Water Sensitive Urban Design (WSUD) Strategies to Mitigate the Impacts of Intense Rainfall on the Sanitary Sewer Network Performance

By

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ABSTRACT

Short duration intense rainfall causes an increase in rainfall derived infiltration and inflow (RDII) in aging sewer networks, which leads to Sanitary Sewer Overflows (SSOs). This, in turn, causes various detrimental impacts, both on human health and the environment. This research aims to quantify the benefits of Water Sensitive Urban Design (WSUD) approaches to mitigate the negative impacts of rainfall induced SSOs. In this context, this research develops a generalised framework for assessing and mitigating the impacts of intense rainfall on the performance of the sanitary sewer network. The first part of the developed framework involves detailed hydraulic modelling to evaluate the performance of the sewer network. The second part deals with the development of SSO mitigation strategies based on popular WSUD approaches. This study also demonstrates the application of the developed framework for a case study catchment in Melbourne, Australia. A detailed hydraulic modelling to analyse the performance of the case study sewer network during a wet (2010) and a dry year (2008) has been presented. The hydraulic performance analysis found that the system experienced 23 ML of sewer overflow volume in 2010 as compared to 3.42 ML in 2008. Towards mitigating the negative impacts of SSOs, this study has implemented two commonly used WSUD approaches, namely rainwater tanks and rain gardens for the case study sewer network. A detailed hydraulic modelling has been undertaken with rainwater tanks and rain gardens (individually and in combination) for the wet year 2010. It was observed that rainwater tanks (individually) could lead to a maximum reduction in SSO volume by 33% when compared to the base case overflow volume of 23 ML. A higher reduction in SSO volume up to a maximum of 45% was observed when rain gardens were implemented in conjunction with rainwater tanks. Such an analysis will benefit the urban water authorities to develop sustainable WSUD based mitigation strategies for controlling SSOs in their sewer system. Thus, the study will be beneficial for the community and the environment.

DECLARATION

"I, Tasnim Nasrin, declare that the Master by Research thesis entitled 'Water Sensitive Urban Design (WSUD) Strategies to Mitigate the Impacts of Intense Rainfall on the Sanitary Sewer Network Performance' is no more than 60,000 words in length including quotes and exclusive of tables, figures, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work"

[redacted]

Signature   Date: 16 March 2018

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I hope this piece of work will benefit the research community in relevant area.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

The following list of abbreviations is used throughout this thesis.

ARR	Australian Rainfall and Runoff
ARI	Average Recurrence Interval
BoM	Bureau of Meteorology
CSOs	Combined Sewer Overflows
DWF	Dry Weather Flow
IPCC	Intergovernmental Panel on Climate Change
IFD	Intensity–Frequency–Duration
E_{NS}	Nash–Sutcliffe Coefficient of Efficiency
GIS	Geographic Information System
GI	Green Infrastructure
LID	Low Impact Development
RDII	Rainfall Derived Infiltration and Inflow
SSOAP	Sanitary Sewer Overflow Analysis and Planning Toolbox
SSOs	Sanitary Sewer Overflows
SRTC	Sensitivity Radio Tuning Calibration
SUDS	Sustainable Urban Drainage System
SUH	Synthetic Unit Hydrograph
SWMM	Stormwater Management Model
PCSWMM	PC-Stormwater Management Model (commercial version of SWMM)
USEPA	U.S. Environmental Protection Agency
WSUD	Water Sensitive Urban Design
WWF	Wet Weather Flow
YVW	Yarra Valley Water

LIST OF PUBLICATIONS

Some sections in this thesis have previously appeared in the following publications.

Journal Papers

1. **Nasrin, T**., Sharma, A.K. and Muttil, N., 2017. Impact of short duration intense rainfall events on sanitary sewer network performance. *Water*, 9(3), pp.225. http://dx.doi.org/10.3390/w9030225.

2. **Nasrin, T**., Muttil, N. and Sharma, A.K, 2016. WSUD Strategies to Minimise the Impacts of Climate Change and Urbanisation on Urban Sewerage Systems: quantifying the effectiveness of rainwater tanks in reducing sanitary sewage overflows in a case study in Melbourne, Victoria. *Water e-Journal*, 1(3), pp.1-7. ISSN 2206-1991. http://dx.doi.org/10.21139/wej.2016.025.

Conference Papers

1. **Nasrin, T**., Tran, H.D. Muttil, N., 2013. Modelling Impact of Extreme Rainfall on Sanitary Sewer System by Predicting Rainfall Derived Infiltration/Inflow. *Proceedings of the 20th International Congress on Modelling and Simulation 2013, MODSIM 2013*, Adelaide, Australia, 1–6 December 2013, pp.2827-2833.
   Accessible through the congress website on the following link:
   http://www.mssanz.org.au/modsim2013/L12/nasrin.pdf.

2. **Nasrin, T**., Muttil, N. and Sharma, A.K, 2015. Modelling the Impacts of Rainwater Tanks on Sanitary Sewer Overflows. *Proceedings of the 21st International Congress on Modelling and Simulation 2015, MODSIM 2015*, Queensland, Australia, 29 November-6 December 2015; pp. 2527-2533.
   Accessible through the congress website on the following link
   https://www.mssanz.org.au/modsim2015/L17/nasrin.pdf.

Chapter 1: Introduction

1.1 Background

The negative impacts of climate change on urban water infrastructure have been an essential part of an intensive scientific discussion over the last couple of decades (Willems, 2013; Gamerith et al., 2012). The Intergovernmental Panel on Climate Change (IPCC) reported an increase in the frequency of intense rainfall as a consequence of global climate change, which will continue to alter hydrologic regimes across the world (Wamsler et al., 2013; Berggren et al., 2011; Nie et al., 2009; Mailhot and Duchesne, 2009; IPCC, 2007). This increasing intensity of extreme rainfall combined with increasing urbanisation (resulting in more impervious areas) are making conventional drainage systems more vulnerable due to increased peak flow volumes and shorter times to peak flow. Recent studies have pointed out that increased intense rainfall events and increased urbanisation have increased the risk of widespread urban flooding and sewage overflow hazards (Huong and Pathirana, 2013; Astaraie-Imani et al., 2012; Willems et al., 2012; Semadeni-Davies et al., 2008; Howe et al., 2005). It was reported that short duration intense rainfall events (with durations of 12, 18, 30 min and 1 h) have become more frequent in recent years (Yilmaz and Perera, 2014).

Conventional drainage systems are divided into combined and separate drainage systems. In a combined drainage system, there is a single pipe that is used to collect and convey both stormwater runoff and sanitary wastewater. In general, such a system carries wastewater to the sewage treatment plant and then releases the treated wastewater to the water bodies (Boyd, 2011). During intense rainfall events, increased stormwater runoff generated in urban areas increase the volume of flow into the drainage system. When the volume of flow exceeds the potential capacity of the system or treatment plant, the untreated sewage along with excess stormwater is released directly into the suburban creeks and waterways to reduce the pressure on the overall system. This discharge of the diluted sewage is defined as combined sewer overflows (CSOs).

On the other hand, in a separate drainage system, there are two pipes that are used to collect and convey stormwater runoff and sanitary wastewater. Sanitary sewer pipes are only designed to convey wastewater whereas stormwater drainage pipes are designed to convey stormwater runoff. In a separate drainage system, intense rainfall increases flow not just into the stormwater drainage system, but also into the sanitary sewer network as well. Intense rainfall increases flow into the sanitary sewer network and this increased portion of flow that occurs during and after a rainfall event is called Rainfall Derived Infiltration and Inflow (RDII). Sanitary sewers are designed to accommodate a certain volume of inflow and infiltration. During intense rainfall events, this designed volume of inflow and infiltration is exceeded and hence lead to sanitary sewer overflows (SSOs) (Pawlowski et al., 2013; Karuppasamy and Inoue, 2012; Zhang, 2007). The SSOs occur when the sewage overflows from the manholes to the surface level due to sewers running under pressure, while manhole surcharge is a situation when sewage rises in the manhole shaft but does not overflow as in the case of SSOs. It is necessary to have a better understanding about the sources of RDII in planning a sewer system and propose mitigation strategies to reduce

SSOs. As the name indicates, RDII is made up of stormwater entering the sanitary sewer system in terms of inflow as well as rainfall derived infiltration. Inflow is stormwater which enters the sewer pipes through direct connections: roof downpipes which are illegally connected to the sanitary sewers, broken manhole covers and cross-connections between stormwater and sewer pipes. On the other hand, infiltration is the runoff that filters through the soil and then enters the sewer network through cracked pipe sections, defective joints and damaged manhole walls. It can also occur due to rise in the water table.

CSOs and SSOs are considered as a serious threat to public health and water quality concerns because these overflows increase large amount of transported nutrients, particles, and metals to the receiving waters (Semadeni-Davies et al., 2008; Li et al., 2010). Thus, they affect the quality of receiving waters and carry inherent risks to human health as well as lead to environmental pollution.

Common approaches of the sewer overflows mitigation strategies focus largely on structural actions and are well documented in literature (Beeneken et al., 2013; Dirckx et al., 2011; Fu et al., 2009; Butler and Schütze, 2005). The structural mitigation strategies are expensive to build and are mostly applied to solve existing sewer overflow problems. In facing the consequences of intense rainfall and increased urbanisation, these conventional sewer overflow mitigation strategies may not meet the general criteria of sustainability. Earlier studies have recommended the implementation of Water Sensitive Urban Design (WSUD) strategies as sustainable and cost-effective approaches for managing stormwater runoff (Blecken et al., 2017; Yazdanfar and Sharma, 2015; Elliott and Trowsdale, 2007; Villarreal et al., 2004). There are different types of sustainable WSUD strategies available in the literature: rainwater tanks, rain gardens, bio-retention cells, permeable pavements, green roofs, infiltration trenches and vegetative swales (Lucas and Sample, 2015; Sharma et al., 2012; Beecham, 2012; Arnbjerg-Nielsen and Fleischer, 2009; Abi Aad et al., 2009). These techniques are also known with different terminologies: low impact development (LID), sustainable urban drainage system (SUDS) and, most recently, green infrastructure (Fletcher et al., 2014; Fryd et al., 2012). These WSUD strategies help in controlling the excess stormwater runoff that enters the sewer system and, thus, can reduce hazards like CSOs and SSOs. Furthermore, these strategies have enormous environment and social benefits other than retarding stormwater runoff and reducing sewer overflows.

This thesis focuses on the negative impacts of short duration intense rainfall on the performance of sanitary sewer network. It also explores sustainable WSUD based mitigation strategies for reducing rainfall induced SSOs and surcharge problems.

1.2 Aims of the Research

The overall aim of this research was to assess and mitigate the impacts of intense rainfall on the sanitary sewer network. To achieve this overall aim, the following three tasks were undertaken.

I. Develop a generalised framework for mitigating SSOs - A generalized framework for assessing and mitigating the impacts of intense rainfall on the performance of a sanitary sewer network was developed in this task.

II. Assess the impacts of intense rainfall on the sanitary sewer network - This task involved implementing the first part of the developed framework to evaluate the hydraulic performance of a case study sanitary sewer network in Melbourne, Australia.

III. Develop and evaluate WSUD strategies for mitigating SSOs – This task involved implementing the second part of the developed framework to perform a detailed hydraulic modelling of commonly used WSUD approaches for minimising SSOs.

1.3 Brief Research Methodology

The methodology used to implement the three tasks presented in Section 1.2 are described briefly in this section.

Task 1: Develop a generalised framework for mitigating SSOs

This task involves developing a generalised framework for firstly assessing and then mitigating the impacts of intense rainfall on the sanitary sewer network. The first part undertakes detailed hydraulic modelling to evaluate the hydraulic performance of the existing sewer network in terms of SSOs and surcharges. The second part of the framework deals with the development and evaluation of sustainable SSO mitigation strategies based on Water Sensitive Urban Design (WSUD) approaches.

Task 2: Assess the impacts of intense rainfall on the sanitary sewer network

This task involves RDII analysis and developing a hydraulic model for the sewer network. The developed hydraulic model is then used to assess the hydraulic performance of the case study sewer network based on a set of performance indicators for a representative wet and a dry year. In this study, the chosen wet year was 2010. This year was identified by the Australian Bureau of Meteorology (BoM) as the third wettest year on record for Australia (BoM Australia, 2015). For the case study area, the total annual rainfall in 2010 was 681.2 mm, which was well above the annual mean rainfall of 588 mm. However, the total annual rainfall for the 2008 was 369.8, which was well below the long-term average (589.6 mm) and was defined as a dry year (Walsh et al., 2014). The modelling steps are described in the following sections:

- Selection of suitable modelling tool – Suitable modelling tools are required for RDII analysis and hydraulic evaluation of the sewer network. The modelling software has been selected based on literature review and discussion with local water professionals. The Sanitary Sewer Overflow Analysis and Planning (SSOAP) Toolbox (Vallabhaneni and Camp, 2007) has been selected for RDII analysis. PCSWMM (which uses Stormwater Management Model (SWMM) as its basic engine) is used in this study for the sewer hydraulic modelling based on its availability.

- Selection of case study and data collection – As stated earlier, a case study has been selected in this research for the application of the proposed framework. The selected case study sewershed area is a residential suburb in Glenroy, which comes under the jurisdiction of one of Melbourne's three local water utilities, Yarra Valley Water. The main reason for choosing this sewer network as the case study is that the main sewer pipe was quite old. Hence, it is expected that conduits would have some ageing effects (pipe cracks and joint defects). Hence, RDII would be the major contributor for SSO and surcharge problems. Rainfall data measured sewer flow data and physical sewer system network geometry data used for this hydraulic performance assessment were collected from different Australian Government authorities. Six minutes resolution rainfall data were obtained from the Bureau of Meteorology, Australia for a nearby rain gauge station. One downstream manhole (named GLN8) was used to measure sewer flow data at six minutes time-steps during the period November-December 2010.

- RDII analysis – This RDII analysis is conducted by computing the RDII parameters through a systematic analysis of measured sewer flow data and rainfall data. The SSOAP Toolbox implements the popular synthetic unit hydrograph (SUH) method to determine RDII parameters (R, T, K). This analysis is undertaken in two parts. In the first part, the measured wastewater flow is analysed to generate the RDII hydrograph. This RDII hydrograph is then used in the second part to identify the RDII parameters. A description of this analysis is presented in Chapter 3, sub-sections 3.2.4 and the results are presented in Chapter 4, sub-section 4.2.2.

- Sewer Hydraulic Modelling – A detailed hydraulic modelling of the case study sewer network has been performed for the existing network for 2010. The existing network is act as base case in this study. The hydraulic modelling is followed by developing the hydraulic model for the sewer network, calibrating and validating the model and finally evaluating the hydraulic performance. The input data required for sewer hydraulic model were the rainfall, measured flow and sewer system data and the RDII parameters. Geographic Information System (GIS) is applied to delineate the study area into small sub-catchments leading to the flow loading points (manholes) in the developed sewer network model. The sewer model is then calibrated and validated based on measured sewer flow data at the downstream GLN8 manhole for the wet months of November-December 2010. Details of sewer hydraulic modelling and calibration validation results are presented in Chapter 4, sub-section 4.2.3.

- Sewer system performance evaluation - After calibration and validation, a continuous simulation has been conducted for the year 2010 and 2008 to evaluate the hydraulic performance of the network. A set of performance indicators have been developed to analyse the performance. The analysis is presented in Chapter 4, sub-section 4.2.4.

Task 3: Develop and evaluate WSUD strategies for mitigating SSOs

In this task, sustainable SSO mitigation strategies are developed and assessed. Recently, WSUD approaches have been promoted for providing a sustainable solution to stormwater management. These sustainable strategies can reduce SSOs and surcharges by controlling excess stormwater runoff entering the sanitary sewer network in terms of RDII. Many studies have remarked the enormous benefits of various WSUD approaches and their impacts in terms of minimizing rainfall induced sewer overflow volumes, events and peak overflows. Therefore, a detailed hydraulic modelling of WSUD approaches has been carried out to assess the reduction in SSOs. The steps involved in the modelling are described below:

- Selection of suitable WSUD approaches - As stated earlier, PCSWMM (CHI, 2016) has been selected for the hydraulic modelling of the sewer network. This software can model five common types of WSUD strategies namely rainwater tanks, rain gardens/bio-retention cells, permeable pavements, green roofs, infiltration trenches and vegetative swales. This study has selected widely-used WSUD approaches in Australia, rainwater tanks and rain gardens for the hydraulic modelling of the case study sewer network.

- Evaluation of hydraulic performance with selected strategies - After developing the PCSWMM model with rainwater tanks and rain gardens parameters, a detailed hydraulic modelling has been conducted to analyse the performance of the sewer network for the year 2010. Then, the results have been compared with the base case (with no WSUD strategies). Various parameters are varied in the modelling for assessing the reduction in SSOs. The detailed outcomes are given in Chapter 5.

1.4 Research Significance

Short duration intense rainfall has an adverse impact on the performance of the sewer network by causing SSOs and surcharges. These overflows release many harmful contaminants and spread pollutants, nutrients, and hazardous substances into the suburban creeks and waterways. Thus, these sewage overflows affect the ecosystem and biota in the receiving waters. The generalized framework developed in this research can benefit the water authorities to develop mitigation strategies for controlling this rainfall induced SSOs in their sewer systems. The hydraulic performance assessment includes determining RDII flows and conducting hydraulic modelling of sewer system for performance assessment. This study has demonstrated a simple and accurate method of determining RDII flows. Moreover, a set of performance indicators developed in this study can evaluate the current situation of the existing sewer system. Such an analysis will help the relevant water authorities to take adequate measures to minimize the environmental and human health impacts at the identified locations which are at risk or prone to SSOs. The number of sewer overflows and surcharges at those locations are expected to increase since the short duration intense rainfall events are becoming more frequent as a consequence of climate change.

The conventional SSOs mitigation strategies are expensive to build and unable to cope with the increased intensity of rainfall events, mainly due to non-stationary climate and rapid urbanisation. Hence, this research has developed sustainable WSUD approaches for mitigating SSOs. SSOs are caused by RDII, which is the increased portion of flow in a sewer system that occurs during and after a rainfall event. According to Water Service Association Australia (WSAA) guidelines, inflow and infiltration, I/I reduction program focuses on the I/I source detection and I/I system rehabilitation (Carne, 2013). However, I/I source detection in every property were discussed with the water utility, Yarra Valley Water (YVW) and were not performed in this study due to the budgetary and time issues. Therefore, this study has developed popular WSUD based SSO mitigation strategies.

Implementing WSUD strategies in terms of minimizing SSOs is innovative because there is no study in Australia that has emphasized the effectiveness of WSUD approaches in reducing SSOs. These WSUD strategies are commonly used for stormwater management. This study has shown that these strategies can help in controlling the excess stormwater runoff entering the sewer network and thus, reduce hazards like SSOs. Apart from their managing stormwater runoff and decreasing flows to sewer network, this research has also chosen WSUD strategies because of their enormous environmental and public health benefits. These sustainable strategies can improve water quality into receiving waterways by reducing pollutants and hazardous substances and thus, protect aquatic ecosystems. They can replace potable water with an alternative source of water supply in the households, which in turn will benefit the home owners. The other benefits include improving urban landscape and community aesthetic, providing green space, reducing urban heat island effects, direct energy uses and improving air quality. Thus, these WSUD strategies will be beneficial for the health of the community and the environment.

1.5 Structure of the Thesis

This thesis is organized in six chapters as presented in Figure 1.1. The three tasks presented in Section 1.2 have been implemented in Chapters 3, Chapter 4 and Chapter 5 respectively. A brief description of all the chapters are given below.

Chapter 1 describes the background of this research study. In this regard, the chapter focuses on the negative impacts of intense rainfall on urban water infrastructure, especially the sanitary sewer network. Then it presents the aims of the research project and a brief research methodology. Finally, the significance of the proposed research is highlighted.

Chapter 2 presents a comprehensive review of mitigation strategies for reducing rainfall induced sewer overflows. The chapter highlights the benefits and importance of various WSUD approaches to manage stormwater runoff, improve water quality and mitigate sewer overflows.

Chapter 3 presents Task 1, which is a generalized framework for assessing and mitigating the impacts of intense rainfall on the performance of a sanitary sewer network. The first part of the developed framework involves detailed hydraulic modelling for sewer network performance evaluation. Various indicators are presented to assess the performance of the sewer network in terms of SSOs. The second part proposes and evaluates SSO mitigation approaches based on sustainable WSUD strategies. The generalised framework developed in this chapter has been applied for a case study residential catchment in Melbourne, Australia. The detailed outcomes for the two parts are presented in **Chapter 4** and **Chapter 5,** respectively.

Chapter 4 presents Task 2, which is the application of the first part of the developed framework for the case study sewer network. This chapter starts with a description of the case study area. It then evaluates the hydraulic performance of the existing sewer network under intense rainfall events. This includes determination of the RDII flows and developing the hydraulic model for the sewer network. The developed hydraulic model is then used to assess the hydraulic performance of the sewer network based on a set of performance indicators.

Chapter 5 presents Task 3, which is the detailed outcomes of modelling for the second part of the framework. A detailed hydraulic modelling popular WSUD approaches in Australia, rainwater tanks and rain gardens is performed for controlling the existing SSOs problems. Finally, the modelling results are compared with the base case (no WSUD strategies) for assessing the performance of the sewer network with proposed strategies.

Chapter 6 provides the summary of the thesis, main conclusion as well as limitations of the study and recommendations for future research.

Chapter 1: Introduction

- Background, Aims of Research and Brief Research Methodology
- Research Significance and Thesis Structure

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Chapter 2: Review of Literature

- Overview of Literature
- Conventional Strategies to Mitigate Sewer Overflows
- WSUD Approaches as Strategies to Mitigate Sewer Overflows

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Chapter 3 (Task 1): A Generalised Framework for Mitigating SSOs

- Evaluation of the Hydraulic Performance of the Sewer Network
- Define Strategies for Sanitary Sewer Overflow Mitigation

↓

Chapter 4 (Task 2): Impacts of Intense Rainfall on Sanitary Sewer Network

- Description of Case Study
- Sewer Network Performance Evaluation Under Intense Rainfall Events

↓

Chapter 5 (Task 3): WSUD Strategies for Mitigating SSOs

- Development of WSUD Strategies
- Perform Sewer Hydraulic Modelling with Developed Strategies

↓

Chapter 6: Summary, Conclusions and Future Recommendations

- Summary
- Conclusions
- Limitations and Recommendations for Future Study

Figure 1.1 Structure of the thesis

Chapter 2: Review of Literature

2.1 Introduction

Urban drainage systems are critical component of a city's infrastructure which collect and convey stormwater and wastewater. These systems are becoming more vulnerable to failure, partly due to the lack of consideration to what occurs when their design criteria are exceeded. As a consequence of the global warming, high-intensity rainfall events will become more severe and frequent (Berggren et al., 2011; Willems et al., 2012). At the same time, increasing urbanisation (resulting in more impervious areas) in cities is leading to shorter response time of urban catchments, which increases stormwater runoff volumes beyond the capacity of existing urban drainage systems. Urban sewerage systems are becoming more vulnerable to failure mainly due to climate change and rapid urbanisation. As these systems are becoming less efficient, issues such as urban flooding, CSOs and SSOs are increasing.

CSOs and SSOs contain substantial amount of pollutants associated with dissolved contaminants and colloidal particles. These include substances creating a biochemical oxygen demand (BOD), nutrients such as N and P, turbidity, sediments, toxic metals and microbial pathogens (Balmforth, 1990; Li et al., 2010). Many studies have remarked these sewer overflows as prominent sources of water pollution to receiving watercourses (Pennino et al., 2016; Casal-Campos, et al., 2015; Chaosakul et al., 2013). These overflows are also affecting the quality of receiving water, ecological benefits for fish and wildlife population and decreasing biodiversity. Hence, selection of suitable mitigation strategies is of prime importance for reducing the negative impacts of rainfall induced sewer overflows and protecting the health of aquatic ecosystems.

There are several conventional approaches commonly applied to eliminate the potential effect of sewer overflows. Conventional sewer overflow mitigation strategies suggest mainly structural actions which include maximizing storage capacity, replacing sewer pipes, increasing pump stations and maximizing treatment facilities (Hansen, 2013; Samples and Zhang, 2000). The structural strategies are often costly to build, and their implementation need tremendous amount of time and labour. In addition, they fail to cope with the consequences of the increasing intensities of extreme rainfall and urbanisation. Thus, these strategies are less attractive to enhance the sustainability of the sewer network under future uncertainties.

In this regard, this study focuses mitigation strategies which are developed based on their sustainability. Recent studies have demonstrated that the Water Sensitive Urban Design (WSUD) strategies are sustainable, innovative and cost-effective approaches for managing stormwater runoff in urban developments. It is worth mentioning that such runoff from excessive rainfall can cause sewer system overflows. These approaches can capture excess stormwater runoff which enters the sewer network during intense rainfall events. (Liao et al., 2015; Shamsi, 2012; Cahill, 2012; Perez et al., 2010 and Kloss, 2008). These WSUD strategies have other benefits than retarding stormwater runoff, which include reducing pollutant load into receiving waterways, replacing potable water with alternate sources for non-consumptive uses and improving urban landscape. These benefits have led to various water utilities and local councils adopting the use of WSUD strategies as a part of existing and new developments. In spite of these benefits, there are only a handful of studies available in literature which quantify the benefits of various WSUD strategies (Liao et al., 2015; Locatelli et al., 2015; Myers et al., 2014; Walsh et al., 2014; Shamsi, 2012; Rahman et al., 2012; Roldin et al., 2012; Khastagir and Jayasuriya, 2010).

Many recent studies discussed the impacts of WSUD approaches for reducing rainfall induced sewer overflow volumes, events and peak overflows. Therefore, this chapter provides a comprehensive review about sustainable WSUD strategies studied in the literature for mitigating rainfall induced CSOs and SSOs. This review chapter is organized as follows. In Section 2.2, details are given on how the database of the review papers have been assembled including overview of the research activity in the use of WSUD techniques. Furthermore, this section also explains the selection of suitable WSUD modelling tools which are essential to check technical feasibility. Then Section 2.3 provides a detailed description of the WSUD based overflow mitigation strategies and a brief description of the commonly applied traditional overflow mitigation strategies. Finally, a summary of the chapter is provided.

2.2 Overview

This literature review chapter has been reviewed 47 papers based upon various WSUD techniques for reducing rainfall induced sewer overflows. These articles have been assembled from peer reviewed journals, international conference proceedings, reports from government agencies, book chapters and dissertations. These reviewed articles have been published in duration of 1999-2016.

It is essential having a detailed overview about the selected articles which have been contributed efficiently in this entire literature. Therefore, Appendix A presents the summarized details of all the 47 reviewed articles. The table in the appendix is divided into five different sections: authors name and published year, study locations, information about the systems, type of WSUD strategies implemented and finally, the type of applications which are essential for proving the benefits of the WSUD techniques.

Figure 2.1 shows the list of the selected papers including their published years. Since 2008, there has been a rising trend of publishing WSUD techniques based papers. Therefore, it can be concluded from Figure 2.1 that there has been an increase in the implementation of the WSUD approaches during the past decade for mitigating the negative impacts of rainfall induced sewer overflows.

As stated earlier, different types of sustainable WSUD strategies are studied in the literature. Figure 2.2 presents the most commonly used WSUD approaches and the list of the reviewed papers applied corresponding approaches. This figure will help to get a clear idea about the selection of suitable WSUD approaches based on literature review. It can be observed that the popular WSUD strategies widely applied in the literature are rainwater tank, raingarden/bio-retention cell, green roof and permeable pavement. 29 out of 47 selected articles have recommended raingarden/bio-retention cell, whereas 28 papers have suggested green roof and 24 papers have considered rainwater tank and permeable pavement as options for assessing their impacts on CSOs and SSOs.

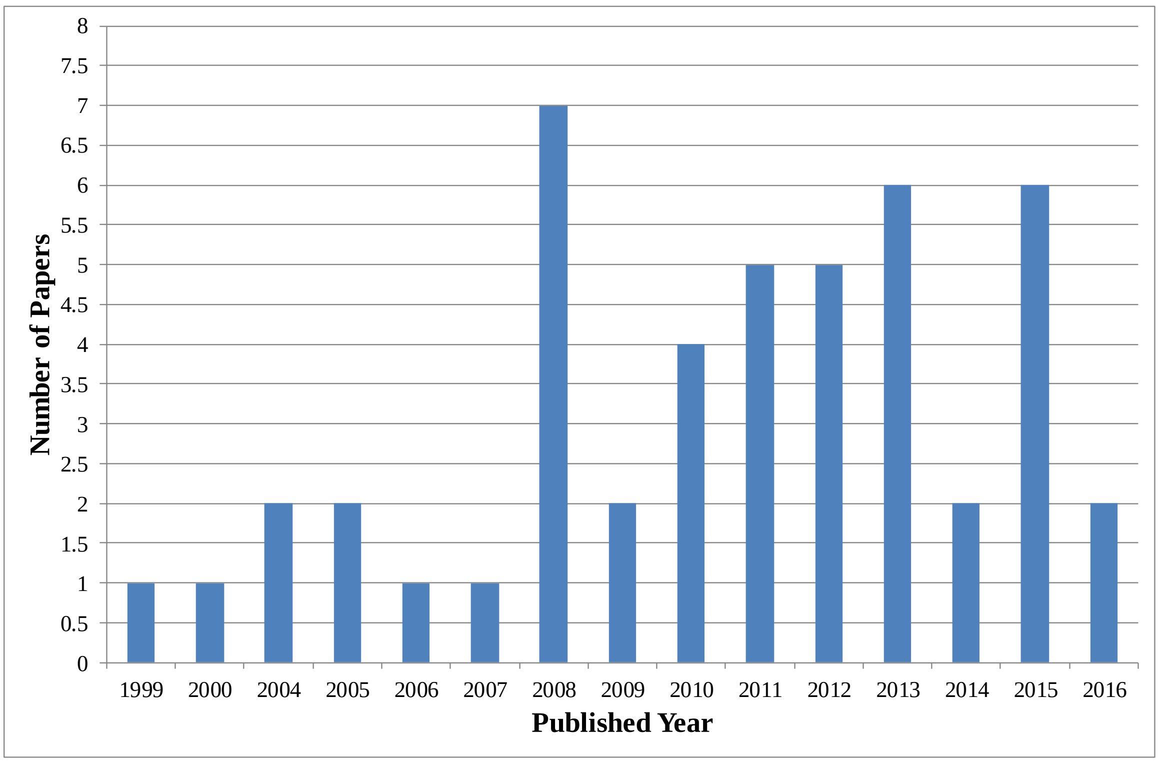

Figure 2.1. Number of reviewed papers by their published years.

Furthermore, the selection of suitable modelling software is also essential for evaluating the performance of the system. Thus, an overview of the suitable modelling tools based on literature review are presented in Table 2.1. As observed in this Table 2.1, authors of 33 out of 47 reviewed papers have recommended various tools for the WSUD modelling.

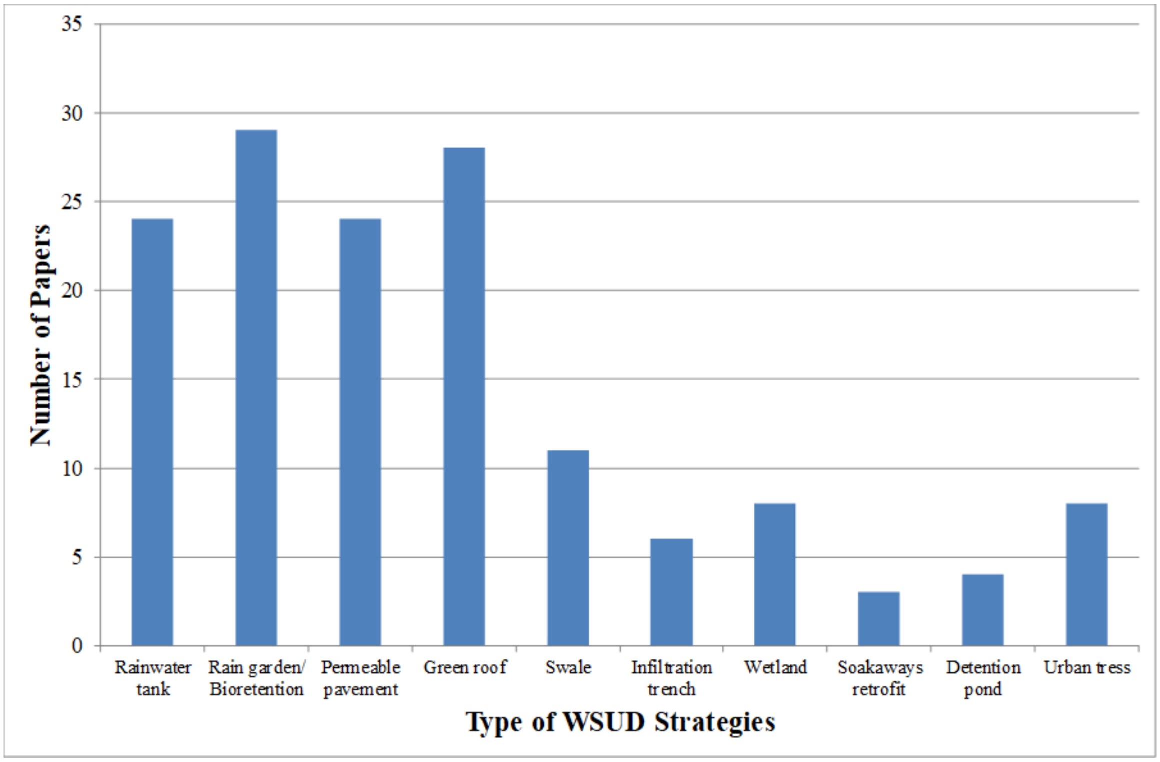

Figure 2.2. Popular WSUD strategies which have been used in reviewed papers.

Table 2.1. Overview of modelling tools.

	Author and year	**Modelling tools**
1.	Abi Aad et al.,2009	Stormwater Management Model (SWMM)
2.	Autixier et al., 2014	Stormwater Management Model (SWMM)
3.	Boyd, 2011	Geographic Information Systems (GIS) Microsoft Excel simulation model
4.	Casal-Campos et al., 2015	Stormwater Management Model (SWMM) SIMBA 6.0
5.	Chaosakul et al., 2013	PCSWMM (advanced modelling software for Stormwater Management Model ,SWMM)
6.	Cahill, 2012	Stormwater Management Model (SWMM) SIMBA 6.0

7.	Colwell and Tackett, 2015	Stormwater Management Model (SWMM)
8.	De Sousa et al., 2012	Stormwater Management Model (SWMM)
9.	Doug et al., 2005	Analytical probabilistic models, SUDS
10.	Hartman, 2008	RAINMAN Stormwater Management Model (SWMM) InfoWorks
11.	Liao et al., 2015	Stormwater Management Model (SWMM)
12.	Li, 2008	Analytical probabilistic models, SUDS
13.	Lucas and Sample, 2015	Stormwater Management Model (SWMM), PCSWMM
14.	The Milwaukee Metropolitan Sewerage District (MMSD), 2011	System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN) model
15.	Montalto et al., 2007	Stormwater Management Model (SWMM)
16.	Myers et al., 2004	Stormwater Management Model (SWMM) PCSWMM (advanced modeling software for Stormwater Management Model ,SWMM)
17.	Nasrin et al., 2016	PCSWMM (advanced modeling software for Stormwater Management Model ,SWMM)
18.	Patwardhan et al., 2005	LIFE™ Model (physically-based hydrologic and water quality simulation tool)
19.	Pennino et al., 2016	MATLAB 8.3.0 (MATLAB and Statistics Toolbox Release R2014a Student) USGS FORTRAN program LOADEST
20.	Pitt and Voorhees, 2011	Source Loading and Management Model for Windows (WinSLAMM)Stormwater Management Model (SWMM)
21.	Ptomey, 2013	Geographic Information Systems (GIS) model

22.	Quigley and Brown, 2015	Stormwater Management Model (SWMM)
23.	Roldin et al., 2012	MIKE URBAN CS/MOUSE model
24.	Spatari and Montalto, 2011	Low Impact Development Rapid Assessment (LIDRA 2.0)
25.	Semadeni-Davies et al., 2008	MOUSE (Model of Urban Sewers)
26.	Shamsi, 2012	PCSWMM (advanced modeling software for Stormwater Management Model ,SWMM)
27.	Smullen et al., 2008	Stormwater Management Model (SWMM)
28.	Stovin et al., 2013	Stormwater Management Model (SWMM)
29.	Struck et al., 2010	Source Loading and Management Model for Windows (WinSLAMM) Stormwater Management Model (SWMM)
30.	Tackett and Mills, 2010	The Green Stormwater Infrastructure Toolbox (GSI)
31.	Vaes and Berlamont, 1999	The Reservoir Modelling System Remuli
32.	Villarreal et al., 2004	PondPack (Surface Stormwater Modelling Program)
33.	Wang et al., 2013	Stormwater Management Model (SWMM)

The list of modelling tools selected from reviews are shown in Figure 2.3. From Figure 2.3, it can be seen that the most popular WSUD modelling software is EPA SWMM and its commercial version is PCSWMM (CHI, 2016). In the reviewed papers, 20 out of 33 papers which accounted for 61% of the total articles have used SWMM/PCSWMM software for WSUD modelling, whereas 2 papers have applied MOUSE (DHI software) and WinSLAMM (PV & associates) for WSUD modelling. SWMM, which is developed by US Environmental Protection Agency (EPA), is a widely used platform for sewer hydraulic analysis

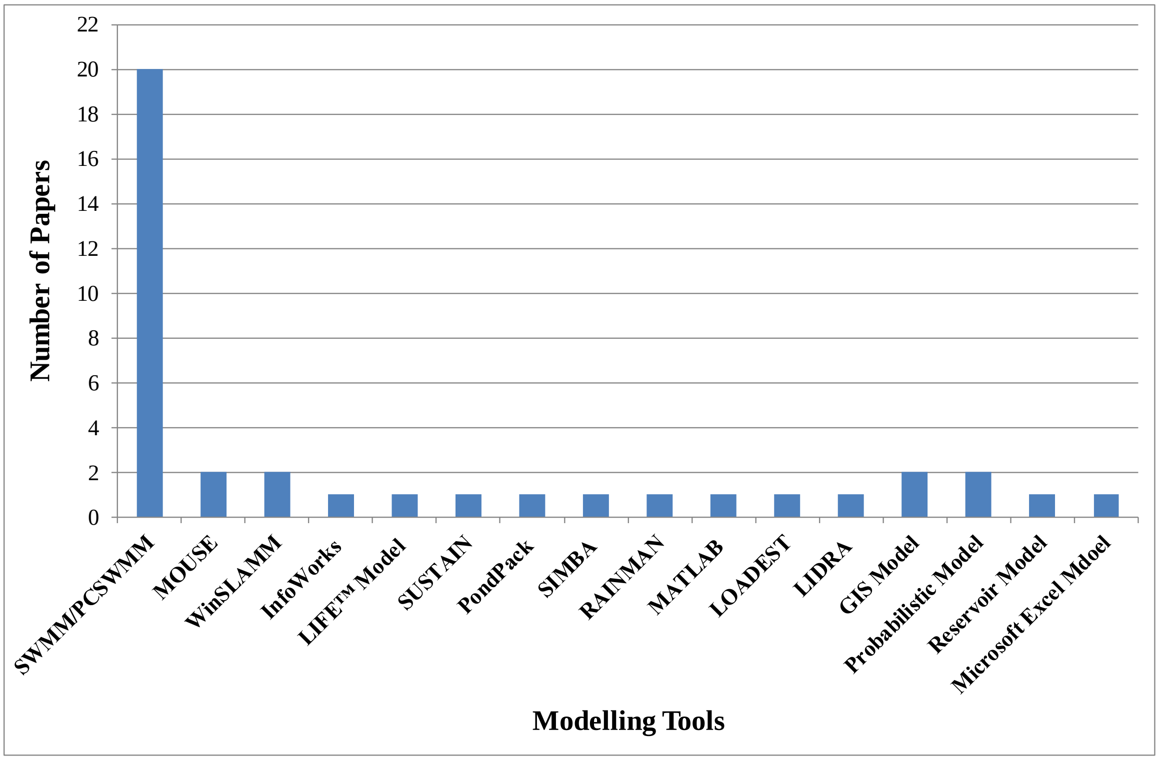

Figure 2.3. Popular modelling tools which have been applied in reviewed papers.

On the other hand, PCSWMM (which uses SWMM as its basic engine) provides a complete GIS system for data pre-processing and model parameterization. EPA SWMM and PCSWMM can be used to model common types of WSUD strategies. These WSUD strategies are programmed into SWMM algorithms and can be accessed easily through simple dialog boxes (Rossman, 2010). Various parameters need to be added as input for developing the model. Detailed descriptions of the commonly applied WSUD strategies are provided in the later section.

2.3 Mitigation Strategies

This chapter reviews mitigation strategies for reducing rainfall-induced SSOs and CSOs problems. As mentioned earlier, this study focuses sustainable WSUD based strategies to mitigate the adverse impacts of sewer system overflows due to increase in extreme rainfall events and increase in urbanisation. However, there are several conventional approaches commonly applied to eliminate the potential effect of sewer overflows. The following sections describe commonly applied conventional management (in brief) and WSUD based sustainable management (in detailed).

2.3.1 Conventional strategies to mitigate sewer overflows

As stated earlier, conventional mitigation strategies are comprised of a large number of structural measures. There are some maintenance and operational actions also applied for short term management of sewer overflows. These conventional sewer overflow mitigation strategies are described below.

Sewer rehabilitation is most commonly used to reduce the sewer overflows and sewage spills during heavy rainfall. Some sewer facilities were put in place many years and these ageing sewer networks cannot hold the capacity needed by expansion of cities. Replacement of sewer pipes aims at introducing new volume and structural capacity to cope with the increasing intensity of extreme rainfall combined with increasing urbanisation. Additionally, some old sewer networks have been blocked or have cracks and joint defects. Excessive build up, poor installations, and foreign objects in a sewer may reduce its capacity and require sewer pipe replacement (De Sousa et al., 2012). In such case, these clogged sewer lines need to be repaired by its utility.

Maximizing storage capacity is another traditional method of reducing sewer overflows. More storage is built to reduce the effect of widespread urban flooding and sewage overflow hazards. The structural component of a storage facility is to store wastewater directly. The method is effective if there exist enough space far from the people in the urban zones. However, the cost of the conventional storage facility is tremendous as well as has adverse aesthetic impacts. (Field et al., 1972).

Increase in pump stations has been applied for a long time. When an overflow is about to happen, the pumps helps to transfer the overflow to safe areas. Additionally, due to high pressure from pumps, a small volume channel can be used to carry higher capacity as compared to where pumps have not been used (Struck et al., 2010). People who are located at low level grounds can install more pumps in the occurrence of intense rainfall to reduce overflows. Pump stations can also be increased where there is a higher risk of overflow to help in pumping out the excess stormwater.

These aforementioned traditional strategies lack sufficient flexibility to adapt negative impacts of climate change and urbanisation. In addition, these mitigation strategies are expensive to build and less effective in terms of economic, environment and human health benefits. Hence, structural measures are being less used in recent years and the implementation of sustainable and cost-effective WSUD approaches are on the rise.

2.3.2 WSUD approaches as strategies to mitigate sewer overflows

There are different types of sustainable WSUD strategies available in the literature: rainwater tanks, rain gardens or bio-retention cells, permeable pavements, green roofs, infiltration trenches, swales, wetlands, urban tress, soakways retrofit and detention ponds. These WSUD strategies are described below.

2.3.2.1 Rainwater tanks

Rainwater tanks are one of the widely-used WSUD approaches for non-potable reuses or outdoor uses (Rahman et al., 2012). These are popular on-site stormwater rainwater collection method which store water during a storm event. These storage tanks are usually placed beneath roof downspouts, which capture roof runoff and thus prevent stormwater inflow entering the sewer network. (Chaosakul et al., 2013; Boyd, 2011; Abi Aad et al., 2009; Smullen et al., 2008).

2.3.2.2 Rain gardens or bio-retention cells

Bio-retention cells/rain gardens are shallow depression storages which contain vegetation layers over an engineered soil mixture. There is a gravel bed underneath the vegetation. These can provide storage, infiltration and evaporation of direct rainfall and surface runoff (Shamsi, 2012; Rossman, 2010). These vegetated depressions can provide a wide range of benefits to private properties and community communal entities. They are designed to retain, filter and treat stormwater runoff in the urban areas. They are also effective to improve water quality by removing suspended solids as well as pollutants, metals and organic compounds (Autixier et al., 2014).

2.3.2.3 Permeable pavements

Permeable pavements are excavated areas where gravel is used to fill the area. Here, porous concrete or asphalt mix is used for paving the surface. Stormwater runoff can pass through the permeable surface, filter by the soil layer and then enter the gravel storage zone beneath the pavement. After that, runoff can easily infiltrate the natural soil or convey to storm drain through optional drainage system. They are effective reducing peak runoff and improving groundwater recharge (Patwardhan et al., 2005). They can improve water quality as well by reducing sediments, nutrients and metals (Sample et al., 2014).

2.3.2.4 Green roofs

They are also known as vegetated roof covers. Green roofs have a surface layer of living plants that grow on the top of a roof, a thin soil layer and a special drainage mat below the soil layer. They can retain significant amount of rainfall and roof runoff, then filter through soil layer and drain excess percolated water off the roof (Hartman, 2008). They have multitude of benefits other than retarding stormwater runoff and decreasing flows to sewer network during intense rainfall. This include reducing direct energy uses and urban heat island effects through evaporative cooling, removing sound pollution and improving air quality and biodiversity (Wise et al., 2010). They can also provide green space in dense urban zones and thus, improve community aesthetic.

2.3.2.5 Infiltration trenches

These are narrow ditches filled with gravel to the ground level. They provide storage and capture stormwater runoff from the impervious areas. The captured runoff then infiltrates into the natural soil (Rossman, 2010). They can significantly reduce runoff volume that enter sewer system. They can also improve landscape and aesthetic by providing green space (Sample et al., 2014).

2.3.2.6 Swales

These are depressed areas which act as channels to route the surface runoff. Grass or vegetation is used to cover the sliding slopes of the depression areas (Rossman, 2010). Vegetative swales help to reduce the conveyance capacity of stormwater runoff and provide sufficient time to infiltrate the stormwater into the natural soil.

2.3.2.7 Wetlands

Wetlands are most efficient stormwater treatment areas which help to remove stormwater pollutants including dissolved contaminants, heavy metals, colloidal particles, suspended solids, ammonia and nutrients. These are shallow heavily vegetated artificial ponds consist of a sedimentation zone which is used to remove coarse sediments, a macrophyte zone associated with plant area to remove fine particulate and absorb soluble pollutants and finally, the high flow bypass channel that protect the plant zone. In addition of improving water quality, they have proven to reduce the stormwater runoff volume and peak flows that enter the sewer system during intense rainfall. In various urban areas, they have also been used as recreational amenities and wildlife habitat (Myers et al., 2014; Raucher and Clements, 2010; Montalto et al., 2007).

2.3.2.8 Urban trees

Trees are an important component of stormwater management in urban areas by providing a direct ground absorption by trunk flow and rainfall absorption using roots. Additionally, they decrease nitrogen in rainwater and other pollutants in stormwater runoff. They are efficient in improving air quality as well reducing urban heat island effects and energy consumptions. They are usually located alongside urban streets and thus, enhance landscape and aesthetic (Raucher and Clements, 2010).

2.3.2.9 Soakaways retrofits

These are circular or square excavations which are then filled with rubble or lined with brickwork, perforated storage structures with granular backfill or precast concrete. They act as underground seepage pits to filter stormwater and popularly use on private properties or side of the streets in densely urban zones. They provide stormwater attenuation, groundwater recharge and stormwater treatment (Roldin et al., 2012; Fryd et al., 2012).

2.3.2.10 Detention ponds

They are used to retain stormwater runoff from impervious area during storm event and then, completely release through some specific outlets within few hours. They store stormwater runoff temporarily and thus, reduce runoff volume and peak flows (Pennino et al., 2016). They have varying styles in terms of manicured or natural appearing vegetation.

2.4 Summary

Short duration intense rainfall along with rapid urbanisation has an adverse impact on the performance of the sewer network by causing sewage overflow hazards. Conventional overflow mitigation strategies lack sufficient flexibility to adopt critical circumstances. WSUD strategies can manage stormwater runoff more sustainably and cost effectively in ways the conventional strategies are unable to do. This chapter has highlighted the increasing trend of implementing WSUD approaches over the past decades for mitigating rainfall induced sewer overflows.

Furthermore, this chapter has elaborated the popular WSUD approaches based upon their extensive studies. In terms of popularity and suitability, rainwater tank, raingarden/bio-retention cell, green roof and permeable pavement have been widely applied and recommended in almost all reviewed articles. Rainwater tanks capture significant amount of stormwater and thus reduce stormwater runoff volume to sewer system during intense rainfall events. Many studies have explored the impact of rainwater tanks on reducing CSO and SSO volumes and overflow events. Apart from reducing surface runoff and sewer overflows, rainwater tanks are also popular for non-potable water supply with fit-for-purpose concept. Studies have discussed rain gardens or bio-retention cells are most effective in removing stormwater pollutants including suspended solids, E. coli, nutrients and heavy metals. Rain gardens and green roofs show a better reduction of sewer overflow volume than sewer overflow events or hours. Green roofs have other benefits including reducing direct energy consumption and urban temperature, removing noise pollution, improving air quality and urban aesthetics. Permeable pavements are also effective for reducing pollutant loads into receiving waterways. They are most popular for reducing peak runoff by storing and infiltrating into soil.

WSUD strategies have enormous environment and social benefits other than minimising the negative impact of sewer overflow and sewage release problems. The environmental benefits include reducing pollutant loads and improving water quality of receiving water, protecting the existing natural and ecological processes and maintaining natural hydrologic cycles and aquatic ecosystems. Moreover, the social benefits include protecting public health, improving landscape and aesthetics, providing green space and increasing biodiversity. Regardless of these benefits, there are only a handful of studies available in literature that quantify the benefits of various WSUD strategies, mainly in CSO context. However, there are only a few studies about the benefits of WSUD for reducing rainfall induced sanitary sewer overflows. To address this drawback, this research has attempted to highlight the effectiveness of WSUD approaches in reducing rainfall induced SSOs. Although the WSUD strategies are commonly used for stormwater management, they can also reduce SSOs and surcharges by controlling excess stormwater runoff entering the sewer network in terms of RDII. In addition, there is no available systematic method in the current practice where WSUD strategies have been implemented in SSO context. Hence, this study has developed a generalised methodology to address the existing research gap and to formulate an effective method of WSUD modelling in sanitary sewer system. Such a method can be implemented to any existing urban residential area to enhance the sustainability of the sewer network along with reducing rainfall induced SSOs. The methodology used for this modelling is described in Chapter 3 and the detailed hydraulic modelling outcomes have been presented in Chapter 4 and Chapter 5.

In this review, various tools extensively used for the WSUD modelling are also identified. Selection of suitable modelling tool is essential to evaluate the hydraulic performance of the system and to quantify the impact of WSUD strategies in managing sewer overflows. Among various WSUD modelling software, this study has found EPA stormwater management model (SWMM) and its commercial version PCSWMM is the most popular and suitable software for the sewer hydraulic modelling. The majority of the review studies have selected the EPA SWMM/PCSWMM for assessing the modelling impacts of commonly applied WSUD strategies on reducing CSOs and SSOs. Therefore, PCSWMM with GIS interface has also chosen for this study for hydraulic performance assessment.

Based upon the reviewed literature, it can be concluded that WSUD approaches have been successful in meeting their innovative and cost-effective criteria for managing excess stormwater runoff, improving water quality and mitigating rainfall induced CSOs and SSOs.

Chapter 3: A Generalised Framework for Mitigating SSOs

3.1 Introduction

Short duration intense rainfall events are becoming more frequent as a consequence of global climate change (Hajani and Rahman,2018; Hajani et al., 2017; Yilmaz and Perera, 2014). This causes an increase in rainfall derived infiltration and inflow (RDII) into the aging sewer networks. This in turn has led to increase in occurrences of Sanitary Sewer Overflows (SSOs), which have a detrimental impact on human health and the environment. This chapter presents a generalised framework for assessing and mitigating the impacts of intense rainfall on the sanitary sewer networks. The developed framework is divided into two major parts. The first part of this framework aims to evaluate the possible impacts of short duration intense rainfall on the performance of the sanitary sewer system. This will include determining RDII flows and conducting hydraulic modelling of sanitary sewer system for performance assessment. The performance of the sewer network is assessed based on various indicators that were used to quantify the SSOs and manhole surcharges. These indicators will help to investigate the hydraulic performance of the existing sewer system under short duration intense rainfall events. The second part of this framework proposes sustainable WSUD based mitigation strategies for controlling the problems of SSO and surcharge.

Figure 3.1 presents the generalised framework used for assessing and mitigating the impacts of short duration intense rainfall on the sewer network. The following sections will describe developed framework in detail.

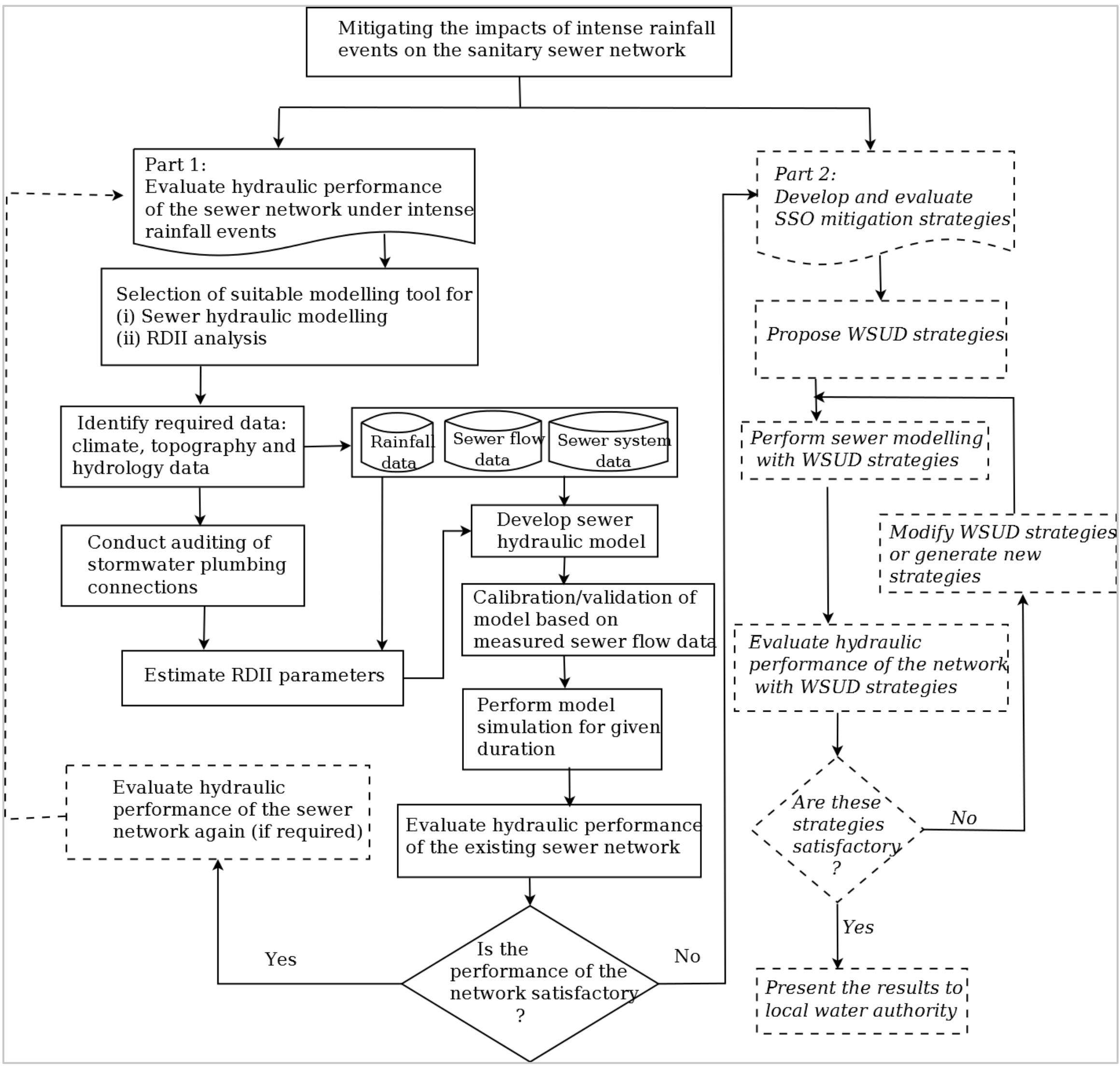

Figure 3.1. Generalised framework for assessing and mitigating the impacts of intense rainfall on the sanitary sewer network.

3.2 Evaluation of the Hydraulic Performance of the Sewer Network

The first part of the developed framework involves a detailed hydraulic modelling to evaluate the performance of the sewer network. The detailed modelling steps involved in evaluating the performance of the sewer system are described in the following subsections.

3.2.1 Selection of suitable modelling tools

Selection of suitable modelling software based on literature review and discussion with local water professionals is essential. Here, two modelling tools are required (1) Model for hydraulic evaluation of the sewer network and (2) Model to evaluate RDII parameters.

PCSWMM which uses Stormwater Management Model (SWMM) as its basic engine has been used in this study for the sewer hydraulic modelling. PCSWMM (CHI, 2016) has been selected because EPA SWMM is a widely used platform to investigate sewer overflows (Colwell and Tackett, 2015; Autixier et al., 2014; Rossman., 2010). PCSWMM is used to simulate sewer flows and compute surcharge and overflow through manholes. It also provides hydrographs at each surcharged manhole including duration and surcharge depth, which can be used to assess the hydraulic performance of the existing sewer system (Bennis et al., 2003; Hsu et al., 2000).

The Sanitary Sewer Overflow Analysis and Planning (SSOAP) Toolbox (Vallabhaneni and Camp, 2007) has been selected to estimate RDII parameters. The SSOAP toolbox is a relatively new public-domain tool designed by the U.S. Environmental Protection Agency (USEPA). The toolbox performs rainfall and flow data analysis to identify dry weather flow (DWF) and wet weather flow (WWF). Then, the software applies the synthetic unit hydrograph method (SUH) to estimate the RDII parameters (Vallabhaneni et al., 2008). This procedure is recommended in the literature as accurate and the industry standard methodology to quantify RDII parameters (Karuppasamy and Inoue, 2012; Mikalson, 2011; Muleta and Boulos, 2008; Loehlein et al., 2005). These RDII parameters can be incorporated as input into PCSWMM for sewer hydraulic analysis.

3.2.2 Data collection

Data required for the hydraulic performance analysis are rainfall, measured sewer flow at point of interest and physical sewer system network geometry and layout. The SSOAP toolbox requires rainfall and measured sewer flow to estimate RDII flows. The sewer system data are needed for the hydraulic modelling to assess the hydraulic performance of the required network.

3.2.3 Auditing of households stormwater plumbing connections

The connections of properties in the study area should be checked (if possible) for any cross-connections between the stormwater plumbing and existing sewer pipes. This is because the inflow component of the RDII depends on the stormwater that enters the sewer network through direct connections and it plays a significant role in generating peak RDII flows.

3.2.4 RDII parameters estimation

The SSOAP toolbox identifies the unit hydrograph parameters or the RDII parameters (R, T, K) through a systematic analysis of measured sewer flow data and rainfall data. The software applies the popular synthetic unit hydrograph method to estimate RDII parameters. This method contains three unit hydrographs and each unit hydrograph is characterized by a set of R, T and K parameters. These parameters are defined as follows (Muleta and Boulos, 2008; Karuppasamy and Inoue, 2012)

- R parameter represents the fraction of rainfall volume that enters the sanitary sewer system as RDII during a rainfall event. The sum of three unit hydrograph parameters (R1, R2, and R3) allocates total R value for the rainfall event.

- T parameter is the time from the onset of rainfall to the peak of the RDII hydrograph in hours.

- K parameter represents the ratio of time to recession of the RDII hydrograph to the time to peak.

Fig. 3.2 (adopted from Vallabhaneni and Camp, 2007) shows the RTK parameters and summation of the three unit hydrographs.

Here, the three triangles indicate fast, medium and slow responses of RDII flows. The fast response of the RDII hydrograph represents rainfall derived inflow, whereas medium response defines rainfall derived inflow and infiltration and the slow response denotes the delayed response of rainfall derived infiltration. This analysis is undertaken in two steps.

In the first step, the measured wastewater flow is analysed to generate the RDII hydrograph which is then used (in the second step) to identify the RDII parameters (R, T, K). These two steps are described in detail in Chapter 4.

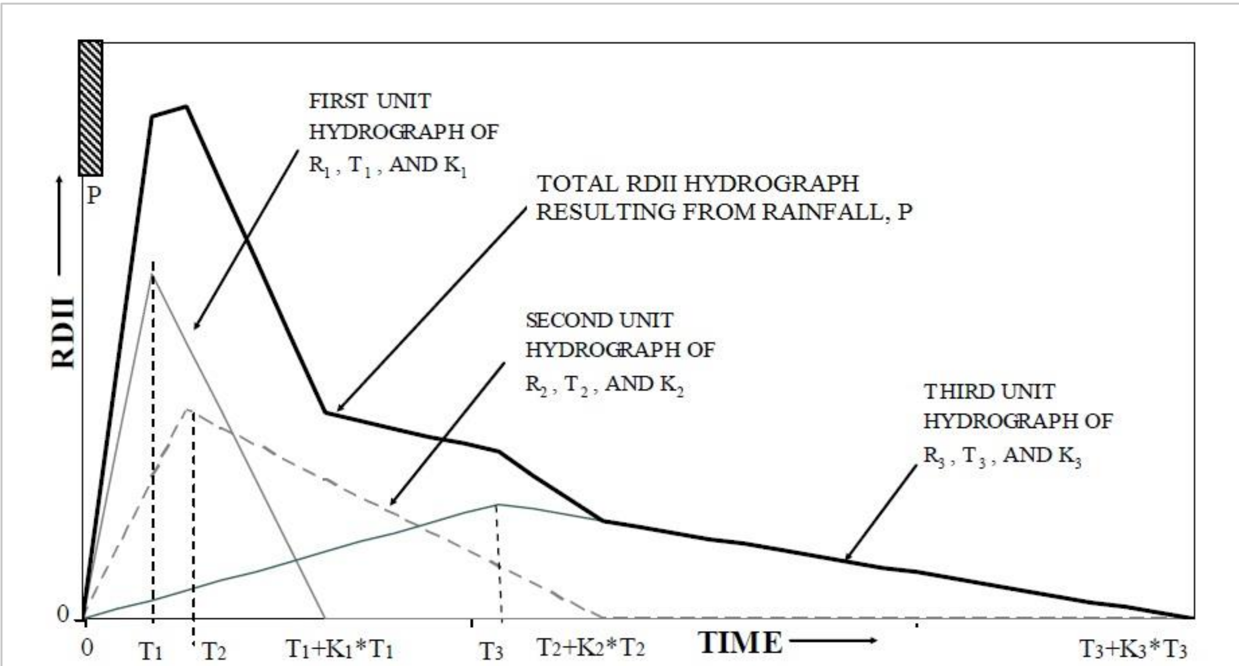

Figure 3.2. R, T and K parameters and summation of the three unit hydrographs (adopted from Vallabhaneni and Camp, 2007).

3.2.5 Developing a hydraulic model of the sewer network

The rainfall, flow, sewer system data and RDII parameters are as input to the sewer hydraulic model. After assigning the input data to the model, the next step is to divide the total catchment area into the sub-catchment areas to prepare a hydrologic model for a sanitary sewer system and divert wastewater flows to various loading point of sewer system. Geographic Information System (GIS) has been used to delineate the sewer-shed area into small sub-catchments leading to the flow monitoring locations (manholes). Here, each sub-catchment area is associated with a flow loading point (i.e., manhole) in the developed sewer network model.

3.2.6 Model calibration and validation

The successful application of a model depends on how well it is calibrated. During calibration, model parameters are adjusted within their physically meaningful ranges until the simulated flow matches the observed flow. Validation is then conducted to confirm that the calibrated parameters provide a consistent prediction. Model calibration and validation can be conducted using peak rainfall events from the available data.

3.2.7 Sewer system performance evaluation

After calibration and validation, the next step is to perform a continuous simulation of the sewer network for a given duration. This simulation will help to assess the impacts of intense rainfall events on the performance of the sewer network in terms of SSOs and surcharges. In addition, a set of performance indicators needs to be developed for evaluating the performance of the sewer system. The performance indicators that could be selected can include number of overflowing manholes, number of overflow hours, total overflow volume, peak overflow rates, manhole with maximum volume of overflow, manhole with maximum hours flooded, number of surcharging manholes and manhole with maximum hours surcharged. Based on the local conditions, other performance indicators can also be selected. Earlier studies such as Engelhard et al., (2008) and Berggren (2008) have recommended performance indicators as assessment tools because simulation results do not adequately reflect the sewer network performance. Moreover, these indicators can also be used for describing and comparing the possible impacts of intense rainfall on the sewer system. Mitigation strategies are proposed based on the results of these performance indicators. If the system experiences SSO and surcharges, the next step is to develop mitigation strategies for controlling these problems.

3.3 Define Strategies for Sanitary Sewer Overflow Mitigation

In the second part of the developed framework, mitigation strategies are proposed and assessed. These strategies are selected based on their sustainability. WSUD strategies have shown to be are sustainable, innovative and cost-effective approaches for controlling stormwater runoff. These strategies can also reduce sewer overflow volume and peak overflow rate by capturing excess stormwater runoff entering the sewer network during intense rainfall events (Sharma et al., 2016; Liao et al., 2015; Llopart-Mascaró et al., 2015; Lucas and Sample, 2015; Shamsi, 2012; Montalto et al., 2007). The steps involved in the modelling of WSUD strategies for reducing sewer overflows are presented below.

3.3.1 Selection of suitable WSUD approaches

WSUD approaches are selected based on literature review and discussion with local water professionals. There are different types of sustainable WSUD strategies available in the literature, namely rainwater tanks, rain gardens, bio-retention cells, permeable pavements, green roofs, infiltration trenches and vegetative swales (Myers et al., 2014). These strategies if adopted alone or in combination can reduce urban flooding and SSOs by controlling the excess stormwater runoff that enters the sewer system.

3.3.2 Develop model with WSUD strategies and perform sewer modelling

After selecting suitable WSUD strategies, the next step is to develop model with selected WSUD strategies. As stated earlier, PCSWMM has been selected for the hydraulic modelling of the sewer network. It can be used to model common types of WSUD strategies. These WSUD strategies are programmed into SWMM algorithms and can be accessed through simple dialog boxes (Rossman, 2010). Various parameters need to be added as input for developing the model. After developing model with the strategies (alone and in combination), then perform a continuous simulation of the sewer network for a given duration.

3.3.3 Evaluation of hydraulic performance with strategies

After completing the detailed hydraulic modelling of WSUD approaches, the next step to analyse the performance of the sewer network and to compare the results with the base case (no WSUD strategies). Evaluation of hydraulic performance helps to assess the improvement in the performance of the network. If the proposed strategies fail to provide satisfactory results, then modify or generate new strategies.

3.4 Summary

This chapter provides a brief description of a generalized framework proposed in this study to assess the hydraulic performance of a sanitary sewer network during intense rainfall events and to develop sustainable mitigation strategies for controlling rainfall induced sewer overflows. Such a framework can be applied to existing urban areas to improve the sustainability of the sewer network. Hence, the generalised framework developed in this chapter has been applied for a case study residential catchment in Melbourne, Australia, which is described in Chapter 4 and Chapter 5 respectively. Chapter 4 presents the detailed modelling results for the first part of the framework, whereas Chapter 5 presents the detailed outcomes of modelling for the second part of the framework. The next chapter is followed by a description of the case study area. The first part of framework is then applied to this selected sewershed area for evaluating the hydraulic performance under intense rainfall events. This includes RDII analysis and conducting hydraulic modelling of a sewer system for performance assessment. The performance of the sewer network is assessed based on various indicators that were used to quantify the SSOs and manhole surcharges. The second part of the framework includes a detailed modelling of selected WSUD approaches for controlling the existing SSO and surcharge problems (Chapter 5).

Chapter 4: Impacts of Intense Rainfall on Sanitary Sewer Network

4.1 Case Study

The selected case study area is a residential catchment in Glenroy (a suburb in northern Melbourne), which comes under the jurisdiction of Yarra Valley Water, a water retailer servicing 1.6 million people. The study area is located within the larger Pascoe Vale catchment and consists mainly of residential households.. The total contributing sewershed area of the catchment is 6.88km^2 and there are 3,750 households connected to the network. The length of the main sewer pipe is approximately 3.2 km and the pipe material is concrete. A flow meter was temporarily installed in the sewer network at a downstream manhole (named GLN8) (Yarra Valley Water sewer network identification number) for flow data collection from the whole catchment. The location of the study area and the layout of Glenroy sewer network indicating the main sewer pipe and the downstream flowmeter location (GLN8) are shown in Figure 4.1.

At the GLN8 manhole, flow data was measured at a six-minute time-step during the period November–December of 2010. Flow data was measured continuously at the GLN8 manhole using an area velocity flowmeter, Sigma 940 flow meter. This flow meter is widely used for long-term flow monitoring and sanitary sewer evaluation studies. It has high accuracy levels of data measurement in low-flow, full-pipe or reversed-flow conditions (Hach Sigma 940, 2007).

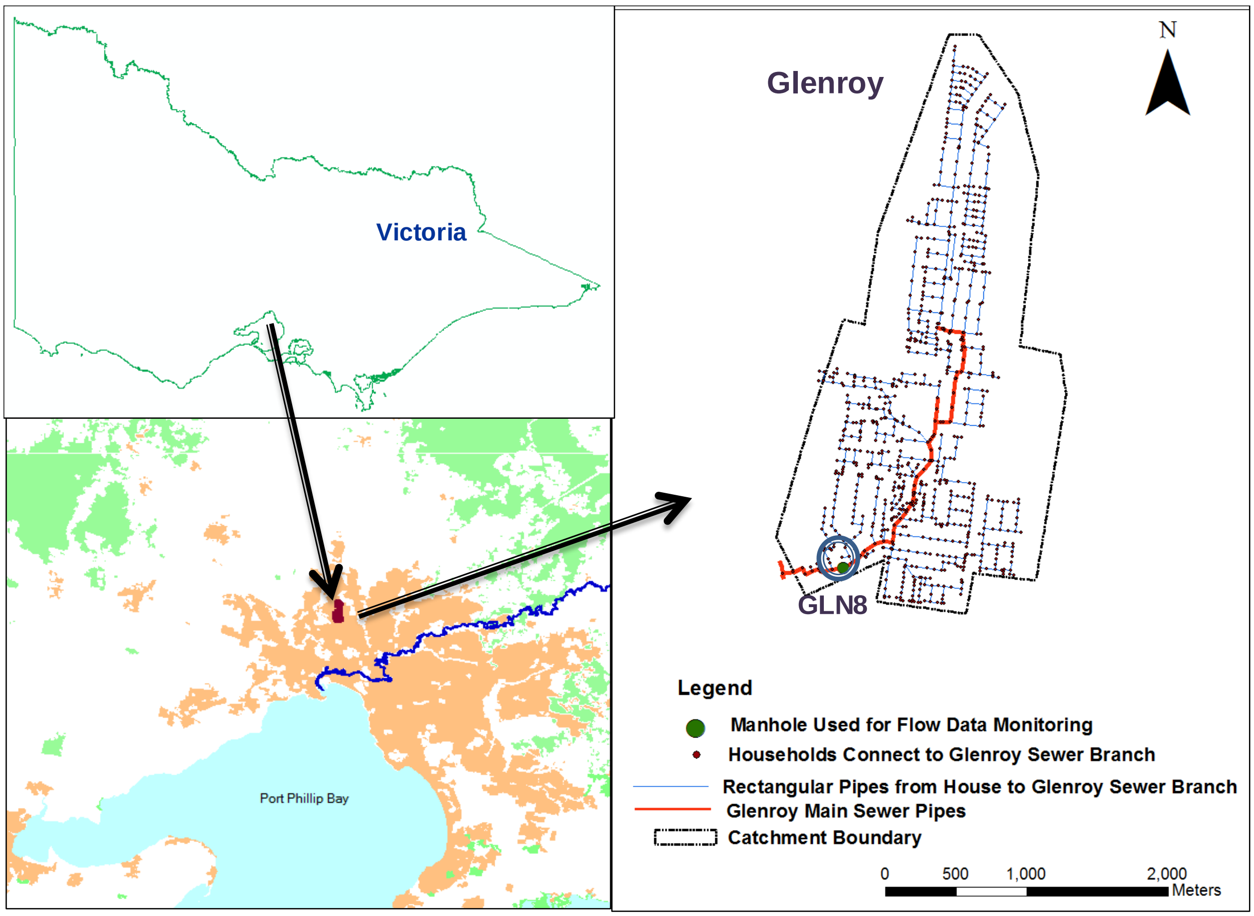

Figure 4.1. Location of the Glenroy sewershed in Melbourne.

Six-minute time-step rainfall data were obtained from the Bureau of Meteorology, Australia, for a nearby rain gauge station (Essendon Airport Melbourne; station no 086038). The total rainfall in 2010 at this station was 681.2 mm. There were several intense rainfall events in 2010 and a number of them occurred during the months of November and December. Few events occurred on 8 December 2010 (23.4 mm of rainfall occurred on that day) with 9.8 mm falling in an interval of 18 min (from 9.48 a.m. to 10.06 a.m.) with an Average Recurrence Interval (ARI) of about 1.5 years. The ARIs were calculated using the 2016 Intensity–Frequency–Duration (IFD) design rainfalls that are provided by the Bureau of Meteorology for use in conjunction with the 2016 edition of Australian Rainfall and Runoff (ARR) (BoM, 2016). This intense rainfall over a short duration had caused the downstream manhole GLN8 to overflow (which was observed during the flow measurements).

4.2 Sewer System Hydraulic Performance Assessment

The first part of the proposed framework (presented in Chapter 3) has been systematically implemented for this case study sewershed area. This includes the detailed hydraulic modelling to analyse the performance of the case study sewer network during a wet and a dry year. The chosen wet year was 2010, which was identified by the Australian Bureau of Meteorology (BoM) as the third wettest year on record for Australia (BoM Australia, 2015). For the case study area, the total annual rainfall in 2010 was 681 mm, which was well above the annual mean rainfall of 588 mm. The detailed modelling of the hydraulic performance analysis is described in the following subsections.

4.2.1 Data collection

Climate, topography, and hydrology data are needed for this hydraulic performance assessment. The preliminary data required for the hydraulic modelling are rainfall data, measured sewer flow data and physical sewer system network geometry data. The data used for this study were collected from various Australian government authorities. Rainfall time series data of 6-min resolution were obtained from the Bureau of Meteorology for a nearby rain gauge station. The GIS data for the catchment and the sewer network data were collected from Yarra Valley Water. All datasets used for the sewer performance analysis are presented in Table 4.1.

The investigation of stormwater plumbing connections at the properties were acquired from discussions with the water utility (YVW) and were not performed for this study due to the budgetary and time constraints. However, the utility is planning to conduct auditing of household stormwater connections in some other catchment.

Table 4.1. Input data for model development.

Data type	Specifications	Data Source
Meteorological Data	Rainfall time series data of 6-minutes resolution (from January 1 to December 31) for the wet year (2010) and for the dry year (2008)	Bureau of Meteorology (Essendon Airport Melbourne; station no 086038)
Observed Flow Data	Sewer flow data of 6 minutes interval at the downstream manhole (GLN8) during wet weather period (24 November-16 December, 2010)	Yarra Valley Water
Sewer Network Data	Sewer pipes, junctions, outlets with manhole and pipe properties	Yarra Valley Water
Subcatchment	GIS layers of catchment area and subcatchment properties	Yarra Valley Water
Impervious Area Map	Vector polygons	Yarra Valley Water

4.2.2 RDII analysis

To quantify RDII flow, the SSOAP toolbox determines the RDII hydrograph parameters (R, T, K) through unit hydrograph curve fitting analysis. As stated in Chapter 3, this analysis is undertaken in two steps. These two steps of the analysis in the following sub-sections were described by Vallabhaneni and Camp (2007).

4.2.2.1 Hydrograph decomposition

The SSOAP toolbox applies the Hydrograph Decomposition method to decompose the measured wastewater flows into Dry Weather Flow (DWF) and RDII components. A description of the steps involved in the hydrograph decomposition are given below.

- Step 1 - Dry Weather Flow analysis: The DWF analysis determines the typical characteristics of DWF diurnal patterns in each flow meter location.
- Step 2 - Wet Weather Flow analysis: After computing the average DWF hydrograph, the model performs wet weather flow (WWF) analysis to calculate the RDII hydrograph for each rainfall event. WWF is the combination of DWF (identified in Step 1 above) and RDII. The latter component for each rainfall event is calculated by deducting the average DWF hydrograph from the total WWF hydrograph (which is the measured flow). This difference is the rainfall induced RDII volume entering the sewer network during the rainfall event.

Figure 4.2 shows the RDII hydrograph determined by subtracting the DWF from the measured wastewater flows. The figure also indicates the two significant rainfall events selected for the RDII analysis at the GLN8 flow meter.

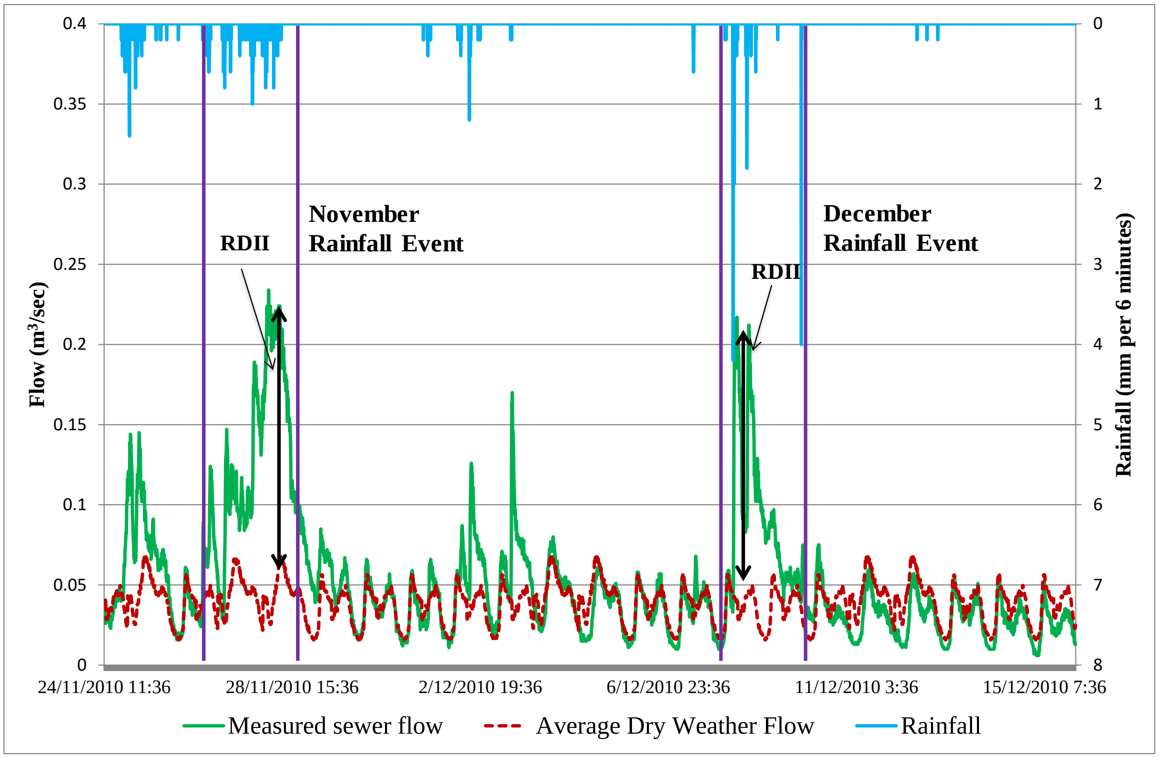

Figure 4.2. The RDII hydrograph determined using the Hydrograph Decomposition method.

4.2.2.2 Triangular unit hydrograph curve fitting

The SSOAP software defines the triangular unit hydrograph (UH) curve fitting method to simulate the RDII. This method is based on fitting three triangular unit hydrographs to an actual RDII hydrograph derived (in the previous step) from the flow data. As stated earlier, each hydrograph has three parameters of R, T, K. Total R value is the sum of three unit hydrograph parameters (R1, R2, and R3) and it denotes the percentage of rainfall volume which enters the sewer network in terms of RDII. A high value of R1 suggests that the inflow is a major component of RDII. If the proportion of R2 and R3 dominants in the total R, it denotes that infiltration is a major component of RDII (Karuppasamy and Inoue, 2012). These three unit hydrographs also describe fast, medium and slow response of RDII.

Figure 4.3 shows estimation of the R, T, K parameters based on the triangular unit hydrograph method (using the SSOAP software).

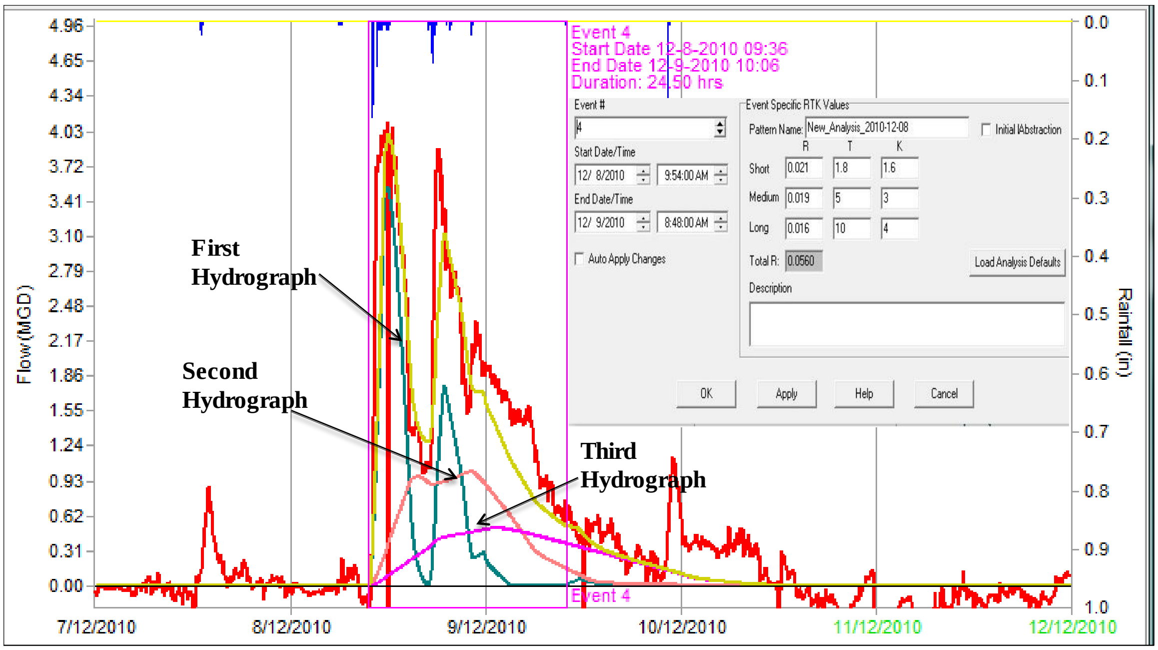

Figure 4.3. Estimation of the R, T, K parameters based on the triangular unit hydrograph method in the SSOAP toolbox.

The first hydrograph (Figure 4.3) indicates the fast response of the rainfall derived inflow component. The second hydrograph represents a medium response component of the RDII hydrograph, which contains both rainfall derived infiltration and inflow. The third hydrograph denotes rainfall derived infiltration and represents the slow response of the RDII.

In the past, the calibration of R, T and K parameters has been done manually using a tedious and inaccurate trial and error process and manually adjusted (Bennett, 1999). Automatic calibration using a genetic algorithm has also been recently used to calibrate the R, T and

K parameters (Muleta and Boulos, 2008). The SSOAP software simplifies the calibration procedure by using a built-in graphical tool (shown in Figure 4.3) that provides a visual-based automatic calibration approach. The graphical tool helps to identify the best combination of the R, T, and K values for each of the three triangular unit hydrographs (Nasrin et al., 2013). The visual curve fitting is accomplished by iteration and it continues until the simulated RDII flows closely match the RDII flows generated by decomposing the measured flow.

The model uses a FPS (foot–pound–second) unit system and the same parameters and their units are depicted in Figure 4.3. Table 4.2 presents the three sets of calibrated R, T and K parameters (nine parameters in total) for the two intense rainfall events during the period November–December 2010 at the GLN8 flow meter location.

Table 4.2. R, T and K parameters at GLN8 manhole for the November and December intense rainfall events.

Downstream manhole, GLN8		R	T	K
November rainfall event	Short (R1, T1, K1)	0.021	1.5	1.6
	Medium (R2,T2, K2)	0.028	3	3
	Long (R3,T3, K3)	0.035	4	8
	Total R = (R1+R2+R3)	0.084	-	-
December rainfall event	Short (R1, T1, K1)	0.021	1.8	1.6
	Medium (R2,T2, K2)	0.019	5	3
	Long (R3,T3, K3)	0.016	10	4
	Total R = (R1+R2+R3)	0.0560	-	-

RDII responses within the sanitary sewer network vary from event to event because different rainfall events could lead to different RDII responses throughout the year. Therefore, the ideal condition for determining the characteristics of the relationship between rainfall and RDII responses needs accurate long-term (a year or more) rainfall and measured sewer flow data. Total R, which is the fraction of rainfall volume entering the network as RDII, depends on many factors including total event rainfall, event rainfall intensity, ground water infiltration and antecedent moisture conditions. Hence, total R is the main parameter causing the variability of the RDII responses. The other parameters, T and K, are not changing significantly between rainfall events since they depend on the geometry and sewer system layout. These parameter values are only used for the iterative process in the triangular unit hydrograph curve fitting method. For continuous simulation of the hydraulic routing, monthly varying R, T, K parameters were required for evaluating the different RDII responses throughout the year. Therefore, we sought to establish a multi-variable linear regression equation to predict the remaining months (January–October) RDII responses based on the limited data (measured during November–December, 2010). It is recommended in the literature to apply multi linear regression to predict better responses of RDII when long-term data is unavailable (Vallabhaneni and Camp, 2007; Loehlein et al., 2005).

In the multi-variable linear regression analysis, the dependent variable is total R and the selected independent variables are total event rainfall, peak rainfall intensity and 7 days rainfall total before the event. For developing the multi-variable linear regression model, six significant rainfall events from the wet months of November and December were considered for calibration (including one large rainfall event of November, 2010). The coefficient of determination (R2) was used to identify the best regression equation and a satisfactory value of 0.99 was obtained for the calibration. The regression model was validated for two significant rainfall events in December 2010 (including one large rainfall event). The coefficient of determination (R2) for the validation was 0.96, which indicates a good predictive capability of the regression equation. The equation (with regression coefficients) developed from this multi-variable linear regression analysis is as follow.

Total R = 0.0244+ [total event rainfall × (0.095)] + [peak rainfall intensity × (-0.1465)] + [7 days total rainfall before the event × (-0.00622)]

After calculating the monthly varied total R value, the fast, medium and slow RDII responses (R1, R2 and R3) were determined using RDII analysis tool of the SSOAP software over the analysis period total months. These calibrated R, T and K parameters will now be used as inputs to the sewer hydraulic model for continuous simulation.

4.2.3 Sewer hydraulic modelling

This task involves the simulation of the sewer model using PCSWMM for assessing the performance of the existing sewer network.

4.2.3.1 Model development

In this part of the study, GIS has been applied to delineate the study area into 38 sub-catchments with areas varying from 2 ha to 101 ha based on the overall layout of the sewer network. The sewer modelling has been undertaken using the dynamic wave routing approach (since it is the most accurate approach to route the sewer flows), which considers unsteady, gradually varied flow and solves the complete one-dimensional Saint Venant equations (Leandro et al., 2009; Schmitt et al., 2004; Mark et al., 2004). A set of model parameters have been used in the study to assess the changing behaviour of the model results with these selected parameters. As PCSWMM provides a complete GIS system for data pre-processing and model parameterization, most sewer system data (sewershed and hydraulic data) can be extracted from the GIS layers. Some model parameters have a high degree of spatial variability; hence, their values are identified either from empirical relationships or are established through model calibration (Sun et al., 2012). The identified model parameters are: Percentage of imperviousness (*Imp)*, Catchment slope (*S*), Manning's n for overland flow (n_{Imp} and n_{Per}), Manning's n for closed conduit (n_{Conduit}), Depression storage for impervious and pervious areas (DS_{Imp} and DS_{Per}), and the Infiltration parameters. The parameters calibrated, the calibration procedure and the parameter values are discussed in the next sub-section.

4.2.3.2 Model calibration and validation

Model calibration and validation have been conducted using two intense rainfall events during the wet months of November and December 2010. The sewer model has been calibrated by using the measured sewer flow at the GLN8 flow meter location for the November rainfall event, 27–28 November. Then the calibrated model has been validated for another intense rainfall event that occurred from 8 to 9 December. The time series plots of the calibration and validation rainfall events are shown in Figure 5. The selected intense rainfall event for November was from 12:06 am on 27th November till 11:54 pm on 28th

November and for December was from 12:06 am on 8th December till11:54 pm on 9th December. In PCSWMM, calibration is done by using the Sensitivity Radio Tuning Calibration (SRTC) tool (CHIWater Support, 2014), which was adopted for this study.

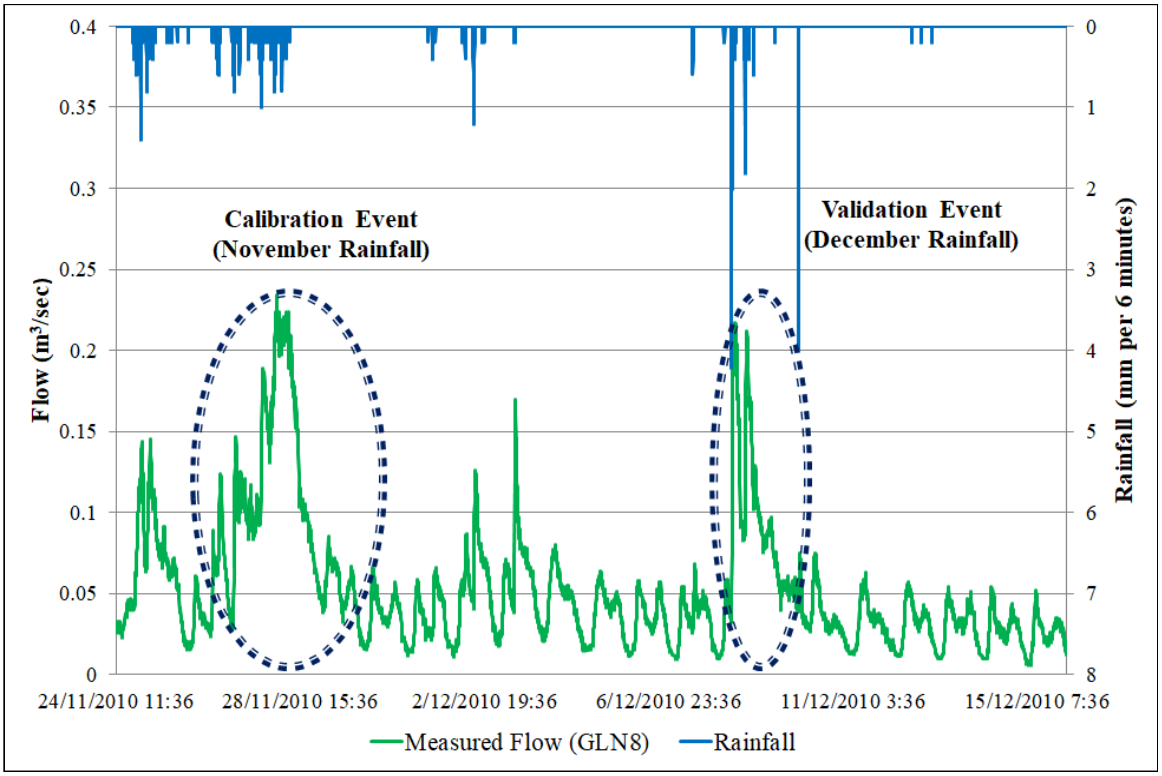

Figure 4.4. Selected rainfall events used for the calibration and validation of the hydraulic model.

However, the automatic calibration is also popular in rainfall-runoff modelling to estimate the best combination of model parameters (Barco et al., 2008; Muttil and Jayawardena, 2008). Especially, the population-evolution-based Genetic algorithm (GA) has been extensively used for evaluating the optimal values of model parameters (Jin et al., 2011; Fang et al., 2007; Liong et al., 1995). As the SRTC tool provided acceptable accuracy for calibration and validation (discussed in the next sub-section), automatic calibration tools like the GA were not employed in this study. The different model parameters and their calibrated values are shown in Table 4.3, which also presents typical values for the model parameters obtained from literature or calculated from the catchment data.

Table 4.3. Model parameters and their values.

Parameters	Parameter values calculated from catchment data	Calibrated value
Percentage of imperviousness (*Imp*)	51%	60%
Catchment Slope (*S*)	0.21	Actual data available
Parameters	Typical parameter values obtained from literature	Calibrated values
Manning's n for overland flow over impervious area (n_{Imp})	0.01-0.015 (Sun et al., 2012)	0.01
Manning's n for overland flow over pervious area (n_{Per})	0.02-0.8 for pervious surfaces (Sun et al., 2012)	0.1
Manning's n for closed conduits (n_{Conduit})	0.011 – 0.015 to 0.017 (Chow et al.,1988, Rossman, 2010)	0.0125
Depression storage for impervious areas (DS_{Imp})	0.03-0.25 (Tsihrintzis and Hamid 1998, Sun et al., 2012)	0.05
Depression storage for pervious areas (DS_{Per})	0.25- 0.5 for pervious surfaces (Tsihrintzis and Hamid, 1998, Sun et al., 2012)	0.25
Infiltration parameters (Green-Ampt)	SWMM Manual (Rossman, 2010) Suction Head: 316 mm Conductivity (K): 0.6 mm/hr Initial Deficit: 0.21	Not calibrated for this study

Other than the parameters presented in Table 4.3, the unit hydrograph parameters (R, T and K) are also important parameters to be calibrated. These parameters have already been calibrated in the RDII analysis presented earlier using the SSOAP toolbox.

4.2.3.3 Calibration/validation results

As mentioned earlier, the model was calibrated for the November rainfall event and validated for the December event by comparing the simulated and measured flows at the GLN8 manhole. The fitness evaluation of the calibration and validation hydrographs has been undertaken based on the Nash-Sutcliffe coefficient of efficiency (E_{NS}), which is a commonly used goodness-of-fit measure in hydrological models. The E_{NS} is suitable for reflecting the trends and overall fit of a flow hydrograph (Coutu et al., 2012). The E_{NS} is represented by Equation (4.1) (taken from Nash and Sutcliffe, 1970), where Q_{obs} and Q_{simu} refer to the measured sewer flows and model simulated flows, respectively and N defines the number of observations.

$$E_{NS} = 1 - \left(\frac{\sum_{i=1}^{N} \left| Q_{obs}^{i} - Q_{simu}^{i} \right|^2}{\sum_{i=1}^{N} \left| Q_{obs}^{i} - \overline{Q_{obs}^{i}} \right|^2} \right) \quad (4.1)$$

If the value of the E_{NS} is close to 1, it denotes that the prediction of the model simulated flow is as accurate as the measured flow. A comparison of the measured and simulated hydrograph for the calibration period is presented in Figure 4.5, whereas the validation hydrographs are presented in Figure 4. 6. The E_{NS} values are also indicated in both these figures.

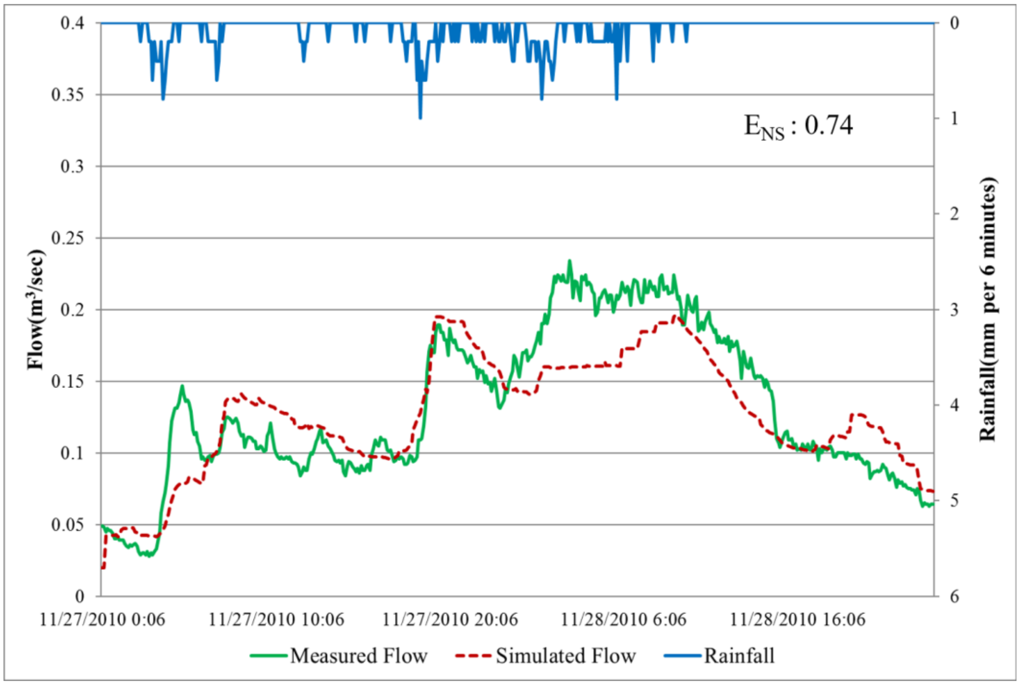

Figure 4.5. Hydrographs for the calibration period (November rainfall event) at GLN8 manhole.

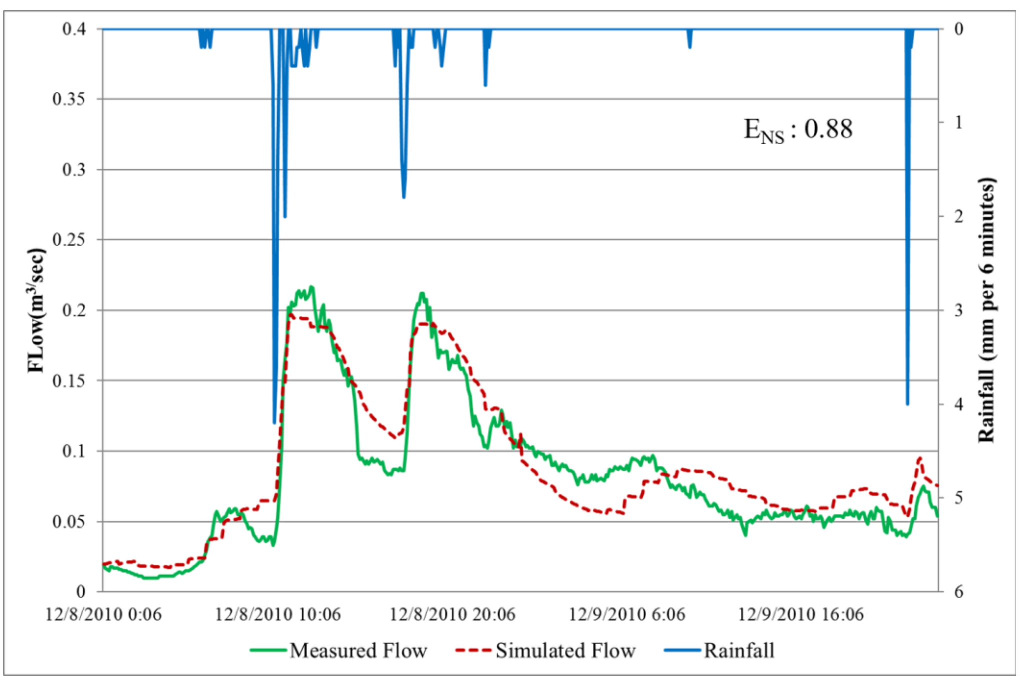

Figure 4.6. Hydrographs for the validation period (December rainfall event) at GLN8 manhole.

From Figure 4.5, it can be seen that the calibration results are satisfactory with an E_{NS} coefficient of 0.74 and, although the model is not able to accurately capture some of the peak flows. An error of 13% was observed between the measured and simulated values over the calibration period, whereas the error over the validation period was 5%. Good performance is also achieved for the validation results, as can be seen in Figure 4.6. The validation results again indicate an accurate match between the measured and simulated hydrographs and a much better simulation of the peak flows (when compared to that in the calibration).

4.2.4 Sewer network performance evaluation

As stated earlier, a set of performance indicators were developed that would help in assessing the hydraulic performance of the sewer network under intense rainfall events. The performance indicators were compared for two years, one of which (2010) was a wet year in Melbourne with many intense rainfall events, whereas the other (2008) was a relatively dry year (Nasrin et al.,2017). According to the Bureau of Meteorology, if the daily rainfall exceeds 10 mm, the day is known to be a heavy precipitation day (BoM, Australia. 2016). The year 2010 had 19 heavy precipitation days whereas 2008 had nine such days. Moreover, the total annual rainfall for 2010 was 681.2 mm, which exceeds the long-term average of 587.9 mm and was accordingly denoted as a wet year (Walsh et al., 2014). However, the total annual rainfall for 2008 was 369.8 mm, which was well below the long-term average (587.9 mm) and defined as a dry year. A continuous simulation of the sewer model was undertaken individually for both years using a six-minute time-step.

Figure 4.7 presents a hydraulic profile plot that indicates the manholes which had SSOs and surcharges due to the most intense rainfall event in 2010, which occurred on 30 October. On that day, the total daily rainfall was 55.2 mm, which was the most for a day in 2010. A rainfall of 29.2 mm occurred from 1:00 p.m. to 3.30 p.m., which corresponds to an ARI of 5 years. As a consequence of the intense rainfall over a short duration, 11 manholes had sewer overflows and 53 manholes had sewer surcharges (out of a total of 57 manholes in the network). Figure 4.7 shows the location of the overflowing manholes, which in turn can be used by the water authorities to implement sewer overflow mitigation strategies.

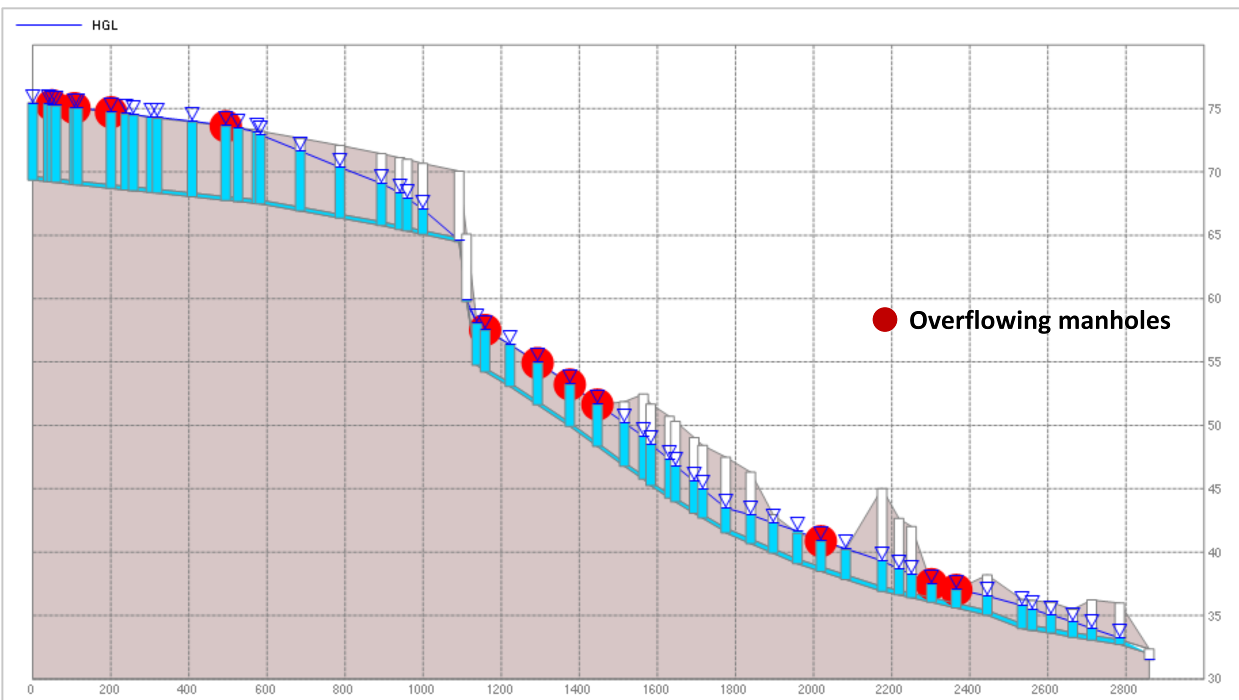

Figure 4.7. Hydraulic profile plot indicating the locations of SSOs and surcharges that occurred at 3:15 pm on October 30, 2010 (units for x- and y-axis are metres).

The performance indicators used in this study to assess the performance of the sewer network in terms of SSOs and sewer surcharges and their values for 2008 and 2010 are presented in Table 4.4.

Table 4.4. Sewer network performance indicators for a dry (2008) and a wet (2010) year.

Type	Performance Indicators	Year	
		2008	2010
Manhole Overflows	Number of overflowing manholes	6 manholes	11 manholes
	Number of overflow hours	Manholes overflowed 48 hours	Manholes overflowed 264 hours
	Total overflow volume	3.42 ML	23 ML
	Peak overflow rates	$0.14\ m^3/sec$	$0.4\ m^3/sec$
	Manhole with maximum volume of overflow	GLN8A (1.8 ML)	GLN8A (8.8 ML)
	Manhole with maximum hours flooded	GLN8 (17.89 hours)	GLN8 (79.70 hours)
Manhole Surcharges	Number of surcharging manholes	52 manholes	53 manholes
	Manhole with maximum hours surcharged	GLN6 (80.94 hours)	GLN6 (174.39 hours)

The performance indicators presented in Table 4.4 for the wet year (2010) showed that 11 manholes had sewer overflows, whereas 53 had sewer surcharges. There were several intense rainfall events in 2010 and sewer overflows occurred on 11 days in that year. However, for the dry year (2008), there was an intense rainfall event on 13 December (14 mm rainfall in two hours) and it caused six manholes to overflow and 52 manholes to surcharge. It can also be seen that 23 ML of sewage overflowed in 2010. (wet year) but only 3.42 ML in 2008 (dry year), which could have serious aesthetic, environmental and health issues for the selected residential catchment.

4.3 Summary

The hydraulic performance assessment describes and compares the impact of short duration intense rainfall events on an existing sewer network. In this analysis, we sought to establish a set of sewer network performance indicators which will help to evaluate the current situation of the existing sewer system in terms of its hydraulic performance. Since the sewer network in this case study area was quite old, RDII would be a major problem, in addition to pipe collapse, debris build-up and blockages. These in turn will lead to SSOs and surcharges. Comparing the sewer network's performance for the representative wet and dry years (aforementioned results) showed that the wet year with frequent intense rainfall events had five times the number of sewer overflow hours than the dry year. The sewer overflow volume on the other hand was 23 ML for the wet year as compared to 3.42 ML for the dry year. These overflows release many harmful contaminants and spread pollutants, nutrients, and hazardous substances into the suburban creeks and waterways. This, in turn, causes various harmful impacts, both on human health and the environment. Another point to note is that an increase in rainfall intensity or extended surcharge conditions will eventually lead to more of the surcharging manholes to overflow. The existing network fails to cope with the intense rainfall events and as a consequence, the wet year indicates a significant amount of overflow volume, more overflowing days and a large number of critical locations where overflows and surcharges occurred frequently. The results (presented in Table 4.4) seem to indicate that the existing system in the case study catchment will fail to cope with the increased rainfall intensities. Therefore, the second part of the framework proposes sustainable WSUD approaches for mitigating these negative impacts of sewer overflows. Chapter 5 presents detailed hydraulic modelling with selected WSUD strategies for reducing rainfall induced sewer overflows for the same sewershed area.

Chapter 5: WSUD Strategies for Mitigating SSOs

5.1 Introduction

This chapter presents the application of the second part of the developed framework. As stated in Chapter 3, the second part of the developed framework demonstrates SSOs mitigation strategies based on sustainable Water Sensitive Urban Design (WSUD) approaches. WSUD is a holistic approach to the planning and design of urban development that aims to minimise negative impacts on the natural water cycle and protect the health of aquatic ecosystems. There has been an increasing trend of implementing WSUD approaches over the past decade for mitigating rainfall induced sewer overflows in combined sewers, however some examples are also available for the implementation of these approaches in mitigating sewer overflows in sanitary sewers (Molloy and Albert, 2008; The Milwaukee Metropolitan Sewerage District (MMSD), 2011)).

The hydraulic model of the case study sewer network, presented in Chapter 4, was used with selected WSUD strategies to investigate their effectiveness. Since the sewer network in this case study area is quite old, RDII and consequent SSOs are expected to be major problems. The hydraulic analysis indicated that the network failed to cope with the intense rainfall events and as a consequence, the system experienced 23 ML of SSO volume in 2010. There were 11 manholes (out of 57 manholes in the 3.2km main network) that experienced overflows in the wet year 2010. Figure 4.2 presented in Chapter 4 shows significant rainfall events that took place in November and December of 2010, resulting in sewer overflows from the GLN8 manhole (which were observed during the flow measurements). The developed hydraulic model indicated that the GLN8 (Figure 4.1) manhole starts to overflow at a flow rate of 0.084 m^3/sec. Figure 4.2 also depicts the RDII flows into the sewer pipe, determined by subtracting the dry weather flow (DWF) from wet weather flows (WWF). This manhole (GLN8) is located in a reserved park area and the residents may not have come directly in contact with the overflowing sewage during the rainfall events. However, these significant amounts of sewage would have led to environmental issues.

Towards mitigating these negative impacts of SSOs, this chapter provides an outcome of a detailed hydraulic modelling by implementing two commonly used WSUD approaches, namely rainwater tanks and rain gardens for case study sewershed area. A continuous simulation of the hydraulic sewer model was again undertaken with rainwater tanks and rain gardens (individually and in combination) for the same year 2010. The outcomes of this hydraulic model quantify the benefits of implementing WSUD approaches in terms of minimising SSOs. The detailed modelling steps are described in the following sections.

5.2 Development of WSUD Strategies

PCSWMM (CHI, 2016) was selected for the hydraulic modelling. PCSWMM uses the US Environmental Protection Agency's stormwater management model (EPA SWMM), which can be used to model five common types of WSUD strategies. These strategies are programmed into SWMM algorithms and can be accessed through simple dialog boxes (Rossman, 2010). These five WSUD strategies are rainwater tanks, rain gardens/bio-retention cells, permeable pavements, infiltration trenches and vegetative swales. These WSUD strategies help in controlling the excess stormwater runoff that enters the sewer system and thus can reduce hazards like SSOs (Hansen, 2013; Shamsi, 2012; Perez et al., 2010; Kloss, 2008). Among these five WSUD strategies, this study has selected rainwater tanks and rain gardens/bio-retention cells to evaluate the reduction in SSOs. Rainwater tanks are one of the most widely used WSUD approaches in Australia for non-potable water supply with fit-for-purpose concept; however, in this study rainwater tanks are considered as an option for stormwater management only. It is usually placed beneath roof downspouts, which captures roof runoff and thus reduces surface stormwater runoff during a rainfall event (Rahman et al., 2012; Rossman, 2010). Rain gardens or bio-retention cells are also popular in Australia. Rain gardens act as shallow depression storages that contain vegetation layers over an engineered soil mixture. There is a gravel bed underneath the vegetation. These bio-retention cells are designed to provide storage and improve water quality by treating stormwater runoff in urban areas (Autixier et al., 2014).

5.3 Perform Sewer Hydraulic Modelling with WSUD Strategies

A detailed hydraulic modelling of the case study sewer network was conducted with rainwater tank and rain garden (individually and in combination) to analyse the performance of the existing sewer network during the year 2010. The hydraulic performance was assessed in terms of reduction in total annual SSO volumes (ML). The annual overflow volume is the total volume of sewage overflowing from the manholes throughout the year as a consequence of a large numbers of individual intense rainfall events. Earlier studies have recommended sewer overflow volume as an important indicator that would help in assessing the performance of the sewer network (Engelhard et al., 2008; Berggren, 2008). Also, two scenarios were considered with respect to the number of households that had rainwater tanks and rain garden installed, namely 100% (i.e. all households) and 50% households.

5.3.1 Modelling of rainwater tanks for SSO reduction

A continuous simulation of the sewer model was performed with different rainwater tank parameters (namely tank size, drain time and drain delay) to analyse the performance of the sewer network. Drain time is the time allowed to drain the rainwater tank, hence, the shorter the drain time, the larger the flow from the underdrain orifice. On the other hand, the parameter drain delay is the number of dry weather hours that must elapse after the rainfall event before the underdrain orifice is opened. When the drain delay is taken as zero, it represents a continuously draining rainwater tank as the rainwater flows into it. These parameters were assessed in terms of reduction in SSO volume. The rainwater tank parameters and model simulation results are described in the following sub-sections.

5.3.1.1 Characteristics of rainwater tanks

Table 5.1 presents the rainwater tank parameters used in PCSWMM for the WSUD modelling. The various rainwater tank parameters that were analysed included tank volume (in liters), drain time (T in hours) and the drain delay (in hours). Four different tank sizes (500, 1000, 1200 and 1500 L), four drain times (12, 24 and 36 and 48 hours) and four drain delay times (0, 12, 24 and 36 hours) were analysed.

In SWMM, flow through the underdrain from a rainwater tank is governed by the submerged orifice equation as shown in Eq. (5.1) (Walsh et al., 2014). C represents the drain coefficient, D is the height of stored water, H_d is the drain offset and *n* is the drain exponent.

$$q = C\ (D - H_d\ )^n \tag{5.1}$$

The drain coefficient (*C*) can be estimated by integrating Eq. (5.1) and is presented in Eq. (5.2). As can be seen, *C* is a function of two variables, namely the drain time (*T*) and the depth (*D*) of the stored water. Drain time (*T*) is the time required to drain out a depth *D* of stored water in the rainwater tank.

$$C = \frac{2(D^{0.5})}{T} \tag{5.2}$$

In SWMM, *D* is in units of inches and *T* is in hours (Walsh et al., 2014). Therefore, for calculating *C* using the values of *D* in mm (as provided in Table 5.1), Eq. (5.2) was modified to that presented in Eq. (5.3). The values of *C* presented in Table 5.1 are calculated using Eq. (5.3) with the values of *D* and *T* in mm and hours respectively (as presented in Table 5.1).

$$C = \frac{2[25.4(D)]^{0.5}}{T} \tag{5.3}$$

Table 5.1. Rainwater tank parameters used in PCSWMM.

Volume (L)		500L	1000L	1200L	1500L
Height (*D*) (mm)		500	900	900	1200
Drain Coefficient (*C*) ($mm^{0.5}/hr$)	T=36 Hours	C= 6.26	C=8.39	C=8.39	C=9.69
	T=24 Hours	C= 9.39	C=12.59	C=12.59	C=14.54
	T=12 Hours	C=18.78	C=25.19	C=25.19	C=29.09
Drain Exponent (*n*)		0.5	0.5	0.5	0.5
Drain Offset Height (H_d)		0	0	0	0
Drain Delay (hours)		0, 12, 24	0, 12, 24	0, 12, 24	0, 12, 24
Impervious area Treated (%)		24%	24%	24%	24%

Since drain times (T) have an impact on the underdrain flow, four different drain times (of 12, 24, 36 and 48 hours) were used in this study. The drain times were proposed to not exceed 48 hours due to the risk of mosquito breeding. The standard range of drain time for storage-based WSUD strategies is 24 to 48 hours (Walsh et al., 2014). The drain exponent has been taken as 0.5, assuming the underdrain acts like an orifice (Walsh et al., 2014; Rossman, 2010). Drain offset has been taken as zero, assuming that the orifice is at the bottom of the rainwater tank.

The stormwater from the outlet pipe (as well as the overflows from the tanks) was routed to pervious areas. The parameter impervious area treated (%) in Table 5.1 represents roof impervious area, whose runoff is captured in the rainwater tanks. The total impervious area of this sewershed was 4.128 km^2 and the total roof area was estimated as 0.99 km^2, which represents 24% of the total impervious area reported in Table 5.1. As stated earlier, the total area of the sewershed was 6.88 km^2 (total pervious and impervious). The total roof area of 0.99 km^2 was calculated based on an average roof size of 264 m^2 estimated for the 3,750 households in the sewershed.

5.3.1.2 Model simulation results and discussions

The outcomes of the sewer modelling with the different rainwater tank parameters during 2010 are presented in Figures 5.1 and 5.2. For the results presented in both these figures, 100% of households were considered having rainwater tanks and a comparison with the base case (which is the current condition without implementing rainwater tanks) is presented. In these figures, the reduction in overflow volume when compared to the base case (in %) is also shown on the secondary x-axis. As mentioned earlier, the overflow volume for the base case was 23 ML.

Figure 5.1 presents the annual overflow volume for the four different drain times (T). In these model runs, the rainwater tanks are assumed to be continuously flowing (i.e. with a drain delay of 0 hours). As seen in this figure, the drain time of 48 hours resulted in the maximum reductions in sewer overflow when compared to the base case. For the 500L, 1000L, 1200L and 1500L rainwater tanks, the reduction in SSO volumes were by 13.8%, 23.6%, 24.1% and 27.2% respectively (for the drain time of 48 hours). In the continuous draining process, the outlet orifice pipe is assumed to be open during rainfall events and the stormwater is continuously routed to the pervious area. Therefore, rainwater tanks lead to a reduction in surface runoff since it slowly releases the stored water through the outlet orifice pipe. Thus, for a fixed tank size, the increase in drain time increases the SSO volume reduction. Hence, in our case, the 1500L rainwater tank with a drain time of 48 hours provided the maximum SSO volume reduction. Thus, larger the size of the tank higher will be reduction in SSOs. However, the increase in SSO reduction is marginal in comparison to increase in tank size for tank capacities above 1000L.

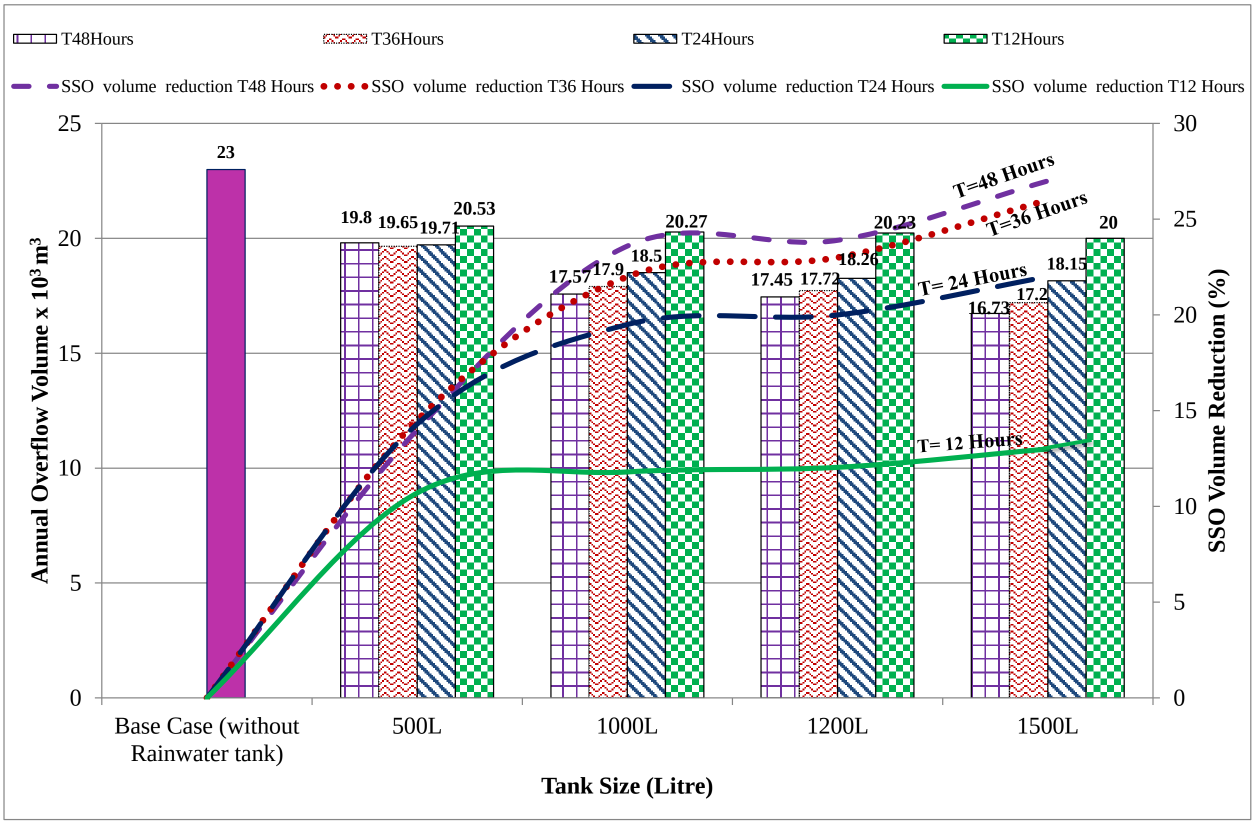

Figure 5.1. Annual SSO volume reduction for different tank sizes and drain times.

Figure 5.2 presents the annual overflow volume for drain delays of 0, 12, 24 and 36 hours. In these model runs, the drain time (T) was kept as 48 hours since it had resulted in the maximum reduction in sewer overflows. It can be seen from this figure that the 1500L rainwater tank with drain delay of 12 hours resulted in the maximum reduction in sewer overflows (when compared to the base case overflow volume of 23 ML). In the drain delay options, the outlet orifice pipe is assumed to be closed during the rainfall events and drain delay is the time that must elapse after the storm before the outlet orifice is opened. The 1500L tank with a drain delay of 12 hours resulted in a 33% reduction in SSO volume, whereas the same tank with continuous draining resulted in a 27% reduction. The results also indicate that shorter drain delay time reduce more SSO volumes than longer drain delay times.

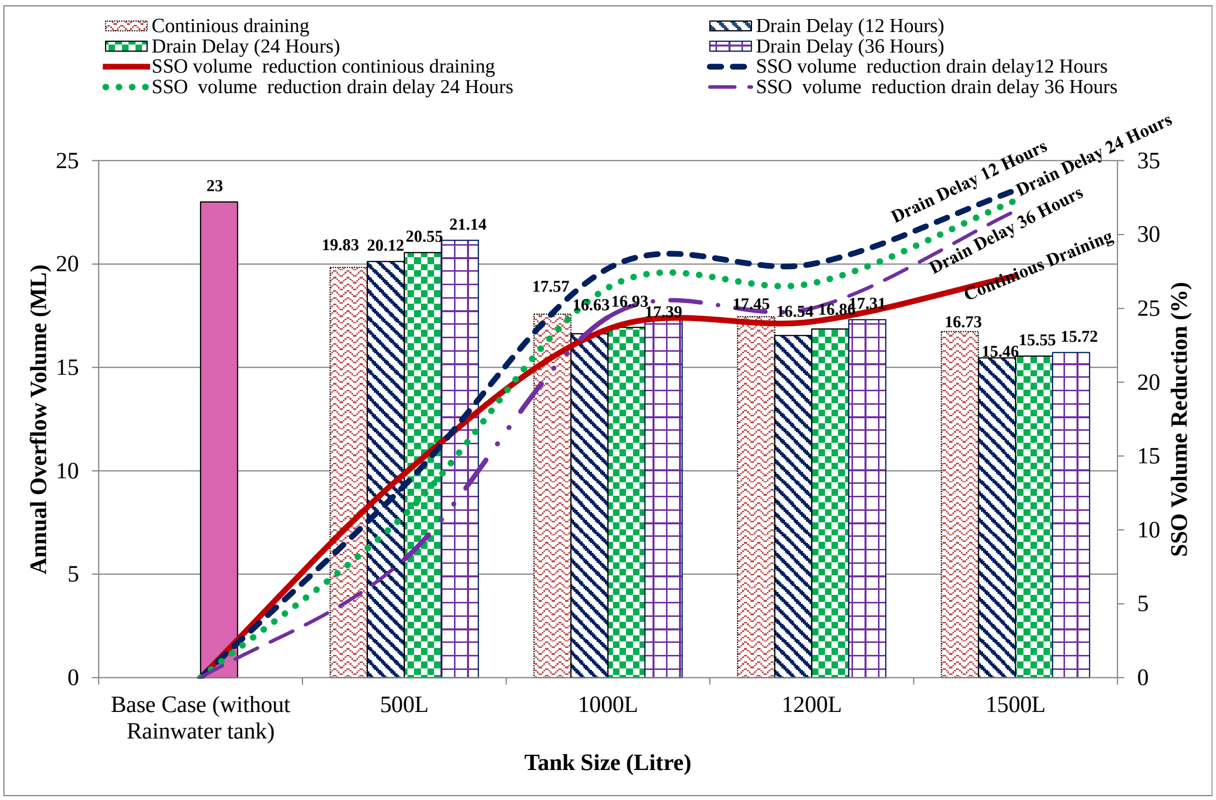

Figure 5.2. Annual SSO volume reduction for different tank sizes and drain delays.

Hence, for the 1000L tank and 1200L tank, 12 hours drain delay resulted in a reduction of SSO volume by 27% and 28% respectively. On the other hand, the 1000L tank with 36 hours drain delay resulted in a 24% reduction and 1200L tank with 36 hours drain delay resulted in a 25% reduction.

For longer drain delay options such as with drain delay of 36 hours, the outlet orifice pipes were opened after 36 hours of a storm event. The stored stormwater is then gradually released to the pervious area (with a maximum drain time of 48 hours). The results indicate that for the drain time of 48 hours, the shorter drain delay times (not more than 24 hours) need to be chosen. Otherwise, the tank would not be able to store enough roof runoff from the next event and hence would lead to more surface runoff.

On the other hand, for the smallest tank size of 500L, the reduction in SSO volume was much less when compared to that in the 1000L-1500L tanks. This is obviously because the 500L tank collects less volume of stormwater when comparing to the larger tanks. Also, for the 500L tank, the reduction of SSO volume with reduction in drain delay times was marginal. The continuous draining 500L tank (i.e. with no drain delay) reduced the SSO volume by 13.8%, whereas the tank with 12, 24 and 36 hours drain delay reduced the volume by 13%, 11% and 8% respectively. This is because by choosing a high drain delay, for example of 36 hours, the orifice pipe will open after 36 hours of a storm event and then, the stored storm water is gradually released (drain time of 48 hours) to the pervious area. Thus, there is a high possibility that when the next storm arrives, the tank might already be full (or close to full) and the pervious area may be saturated, which does not lead to a reduction in surface runoff. Therefore, the 500L tank with 36 hours drain delay resulted in the least reduction in SSO volume (of 8% when compared to the base case).

In the results presented above, it was assumed that the rainwater tanks are installed in all the households. Further model runs were conducted with rainwater tanks installed in only 50% of the households. The drain time was kept as 48 hours and the drain delay was taken as 12 hours. For the 500L, 1000L, 1200L and 1500L rainwater tanks, the reduction in SSO volumes were 3%, 13%, 16% and 21% respectively when compared to the base case.

5.3.2 Modelling of rain gardens for SSO reduction

A hydraulic modelling was undertaken for this case study with rain gardens. The analysis was performed with rain garden of 10 m^2 area, again for the wet year of 2010. Only one size of rain garden was selected for the hydraulic modelling and the results were assessed in terms of reduction in SSO volume. The number of households was taken as 100% (all the households) and 50% with raingardens. The rain garden parameters and the simulation results are presented in the following sub-sections.

5.3.2.1 Characteristics of rain gardens

There are four types of components in PCSWMM for bio-retention cell or rain garden modelling: surface layer, engineered soil layer (filter media), gravel storage layer, and an optional underdrain system. Figure 5.3 shows a typical bio-retention cell/ rain garden layout in PCSWMM. The underdrain orifice is located nearby the storage layer. The storage layer usually captures some amount of stormwater, which then eventually infiltrates into the native soil (Rossman, 2010). If there is an underdrain system in bio-retention, then some amount of stormwater from the storage layer will be conveyed through the underdrain orifice to the conventional stormwater drain.

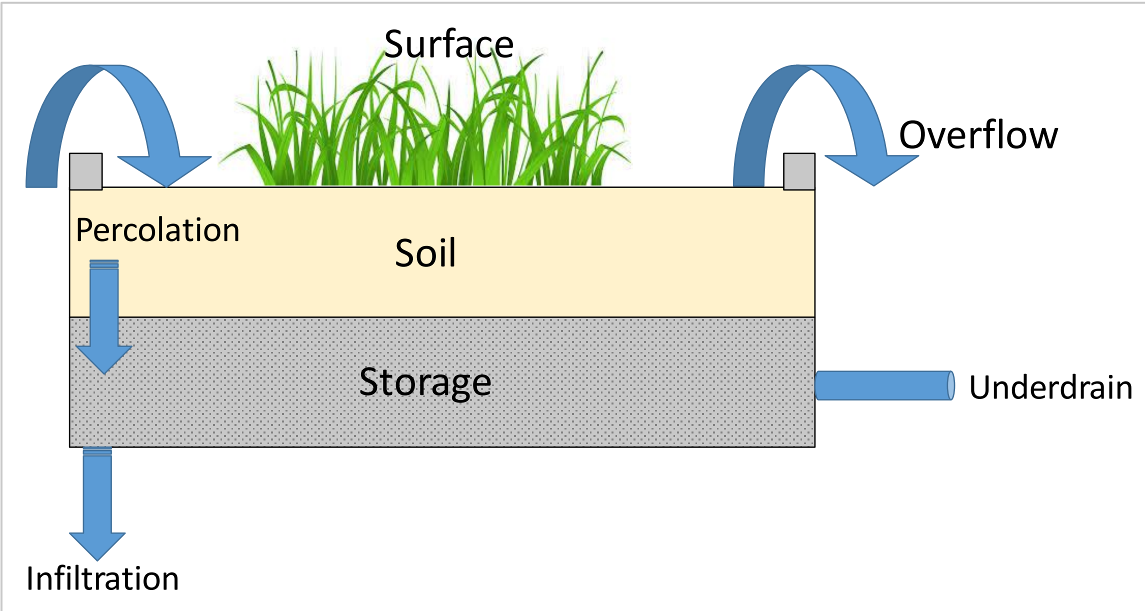

Figure 5.3. A typical rain garden layout in PCSWMM.

However, the underdrain component was not considered for rain garden modelling in this study. It is to be noted that, there were no stormwater pipes in the system where the underdrain orifice of the rain garden could convey the stormwater. The hydraulic model was based on only considering sewer network. When the capacity of the rain garden is exceeded, the overflows from the rain garden is routed to the pervious areas. The rain garden parameters used in PCSWMM for this WSUD modelling are provided in Table 5.2. The values of various rain garden parameters were not varied in this modelling to assess the reduction in SSOs. In the future studies, detailed modelling with various sizes of rain gardens along with different rain garden parameters could be analysed to assess the reduction in sewer overflows.

Table 5.2. Rain garden parameters used in PCSWMM.

Surface Layer		
Storage depth (mm)	125	Typical value 100-300 mm (Rossman, 2010)
Vegetation volume fraction	0	
Surface roughness (n Manning)	0	
Surface slope (%)	0	
Engineered Soil Layer		
Thickness (mm)	850	Typical value range 450 to 900 mm
Porosity (volume fraction)	0.4	Typical value for a sandy soil (Rossman, 2010)
Field capacity (volume fraction)	0.062	
Wilting point (volume fraction)	0.024	
Conductivity (mm/h)	150	
Conductivity Slope	5	
Sunction head (mm)	1.93	
Storage layer		
Height (mm)	250	Typical gravel layer 150 to 450 mm (Rossman, 2010)
Void ratio (Voids/solids)	0.7	Typical value 0.5 to 0.75 for gravel bed (Rossman, 2010)
Conductivity (mm/h)	0.6	Saturated hydraulic conductivity of the subcatchment used in Green-Ampt Infiltration method
Clogging factor	0	
Under drain		
Drain coefficient	0	
Drain exponent	0	Under drain is not considered
Drain offset height (mm)	0	
Impervious area treated (%)		
9%		

The parameter impervious area treated (%) in Table 5.2 represents driveway and pavement impervious areas, whose surface runoff was collected in the rain gardens. The total impervious area of this sewershed was 4.128 km^2 and the paved surface was estimated as 0.37 km^2, which represents 9% of the total impervious area (used in the modelling). The paved surface represents 5.4% of the total area of 6.88 km^2. This paved surface does not include road surfaces and only represents the household driveways whose surface runoff will be captured by the rain garden. The total paved area of 0.37 km^2 was calculated based on an average paved area size of 98 m^2 for the 3,750 households in the sewershed. The road area was estimated as 1.18 km^2, which represents 28.5% of the total impervious area (4.128 km^2) and 17.1% of the total area (6.88 km^2).

5.3.2.2 Model simulation results and discussions

After implementing 10 m^2 rain garden in 100% of the households, the result showed that SSO volume was reduced by 11% (when compared to the base case overflow volume of 23 ML). When 10 m^2 rain garden was applied to 50% of the households, the result showed that the SSO volume was reduced by 5.2%. It can be seen that the rain garden resulted in limited reduction in SSO volume. This is because rain gardens captured a small percentage of runoff from only the paved areas. As indicated earlier, the overflows from rain garden was considered to be routed to the pervious areas.

5.3.3 Modelling of rainwater tanks and rain gardens for SSO reduction

A much larger reduction in SSO volumes could be expected when a combination of WSUD strategies (such as rain gardens in conjunction with rainwater tanks) were implemented.

Implementing of rainwater tanks along with rain gardens can capture more stormwater runoff from impervious areas and thus it can be expected to provide a higher reduction in SSO volume (when compared to the base case). Hence, hydraulic modelling was undertaken for this case study with a combination of rainwater tanks and rain gardens for the same year of 2010.

The rainwater tank size was kept as 1500L with a drain delay of 12 hours, since it had resulted in the maximum reduction in SSO volume (of 33%). The rain garden was kept as 10 m^2 which had resulted a SSO volume reduction of 11%. A continuous simulation was conducted with 1500L rainwater tank and 10 m^2 rain garden for the year 2010. The parameter impervious area treated (%) was used as 33%, which included 24% for rainwater tanks (100% of roof impervious runoff connected to rainwater tanks) and paved impervious runoff (9%) connected to rain gardens.

Another point to note is that the overflow and under drain flow of the rainwater tank has been routed to the pervious area of the sewershed (and not considered to be routed to the rain garden). The overflows from the rain garden have also been routed to the pervious areas.

5.3.3.1 Model simulation results and discussions

Two scenarios were considered for this combination of modelling. Firstly, the number of households was taken as 100% (all the households) that had installed 1500L rainwater tanks and 10 m^2 rain gardens. The hydraulic modelling was undertaken for the year 2010 and the result indicated a reduction in SSO volume by 45%, when compared to the base case overflow volume of 23 ML. Further model run was conducted by considering 50% of the total households having both 1500L rainwater tanks and 10 m^2 rain gardens. The analysis showed that SSO volume was reduced by 30% (when compared to the base case). The hydraulic performance of the case study was assessed in terms of reduction in SSO volume. It is worth mentioning that the results in terms of percentage reductions in SSO volumes are specific to this catchment and would vary from catchment to catchment. Moreover, as indicated earlier, the presented results are for the year 2010 and would vary for a different time period (when parameters like size of the storms and recurrence interval would be different).

In the results presented above, 1500L rainwater tanks and 10 m^2 rain gardens (installed in 100% households) had the maximum SSO volume reduction (of 45%). On the other hand, 1500L rainwater tank (installed in 100% households) also had a large reduction in SSO volume (33%). Since rainwater tanks in conjunction with rain gardens and rainwater tanks (individually) provided good results, this study also sought to investigate other performance indicators other than SSO volume. Therefore, Table 5.3 presents a set of performance indicators to assess the hydraulic performance of the case study after implementing WSUD strategies (rainwater tank and rain garden). A comparison is made in this table with the base case for the wet year of 2010.

Table 5.3. Sewer network performance indicators for the wet year (2010) after implementing WSUD strategies.

Type	Performance Indicators	Wet Year 2010		
		Base Case (without implementing WSUD strategies)	1500L Rainwater tank (alone)	1500L Rainwater tank and 10 m^2 Rain garden (combination)
Manhole Overflows	Total overflow volume	23 ML	15.46 ML (33% reduction)	12.6 ML (45% Reduction)
	Peak overflow rates	0.4 m^3/sec	0.3 m^3/sec (25% reduction)	0.26 m^3/sec (35% reduction)
	Number of overflow hours	Manholes overflowed 264 hours	Manholes overflowed 200 hours (24% reduction)	Manholes overflowed 170 hours (36% reduction)
	Number of overflowing manholes	11 manholes	10 manholes	9 manholes
Manhole Surcharges	Manhole with maximum hours surcharged	GLN6 (174.39 h)	GLN6 (139.42 hours) (20% reduction)	GLN6 (123.96 hours) (31% reduction)

The performance indicators presented in Table 5.3 for the wet year (2010) showed that after implementing 1500L rainwater tanks in conjunction with 10 m^2 rain gardens, peak overflow rate was reduced by 35%, number of overflow hours were reduced by 36% and 9 manholes had sewer overflows. On the other hand, 1500L rainwater tank (alone) reduced peak overflow rates by 25%, number of overflow hours by 24% and 10 manholes had sewer overflows.

5.4 Summary

This chapter demonstrates the benefit of implementing common WSUD strategies for reducing rainfall induced SSOs. The hydraulic performance was assessed with rainwater tanks and rain gardens (individually and in combination) for the wet year 2010. Detailed hydraulic modelling was undertaken with different parameter values for rainwater tank capacities, drain times and drain delays. The analysis indicated that an increase in rainwater tank capacity linearly increases the reduction of the SSO volumes. Thus, 1500L tank reduced 33% when compared to the SSO volumes in the base case. The analysis also indicated that drain time has an impact on the reduction of overflow volumes, with higher drain times leading to a larger reduction in SSO volumes. A hydraulic modelling was also conducted with 10 m^2 of rain garden for the same year 2010. However, the rain garden modelling resulted in not a significant reduction in SSO volume (of 11% when compared to the base case). The analysis indicated that rainwater tanks by themselves can reduce the SSO volumes in the range of 20%-30% when compared to the base case. Hence, implementation of other strategies along with rainwater tanks is expected to provide a higher reduction in SSO volumes. Therefore, a detailed hydraulic modelling was undertaken for this case study with combination of 1500L rainwater tanks and 10 m^2 rain gardens for the same year 2010. The results showed that the combination of these two strategies provided the maximum reduction of the overflow volumes, peak overflow rates and overflow hours. The SSO volume was reduced by 45%, whereas peak overflow was reduced by 35% and overflows hours was reduced by 36%. In summary, such an analysis is expected to provide a decision support tool for urban managers and water professionals to consider the installation of combination of various WSUD strategies for sewer overflow mitigation during intense rainfall events. This in turn will be beneficial for the health of the community and the environment.

Chapter 6: Summary, Conclusions and Future Recommendations

6.1 Summary

Urban drainage systems are becoming more vulnerable to failure mainly due to non-stationary climate and rapid urbanisation (resulting in more impervious areas). As these systems are becoming less efficient, issues such as urban flooding and sanitary sewer overflows (SSOs) are increasing. This is in turn causing various detrimental impacts including that on human health and the environment. Therefore, the aim of this research was to mitigate the negative impacts of the intense rainfall events on the performance of the sanitary sewer network. Since stormwater management using water sensitive urban design (WSUD) is expected to be a part of future urban planning, this study explored the impact of the commonly used WSUD approaches as mitigation strategies for reducing the rainfall induced SSOs. The following tasks were undertaken to achieve the research aim.

- Literature review
- Developing a generalized framework for mitigating SSOs
- Evaluating sanitary sewer network performance during intense rainfall
- Investigating the impacts of WSUD strategies in mitigating SSOs through hydraulic modelling

A summary of and major conclusions from each of these tasks are presented below.

6.1.1 Literature review

This research provided a comprehensive literature review about the impacts of WSUD approaches as mitigation strategies for reducing rainfall induced sewer overflows. The literature review indicated that there has been an increase in the implementation of the WSUD approaches during the past decade for mitigating the negative impacts of rainfall induced sewer overflows. Moreover, this research had evaluated the common WSUD approaches and their various applications in sewer systems. This literature review also highlighted the enormous environmental and social benefits of various WSUD strategies. These include improving the water quality of receiving waterways, replacing potable water with alternate sources for non-consumptive uses, improving landscapes, aesthetics and biodiversity. These benefits have led to various water utilities and local councils adopting the use of WSUD strategies as part of existing and new developments. In spite of these benefits, there are only a handful of studies available in literature that quantify the benefits of various WSUD strategies in SSOs mitigation. In this context, this study demonstrated a detailed hydraulic modelling with selected WSUD strategies for the reduction in SSOs. Furthermore, the study also identified SWMM/PCSWMM as a widely applied modelling tool recommended in literature for hydraulic analysis as well as WSUD modelling to quantify their benefits in the sewer systems.

6.1.2 Developing a generalised framework for mitigating SSOs

A generalized framework was developed for mitigating the impacts of intense rainfall on the sanitary sewer performance. The developed framework firstly assessed the hydraulic performance of the sanitary sewer network during intense rainfall events. Then the framework introduced WSUD approaches as mitigation strategies for controlling rainfall induced SSOs. Such a framework can be applied to any existing sewerage system of urban development facing SSOs and surcharges as a consequence of intense rainfall events and urbanisation. Hence, the framework developed in this research will benefit the water industry as it will improve the sustainability of the sewer network.

6.1.3 Evaluating sanitary sewer network performance during intense rainfall

1. The framework had been applied to a case study area in Melbourne and assessed the hydraulic performance of the sewer system under intense rainfall events. The selected case study sewershed area was a residential catchment in Glenroy (a suburb in northern Melbourne). The study area was located within the larger Pascoe Vale catchment and consists mainly of residential households. The total contributing sewershed area was 6.88 km^2 and the length of the main concrete sewer pipe was approximately 3.2 km. The sewer network in this case study area was quite old. Hence, RDII was a major problem including pipe collapses, debris build-up and sewer blockages. These in turn lead to SSOs and surcharges. One downstream manhole, GLN8 (Figure 4.1), was used to measure sewer flow data at six minutes time-steps during the period 24 November-16 December, 2010 (Figure 4.2). Six minutes resolution rainfall data were obtained from the Bureau of Meteorology, Australia for a nearby rain gauge station (Essendon Airport Melbourne; station no 086038).

2. The detailed hydraulic modelling was performed to analyse the hydraulic performance of the case study sewer network during a wet and a dry year. The chosen wet year was

2010 with many intense rainfall events. The total annual rainfall for 2010 was 681.2 mm, whereas the relatively dry year of 2008 had 369.8 mm of annual rainfall. The performance assessment modelling firstly involved computing the RDII parameters (R, T. K), which was done using the Sanitary Sewer Overflow Analysis and Planning (SSOAP) toolbox developed by the USEPA. The estimated RDII parameters was then used as an input to a hydraulic sewer model (PCSWMM) for sewer hydraulic analysis. The sewer model was calibrated and validated using two significant rainfall events during the wet months of November and December, 2010. Good performance was achieved for the calibration and validation results. The Nash–Sutcliffe coefficient of efficiency (E_{NS}) was 0.74 and 13% error was observed between the measured and simulated values over the calibration period. On the other hand, an E_{NS} coefficient of 0.88 and an error of 5% was observed between the measured and simulated values over the validation period.

3. The developed sewer model was then used to assess the performance of the sewer network in terms of SSOs and surcharges using a set of performance indicators. The model was used to perform a continuous simulation, separately for the dry year (2008) and the wet (2010) and the performance indicators were calculated for these years. The hydraulic analysis undertaken in this study indicates that the network failed to cope with the intense rainfall events and as a consequence overflows and surcharges were very frequent, especially for the wet year. The system experienced 23 ML of SSO volume in 2010 which could have led to serious aesthetic, environmental and health

problems for this residential catchment. There were 11 manholes (out of 57 manholes in the 3.2 km main network) that experienced overflows during the wet year of 2010.

In summary, the hydraulic performance assessment would provide necessary information to the concerned water authorities in local councils for undertaking suitable measures for controlling the SSOs associated problems during intense rainfall events. This in turn will be beneficial for the health of the community and the environment.

6.1.4 Investigating the impacts of WSUD strategies in mitigating SSOs through hydraulic modelling

This task aimed to assess and quantify the benefits of implementing WSUD strategies for the reduction in SSOs for the case study sewer network. Among five common types of WSUD strategies available in PCSWMM, this study had chosen rainwater tank and bio-retention cell/ rain garden (which are popular in Australia) for the hydraulic performance analysis during the wet year (of 2010). It is to be noted that the hydraulic model of the case study sewer network was used as a basis for this modelling. A detailed hydraulic modelling was undertaken with different rainwater tank parameters (namely tank size, drain time and drain delay) to analyse the performance of the sewer network during the year 2010. The analysis indicated that the 1500L rainwater tank (installed in all the 3750 households), with a 48 hour drain time and 12 hours drain delays, resulted in 33% reduction in SSO volume, 25% reduction in peak overflows and 24% reduction in overflowing hours (when compared to the base case). A much larger reduction in sewer overflows could be expected when a combination of WSUD strategies (rainwater tanks and rain gardens) were implemented in the model. Hence, a continuous simulation was conducted with 1500L rainwater tank and rain garden of 10 m^2 area for the year 2010 implemented in all the houses. The results showed a significant reduction in sewer overflows including volumes, peak flows and overflowing days. The 1500L rainwater tank in conjunction with 10 m^2 rain garden (installed in all the 3750 households) reduced SSO volume by 45%, peak overflows by 35% and overflowing hours by 36%. The hydraulic performance assessment with WSUD strategies indicates that implementing small rainwater tanks and rain gardens would also be beneficial for reducing sewer overflows during intense rainfall events. Thus, the analysis provides information to wastewater systems managers to take informed decision for implementing these WSUD approaches as sewer overflow mitigation strategies. This analysis can also be applied under future climate change scenarios.

6.2 Conclusions

The key conclusions drawn from this study are as below:

- A framework for use of WSUD strategies in SSO context was not available in the current practice. This study identified the existing gaps and developed a generalised framework for mitigating the impacts of intense rainfall on the sanitary sewer network. This framework was successfully implemented for a case study residential catchment in Melbourne, Australia.

- The first part of the developed framework which included the hydraulic performance assessment developed a set of sewer network performance indicators. These indicators evaluated the current situation of the existing sewer system in terms of its hydraulic performance. The performance assessment modelling identified the most critical locations (manholes) where overflows and surcharges frequently occur as well as providing the overflow volumes. The application of the first part of framework found that the case study sewer system experienced 23 ML of sewer overflow volume in a wet year. In this regard, suitable measures could be taken to alleviate the problem.

- The second part of the developed framework, which included SSO mitigation strategies was successfully implemented using two popular WSUD strategies, namely rainwater tanks and rain gardens (individually and in combination). The application of the second part of framework found that the combination of these two strategies provided the maximum reduction of the overflow volumes, peak overflows and overflow hours (when compared to the base case). The hydraulic performance analysis indicated that 1500L rainwater tank (installed in all the 3750 households) could lead to a maximum reduction in SSO volume by 33% when compared to the base case overflow volume of 23 ML. A significant reduction in SSO volume up to a maximum of 45% was observed when 10 m^2 of rain garden was implemented (all the 3750 households) in conjunction with 1500L rainwater tank.

- Thus, this study indicates that WSUD strategies can be successfully implemented for mitigating rainfall induced SSOs.

6.3 Limitations and Recommendations for Future Study

This study has demonstrated a methodological framework and application of WSUD strategies to mitigate the impacts of intense rainfall on the sanitary network performance. The hydraulic performance assessment modelling has been constrained due to some limitations. The hydraulic performance assessment can be improved by addressing the following limitations and overcoming these in future studies.

- The data collected for sewer flows was limited to a short period of time, especially the measured sewer flow data, which was from 24 November-16 December, 2010. The data was collected for the wet weather period of 2010. For the hydraulic assessment of case study catchment, monthly RDII parameters (R, T, K) were required for evaluating the different RDII responses throughout the year. Due to limited data, this study established a multi-variable linear regression equation to predict the remaining month's (January–October) RDII responses for continuous simulation (presented in Chapter 4). It is recommended for future studies to monitor long-term sewer flow data, which will help to accurately estimate the monthly varying R, T, K parameters for assessing the actual RDII responses throughout the year.

- Auditing of household's stormwater plumbing connections should be checked to identify any cross-connections between the stormwater plumbing and existing sewer pipes. As per RDII analysis, the inflow component of RDII enters the sewer network through direct connections and it plays a significant role in generating peak RDII flows. However, the investigation of stormwater plumbing connections at the properties were acquired from the water utility company but were not undertaken for this study due to the budgetary and time constraints.

- The analysis presented in this study was for the wet year of 2010, which was one of the wettest years experienced in Melbourne since records began. A different time period would have different storm characteristics (like storm size) and different catchment characteristics (like dry weather flow). For future studies, the analysis needs to be further extended with climate data from relatively drier years (say, 2014 and 2015, when rainfall was 440 mm and 446 mm respectively) and recorded sewage flow data would be obtained for the same period in collaboration with the local water utility to understand SSOs under different rainfall conditions.

- This study aimed to quantify the impacts of implementing two commonly used WSUD approaches, namely rainwater tanks and rain gardens, in terms of minimising SSOs. It is to be noted that rain garden sizes were not varied in this modelling to assess the impact of sizes on SSOs reduction (due to time constraints). It is recommended to conduct a detailed hydraulic modelling with various sizes of rain gardens along with different rain garden parameters (similar to the analysis using rainwater tanks). The comparison between various performance indicators over different wet/dry years can be presented in future studies for the benefit of water professionals.

- For hydraulic performance assessment with rainwater tanks and raingardens, it was assumed that the stormwater from the outlet orifice pipe of the rainwater tank as well as the overflows from the tanks and raingardens were routed to pervious areas. There were no stormwater pipes in the system where the underdrain orifice can convey excess stormwater to conventional stormwater drains. Therefore, it is recommended for future studies to conduct WSUD modelling by considering the stormwater drainage network in conjunction with the sewer network.

- Rainwater tanks are one of the most widely used WSUD approaches in Australia for non-potable reuses in the households, thus reducing the use of freshwater resources. However, in this study, rainwater tanks were not considered as alternate sources for non-consumptive uses. Here, the rainwater tanks were considered only as an option for reducing excess stormwater runoff flowing into the sewer network as RDII during intense rainfall events. In future, it is recommended to undertake a detailed modelling considering rainwater tanks for non-potable household uses (along with reducing RDII into sewer networks).

- A detailed economic analysis of the proposed strategies would be required to develop any policy based on the presented investigation for SSO management. However, this study did not conduct detailed life-cycle cost analysis due to time constraints. It is recommended for future studies to undertake a detailed life-cycle cost analysis for evaluating the cost efficiency of the considered WSUD strategies.

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Appendix

Appendix A - Summarised details of the reviewed literature.

	Author and year	Country of application	Type of systems	Strategies used	Type of applications
1.	Abi Aad et al., 2009	USA	Combined Sewer	Rainwater tank Rain garden	Reduce stormwater runoff volume and thus reduce CSO Reduce peak runoff
2.	Autixier et al., 2014	Montreal, Québec, Canada	Combined Sewer	Rain garden	Reduce runoff volume Reduce CSO volume
3.	Boyd, 2011	Olympia, Washington, USA	Combined Sewer	Rainwater Tank	Reduce stormwater runoff volume Reduce CSO events
4.	Casal-Campos, et al., 2015	United Kingdom	Combined Sewer	• Green: Rain garden Permeable pavement • Grey: Separation of combined sewer Rehabilitation of existing sewer pipes Expansion of centralized storage Onsite treatment	Reduce CSO volume Reduce ammonia and dissolved oxygen concentration in the river
5.	Chaosakul et al., 2013	Thailand	Combined Sewer	Rainwater tank Bio-retention cell	Reduce CSO volume Reduce pollutants Reduce duration of surface flooding.

6.	Cahill, 2012	USA	Combined Sewer, Sanitary Sewer	Rainwater tank Rain Garden Green roof Permeable pavement	Reduce stormwater runoff volume and thus reduce CSOs Reduce CSO events Reduce pollutants and improve water quality in receiving water • Sanitary Sewer System Reduce stormwater runoff volume entering as inflow and thus reduce SSOs
7.	Coffman et al., 2000	Washington, D.C. area.	Combined Sewer	LID	Reducing CSO volume Reduce stormwater runoff volume Improve water quality
8.	Colwell and Tackett, 2015	Seattle, USA	Combined Sewer	Rain Garden	Reducing CSO volume
9.	De Sousa et al., 2012	Bronx, New York, USA	Combined Sewer	Bioretention/ Rain garden Cisterns/Rainwater tank Permeable pavement	Reduce CSO volume Reduce CSO events Reduce stormwater runoff volume Reduce CO_2 emissions
10.	Doug et al., 2005	Toronto, Canada	Combined Sewer	Green Roof	Reduce CSO volume Reduce CSO events Reduce pollutants Reduce stormwater runoff volume Reduce peak runoff Improve air quality Reduce direct energy use Reduce urban heat island effect
11.	Foster et al., 2011	USA	Combined Sewer	Green roof Permeable pavement	Reduce CSO volume Reduce CSO events

				Rainwater tank Rain garden Swale Urban trees Wetland	Reduce stormwater runoff volume Reduce peak runoff Reduce nutrient pollutants Reduce CO_2 emissions Reduce ambient temperature and urban heat island effect Reduce air pollutants Reduce energy use
12.	Fryd et al., 2012	Copenhagen, Denmark	Combined Sewer	Rain garden Swale Infiltration trench Green roof Soakaways retrofit	Reduce CSO events Reduce CSO volume Reduce stormwater runoff volume Reduce groundwater rise
13.	Gao and Sage, 2015	Onondaga County, Syracuse, New York, USA	Combined Sewer	Rainwater tank Urban tress Green roof	Reduce CSO volume Improve water quality
14.	Hartman, 2008	The Bronx, New York	Combined Sewer	Green Roof	Reduce stormwater runoff volume Reduce CSO volume Reduce CSO events Reduce overflow hours Reduce peak runoff
15.	Hansen, 2013	USA	Combined Sewer Sanitary Sewer	Green roof Permeable pavement Wetland Swale Urban trees	Reduce stormwater runoff volume and thus reduce CSO and SSO Reduce pollutant loads and improve water quality
16.	Keeley et al., 2013	Cleveland, OH and Milwaukee, WI.	Combined Sewer	Rainwater tank Rain garden Green roof Swale Permeable pavement Urban trees	Reduce stormwater runoff volume Reduce CSO events

17.	Kloss, 2008	USA	Combined Sewer Sanitary Sewer	Green Roof Permeable pavement Rainwater tank Rain garden Swales Wetland Urban forests	Reduce CSO volume Reduce SSO volume Reduce stormwater runoff volume Reduce pollutants Reduce energy consumption Reduce urban temperature Improve urban aesthetics Economic benefits by saving structural and energy cost.
18.	Kloss and Calarusse, 2006	Chicago, Illinois. Milwaukee, Wisconsin Pittsburgh, Pennsylvania Portland, Oregon Washington, D.C. Rouge River, Michigan Seattle Washington. Toronto, Ontario Vancouver, B.C.	Combined Sewer	Green roof, Rain garden Swales, Rainwater tank, Wetland Permeable pavement	Reduce stormwater runoff volume Reduce CSO volume Reduce peak overflow Reduce CSO events Reduce nutrients and pollutants
19.	Liao et al., 2015	Shanghai, China	Combined Sewer	▪ LID practice: Rainwater tank Bio-retention cell Infiltration trench ▪ Grey infrastructure practice:	Reduce annual CSO volume. Reduce peak flow Reduce pollutant loadings.

				Storage tank Pipe reconstruction	
20.	Li, 2008	Toronto, Canada	Combined Sewer	Green Roof	Reduce stormwater runoff volume Reduce CSO volume Reduce annual number of CSO Reduce pollutants
21.	Lucas and Sample, 2015	Richmond, Virginia, USA	Combined Sewer	▪ LID: Bio-retention cell Green roof Infiltration trench Permeable pavement ▪ Grey: Storage tank	Reduce volume of stormwater runoff volume Reduce CSO volume Reduce peak flow
22.	The Milwaukee Metropolitan Sewerage District (MMSD), 2011	Milwaukee, USA	Combined Sewer, Sanitary Sewer	Rain Garden Rainwater tank Permeable pavement	▪ Combined Sewer System: Reduce CSO volume. Reduce CSO events. Reduce pollutant such as total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP). ▪ Sanitary Sewer System: Reduce pollutant For Inflow/Infiltration Reduction ○ Reduce stormwater runoff

					○ Reduce peak runoff
23.	Montalto et al., 2007	Brooklyn, New York, USA.	Combined Sewer	Green roof Permeable pavement Wetland	Reduce stormwater runoff volume Reduce peak runoff Reduce CSO discharge
24.	Myers et al.,2004	Pennsylvania, USA	Combined Sewer	Green roof Permeable pavement Rainwater tank Infiltration trench Bio-retention cell Swale Wetland	Reduce stormwater runoff volume Reduce pollutant loads
25.	Nasrin et al., 2016	Glenroy, Victoria, Australia	Sanitary Sewer	Rainwater tank	Reduce annual SSO volume
26.	Patwardhan et al., 2005	USA	Combined Sewer	Bio-retention cell, Rainwater tank Permeable pavement Green roof	Reduce annual stormwater runoff volume Reduce peak flows Reduce CSO events
27.	Perez et al., 2010	Milwaukee, Wisconsin, USA	Combined Sewer Sanitary Sewer	Green Roof	Reduce stormwater runoff volume Reduce CSO volume Reduce SSO volume Reduce pollutants improve receiving water quality Reduce energy usage Reduce greenhouse gas emissions
28.	Pennino et al., 2016	Washington, DC, Montgomery County, MD, Baltimore County, MD	Combined Sewer	Rain garden Detention pond Swale Green roof	Reduce stormwater runoff volume Reduce CSO volume Reduce CSO events Reduce CSO hours Reduce peak runoff Reduce nutrients: TN, NO_3^-, TP, PO_4^{-3}

29.	Pitt and Voorhees, 2011	Kansas, Missouri, USA	Combined Sewer	Rain garden Rainwater tank	Reduce stormwater runoff volume Reduce CSO volume Reduce pollutant loads
30.	Podolsky, 2008	USA Canada	Combined Sewer	Rainwater tank Green roof Rain garden Permeable pavement	Reduce CSO volume Reduce CSO frequency Reduce stormwater runoff volume Reduce pollutant loads Reuse rainwater and reduce demand of potable water
31.	Ptomey, 2013	Kansas, USA	Combined Sewer	Rain garden Rainwater tank Permeable pavement Green roof Swale Infiltration trench Wetland Detention pond	Reduce CSO volume Reduce stormwater runoff volume
32.	Quigley and Brown, 2015	New Bern, NC Austin, TX St. Louis, MO Denver, CO Lawrenceville, GA Seattle, WA Saint Joseph, MO Newtown Square, PA Omaha, NE Lawrenceville, GA	Combined Sewer	Rainwater tank Bio-retention cell Permeable pavement Green roof Wetland	Reduce stormwater runoff volume Reduce CSO volume Improve water quality
33.	Raucher and Clements, 2010	Philadelphia, USA	Combined Sewer	Green roof Bio-retention cell Permeable pavement Urban trees	Reduce CSO events

34.	Roldin et al., 2012	Copenhagen, Denmark	Combined Sewer	Soakaways Retrofit	Reduce stormwater runoff volume Reduce CSO volume Reduce CSO events
35.	Sample et al.,2014	Virginia, Richmond, USA	Combined Sewer	Bio-retention cell Infiltration trench Permeable pavement Green roof	Reduce stormwater runoff volume Reduce peak runoff Reduce CSO volume
36.	Spatari and Montalto, 2011	New York City	Combined Sewer	Permeable pavement Urban trees	Reduce stormwater runoff volume Reduce CSO events Reduce energy consumption Reduce green house gas (GRC) emissions
37.	Semadeni-Davies et al., 2008	Helsingborg, Sweden	Combined Sewer	Rain garden Permeable pavement Green roof Detention pond	Reduce CSO volume Reduce number of CSO Reduce pollutants
38.	Shamsi, 2012	Southwestern Pennsylvania, USA	Combined Sewer	Rain garden	Reduce CSO volume Reduce peak overflow Reduce CSO events.
39.	Smullen et al., 2008	Philadelphia, USA	Combined Sewer	Green Roof Permeable pavement	Reduce CSO volume
40.	Stovin et al., 2013	London, UK	Combined Sewer	Green roof Soakaways Retrofit Permeable pavement	Reduce CSO volume Reduce CSO events
41.	Struck et al., 2010	Kansas City, Missouri, USA	Combined Sewer	Rainwater tank Rain garden Permeable pavement Swale	Reduce CSO volume Reduce stormwater runoff volume Reduce pollutant loads
42.	Tackett and Mills, 2010	Seattle, USA	Combined Sewer	Rain garden Rainwater tank Permeable pavement Green roof Urban trees	Reduce CSO volume Reduce stormwater runoff volume

43.	Vaes and Berlamont, 1999	Leuven, Belgium	Combined Sewer	Rainwater tank	Reduce CSO volume Reduce peak runoff
44.	Villarreal et al., 2004	Malmo, Sweden	Combined Sewer	Green roof Detention pond	Reduce stormwater runoff volume and thus reduced CSO Reduce peak runoff
45.	Wang et al., 2013	Northeast US watershed	Combined Sewer	• Green Bio-retention cell Green roof Permeable pavement • Gray Separate storm sewer system	Reduce greenhouse gas (GHG) emissions and improve water quality Reduce stormwater runoff volume Reduce CSO events
46.	Wise, 2008	USA	Combined Sewer	Rainwater tank Rain garden Swale Permeable pavement Urban tress	Reduce stormwater runoff volume Reduce CSO volume Reduce pollutants and improve water quality
47.	Wise et al., 2010	USA	Combined Sewer	Rainwater tank Rain garden Green roof Swale Wetland	Reduce stormwater runoff volume and thus reduce CSO Reduce pollutant loads Reduce urban heat island effects Reduce energy consumption Reduce CO_2 Reduce air pollution Reduce potable water use Reduce treatment costs