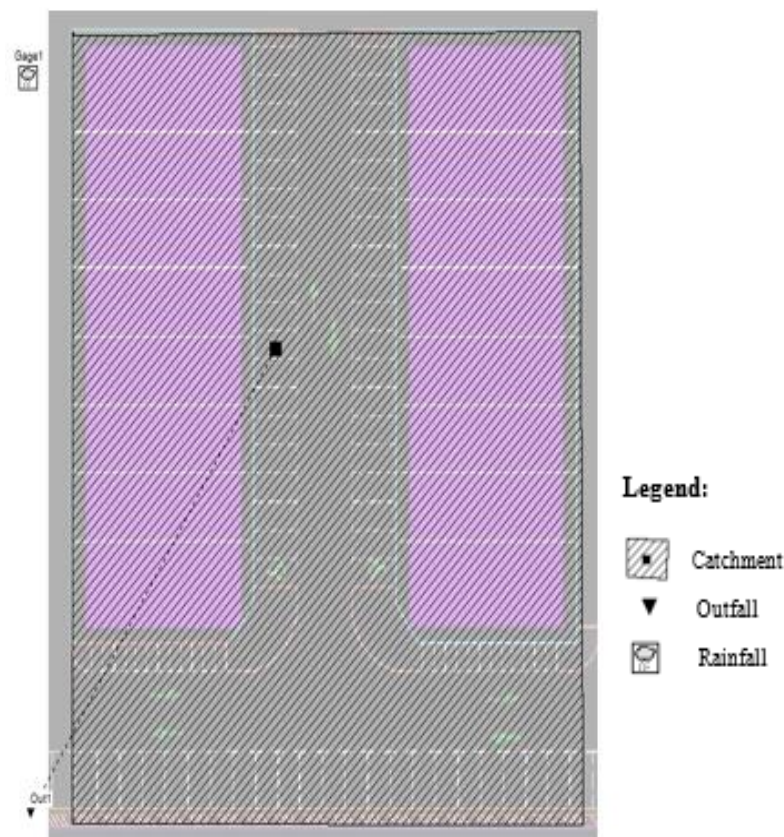


Figure 3.12: SWMM Modeling of Scenario 1

Table 3.8: Cross-checking of Surface Runoff for Pre-Development

Storm duration (mins)	Land use	C	I (mm/h)	A (ha)	Q Rational method (m ³ /s)	Q SWMM (m ³ /s)	Re-mark Q	C SWMM	Re-mark C
5	Grass cover	0.4	210	0.4	0.0931	0.0931	Match	0.405	Match
10			180.8	0.4	0.0801	0.0802	Match	0.405	Match
15			161.2	0.4	0.0715	0.0715	Match	0.405	Match
20			148.2	0.4	0.0657	0.0657	Match	0.405	Match
30			132.5	0.4	0.0587	0.0588	Match	0.405	Match
60			101.3	0.4	0.0449	0.0449	Match	0.405	Match
120			73.4	0.4	0.0325	0.0325	Match	0.388	Match
180			59.5	0.4	0.0264	0.0264	Match	0.394	Match

Modelling of scenario 2 is depicted in Figure 3.13. This scenario models the conventional drainage, in which the drains are designed surround the buildings. In this case, rainfall is intercepted by the surfaces on roof and road. Thus, these form the catchment areas to generate surface runoff. The C in this scenario is taken as 1 both roof and road catchments are impervious surfaces. Generated runoffs are directed to the drains represented by nodes (black dots) and links (black lines) and the flow direction of the drainage system is indicated by the arrows. The dimensions of the drains at the front and back of the buildings are taken as 0.5 m x 0.5 m while drain beside the main road as 1.0 m x 1.0 m according to the recommendations of MSMA 2. Runoffs flow along these drains and leave the system at an outfall.

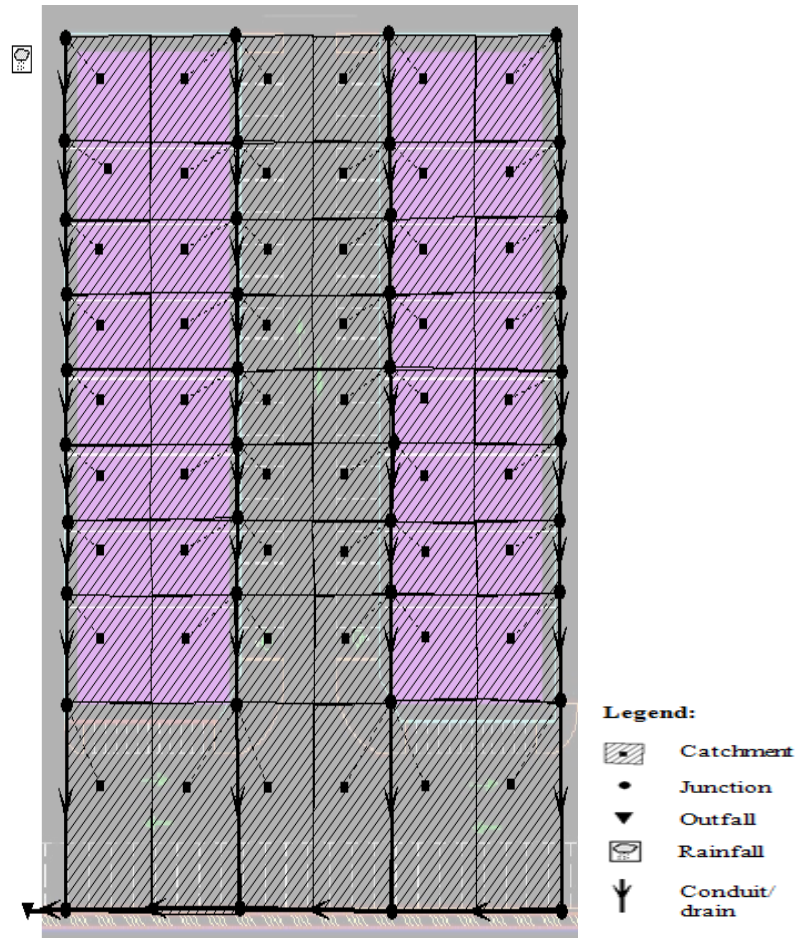


Figure 3.13: SWMM Modeling of Scenario 2

3.6 SolidWorks Flow Simulation

SolidWorks is one of the CFD commercial software. This study uses one of SolidWorks' toolbox, namely the Flow Simulation for flow visualization and verification of results obtained in SWMM. However, it could not simulate the runoff quantity from a given rainfall in an area as SWMM does. Thus, another question befalls: how SolidWorks is used for verification of model in SWMM?

In SolidWorks Flow Simulation, StormPav Green Pavement is represented by modelling the compartments within the pavement as SolidWorks able to construct or model

each modular unit of StormPav (Figure 3.14) as discussed in Section 3.3. Assembly of the components is done by merging multi units of StormPav within a container that represents the surrounded beams then eventually forming a StormPav Green Pavement System.

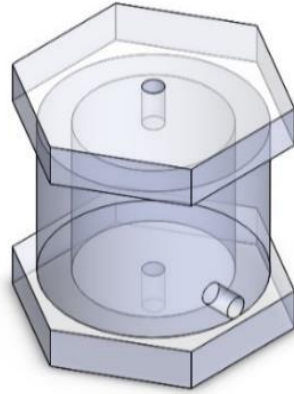


Figure 3.14: Single Modular Unit of StormPav in SolidWorks

As the StormPav road is made up of close to 5,600 modular units, CFD modelling of all these units require high-end computer. Unfortunately, the available hardware from the author's end is insufficient to support the huge number of StormPav units and simplification of the StormPav has to be carried out. Only a selection section of StormPav is used for the simulation to reduce the computational load. Figure 3.15 shows the road is divided into parts according to premise unit. Due to symmetrical and repetition of parts, three parts (i) top corner part, (ii) intermediate part and (iii) bottom corner part are selected for CFD modelling, in which these represent well the whole stretch of StormPav Green Pavement as depicted in Figure 3.16. Each part consists of two circular inlets to convey the surface runoff from roof catchment to StormPav Green Pavement System. The input of flows to selected parts are described in Table 3.9. The inlet boundary condition of the model is assigned as the volume flow which is extracted from SWMM model. This approach is in the same way as in the past study (see Section 2.11). On the other hand, by not defining any measured pressure quantity to the outlet boundary condition of the model, environment pressure is assigned.

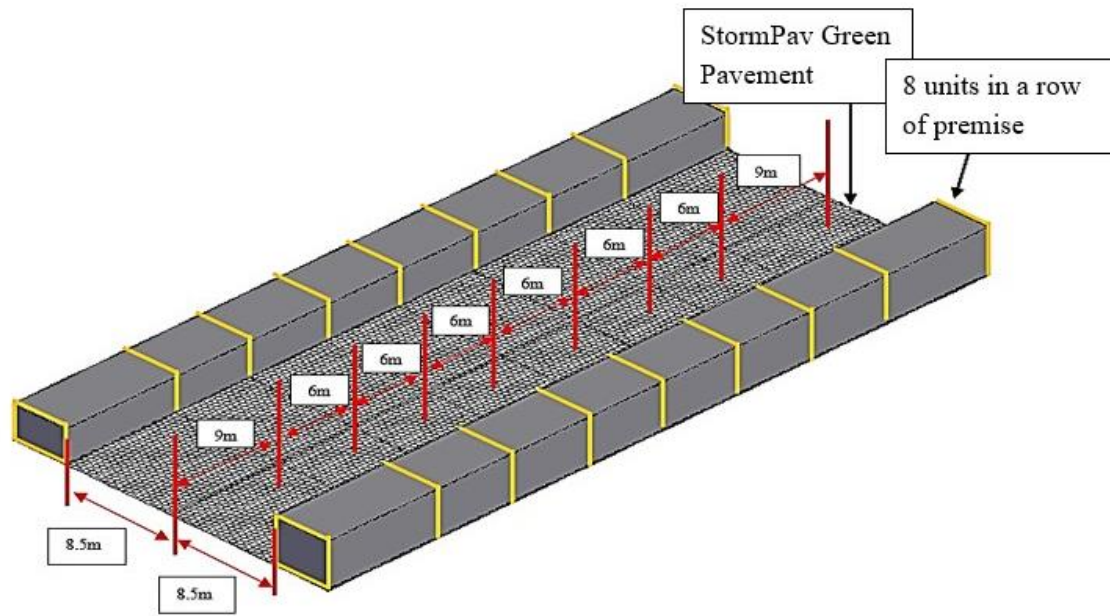


Figure 3.15: Schematic of StormPav with Premises

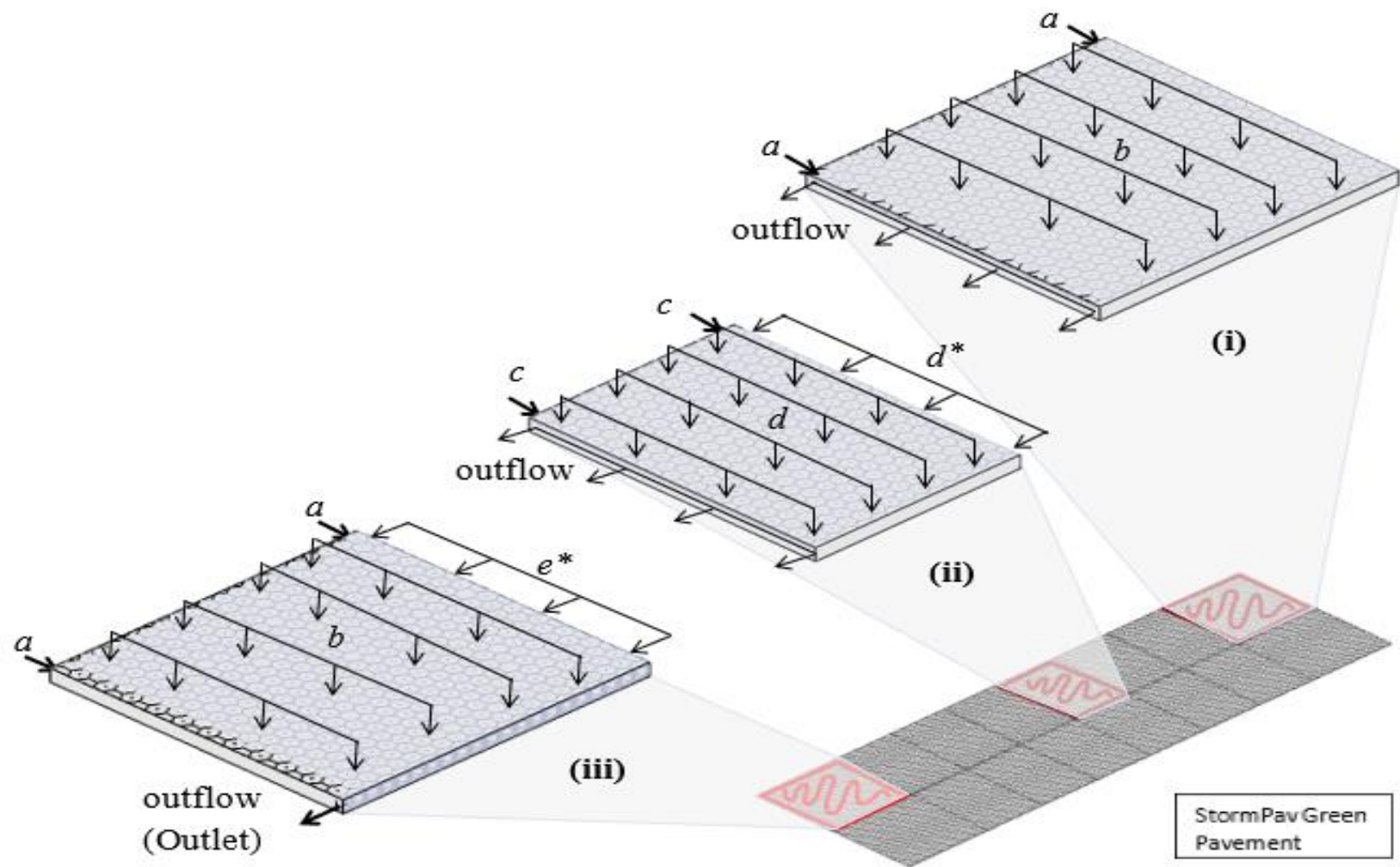


Figure 3.16: SolidWorks Flow Simulation in (i) Upper Stretch, (ii) Intermediate Stretch and (iii) Lower Stretch of StormPav Road

Table 3.9: Specifying the Boundary Conditions

	Storm duration (mins)	Inlet volume flow (m³/s)					
		<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>d</i> *	<i>e</i> *
Inlet boundary condition	5	0.00525	0.00446	0.00350	0.00298	0.01352	0.01804
	10	0.00452	0.00384	0.00301	0.00256	0.01344	0.02266
	15	0.00403	0.00343	0.00269	0.00228	0.01202	0.02087
	20	0.00371	0.00315	0.00247	0.00210	0.01240	0.02205
	30	0.00331	0.00282	0.00221	0.00188	0.01302	0.02568
	60	0.00253	0.00215	0.00169	0.00143	0.01377	0.02885
	120	0.00183	0.00156	0.00122	0.00104	0.01196	0.02514
	180	0.00149	0.00126	0.00099	0.00084	0.00986	0.02124
Outlet boundary condition	Environmental pressure (101325Pa)						

* Value obtained from the SWMM (distributed runoff pattern)

Note: Refer Figure 3.16 for *a*, *b*, *c*, *d*, *d** and *e**

The modelling settings are described in Table 3.10. The initial conditions such as velocity of the model is set to zero to represent the onset of a storm event. Note that, the input flows to the system are the maximum flow obtained in SWMM, therefore, the outcomes are representing the maximum flows which can be indicated in velocity cut plots in SolidWorks Flow Simulation. Also note that, SWMM is a one-dimensional model while SolidWorks Flow Simulation is a three-dimensional model (x, y, z). Therefore, the selected direction of velocities in SolidWorks should be corresponding with the direction of velocities

in SWMM. Besides verification, readers are given a better visualization of flow within the StormPav Green Pavement.

Table 3.10: Specifications Used in Flow Simulation

Type	Specification
Analysis type	Internal with exclude cavities without flow conditions
Unit system	SI (m-kg-s)
Physical features	Gravity
Fluids	Water
Flow type	Laminar and Turbulent
Wall condition	Adiabatic wall
Initial velocity/ flow depth	Zero

3.7 Summary

In this current case study, the conceptual model is being verified by computerized models as depicted in Figure 3.17. This is to ensure that the computer program of the computerized model and its implementation are correct (Sargent, 2013). Two computerized models as mentioned above are produced to verify the concept of “A road that flows stormwater”. In order to enrich the confidence of the conceptual model, SolidWorks Flow Simulation is incorporated by comparing with the result in SWMM.

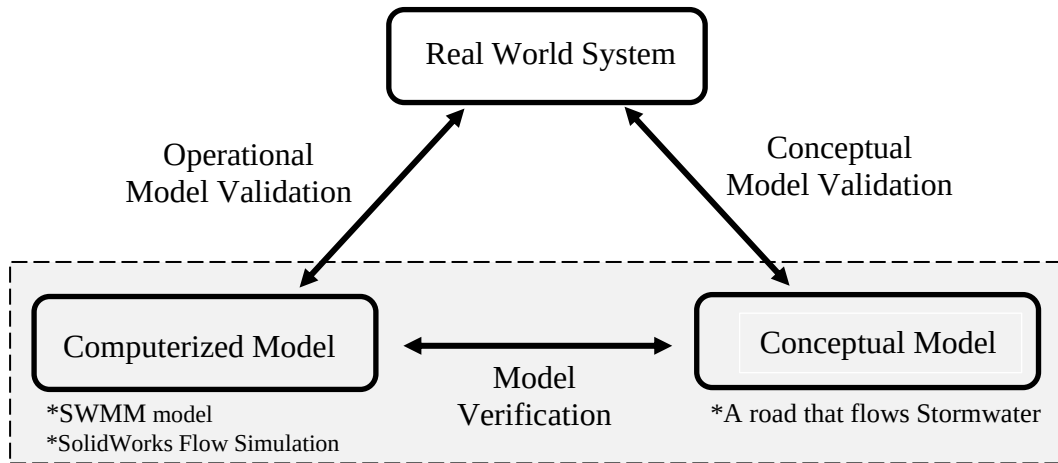


Figure 3.17: Framework of A Model Credibility (Sargent, 2013)

CHAPTER 4

RESULT AND DISCUSSION

4.1 Flow Simulation

4.1.1 Velocity

SolidWorks Flow Simulation produces velocity cut plots of the StormPav Road for varying durations of design rainfall are demonstrated in Figure 4.1 to Figure 4.10. Author observes the colour displayed in each stretch with varying rainfall durations. Taking the 180-minute rainfall as an example for the discussion as shown in Figure 4.1 to Figure 4.3.

The velocity cut plot of top stretch of StormPav Road is illustrated in Figure 4.1. The colour being displayed is more prominent (0.119 – 0.142 m/s) at the inlets relative to the whole stretch; inconsistent of flow velocity at the inlets. Whereas, the flow velocity at the rest of the region is rather uniform and is in the range of 0 - 0.024 m/s. As the velocity at the inlets has little coverage compared to other regions, therefore it is not considered to represent the velocity of the model stretch. Velocity range at other regions is taken as the representative of Stretch i.

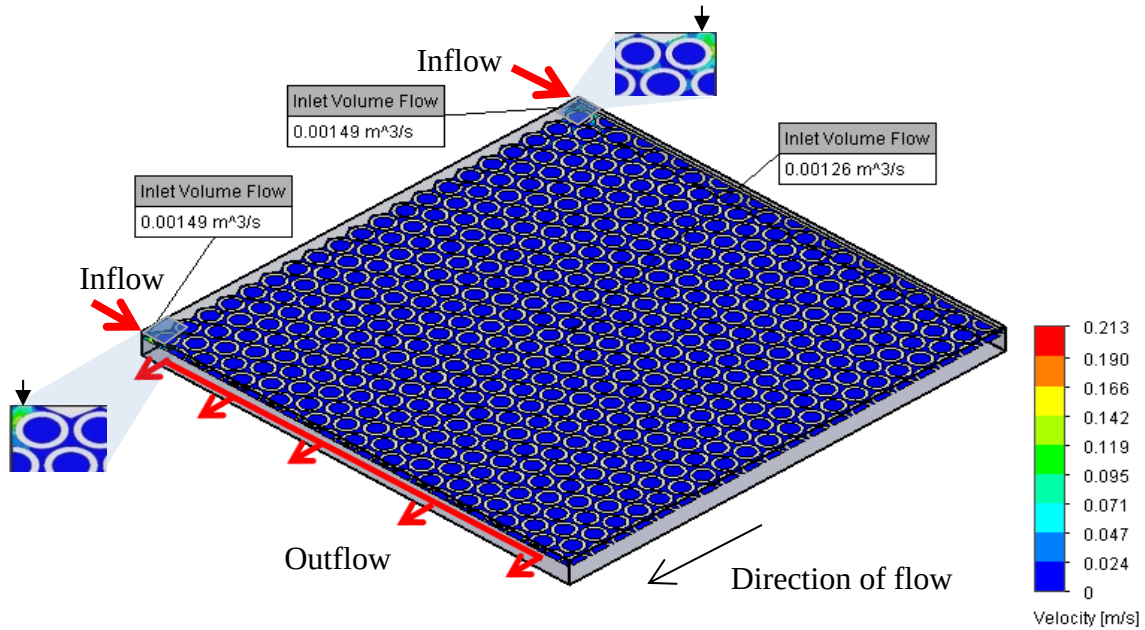


Figure 4.1: Velocity Cut Plot of Stretch i due to 180-minute 10-Year ARI Design Rainfall

The velocity cut plot of intermediate stretch of StormPav Road is illustrated in Figure 4.2. Comparatively, velocity at inlets marks a lower range of 0.065 - 0.086 m/s due to lower inflow from downpipe is assigned compared to Stretch i. The region away from the inflow shows higher velocity range (0.022 – 0.043 m/s) as compared to the same region in Stretch i.

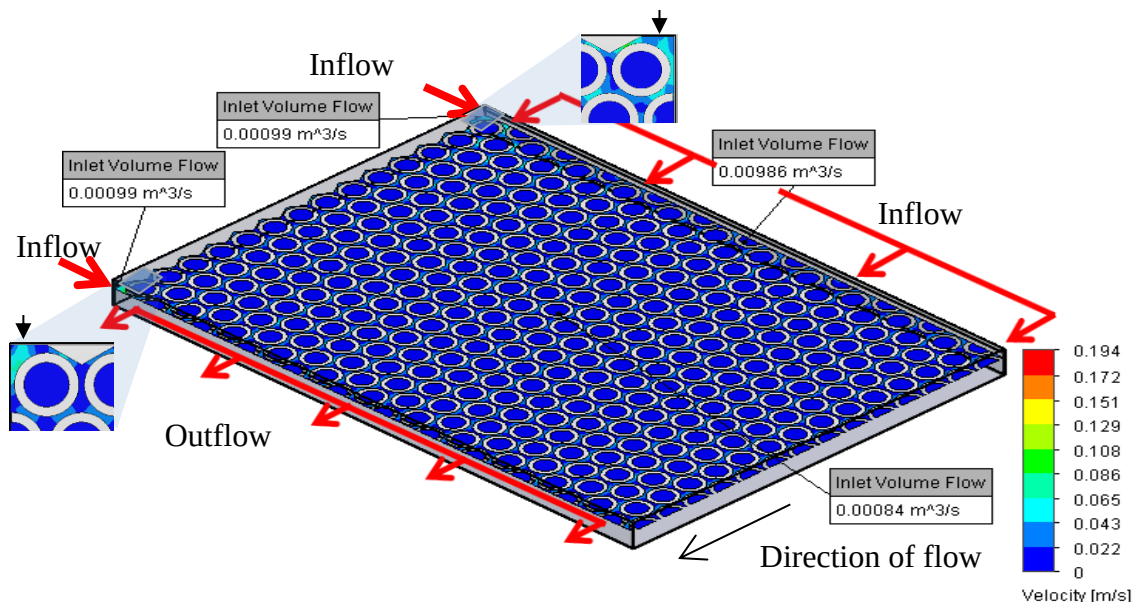


Figure 4.2: Velocity Cut Plot of Stretch ii due to 180-minute 10-Year ARI Design Rainfall

The velocity cut plot of bottom stretch of StormPav Road where stormwater from upstream eventually accumulated is illustrated in Figure 4.3. The flow is expected to leave the system through the outlet structure and it is estimated that the velocity is the highest at the outlet, which marks in the range of 1.070 – 1.284 m/s. Nonetheless, the range of general velocity of the system reported as 0 – 0.214 m/s which is higher than previous stretches.

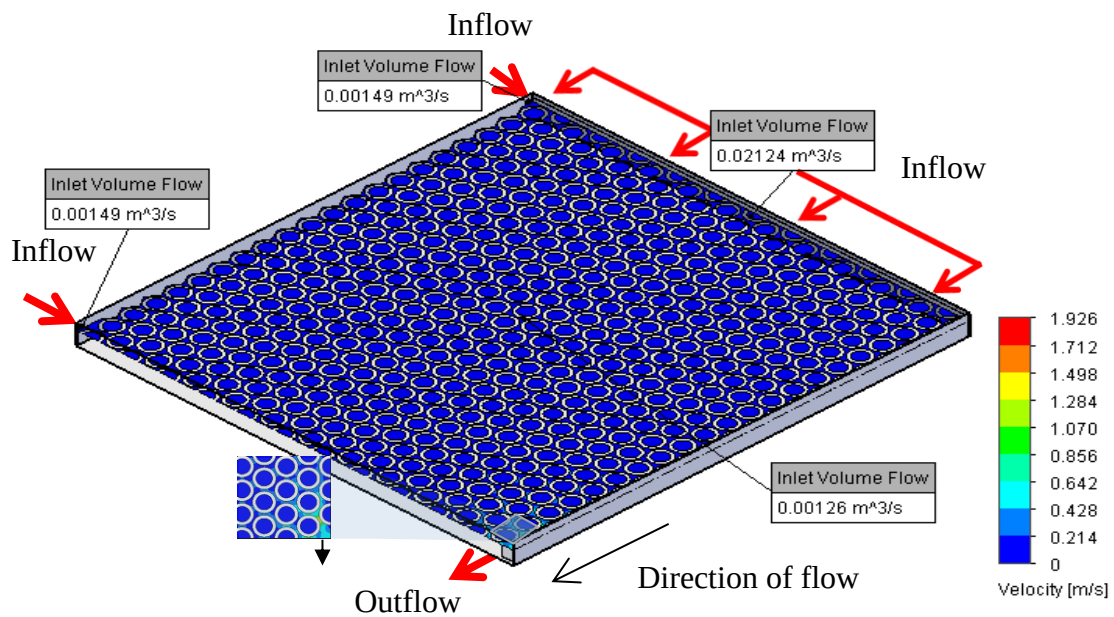


Figure 4.3: Velocity Cut Plot of Stretch iii due to 180-minute 10-Year ARI Design Rainfall

This finding is consistent with results from previous study, as in Ngu, Mah and Bong (2016) had documented, which shows that a rather uniform velocity reported in majority of the flow within the StormPav detention system. A low velocity resulted from the simulation as each unit of the StormPav acts as an energy dissipator to calm the runoff from the inflow which results in ponding effect, yet, the whole system is able to transport the surface runoff from one point to another.

A similar pattern could be observed when simulating other storm durations for 5, 10, 15, 20, 30, 60 and 120 minutes of 10-year ARI design rainfall event. These are presented in the following Figure 4.4 to Figure 4.10.

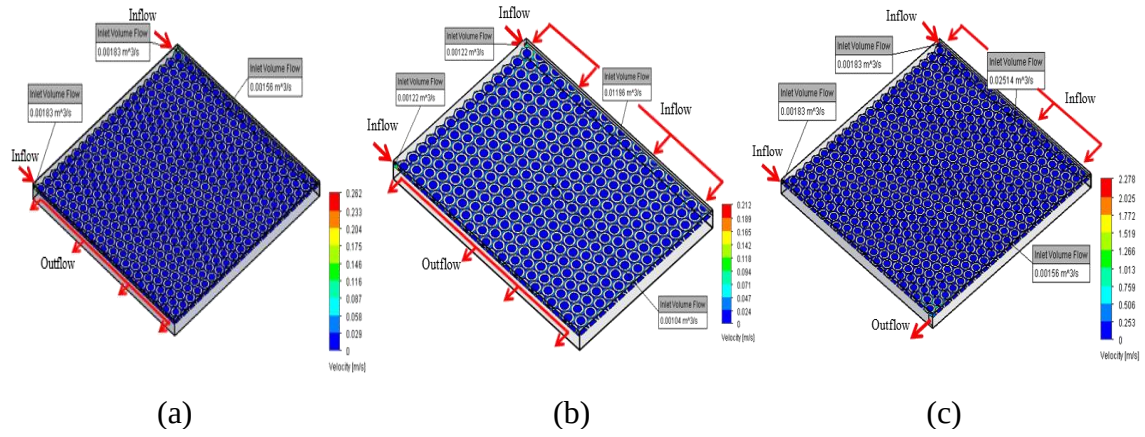


Figure 4.4: Velocity Cut Plot of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 120-minute 10-Year ARI Design Rainfall

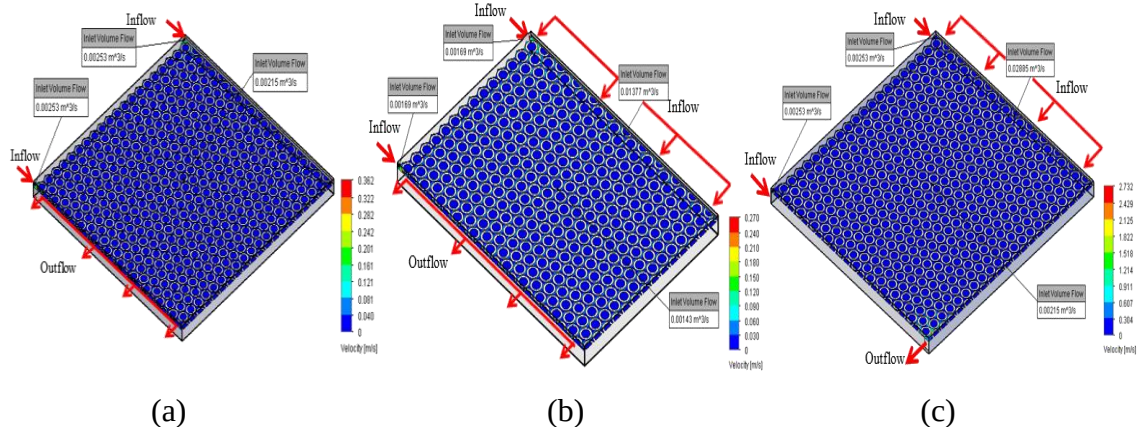


Figure 4.5: Velocity Cut Plot of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 60-minute 10-Year ARI Design Rainfall

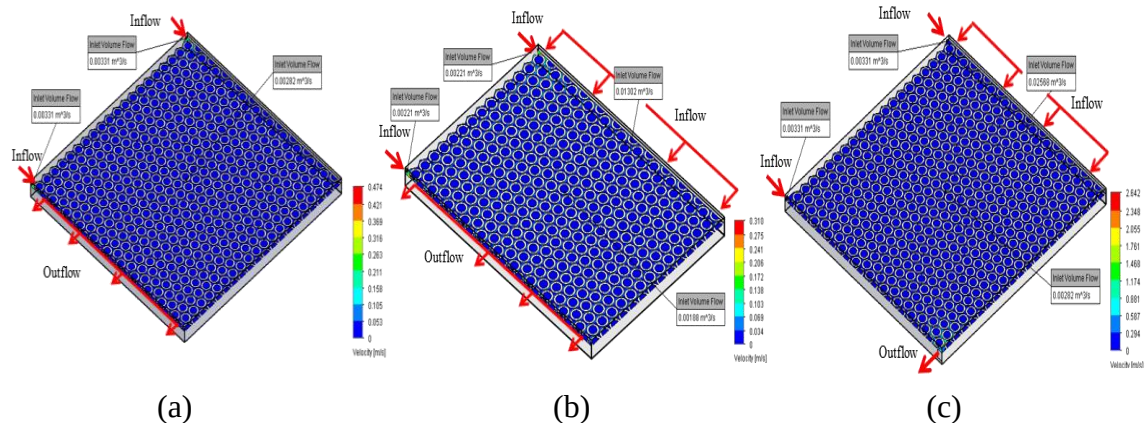


Figure 4.6: Velocity Cut Plot of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 30-minute 10-Year ARI Design Rainfall

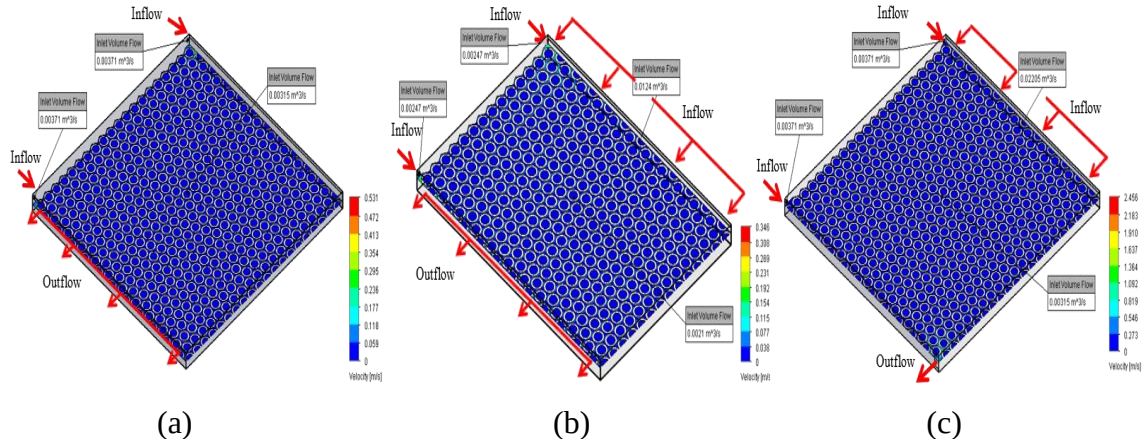


Figure 4.7: Velocity Cut Plot of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 20-minute 10-Year ARI Design Rainfall

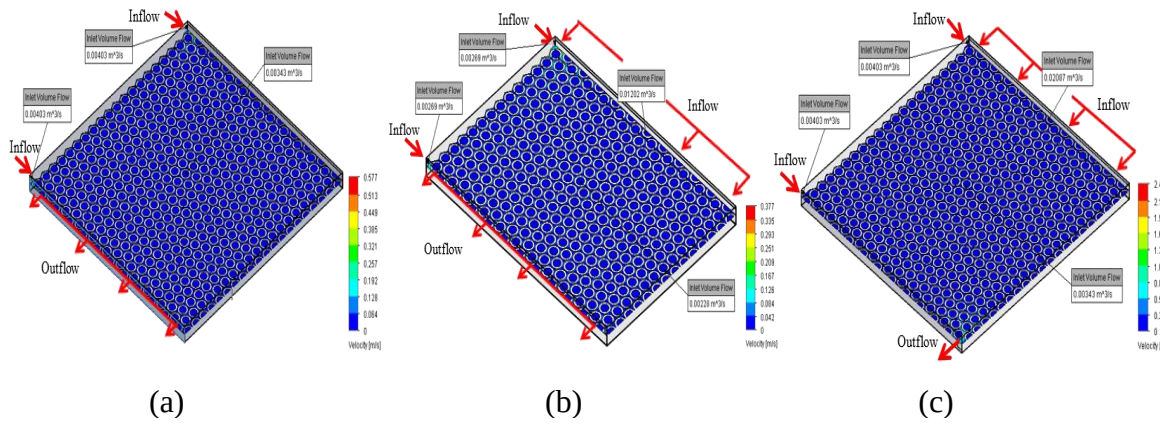


Figure 4.8: Velocity Cut Plot of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 15-minute 10-Year ARI Design Rainfall

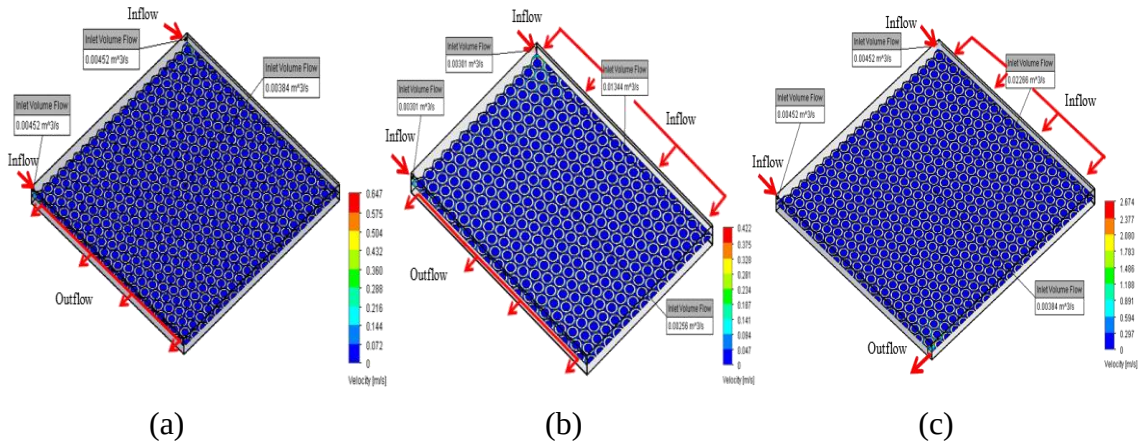


Figure 4.9: Velocity Cut Plot of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 10-minute 10-Year ARI Design Rainfall

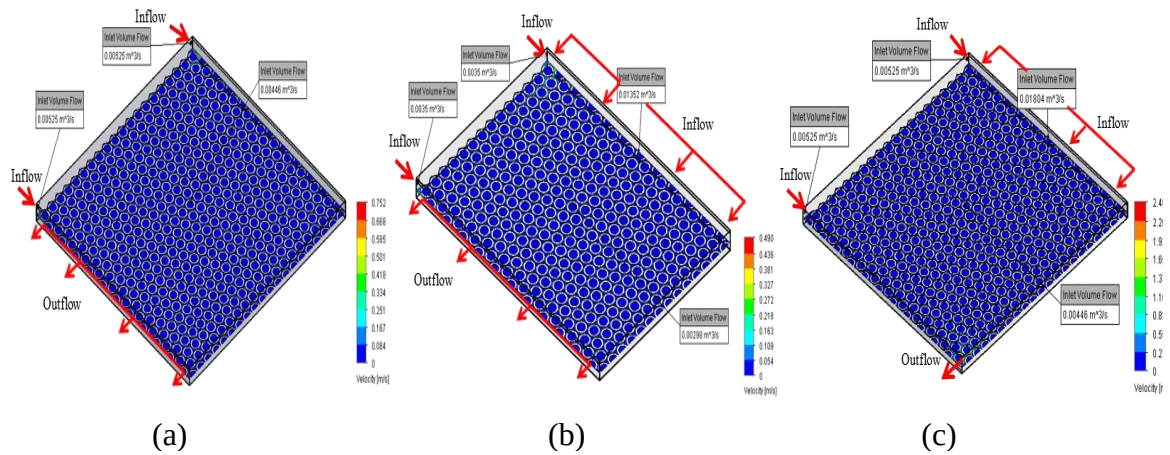


Figure 4.10: Velocity Cut Plot of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 5-minute 10-Year ARI Design Rainfall

Comparison

The comparison of velocities within the StormPav Green Pavement are tabulated in Table 4.1.

Table 4.1: Modelled Velocities in Different Design Storm Durations

Durations (mins)	Modelled velocities (m/s)						Differences (%)
	Stretch i		Stretch ii		Stretch iii		
	SWMM	SWFS	SWMM	SWFS	SWMM	SWFS	
5	0.050	0.066	0.053	0.082	0.098	0.117	35
10	0.047	0.066	0.050	0.072	0.092	0.111	35
15	0.045	0.062	0.047	0.071	0.090	0.100	33
20	0.044	0.061	0.045	0.065	0.086	0.092	30
30	0.043	0.046	0.043	0.061	0.082	0.088	19
60	0.039	0.035	0.037	0.058	0.073	0.083	27
120	0.034	0.027	0.031	0.041	0.065	0.078	24
180	0.032	0.020	0.028	0.039	0.059	0.069	31

Results show that the velocities modelled by SolidWorks Flow Simulation are generally higher than the model in SWMM. This is due to the fact that, model in SolidWorks Flow Simulation reported the results in full depth condition and the water is flowing through the tight spaces around the StormPav units, causing it to have a higher velocity comparing to the model in SWMM. From this point of view, the results are reasonably acceptable and matching with the reported differences of the StormPav road between models are not more than 40%. Therefore, it enhances the reliability of both the SWMM and SolidWorks Flow Simulation models. As such, author continues to explore another capability of SolidWorks Flow Simulation in presenting flow trajectory within StormPav.

4.1.2 Flow Trajectories

The flow trajectories as flow streamlines for different rainfall durations are demonstrated in Figure 4.11 to Figure 4.20. They show the flow direction or flow distribution from inlets towards outlet of the system. Taking the 180-minute rainfall duration as an example for the discussion as shown in Figure 4.11 to Figure 4.13.

The flow trajectories of top stretch of StormPav Road is illustrated in Figure 4.11. Since the premise's catchment area is doubly larger than the road catchment, the force of stormwater from roof catchment is dominant than surface water from road catchment. Besides, that, it can be explained that, in real situation, flow at the inlet has higher kinetic energy velocity as it is supplied by the water from the roof catchment which is has high potential energy. Thus, in the plan view, the flow patterns indicates that water jets being injected to the system and bend inward the outflow region following the direction of flow. The bending of flow can be explained as it flows through/around the multi-units of StormPav in the model.

Cutting plane a-a of Stretch i is done at the middle of the stretch to present another perspective about the vertical flow. The section view is showing the flow trajectories within the units of StormPav in which inflow on the pavement is allowed to permeate through the holes of top plates and leave through the side service inlet.

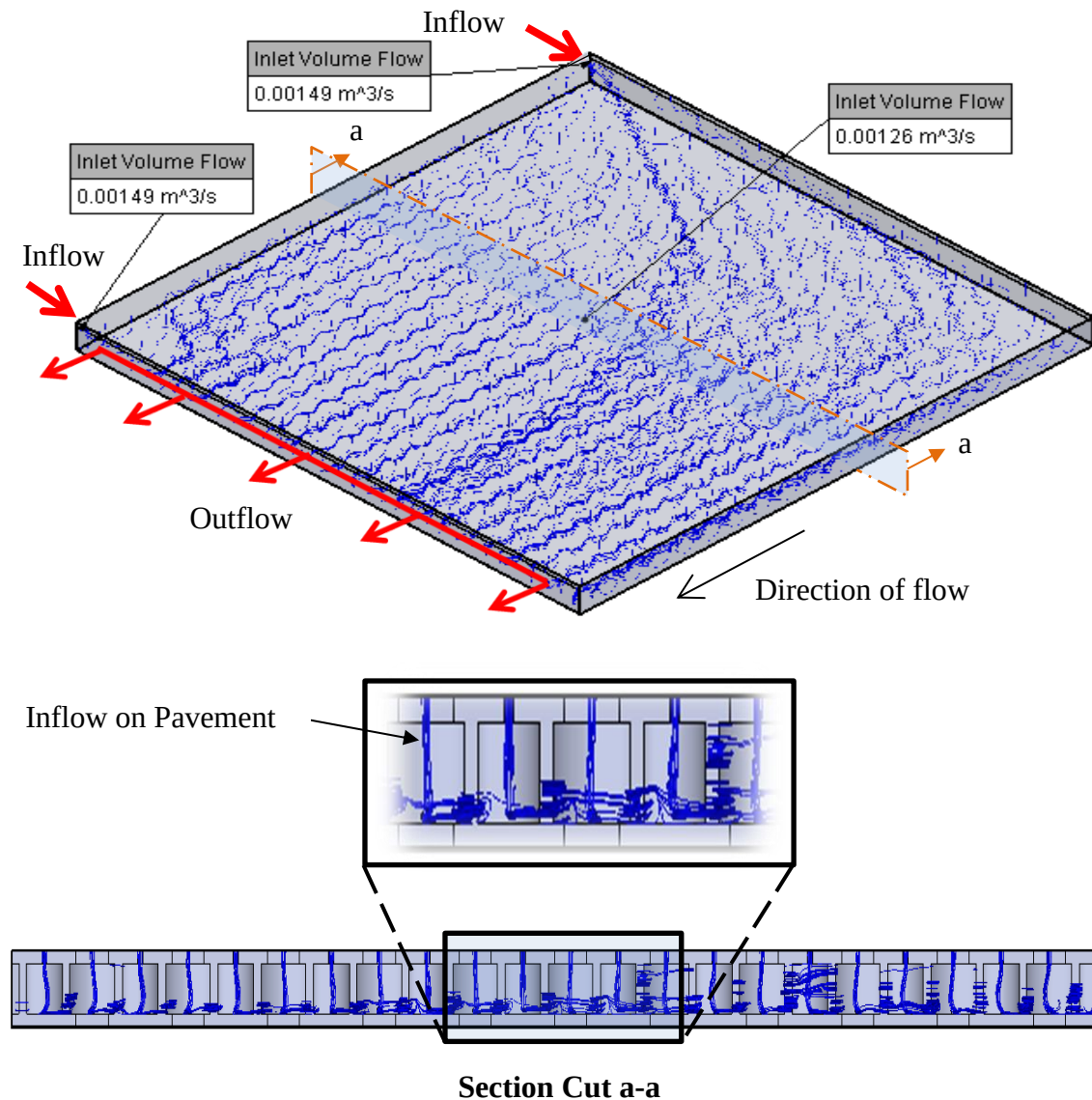


Figure 4.11: Flow Trajectories of Stretch i due to 180-minute 10-Year ARI Design Rainfall

The flow trajectories of intermediate stretch of StormPav Road is illustrated in Figure 4.12. In this circumstance, the force of upstream is more dominant than the flow from the

premise and road surface. In terms of flow pattern, as the runoff flowing across the system, the flow trajectories run straight toward the outflow region.

Cutting plane b-b of Stretch ii is done at the middle of the stretch to present the section view. It shows indistinguishable patterns in vertical and horizontal flows as the previous stretch.

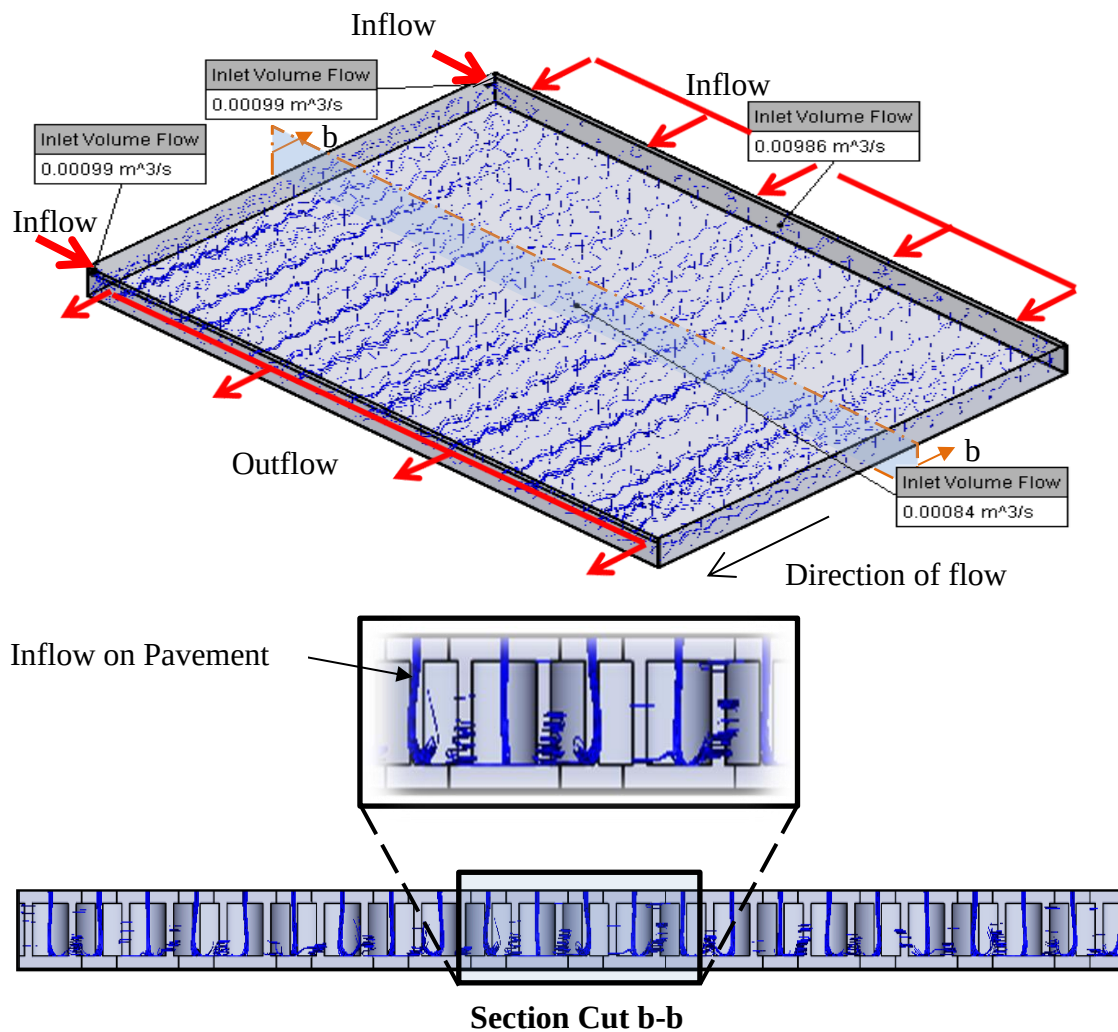


Figure 4.12: Flow Trajectories of Stretch ii due to 180-minute 10-Year ARI Design Rainfall

The flow trajectories of bottom stretch of StormPav Road is illustrated in Figure 4.13, in which the stormwater from upper catchments shall eventually end up at this stretch before

flowing out of the system. Therefore, in this stretch, the upstream flow is the most dominant among the other stretches. In terms of flow pattern, the flow trajectories run straight then again bend but toward the outlet of the StormPav Green Pavement.

Cutting plane c-c of Stretch iii is done at the middle of the stretch to present the section view. The flow trajectories within units of StormPav are showing no swirling in Stretch i and ii but in Stretch iii as the surrounding flow velocity (see Table 4.1) is higher when approaching the outlet of the system, making the flow within the StormPav slowing down and swirling before leaving the hollow cylinders.

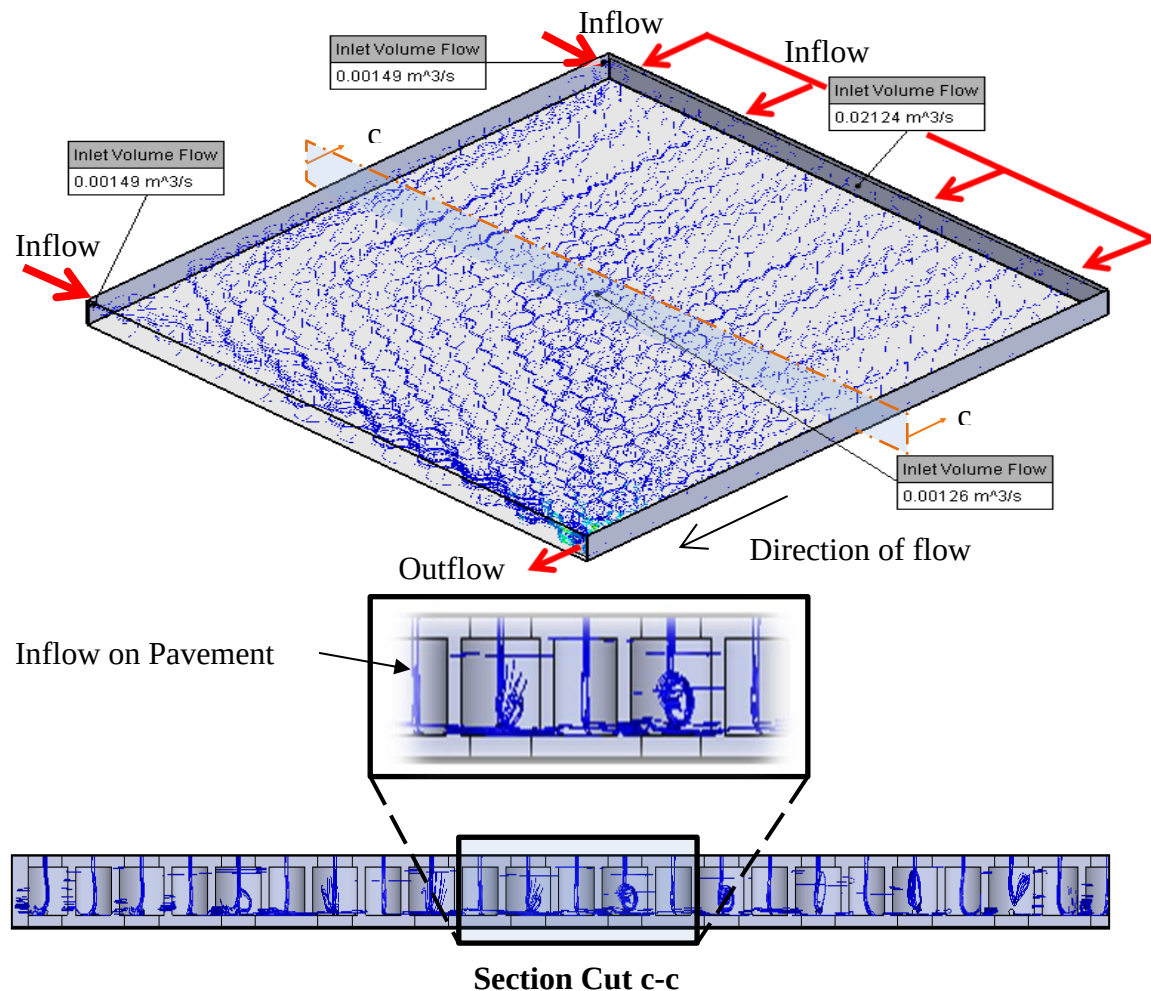


Figure 4.13: Flow Trajectories of Stretch iii due to 180-minute 10-Year ARI Design Rainfall

Author notices that horizontal flow occurs within the spaces in between the hollow cylinders. Continuous flow happens because of these tight spaces. Whereas, vertical flows are only happened within the hollow cylinder before leaving the cylinder and joining the horizontal flow downstream. Yet, the stormwater within the cylinder is increasingly difficult to flow out as stretch is approaching downstream end. Therefore, special attention shall be paid when designing of downstream stretch in order to prevent any undesired overflowing of stormwater.

For other rainfall durations, author realizes that flow trajectories show repetitive pattern as presented in Figure 4.14 to Figure 4.20.

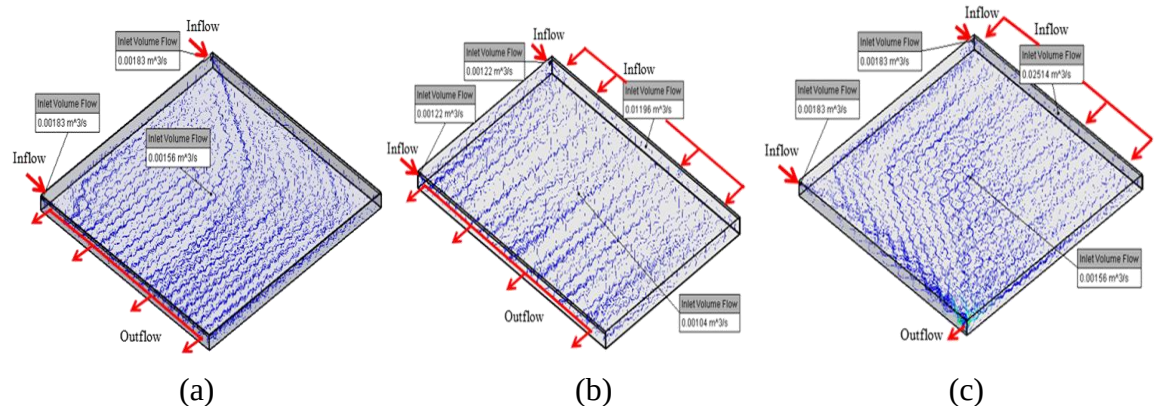


Figure 4.14: Flow Trajectories of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 120-minute 10-Year ARI Design Rainfall

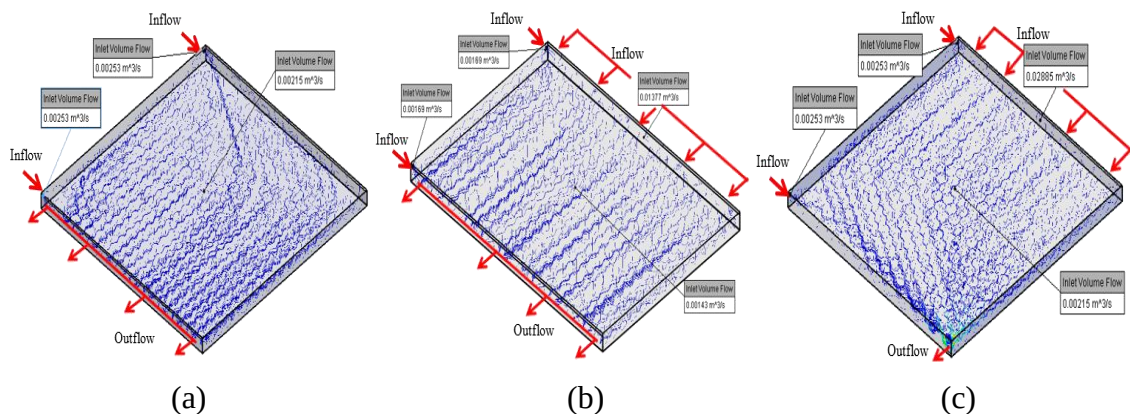


Figure 4.15: Flow Trajectories of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 60-minute 10-Year ARI Design Rainfall

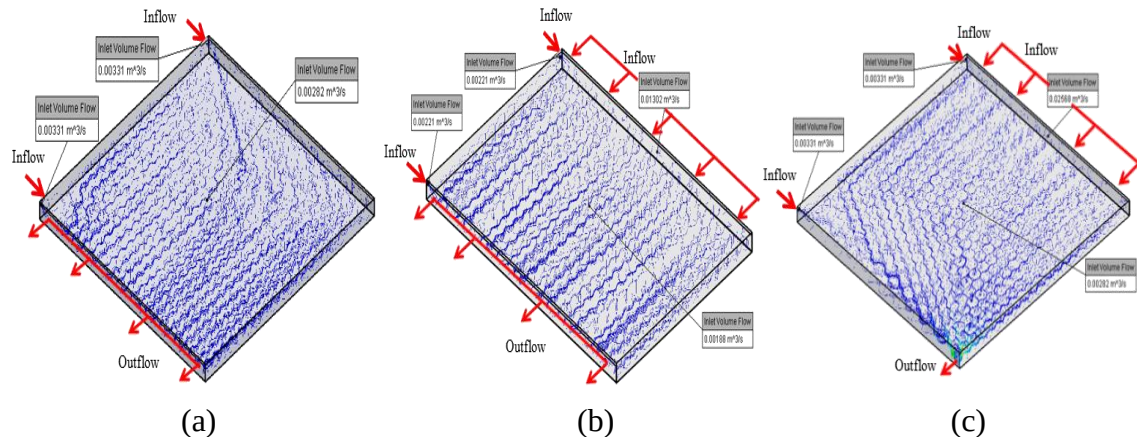


Figure 4.16: Flow Trajectories of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 30-minute 10-Year ARI Design Rainfall

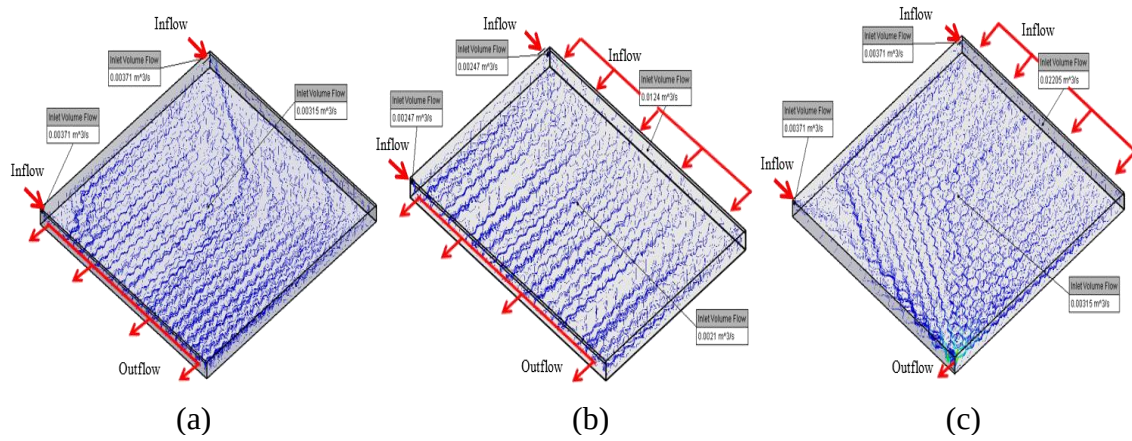


Figure 4.17: Flow Trajectories of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 20-minute 10-Year ARI Design Rainfall

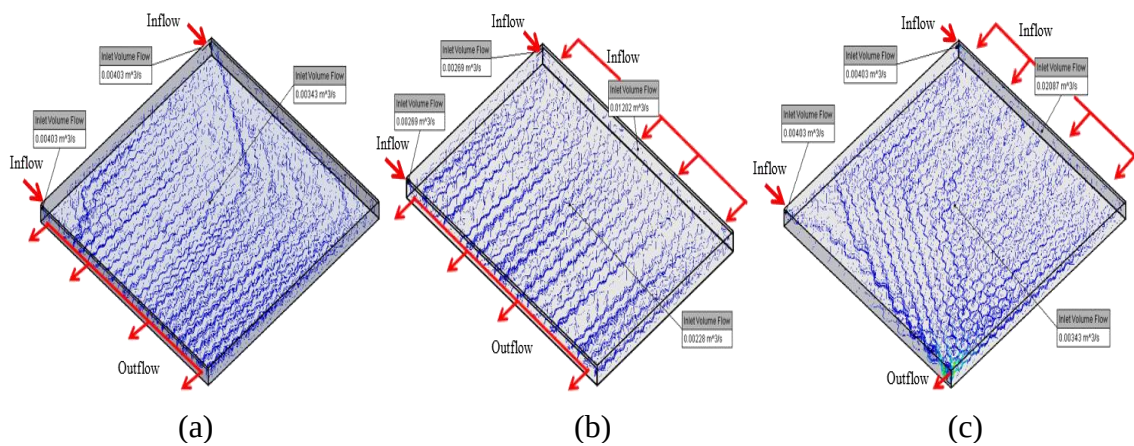


Figure 4.18: Flow Trajectories of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 15-minute 10-Year ARI Design Rainfall

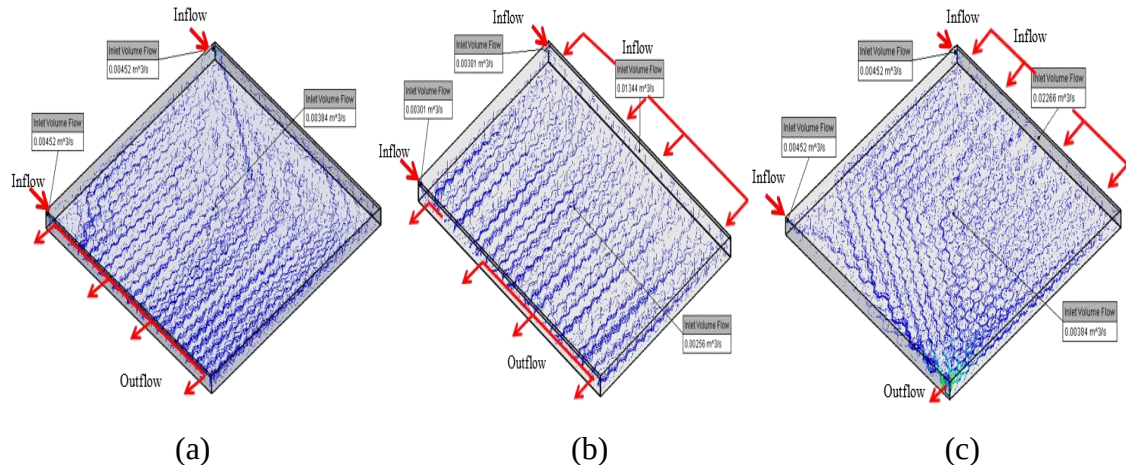


Figure 4.19: Flow Trajectories of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 10-minute 10-Year ARI Design Rainfall

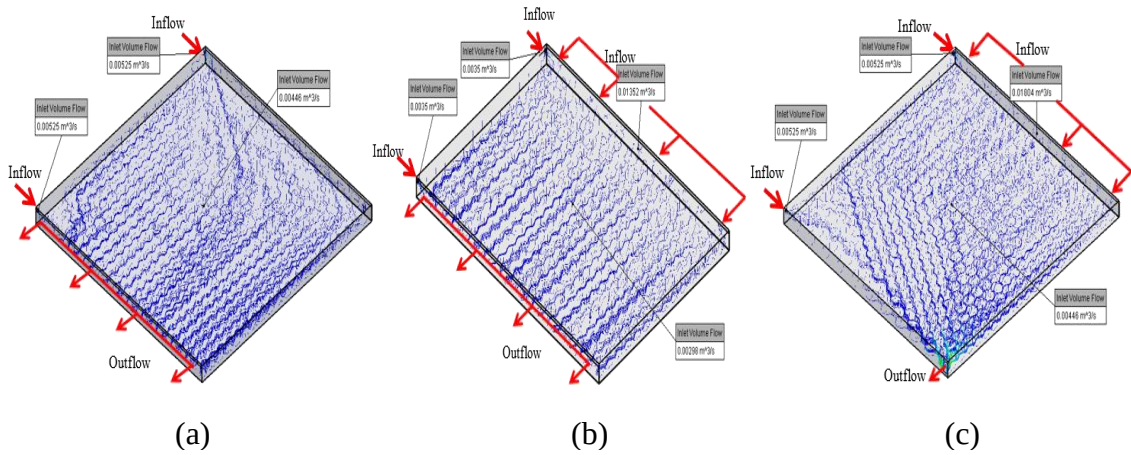


Figure 4.20: Flow Trajectories of (a) Stretch i, (b) Stretch ii and (c) Stretch iii due to 5-minute 10-Year ARI Design Rainfall

4.2 Inlet and Outlet of StormPav Green Pavement

From this point onwards, all investigations are done in SWMM since the model is verified to represent the StormPav system reasonably.

4.2.1 Inlet Analysis

In this context, inlet size refers to inlet from downpipes. Each unit of the buildings consists of two circular downpipes, a normal practice in urban shophouses that the pipes are installed on the wall or hidden/ besides the columns of the shophouse. To represent the two

downpipes from each unit of premise to the system, it is a common modelling practice to integrate the two as one inlet (virtually) to be represented in SWMM. The parameters of the merged inlets are tabulated in Table 4.2. Maximum depth capacity for each inlet size is computed in which any water depth exceeding the value indicates surcharging. Surcharging in this context simply means water depth from the roof catchment hydraulically rises above the top of the inlet.

Table 4.2: Maximum Capacity of Varying Inlet Sizes

Inlet size (mm)	Total area (mm)	Model inlet diameter size (mm)	Maximum depth capacity (mm)
2 x 50	3927	70.7	70.7
2 x 75	8836	106.1	106.1
2 x 100	15708	141.4	141.4
2 x 125	24544	176.8	176.8

Analysis is done on corner and intermediate lots. This is because the corner lot has a relatively larger than the intermediate lot. Therefore, there are two different roof catchment sizes. Figure 4.21 to Figure 4.32 report the bar graphs of water depth just before the inlet opening with varying combinations of inlet and outlet orifice sizes for corner and intermediate in different design rainfall durations. The inlet sizes are 50 mm, 75 mm, 100 mm and 125 mm. The outlet sizes are explained in the next section. However, the author also models a sub-scenario which the outlet is open across the width of the road and it is denoted as ∞^* in Table 4.3. This sub-scenario models the stormwater to free flow out of the StormPav system to compare with flow restriction due to an outlet.

Water depth at inlet with varying inlet sizes and ∞^* outlet size in different design rainfall durations at corner lot and intermediate lot are presented in Figure 4.21 and Figure 4.22 respectively. In both corner and intermediate lots, the inlet sizes of 50 mm and 75 mm reach the maximum depth capacity with different design rainfall durations. Whereas, 100 mm and 125 mm are observed below the maximum depth capacity.

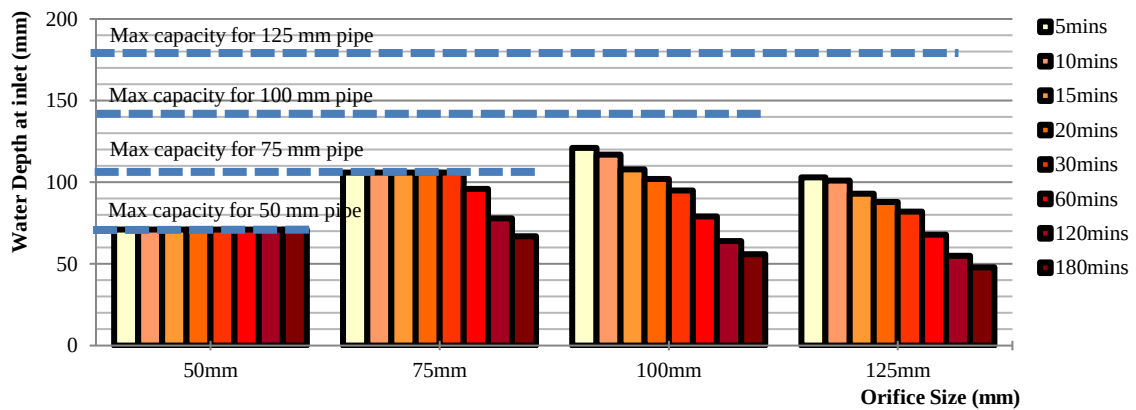


Figure 4.21: Water Depth at Inlet with Varying Inlet Sizes and ∞^* Outlet Size in Different Design Rainfall Durations at Corner Lot

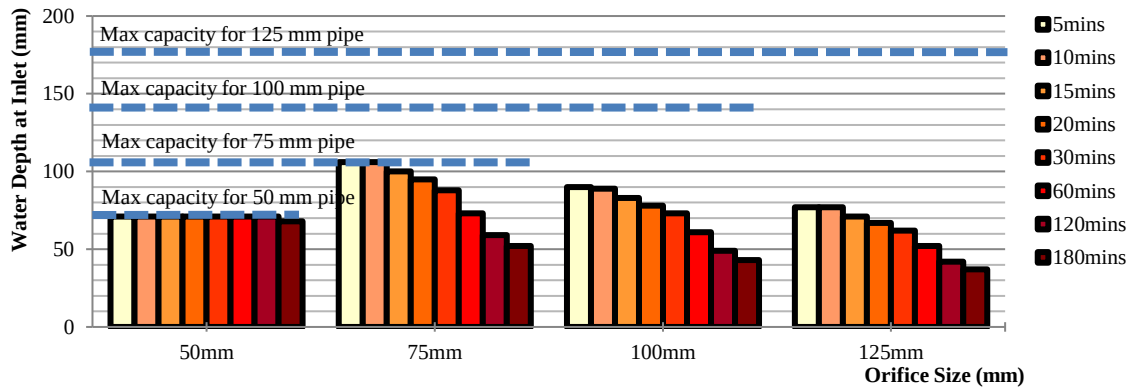


Figure 4.22: Water Depth at Inlet with Varying Inlet Sizes and ∞^* Outlet Size in Different Design Rainfall Durations at Intermediate Lot

Water depth at inlet with varying inlet sizes and 190 mm diameter outlet size in different design rainfall durations at corner lot and intermediate lot are presented in Figure

4.23 and Figure 4.24 respectively. In both corner and intermediate lots, all the investigated inlet sizes reach the maximum depth capacity with different design rainfall durations.

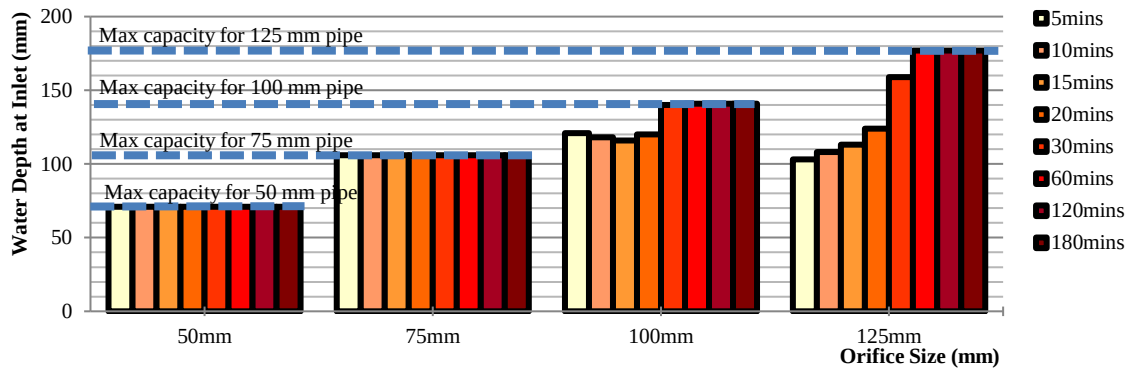


Figure 4.23: Water Depth at Inlet with Varying Inlet Sizes and 190 mm Outlet Size in Different Design Rainfall Durations at Corner Lot

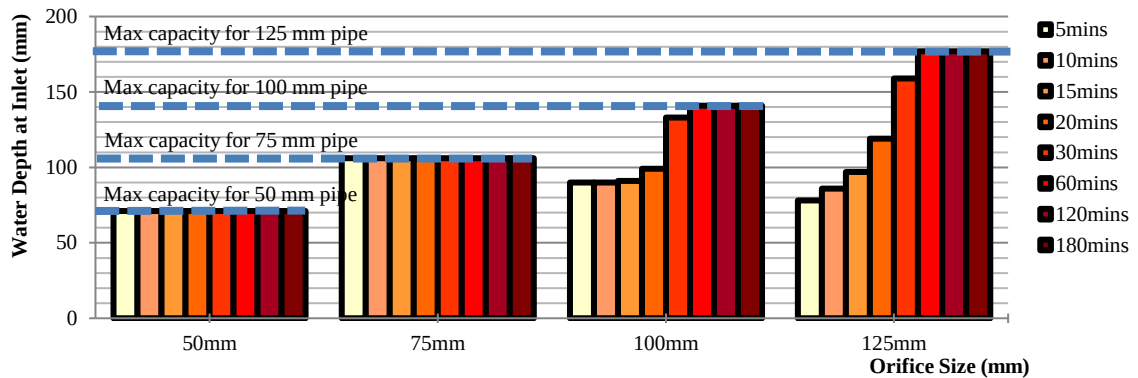


Figure 4.24: Water Depth at Inlet with Varying Inlet Sizes and 190 mm Outlet Size in Different Design Rainfall Durations at Intermediate Lot

Water depth at inlet with varying inlet sizes and 190 mm x 300 mm diameter outlet size in different design rainfall durations at corner lot and intermediate lot are presented in Figure 4.25 and Figure 4.26 respectively. In both corner and intermediate lots, all the investigated inlet sizes reach the maximum depth capacity with different design rainfall durations.

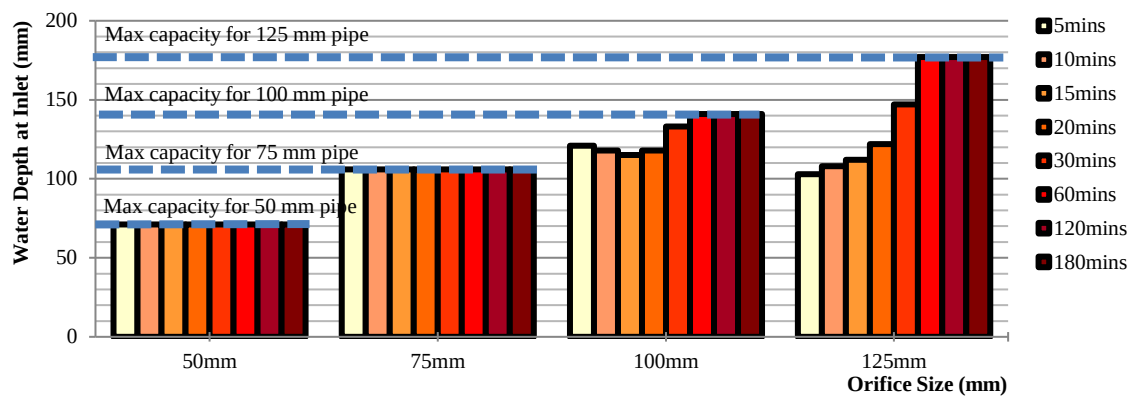


Figure 4.25: Water Depth at Inlet with Varying Inlet Sizes and 190 mm x 300 mm Outlet Size in Different Design Rainfall Durations at Corner Lot

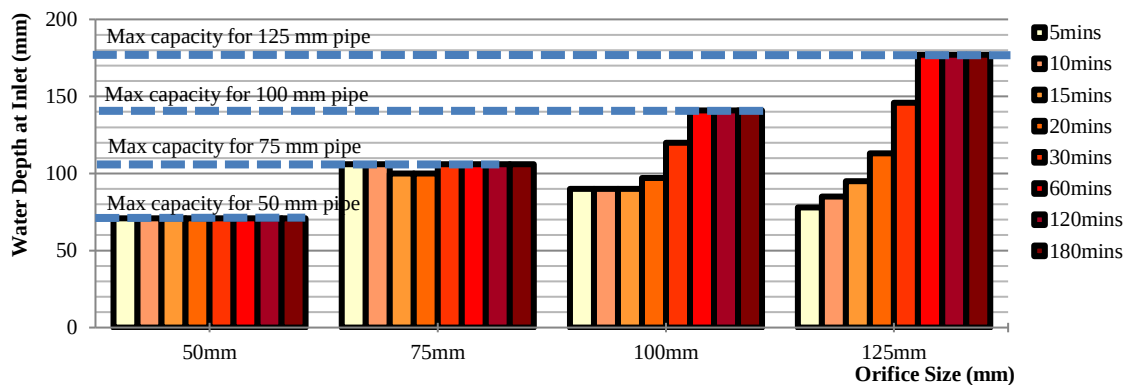


Figure 4.26: Water Depth at Inlet with Varying Inlet Sizes and 190 mm x 300 mm Outlet Size in Different Design Rainfall Durations at Intermediate Lot

Water depth at inlet with varying inlet sizes and 190 mm x 500 mm diameter outlet size in different design rainfall durations at corner lot and intermediate lot are presented in Figure 4.27 and Figure 4.28 respectively. In both corner and intermediate lots, the inlet sizes of 50 mm and 75 mm reach the maximum depth capacity with different design rainfall durations. Whereas, 100 mm and 125 mm are reported nearly reach the maximum depth capacity.

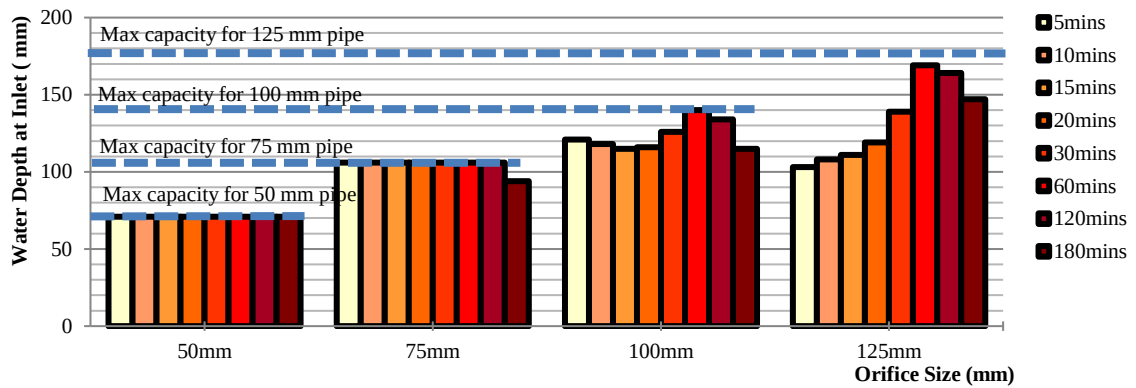


Figure 4.27: Water Inlet Depth with Varying Inlet Sizes and 190 mm x 500 mm Outlet Size in Different Design Rainfall Durations at Corner Lot

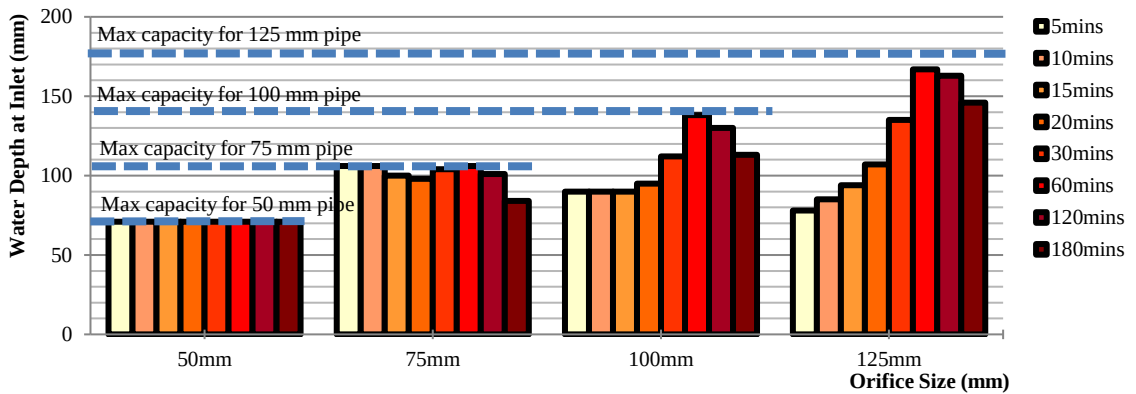


Figure 4.28: Water Inlet Depth with Varying Inlet Sizes and 190 mm x 500 mm Outlet Size in Different Design Rainfall Durations at Intermediate Lot

Water depth at inlet with varying inlet sizes and 190 mm x 700 mm diameter outlet size in different design rainfall durations at corner lot and intermediate lot are presented in Figure 4.29 and Figure 4.30 respectively. In both corner and intermediate lots, the inlet sizes of 50 mm and 75 mm reach the maximum depth capacity. Whereas, 100 mm and 125 mm are below the maximum depth capacity with different design rainfall durations.

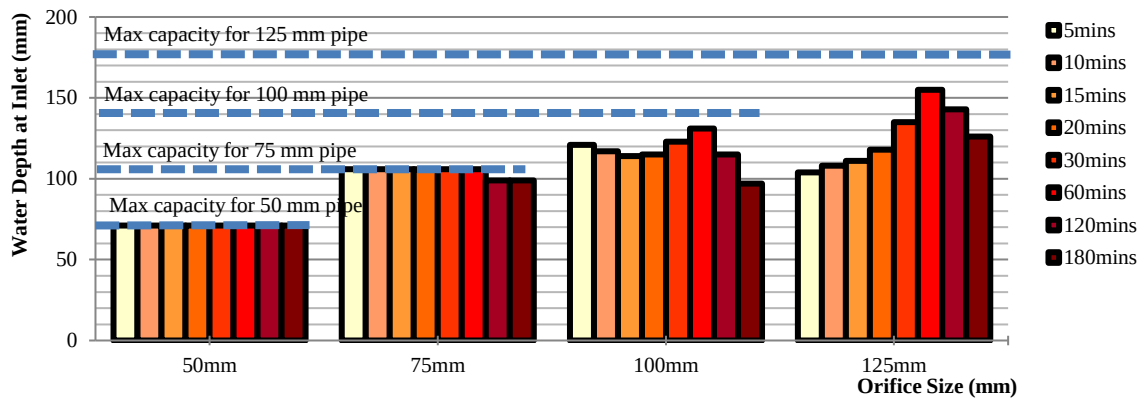


Figure 4.29: Water Inlet Depth with Varying Inlet Sizes and 190 mm x 700 mm Outlet Size in Different Design Rainfall Durations at Corner Lot

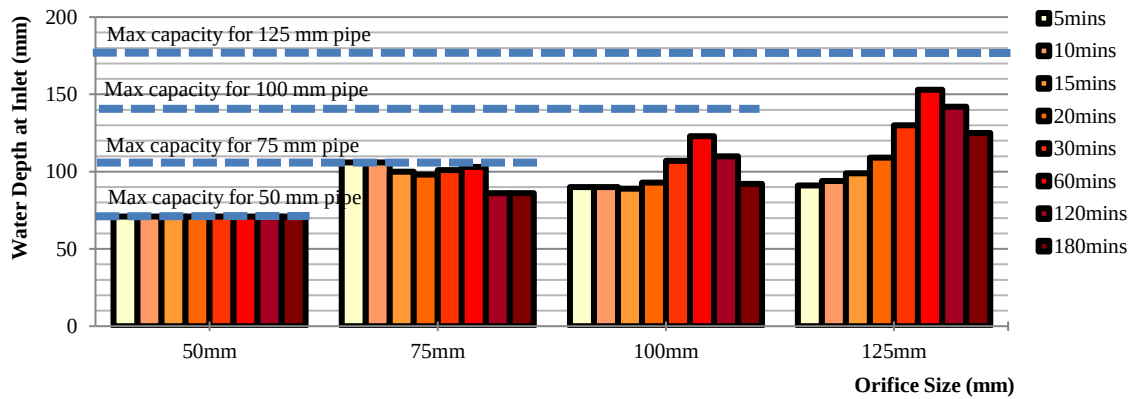


Figure 4.30: Water Inlet Depth with Varying Inlet Sizes and 190 mm x 700 mm Outlet Size in Different Design Rainfall Durations at Intermediate Lot

Water depth at inlet with varying inlet sizes and 190 mm x 900 mm diameter outlet size in different design rainfall durations at corner lot and intermediate lot are presented in Figure 4.31 and Figure 4.32 respectively. In both corner and intermediate lots, the inlet sizes of 50 mm and 75 mm reach the maximum depth capacity. On the other hand, 100 mm and 125 mm are reported below the maximum depth capacity with different designed rainfall durations.

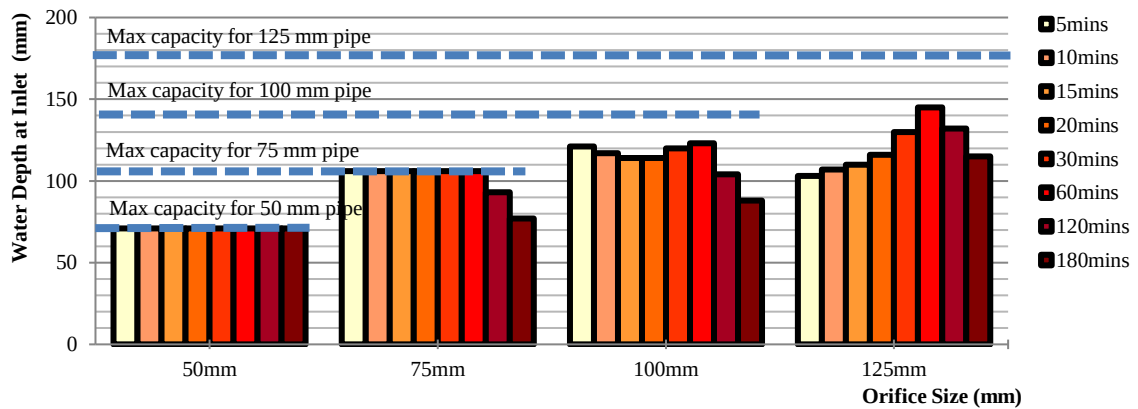


Figure 4.31: Water Inlet Depth with Varying Inlet Sizes and 190 mm x 900 mm Outlet Size in Different Design Rainfall Durations at Corner Lot

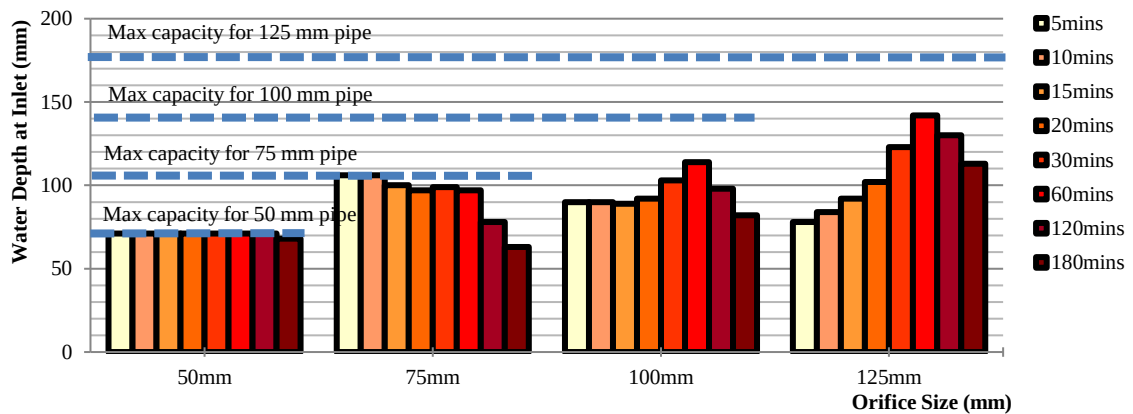


Figure 4.32: Water Inlet Depth with Varying Inlet Sizes and 190 mm x 900 mm Outlet Size in Different Design Rainfall Durations at Intermediate Lot

To conclude the inlet analysis, Table 4.3 presents the summary of inlet analysis in varying combinations of inlet and outlet sizes. The inlet diameter sizes of 50 mm and 75 mm reach the maximum depth capacity with different design rainfall durations. Meaning, surcharging at these inlets are indicated in SWMM. Comparing 100 mm and 125 mm inlet sizes, the latter size reports a greater contrast of water depths that are suggesting oversizing of pipe size. Therefore, 100 mm circular inlet size is selected as the optimum inlet size design for StormPav Green Pavement System.

Surcharging could occur when the outlet sizing is small as a result of slow water draining out of the system and thus raising the water level in the system; causing water reaches the maximum depth capacity of inlets. For example, according to Table 4.3, the inlet sizes of 100 mm and 125 mm report surcharging when smaller sizes of outlet are tested. On the other hand, inlet diameter sizes of 100 mm and 125 mm with larger outlet sizes shown no surcharging at the inlets in all the design rainfall durations; the water depths from the roof catchment are well below the maximum depths of downpipes.

Table 4.3: Summary of Inlet Analysis in Varying Combinations of Inlet and Outlet Sizes for All the Design Rainfall Durations

Inlet (mm) Outlet (mm)	50	75	100	125
∞*	S	S	NS	NS
190	S	S	S	S
190 x 300	S	S	S	S
190 x 500	S	S	NS	NS
190 x 700	S	S	NS	NS
190 x 900	S	S	NS	NS

S = surcharging; NS = non-surcharging

∞* = Outlet is placed over the entire width of the road (as the control to the inlet analysis)

4.2.2 Outlet Analysis

This section presents the outlet orifice structure size of the StormPav Green Pavement to control the ponding and draining effects. The outlet structure is designed at the end of the StormPav Green Pavement. Inlet size of ∞^{**} is modelled to represent the stormwater to free flow into the StormPav system; set as a control to isolate the influence of the inlet size in outlet analysis.

From Table 4.4, the outlet sizes are circular 190 mm in diameter, followed by 190 mm x 300 mm, 190 mm x 500 mm, 190 mm x 700 mm, 190 mm x 900 mm. The 190 mm is the effective depth of the StormPav system, in which the depth represents the maximum depth the SWMM modelled. The others 300 mm – 900 mm are the varying widths of the rectangular orifice opening. One circular orifice opening is modelled to distinguish whether the conventionally use circular underground pipe would have any advantage than the desired rectangular underground channel that is easier to construct and maintain in long run. The range of 300 mm – 900 mm widths could only be achieved in rectangular shape.

Apart from that, inlet sizes control the amount of the runoff conveyed into the system are summarized in Table 4.4. For example, when inlet size is set to be ∞^{**} with outlet size of 190 mm x 500 mm, overflowing is observed in SWMM, however, when comes to other inlets sizes with 190 mm x 500 mm outlet size, StormPav Green Pavement responses with no overflowing. Generally, the system shows no overflowing when the outlet size increases as shown in Table 4.4.

Table 4.4: Summary of Outlet Analysis in Varying Combinations of Inlet and Outlet Sizes for All the Design Rainfall Durations

Outlet (mm) Inlet (mm)	190	190 x 300	190 x 500	190 x 700	190 x 900
∞**	O	O	O	NO	NO
100	O	O	NO	NO	NO
125	O	O	NO	NO	NO

O = overflowing; NO = non-overflowing

∞** = Inlet is placed over the entire length of the road (as the control to the outlet analysis)

Discussions are presented for the varying outlet sizes with inlet size of 100 mm, which is selected as the best inlet size in the previous section. Other inlet sizes are documented in the Appendix. The findings are reported in Figure 4.33 to Figure 4.37.

According to Figure 4.33 and Figure 4.34, results show that the 190 mm diameter circular orifice outlet and the 190 mm x 300 mm rectangular orifice outlet show overflowing from the StormPav system when larger design rainfall durations are being tested. For instance, both cases report that durations of 60 minutes to 180 minutes have the captured stormwater exceeding the volume capacity provided by StormPav system. Thus, bigger orifice sizes are investigated and the results are reported as shown in Figure 4.35 to Figure 4.37.

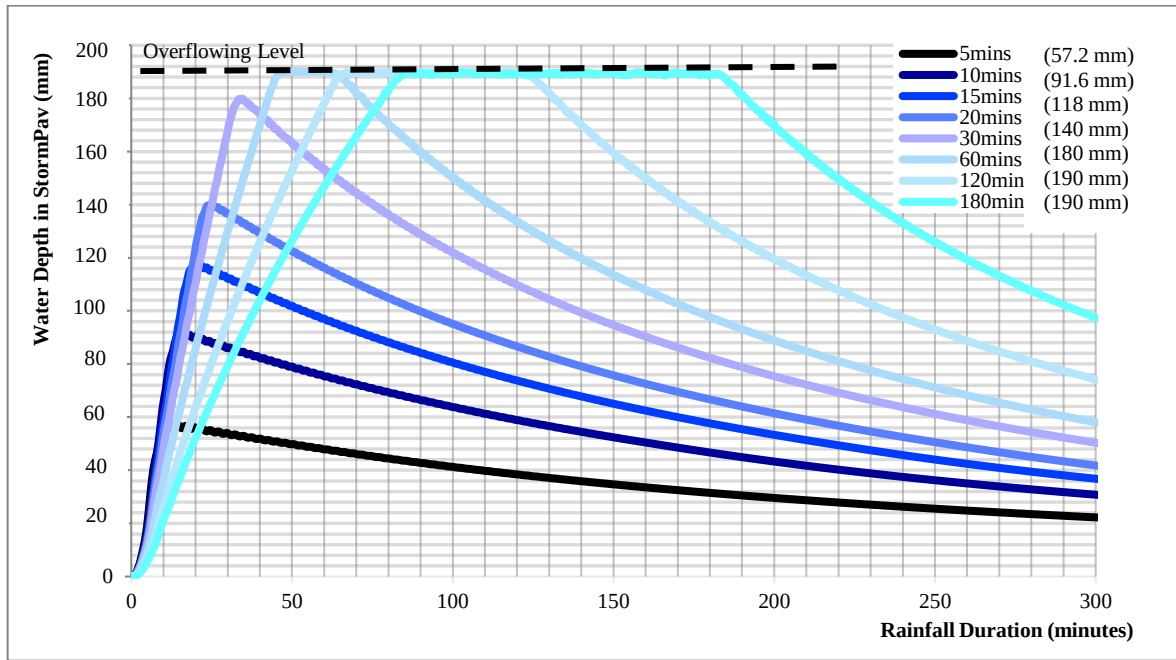


Figure 4.33: Time Series of Water Depth in StormPav in Varying Rainfall Durations For 190 mm Diameter Circular Orifice Outlet

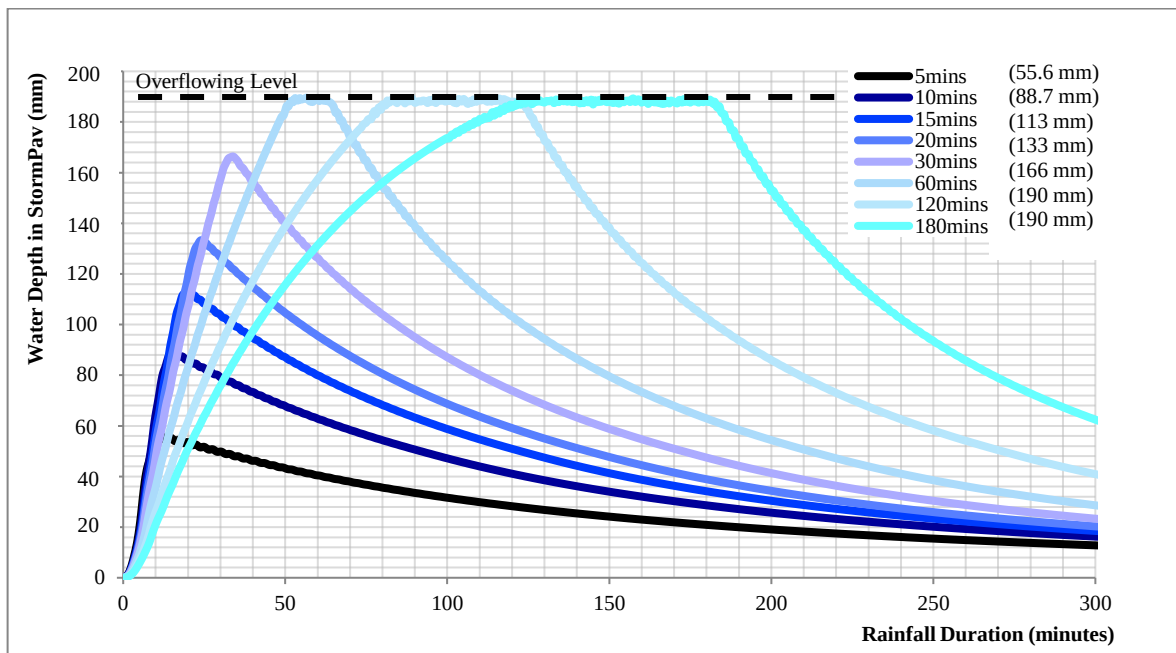


Figure 4.34: Time Series of Water Depth in StormPav in Varying Rainfall Durations For 190 mm x 300 mm Rectangular Orifice Outlet

According to Figure 4.35 to Figure 4.37, the water depths in the StormPav of tested outlet sizes are well below the overflowing level for all the design rainfall durations. 5-

minute design rainfall duration reports the least peak water depth. This may due to the fact that, although the intensity (210 mm/hr) is the greatest among other design rainfall durations, the 5-minute duration is short to raise the water level in the StormPav Green Pavement. Meaning, the detention volume provided is adequate to cater such short duration. In contrary, 60-minute design rainfall duration in this study area, taking into account of filling, ponding and draining effect, marks the highest peak flow depth. Besides that, the graphs report that the peak water depth increasing from 5-minute to 60-minute design rainfall duration and decreasing after then. The decreasing trend is attributed by the intensities are too insignificant to outweigh the draining effect in the StormPav system.

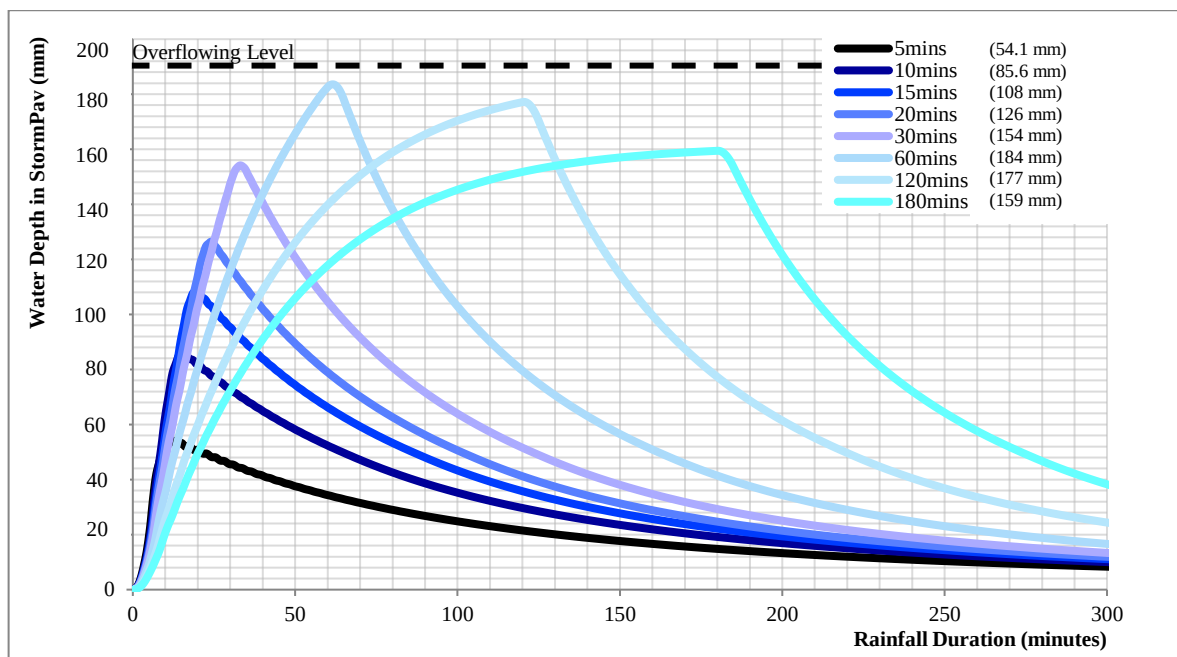


Figure 4.35: Time Series of Water Depth in StormPav in Varying Rainfall Durations For 190 mm x 500 mm Rectangular Orifice Outlet

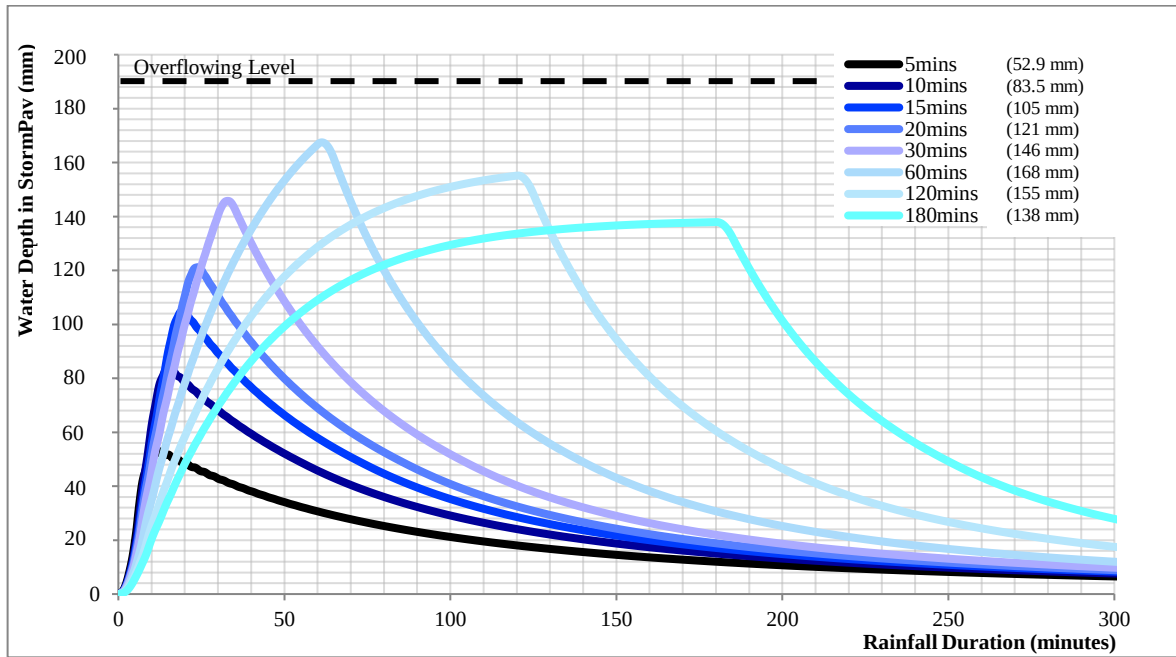


Figure 4.36: Time Series of Water Depth in StormPav in Varying Rainfall Durations For 190 mm x 700 mm Rectangular Orifice Outlet

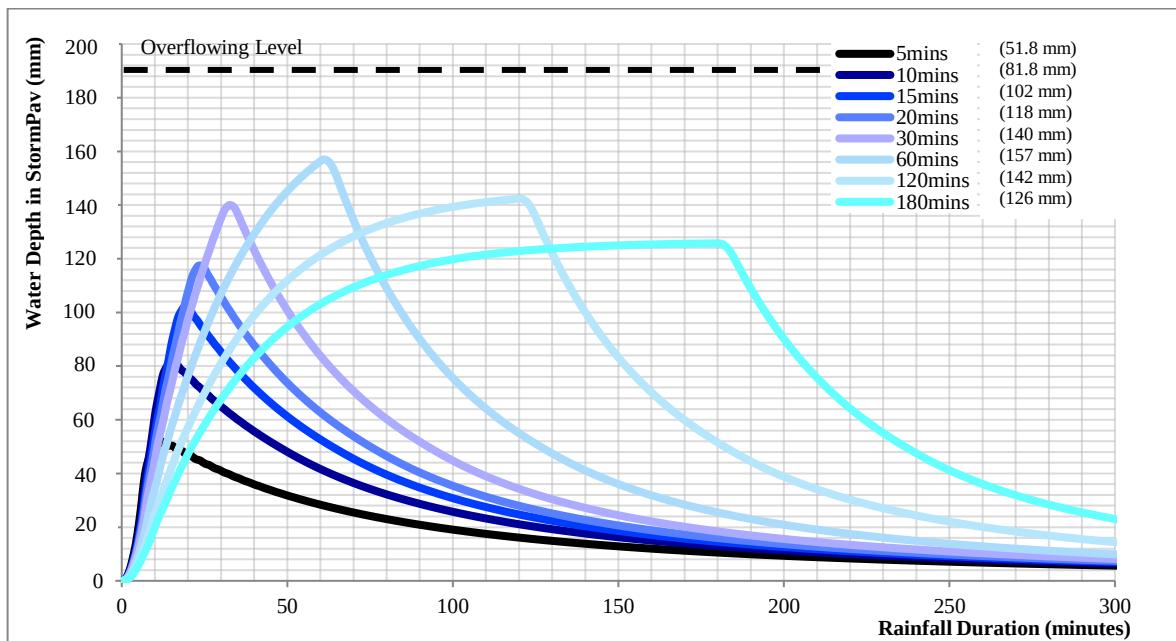
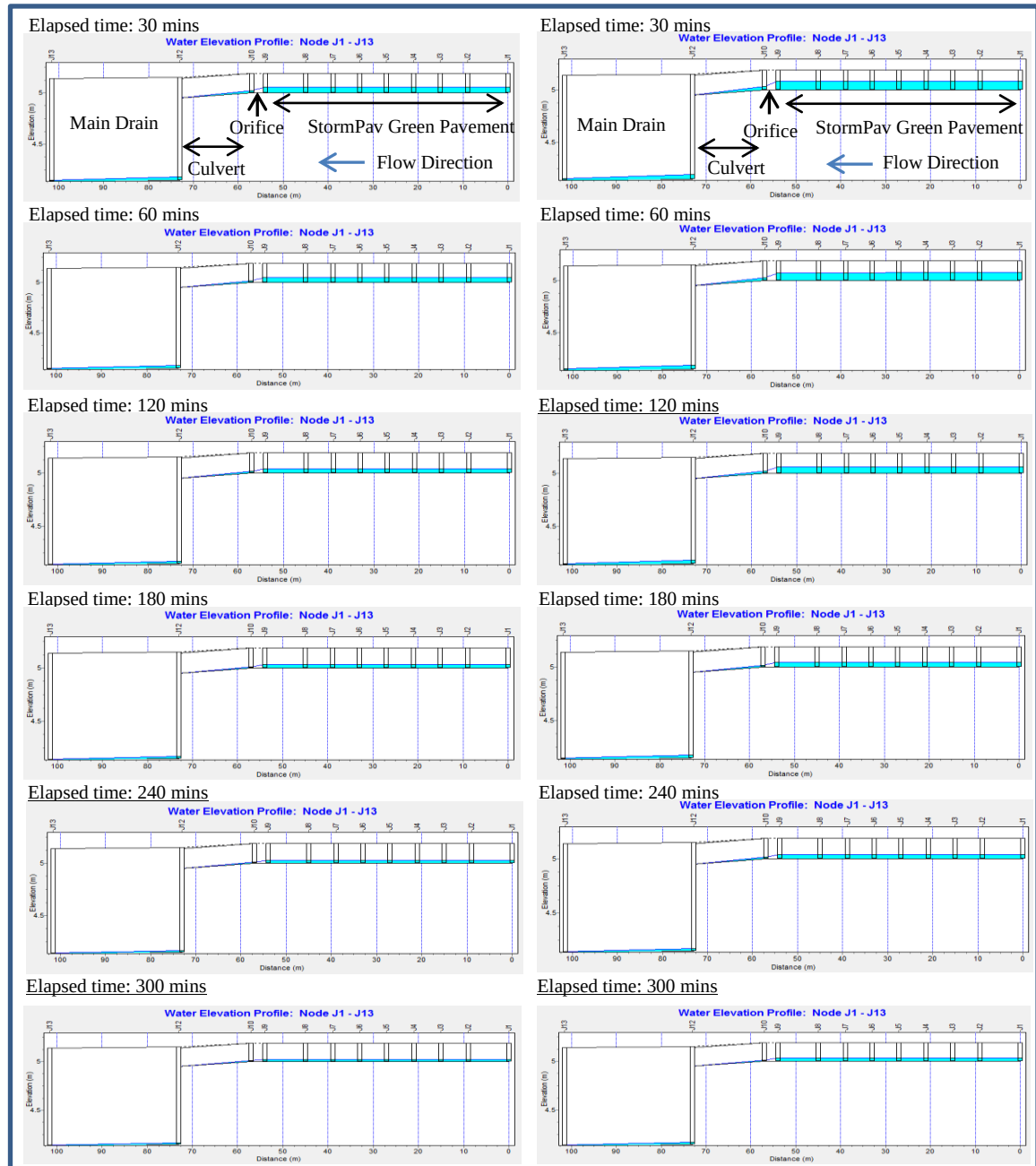


Figure 4.37: Time Series of Water Depth in StormPav in Varying Rainfall Durations For 190 mm x 900 mm Rectangular Orifice Outlet

The profile plots are presented in Figure 4.38 to Figure 4.42 to show the filling, ponding and draining of the StormPav Green Pavement with varying outlet orifice sizes and different design rainfall durations. The flow process over 5 hours are presented.

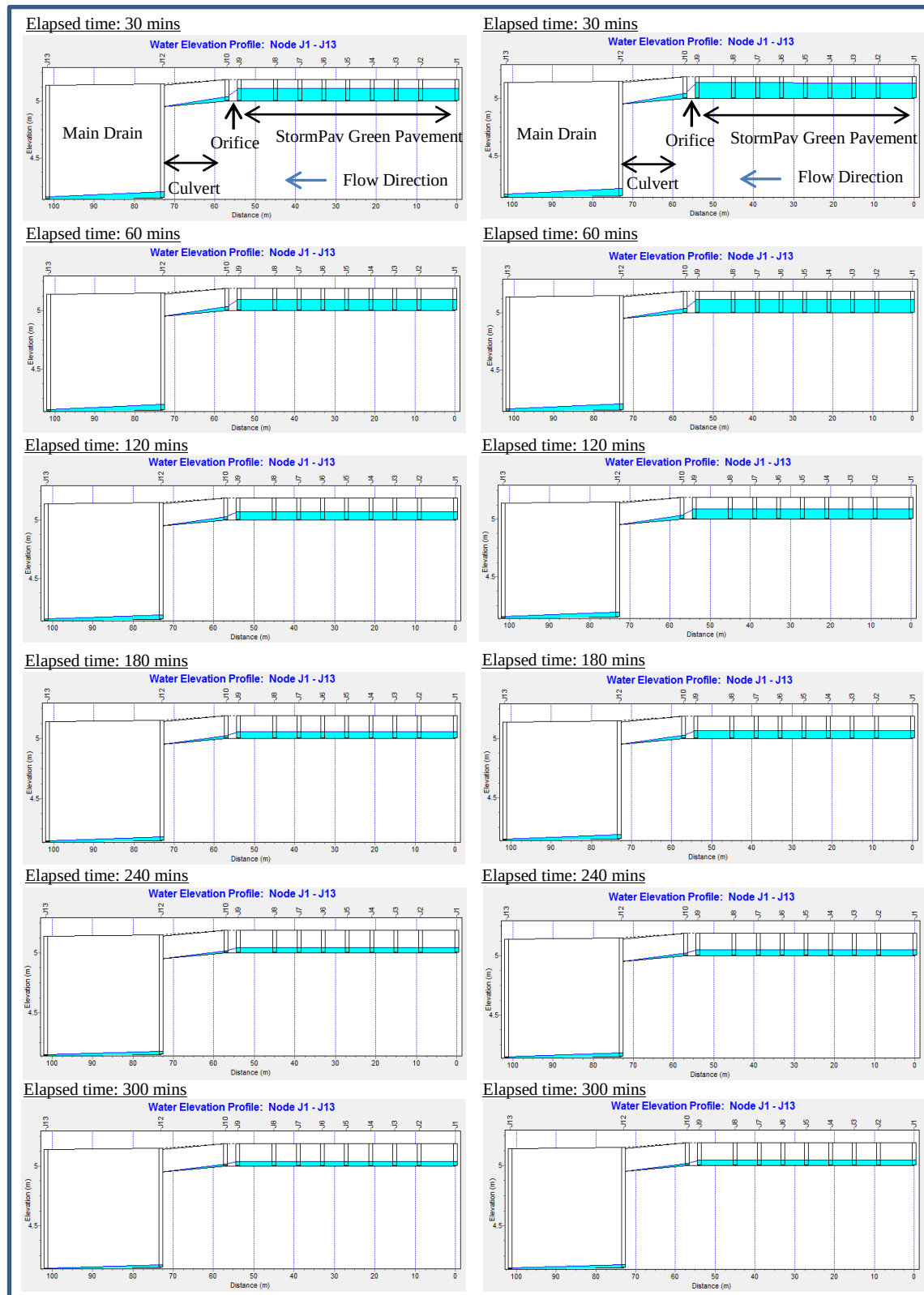
The flowing of stormwater for 190 mm diameter circular orifice outlet in different time elapsed is depicted in Figure 4.38. It was observed that no overflowing occurred except at 60- to 180-minute design rainfall durations.



(a) 5-minute design rainfall duration

(b) 10-minute design rainfall duration

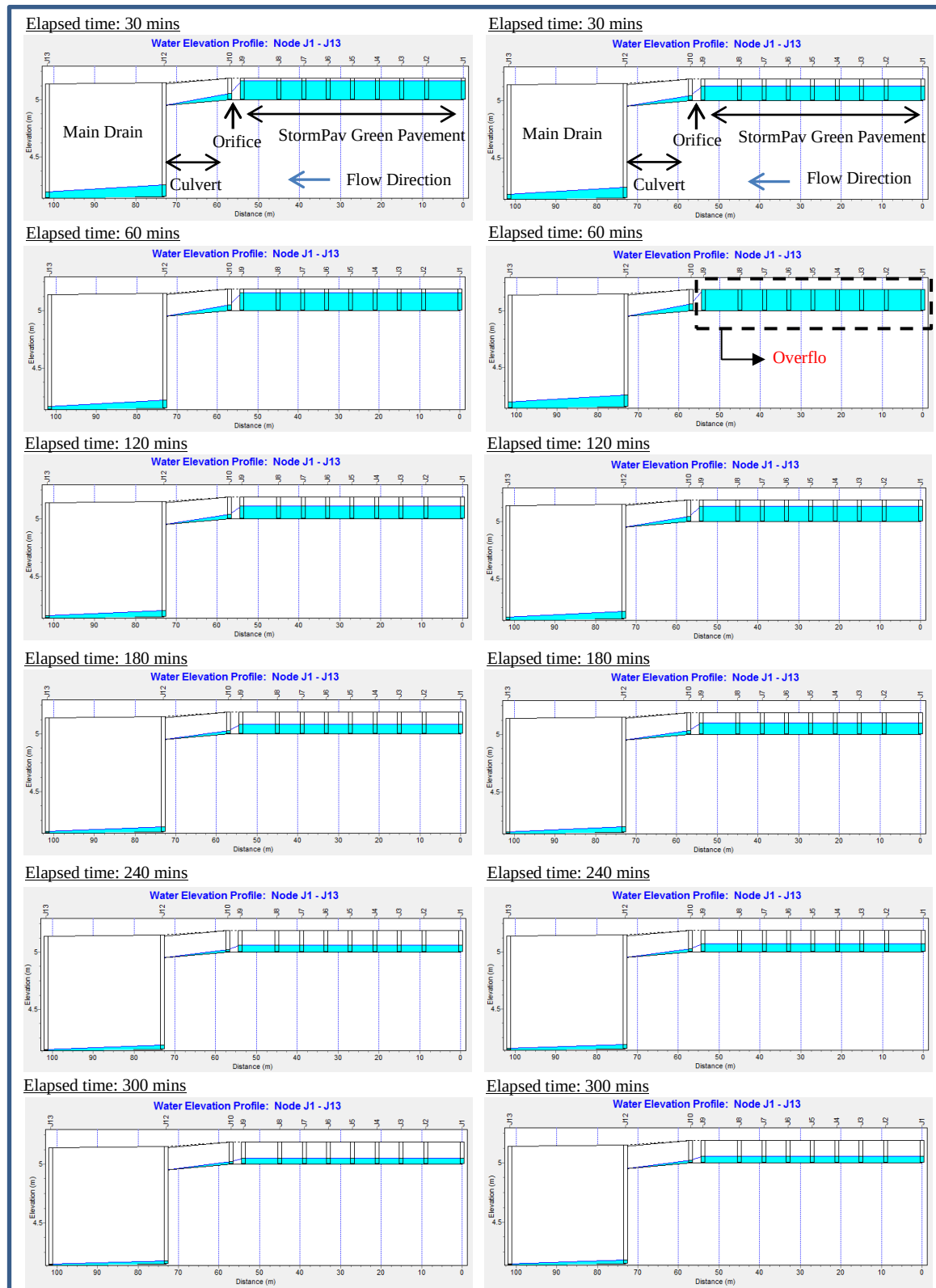
Figure 4.38: Flowing of Stormwater for 190 mm Diameter Circular Orifice Outlet in Different Elapsed Times



(c) 15-minute design rainfall duration

(d) 20-minute design rainfall duration

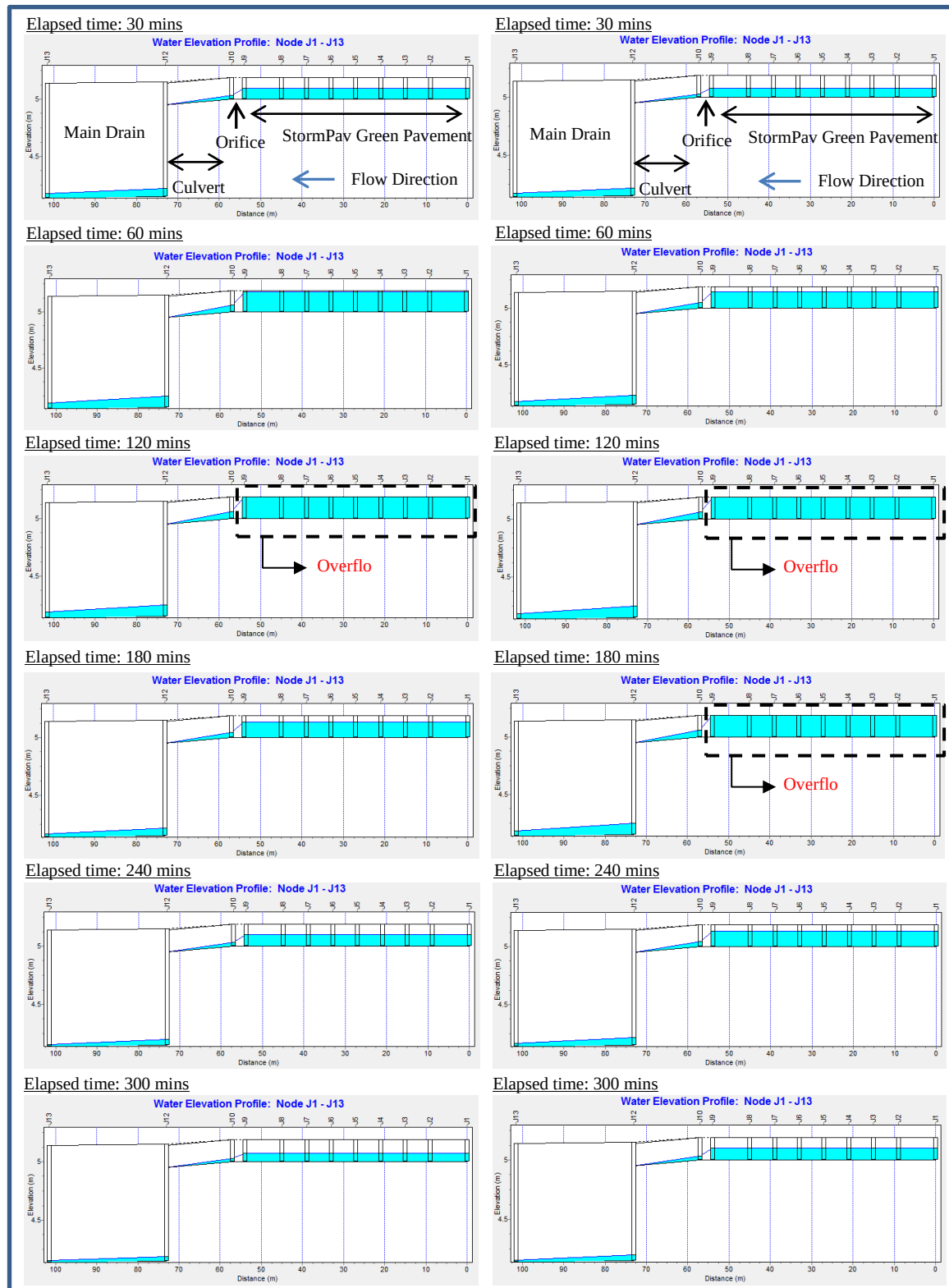
Figure 4.38 continued



(e) 30-minute design rainfall duration

(f) 60-minute design rainfall duration

Figure 4.38 continued

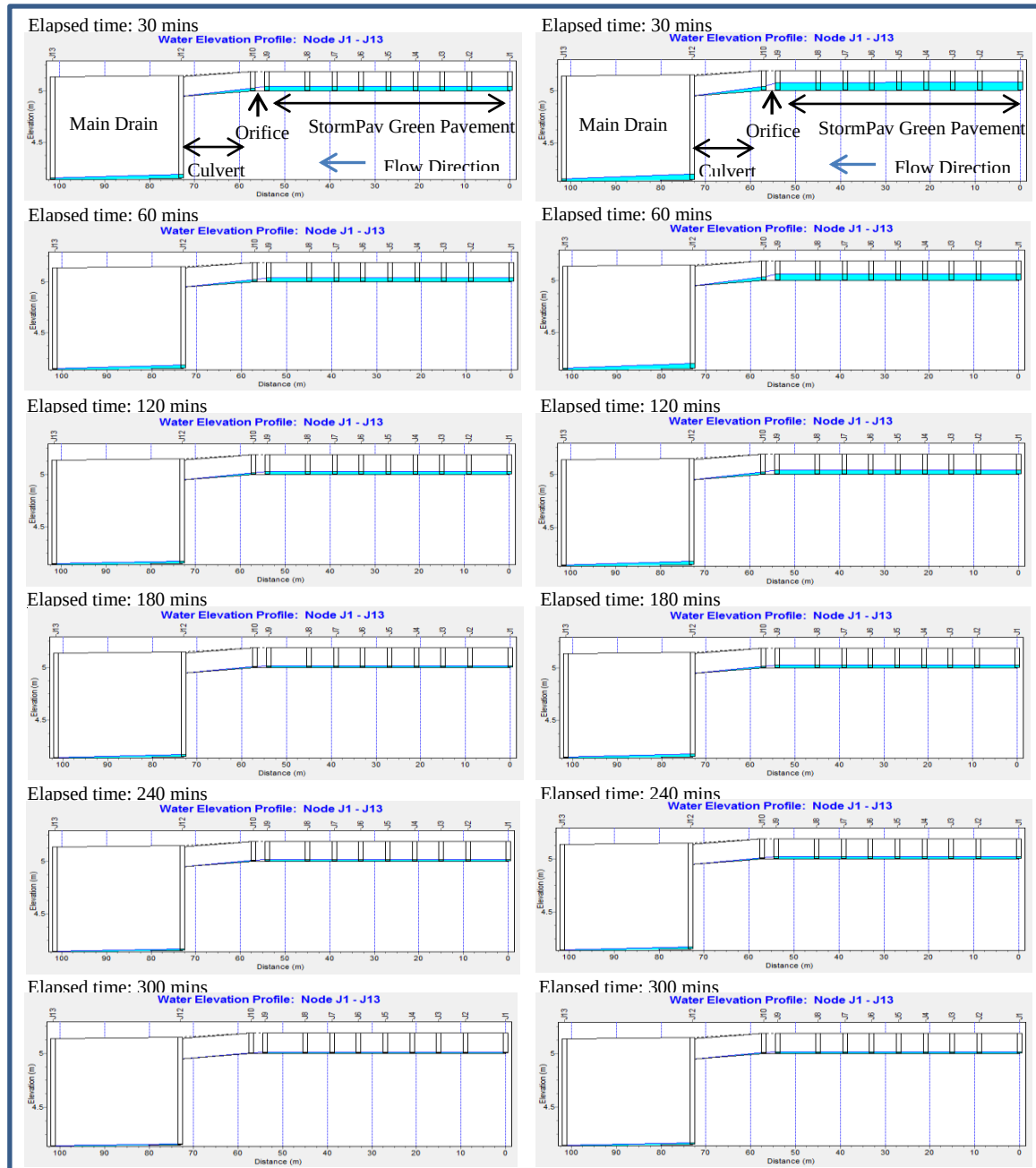


(g) 120-minute design rainfall duration

(h) 180-minute design rainfall

Figure 4.38 continued

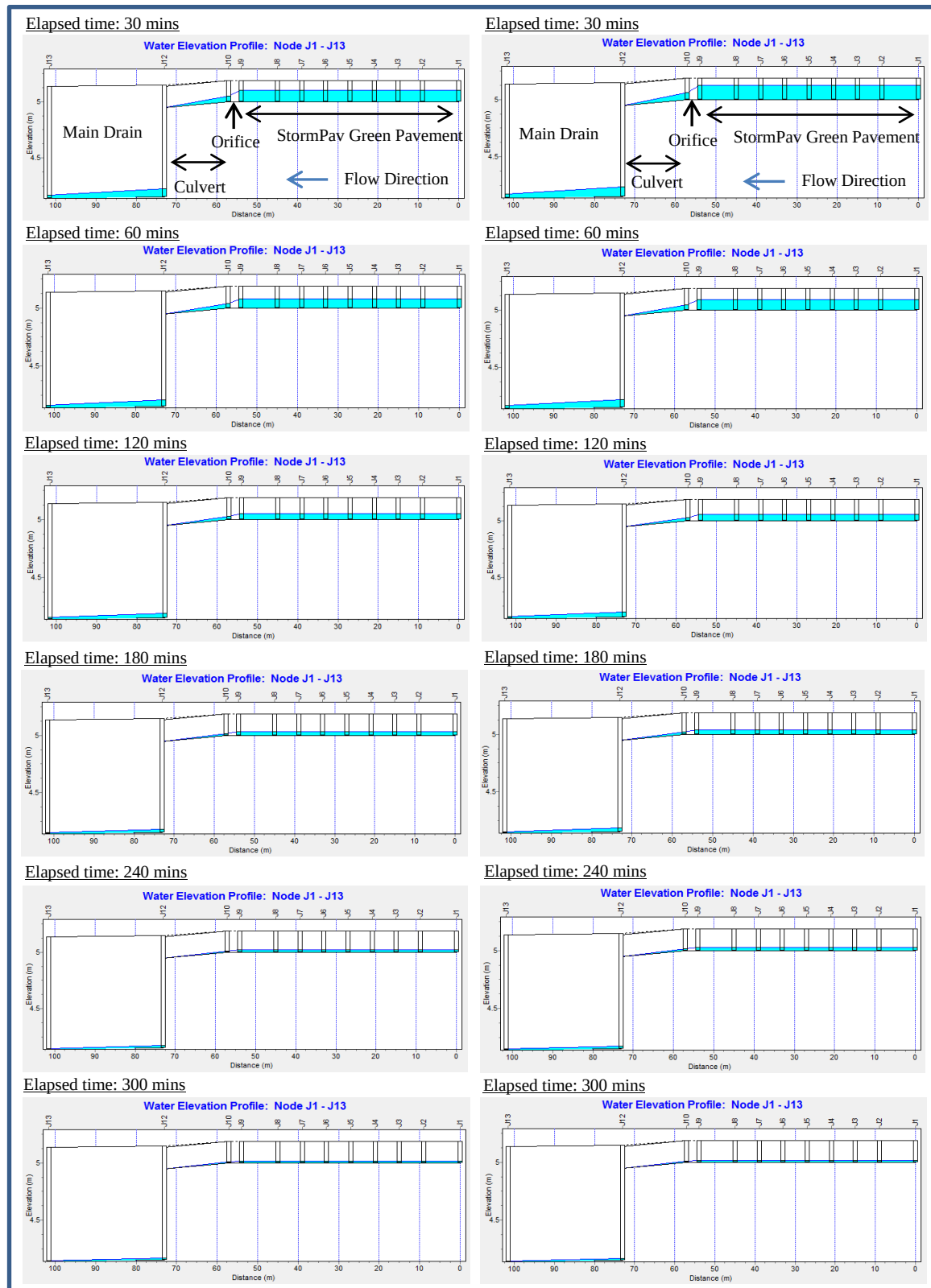
The flowing of stormwater for 190 mm x 300 mm rectangular orifice outlet in different time elapsed is depicted in Figure 4.39. It was observed that no overflowing occurred except at 60- to 180-minute design rainfall durations.



(a) 5-minute design rainfall duration

(b) 10-minute design rainfall duration

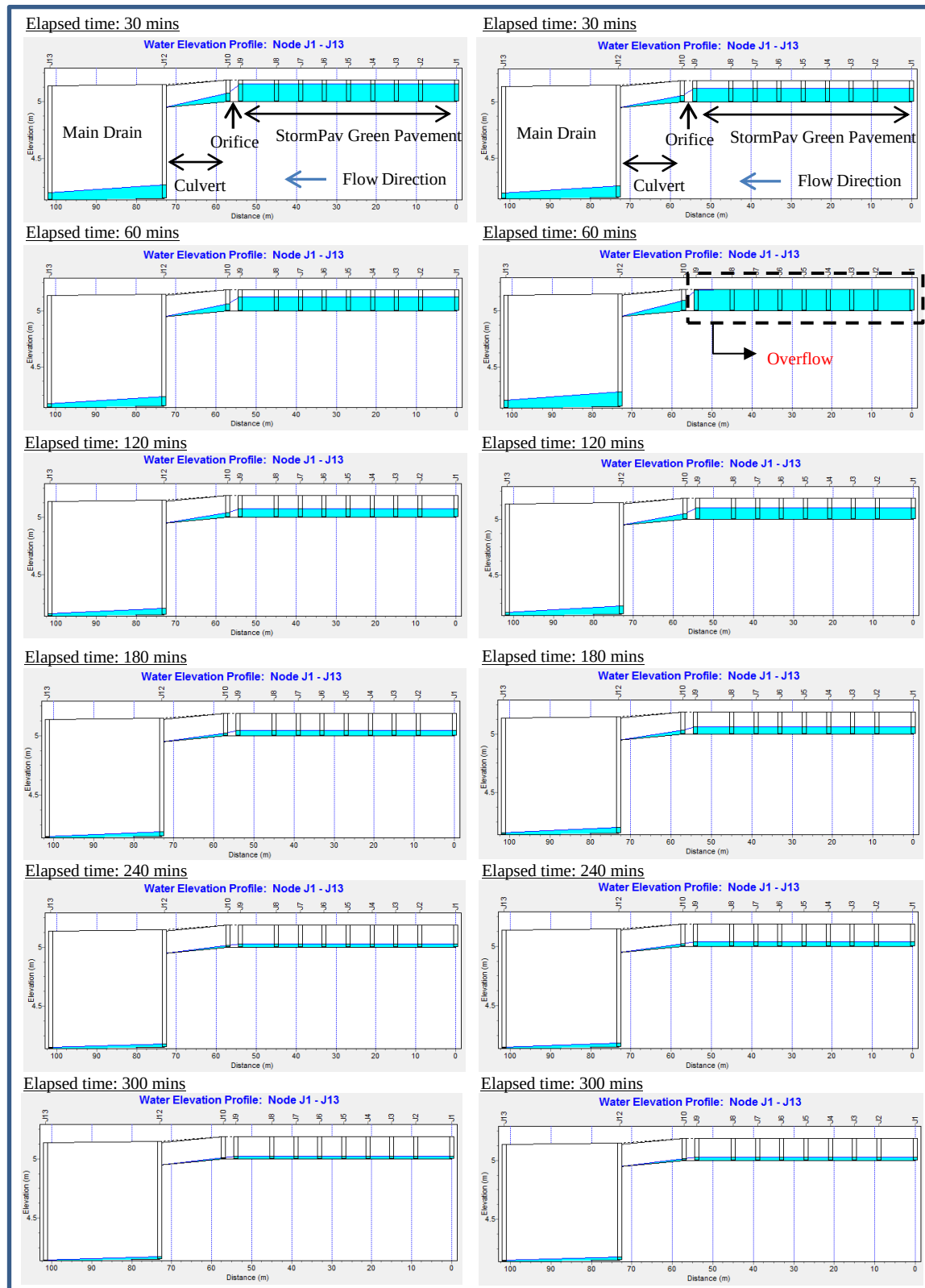
Figure 4.39: Flowing of Stormwater for 190 mm x 300 mm Rectangular Orifice Outlet in Different Elapsed Times



(c) 15-minute design rainfall duration

(d) 20-minute design rainfall duration

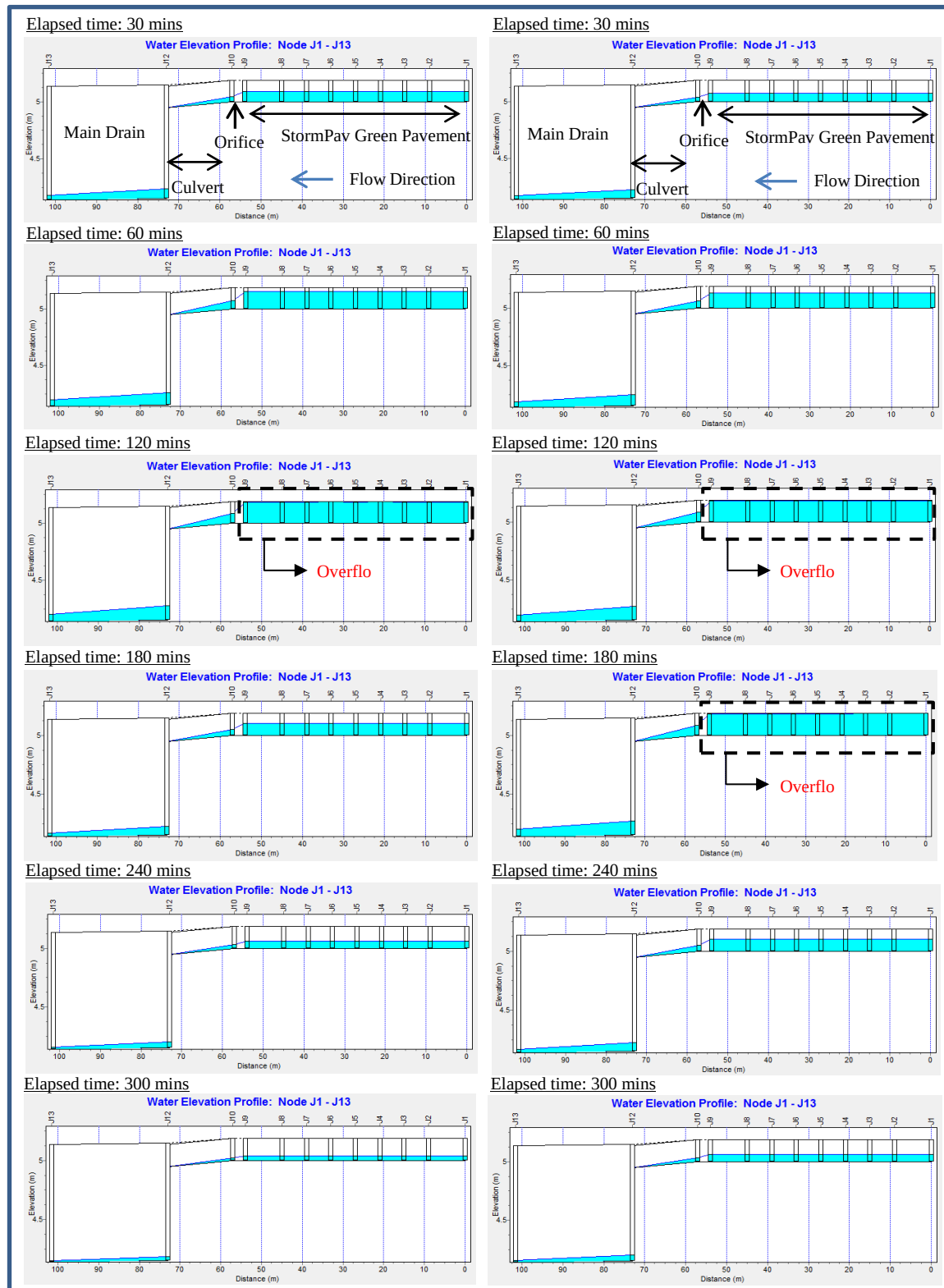
Figure 4.39 continued



(e) 30-minute design rainfall duration

(f) 60-minute design rainfall duration

Figure 4.39 continued

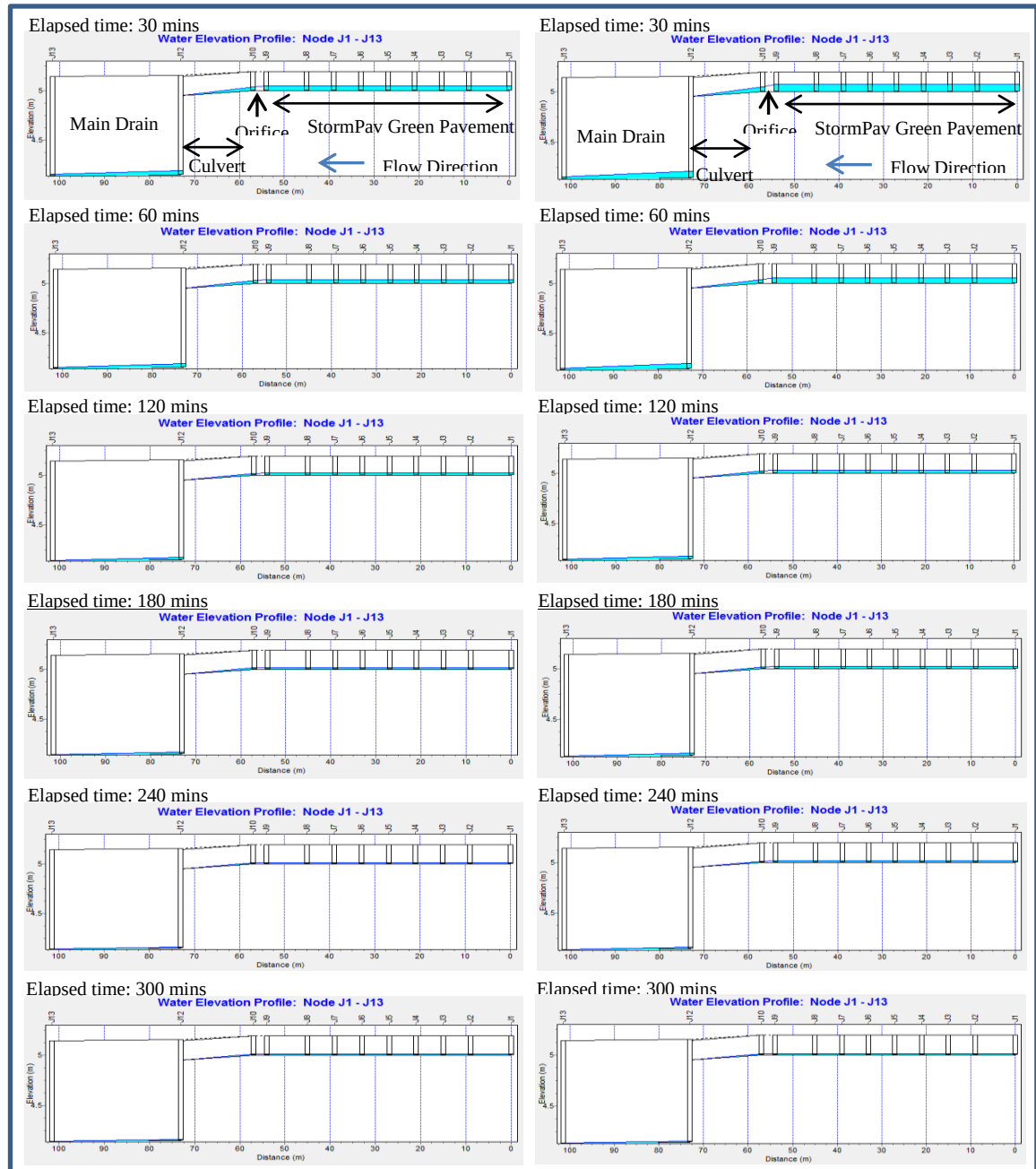


(g) 120-minute design rainfall duration

(h) 180-minute design rainfall

Figure 4.39 continued

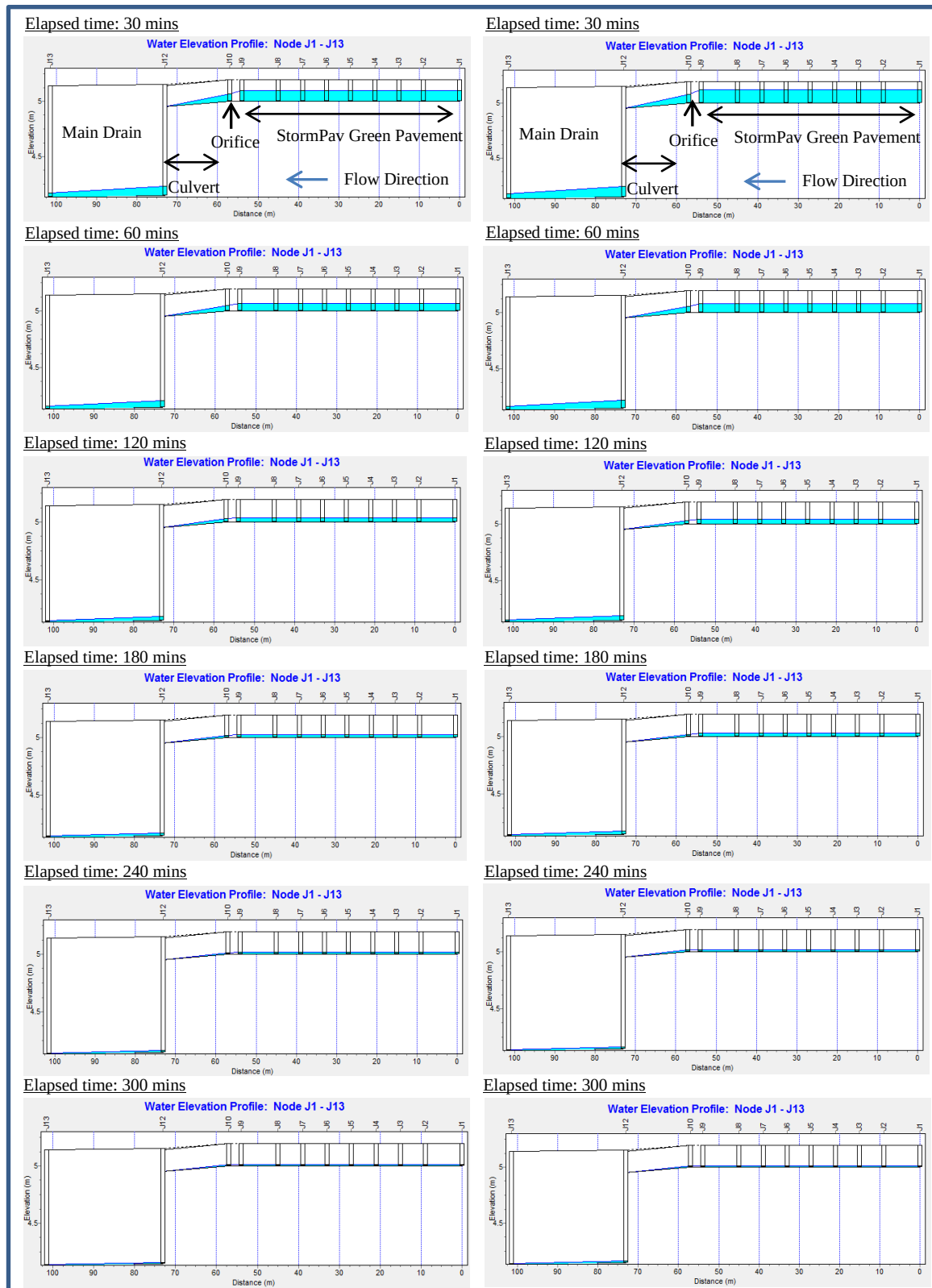
The flowing of stormwater for 190 mm x 500 mm rectangular orifice outlet in different time elapsed is depicted in Figure 4.40. It was observed that no overflowing occurred at any design rainfall durations.



(a) 5-minute design rainfall duration

(b) 10-minute design rainfall duration

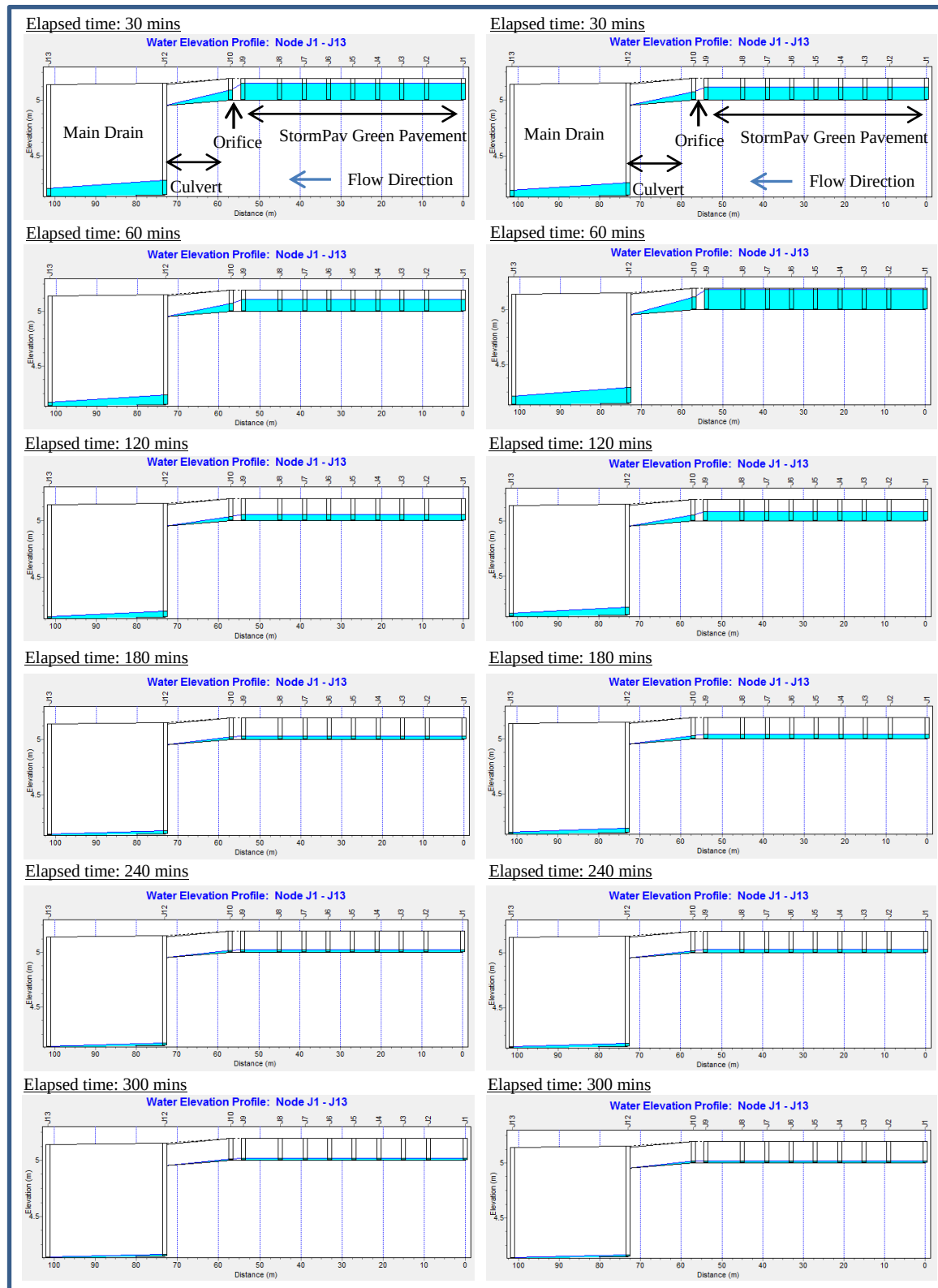
Figure 4.40: Flowing of Stormwater for 190 mm x 500 mm Rectangular Orifice Outlet in Different Elapsed Times



(c) 15-minute design rainfall duration

(d) 20-minute design rainfall duration

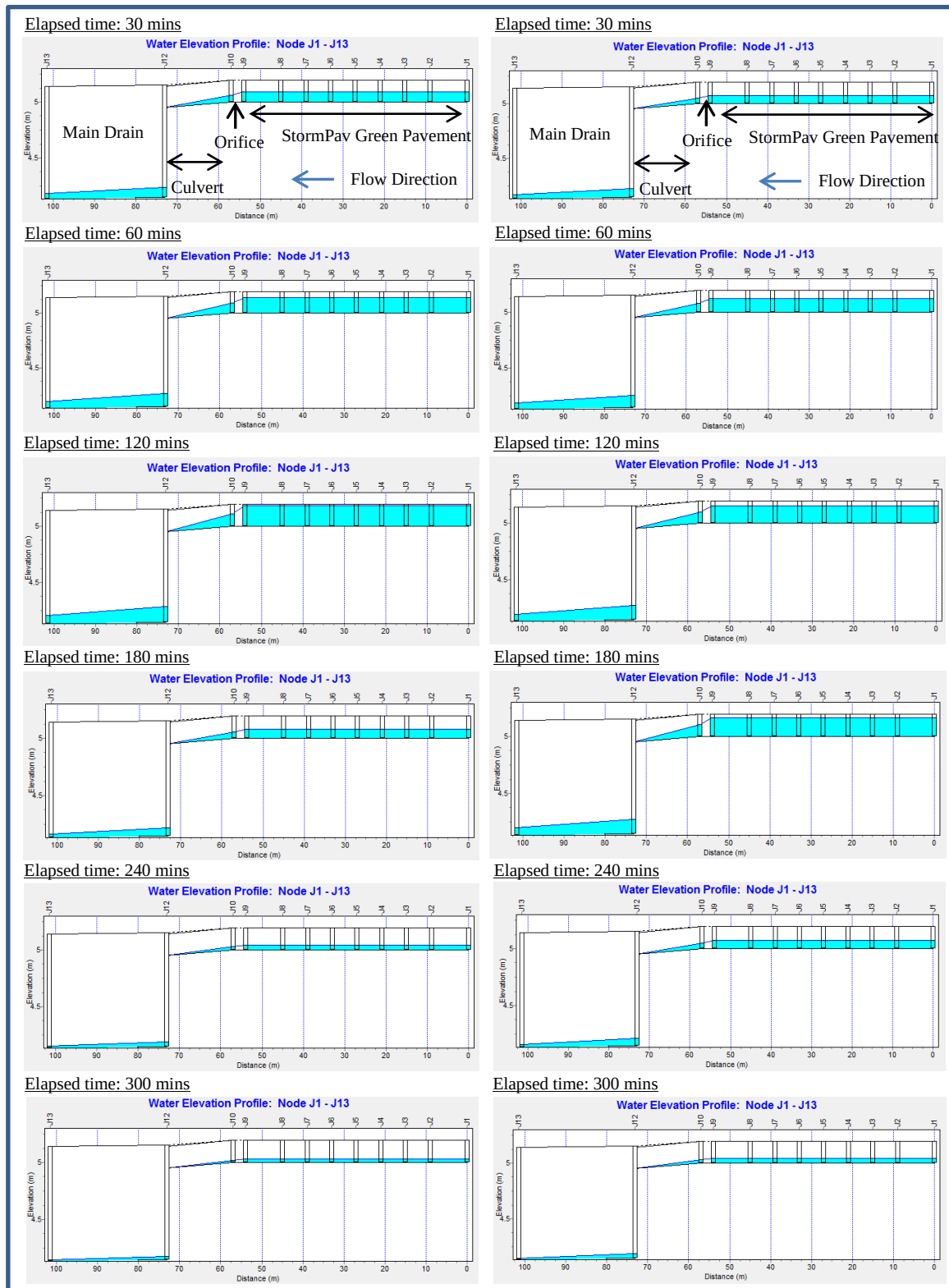
Figure 4.40 continued



(e) 30-minute design rainfall duration

(f) 60-minute design rainfall duration

Figure 4.40 continued

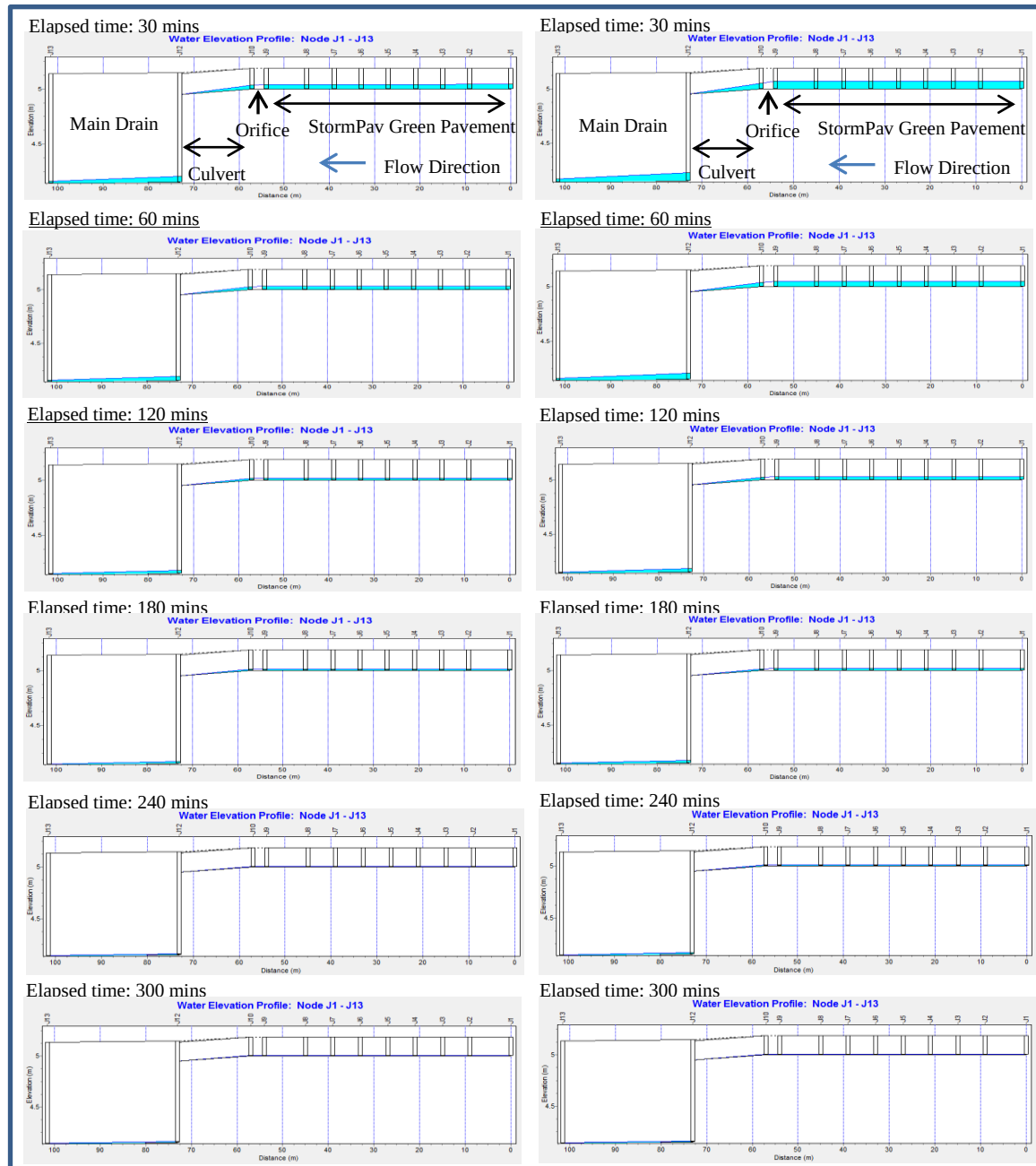


(g) 120-minute design rainfall duration

(h) 180-minute design rainfall

Figure 4.40 continued

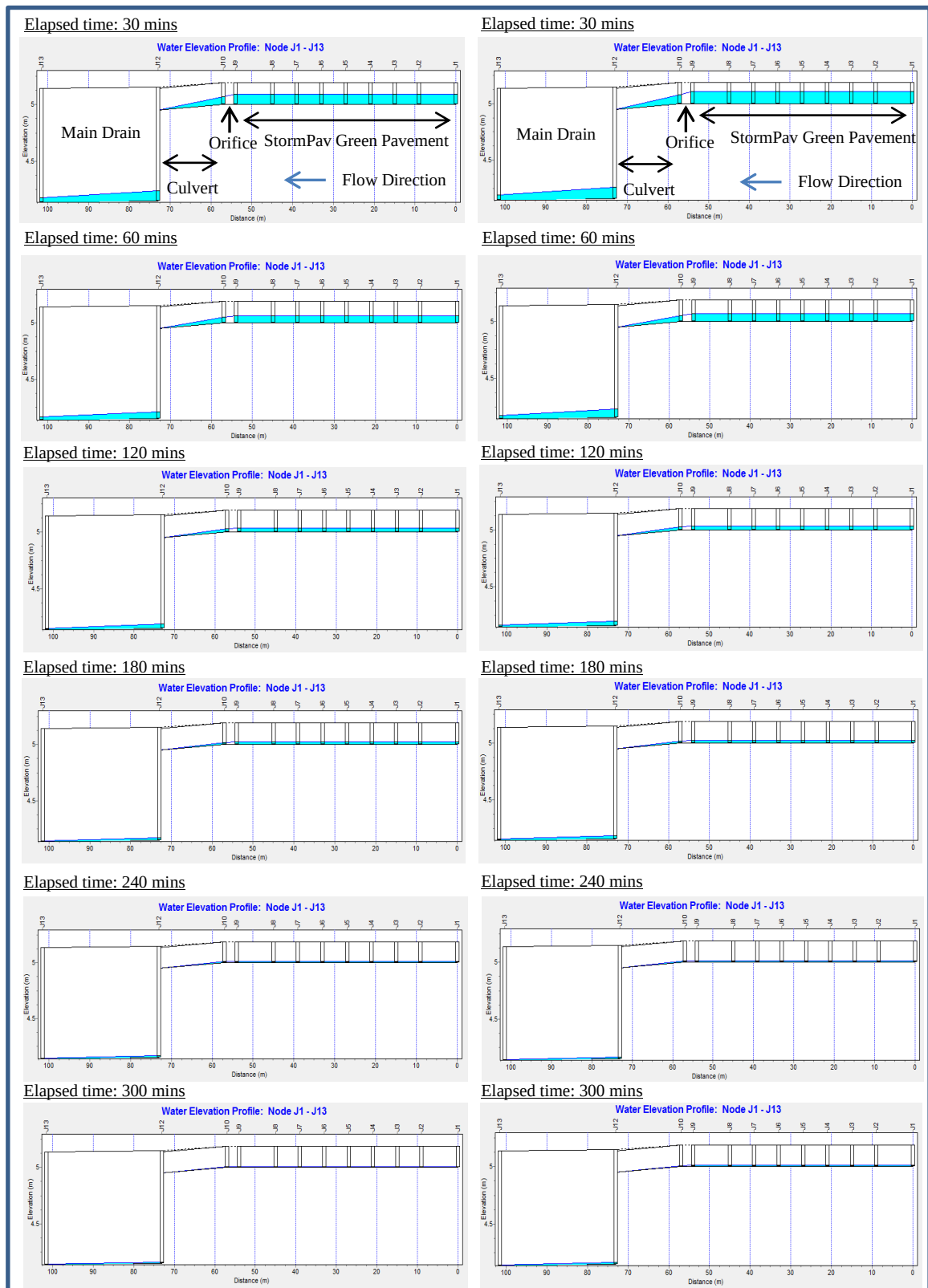
The flowing of stormwater for 190 mm x 700 mm rectangular orifice outlet in different time elapsed is depicted in Figure 4.41. It was observed that no overflowing occurred at any design rainfall durations.



(a) 5-minute design rainfall duration

(b) 10-minute design rainfall duration

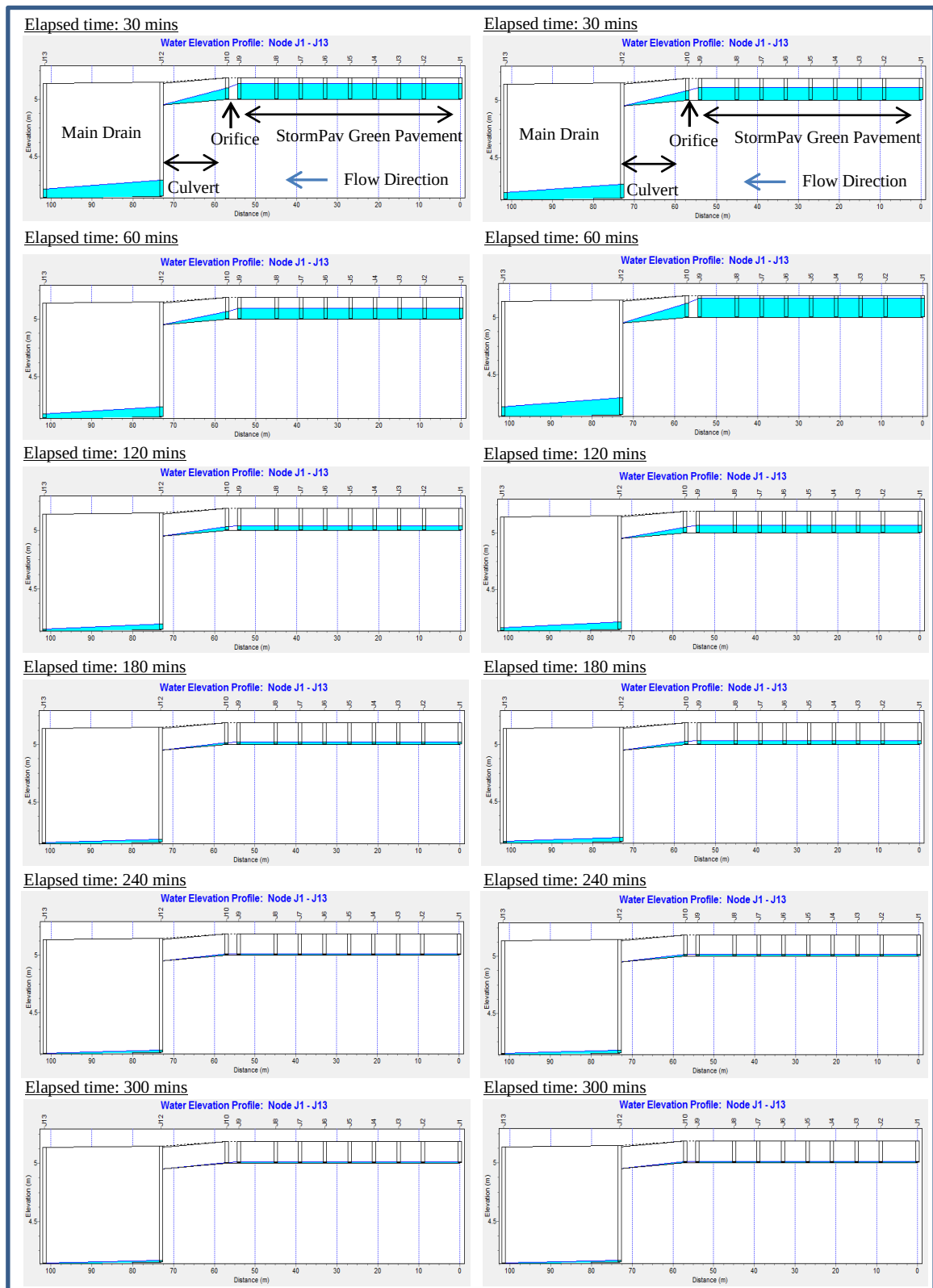
Figure 4.41: Flowing of Stormwater for 190 mm x 700 mm Rectangular Orifice Outlet in Different Elapsed Times



(c) 15-minute design rainfall duration

(d) 20-minute design rainfall duration

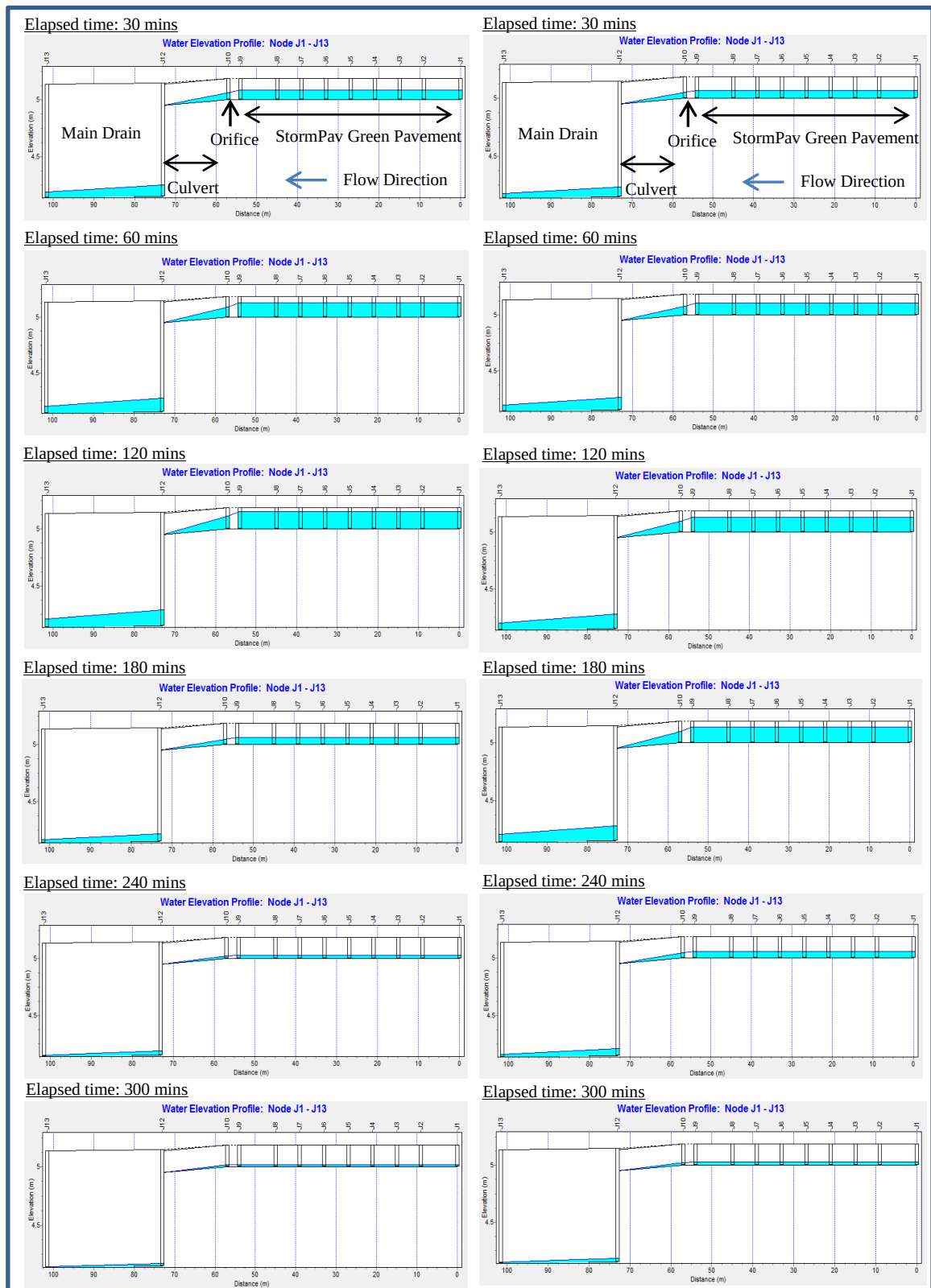
Figure 4.41 continued



(e) 30-minute design rainfall duration

(f) 60-minute design rainfall duration

Figure 4.41 continued

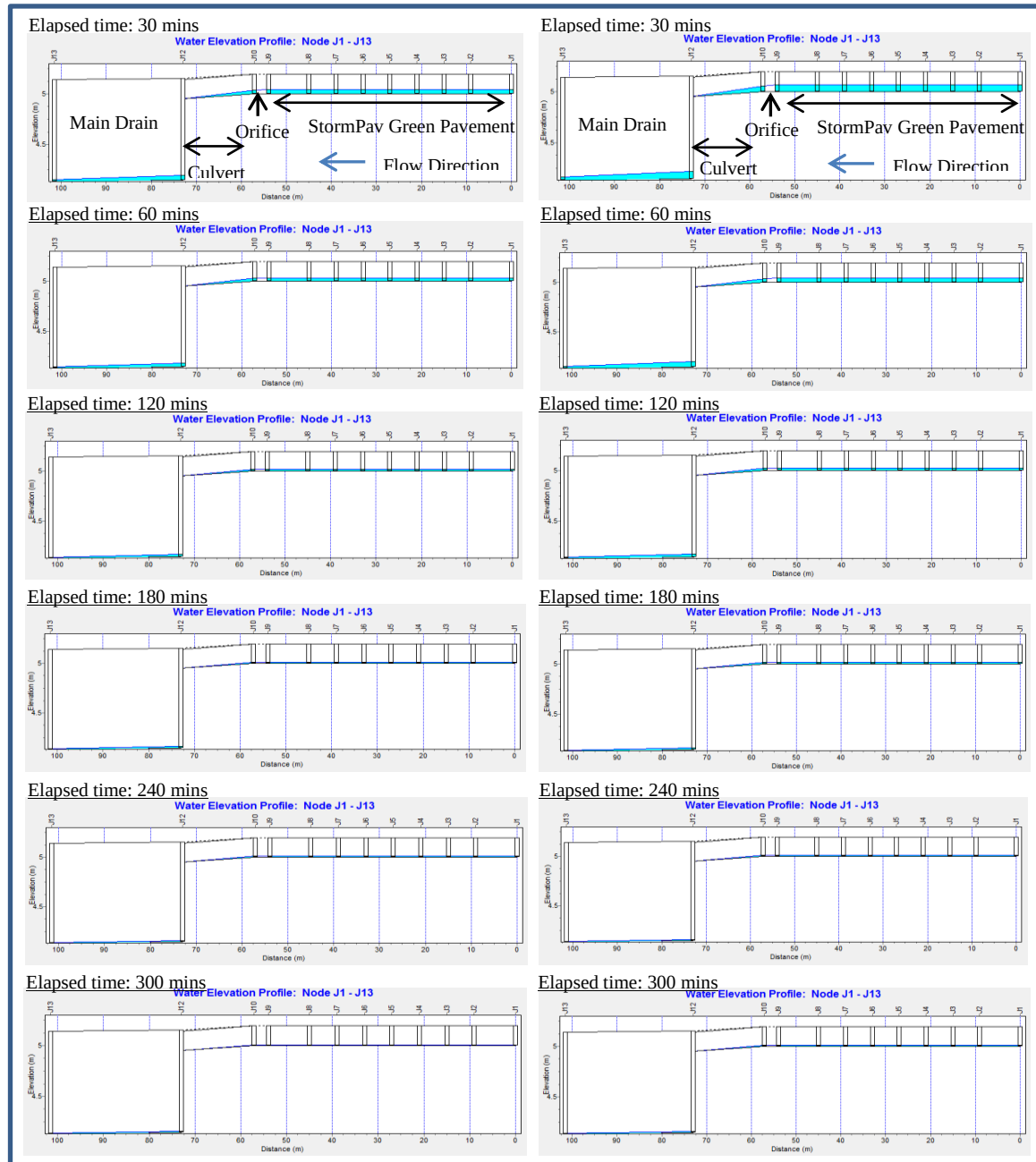


(g) 120-minute design rainfall duration

(h) 180-minute design rainfall

Figure 4.41 continued

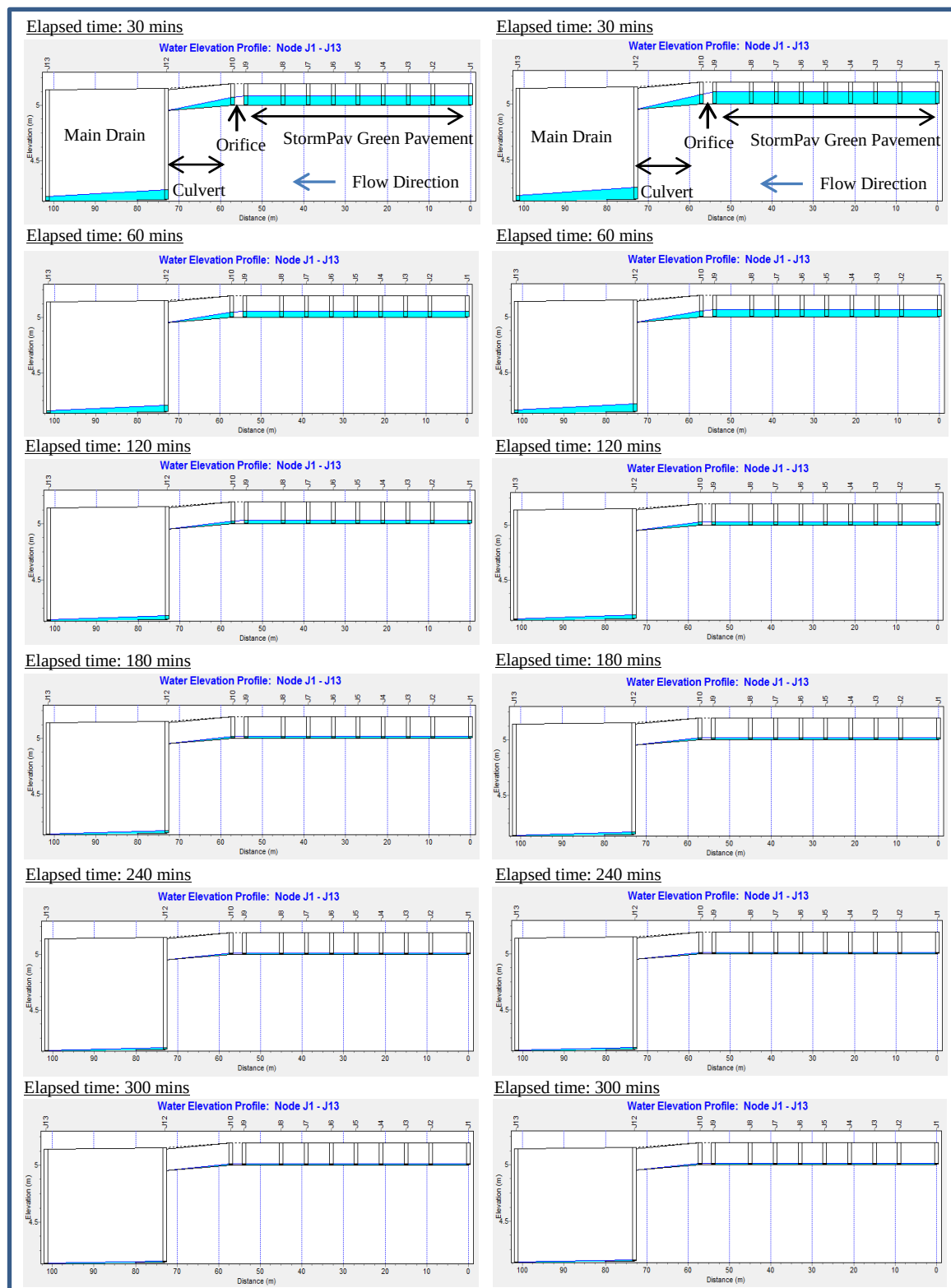
The flowing of stormwater for 190 mm x 900 mm rectangular orifice outlet in different time elapsed is depicted in Figure 4.42. It was observed that no overflowing occurred at any design rainfall durations.



(a) 5-minute design rainfall duration

(b) 10-minute design rainfall duration

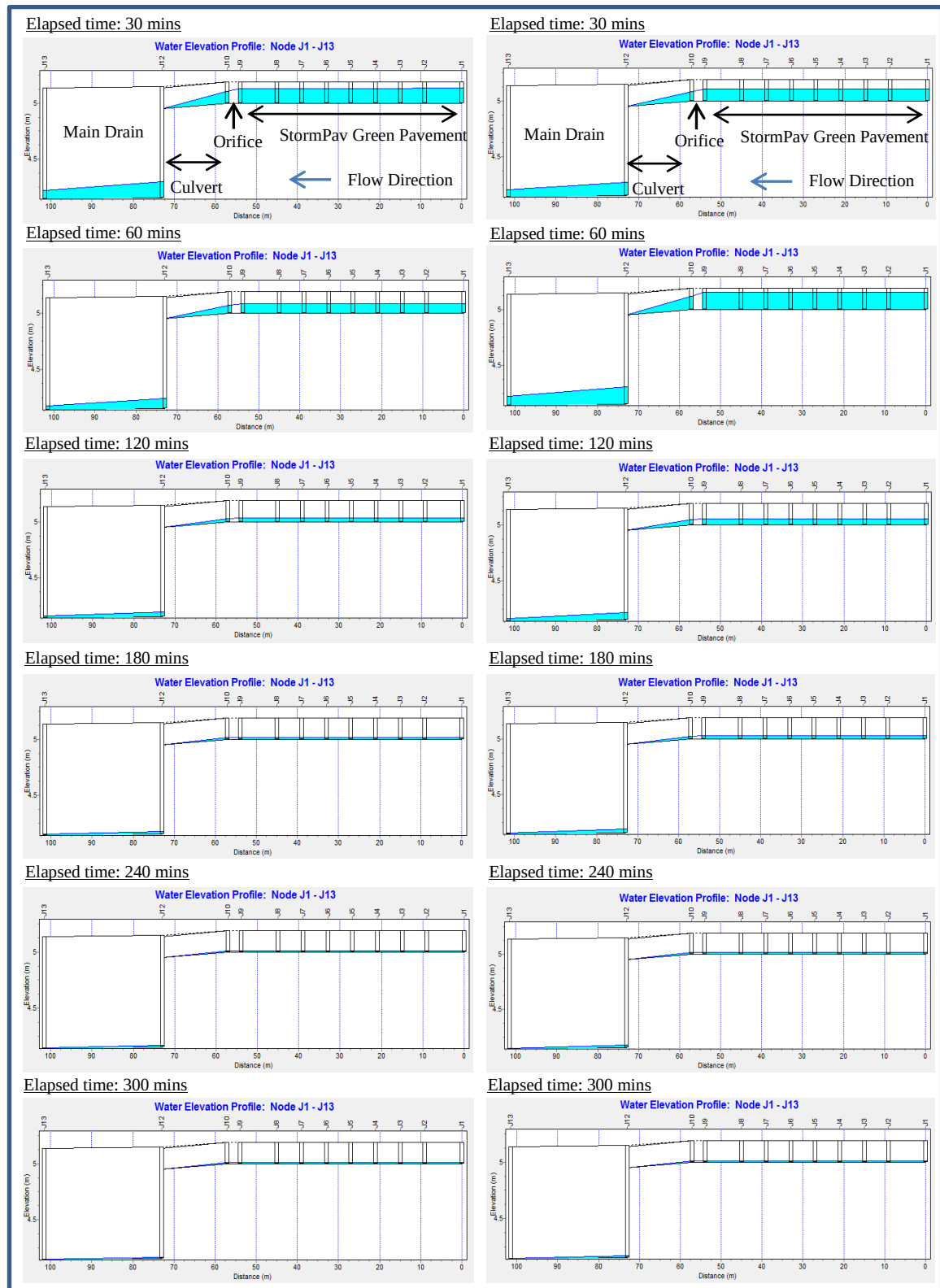
Figure 4.42: Flowing of Stormwater for 190 mm x 900 mm Rectangular Orifice Outlet in Different Elapsed Times



(c) 15-minute design rainfall duration

(d) 20-minute design rainfall duration

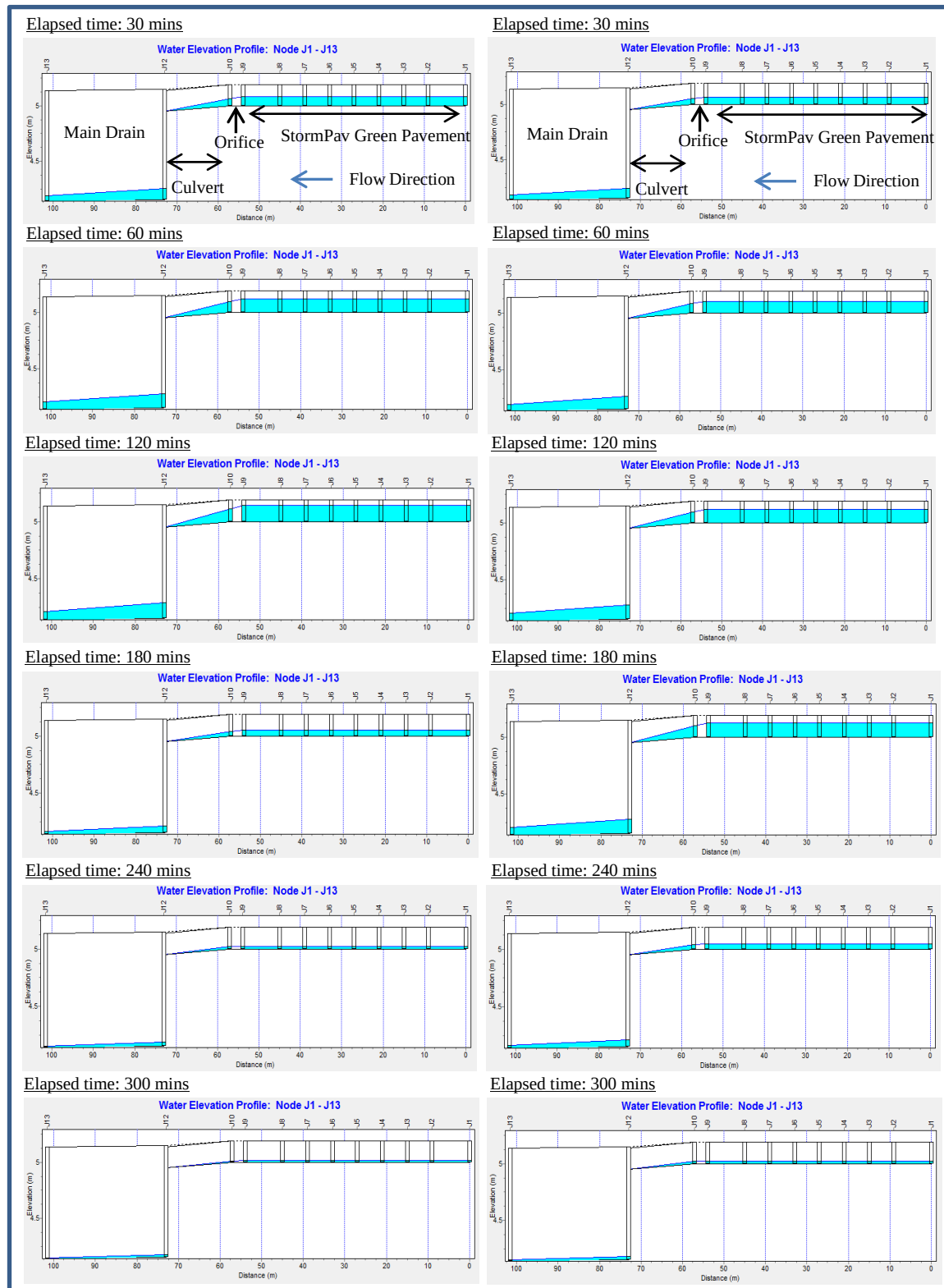
Figure 4.42 continued



(e) 30-minute design rainfall duration

(f) 60-minute design rainfall duration

Figure 4.42 continued



(g) 120-minute design rainfall duration

(h) 180-minute design rainfall

Figure 4.42 continued

Figure 4.43 reports the occupied volume capacity with varying outlet orifice sizes and design rainfall durations. The water volume due to restriction of 190 mm and 190 mm x 300 mm orifice sizes occupied 100% of the volume system provided when subjected to higher design rainfall durations. On the other hand, 190 mm x 900 mm takes up the least volume provided by the StormPav Green Pavement among the other orifice sizes in all design rainfall durations. This is by virtue, too small an outlet shall result in overflowing, while too big shall result in quick discharge out of the system.

Besides that, 190 mm x 500 mm orifice provides the least percentage to cater volume runoff for weather variability, followed by 190 mm x 700 mm and 190 mm x 900 mm. For instance, 190 mm x 500 mm, 190 mm x 700 mm and 190 mm x 900 mm orifice provide 3.4%, 11.9% and 17.4% respectively to cater weather variability.

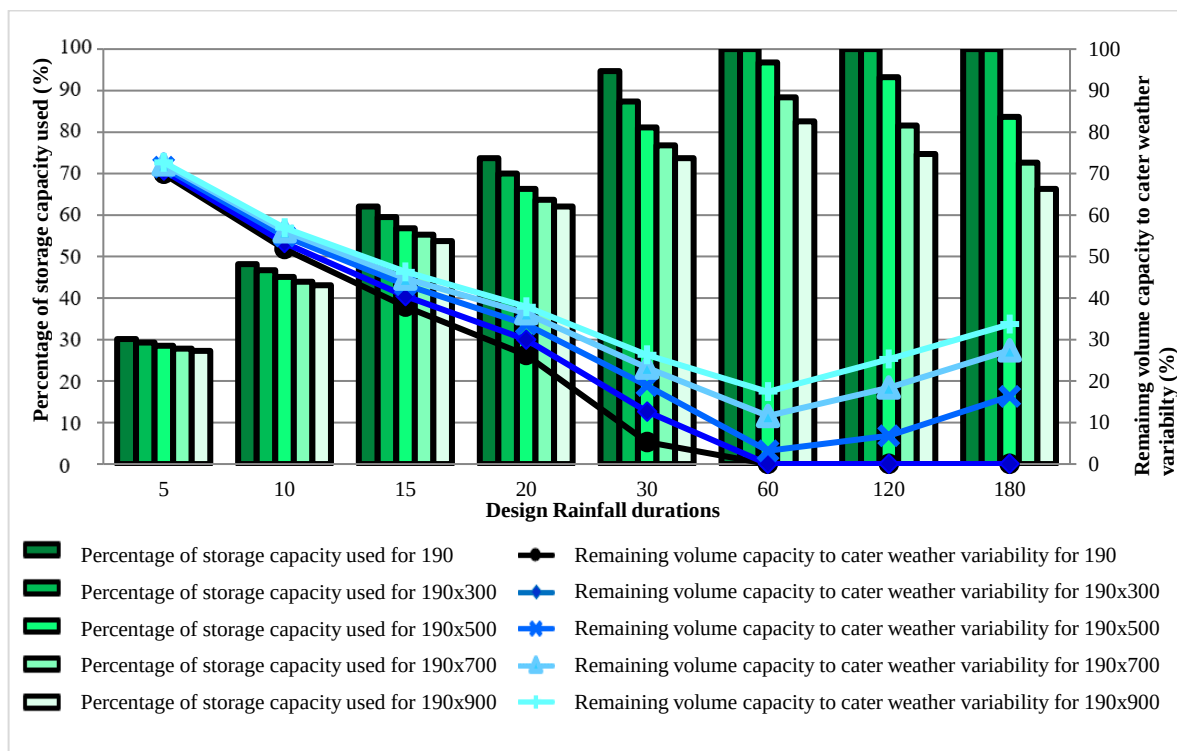


Figure 4.43: Occupied Volume Capacity with Varying Orifice Sizes and Design Rainfall Durations

Thus, it can be deduced that, when outlet orifice size is getting larger, the lower the maximum flow depth it is within the StormPav Green Pavement. In other words, the safer the StormPav system from overflowing. However, if the outlet size is too large, ponding effect of the system will be trivial. Therefore, the best size is 190 mm x 700 mm to provide the optimum ponding and draining effects.

4.3 Outfall Analysis

In this section, outfall discharges of (a) pre-development condition, post development with (b) conventional drainage system condition and (c) StormPav Green Pavement condition are presented.

4.3.1 Pre-Development Condition

The results showing the hydrographs for design rainfall durations up 180-minute storm duration are reported in Figure 4.44. As depicted in Figure 4.44, 5, 10, 15, 20, 30, 60, 120 and 180-minutes rainfall durations mark the peak discharges as 0.093 m³/s, 0.080 m³/s, 0.071 m³/s, 0.066 m³/s, 0.059 m³/s, 0.045 m³/s, 0.033 m³/s and 0.026 m³/s respectively.

Generally, the smaller the design rainfall duration, the higher the discharge runoff and the lower the total volume produced. For instance, the maximum peak discharge is higher for 5-minute design rainfall (0.093 m³/s), compared to 180-minute design rainfall (0.026 m³/s). Apart from that, the shapes of the hydrographs are also generated differently from each other which makes a varying time to peak values.

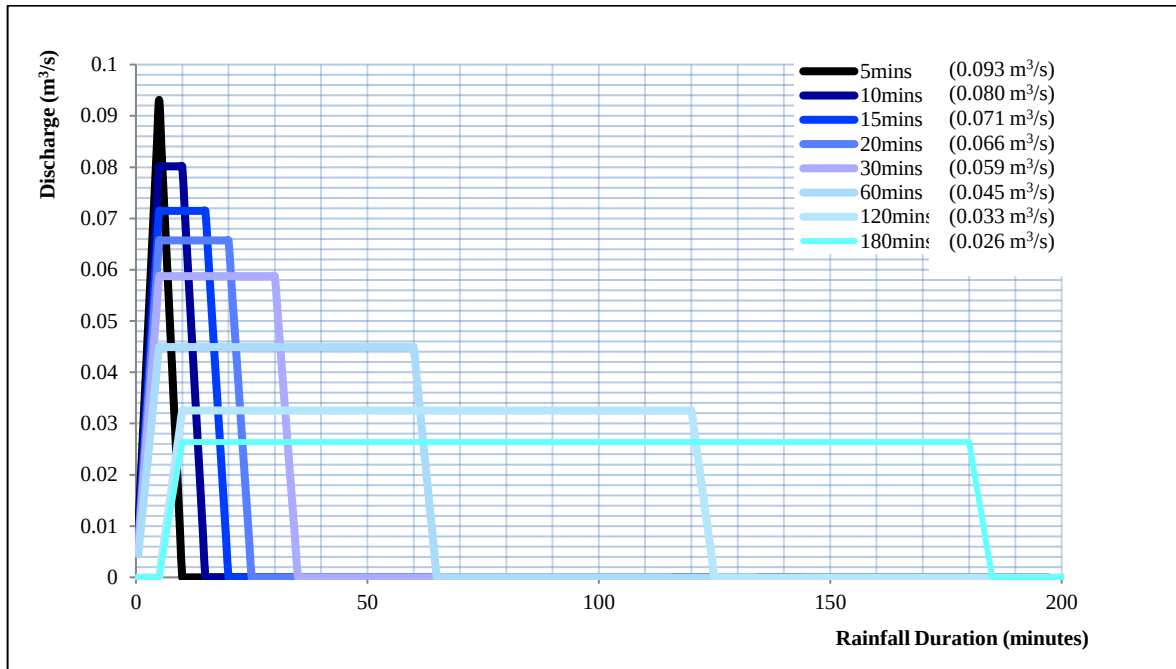


Figure 4.44: Hydrographs at Outfall of Pre-development Condition in Varying Rainfall Durations

4.3.2 Post-development with Conventional Drainage System

As depicted in Figure 4.45, 5, 10, 15, 20, 30, 60, 120 and 180-minutes rainfall durations mark the peak discharges as 0.199 m³/s, 0.200 m³/s, 0.178 m³/s, 0.164 m³/s, 0.147 m³/s, 0.112 m³/s, 0.081 m³/s and 0.066 m³/s respectively. From the hydrographs displayed in Figure 4.45, it can be deduced that the time of concentration of this model catchment is approximately 10 minutes as maximum peak discharge is obtained among other durations. Meaning, it takes approximate 10 minutes time to travel from the most distant point of the catchment to the outfall point. Therefore, any design rainfall duration less than 10 minutes in this model catchment, for example, 5-minutes duration, will produce a lower peak discharge. Meanwhile, longer design rainfall durations result in hydrographs with longer spans and lower peak discharges than the maximum peak discharge produced, for example, 10 minutes in this study.

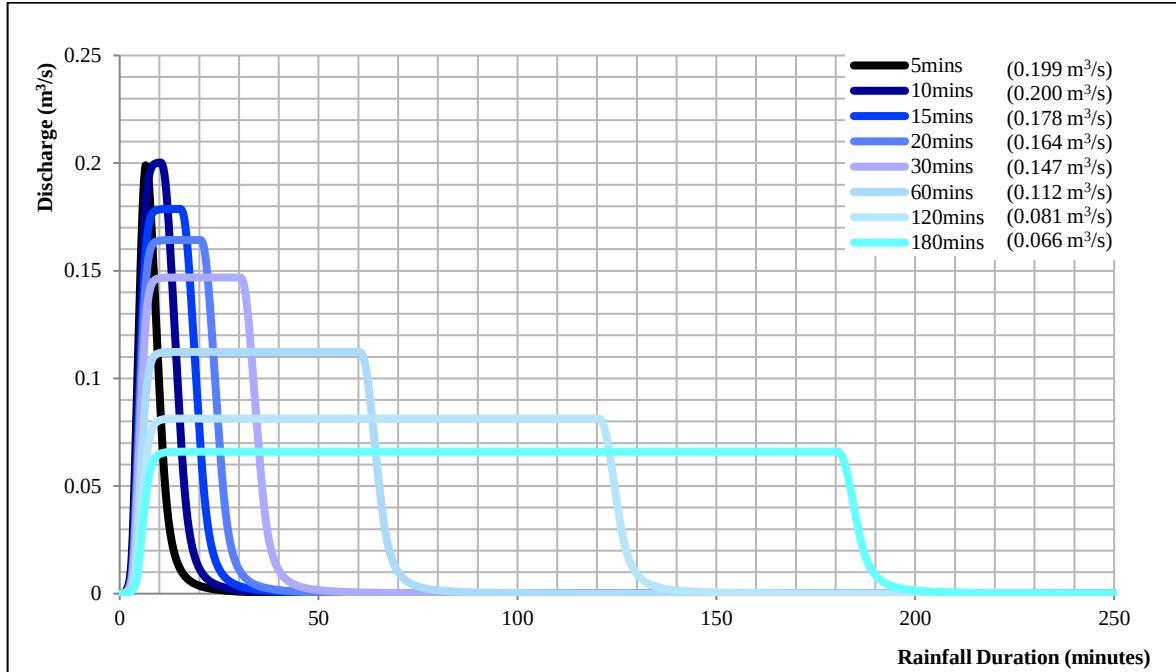


Figure 4.45: Hydrographs at Outfall of Conventional Drainage System for Varying Rainfall Durations

4.3.3 Post-development with StormPav Green Pavement System

This scenario is modelled as discussed in Section 3.5.1. Total flow at the outfall is analysed for outlet orifice sizes of 190 mm x 500 mm, 190 mm x 700 mm and 190 mm x 900 mm, in which no occurrence of overflowing is noticed in the StormPav Green Pavement. With the modelling efforts, Figure 4.46 to Figure 4.48 report the runoff hydrographs for the mentioned orifice outlet sizes at the outfall of the system.

According to Figure 4.46 to Figure 4.48, different times to peak are observed with StormPav Green Pavement. Same trend has been noticed as in the water depth time series graphs at the outlet of the StormPav Green Pavement. Outflow rate or discharge at the outfall for all cases show increasing trend from 5 to 60 minutes and declining from 60 to 180 minutes. For all cases, 5-minute rainfall duration reports the least discharge at outfall whereas 60-minute rainfall duration marks the highest discharge at outfall. As an illustration,

in the case of outlet orifice size of 190 mm x 500 mm, 5-minute duration reports 0.0416 m³/s while 60-minute shows 0.0819 m³/s at the outfall. Besides that, it can be deduced that the larger the orifice outlet size, the greater the discharge at the outfall of the system as well. For example, in the case of 60-minute duration, 190 mm x 500 mm, 190 mm x 700 mm, 190 mm x 900 mm outlet orifice outlet sizes mark the peak discharge of 0.0819 m³/s, 0.0915 m³/s and 0.0973 m³/s respectively. These trends are explained as in the Section 4.2.2.

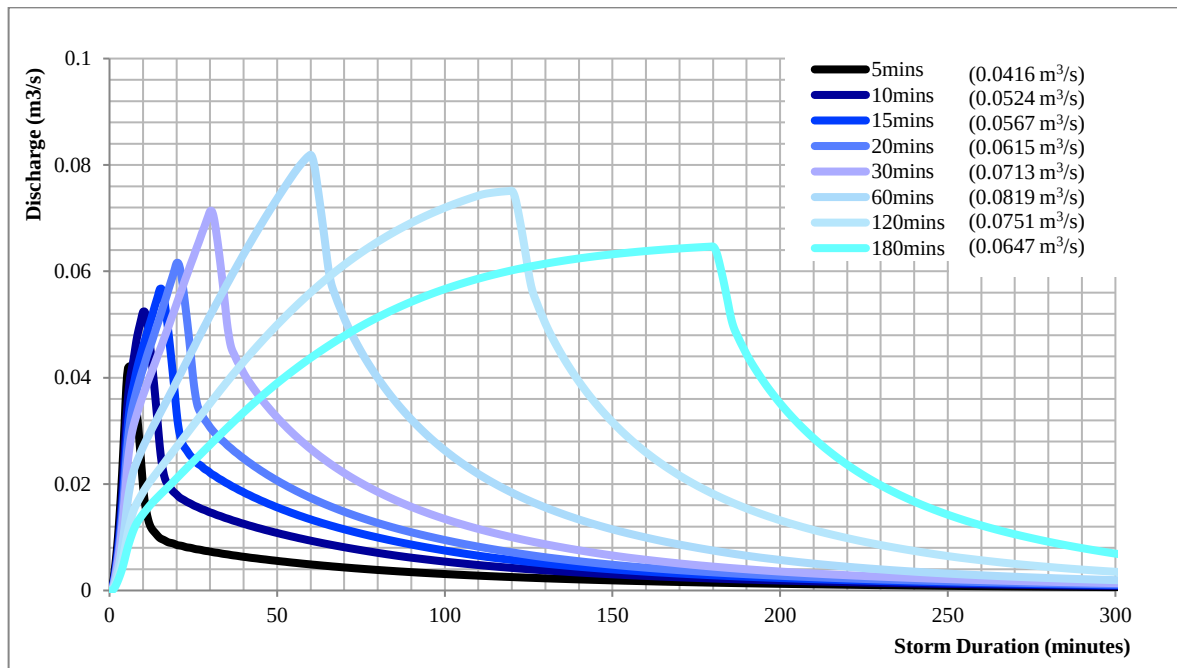


Figure 4.46: Hydrographs at Outfall of 190 mm x 500 mm Outlet Orifice for Varying Rainfall Durations

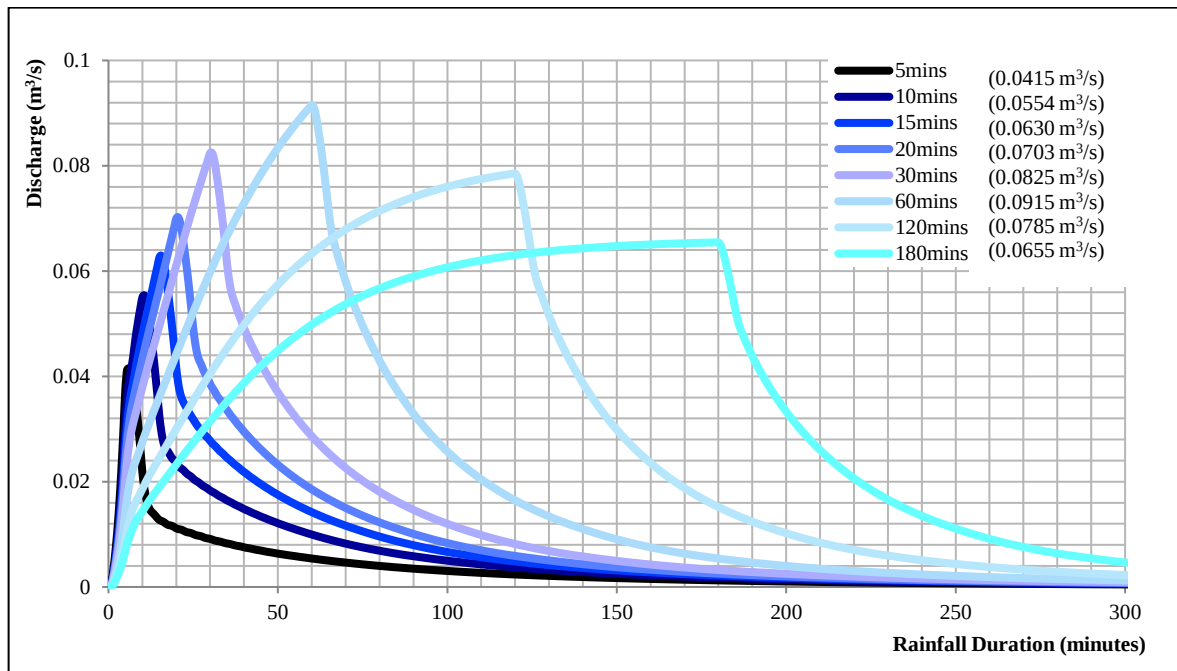


Figure 4.47: Hydrographs at Outfall of 190 mm x 700 mm Outlet Orifice for Varying Rainfall Durations

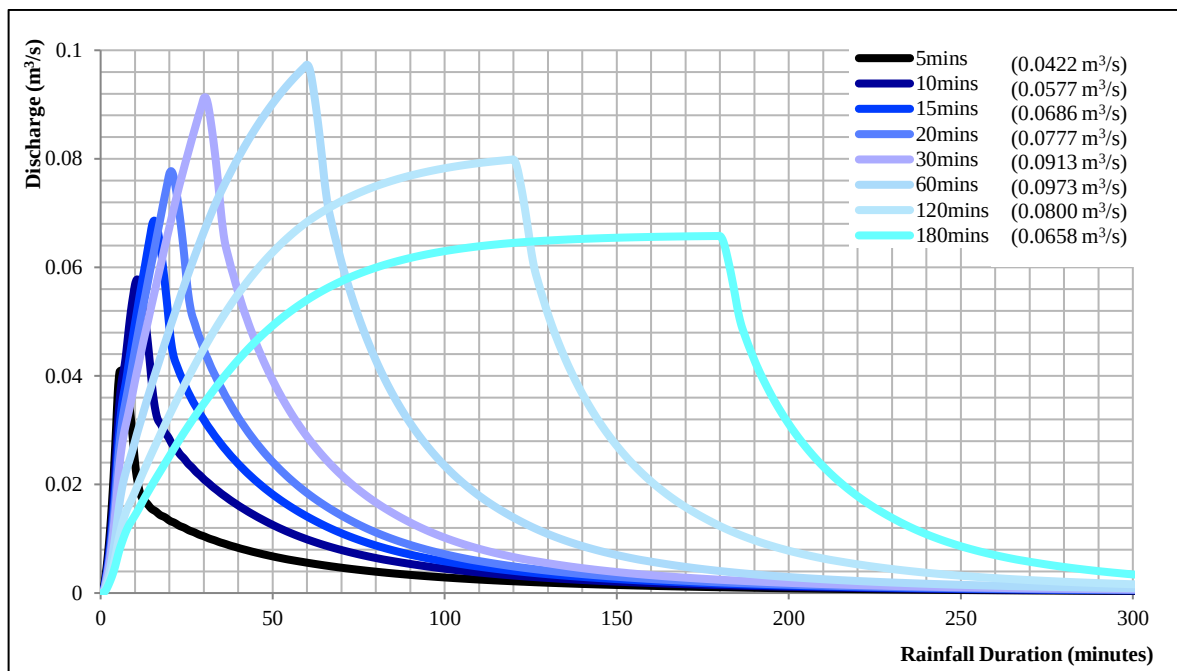


Figure 4.48: Hydrographs at Outfall of 190 mm x 900 mm Outlet Orifice for Varying Rainfall Durations

4.3.4 Summary

The discharge at the outfall of the system in three different scenarios are summarized in Table 4.5. It can be deduced that, for this current study area, the outfall discharges in post development conventional drainage system of all the rainfall durations are greater than the pre-development. It gives approximate 100% - 150% increment which poses a possibility to flood. With regarding to the MSMA requirement, post development discharge shall be as near as or lower than the pre-development discharge.

As the catchment size is small in this study, smaller design rainfall durations are usually reasonable to be considered in normal practice. For example, in the case of 15-minute of design rainfall duration, the discharge of post-development with StormPav Green Pavement regardless the outlet size, is lesser than the discharge of pre-development which is 0.071 m³/s. This shows that, the filling, ponding and draining effect of StormPav Green Pavement is not only capable to perform as a multi-purpose structure, but also able to alleviate the discharge at the outfall with reasonable design rainfall durations.

Table 4.5: Outfall Discharge of Three Scenarios in Different Rainfall Durations

Rainfall durations (mins)	Outfall discharge (m ³ /s)				
	Pre-development condition	Post development condition			
		Conventional drainage system	(1)*	(2)*	(3)*
5	0.093	0.199	0.042	0.042	0.042
10	0.080	0.200	0.052	0.055	0.058
15	0.071	0.178	0.057	0.063	0.069
20	0.066	0.164	0.062	0.070	0.078

Table 4.5 continued

30	0.059	0.147	0.071	0.083	0.091
60	0.045	0.112	0.082	0.092	0.097
120	0.033	0.081	0.075	0.079	0.080
180	0.026	0.066	0.065	0.066	0.066

* (1), (2) and (3) represent the StormPav Green Pavement with outlet orifice of 190 mm x 500 mm, 190 mm x 700 mm, 190 mm x 900 mm respectively

Analysis is also carried out to determine the percentage of discharge reduction of StormPav Green Pavement System compared to the conventional drainage system as shown in Table 4.6. Three different sizes reported nearly the same percentage of discharge reduction at any design rainfall durations. The percentage reductions are varying from 0 to 80% compared to the conventional drainage system for 5 to 180 minutes, 10-year ARI. It reports that, the percentage reduction in 5-minute duration marks the highest value for all the cases, while 180-minute shows the lowest value among all the cases. For instance, orifice outlet size of 190 mm x 700 mm, 5-minute and 180-minute design rainfall durations show a percentage reduction of 79.1% and 0.8% respectively. Besides that, it can be noticed that, all cases for design rainfall durations of 180-minute show almost no reduction. Meaning, this structure has reached its limit or range of service at this rainfall duration.

Table 4.6: Percentage of Discharge Reduction under Different Outlet Orifice Sizes in Rainfall Durations

Rainfall durations (mins)	Percentage reduction (%)		
	(1)*	(2)*	(3)*
5	79.1	79.1	78.8

Table 4.6 continued

10	73.8	72.3	71.2
15	68.1	64.6	61.5
20	62.5	57.1	52.6
30	51.5	43.9	37.9
60	26.9	18.3	13.1
120	7.3	3.1	1.4
180	2.0	0.8	0.3

** (1), (2) and (3) represent the StormPav Green Pavement with outlet orifice of 190 mm x 500 mm, 190 mm x 700 mm, 190 mm x 900 mm respectively*

Therefore, due to the percentage of discharge reduction at any design rainfall durations gives approximate the same value in different outlet size (see Table 4.6), 100 mm inlet size from downpipe (see Section 4.2.1) and 190 mm x 700 mm outlet size (see Section 4.2.2) provides the optimum workability of a permeable road that flows stormwater underneath its pavement.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

As stated in Chapter 1, there are three objectives for the current study; namely to create investigative computer models that represent the StormPav Green Pavement and its flow mechanism; to investigate flow condition at the stormwater inlet and outlet of the above mentioned permeable road system to allow filling, ponding and draining effects; and to analyse the filling, ponding and draining effects regarding to MSMA requirement. Simulations are performed under 10-year ARI with different design rainfall durations. It has been found that the StormPav shows a plausible result to convey stormwater underneath its pavement. Its multipurpose structure features have been demonstrated to store and convey stormwater from building and road together. From the results of the current study, the conclusions are drawn and presented in the following subsections.

5.1.1 Computer Models

StormPav Green Pavement is successfully modelled in SWMM and SolidWorks Flow Simulation through a case study of disconnected system. Its flow mechanisms are demonstrated in different design rainfall durations range from 5 minutes to 180 minutes. The models are found to reproduce matching velocities within StormPav system and the outcomes enhance confidence level of both the SWMM and SolidWorks Flow Simulation models. It is reported that, for all the design rainfall durations, the flow velocity is more prominent at the inlets and outlet of the system relative to the whole stretch. While, consistency of velocity is reported in other region (majority of the system). In terms of flow trajectories, the flow streamlines demonstrate two distinct flow patterns, firstly as the vertical

flow from road surfaces to the storage; secondly, as the horizontal flow from upstream to downstream stretches. Apart from that, special attention shall be paid at the outlet of StormPav Green Pavement to avoid any undesired overflowing from the system.

5.1.2 Stormwater Inlet and Outlet

Inlet sizes of 100 mm and 125 mm in diameter show no surcharging except for 50 mm and 75 mm when different design rainfall durations are tested. Besides, inlet size of 125 mm is found to be oversized. On the other hand, outlet sizes of 190 mm x 500 mm, 190 mm x 700 mm and 190 mm x 900 mm show no overflowing except for 190 mm, and 190 mm x 300 mm. If the outlet size is too big, ponding effect within the system will be trivial. Thus, the optimum inlet and outlet sizes are found to be 100 mm and 190 mm x 700 mm respectively to allow filling, ponding and draining effects. These optimum sizes are reported to perform without surcharging and overflowing. Besides that, it allows approximate ten percent (11.9%) additional spaces to cater for runoff volume in case of weather variability.

5.1.3 The Filling, Ponding and Draining Effects

Three different conditions are produced; namely pre-development, post-development with traditional drainage system and post-development with StormPav Green Pavement. In the case of current study area, the outfall discharge in post-development with traditional drainage system gives an increment of approximate 100% - 150% of peak discharge compared to pre-development in different design rainfall durations. By implementing the StormPav system, the discharge could be alleviated to the pre-development condition for design rainfall durations up to 20 minutes.

Besides that, when comparing between post-development with traditional drainage system and StormPav Green Pavement, the percentage of peak discharge reduction reported

up to 80%. However, 180-minute design rainfall duration marks nearly 0% of reduction. In other words, this system/structure has reached its limit or range of service at design rainfall durations of 180 minutes.

5.2 Recommendations for Future Study

The recommendations for future study in relation to the current study are as follows:

- a) In this thesis, verification of the models was carried out. Thus, in future study, a field test 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 stormwater inlet and outlet sizes of the system according to larger catchments area and longer design rainfall durations;
- c) Further investigation into the number and positioning of outlet of the system to allow more effective filling, ponding and draining effects.

REFERENCES

- Agouridis, C. T., Villines, J. A., & Luck, J. D. (2011). Permeable Pavement for Stormwater Management. *University of Kentucky College of Agriculture, Lexington*.
- Ahmad, H., Miller, J., & George, R. (2014). Minimizing pond size using an off-site pond in a closed basin: a storm flow mitigation design and evaluation. *International Journal of Sustainable Development and Planning*, 9(2), 211-224.
- Al-Hamati, A. A. N., Ghazali, A. H., & Mohammed, T. A. (2010). Determination of storage volume required in a sub-surface stormwater detention/retention system. *Journal of Hydro-Environment Research*, 4, 47-53.
- American Society of Civil Engineers (ASCE). (2015). *Permeable Pavements*. Permeable Pavements Task Committee, Edited by B. Eisenberg, K. Collins Lindow and D. R. Smith. American Society of Civil Engineers, Reston, VA.
- Anderson, J. D. Jr. (1992). *Chapter 2: Governing Equations of Fluid Dynamics*. Retrieved from http://www.springer.com/cda/content/document/cda_downloaddocument/9783540850557-c1.pdf?SGWID=0-0-45-621403-p173839306
- Arnold, C. L., & Gibbons, C. J. (1996). Impervious surface coverage: the emergence of a key environmental indicator. *Journal of the American Planning Association*, 62, 243–258.
- Arokiasamy, M. (2017). Computational fluid dynamics and its applications. *International Journal of Advanced in Management, Technology and Engineering Science*, 7(12), 146-154.
- Australian Environment, Communications, Information Technology and the Arts Legislation Committee. (2002). *The Australian Telecommunications Networks*.

- Barbosa, A. E., Fernandes, J. N., & David, L. M. (2012). Key issues for sustainable urban stormwater management. *Water Resources*, 46, 6787-6798.
- Bean, E. Z., Hunt, W. F., & Bidelsbach, D. A. (2007a). Evaluation of four permeable pavement sites in eastern North Carolina for runoff reduction and water quality impacts. *Journal of Irrigation and Drainage Engineering*, 133(6), 583-592.
- Bean, E. Z., Hunt, W. F., & Bidelsbach, D. A. (2007b). Field survey of permeable pavement surface infiltration rates. *Journal of Irrigation and Drainage Engineering*, 133(3), 249–255.
- Bezák, N., Šraj, M., & Mikoš, M. (2018). Design rainfall in engineering applications with focus on the design discharge. In *Engineering and Mathematical Topics in Rainfall*, In Tech Press: London, UK.
- Brattebo, B. O., & Booth, D. B. (2003). Long-term stormwater quantity and quality performance of permeable pavement systems. *Water Research*, 37(18), 4369-4376.
- Butler, D., & Parkinson, J. (1997). Towards sustainable drainage. *Water Science and Technology*, 35(9), 53–63.
- Chang, N. B., Xuan, Z., Marimon, Z., Islam, K., & Wanielista, M. P. (2013). Exploring hydrobiogeochemical processes of floating treatment wetlands in a subtropical stormwater wet detention pond. *Ecological Engineering*, 54, 66-76.
- Chithra, S. V., Nair, M. V. H., Amarnath, A., & Anjana, N. S. (2015). Impacts of Impervious Surfaces on the Environment. *International Journal of Engineering Science Invention*, 4(5), 2319–6726.
- Chowdhury, R. K., Sharvelle, S. E., & Beecham, S. (2016). Greywater quality changes in a permeable pavement reservoir. In *Proceedings of Institution Civil Engineers - Water Managament*, (pp. 190–198).

- Collins, K. A., Hunt, W. F., & Hathaway, J. M. (2008). Hydrologic comparison of four types of permeable pavement and standard asphalt in eastern North Carolina. *Journal of Hydrologic Engineering*, 13(12), 1146-1157.
- Cunha, M. C., Zeferino, J. A., Simões, N. E., & Saldarriaga, J. G. (2016). Optimal location and sizing of storage units in a drainage system. *Environmental Modelling and Software*, 83(C), 155-166.
- Department of Irrigation and Drainage (DID) Malaysia. (2000). *Urban Stormwater Management Manual for Malaysia (Manual Saliran Mesra Alam, MSMA)*. Percetakan Nasional Malaysia, Kuala Lumpur, Malaysia.
- Department of Irrigation and Drainage (DID) Malaysia. (2012). *Urban Storm water Management Manual for Malaysia (Manual Saliran Mesra Alam, MSMA)*. Percetakan Nasional Malaysia, Kuala Lumpur, Malaysia.
- Dierks, S. (2009). *Hydrologic and Water Quality Performance Evaluation of Porous Pavers and Vegetated Swales on Easy Street in Ann Arbor, Michigan*. Final Report submitted to the City of Ann Arbor, Michigan.
- District Department of Transportation. (2014). *Q Street Green Alley*. Retrieved from <https://ddot.dc.gov/node/806842>
- Elliott, A. H., & Trowsdale, S. A. (2007). A review of models for low impact urban stormwater drainage. *Environmental Modelling and Software*, 22(3), 394-405.
- Fassman, E. A. & Blackbourn, S. (2010). Urban Runoff Mitigation by a Permeable Pavement System over Impermeable Soils. *Journal of Hydrologic Engineering*, 15(6), 475-485.
- Goonetilleke, A., Thomas, E., Ginnc, S., & Gilbert, D. (2005). Understanding the role of land use in urban stormwater quality management. *Journal of Environmental Management*, 74, 31-42.

- Heiner, B.J., & MacKenzie, K. (2015). Extended Detention Stormwater Basins Outlet Structure Flow Physical Model Study. *World Environmental and Water Resources Congress 2015*: 2431-2442.
- Hill, K. D., & Beecham, S. (2018). The effect of particle size on sediment accumulation in permeable pavements. *Water* 2018, 10(4), 403.
- Hirsch, R. M., Walker, J. F., Day, J. C., & Kallio, R. (1990). The influence of man on hydrologic systems. In: M.G. Wolman and H.C. Riggs, eds. *Surface water hydrology (the geology of America, vol. 0–1)*. Boulder, CO, 329–359.
- Hjertager, B. H. (2001). *Computational Analysis of Fluid Flow Processes*. University of Stavanger.
- Hollis, G. E. (2010). The effect of urbanization on floods of different recurrence interval. *Water Resources Research*, 11(3), 431–435.
- Houston, D., Werritty, A., Bassett, D., Geddes, A., Hoolachan, A., & McMillan, M. (2011). *Pluvial (Rain-Related) Flooding In Urban Areas: The Invisible Hazard*. Joseph Rowntree Foundation. Retrieved from <http://eprints.gla.ac.uk/162145/7/162145.pdf>
- Hsu, M. H., Chen, S. H., & Chang, T. J. (2000). Inundation simulation for urban drainage basin with storm sewer system. *Journal of Hydrology*, 234(1), 21-37.
- Huber, W. C. & Dickinson, R.E. (1988). *Storm Water Management Model, Version 4: User's Manual*, EPA/600/3-88/001a, Environmental Research Laboratory, U.S. Environmental Protection Agency, Athens.
- Hunt, B., Stevens, S., & Mayes, D. (2002). Permeable pavement use and research at two sites in Eastern North Carolina. In *Global Solutions for Urban Drainage. Proceeding 9th International Conference on Urban Drainage*, (pp. 1-10).
- Hunt, W. F., & Collins, K. A. (2007). Permeable pavement: Research update and design

- implications. *Urban waterways*. North Carolina Cooperative Extension Service.
- Jang, S., Cho, M., Yoon, J., Yoon, Y., Kim, S., Kim, G., Kim, L., & Aksoy, H. (2007). Using SWMM as a tool for hydrologic impact assessment. *Desalination*, 212(1-3), 344-356.
- Kenter, P. (2011). *Precast System Helps Solve Stormwater Challenges*. Retrieved from <https://canada.constructconnect.com/joc/news/others/2011/04/precast-system-helps-solve-stormwater-challenges-joc043933w>
- Konrad, C. P. (2013). US Geological Survey Fact Sheet 076-03: Effects of Urban Development on Floods. Retrieved from <http://pubs.usgs.gov/fs/fs07603/>
- Kwiatkowski, M., Welker, A. L., Traver, R.G., Vanacore, M., & Ladd, T. (2007). Evaluation of an infiltration best management practice utilizing pervious concrete. *Journal of the American Water Resources Association*, 43(5), 1-15.
- Lee, J. M., Hyun, K. H., & Choi, J. S. (2013). Analysis of the impact of low impact development on runoff from a new district in Korea. *Water Science and Technology*, 68(6), 1315-1321.
- Lucke, T., & Beecham, S. (2011). Field investigation of clogging in a permeable pavement system. *Journal Building Research & Information*, 39(6), 603-615.
- Mah, D. Y. S. (2016). *Potention of Road Subsurface On-Site Stormwater Detention System*. Universiti Malaysia Sarawak Publisher, Kota Samarahan, Malaysia.
- Mah, D. Y. S., Ngu, J. O. K., Liew, V., & Ibrahim, W. H. W. (2018a). Augmenting Drainage System in the Old Town of Kuching, Sarawak, Malaysia. *International Journal of Engineering & Technology*, 7(3.18), 36-39.
- Mah, D. Y. S., Loh, S. L., Mannan, M. A., & Ibrahim, W. H. W. (2018b). Modelling of surface permeation in multiple-orifice permeable road. *International Journal of Engineering & Technology*, 7(3.18), 40-43.

- Mah, D. Y. S., Mannan, M. A., & Ibrahim, W. H. W. (2018c). Pilot study of StormPav green pavement. *International Journal of Research in Engineering & Advanced Technology*, 6(5), 29-35.
- Mah, D. Y. S., Putuhena, F. J., & Rosli, N. A. (2014). Environmental technology: potential of merging road pavement with stormwater detention. *Journal of Applied Science and Process Engineering*, 1(1), 1-8.
- Martin, C., Ruperd, Y., & Legret, M. (2007). Urban stormwater drainage management: the development of multicriteria decision aid approach for best management practices. *European Journal of Operational Research*, 181(1), 338 – 349.
- McIntosh, N. D. (2015). *A study of underground stormwater detention chambers and the creation of the model for underground detention of sediment* (Doctoral dissertation). University of Toronto, Toronto, Canada.
- National Corrugated Steel Pipe Association (NCSPA). (1999). *Condition Survey of Corrugated Steel Pipe Detention System*. NW Washington, DC.
- Ngu, J. O. K., Mah, D. Y. S., & Bong, C. H. J. (2016). Flow characteristics of individual lot stormwater detention. *Water Practice and Technology*, 11(4), 721-727.
- O'Loughlin, G., Beecham, S., Lees, S., Rose, L., & Nicholas, D. (1995). Onsite stormwater detention systems in Sydney. *Water Science and Technology*, 32(1), 169-175.
- Old Castle Infrastructure. (2018). *StormCapture System*. Retrieved from <https://oldcastleprecast.com/stormcapture/>
- Ong, S. K., Wang, K., Ling, Y., & Shi, G. Y. (2016). *Pervious Concrete Physical Characteristics and Effectiveness in Stormwater Pollution Re-duction*. Institute for Transportation, Iowa State University, Ames, Iowa, U.S.
- Park, D. G., Sandoval, N., Lin, W., Kim, H., & Cho, Y. H. (2014). A case study: evaluation

- of water storage capacity in permeable block pavement. *Korean Society of Civil Engineers Journal of Civil Engineering*, 18(2), 514-520.
- Parkinson, J., & Mark, O. (2005). *Urban stormwater management in developing countries*. International Water Association Publishing, London, England.
- Pazwash, H. (2011). *Urban Storm Water Management*. CRC Press, Boca Raton, FL.
- Phillips, D. I. (1995). A generic method of design of on-site stormwater detention storages. *Water Science and Technology*, 32(1), 93-99.
- Pratt, C. J., Mantle, J. D. G., & Schofield, P. A. (1989). Urban stormwater reduction and quality improvement through the use of permeable pavements. *Water Science and Technology*, 21(8), 769-778.
- Priyadarsini, C., Modali, M., Krishna, S. V., & Reddy, N. (2016). Design and analysis of muffler to reduce the back pressure. *International Journal of Scientific Research Engineering and Technology*, 5(9), 470-474.
- Public Utilities Board (PUB). (2010). *Technical Guide for On-site Storm Water Detention Tank Systems*. National Water Agency, Singapore.
- Rao, R. A., Delleur, J. W., & Sarma, B. S. P. (1972). Conceptual hydrologic models for urbanizing basins. *Journal of the Hydraulics Division*, 98(7), 1205-1220.
- Rhodeside & Harwell. (n.d.). *Q Street Green Alley*. Retrieved from <http://rhodeside-harwell.com/q-street-green-alley/>
- Ronalds, R., & Zhang, H. (2017). An alternative method for on-site stormwater detention design. *Journal of Hydrology (New Zealand)*, 56(2), 137-153.
- Ronalds, R., Rowlands, A., & Zhang, H. (2017). The performance of on-site stormwater detention systems in response to recent advances in hydrologic theory. In *13th Hydraulics in Water Engineering Conference* (p. 354). Engineers Australia.

- Rossmam L. A. (2009). *Storm Water Management Model User's Manual Version 5.0 EPA/600/R-05/040*. National Risk Management Research Laboratory, Environmental Protection Agency, Cincinnati, OH.
- Rossmam, L. A. (2015). *Storm Water Management Model User's Manual, Version 5.1*. National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency.
- Sargent, R. G. (2013). Verification and validation of simulation models. *Journal of Simulation*, 7(12), 12-23.
- Sayma, A. (2009). *Computational Fluid Dynamics*. Ventus Publishing.
- Schlesinger, S. (1979). Terminology for model credibility. *Simulation*, 32(3), 103-104.
- Scott, P., Santos, R., & Argue, J. R. (1999). Performance, environmental and cost comparisons of on site detention (OSD) and on-site retention (OSR) in re-developed residential catchments. *Water Science and Technology*, 39(2), 33–41.
- Sidek, L. M., Takara, K., Zakaria, N. A., Ghani, A. A., & Abdullah, R. (2004). An assessment of stormwater management practices using MSMA Manual in Malaysia. *1st International Conference on Managing Rivers in the 21st Century: Issues & Challenges*.(pp. 479-495).
- Stahre, P., & Urbonas, B. (1990). *Stormwater detention for drainage, water quality and CSO management*. Prentice-Hall, New Jersey.
- StormTrap. (2018). Retrieved from <http://stormtrap.com/products/doubletrap/#doubletrap-Docs>
- Subramanya, K. (2008). *Engineering Hydrology* (3rd ed.). Tata McGraw-Hill Education. New Delhi, India.
- ten Veldhuis, J. A. E., & Olsen, A. S. (2012). Hydrological response times in lowland urban

- catchments characterized by looped drainage systems. In *Proceedings of the 9th international workshop on precipitation in urban areas*. St. Moritz: ETH Publications.
- Texas Department of Transportation (TxDOT). (2009). *Hydraulic Design Manual*. Texas, USA.
- U.S. Environmental Protection Agency (EPA). (2001). *Storm Water Technology Fact Sheet: On-Site Underground Retention/ Detention*. EPA 832-F-01-005, Office of Water, Washington DC.
- U.S. Environmental Protection Agency (EPA). (2008). *Protecting Water Quality: Urban Storm Water Management in the United States*. Urban Runoff EPA 841-F-03-003, National Research Council. Washington DC.
- Urbonas, B., & Stahre, P. (1993). *Stormwater Best Management Practices and Detention for Water Quality, Drainage and CSO management*. Prentice Hall, New Jersey, NY.
- Veersteg, H. K., & Malalasekera, W. (2007). *An Introduction to Computational Fluid Dynamics*. Essex, England, Pearson Education Limited.
- Vorogushyn, S., Lindenschmidt, K. E., Kreibich, H., Apel, H., & Merz, B. (2012). Analysis of a detention basin impact on dike failure probabilities and flood risk for a channel-dike-floodplain system along the river Elbe, Germany. *Journal of Hydrology*, 436, 120-131.
- Walesh, S. G. (1989). *Urban Surface Water Management*. John Wiley & Sons, New York.
- Zakaria, N. A., Ghani, A. A., Abdullah, R., Sidek, L. M., Kassim, A. H., & Ainan, A. (2004). MSMA - a new urban stormwater management manual for Malaysia. *The 6th International Conference on Hydrosience and Engineering*. 30 May - 3 June, Brisbane, Australia.

APPENDICES

Appendix A: Data for Inlet Analysis in Varying Combinations of Inlet and Outlet Sizes for all the Design Rainfall Durations

Appendix A1: Varying Inlet Sizes with ∞* Outlet Size

Design Rainfall Duration (minutes)	Corner Lot				Intermediate Lot			
	Diameter of pipes (mm)							
	50	75	100	125	50	75	100	125
5	71	106	121	103	71	106	90	77
10	71	106	117	101	71	106	89	77
15	71	106	108	93	71	100	83	71
20	71	106	102	88	71	95	78	67
30	71	106	95	82	71	88	73	62
60	71	96	79	68	71	73	61	52
120	71	78	64	55	71	59	49	42
180	71	67	56	48	68	52	43	37

Appendix A2: Varying Inlet Sizes with 190 mm Outlet Size

Design Rainfall Duration (minutes)	Corner Lot				Intermediate Lot			
	Diameter of pipes (mm)							
	50	75	100	125	50	75	100	125
5	71	106	121	103	71	106	90	78
10	71	106	118	108	71	106	90	86
15	71	106	116	113	71	106	91	97
20	71	106	120	124	71	106	99	119
30	71	106	140	159	71	106	133	159
60	71	106	141	177	71	106	141	177
120	71	106	141	177	71	106	141	177
180	71	106	141	177	71	106	141	177

Appendix A3: Varying Inlet Sizes with 190 mm X 300 mm Outlet Size

Design Rainfall Duration (minutes)	Corner Lot				Intermediate Lot			
	Diameter of pipes (mm)							
	50	75	100	125	50	75	100	125
5	71	106	121	103	71	106	90	78
10	71	106	118	108	71	106	90	85
15	71	106	115	112	71	100	90	95
20	71	106	118	122	71	100	97	113
30	71	106	133	147	71	106	120	146
60	71	106	141	177	71	106	141	177
120	71	106	141	177	71	106	141	177
180	71	106	141	177	71	106	141	177

Appendix A4: Varying Inlet Sizes with 190 mm X 500 mm Outlet Size

Design Rainfall Duration (minutes)	Corner Lot				Intermediate Lot			
	Diameter of pipes (mm)							
	50	75	100	125	50	75	100	125
5	71	106	121	103	71	106	90	78
10	71	106	118	108	71	106	90	85
15	71	106	115	111	71	100	90	94
20	71	106	116	119	71	98	95	107
30	71	106	126	139	71	104	112	135
60	71	106	140	169	71	106	138	167
120	71	106	134	164	71	101	130	163
180	71	94	115	147	71	84	113	146

Appendix A5: Varying Inlet Sizes with 190 mm X 700 mm Outlet Size

Design Rainfall Duration (minutes)	Corner Lot				Intermediate Lot			
	Diameter of pipes (mm)							
	50	75	100	125	50	75	100	125
5	71	106	121	104	71	106	90	91
10	71	106	117	108	71	106	90	94
15	71	106	114	111	71	100	89	99
20	71	106	115	118	71	98	93	109
30	71	106	123	135	71	101	107	130
60	71	106	131	155	71	103	123	153
120	71	99	115	143	71	86	110	142
180	71	99	97	126	71	86	92	125

Appendix A6: Varying Inlet Sizes with 190 mm X 900 mm Outlet Size

Design Rainfall Duration (minutes)	Corner Lot				Intermediate Lot			
	Diameter of pipes (mm)							
	50	75	100	125	50	75	100	125
5	71	106	121	103	71	106	90	78
10	71	106	117	107	71	106	90	84
15	71	106	114	110	71	100	89	92
20	71	106	114	116	71	97	92	102
30	71	106	120	130	71	99	103	123
60	71	106	123	145	71	97	114	142
120	71	93	104	132	71	78	98	130
180	71	77	88	115	68	63	82	113

**Appendix B: Data for Outlet Analysis in Varying Combinations of Inlet and Outlet Sizes
for all the Design Rainfall Durations**

Appendix B1: Outlet size of 190 mm with ∞ inlet size**

Time lapse (min)	Water Depth in StormPav (mm)							
	5 ^a	10 ^a	15 ^a	20 ^a	30 ^a	60 ^a	120 ^a	180 ^a
0	0	0	0	0	0	0	0	0
5	0.029	0.024	0.021	0.019	0.017	0.013	0.010	0.008
10	0.057	0.073	0.066	0.061	0.055	0.042	0.030	0.024
15	0.057	0.098	0.108	0.099	0.089	0.068	0.050	0.040
20	0.056	0.095	0.127	0.136	0.122	0.094	0.068	0.055
25	0.055	0.092	0.124	0.153	0.154	0.119	0.086	0.070
30	0.054	0.091	0.120	0.148	0.185	0.142	0.104	0.085
35	0.053	0.088	0.117	0.143	0.189	0.164	0.121	0.099
40	0.052	0.086	0.113	0.138	0.182	0.185	0.137	0.112
45	0.051	0.083	0.109	0.134	0.176	0.190	0.152	0.125
50	0.050	0.082	0.106	0.130	0.169	0.190	0.167	0.137
55	0.049	0.079	0.104	0.126	0.163	0.190	0.181	0.148
60	0.048	0.078	0.101	0.122	0.158	0.190	0.190	0.159
65	0.047	0.076	0.098	0.118	0.152	0.189	0.190	0.169
70	0.047	0.073	0.095	0.114	0.147	0.182	0.190	0.178
75	0.046	0.072	0.093	0.111	0.142	0.175	0.190	0.188
80	0.045	0.070	0.090	0.107	0.138	0.169	0.190	0.190
85	0.044	0.069	0.088	0.104	0.133	0.163	0.190	0.190
90	0.043	0.067	0.085	0.102	0.129	0.158	0.190	0.190
95	0.042	0.066	0.083	0.099	0.124	0.152	0.190	0.190
100	0.041	0.064	0.081	0.096	0.121	0.147	0.190	0.190
105	0.041	0.063	0.079	0.093	0.117	0.142	0.190	0.190

Appendix B1 continued

110	0.040	0.061	0.077	0.091	0.114	0.137	0.190	0.190
115	0.039	0.060	0.075	0.088	0.110	0.132	0.190	0.190
120	0.039	0.059	0.073	0.086	0.107	0.128	0.190	0.190
125	0.038	0.057	0.072	0.084	0.104	0.124	0.188	0.190
130	0.037	0.056	0.070	0.082	0.101	0.120	0.182	0.190
135	0.037	0.055	0.068	0.080	0.098	0.117	0.176	0.190
140	0.036	0.054	0.067	0.078	0.095	0.113	0.169	0.190
145	0.035	0.053	0.065	0.076	0.093	0.110	0.163	0.190
150	0.035	0.052	0.064	0.074	0.090	0.107	0.157	0.190
155	0.034	0.051	0.062	0.072	0.088	0.104	0.152	0.190
160	0.034	0.050	0.061	0.071	0.086	0.101	0.147	0.190
165	0.033	0.049	0.060	0.069	0.083	0.098	0.142	0.190
170	0.033	0.048	0.058	0.067	0.081	0.095	0.137	0.190
175	0.032	0.047	0.057	0.066	0.079	0.093	0.132	0.190
180	0.032	0.046	0.056	0.064	0.077	0.090	0.128	0.190
185	0.031	0.045	0.055	0.063	0.075	0.088	0.124	0.188
190	0.031	0.044	0.054	0.061	0.073	0.085	0.120	0.182
195	0.030	0.043	0.053	0.060	0.072	0.083	0.117	0.175
200	0.030	0.043	0.051	0.059	0.070	0.081	0.113	0.168
205	0.029	0.042	0.050	0.057	0.068	0.079	0.110	0.163
210	0.029	0.041	0.049	0.056	0.067	0.077	0.107	0.157
215	0.028	0.040	0.048	0.055	0.065	0.075	0.104	0.151
220	0.028	0.040	0.047	0.054	0.064	0.073	0.101	0.147
225	0.028	0.039	0.047	0.053	0.062	0.072	0.098	0.141
230	0.027	0.038	0.046	0.052	0.061	0.070	0.095	0.136
235	0.027	0.038	0.045	0.051	0.060	0.068	0.093	0.132
240	0.026	0.037	0.044	0.050	0.058	0.067	0.090	0.128
245	0.026	0.036	0.043	0.049	0.057	0.065	0.088	0.124
250	0.026	0.036	0.042	0.048	0.056	0.064	0.085	0.120
255	0.025	0.035	0.042	0.047	0.055	0.062	0.083	0.116
260	0.025	0.035	0.041	0.046	0.054	0.061	0.081	0.113
265	0.025	0.034	0.040	0.045	0.053	0.060	0.079	0.110
270	0.024	0.033	0.039	0.044	0.052	0.058	0.077	0.106
275	0.024	0.033	0.039	0.043	0.050	0.057	0.075	0.104
280	0.024	0.032	0.038	0.043	0.049	0.056	0.073	0.100
285	0.023	0.032	0.037	0.042	0.049	0.055	0.072	0.098
290	0.023	0.031	0.037	0.041	0.048	0.054	0.070	0.095
295	0.023	0.031	0.036	0.040	0.047	0.053	0.068	0.092
300	0.022	0.030	0.036	0.040	0.046	0.051	0.067	0.090
305	0.022	0.030	0.035	0.039	0.045	0.050	0.065	0.088
310	0.022	0.029	0.034	0.038	0.044	0.049	0.064	0.085
315	0.021	0.029	0.034	0.038	0.043	0.048	0.062	0.083
320	0.021	0.029	0.033	0.037	0.042	0.048	0.061	0.081
325	0.021	0.028	0.033	0.036	0.042	0.047	0.060	0.079
330	0.021	0.028	0.032	0.036	0.041	0.046	0.058	0.077

Appendix B1 continued

335	0.020	0.027	0.032	0.035	0.040	0.045	0.057	0.075
340	0.020	0.027	0.031	0.035	0.040	0.044	0.056	0.073
345	0.020	0.027	0.031	0.034	0.039	0.043	0.055	0.072
350	0.020	0.026	0.030	0.033	0.038	0.042	0.054	0.070
355	0.019	0.026	0.030	0.033	0.037	0.042	0.053	0.068
360	0.019	0.025	0.029	0.032	0.037	0.041	0.051	0.067
365	0.019	0.025	0.029	0.032	0.036	0.040	0.050	0.065
370	0.019	0.025	0.028	0.031	0.036	0.039	0.049	0.064
375	0.018	0.024	0.028	0.031	0.035	0.039	0.048	0.062
380	0.018	0.024	0.028	0.030	0.034	0.038	0.048	0.061
385	0.018	0.024	0.027	0.030	0.034	0.037	0.047	0.060
390	0.018	0.023	0.027	0.030	0.033	0.037	0.046	0.058
395	0.018	0.023	0.026	0.029	0.033	0.036	0.045	0.057
400	0.017	0.023	0.026	0.029	0.032	0.036	0.044	0.056

^a Design rainfall durations

Appendix B2: Outlet size of 190 mm X 300 mm with ∞** inlet size

Time lapse (min)	Water Depth in StormPav (mm)							
	5 ^a	10 ^a	15 ^a	20 ^a	30 ^a	60 ^a	120 ^a	180 ^a
0	0	0	0	0	0	0	0	0
5	0.028	0.024	0.021	0.019	0.017	0.013	0.010	0.008
10	0.056	0.072	0.065	0.060	0.054	0.041	0.029	0.024
15	0.055	0.094	0.105	0.096	0.086	0.066	0.049	0.039
20	0.053	0.089	0.121	0.130	0.118	0.091	0.066	0.054
25	0.051	0.086	0.115	0.142	0.146	0.113	0.083	0.068
30	0.050	0.081	0.108	0.135	0.171	0.133	0.098	0.081
35	0.048	0.078	0.103	0.127	0.178	0.152	0.113	0.093
40	0.047	0.075	0.098	0.120	0.166	0.169	0.126	0.104
45	0.045	0.071	0.093	0.113	0.156	0.183	0.138	0.114
50	0.043	0.068	0.089	0.107	0.146	0.190	0.149	0.123
55	0.042	0.066	0.084	0.102	0.137	0.190	0.159	0.132
60	0.040	0.063	0.080	0.097	0.129	0.190	0.168	0.140
65	0.039	0.060	0.077	0.092	0.121	0.187	0.175	0.147
70	0.038	0.058	0.073	0.087	0.115	0.174	0.183	0.154
75	0.037	0.056	0.070	0.083	0.108	0.164	0.190	0.160
80	0.036	0.054	0.067	0.079	0.103	0.153	0.190	0.165
85	0.035	0.052	0.064	0.076	0.098	0.143	0.190	0.169
90	0.034	0.050	0.062	0.072	0.093	0.135	0.190	0.175
95	0.033	0.048	0.059	0.069	0.088	0.127	0.190	0.177
100	0.032	0.046	0.057	0.066	0.084	0.120	0.190	0.182
105	0.031	0.045	0.055	0.064	0.080	0.113	0.190	0.185
110	0.030	0.043	0.053	0.061	0.076	0.107	0.190	0.186
115	0.029	0.042	0.051	0.059	0.073	0.101	0.190	0.190

Appendix B2 continued

120	0.028	0.040	0.049	0.056	0.070	0.096	0.190	0.190
125	0.028	0.039	0.047	0.054	0.067	0.091	0.185	0.190
130	0.027	0.038	0.046	0.052	0.064	0.087	0.173	0.190
135	0.026	0.037	0.044	0.050	0.062	0.083	0.162	0.190
140	0.025	0.036	0.043	0.048	0.059	0.079	0.152	0.190
145	0.025	0.034	0.041	0.047	0.057	0.075	0.142	0.190
150	0.024	0.033	0.040	0.045	0.055	0.072	0.134	0.190
155	0.024	0.032	0.039	0.044	0.053	0.069	0.126	0.190
160	0.023	0.032	0.037	0.042	0.051	0.066	0.119	0.190
165	0.022	0.031	0.036	0.041	0.049	0.063	0.112	0.190
170	0.022	0.030	0.035	0.039	0.047	0.061	0.106	0.190
175	0.021	0.029	0.034	0.038	0.045	0.058	0.101	0.190
180	0.021	0.028	0.033	0.037	0.044	0.056	0.096	0.190
185	0.020	0.027	0.032	0.036	0.042	0.054	0.091	0.184
190	0.020	0.027	0.031	0.035	0.041	0.052	0.087	0.172
195	0.020	0.026	0.030	0.034	0.040	0.050	0.082	0.161
200	0.019	0.025	0.029	0.033	0.038	0.048	0.079	0.151
205	0.019	0.025	0.029	0.032	0.037	0.047	0.075	0.141
210	0.018	0.024	0.028	0.031	0.036	0.045	0.072	0.133
215	0.018	0.024	0.027	0.030	0.035	0.043	0.069	0.125
220	0.017	0.023	0.026	0.029	0.034	0.042	0.066	0.118
225	0.017	0.022	0.026	0.028	0.033	0.041	0.063	0.111
230	0.017	0.022	0.025	0.028	0.032	0.039	0.061	0.106
235	0.016	0.021	0.024	0.027	0.031	0.038	0.058	0.100
240	0.016	0.021	0.024	0.026	0.030	0.037	0.056	0.095
245	0.016	0.020	0.023	0.026	0.029	0.036	0.054	0.090
250	0.015	0.020	0.023	0.025	0.029	0.035	0.052	0.086
255	0.015	0.019	0.022	0.024	0.028	0.034	0.050	0.082
260	0.015	0.019	0.022	0.024	0.027	0.033	0.048	0.078
265	0.015	0.019	0.021	0.023	0.026	0.032	0.046	0.075
270	0.014	0.018	0.021	0.023	0.026	0.031	0.045	0.071
275	0.014	0.018	0.020	0.022	0.025	0.030	0.043	0.068
280	0.014	0.017	0.020	0.021	0.024	0.029	0.042	0.066
285	0.014	0.017	0.019	0.021	0.024	0.028	0.041	0.063
290	0.013	0.017	0.019	0.021	0.023	0.028	0.039	0.060
295	0.013	0.016	0.018	0.020	0.023	0.027	0.038	0.058
300	0.013	0.016	0.018	0.020	0.022	0.026	0.037	0.056
305	0.013	0.016	0.018	0.019	0.022	0.025	0.036	0.054
310	0.012	0.015	0.017	0.019	0.021	0.025	0.035	0.052
315	0.012	0.015	0.017	0.018	0.021	0.024	0.034	0.050
320	0.012	0.015	0.017	0.018	0.020	0.024	0.033	0.048
325	0.012	0.015	0.016	0.018	0.020	0.023	0.032	0.046
330	0.012	0.014	0.016	0.017	0.019	0.022	0.031	0.045
335	0.011	0.014	0.016	0.017	0.019	0.022	0.030	0.043
340	0.011	0.014	0.015	0.016	0.018	0.021	0.029	0.042

Appendix B2 continued

345	0.011	0.014	0.015	0.016	0.018	0.021	0.028	0.040
350	0.011	0.013	0.015	0.016	0.018	0.020	0.028	0.039
355	0.011	0.013	0.014	0.016	0.017	0.020	0.027	0.038
360	0.010	0.013	0.014	0.015	0.017	0.020	0.026	0.037
365	0.010	0.013	0.014	0.015	0.017	0.019	0.025	0.036
370	0.010	0.012	0.014	0.015	0.016	0.019	0.025	0.034
375	0.010	0.012	0.013	0.014	0.016	0.018	0.024	0.033
380	0.010	0.012	0.013	0.014	0.016	0.018	0.024	0.032
385	0.010	0.012	0.013	0.014	0.015	0.018	0.023	0.032
390	0.010	0.012	0.013	0.014	0.015	0.017	0.022	0.031
395	0.009	0.011	0.012	0.013	0.015	0.017	0.022	0.030
400	0.009	0.011	0.012	0.013	0.014	0.016	0.021	0.029

^a Design rainfall durations

Appendix B3: Outlet size of 190 mm X 500 mm with ∞** inlet size

Time lapse (min)	Water Depth in StormPav (mm)							
	5 ^a	10 ^a	15 ^a	20 ^a	30 ^a	60 ^a	120 ^a	180 ^a
0	0	0	0	0	0	0	0	0
5	0.028	0.023	0.021	0.019	0.017	0.013	0.010	0.008
10	0.055	0.071	0.064	0.059	0.053	0.040	0.029	0.024
15	0.053	0.090	0.101	0.093	0.084	0.064	0.047	0.038
20	0.050	0.084	0.114	0.125	0.112	0.087	0.064	0.052
25	0.048	0.079	0.106	0.133	0.137	0.107	0.079	0.065
30	0.046	0.074	0.098	0.123	0.159	0.124	0.093	0.076
35	0.043	0.069	0.091	0.113	0.161	0.140	0.105	0.087
40	0.041	0.065	0.085	0.104	0.147	0.153	0.116	0.096
45	0.039	0.061	0.079	0.096	0.134	0.165	0.125	0.104
50	0.038	0.058	0.074	0.089	0.123	0.175	0.134	0.112
55	0.036	0.054	0.069	0.083	0.113	0.184	0.141	0.118
60	0.034	0.051	0.065	0.078	0.104	0.190	0.147	0.124
65	0.033	0.049	0.061	0.072	0.096	0.183	0.153	0.129
70	0.031	0.046	0.058	0.068	0.089	0.166	0.157	0.133
75	0.030	0.044	0.054	0.064	0.083	0.150	0.161	0.137
80	0.029	0.042	0.051	0.060	0.077	0.137	0.165	0.140
85	0.028	0.040	0.049	0.057	0.072	0.125	0.168	0.143
90	0.027	0.038	0.046	0.053	0.068	0.115	0.171	0.145
95	0.026	0.036	0.044	0.051	0.064	0.106	0.173	0.148
100	0.025	0.035	0.042	0.048	0.060	0.098	0.175	0.150
105	0.024	0.033	0.040	0.045	0.056	0.091	0.176	0.151
110	0.023	0.032	0.038	0.043	0.053	0.084	0.178	0.153
115	0.022	0.030	0.036	0.041	0.050	0.079	0.179	0.154
120	0.021	0.029	0.035	0.039	0.048	0.073	0.180	0.155
125	0.021	0.028	0.033	0.037	0.045	0.069	0.172	0.156

Appendix B3 continued

130	0.020	0.027	0.032	0.036	0.043	0.065	0.156	0.157
135	0.019	0.026	0.030	0.034	0.041	0.061	0.142	0.157
140	0.019	0.025	0.029	0.033	0.039	0.057	0.130	0.158
145	0.018	0.024	0.028	0.031	0.037	0.054	0.119	0.158
150	0.018	0.023	0.027	0.030	0.036	0.051	0.109	0.159
155	0.017	0.022	0.026	0.029	0.034	0.048	0.101	0.159
160	0.017	0.022	0.025	0.028	0.033	0.046	0.093	0.159
165	0.016	0.021	0.024	0.027	0.031	0.044	0.087	0.160
170	0.016	0.020	0.023	0.026	0.030	0.041	0.081	0.160
175	0.015	0.020	0.022	0.025	0.029	0.039	0.075	0.160
180	0.015	0.019	0.022	0.024	0.028	0.038	0.071	0.160
185	0.014	0.018	0.021	0.023	0.027	0.036	0.066	0.153
190	0.014	0.018	0.020	0.022	0.026	0.034	0.062	0.140
195	0.014	0.017	0.020	0.021	0.025	0.033	0.059	0.128
200	0.013	0.017	0.019	0.021	0.024	0.032	0.055	0.117
205	0.013	0.016	0.018	0.020	0.023	0.030	0.052	0.108
210	0.013	0.016	0.018	0.019	0.022	0.029	0.049	0.100
215	0.012	0.015	0.017	0.019	0.021	0.028	0.047	0.092
220	0.012	0.015	0.017	0.018	0.021	0.027	0.044	0.086
225	0.012	0.014	0.016	0.018	0.020	0.026	0.042	0.080
230	0.011	0.014	0.016	0.017	0.019	0.025	0.040	0.075
235	0.011	0.014	0.015	0.017	0.019	0.024	0.038	0.070
240	0.011	0.013	0.015	0.016	0.018	0.023	0.037	0.066
245	0.011	0.013	0.014	0.016	0.018	0.022	0.035	0.062
250	0.010	0.013	0.014	0.015	0.017	0.022	0.033	0.058
255	0.010	0.012	0.014	0.015	0.017	0.021	0.032	0.055
260	0.010	0.012	0.013	0.014	0.016	0.020	0.031	0.052
265	0.010	0.012	0.013	0.014	0.016	0.019	0.029	0.049
270	0.009	0.011	0.013	0.014	0.015	0.019	0.028	0.047
275	0.009	0.011	0.012	0.013	0.015	0.018	0.027	0.044
280	0.009	0.011	0.012	0.013	0.014	0.018	0.026	0.042
285	0.009	0.011	0.012	0.013	0.014	0.017	0.025	0.040
290	0.009	0.010	0.011	0.012	0.014	0.017	0.024	0.038
295	0.009	0.010	0.011	0.012	0.013	0.016	0.023	0.036
300	0.008	0.010	0.011	0.012	0.013	0.016	0.023	0.035
305	0.008	0.010	0.011	0.011	0.013	0.015	0.022	0.033
310	0.008	0.010	0.010	0.011	0.012	0.015	0.021	0.032
315	0.008	0.009	0.010	0.011	0.012	0.014	0.020	0.031
320	0.008	0.009	0.010	0.011	0.012	0.014	0.020	0.029
325	0.008	0.009	0.010	0.010	0.011	0.014	0.019	0.028
330	0.007	0.009	0.009	0.010	0.011	0.013	0.018	0.027
335	0.007	0.009	0.009	0.010	0.011	0.013	0.018	0.026
340	0.007	0.008	0.009	0.010	0.011	0.013	0.017	0.025
345	0.007	0.008	0.009	0.009	0.010	0.012	0.017	0.024
350	0.007	0.008	0.009	0.009	0.010	0.012	0.016	0.023

Appendix B3 continued

355	0.007	0.008	0.009	0.009	0.010	0.012	0.016	0.022
360	0.007	0.008	0.008	0.009	0.010	0.011	0.015	0.022
365	0.006	0.008	0.008	0.009	0.009	0.011	0.015	0.021
370	0.006	0.007	0.008	0.008	0.009	0.011	0.015	0.020
375	0.006	0.007	0.008	0.008	0.009	0.011	0.014	0.020
380	0.006	0.007	0.008	0.008	0.009	0.010	0.014	0.019
385	0.006	0.007	0.008	0.008	0.009	0.010	0.013	0.018
390	0.006	0.007	0.007	0.008	0.008	0.010	0.013	0.018
395	0.006	0.007	0.007	0.008	0.008	0.010	0.013	0.017
400	0.006	0.007	0.007	0.008	0.008	0.009	0.012	0.017

^a Design rainfall durations

Appendix B4: Outlet size of 190 mm X 700 mm with ∞** inlet size

Time lapse (min)	Water Depth in StormPav (mm)							
	5 ^a	10 ^a	15 ^a	20 ^a	30 ^a	60 ^a	120 ^a	180 ^a
0	0	0	0	0	0	0	0	0
5	0.027	0.023	0.021	0.019	0.017	0.013	0.010	0.008
10	0.054	0.070	0.063	0.058	0.052	0.039	0.029	0.023
15	0.051	0.087	0.098	0.091	0.082	0.063	0.046	0.038
20	0.048	0.081	0.110	0.120	0.108	0.084	0.062	0.051
25	0.046	0.074	0.100	0.127	0.131	0.102	0.076	0.063
30	0.043	0.069	0.091	0.115	0.150	0.118	0.089	0.073
35	0.040	0.064	0.083	0.104	0.150	0.132	0.099	0.082
40	0.038	0.059	0.076	0.094	0.134	0.143	0.109	0.091
45	0.036	0.055	0.070	0.086	0.121	0.153	0.117	0.098
50	0.034	0.051	0.065	0.079	0.109	0.161	0.123	0.104
55	0.032	0.048	0.060	0.072	0.098	0.168	0.129	0.109
60	0.030	0.045	0.056	0.067	0.090	0.173	0.134	0.113
65	0.029	0.042	0.052	0.062	0.082	0.165	0.138	0.117
70	0.028	0.040	0.049	0.057	0.075	0.147	0.142	0.121
75	0.026	0.037	0.046	0.053	0.069	0.131	0.145	0.123
80	0.025	0.035	0.043	0.050	0.064	0.118	0.147	0.126
85	0.024	0.033	0.040	0.047	0.059	0.106	0.149	0.128
90	0.023	0.032	0.038	0.044	0.055	0.096	0.151	0.129
95	0.022	0.030	0.036	0.041	0.052	0.088	0.153	0.131
100	0.021	0.029	0.034	0.039	0.048	0.080	0.154	0.132
105	0.020	0.027	0.032	0.037	0.045	0.074	0.155	0.133
110	0.019	0.026	0.031	0.035	0.042	0.068	0.156	0.134
115	0.019	0.025	0.029	0.033	0.040	0.063	0.156	0.135
120	0.018	0.024	0.028	0.031	0.038	0.058	0.157	0.135
125	0.017	0.023	0.026	0.030	0.036	0.054	0.149	0.136
130	0.017	0.022	0.025	0.028	0.034	0.051	0.133	0.136
135	0.016	0.021	0.024	0.027	0.032	0.047	0.119	0.137

Appendix B4 continued

140	0.016	0.020	0.023	0.026	0.030	0.044	0.108	0.137
145	0.015	0.019	0.022	0.024	0.029	0.042	0.097	0.137
150	0.014	0.018	0.021	0.023	0.027	0.039	0.089	0.138
155	0.014	0.018	0.020	0.022	0.026	0.037	0.081	0.138
160	0.014	0.017	0.019	0.021	0.025	0.035	0.075	0.138
165	0.013	0.017	0.019	0.021	0.024	0.033	0.069	0.138
170	0.013	0.016	0.018	0.020	0.023	0.032	0.064	0.138
175	0.012	0.015	0.017	0.019	0.022	0.030	0.059	0.138
180	0.012	0.015	0.017	0.018	0.021	0.028	0.055	0.138
185	0.012	0.014	0.016	0.018	0.020	0.027	0.051	0.131
190	0.011	0.014	0.016	0.017	0.019	0.026	0.048	0.118
195	0.011	0.013	0.015	0.016	0.019	0.025	0.045	0.107
200	0.011	0.013	0.015	0.016	0.018	0.024	0.042	0.097
205	0.010	0.013	0.014	0.015	0.017	0.023	0.040	0.088
210	0.010	0.012	0.014	0.015	0.017	0.022	0.037	0.081
215	0.010	0.012	0.013	0.014	0.016	0.021	0.035	0.074
220	0.010	0.012	0.013	0.014	0.015	0.020	0.033	0.068
225	0.009	0.011	0.012	0.013	0.015	0.019	0.032	0.063
230	0.009	0.011	0.012	0.013	0.014	0.018	0.030	0.059
235	0.009	0.011	0.012	0.012	0.014	0.018	0.029	0.055
240	0.009	0.010	0.011	0.012	0.013	0.017	0.027	0.051
245	0.008	0.010	0.011	0.012	0.013	0.016	0.026	0.048
250	0.008	0.010	0.011	0.011	0.013	0.016	0.025	0.045
255	0.008	0.009	0.010	0.011	0.012	0.015	0.024	0.042
260	0.008	0.009	0.010	0.011	0.012	0.015	0.023	0.040
265	0.008	0.009	0.010	0.010	0.012	0.014	0.022	0.037
270	0.007	0.009	0.010	0.010	0.011	0.014	0.021	0.035
275	0.007	0.009	0.009	0.010	0.011	0.013	0.020	0.033
280	0.007	0.008	0.009	0.010	0.011	0.013	0.019	0.032
285	0.007	0.008	0.009	0.009	0.010	0.013	0.018	0.030
290	0.007	0.008	0.009	0.009	0.010	0.012	0.018	0.029
295	0.007	0.008	0.008	0.009	0.010	0.012	0.017	0.027
300	0.007	0.008	0.008	0.009	0.009	0.011	0.017	0.026
305	0.006	0.007	0.008	0.008	0.009	0.011	0.016	0.025
310	0.006	0.007	0.008	0.008	0.009	0.011	0.015	0.024
315	0.006	0.007	0.008	0.008	0.009	0.011	0.015	0.023
320	0.006	0.007	0.007	0.008	0.009	0.010	0.014	0.022
325	0.006	0.007	0.007	0.008	0.008	0.010	0.014	0.021
330	0.006	0.007	0.007	0.008	0.008	0.010	0.013	0.020
335	0.006	0.006	0.007	0.007	0.008	0.009	0.013	0.019
340	0.006	0.006	0.007	0.007	0.008	0.009	0.013	0.018
345	0.005	0.006	0.007	0.007	0.008	0.009	0.012	0.018
350	0.005	0.006	0.007	0.007	0.007	0.009	0.012	0.017
355	0.005	0.006	0.006	0.007	0.007	0.009	0.012	0.016
360	0.005	0.006	0.006	0.007	0.007	0.008	0.011	0.016

Appendix B4 continued

365	0.005	0.006	0.006	0.006	0.007	0.008	0.011	0.015
370	0.005	0.006	0.006	0.006	0.007	0.008	0.011	0.015
375	0.005	0.006	0.006	0.006	0.007	0.008	0.010	0.014
380	0.005	0.005	0.006	0.006	0.006	0.008	0.010	0.014
385	0.005	0.005	0.006	0.006	0.006	0.007	0.010	0.013
390	0.005	0.005	0.006	0.006	0.006	0.007	0.009	0.013
395	0.005	0.005	0.005	0.006	0.006	0.007	0.009	0.013
400	0.004	0.005	0.005	0.006	0.006	0.007	0.009	0.012

^a Design rainfall durations

Appendix B5: Outlet size of 190 mm X 900 mm with ∞** inlet size

Time lapse (min)	Water Depth in StormPav (mm)							
	5 ^a	10 ^a	15 ^a	20 ^a	30 ^a	60 ^a	120 ^a	180 ^a
0	0	0	0	0	0	0	0	0
5	0.027	0.023	0.021	0.019	0.017	0.013	0.010	0.008
10	0.053	0.069	0.062	0.057	0.051	0.039	0.028	0.023
15	0.050	0.085	0.096	0.089	0.080	0.062	0.045	0.037
20	0.047	0.078	0.106	0.117	0.105	0.082	0.061	0.050
25	0.044	0.071	0.096	0.122	0.126	0.099	0.074	0.061
30	0.041	0.065	0.086	0.109	0.144	0.114	0.086	0.071
35	0.038	0.060	0.078	0.097	0.143	0.126	0.095	0.079
40	0.036	0.055	0.071	0.088	0.126	0.136	0.104	0.087
45	0.033	0.051	0.065	0.079	0.112	0.145	0.111	0.093
50	0.032	0.047	0.060	0.072	0.100	0.152	0.117	0.098
55	0.030	0.044	0.055	0.066	0.090	0.157	0.122	0.103
60	0.028	0.041	0.051	0.060	0.081	0.162	0.126	0.107
65	0.027	0.038	0.047	0.055	0.073	0.153	0.129	0.110
70	0.025	0.036	0.044	0.051	0.067	0.135	0.132	0.113
75	0.024	0.034	0.041	0.048	0.061	0.119	0.135	0.115
80	0.023	0.032	0.038	0.044	0.056	0.106	0.136	0.117
85	0.022	0.030	0.036	0.041	0.052	0.095	0.138	0.118
90	0.021	0.028	0.034	0.038	0.048	0.085	0.139	0.120
95	0.020	0.027	0.032	0.036	0.045	0.077	0.140	0.121
100	0.019	0.025	0.030	0.034	0.042	0.070	0.141	0.122
105	0.018	0.024	0.028	0.032	0.039	0.064	0.142	0.122
110	0.017	0.023	0.027	0.030	0.037	0.059	0.143	0.123
115	0.017	0.022	0.025	0.028	0.034	0.054	0.143	0.124
120	0.016	0.021	0.024	0.027	0.032	0.050	0.144	0.124
125	0.015	0.020	0.023	0.025	0.030	0.047	0.135	0.124
130	0.015	0.019	0.022	0.024	0.029	0.043	0.120	0.125
135	0.014	0.018	0.021	0.023	0.027	0.040	0.107	0.125
140	0.014	0.017	0.020	0.022	0.026	0.038	0.095	0.125
145	0.013	0.017	0.019	0.021	0.024	0.035	0.086	0.125

Appendix B5 continued

150	0.013	0.016	0.018	0.020	0.023	0.033	0.078	0.126
155	0.012	0.015	0.017	0.019	0.022	0.031	0.071	0.126
160	0.012	0.015	0.017	0.018	0.021	0.030	0.065	0.126
165	0.012	0.014	0.016	0.018	0.020	0.028	0.059	0.126
170	0.011	0.014	0.015	0.017	0.019	0.026	0.055	0.126
175	0.011	0.013	0.015	0.016	0.018	0.025	0.050	0.126
180	0.010	0.013	0.014	0.015	0.018	0.024	0.047	0.126
185	0.010	0.012	0.014	0.015	0.017	0.023	0.044	0.119
190	0.010	0.012	0.013	0.014	0.016	0.022	0.041	0.106
195	0.010	0.012	0.013	0.014	0.016	0.021	0.038	0.095
200	0.009	0.011	0.012	0.013	0.015	0.020	0.036	0.086
205	0.009	0.011	0.012	0.013	0.014	0.019	0.033	0.078
210	0.009	0.010	0.012	0.012	0.014	0.018	0.032	0.071
215	0.009	0.010	0.011	0.012	0.013	0.017	0.030	0.065
220	0.008	0.010	0.011	0.012	0.013	0.017	0.028	0.059
225	0.008	0.010	0.010	0.011	0.013	0.016	0.027	0.055
230	0.008	0.009	0.010	0.011	0.012	0.015	0.025	0.050
235	0.008	0.009	0.010	0.011	0.012	0.015	0.024	0.047
240	0.007	0.009	0.010	0.010	0.011	0.014	0.023	0.044
245	0.007	0.009	0.009	0.010	0.011	0.014	0.022	0.041
250	0.007	0.008	0.009	0.010	0.011	0.013	0.021	0.038
255	0.007	0.008	0.009	0.009	0.010	0.013	0.020	0.036
260	0.007	0.008	0.009	0.009	0.010	0.012	0.019	0.033
265	0.007	0.008	0.008	0.009	0.010	0.012	0.018	0.032
270	0.006	0.007	0.008	0.009	0.009	0.011	0.017	0.030
275	0.006	0.007	0.008	0.008	0.009	0.011	0.017	0.028
280	0.006	0.007	0.008	0.008	0.009	0.011	0.016	0.027
285	0.006	0.007	0.007	0.008	0.009	0.010	0.015	0.025
290	0.006	0.007	0.007	0.008	0.008	0.010	0.015	0.024
295	0.006	0.007	0.007	0.008	0.008	0.010	0.014	0.023
300	0.006	0.006	0.007	0.007	0.008	0.010	0.014	0.022
305	0.006	0.006	0.007	0.007	0.008	0.009	0.013	0.021
310	0.005	0.006	0.007	0.007	0.008	0.009	0.013	0.020
315	0.005	0.006	0.006	0.007	0.007	0.009	0.012	0.019
320	0.005	0.006	0.006	0.007	0.007	0.009	0.012	0.018
325	0.005	0.006	0.006	0.006	0.007	0.008	0.012	0.017
330	0.005	0.006	0.006	0.006	0.007	0.008	0.011	0.017
335	0.005	0.006	0.006	0.006	0.007	0.008	0.011	0.016
340	0.005	0.005	0.006	0.006	0.007	0.008	0.010	0.015
345	0.005	0.005	0.006	0.006	0.006	0.007	0.010	0.015
350	0.005	0.005	0.006	0.006	0.006	0.007	0.010	0.014
355	0.005	0.005	0.005	0.006	0.006	0.007	0.010	0.014
360	0.004	0.005	0.005	0.006	0.006	0.007	0.009	0.013
365	0.004	0.005	0.005	0.005	0.006	0.007	0.009	0.013
370	0.004	0.005	0.005	0.005	0.006	0.007	0.009	0.012

Appendix B5 continued

375	0.004	0.005	0.005	0.005	0.006	0.006	0.009	0.012
380	0.004	0.005	0.005	0.005	0.005	0.006	0.008	0.012
385	0.004	0.005	0.005	0.005	0.005	0.006	0.008	0.011
390	0.004	0.004	0.005	0.005	0.005	0.006	0.008	0.011
395	0.004	0.004	0.005	0.005	0.005	0.006	0.008	0.010
400	0.004	0.004	0.005	0.005	0.005	0.006	0.007	0.010

^a Design rainfall durations

Appendix B6: Outlet size of 190 mm with 100 mm inlet size

Time lapse (min)	Water Depth in StormPav (mm)							
	5 ^a	10 ^a	15 ^a	20 ^a	30 ^a	60 ^a	120 ^a	180 ^a
0	0	0	0	0	0	0	0	0
5	0.020	0.017	0.015	0.014	0.012	0.010	0.007	0.006
10	0.055	0.065	0.059	0.054	0.048	0.036	0.026	0.021
15	0.057	0.090	0.097	0.090	0.081	0.062	0.046	0.037
20	0.056	0.090	0.118	0.124	0.110	0.086	0.064	0.052
25	0.055	0.088	0.115	0.140	0.140	0.108	0.080	0.066
30	0.054	0.086	0.112	0.137	0.168	0.130	0.096	0.079
35	0.053	0.085	0.110	0.133	0.179	0.150	0.112	0.092
40	0.052	0.082	0.107	0.129	0.174	0.170	0.126	0.104
45	0.051	0.081	0.104	0.126	0.168	0.188	0.140	0.115
50	0.050	0.079	0.102	0.122	0.163	0.190	0.153	0.126
55	0.049	0.077	0.099	0.119	0.158	0.190	0.166	0.137
60	0.048	0.075	0.097	0.116	0.154	0.190	0.178	0.147
65	0.047	0.074	0.094	0.113	0.149	0.188	0.188	0.156
70	0.046	0.072	0.093	0.110	0.145	0.182	0.190	0.166
75	0.045	0.071	0.090	0.108	0.141	0.176	0.190	0.175
80	0.044	0.069	0.088	0.105	0.136	0.171	0.189	0.183
85	0.044	0.068	0.086	0.102	0.133	0.165	0.190	0.189
90	0.043	0.066	0.084	0.100	0.129	0.160	0.190	0.189
95	0.042	0.065	0.082	0.097	0.125	0.155	0.190	0.189
100	0.041	0.064	0.081	0.095	0.122	0.150	0.190	0.190
105	0.041	0.063	0.079	0.093	0.119	0.146	0.189	0.190
110	0.040	0.061	0.077	0.091	0.116	0.141	0.190	0.189
115	0.039	0.060	0.075	0.089	0.113	0.137	0.190	0.189
120	0.038	0.059	0.074	0.087	0.110	0.133	0.190	0.189
125	0.038	0.058	0.072	0.085	0.107	0.130	0.188	0.190
130	0.037	0.057	0.071	0.083	0.104	0.126	0.182	0.189
135	0.037	0.056	0.069	0.081	0.102	0.123	0.176	0.189
140	0.036	0.054	0.068	0.079	0.099	0.120	0.170	0.189
145	0.035	0.053	0.066	0.077	0.097	0.117	0.165	0.189
150	0.035	0.052	0.065	0.076	0.095	0.113	0.159	0.189
155	0.034	0.051	0.064	0.074	0.092	0.111	0.155	0.189

Appendix B6 continued

160	0.034	0.050	0.062	0.073	0.090	0.108	0.150	0.189
165	0.033	0.049	0.061	0.071	0.088	0.105	0.146	0.189
170	0.033	0.049	0.060	0.070	0.086	0.103	0.142	0.189
175	0.032	0.048	0.059	0.068	0.084	0.100	0.138	0.190
180	0.031	0.047	0.058	0.067	0.082	0.098	0.134	0.189
185	0.031	0.046	0.057	0.065	0.081	0.095	0.130	0.187
190	0.031	0.045	0.055	0.064	0.079	0.093	0.126	0.182
195	0.030	0.044	0.054	0.063	0.077	0.091	0.123	0.175
200	0.030	0.043	0.053	0.061	0.075	0.089	0.119	0.170
205	0.029	0.042	0.052	0.060	0.074	0.087	0.117	0.164
210	0.029	0.042	0.051	0.059	0.072	0.085	0.113	0.159
215	0.028	0.041	0.050	0.058	0.071	0.083	0.110	0.154
220	0.028	0.040	0.049	0.057	0.069	0.081	0.108	0.150
225	0.027	0.040	0.048	0.056	0.068	0.079	0.105	0.145
230	0.027	0.039	0.048	0.055	0.066	0.078	0.102	0.141
235	0.027	0.038	0.047	0.054	0.065	0.076	0.100	0.137
240	0.026	0.038	0.046	0.053	0.064	0.074	0.098	0.133
245	0.026	0.037	0.045	0.052	0.062	0.073	0.095	0.129
250	0.026	0.036	0.044	0.051	0.061	0.071	0.093	0.126
255	0.025	0.036	0.043	0.050	0.060	0.070	0.091	0.122
260	0.025	0.035	0.042	0.049	0.059	0.068	0.089	0.119
265	0.024	0.034	0.042	0.048	0.058	0.067	0.087	0.116
270	0.024	0.034	0.041	0.047	0.057	0.065	0.085	0.113
275	0.024	0.033	0.040	0.046	0.055	0.064	0.083	0.110
280	0.023	0.033	0.039	0.045	0.054	0.063	0.081	0.108
285	0.023	0.032	0.039	0.044	0.053	0.062	0.079	0.105
290	0.023	0.032	0.038	0.043	0.052	0.060	0.078	0.102
295	0.023	0.031	0.037	0.043	0.051	0.059	0.076	0.100
300	0.022	0.031	0.037	0.042	0.050	0.058	0.074	0.097
305	0.022	0.030	0.036	0.041	0.049	0.057	0.073	0.095
310	0.022	0.030	0.036	0.040	0.048	0.056	0.071	0.093
315	0.021	0.029	0.035	0.040	0.048	0.055	0.070	0.091
320	0.021	0.029	0.034	0.039	0.047	0.054	0.068	0.089
325	0.021	0.029	0.034	0.038	0.046	0.053	0.067	0.087
330	0.021	0.028	0.033	0.038	0.045	0.052	0.065	0.085
335	0.020	0.028	0.033	0.037	0.044	0.051	0.064	0.083
340	0.020	0.027	0.032	0.036	0.043	0.050	0.063	0.081
345	0.020	0.027	0.032	0.036	0.042	0.049	0.062	0.079
350	0.020	0.027	0.031	0.035	0.042	0.048	0.060	0.077
355	0.019	0.026	0.031	0.035	0.041	0.047	0.059	0.076
360	0.019	0.026	0.030	0.034	0.040	0.046	0.058	0.074
365	0.019	0.025	0.030	0.033	0.039	0.045	0.057	0.073
370	0.019	0.025	0.029	0.033	0.039	0.044	0.056	0.071
375	0.018	0.025	0.029	0.032	0.038	0.043	0.055	0.070
380	0.018	0.024	0.028	0.032	0.037	0.043	0.054	0.068

Appendix B6 continued

385	0.018	0.024	0.028	0.031	0.037	0.042	0.053	0.067
390	0.018	0.024	0.028	0.031	0.036	0.041	0.052	0.065
395	0.018	0.023	0.027	0.030	0.036	0.040	0.051	0.064
400	0.017	0.023	0.027	0.030	0.035	0.040	0.050	0.063

^a Design rainfall durations

Appendix B7: Outlet size of 190 mm X 300 mm with 100 mm inlet size

Time lapse (min)	Water Depth in StormPav (mm)							
	5 ^a	10 ^a	15 ^a	20 ^a	30 ^a	60 ^a	120 ^a	180 ^a
0	0	0	0	0	0	0	0	0
5	0.020	0.017	0.015	0.014	0.012	0.010	0.007	0.006
10	0.054	0.064	0.058	0.053	0.047	0.036	0.026	0.021
15	0.055	0.088	0.095	0.088	0.078	0.061	0.045	0.036
20	0.054	0.086	0.113	0.119	0.107	0.083	0.062	0.051
25	0.052	0.083	0.108	0.133	0.133	0.104	0.077	0.064
30	0.050	0.079	0.104	0.127	0.157	0.123	0.092	0.076
35	0.048	0.076	0.099	0.121	0.165	0.140	0.105	0.087
40	0.046	0.073	0.095	0.115	0.157	0.156	0.117	0.097
45	0.045	0.071	0.091	0.110	0.148	0.171	0.128	0.107
50	0.043	0.068	0.087	0.105	0.140	0.185	0.139	0.116
55	0.042	0.065	0.083	0.100	0.133	0.189	0.148	0.124
60	0.040	0.063	0.080	0.096	0.126	0.190	0.157	0.131
65	0.039	0.061	0.077	0.091	0.120	0.186	0.165	0.138
70	0.038	0.058	0.074	0.088	0.114	0.174	0.173	0.145
75	0.037	0.056	0.071	0.084	0.109	0.165	0.180	0.151
80	0.036	0.054	0.068	0.081	0.104	0.156	0.187	0.156
85	0.035	0.052	0.066	0.077	0.099	0.147	0.189	0.161
90	0.034	0.051	0.063	0.074	0.095	0.139	0.188	0.166
95	0.033	0.049	0.061	0.071	0.091	0.132	0.188	0.170
100	0.032	0.047	0.059	0.069	0.087	0.125	0.189	0.174
105	0.031	0.046	0.057	0.066	0.084	0.119	0.189	0.177
110	0.030	0.044	0.055	0.064	0.080	0.113	0.189	0.181
115	0.029	0.042	0.053	0.061	0.077	0.108	0.188	0.184
120	0.028	0.041	0.051	0.059	0.074	0.103	0.188	0.186
125	0.028	0.040	0.049	0.057	0.071	0.099	0.185	0.188
130	0.027	0.038	0.047	0.055	0.068	0.094	0.173	0.188
135	0.026	0.037	0.046	0.053	0.066	0.090	0.163	0.189
140	0.025	0.036	0.044	0.051	0.063	0.086	0.154	0.188
145	0.025	0.035	0.043	0.049	0.061	0.083	0.146	0.187
150	0.024	0.034	0.041	0.048	0.059	0.080	0.138	0.188
155	0.024	0.033	0.040	0.046	0.057	0.076	0.131	0.188
160	0.023	0.032	0.039	0.044	0.055	0.073	0.124	0.188
165	0.022	0.031	0.037	0.043	0.053	0.071	0.118	0.188

Appendix B7 continued

170	0.022	0.030	0.036	0.042	0.051	0.068	0.113	0.188
175	0.021	0.029	0.035	0.040	0.049	0.065	0.108	0.188
180	0.021	0.029	0.034	0.039	0.047	0.063	0.102	0.189
185	0.020	0.028	0.033	0.038	0.046	0.061	0.098	0.183
190	0.020	0.027	0.032	0.037	0.044	0.058	0.094	0.173
195	0.020	0.026	0.031	0.035	0.043	0.056	0.090	0.162
200	0.019	0.026	0.030	0.034	0.041	0.054	0.086	0.153
205	0.019	0.025	0.030	0.033	0.040	0.052	0.082	0.145
210	0.018	0.024	0.029	0.032	0.039	0.051	0.079	0.137
215	0.018	0.024	0.028	0.031	0.038	0.049	0.076	0.130
220	0.017	0.023	0.027	0.031	0.036	0.047	0.073	0.124
225	0.017	0.023	0.027	0.030	0.035	0.046	0.070	0.118
230	0.017	0.022	0.026	0.029	0.034	0.044	0.068	0.112
235	0.016	0.022	0.025	0.028	0.033	0.043	0.065	0.107
240	0.016	0.021	0.025	0.027	0.032	0.041	0.063	0.102
245	0.016	0.021	0.024	0.027	0.031	0.040	0.060	0.098
250	0.015	0.020	0.023	0.026	0.030	0.039	0.058	0.094
255	0.015	0.020	0.023	0.025	0.030	0.037	0.056	0.089
260	0.015	0.019	0.022	0.025	0.029	0.036	0.054	0.086
265	0.015	0.019	0.022	0.024	0.028	0.035	0.052	0.082
270	0.014	0.018	0.021	0.023	0.027	0.034	0.050	0.079
275	0.014	0.018	0.021	0.023	0.027	0.033	0.049	0.076
280	0.014	0.018	0.020	0.022	0.026	0.032	0.047	0.073
285	0.014	0.017	0.020	0.022	0.025	0.031	0.045	0.070
290	0.013	0.017	0.019	0.021	0.025	0.030	0.044	0.067
295	0.013	0.017	0.019	0.021	0.024	0.029	0.042	0.065
300	0.013	0.016	0.018	0.020	0.023	0.029	0.041	0.062
305	0.013	0.016	0.018	0.020	0.023	0.028	0.040	0.060
310	0.012	0.016	0.018	0.019	0.022	0.027	0.038	0.058
315	0.012	0.015	0.017	0.019	0.022	0.026	0.037	0.056
320	0.012	0.015	0.017	0.019	0.021	0.026	0.036	0.054
325	0.012	0.015	0.017	0.018	0.021	0.025	0.035	0.052
330	0.012	0.014	0.016	0.018	0.020	0.024	0.034	0.050
335	0.011	0.014	0.016	0.017	0.020	0.024	0.033	0.049
340	0.011	0.014	0.016	0.017	0.019	0.023	0.032	0.047
345	0.011	0.014	0.015	0.017	0.019	0.023	0.031	0.045
350	0.011	0.013	0.015	0.016	0.019	0.022	0.030	0.044
355	0.011	0.013	0.015	0.016	0.018	0.022	0.029	0.042
360	0.010	0.013	0.014	0.016	0.018	0.021	0.029	0.041
365	0.010	0.013	0.014	0.015	0.017	0.021	0.028	0.040
370	0.010	0.012	0.014	0.015	0.017	0.020	0.027	0.038
375	0.010	0.012	0.014	0.015	0.017	0.020	0.026	0.037
380	0.010	0.012	0.013	0.015	0.016	0.019	0.026	0.036
385	0.010	0.012	0.013	0.014	0.016	0.019	0.025	0.035
390	0.009	0.012	0.013	0.014	0.016	0.018	0.024	0.034

Appendix B7 continued

395	0.009	0.011	0.013	0.014	0.015	0.018	0.024	0.033
400	0.009	0.011	0.012	0.013	0.015	0.018	0.023	0.032

^a Design rainfall durations

Appendix B8: Outlet size of 190 mm X 500 mm with 100 mm inlet size

Time lapse (min)	Water Depth in StormPav (mm)							
	5 ^a	10 ^a	15 ^a	20 ^a	30 ^a	60 ^a	120 ^a	180 ^a
0	0	0	0	0	0	0	0	0
5	0.020	0.017	0.015	0.014	0.012	0.010	0.007	0.006
10	0.053	0.063	0.057	0.052	0.046	0.035	0.026	0.021
15	0.053	0.085	0.092	0.085	0.076	0.059	0.044	0.035
20	0.051	0.082	0.108	0.114	0.103	0.080	0.060	0.049
25	0.048	0.077	0.102	0.125	0.127	0.099	0.074	0.061
30	0.046	0.073	0.095	0.117	0.148	0.116	0.087	0.072
35	0.043	0.069	0.089	0.109	0.152	0.131	0.099	0.082
40	0.041	0.065	0.084	0.102	0.141	0.144	0.109	0.091
45	0.039	0.061	0.079	0.095	0.130	0.155	0.118	0.099
50	0.038	0.058	0.074	0.089	0.121	0.166	0.126	0.106
55	0.036	0.055	0.070	0.084	0.112	0.175	0.133	0.112
60	0.034	0.052	0.066	0.079	0.105	0.183	0.140	0.118
65	0.033	0.050	0.063	0.074	0.098	0.178	0.145	0.123
70	0.031	0.047	0.059	0.070	0.092	0.163	0.151	0.127
75	0.030	0.045	0.056	0.066	0.086	0.150	0.155	0.131
80	0.029	0.043	0.053	0.063	0.081	0.138	0.159	0.135
85	0.028	0.041	0.051	0.059	0.076	0.128	0.162	0.138
90	0.027	0.039	0.048	0.056	0.072	0.119	0.165	0.141
95	0.026	0.037	0.046	0.053	0.068	0.110	0.168	0.143
100	0.025	0.035	0.043	0.051	0.064	0.103	0.170	0.145
105	0.024	0.034	0.041	0.048	0.060	0.096	0.172	0.147
110	0.023	0.032	0.039	0.046	0.057	0.090	0.174	0.149
115	0.022	0.031	0.037	0.043	0.054	0.085	0.176	0.150
120	0.022	0.030	0.036	0.041	0.052	0.080	0.177	0.152
125	0.021	0.028	0.034	0.039	0.049	0.075	0.170	0.153
130	0.020	0.027	0.033	0.037	0.046	0.071	0.156	0.154
135	0.019	0.026	0.031	0.036	0.044	0.067	0.144	0.155
140	0.019	0.025	0.030	0.034	0.042	0.063	0.133	0.156
145	0.018	0.024	0.029	0.033	0.040	0.060	0.123	0.156
150	0.018	0.024	0.028	0.031	0.038	0.057	0.115	0.157
155	0.017	0.023	0.027	0.030	0.036	0.054	0.107	0.158
160	0.017	0.022	0.026	0.029	0.035	0.051	0.100	0.158
165	0.016	0.021	0.025	0.028	0.033	0.048	0.093	0.158
170	0.016	0.020	0.024	0.027	0.032	0.046	0.087	0.159
175	0.015	0.020	0.023	0.026	0.031	0.044	0.082	0.159

Appendix B8 continued

180	0.015	0.019	0.022	0.025	0.029	0.041	0.077	0.159
185	0.014	0.019	0.021	0.024	0.028	0.039	0.073	0.153
190	0.014	0.018	0.021	0.023	0.027	0.038	0.069	0.142
195	0.014	0.017	0.020	0.022	0.026	0.036	0.065	0.131
200	0.013	0.017	0.019	0.021	0.025	0.034	0.061	0.122
205	0.013	0.016	0.019	0.021	0.024	0.033	0.058	0.113
210	0.013	0.016	0.018	0.020	0.023	0.031	0.055	0.105
215	0.012	0.015	0.018	0.019	0.022	0.030	0.052	0.099
220	0.012	0.015	0.017	0.019	0.022	0.029	0.050	0.092
225	0.012	0.015	0.017	0.018	0.021	0.028	0.047	0.087
230	0.011	0.014	0.016	0.018	0.020	0.027	0.045	0.081
235	0.011	0.014	0.016	0.017	0.020	0.026	0.043	0.076
240	0.011	0.013	0.015	0.017	0.019	0.025	0.040	0.072
245	0.011	0.013	0.015	0.016	0.018	0.024	0.039	0.068
250	0.010	0.013	0.014	0.016	0.018	0.023	0.037	0.064
255	0.010	0.012	0.014	0.015	0.017	0.022	0.035	0.061
260	0.010	0.012	0.014	0.015	0.017	0.021	0.034	0.058
265	0.010	0.012	0.013	0.014	0.016	0.021	0.032	0.055
270	0.009	0.012	0.013	0.014	0.016	0.020	0.031	0.052
275	0.009	0.011	0.013	0.014	0.015	0.019	0.030	0.049
280	0.009	0.011	0.012	0.013	0.015	0.019	0.028	0.047
285	0.009	0.011	0.012	0.013	0.014	0.018	0.027	0.044
290	0.009	0.010	0.012	0.013	0.014	0.018	0.026	0.042
295	0.009	0.010	0.011	0.012	0.014	0.017	0.025	0.040
300	0.008	0.010	0.011	0.012	0.013	0.017	0.024	0.038
305	0.008	0.010	0.011	0.012	0.013	0.016	0.023	0.037
310	0.008	0.010	0.011	0.011	0.013	0.016	0.023	0.035
315	0.008	0.009	0.010	0.011	0.012	0.015	0.022	0.033
320	0.008	0.009	0.010	0.011	0.012	0.015	0.021	0.032
325	0.008	0.009	0.010	0.011	0.012	0.014	0.020	0.031
330	0.007	0.009	0.010	0.010	0.011	0.014	0.020	0.029
335	0.007	0.009	0.009	0.010	0.011	0.014	0.019	0.028
340	0.007	0.008	0.009	0.010	0.011	0.013	0.019	0.027
345	0.007	0.008	0.009	0.010	0.011	0.013	0.018	0.026
350	0.007	0.008	0.009	0.009	0.010	0.013	0.017	0.025
355	0.007	0.008	0.009	0.009	0.010	0.012	0.017	0.024
360	0.007	0.008	0.008	0.009	0.010	0.012	0.016	0.023
365	0.007	0.008	0.008	0.009	0.010	0.012	0.016	0.023
370	0.006	0.007	0.008	0.009	0.010	0.011	0.015	0.022
375	0.006	0.007	0.008	0.008	0.009	0.011	0.015	0.021
380	0.006	0.007	0.008	0.008	0.009	0.011	0.015	0.020
385	0.006	0.007	0.008	0.008	0.009	0.011	0.014	0.020
390	0.006	0.007	0.008	0.008	0.009	0.010	0.014	0.019
395	0.006	0.007	0.007	0.008	0.009	0.010	0.013	0.018
400	0.006	0.007	0.007	0.008	0.008	0.010	0.013	0.018

Appendix B8 continued

^a Design rainfall durations

Appendix B9: Outlet size of 190 mm X 700 mm with 100 mm inlet size

Time lapse (min)	Water Depth in StormPav (mm)							
	5 ^a	10 ^a	15 ^a	20 ^a	30 ^a	60 ^a	120 ^a	180 ^a
0	0	0	0	0	0	0	0	0
5	0.020	0.017	0.015	0.014	0.012	0.010	0.007	0.006
10	0.052	0.062	0.056	0.051	0.046	0.035	0.025	0.020
15	0.052	0.083	0.090	0.083	0.074	0.058	0.043	0.035
20	0.049	0.078	0.104	0.110	0.100	0.078	0.058	0.048
25	0.045	0.073	0.097	0.120	0.122	0.096	0.072	0.060
30	0.043	0.068	0.089	0.111	0.140	0.111	0.084	0.070
35	0.040	0.064	0.083	0.101	0.143	0.124	0.094	0.079
40	0.038	0.059	0.077	0.094	0.130	0.135	0.103	0.086
45	0.036	0.056	0.071	0.086	0.119	0.145	0.111	0.093
50	0.034	0.052	0.066	0.080	0.109	0.153	0.118	0.099
55	0.032	0.049	0.062	0.074	0.100	0.161	0.124	0.104
60	0.031	0.046	0.058	0.069	0.092	0.167	0.129	0.109
65	0.029	0.043	0.054	0.064	0.085	0.161	0.133	0.113
70	0.028	0.040	0.051	0.060	0.079	0.146	0.137	0.116
75	0.026	0.038	0.048	0.056	0.073	0.132	0.140	0.119
80	0.025	0.036	0.045	0.053	0.068	0.120	0.143	0.122
85	0.024	0.034	0.042	0.049	0.063	0.110	0.146	0.124
90	0.023	0.032	0.040	0.046	0.059	0.101	0.148	0.126
95	0.022	0.031	0.037	0.043	0.055	0.093	0.149	0.128
100	0.021	0.029	0.035	0.041	0.052	0.086	0.151	0.129
105	0.020	0.028	0.033	0.038	0.049	0.079	0.152	0.131
110	0.020	0.026	0.032	0.036	0.046	0.074	0.153	0.132
115	0.019	0.025	0.030	0.034	0.043	0.068	0.154	0.133
120	0.018	0.024	0.029	0.033	0.040	0.064	0.155	0.134
125	0.017	0.023	0.027	0.031	0.038	0.060	0.148	0.134
130	0.017	0.022	0.026	0.029	0.036	0.056	0.135	0.135
135	0.016	0.021	0.025	0.028	0.034	0.052	0.123	0.135
140	0.016	0.020	0.024	0.027	0.032	0.049	0.112	0.136
145	0.015	0.019	0.023	0.025	0.031	0.046	0.103	0.136
150	0.015	0.019	0.022	0.024	0.029	0.043	0.094	0.137
155	0.014	0.018	0.021	0.023	0.028	0.041	0.087	0.137
160	0.014	0.017	0.020	0.022	0.026	0.038	0.081	0.137
165	0.013	0.017	0.019	0.021	0.025	0.036	0.075	0.137
170	0.013	0.016	0.018	0.020	0.024	0.034	0.070	0.138
175	0.012	0.016	0.018	0.020	0.023	0.032	0.065	0.138
180	0.012	0.015	0.017	0.019	0.022	0.031	0.061	0.138
185	0.012	0.015	0.016	0.018	0.021	0.029	0.057	0.132

Appendix B9 continued

190	0.011	0.014	0.016	0.017	0.020	0.028	0.053	0.121
195	0.011	0.014	0.015	0.017	0.019	0.026	0.050	0.110
200	0.011	0.013	0.015	0.016	0.019	0.025	0.047	0.101
205	0.010	0.013	0.014	0.016	0.018	0.024	0.044	0.093
210	0.010	0.012	0.014	0.015	0.017	0.023	0.041	0.086
215	0.010	0.012	0.013	0.015	0.017	0.022	0.039	0.080
220	0.010	0.012	0.013	0.014	0.016	0.021	0.037	0.074
225	0.009	0.011	0.013	0.014	0.016	0.020	0.035	0.069
230	0.009	0.011	0.012	0.013	0.015	0.020	0.033	0.064
235	0.009	0.011	0.012	0.013	0.014	0.019	0.031	0.060
240	0.009	0.010	0.011	0.012	0.014	0.018	0.030	0.056
245	0.008	0.010	0.011	0.012	0.014	0.017	0.028	0.053
250	0.008	0.010	0.011	0.012	0.013	0.017	0.027	0.049
255	0.008	0.010	0.011	0.011	0.013	0.016	0.026	0.046
260	0.008	0.009	0.010	0.011	0.012	0.016	0.024	0.043
265	0.008	0.009	0.010	0.011	0.012	0.015	0.023	0.041
270	0.007	0.009	0.010	0.010	0.012	0.015	0.022	0.038
275	0.007	0.009	0.009	0.010	0.011	0.014	0.021	0.036
280	0.007	0.008	0.009	0.010	0.011	0.014	0.020	0.034
285	0.007	0.008	0.009	0.010	0.011	0.013	0.020	0.032
290	0.007	0.008	0.009	0.009	0.010	0.013	0.019	0.031
295	0.007	0.008	0.009	0.009	0.010	0.012	0.018	0.029
300	0.007	0.008	0.008	0.009	0.010	0.012	0.018	0.028
305	0.006	0.007	0.008	0.009	0.010	0.012	0.017	0.027
310	0.006	0.007	0.008	0.008	0.009	0.011	0.016	0.025
315	0.006	0.007	0.008	0.008	0.009	0.011	0.016	0.024
320	0.006	0.007	0.008	0.008	0.009	0.011	0.015	0.023
325	0.006	0.007	0.007	0.008	0.009	0.010	0.015	0.022
330	0.006	0.007	0.007	0.008	0.008	0.010	0.014	0.021
335	0.006	0.007	0.007	0.007	0.008	0.010	0.014	0.020
340	0.006	0.006	0.007	0.007	0.008	0.010	0.013	0.020
345	0.005	0.006	0.007	0.007	0.008	0.009	0.013	0.019
350	0.005	0.006	0.007	0.007	0.008	0.009	0.012	0.018
355	0.005	0.006	0.006	0.007	0.007	0.009	0.012	0.017
360	0.005	0.006	0.006	0.007	0.007	0.009	0.012	0.017
365	0.005	0.006	0.006	0.007	0.007	0.008	0.011	0.016
370	0.005	0.006	0.006	0.006	0.007	0.008	0.011	0.016
375	0.005	0.006	0.006	0.006	0.007	0.008	0.011	0.015
380	0.005	0.005	0.006	0.006	0.007	0.008	0.010	0.015
385	0.005	0.005	0.006	0.006	0.007	0.008	0.010	0.014
390	0.005	0.005	0.006	0.006	0.006	0.007	0.010	0.014
395	0.005	0.005	0.006	0.006	0.006	0.007	0.010	0.013
400	0.004	0.005	0.005	0.006	0.006	0.007	0.009	0.013

^a Design rainfall durations

Appendix B10: Outlet size of 190 mm X 900 mm with 100 mm inlet size

Time lapse (min)	Water Depth in StormPav (mm)							
	5 ^a	10 ^a	15 ^a	20 ^a	30 ^a	60 ^a	120 ^a	180 ^a
0	0	0	0	0	0	0	0	0
5	0.020	0.017	0.015	0.014	0.012	0.010	0.007	0.006
10	0.052	0.061	0.055	0.050	0.045	0.034	0.025	0.020
15	0.050	0.082	0.088	0.081	0.073	0.057	0.042	0.034
20	0.047	0.076	0.102	0.108	0.097	0.076	0.057	0.047
25	0.044	0.070	0.093	0.116	0.118	0.093	0.070	0.058
30	0.041	0.065	0.085	0.106	0.135	0.107	0.081	0.068
35	0.038	0.060	0.078	0.096	0.137	0.119	0.091	0.076
40	0.036	0.056	0.072	0.088	0.123	0.129	0.099	0.083
45	0.034	0.052	0.066	0.080	0.111	0.138	0.106	0.089
50	0.032	0.048	0.061	0.074	0.101	0.145	0.112	0.095
55	0.030	0.045	0.057	0.068	0.092	0.151	0.117	0.099
60	0.028	0.042	0.053	0.063	0.084	0.156	0.121	0.103
65	0.027	0.039	0.049	0.058	0.077	0.150	0.125	0.106
70	0.025	0.036	0.045	0.054	0.071	0.134	0.128	0.109
75	0.024	0.034	0.042	0.050	0.065	0.121	0.131	0.112
80	0.023	0.032	0.040	0.046	0.060	0.109	0.133	0.114
85	0.022	0.030	0.037	0.043	0.056	0.099	0.135	0.116
90	0.021	0.029	0.035	0.040	0.052	0.090	0.137	0.117
95	0.020	0.027	0.033	0.038	0.048	0.082	0.138	0.119
100	0.019	0.026	0.031	0.035	0.045	0.076	0.139	0.120
105	0.018	0.024	0.029	0.033	0.042	0.070	0.140	0.121
110	0.017	0.023	0.027	0.031	0.039	0.064	0.141	0.122
115	0.017	0.022	0.026	0.030	0.037	0.059	0.142	0.122
120	0.016	0.021	0.025	0.028	0.034	0.055	0.142	0.123
125	0.015	0.020	0.023	0.026	0.032	0.051	0.136	0.123
130	0.015	0.019	0.022	0.025	0.030	0.047	0.122	0.124
135	0.014	0.018	0.021	0.024	0.029	0.044	0.110	0.124
140	0.014	0.018	0.020	0.023	0.027	0.041	0.100	0.124
145	0.013	0.017	0.019	0.022	0.026	0.038	0.091	0.125
150	0.013	0.016	0.019	0.021	0.024	0.036	0.083	0.125
155	0.012	0.016	0.018	0.020	0.023	0.034	0.076	0.125
160	0.012	0.015	0.017	0.019	0.022	0.032	0.070	0.125
165	0.012	0.014	0.016	0.018	0.021	0.030	0.065	0.125
170	0.011	0.014	0.016	0.017	0.020	0.028	0.060	0.126
175	0.011	0.013	0.015	0.017	0.019	0.027	0.056	0.126
180	0.011	0.013	0.015	0.016	0.018	0.025	0.052	0.126
185	0.010	0.012	0.014	0.015	0.018	0.024	0.048	0.120
190	0.010	0.012	0.014	0.015	0.017	0.023	0.045	0.109
195	0.010	0.012	0.013	0.014	0.016	0.022	0.041	0.099
200	0.009	0.011	0.013	0.014	0.016	0.021	0.039	0.090
205	0.009	0.011	0.012	0.013	0.015	0.020	0.036	0.082

Appendix B10 continued

210	0.009	0.011	0.012	0.013	0.014	0.019	0.034	0.076
215	0.009	0.010	0.011	0.012	0.014	0.018	0.032	0.070
220	0.008	0.010	0.011	0.012	0.013	0.017	0.030	0.064
225	0.008	0.010	0.011	0.011	0.013	0.017	0.029	0.059
230	0.008	0.009	0.010	0.011	0.012	0.016	0.027	0.055
235	0.008	0.009	0.010	0.011	0.012	0.015	0.026	0.051
240	0.008	0.009	0.010	0.010	0.012	0.015	0.024	0.048
245	0.007	0.009	0.009	0.010	0.011	0.014	0.023	0.044
250	0.007	0.008	0.009	0.010	0.011	0.014	0.022	0.041
255	0.007	0.008	0.009	0.010	0.011	0.013	0.021	0.039
260	0.007	0.008	0.009	0.009	0.010	0.013	0.020	0.036
265	0.007	0.008	0.008	0.009	0.010	0.012	0.019	0.034
270	0.006	0.008	0.008	0.009	0.010	0.012	0.018	0.032
275	0.006	0.007	0.008	0.009	0.009	0.012	0.018	0.030
280	0.006	0.007	0.008	0.008	0.009	0.011	0.017	0.028
285	0.006	0.007	0.008	0.008	0.009	0.011	0.016	0.027
290	0.006	0.007	0.007	0.008	0.009	0.011	0.016	0.026
295	0.006	0.007	0.007	0.008	0.008	0.010	0.015	0.024
300	0.006	0.007	0.007	0.007	0.008	0.010	0.014	0.023
305	0.006	0.006	0.007	0.007	0.008	0.010	0.014	0.022
310	0.005	0.006	0.007	0.007	0.008	0.009	0.013	0.021
315	0.005	0.006	0.007	0.007	0.008	0.009	0.013	0.020
320	0.005	0.006	0.006	0.007	0.007	0.009	0.012	0.019
325	0.005	0.006	0.006	0.007	0.007	0.009	0.012	0.018
330	0.005	0.006	0.006	0.006	0.007	0.008	0.012	0.018
335	0.005	0.006	0.006	0.006	0.007	0.008	0.011	0.017
340	0.005	0.005	0.006	0.006	0.007	0.008	0.011	0.016
345	0.005	0.005	0.006	0.006	0.007	0.008	0.011	0.015
350	0.005	0.005	0.006	0.006	0.006	0.007	0.010	0.015
355	0.005	0.005	0.005	0.006	0.006	0.007	0.010	0.014
360	0.004	0.005	0.005	0.006	0.006	0.007	0.010	0.014
365	0.004	0.005	0.005	0.006	0.006	0.007	0.009	0.013
370	0.004	0.005	0.005	0.005	0.006	0.007	0.009	0.013
375	0.004	0.005	0.005	0.005	0.006	0.007	0.009	0.012
380	0.004	0.005	0.005	0.005	0.006	0.006	0.009	0.012
385	0.004	0.005	0.005	0.005	0.005	0.006	0.008	0.012
390	0.004	0.004	0.005	0.005	0.005	0.006	0.008	0.011
395	0.004	0.004	0.005	0.005	0.005	0.006	0.008	0.011
400	0.004	0.004	0.005	0.005	0.005	0.006	0.008	0.011

^a Design rainfall durations

Appendix B11: Outlet size of 190 mm with 125 mm inlet size

Time lapse (min)	Water Depth in StormPav (mm)							
	5 ^a	10 ^a	15 ^a	20 ^a	30 ^a	60 ^a	120 ^a	180 ^a
0	0	0	0	0	0	0	0	0
5	0.020	0.017	0.015	0.014	0.013	0.010	0.007	0.006
10	0.052	0.062	0.055	0.051	0.045	0.034	0.026	0.021
15	0.052	0.085	0.092	0.085	0.076	0.059	0.043	0.035
20	0.051	0.083	0.110	0.117	0.105	0.081	0.060	0.049
25	0.050	0.082	0.108	0.132	0.133	0.103	0.076	0.062
30	0.049	0.081	0.106	0.129	0.160	0.123	0.091	0.075
35	0.049	0.079	0.103	0.126	0.171	0.143	0.106	0.087
40	0.048	0.077	0.101	0.123	0.166	0.162	0.120	0.098
45	0.047	0.075	0.098	0.119	0.161	0.182	0.133	0.110
50	0.046	0.074	0.096	0.117	0.156	0.190	0.146	0.120
55	0.045	0.073	0.094	0.114	0.151	0.190	0.159	0.131
60	0.045	0.071	0.092	0.111	0.147	0.190	0.171	0.141
65	0.044	0.070	0.090	0.108	0.143	0.189	0.184	0.150
70	0.043	0.068	0.088	0.106	0.139	0.182	0.190	0.159
75	0.042	0.067	0.086	0.103	0.135	0.176	0.190	0.169
80	0.042	0.066	0.084	0.101	0.131	0.171	0.190	0.177
85	0.041	0.064	0.082	0.098	0.128	0.165	0.190	0.186
90	0.041	0.063	0.081	0.096	0.125	0.160	0.190	0.190
95	0.040	0.062	0.079	0.094	0.121	0.155	0.190	0.190
100	0.039	0.061	0.077	0.092	0.118	0.151	0.190	0.190
105	0.039	0.060	0.076	0.090	0.115	0.146	0.190	0.190
110	0.038	0.059	0.074	0.088	0.112	0.142	0.190	0.190
115	0.038	0.058	0.073	0.086	0.109	0.138	0.190	0.190
120	0.037	0.057	0.071	0.084	0.107	0.134	0.190	0.190
125	0.036	0.056	0.070	0.082	0.104	0.130	0.188	0.190
130	0.036	0.055	0.069	0.080	0.102	0.127	0.182	0.190
135	0.035	0.054	0.067	0.079	0.099	0.124	0.176	0.190
140	0.035	0.053	0.066	0.077	0.097	0.121	0.170	0.190
145	0.034	0.052	0.065	0.076	0.095	0.118	0.164	0.190
150	0.034	0.051	0.063	0.074	0.093	0.114	0.160	0.190
155	0.033	0.050	0.062	0.073	0.091	0.112	0.154	0.190
160	0.033	0.049	0.061	0.071	0.089	0.109	0.150	0.190
165	0.032	0.048	0.060	0.070	0.087	0.106	0.146	0.190
170	0.032	0.048	0.059	0.068	0.085	0.104	0.142	0.190
175	0.032	0.047	0.058	0.067	0.083	0.101	0.138	0.190
180	0.031	0.046	0.057	0.066	0.081	0.099	0.134	0.190
185	0.031	0.045	0.056	0.064	0.080	0.097	0.130	0.187
190	0.030	0.045	0.055	0.063	0.078	0.094	0.127	0.182
195	0.030	0.044	0.054	0.062	0.076	0.092	0.123	0.175
200	0.029	0.043	0.053	0.061	0.075	0.090	0.121	0.170
205	0.029	0.042	0.052	0.060	0.073	0.088	0.117	0.165

Appendix B11 continued

210	0.029	0.042	0.051	0.059	0.072	0.086	0.114	0.159
215	0.028	0.041	0.050	0.058	0.070	0.084	0.112	0.155
220	0.028	0.041	0.049	0.057	0.069	0.083	0.109	0.150
225	0.028	0.040	0.048	0.056	0.068	0.081	0.106	0.146
230	0.027	0.039	0.048	0.055	0.066	0.079	0.104	0.142
235	0.027	0.039	0.047	0.054	0.065	0.078	0.101	0.138
240	0.027	0.038	0.046	0.053	0.064	0.076	0.099	0.134
245	0.026	0.038	0.045	0.052	0.063	0.074	0.096	0.131
250	0.026	0.037	0.045	0.051	0.062	0.073	0.094	0.127
255	0.026	0.036	0.044	0.050	0.060	0.072	0.092	0.123
260	0.025	0.036	0.043	0.049	0.059	0.070	0.090	0.120
265	0.025	0.035	0.043	0.048	0.058	0.069	0.088	0.117
270	0.025	0.035	0.042	0.048	0.057	0.067	0.086	0.114
275	0.024	0.034	0.041	0.047	0.056	0.066	0.084	0.111
280	0.024	0.034	0.041	0.046	0.055	0.065	0.083	0.109
285	0.024	0.033	0.040	0.045	0.054	0.064	0.081	0.106
290	0.023	0.033	0.039	0.045	0.053	0.062	0.079	0.104
295	0.023	0.032	0.039	0.044	0.052	0.061	0.077	0.101
300	0.023	0.032	0.038	0.043	0.051	0.060	0.076	0.099
305	0.023	0.032	0.038	0.042	0.050	0.059	0.074	0.096
310	0.022	0.031	0.037	0.042	0.050	0.058	0.073	0.094
315	0.022	0.031	0.036	0.041	0.049	0.057	0.071	0.092
320	0.022	0.030	0.036	0.040	0.048	0.056	0.070	0.090
325	0.021	0.030	0.035	0.040	0.047	0.055	0.069	0.088
330	0.021	0.029	0.035	0.039	0.046	0.054	0.067	0.086
335	0.021	0.029	0.034	0.039	0.046	0.053	0.066	0.084
340	0.021	0.029	0.034	0.038	0.045	0.052	0.065	0.083
345	0.021	0.028	0.033	0.037	0.044	0.051	0.063	0.081
350	0.020	0.028	0.033	0.037	0.043	0.050	0.062	0.079
355	0.020	0.028	0.032	0.036	0.043	0.049	0.061	0.077
360	0.020	0.027	0.032	0.036	0.042	0.049	0.060	0.076
365	0.020	0.027	0.032	0.035	0.041	0.048	0.059	0.074
370	0.019	0.026	0.031	0.035	0.041	0.047	0.058	0.073
375	0.019	0.026	0.031	0.034	0.040	0.046	0.057	0.071
380	0.019	0.026	0.030	0.034	0.040	0.045	0.056	0.070
385	0.019	0.025	0.030	0.033	0.039	0.045	0.055	0.068
390	0.019	0.025	0.029	0.033	0.038	0.044	0.054	0.067
395	0.018	0.025	0.029	0.032	0.038	0.043	0.053	0.066
400	0.018	0.025	0.029	0.032	0.037	0.043	0.052	0.065

^a Design rainfall durations

Appendix B12: Outlet size of 190 mm X 300 mm with 125 mm inlet size

Time lapse (min)	Water Depth in StormPav (mm)							
	5 ^a	10 ^a	15 ^a	20 ^a	30 ^a	60 ^a	120 ^a	180 ^a
0	0	0	0	0	0	0	0	0
5	0.019	0.017	0.015	0.014	0.013	0.010	0.007	0.006
10	0.051	0.061	0.054	0.050	0.044	0.034	0.025	0.021
15	0.050	0.083	0.090	0.083	0.074	0.058	0.042	0.035
20	0.048	0.080	0.106	0.113	0.102	0.079	0.058	0.048
25	0.047	0.077	0.102	0.126	0.127	0.099	0.073	0.060
30	0.046	0.074	0.098	0.120	0.151	0.117	0.087	0.072
35	0.045	0.072	0.094	0.115	0.158	0.134	0.100	0.083
40	0.043	0.069	0.090	0.110	0.150	0.150	0.112	0.093
45	0.042	0.067	0.087	0.105	0.142	0.165	0.123	0.102
50	0.041	0.064	0.083	0.100	0.135	0.179	0.133	0.111
55	0.040	0.062	0.080	0.096	0.128	0.190	0.143	0.119
60	0.039	0.060	0.077	0.092	0.122	0.190	0.152	0.126
65	0.037	0.058	0.074	0.088	0.117	0.187	0.161	0.134
70	0.037	0.056	0.071	0.085	0.111	0.174	0.168	0.140
75	0.036	0.054	0.069	0.082	0.106	0.164	0.176	0.146
80	0.035	0.053	0.066	0.078	0.102	0.156	0.181	0.152
85	0.034	0.051	0.064	0.075	0.097	0.148	0.189	0.157
90	0.033	0.049	0.062	0.073	0.093	0.140	0.189	0.162
95	0.032	0.048	0.060	0.070	0.089	0.133	0.189	0.166
100	0.031	0.046	0.058	0.068	0.086	0.126	0.189	0.171
105	0.030	0.045	0.056	0.065	0.082	0.120	0.189	0.174
110	0.030	0.044	0.054	0.063	0.079	0.115	0.190	0.178
115	0.029	0.042	0.052	0.061	0.076	0.109	0.189	0.181
120	0.028	0.041	0.051	0.059	0.073	0.104	0.189	0.184
125	0.028	0.040	0.049	0.057	0.071	0.100	0.185	0.187
130	0.027	0.039	0.048	0.055	0.068	0.096	0.174	0.189
135	0.026	0.038	0.046	0.053	0.066	0.092	0.163	0.188
140	0.026	0.037	0.045	0.051	0.063	0.088	0.154	0.189
145	0.025	0.036	0.043	0.050	0.061	0.084	0.146	0.188
150	0.025	0.035	0.042	0.048	0.059	0.081	0.138	0.188
155	0.024	0.034	0.041	0.047	0.057	0.078	0.131	0.189
160	0.023	0.033	0.040	0.045	0.055	0.075	0.125	0.188
165	0.023	0.032	0.039	0.044	0.054	0.072	0.120	0.189
170	0.022	0.031	0.038	0.043	0.052	0.070	0.114	0.189
175	0.022	0.031	0.037	0.042	0.050	0.067	0.109	0.188
180	0.021	0.030	0.036	0.040	0.049	0.065	0.104	0.190
185	0.021	0.029	0.035	0.039	0.047	0.063	0.099	0.184
190	0.021	0.028	0.034	0.038	0.046	0.060	0.095	0.172
195	0.020	0.028	0.033	0.037	0.044	0.058	0.091	0.162
200	0.020	0.027	0.032	0.036	0.043	0.057	0.087	0.154
205	0.019	0.026	0.031	0.035	0.042	0.055	0.084	0.146

Appendix B12 continued

210	0.019	0.026	0.030	0.034	0.041	0.053	0.081	0.138
215	0.019	0.025	0.030	0.033	0.040	0.051	0.078	0.131
220	0.018	0.025	0.029	0.033	0.038	0.050	0.075	0.124
225	0.018	0.024	0.028	0.032	0.037	0.048	0.072	0.119
230	0.017	0.024	0.028	0.031	0.036	0.047	0.069	0.114
235	0.017	0.023	0.027	0.030	0.035	0.045	0.067	0.108
240	0.017	0.023	0.026	0.029	0.035	0.044	0.065	0.104
245	0.016	0.022	0.026	0.029	0.034	0.043	0.062	0.099
250	0.016	0.022	0.025	0.028	0.033	0.041	0.060	0.095
255	0.016	0.021	0.025	0.027	0.032	0.040	0.058	0.091
260	0.016	0.021	0.024	0.027	0.031	0.039	0.056	0.087
265	0.015	0.020	0.023	0.026	0.030	0.038	0.054	0.084
270	0.015	0.020	0.023	0.025	0.030	0.037	0.053	0.081
275	0.015	0.019	0.022	0.025	0.029	0.036	0.051	0.077
280	0.014	0.019	0.022	0.024	0.028	0.035	0.050	0.075
285	0.014	0.019	0.022	0.024	0.027	0.034	0.048	0.072
290	0.014	0.018	0.021	0.023	0.027	0.033	0.047	0.069
295	0.014	0.018	0.021	0.023	0.026	0.032	0.045	0.067
300	0.013	0.018	0.020	0.022	0.026	0.032	0.044	0.064
305	0.013	0.017	0.020	0.022	0.025	0.031	0.043	0.062
310	0.013	0.017	0.019	0.021	0.024	0.030	0.041	0.060
315	0.013	0.017	0.019	0.021	0.024	0.029	0.040	0.058
320	0.013	0.016	0.019	0.020	0.023	0.029	0.039	0.056
325	0.012	0.016	0.018	0.020	0.023	0.028	0.038	0.054
330	0.012	0.016	0.018	0.020	0.022	0.027	0.037	0.053
335	0.012	0.015	0.018	0.019	0.022	0.027	0.036	0.051
340	0.012	0.015	0.017	0.019	0.021	0.026	0.035	0.049
345	0.011	0.015	0.017	0.018	0.021	0.025	0.034	0.048
350	0.011	0.015	0.017	0.018	0.021	0.025	0.033	0.046
355	0.011	0.014	0.016	0.018	0.020	0.024	0.032	0.045
360	0.011	0.014	0.016	0.017	0.020	0.024	0.032	0.044
365	0.011	0.014	0.016	0.017	0.019	0.023	0.031	0.042
370	0.011	0.014	0.015	0.017	0.019	0.023	0.030	0.041
375	0.010	0.013	0.015	0.016	0.019	0.022	0.029	0.040
380	0.010	0.013	0.015	0.016	0.018	0.022	0.029	0.039
385	0.010	0.013	0.014	0.016	0.018	0.021	0.028	0.038
390	0.010	0.013	0.014	0.015	0.017	0.021	0.027	0.037
395	0.010	0.012	0.014	0.015	0.017	0.020	0.027	0.036
400	0.010	0.012	0.014	0.015	0.017	0.020	0.026	0.035

^a Design rainfall durations

Appendix B13: Outlet size of 190 mm X 500 mm with 125 mm inlet size

Time lapse (min)	Water Depth in StormPav (mm)							
	5 ^a	10 ^a	15 ^a	20 ^a	30 ^a	60 ^a	120 ^a	180 ^a
0	0	0	0	0	0	0	0	0
5	0.019	0.017	0.015	0.014	0.013	0.010	0.007	0.006
10	0.050	0.060	0.053	0.049	0.044	0.034	0.025	0.020
15	0.048	0.080	0.088	0.081	0.072	0.056	0.041	0.034
20	0.046	0.076	0.102	0.109	0.098	0.076	0.057	0.047
25	0.045	0.072	0.096	0.119	0.121	0.095	0.070	0.058
30	0.043	0.068	0.090	0.112	0.141	0.111	0.083	0.069
35	0.041	0.065	0.085	0.105	0.146	0.126	0.094	0.078
40	0.039	0.062	0.080	0.098	0.135	0.139	0.104	0.087
45	0.038	0.059	0.076	0.092	0.126	0.150	0.114	0.095
50	0.036	0.056	0.072	0.087	0.117	0.161	0.122	0.102
55	0.035	0.053	0.068	0.082	0.109	0.170	0.129	0.108
60	0.033	0.051	0.064	0.077	0.102	0.179	0.136	0.114
65	0.032	0.049	0.061	0.073	0.096	0.175	0.142	0.119
70	0.031	0.046	0.058	0.069	0.090	0.161	0.147	0.124
75	0.030	0.044	0.055	0.065	0.085	0.148	0.152	0.128
80	0.029	0.042	0.053	0.062	0.080	0.137	0.156	0.132
85	0.028	0.041	0.050	0.059	0.075	0.127	0.160	0.135
90	0.027	0.039	0.048	0.056	0.071	0.118	0.163	0.138
95	0.026	0.037	0.046	0.053	0.068	0.110	0.166	0.141
100	0.025	0.036	0.044	0.051	0.064	0.103	0.169	0.143
105	0.024	0.035	0.042	0.049	0.061	0.096	0.171	0.145
110	0.023	0.033	0.040	0.046	0.058	0.090	0.173	0.147
115	0.023	0.032	0.039	0.044	0.055	0.085	0.174	0.149
120	0.022	0.031	0.037	0.043	0.052	0.080	0.176	0.150
125	0.021	0.030	0.036	0.041	0.050	0.076	0.169	0.152
130	0.021	0.029	0.034	0.039	0.048	0.072	0.156	0.153
135	0.020	0.028	0.033	0.037	0.046	0.068	0.144	0.154
140	0.019	0.027	0.032	0.036	0.044	0.064	0.133	0.155
145	0.019	0.026	0.031	0.035	0.042	0.061	0.123	0.156
150	0.018	0.025	0.029	0.033	0.040	0.058	0.115	0.156
155	0.018	0.024	0.028	0.032	0.038	0.055	0.107	0.157
160	0.017	0.023	0.027	0.031	0.037	0.053	0.100	0.157
165	0.017	0.023	0.026	0.030	0.035	0.050	0.094	0.158
170	0.016	0.022	0.026	0.029	0.034	0.048	0.088	0.158
175	0.016	0.021	0.025	0.028	0.033	0.046	0.083	0.159
180	0.015	0.021	0.024	0.027	0.032	0.044	0.079	0.159
185	0.015	0.020	0.023	0.026	0.030	0.042	0.074	0.153
190	0.015	0.019	0.022	0.025	0.029	0.040	0.070	0.142
195	0.014	0.019	0.022	0.024	0.028	0.039	0.067	0.131
200	0.014	0.018	0.021	0.023	0.027	0.037	0.063	0.122
205	0.014	0.018	0.020	0.023	0.026	0.036	0.060	0.114

Appendix B13 continued

210	0.013	0.017	0.020	0.022	0.025	0.034	0.057	0.106
215	0.013	0.017	0.019	0.021	0.025	0.033	0.054	0.099
220	0.013	0.016	0.019	0.021	0.024	0.032	0.052	0.093
225	0.012	0.016	0.018	0.020	0.023	0.031	0.049	0.088
230	0.012	0.015	0.018	0.019	0.022	0.029	0.047	0.083
235	0.012	0.015	0.017	0.019	0.022	0.028	0.045	0.078
240	0.011	0.015	0.017	0.018	0.021	0.027	0.043	0.074
245	0.011	0.014	0.016	0.018	0.020	0.026	0.041	0.070
250	0.011	0.014	0.016	0.017	0.020	0.026	0.040	0.066
255	0.011	0.013	0.015	0.017	0.019	0.025	0.038	0.063
260	0.010	0.013	0.015	0.016	0.019	0.024	0.037	0.059
265	0.010	0.013	0.014	0.016	0.018	0.023	0.035	0.057
270	0.010	0.012	0.014	0.015	0.018	0.022	0.034	0.054
275	0.010	0.012	0.014	0.015	0.017	0.022	0.032	0.051
280	0.009	0.012	0.013	0.015	0.017	0.021	0.031	0.049
285	0.009	0.012	0.013	0.014	0.016	0.020	0.030	0.047
290	0.009	0.011	0.013	0.014	0.016	0.020	0.029	0.045
295	0.009	0.011	0.012	0.013	0.015	0.019	0.028	0.043
300	0.009	0.011	0.012	0.013	0.015	0.019	0.027	0.041
305	0.008	0.011	0.012	0.013	0.014	0.018	0.026	0.039
310	0.008	0.010	0.011	0.012	0.014	0.018	0.025	0.038
315	0.008	0.010	0.011	0.012	0.014	0.017	0.024	0.036
320	0.008	0.010	0.011	0.012	0.013	0.017	0.024	0.035
325	0.008	0.010	0.011	0.012	0.013	0.016	0.023	0.034
330	0.008	0.009	0.010	0.011	0.013	0.016	0.022	0.032
335	0.008	0.009	0.010	0.011	0.012	0.015	0.021	0.031
340	0.007	0.009	0.010	0.011	0.012	0.015	0.021	0.030
345	0.007	0.009	0.010	0.011	0.012	0.014	0.020	0.029
350	0.007	0.009	0.010	0.010	0.011	0.014	0.020	0.028
355	0.007	0.008	0.009	0.010	0.011	0.014	0.019	0.027
360	0.007	0.008	0.009	0.010	0.011	0.013	0.018	0.026
365	0.007	0.008	0.009	0.010	0.011	0.013	0.018	0.025
370	0.007	0.008	0.009	0.009	0.010	0.013	0.017	0.024
375	0.006	0.008	0.009	0.009	0.010	0.012	0.017	0.023
380	0.006	0.008	0.008	0.009	0.010	0.012	0.016	0.023
385	0.006	0.007	0.008	0.009	0.010	0.012	0.016	0.022
390	0.006	0.007	0.008	0.009	0.010	0.011	0.016	0.021
395	0.006	0.007	0.008	0.008	0.009	0.011	0.015	0.021
400	0.006	0.007	0.008	0.008	0.009	0.011	0.015	0.020

^a Design rainfall durations

Appendix B14: Outlet size of 190 mm X 700 mm with 125 mm inlet size

Time lapse (min)	Water Depth in StormPav (mm)							
	5 ^a	10 ^a	15 ^a	20 ^a	30 ^a	60 ^a	120 ^a	180 ^a
0	0	0	0	0	0	0	0	0
5	0.019	0.017	0.015	0.014	0.013	0.010	0.007	0.006
10	0.049	0.059	0.052	0.048	0.043	0.033	0.025	0.020
15	0.047	0.079	0.086	0.079	0.071	0.055	0.041	0.033
20	0.045	0.074	0.099	0.106	0.095	0.074	0.055	0.046
25	0.043	0.069	0.092	0.114	0.116	0.091	0.068	0.056
30	0.040	0.065	0.085	0.105	0.135	0.106	0.080	0.066
35	0.038	0.061	0.079	0.097	0.138	0.119	0.090	0.075
40	0.037	0.057	0.074	0.090	0.126	0.131	0.099	0.083
45	0.035	0.054	0.069	0.084	0.115	0.141	0.107	0.090
50	0.033	0.051	0.065	0.078	0.106	0.149	0.114	0.096
55	0.032	0.048	0.060	0.073	0.098	0.157	0.120	0.101
60	0.030	0.045	0.057	0.068	0.090	0.163	0.126	0.106
65	0.029	0.043	0.054	0.063	0.084	0.158	0.130	0.110
70	0.028	0.041	0.050	0.060	0.078	0.143	0.134	0.114
75	0.027	0.039	0.048	0.056	0.073	0.130	0.138	0.117
80	0.025	0.037	0.045	0.053	0.068	0.119	0.141	0.120
85	0.024	0.035	0.043	0.050	0.063	0.109	0.144	0.122
90	0.023	0.033	0.040	0.047	0.060	0.100	0.146	0.124
95	0.023	0.032	0.038	0.044	0.056	0.093	0.148	0.126
100	0.022	0.030	0.037	0.042	0.053	0.086	0.150	0.128
105	0.021	0.029	0.035	0.040	0.050	0.080	0.151	0.129
110	0.020	0.028	0.033	0.038	0.047	0.074	0.152	0.131
115	0.019	0.027	0.032	0.036	0.044	0.069	0.153	0.132
120	0.019	0.025	0.030	0.034	0.042	0.065	0.154	0.133
125	0.018	0.024	0.029	0.033	0.040	0.061	0.148	0.133
130	0.017	0.023	0.028	0.031	0.038	0.057	0.134	0.134
135	0.017	0.023	0.026	0.030	0.036	0.054	0.123	0.135
140	0.016	0.022	0.025	0.029	0.034	0.051	0.112	0.135
145	0.016	0.021	0.024	0.027	0.033	0.048	0.103	0.136
150	0.015	0.020	0.023	0.026	0.031	0.045	0.095	0.136
155	0.015	0.019	0.022	0.025	0.030	0.043	0.088	0.137
160	0.014	0.019	0.022	0.024	0.029	0.041	0.082	0.137
165	0.014	0.018	0.021	0.023	0.027	0.039	0.076	0.137
170	0.013	0.017	0.020	0.022	0.026	0.037	0.071	0.137
175	0.013	0.017	0.019	0.021	0.025	0.035	0.066	0.138
180	0.013	0.016	0.019	0.021	0.024	0.033	0.062	0.138
185	0.012	0.016	0.018	0.020	0.023	0.032	0.058	0.132
190	0.012	0.015	0.017	0.019	0.022	0.030	0.055	0.121
195	0.011	0.015	0.017	0.018	0.021	0.029	0.052	0.111
200	0.011	0.014	0.016	0.018	0.021	0.028	0.049	0.102
205	0.011	0.014	0.016	0.017	0.020	0.027	0.046	0.094

Appendix B14 continued

210	0.010	0.013	0.015	0.017	0.019	0.025	0.044	0.087
215	0.010	0.013	0.015	0.016	0.018	0.024	0.041	0.081
220	0.010	0.013	0.014	0.016	0.018	0.023	0.039	0.075
225	0.010	0.012	0.014	0.015	0.017	0.023	0.037	0.070
230	0.009	0.012	0.013	0.015	0.017	0.022	0.036	0.066
235	0.009	0.011	0.013	0.014	0.016	0.021	0.034	0.062
240	0.009	0.011	0.013	0.014	0.016	0.020	0.032	0.058
245	0.009	0.011	0.012	0.013	0.015	0.019	0.031	0.054
250	0.008	0.010	0.012	0.013	0.015	0.019	0.029	0.051
255	0.008	0.010	0.011	0.012	0.014	0.018	0.028	0.048
260	0.008	0.010	0.011	0.012	0.014	0.017	0.027	0.046
265	0.008	0.010	0.011	0.012	0.013	0.017	0.026	0.043
270	0.008	0.009	0.010	0.011	0.013	0.016	0.025	0.041
275	0.008	0.009	0.010	0.011	0.012	0.016	0.024	0.039
280	0.007	0.009	0.010	0.011	0.012	0.015	0.023	0.037
285	0.007	0.009	0.010	0.010	0.012	0.015	0.022	0.035
290	0.007	0.008	0.009	0.010	0.011	0.014	0.021	0.034
295	0.007	0.008	0.009	0.010	0.011	0.014	0.020	0.032
300	0.007	0.008	0.009	0.010	0.011	0.013	0.020	0.031
305	0.007	0.008	0.009	0.009	0.010	0.013	0.019	0.029
310	0.006	0.008	0.008	0.009	0.010	0.013	0.018	0.028
315	0.006	0.008	0.008	0.009	0.010	0.012	0.018	0.027
320	0.006	0.007	0.008	0.009	0.010	0.012	0.017	0.026
325	0.006	0.007	0.008	0.008	0.009	0.011	0.016	0.025
330	0.006	0.007	0.008	0.008	0.009	0.011	0.016	0.024
335	0.006	0.007	0.008	0.008	0.009	0.011	0.015	0.023
340	0.006	0.007	0.007	0.008	0.009	0.010	0.015	0.022
345	0.006	0.007	0.007	0.008	0.008	0.010	0.014	0.021
350	0.005	0.006	0.007	0.007	0.008	0.010	0.014	0.020
355	0.005	0.006	0.007	0.007	0.008	0.010	0.013	0.020
360	0.005	0.006	0.007	0.007	0.008	0.009	0.013	0.019
365	0.005	0.006	0.007	0.007	0.008	0.009	0.013	0.018
370	0.005	0.006	0.006	0.007	0.007	0.009	0.012	0.018
375	0.005	0.006	0.006	0.007	0.007	0.009	0.012	0.017
380	0.005	0.006	0.006	0.007	0.007	0.008	0.012	0.016
385	0.005	0.006	0.006	0.006	0.007	0.008	0.011	0.016
390	0.005	0.005	0.006	0.006	0.007	0.008	0.011	0.015
395	0.005	0.005	0.006	0.006	0.007	0.008	0.011	0.015
400	0.005	0.005	0.006	0.006	0.007	0.008	0.010	0.014

^a Design rainfall durations

Appendix B15: Outlet size of 190 mm X 900 mm with 125 mm inlet size

Time lapse (min)	Water Depth in StormPav (mm)							
	5 ^a	10 ^a	15 ^a	20 ^a	30 ^a	60 ^a	120 ^a	180 ^a
0	0	0	0	0	0	0	0	0
5	0.019	0.017	0.015	0.014	0.013	0.010	0.007	0.006
10	0.048	0.058	0.051	0.047	0.042	0.033	0.024	0.020
15	0.046	0.077	0.084	0.077	0.070	0.054	0.040	0.033
20	0.044	0.072	0.096	0.103	0.093	0.073	0.054	0.045
25	0.041	0.066	0.088	0.111	0.113	0.089	0.067	0.055
30	0.039	0.062	0.081	0.101	0.130	0.103	0.078	0.064
35	0.037	0.058	0.075	0.093	0.132	0.115	0.087	0.073
40	0.035	0.054	0.069	0.085	0.119	0.125	0.095	0.080
45	0.033	0.050	0.064	0.078	0.108	0.134	0.103	0.086
50	0.031	0.047	0.060	0.072	0.099	0.142	0.109	0.092
55	0.030	0.044	0.056	0.067	0.090	0.148	0.114	0.096
60	0.028	0.042	0.052	0.062	0.083	0.154	0.119	0.100
65	0.027	0.039	0.049	0.058	0.076	0.148	0.123	0.104
70	0.026	0.037	0.046	0.054	0.070	0.133	0.126	0.107
75	0.024	0.035	0.043	0.050	0.065	0.120	0.129	0.110
80	0.023	0.033	0.040	0.047	0.061	0.108	0.131	0.112
85	0.022	0.031	0.038	0.044	0.056	0.099	0.134	0.114
90	0.021	0.030	0.036	0.042	0.053	0.090	0.135	0.116
95	0.020	0.028	0.034	0.039	0.049	0.083	0.137	0.117
100	0.020	0.027	0.032	0.037	0.046	0.076	0.138	0.119
105	0.019	0.026	0.031	0.035	0.043	0.070	0.139	0.120
110	0.018	0.025	0.029	0.033	0.041	0.065	0.140	0.121
115	0.017	0.023	0.028	0.031	0.039	0.061	0.141	0.121
120	0.017	0.022	0.026	0.030	0.036	0.056	0.142	0.122
125	0.016	0.021	0.025	0.028	0.034	0.053	0.135	0.123
130	0.015	0.021	0.024	0.027	0.033	0.049	0.122	0.123
135	0.015	0.020	0.023	0.026	0.031	0.046	0.110	0.124
140	0.014	0.019	0.022	0.025	0.029	0.043	0.100	0.124
145	0.014	0.018	0.021	0.023	0.028	0.041	0.092	0.124
150	0.013	0.017	0.020	0.022	0.027	0.039	0.084	0.125
155	0.013	0.017	0.019	0.021	0.025	0.036	0.077	0.125
160	0.012	0.016	0.019	0.021	0.024	0.034	0.071	0.125
165	0.012	0.016	0.018	0.020	0.023	0.033	0.066	0.125
170	0.012	0.015	0.017	0.019	0.022	0.031	0.061	0.125
175	0.011	0.014	0.016	0.018	0.021	0.029	0.057	0.126
180	0.011	0.014	0.016	0.017	0.020	0.028	0.053	0.126
185	0.011	0.013	0.015	0.017	0.019	0.027	0.050	0.120
190	0.010	0.013	0.015	0.016	0.019	0.025	0.047	0.109
195	0.010	0.013	0.014	0.016	0.018	0.024	0.044	0.099
200	0.010	0.012	0.014	0.015	0.017	0.023	0.041	0.091
205	0.009	0.012	0.013	0.014	0.017	0.022	0.039	0.083

Appendix B15 continued

210	0.009	0.011	0.013	0.014	0.016	0.021	0.037	0.077
215	0.009	0.011	0.012	0.013	0.015	0.020	0.035	0.071
220	0.009	0.011	0.012	0.013	0.015	0.019	0.033	0.066
225	0.008	0.010	0.012	0.013	0.014	0.019	0.031	0.061
230	0.008	0.010	0.011	0.012	0.014	0.018	0.030	0.057
235	0.008	0.010	0.011	0.012	0.013	0.017	0.028	0.053
240	0.008	0.009	0.010	0.011	0.013	0.017	0.027	0.050
245	0.008	0.009	0.010	0.011	0.012	0.016	0.026	0.046
250	0.007	0.009	0.010	0.011	0.012	0.015	0.024	0.044
255	0.007	0.009	0.010	0.010	0.012	0.015	0.023	0.041
260	0.007	0.008	0.009	0.010	0.011	0.014	0.022	0.039
265	0.007	0.008	0.009	0.010	0.011	0.014	0.021	0.037
270	0.007	0.008	0.009	0.009	0.011	0.013	0.020	0.035
275	0.007	0.008	0.009	0.009	0.010	0.013	0.020	0.033
280	0.006	0.008	0.008	0.009	0.010	0.012	0.019	0.031
285	0.006	0.007	0.008	0.009	0.010	0.012	0.018	0.030
290	0.006	0.007	0.008	0.008	0.009	0.012	0.017	0.028
295	0.006	0.007	0.008	0.008	0.009	0.011	0.017	0.027
300	0.006	0.007	0.007	0.008	0.009	0.011	0.016	0.025
305	0.006	0.007	0.007	0.008	0.009	0.011	0.016	0.024
310	0.006	0.007	0.007	0.008	0.008	0.010	0.015	0.023
315	0.005	0.006	0.007	0.007	0.008	0.010	0.014	0.022
320	0.005	0.006	0.007	0.007	0.008	0.010	0.014	0.021
325	0.005	0.006	0.007	0.007	0.008	0.009	0.013	0.020
330	0.005	0.006	0.006	0.007	0.007	0.009	0.013	0.020
335	0.005	0.006	0.006	0.007	0.007	0.009	0.012	0.019
340	0.005	0.006	0.006	0.007	0.007	0.009	0.012	0.018
345	0.005	0.006	0.006	0.006	0.007	0.008	0.012	0.017
350	0.005	0.005	0.006	0.006	0.007	0.008	0.011	0.017
355	0.005	0.005	0.006	0.006	0.007	0.008	0.011	0.016
360	0.005	0.005	0.006	0.006	0.006	0.008	0.011	0.015
365	0.004	0.005	0.006	0.006	0.006	0.007	0.010	0.015
370	0.004	0.005	0.005	0.006	0.006	0.007	0.010	0.014
375	0.004	0.005	0.005	0.006	0.006	0.007	0.010	0.014
380	0.004	0.005	0.005	0.005	0.006	0.007	0.009	0.013
385	0.004	0.005	0.005	0.005	0.006	0.007	0.009	0.013
390	0.004	0.005	0.005	0.005	0.006	0.007	0.009	0.012
395	0.004	0.005	0.005	0.005	0.006	0.006	0.009	0.012
400	0.004	0.004	0.005	0.005	0.005	0.006	0.008	0.012

^a Design rainfall durations

Appendix B16: Occupied Volume Capacity with Varying Outlet Sizes
and 100 mm Inlet Sizes for All Design Rainfall Durations

Design Rainfall Durations	Occupied Volume Capacity					Percentage to Cater Weather Variability				
	190	190 X 300	190 X 500	190 X 700	190 X 900	190	190 X 300	190 X 500	190 X 700	190 X 900
5	0.301	0.293	0.285	0.278	0.273	69.9	70.7	71.5	72.2	72.7
10	0.482	0.467	0.451	0.439	0.431	51.8	53.3	54.9	56.1	56.9
15	0.621	0.595	0.568	0.553	0.537	37.9	40.5	43.2	44.7	46.3
20	0.737	0.7	0.663	0.637	0.621	26.3	30	33.7	36.3	37.9
30	0.947	0.874	0.811	0.768	0.737	5.3	12.6	18.9	23.2	26.3
60	1	1	0.968	0.884	0.826	0	0	3.2	11.6	17.4
120	1	1	0.932	0.816	0.747	0	0	6.8	18.4	25.3
180	1	1	0.839	0.726	0.663	0	0	16.1	27.4	33.7

Appendix B17: Occupied Volume Capacity with Varying Outlet Sizes
and 125 mm Inlet Sizes for All Design Rainfall Durations

Design Rainfall Durations	Occupied Volume Capacity					Percentage to Cater Weather Variability				
	190	190 X 300	190 X 500	190 X 700	190 X 900	190	190 X 300	190 X 500	190 X 700	190 X 900
5	0.275	0.268	0.263	0.260	0.256	72.5	73.2	73.7	74.0	74.4
10	0.447	0.436	0.426	0.414	0.405	55.3	56.4	57.4	58.6	59.5
15	0.581	0.559	0.539	0.523	0.509	41.9	44.1	46.1	47.7	49.1
20	0.697	0.664	0.631	0.608	0.591	30.3	33.6	36.9	39.2	40.9
30	0.902	0.838	0.778	0.739	0.710	9.8	16.2	22.2	26.1	29.0
60	1	1	0.948	0.865	0.812	0	0	5.2	13.5	18.8
120	1	1	0.926	0.813	0.746	0	0	7.4	18.7	25.4
180	1	1	0.837	0.725	0.661	0	0	16.3	27.5	33.9

Appendix C: Data for Pre-development Condition

Appendix C1: Discharge Hydrograph at Outfall in Varying Rainfall Durations

Time lapse (min)	Water Depth in StormPav (mm)							
	5 ^a	10 ^a	15 ^a	20 ^a	30 ^a	60 ^a	120 ^a	180 ^a
0	0	0	0	0	0	0	0	0
2.5	0.047	0.040	0.036	0.033	0.029	0.022	0.000	0.000
5	0.093	0.080	0.071	0.066	0.059	0.045	0.000	0.000
7.5	0.047	0.080	0.071	0.066	0.059	0.045	0.016	0.013
10	0.000	0.080	0.071	0.066	0.059	0.045	0.033	0.026
12.5	0.000	0.040	0.071	0.066	0.059	0.045	0.033	0.026
15	0.000	0.000	0.071	0.066	0.059	0.045	0.033	0.026
17.5	0.000	0.000	0.036	0.066	0.059	0.045	0.033	0.026
20	0.000	0.000	0.000	0.066	0.059	0.045	0.033	0.026
22.5	0.000	0.000	0.000	0.033	0.059	0.045	0.033	0.026
25	0.000	0.000	0.000	0.000	0.059	0.045	0.033	0.026
27.5	0.000	0.000	0.000	0.000	0.059	0.045	0.033	0.026
30	0.000	0.000	0.000	0.000	0.059	0.045	0.033	0.026
32.5	0.000	0.000	0.000	0.000	0.029	0.045	0.033	0.026
35	0.000	0.000	0.000	0.000	0.000	0.045	0.033	0.026
37.5	0.000	0.000	0.000	0.000	0.000	0.045	0.033	0.026
40	0.000	0.000	0.000	0.000	0.000	0.045	0.033	0.026
42.5	0.000	0.000	0.000	0.000	0.000	0.045	0.033	0.026
45	0.000	0.000	0.000	0.000	0.000	0.045	0.033	0.026
47.5	0.000	0.000	0.000	0.000	0.000	0.045	0.033	0.026
50	0.000	0.000	0.000	0.000	0.000	0.045	0.033	0.026
52.5	0.000	0.000	0.000	0.000	0.000	0.045	0.033	0.026
55	0.000	0.000	0.000	0.000	0.000	0.045	0.033	0.026
57.5	0.000	0.000	0.000	0.000	0.000	0.045	0.033	0.026
60	0.000	0.000	0.000	0.000	0.000	0.045	0.033	0.026
62.5	0.000	0.000	0.000	0.000	0.000	0.022	0.033	0.026
65	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
67.5	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
70	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
72.5	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
75	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
77.5	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
80	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
82.5	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
85	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
87.5	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
90	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
92.5	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
95	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
97.5	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026

Appendix C1 continued

100	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
102.5	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
105	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
107.5	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
110	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
112.5	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
115	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
117.5	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
120	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.026
122.5	0.000	0.000	0.000	0.000	0.000	0.000	0.016	0.026
125	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
127.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
130	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
132.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
135	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
137.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
140	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
142.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
145	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
147.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
150	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
152.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
155	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
157.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
160	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
162.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
165	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
167.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
170	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
172.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
175	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
177.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
180	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
182.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.013
185	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
187.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
190	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
192.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
195	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
197.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
200	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

^a Design rainfall durations

Appendix D: Data for Conventional Drainage System Condition

Appendix D1: Discharge Hydrograph at Outfall in Varying Rainfall Durations

Time lapse (min)	Water Depth in StormPav (mm)							
	5 ^a	10 ^a	15 ^a	20 ^a	30 ^a	60 ^a	120 ^a	180 ^a
0	0	0	0	0	0	0	0	0
5	0.135	0.111	0.095	0.084	0.071	0.047	0.026	0.017
10	0.095	0.200	0.178	0.164	0.147	0.112	0.081	0.065
15	0.012	0.085	0.179	0.164	0.147	0.112	0.081	0.066
20	0.004	0.012	0.078	0.164	0.147	0.112	0.081	0.066
25	0.002	0.004	0.011	0.073	0.147	0.112	0.081	0.066
30	0.001	0.002	0.004	0.011	0.147	0.112	0.081	0.066
35	0.001	0.001	0.002	0.004	0.067	0.112	0.081	0.066
40	0.000	0.001	0.001	0.002	0.011	0.112	0.081	0.066
45	0.000	0.000	0.001	0.001	0.003	0.112	0.081	0.066
50	0.000	0.000	0.000	0.001	0.002	0.112	0.081	0.066
55	0.000	0.000	0.000	0.000	0.001	0.112	0.081	0.066
60	0.000	0.000	0.000	0.000	0.001	0.112	0.081	0.066
65	0.000	0.000	0.000	0.000	0.000	0.055	0.081	0.066
70	0.000	0.000	0.000	0.000	0.000	0.010	0.081	0.066
75	0.000	0.000	0.000	0.000	0.000	0.003	0.081	0.066
80	0.000	0.000	0.000	0.000	0.000	0.002	0.081	0.066
85	0.000	0.000	0.000	0.000	0.000	0.001	0.081	0.066
90	0.000	0.000	0.000	0.000	0.000	0.001	0.081	0.066
95	0.000	0.000	0.000	0.000	0.000	0.000	0.081	0.066
100	0.000	0.000	0.000	0.000	0.000	0.000	0.081	0.066
105	0.000	0.000	0.000	0.000	0.000	0.000	0.081	0.066
110	0.000	0.000	0.000	0.000	0.000	0.000	0.081	0.066
115	0.000	0.000	0.000	0.000	0.000	0.000	0.081	0.066
120	0.000	0.000	0.000	0.000	0.000	0.000	0.081	0.066
125	0.000	0.000	0.000	0.000	0.000	0.000	0.043	0.066
130	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.066
135	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.066
140	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.066
145	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.066
150	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.066
155	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.066
160	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.066
165	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.066
170	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.066
175	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.066
180	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.066
185	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.036
190	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.009
195	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003

Appendix D1 continued

200	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
205	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
210	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
215	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
220	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

^a Design rainfall durations

Appendix E: Data for StormPav Road Condition

Appendix E1: Discharge Hydrograph at Outfall of 190 mm X 500 mm Outlet Orifice
for Varying Rainfall Durations

Time lapse (min)	Water Depth in StormPav (mm)							
	5 ^a	10 ^a	15 ^a	20 ^a	30 ^a	60 ^a	120 ^a	180 ^a
0	0	0	0	0	0	0	0	0
5	0.038	0.032	0.027	0.024	0.021	0.015	0.009	0.007
10	0.020	0.052	0.046	0.042	0.037	0.027	0.018	0.014
15	0.010	0.027	0.057	0.051	0.045	0.033	0.023	0.018
20	0.009	0.018	0.034	0.062	0.054	0.039	0.027	0.021
25	0.008	0.016	0.025	0.040	0.063	0.046	0.031	0.024
30	0.007	0.015	0.022	0.031	0.071	0.052	0.035	0.027
35	0.007	0.014	0.020	0.027	0.050	0.058	0.039	0.031
40	0.006	0.013	0.018	0.025	0.041	0.063	0.043	0.033
45	0.006	0.012	0.017	0.023	0.036	0.069	0.047	0.036
50	0.006	0.011	0.016	0.021	0.033	0.074	0.050	0.039
55	0.005	0.010	0.014	0.019	0.029	0.078	0.053	0.041
60	0.005	0.009	0.013	0.017	0.027	0.082	0.056	0.044
65	0.005	0.009	0.012	0.016	0.024	0.062	0.059	0.046
70	0.004	0.008	0.011	0.015	0.022	0.051	0.061	0.048
75	0.004	0.008	0.011	0.014	0.020	0.045	0.063	0.050
80	0.004	0.007	0.010	0.013	0.019	0.040	0.066	0.051
85	0.004	0.007	0.009	0.012	0.017	0.036	0.067	0.053
90	0.003	0.006	0.009	0.011	0.016	0.032	0.069	0.054
95	0.003	0.006	0.008	0.010	0.015	0.029	0.071	0.056
100	0.003	0.005	0.008	0.009	0.013	0.026	0.072	0.057
105	0.003	0.005	0.007	0.009	0.012	0.024	0.073	0.058
110	0.003	0.005	0.007	0.008	0.012	0.022	0.074	0.059
115	0.003	0.005	0.006	0.008	0.011	0.020	0.075	0.059
120	0.003	0.004	0.006	0.007	0.010	0.018	0.075	0.060
125	0.002	0.004	0.005	0.007	0.009	0.017	0.060	0.061
130	0.002	0.004	0.005	0.006	0.009	0.016	0.050	0.061
135	0.002	0.004	0.005	0.006	0.008	0.014	0.044	0.062
140	0.002	0.003	0.004	0.005	0.008	0.013	0.039	0.062

Appendix E1 continued

145	0.002	0.003	0.004	0.005	0.007	0.012	0.035	0.063
150	0.002	0.003	0.004	0.005	0.007	0.011	0.032	0.063
155	0.002	0.003	0.004	0.005	0.006	0.011	0.029	0.064
160	0.002	0.003	0.004	0.004	0.006	0.010	0.026	0.064
165	0.002	0.003	0.003	0.004	0.005	0.009	0.024	0.064
170	0.002	0.002	0.003	0.004	0.005	0.009	0.022	0.064
175	0.002	0.002	0.003	0.004	0.005	0.008	0.020	0.064
180	0.001	0.002	0.003	0.003	0.004	0.008	0.018	0.065
185	0.001	0.002	0.003	0.003	0.004	0.007	0.017	0.052
190	0.001	0.002	0.003	0.003	0.004	0.007	0.015	0.044
195	0.001	0.002	0.002	0.003	0.004	0.006	0.014	0.039
200	0.001	0.002	0.002	0.003	0.004	0.006	0.013	0.035
205	0.001	0.002	0.002	0.003	0.003	0.005	0.012	0.032
210	0.001	0.002	0.002	0.002	0.003	0.005	0.011	0.029
215	0.001	0.002	0.002	0.002	0.003	0.005	0.011	0.026
220	0.001	0.002	0.002	0.002	0.003	0.004	0.010	0.024
225	0.001	0.002	0.002	0.002	0.003	0.004	0.009	0.022
230	0.001	0.001	0.002	0.002	0.003	0.004	0.009	0.020
235	0.001	0.001	0.002	0.002	0.002	0.004	0.008	0.018
240	0.001	0.001	0.002	0.002	0.002	0.004	0.007	0.017
245	0.001	0.001	0.002	0.002	0.002	0.003	0.007	0.015
250	0.001	0.001	0.002	0.002	0.002	0.003	0.006	0.014
255	0.001	0.001	0.001	0.002	0.002	0.003	0.006	0.013
260	0.001	0.001	0.001	0.002	0.002	0.003	0.006	0.012
265	0.001	0.001	0.001	0.002	0.002	0.003	0.005	0.011
270	0.001	0.001	0.001	0.001	0.002	0.003	0.005	0.011
275	0.001	0.001	0.001	0.001	0.002	0.002	0.005	0.010
280	0.001	0.001	0.001	0.001	0.002	0.002	0.004	0.009
285	0.001	0.001	0.001	0.001	0.002	0.002	0.004	0.009
290	0.001	0.001	0.001	0.001	0.002	0.002	0.004	0.008
295	0.001	0.001	0.001	0.001	0.001	0.002	0.004	0.007
300	0.001	0.001	0.001	0.001	0.001	0.002	0.004	0.007
305	0.001	0.001	0.001	0.001	0.001	0.002	0.003	0.006
310	0.001	0.001	0.001	0.001	0.001	0.002	0.003	0.006
315	0.001	0.001	0.001	0.001	0.001	0.002	0.003	0.006
320	0.001	0.001	0.001	0.001	0.001	0.002	0.003	0.005
325	0.001	0.001	0.001	0.001	0.001	0.002	0.003	0.005
330	0.001	0.001	0.001	0.001	0.001	0.002	0.003	0.005
335	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.004
340	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.004
345	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.004
350	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.004
355	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.004
360	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.003
365	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.003

Appendix E1 continued

370	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.003
375	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.003
380	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.003
385	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.003
390	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.002
395	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.002
400	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.002

^a Design rainfall durations

Appendix E2: Discharge Hydrograph at Outfall of 190 mm X 700 mm Outlet Orifice
for Varying Rainfall Durations

Time lapse (min)	Water Depth in StormPav (mm)							
	5 ^a	10 ^a	15 ^a	20 ^a	30 ^a	60 ^a	120 ^a	180 ^a
0	0	0	0	0	0	0	0	0
5	0.038	0.031	0.027	0.024	0.021	0.014	0.009	0.007
10	0.022	0.055	0.048	0.043	0.038	0.028	0.019	0.014
15	0.013	0.033	0.063	0.057	0.050	0.036	0.024	0.019
20	0.011	0.024	0.042	0.070	0.061	0.044	0.030	0.023
25	0.010	0.021	0.032	0.049	0.072	0.052	0.035	0.027
30	0.009	0.018	0.028	0.039	0.082	0.060	0.041	0.031
35	0.008	0.016	0.025	0.034	0.061	0.067	0.045	0.035
40	0.008	0.015	0.022	0.029	0.049	0.073	0.050	0.039
45	0.007	0.013	0.020	0.026	0.042	0.078	0.054	0.042
50	0.006	0.012	0.018	0.023	0.037	0.083	0.057	0.045
55	0.006	0.011	0.016	0.021	0.032	0.088	0.061	0.048
60	0.005	0.010	0.014	0.019	0.029	0.092	0.063	0.050
65	0.005	0.009	0.013	0.017	0.025	0.071	0.066	0.052
70	0.005	0.008	0.012	0.015	0.023	0.058	0.068	0.054
75	0.004	0.008	0.011	0.014	0.020	0.050	0.070	0.055
80	0.004	0.007	0.010	0.012	0.018	0.043	0.071	0.057
85	0.004	0.006	0.009	0.011	0.016	0.038	0.073	0.058
90	0.003	0.006	0.008	0.010	0.015	0.033	0.074	0.059
95	0.003	0.005	0.007	0.009	0.013	0.029	0.075	0.060
100	0.003	0.005	0.007	0.008	0.012	0.026	0.076	0.061
105	0.003	0.005	0.006	0.008	0.011	0.023	0.077	0.061
110	0.003	0.004	0.006	0.007	0.010	0.020	0.077	0.062
115	0.003	0.004	0.005	0.006	0.009	0.018	0.078	0.063
120	0.002	0.004	0.005	0.006	0.008	0.016	0.079	0.063
125	0.002	0.003	0.004	0.005	0.007	0.015	0.063	0.063
130	0.002	0.003	0.004	0.005	0.007	0.013	0.052	0.064
135	0.002	0.003	0.004	0.005	0.006	0.012	0.044	0.064
140	0.002	0.003	0.004	0.004	0.006	0.011	0.039	0.064

Appendix E2 continued

145	0.002	0.003	0.003	0.004	0.005	0.010	0.034	0.065
150	0.002	0.003	0.003	0.004	0.005	0.009	0.030	0.065
155	0.002	0.002	0.003	0.003	0.005	0.008	0.026	0.065
160	0.002	0.002	0.003	0.003	0.004	0.008	0.024	0.065
165	0.001	0.002	0.003	0.003	0.004	0.007	0.021	0.065
170	0.001	0.002	0.002	0.003	0.004	0.006	0.019	0.065
175	0.001	0.002	0.002	0.003	0.003	0.006	0.017	0.065
180	0.001	0.002	0.002	0.003	0.003	0.005	0.015	0.065
185	0.001	0.002	0.002	0.002	0.003	0.005	0.014	0.053
190	0.001	0.002	0.002	0.002	0.003	0.005	0.012	0.044
195	0.001	0.002	0.002	0.002	0.003	0.004	0.011	0.038
200	0.001	0.001	0.002	0.002	0.002	0.004	0.010	0.033
205	0.001	0.001	0.002	0.002	0.002	0.004	0.009	0.029
210	0.001	0.001	0.002	0.002	0.002	0.003	0.008	0.026
215	0.001	0.001	0.001	0.002	0.002	0.003	0.008	0.023
220	0.001	0.001	0.001	0.002	0.002	0.003	0.007	0.021
225	0.001	0.001	0.001	0.002	0.002	0.003	0.006	0.018
230	0.001	0.001	0.001	0.001	0.002	0.003	0.006	0.017
235	0.001	0.001	0.001	0.001	0.002	0.003	0.006	0.015
240	0.001	0.001	0.001	0.001	0.002	0.002	0.005	0.014
245	0.001	0.001	0.001	0.001	0.002	0.002	0.005	0.012
250	0.001	0.001	0.001	0.001	0.001	0.002	0.004	0.011
255	0.001	0.001	0.001	0.001	0.001	0.002	0.004	0.010
260	0.001	0.001	0.001	0.001	0.001	0.002	0.004	0.009
265	0.001	0.001	0.001	0.001	0.001	0.002	0.004	0.008
270	0.001	0.001	0.001	0.001	0.001	0.002	0.003	0.008
275	0.001	0.001	0.001	0.001	0.001	0.002	0.003	0.007
280	0.001	0.001	0.001	0.001	0.001	0.002	0.003	0.006
285	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.006
290	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.005
295	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.005
300	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.005
305	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.004
310	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.004
315	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.004
320	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.003
325	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.003
330	0.000	0.000	0.001	0.001	0.001	0.001	0.002	0.003
335	0.000	0.000	0.001	0.001	0.001	0.001	0.002	0.003
340	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.003
345	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.003
350	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.002
355	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.002
360	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.002
365	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.002

Appendix E2 continued

370	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.002
375	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.002
380	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002
385	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002
390	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002
395	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001
400	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001

^a Design rainfall durations

Appendix E3: Discharge Hydrograph at Outfall of 190 mm X 900 mm Outlet Orifice
for Varying Rainfall Durations

Time lapse (min)	Water Depth in StormPav (mm)							
	5 ^a	10 ^a	15 ^a	20 ^a	30 ^a	60 ^a	120 ^a	180 ^a
0	0	0	0	0	0	0	0	0
5	0.037	0.031	0.026	0.024	0.020	0.014	0.009	0.007
10	0.024	0.057	0.050	0.045	0.039	0.028	0.019	0.014
15	0.015	0.038	0.068	0.061	0.054	0.039	0.026	0.020
20	0.013	0.028	0.049	0.077	0.067	0.049	0.033	0.025
25	0.012	0.024	0.038	0.058	0.080	0.058	0.039	0.030
30	0.010	0.021	0.032	0.045	0.091	0.067	0.045	0.035
35	0.009	0.018	0.027	0.038	0.070	0.074	0.050	0.039
40	0.008	0.016	0.024	0.032	0.055	0.080	0.055	0.043
45	0.007	0.014	0.021	0.028	0.046	0.086	0.059	0.046
50	0.007	0.013	0.018	0.024	0.039	0.090	0.063	0.049
55	0.006	0.011	0.016	0.021	0.033	0.094	0.066	0.052
60	0.006	0.010	0.014	0.018	0.029	0.097	0.068	0.054
65	0.005	0.009	0.012	0.016	0.025	0.076	0.070	0.056
70	0.005	0.008	0.011	0.014	0.022	0.061	0.072	0.057
75	0.004	0.007	0.010	0.013	0.019	0.051	0.074	0.059
80	0.004	0.006	0.009	0.011	0.017	0.043	0.075	0.060
85	0.004	0.006	0.008	0.010	0.015	0.036	0.076	0.061
90	0.003	0.005	0.007	0.009	0.013	0.031	0.077	0.062
95	0.003	0.005	0.006	0.008	0.011	0.027	0.078	0.062
100	0.003	0.004	0.006	0.007	0.010	0.023	0.078	0.063
105	0.003	0.004	0.005	0.006	0.009	0.020	0.079	0.063
110	0.002	0.004	0.005	0.006	0.008	0.018	0.079	0.064
115	0.002	0.003	0.004	0.005	0.007	0.016	0.080	0.064
120	0.002	0.003	0.004	0.005	0.007	0.014	0.080	0.065
125	0.002	0.003	0.004	0.004	0.006	0.012	0.064	0.065
130	0.002	0.003	0.003	0.004	0.005	0.011	0.051	0.065
135	0.002	0.003	0.003	0.004	0.005	0.010	0.043	0.065
140	0.002	0.002	0.003	0.004	0.005	0.009	0.037	0.065

Appendix E3 continued

145	0.002	0.002	0.003	0.003	0.004	0.008	0.031	0.065
150	0.001	0.002	0.003	0.003	0.004	0.007	0.027	0.065
155	0.001	0.002	0.002	0.003	0.004	0.006	0.024	0.066
160	0.001	0.002	0.002	0.003	0.003	0.006	0.021	0.066
165	0.001	0.002	0.002	0.002	0.003	0.005	0.018	0.066
170	0.001	0.002	0.002	0.002	0.003	0.005	0.016	0.066
175	0.001	0.002	0.002	0.002	0.003	0.004	0.014	0.066
180	0.001	0.001	0.002	0.002	0.002	0.004	0.012	0.066
185	0.001	0.001	0.002	0.002	0.002	0.004	0.011	0.053
190	0.001	0.001	0.002	0.002	0.002	0.003	0.010	0.043
195	0.001	0.001	0.001	0.002	0.002	0.003	0.009	0.036
200	0.001	0.001	0.001	0.002	0.002	0.003	0.008	0.031
205	0.001	0.001	0.001	0.001	0.002	0.003	0.007	0.027
210	0.001	0.001	0.001	0.001	0.002	0.003	0.006	0.023
215	0.001	0.001	0.001	0.001	0.002	0.002	0.006	0.020
220	0.001	0.001	0.001	0.001	0.001	0.002	0.005	0.018
225	0.001	0.001	0.001	0.001	0.001	0.002	0.005	0.016
230	0.001	0.001	0.001	0.001	0.001	0.002	0.004	0.014
235	0.001	0.001	0.001	0.001	0.001	0.002	0.004	0.012
240	0.001	0.001	0.001	0.001	0.001	0.002	0.004	0.011
245	0.001	0.001	0.001	0.001	0.001	0.002	0.003	0.010
250	0.001	0.001	0.001	0.001	0.001	0.002	0.003	0.009
255	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.008
260	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.007
265	0.000	0.001	0.001	0.001	0.001	0.001	0.003	0.006
270	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.006
275	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.005
280	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.005
285	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.004
290	0.000	0.001	0.001	0.001	0.001	0.001	0.002	0.004
295	0.000	0.000	0.001	0.001	0.001	0.001	0.002	0.004
300	0.000	0.000	0.001	0.001	0.001	0.001	0.002	0.003
305	0.000	0.000	0.001	0.001	0.001	0.001	0.002	0.003
310	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.003
315	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.003
320	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.003
325	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.002
330	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.002
335	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002
340	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002
345	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002
350	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002
355	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002
360	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002
365	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001

Appendix E3 continued

370	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001
375	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001
380	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001
385	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001
390	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001
395	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001
400	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001

^a Design rainfall durations