Impact of Water Management Practices in Residential Areas on Odour and Corrosion in Existing Sewer Networks

By

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ABSTRACT

Urban water systems in many developed cities are mostly stressed due to increased demand from population growth and an extended period of drought. The pressure on these systems has led to a number of adaptations such as the adoption of *Water Demand Management* and *Alternative Water Sources*. These adaptations are called Water Management Practices (WMP), which include *Water Demand Management*, *Rainwater Harvesting*, *Greywater Recycling*, *Sewer Mining*, and so on. These WMP lead to an increased uptake of residential rainwater, greywater or mixed wastewater for indoor and outdoor use and thus lead to water savings due to reduced imported water to study area. Besides the well-known benefits of water saving from adoption of WMP, many studies have found that the implementation of WMP reduces wastewater flow, hence causing sewer problems such as blockages, odour and corrosion. While the impact of WMP on sewer blockages has been investigated, the effects on sewer odour and corrosion are still largely unknown.

Therefore, using WMP scenario analysis, this study will investigate the impact of WMP on odour and corrosion problems in sewer networks. Some scenarios developed in this study are 1) *Base case*, 2) *Water Demand Management*, 3) *Greywater reuse/recycling*, 4) *Rainwater Harvesting*, 5) *Sewer Mining* and 6) Combined *Water Demand Management* and *Alternative Water Sources* called as *Sustainable Practice*. A residential area was selected since the adoption of WMP is mostly conducted in households. A model was developed to simulate urban wastewater systems associated with sewerage pipe networks. The results show that *Rainwater Harvesting* scenario of RH-B is a comparatively more effective scenario than other WMP in reducing potable water demand and causing less impact on sewer odour and corrosion. RH-B reduced the total imported water to study area by 38% and increased the hydrogen sulphide concentration in sewer pipe by 6%. For the worst impact, there were two scenarios that were classified as worst scenarios, they are scenario of Greywater Recycling of GR-BL and Sustainable Practice of WDM-GR. GR-BL only reduced the imported water by 15% while increased hydrogen sulphide concentration by 40%. On the other hand WDM-GR reduced the total imported water by 46%, while increased hydrogen sulphide concentration by 62%. Scaling up the number of households adopted WMP also increased the risk of sewer odour and corrosion.

DECLARATION

I, Ni Nyoman Nepi Marleni, declare that the PhD thesis entitled **'Impact of Water Management Practices in Residential Areas on Odour and Corrosion in Existing Sewer Networks'** is no more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, 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.

Signature [redacted]....

Ni Nyoman Nepi Marleni

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α	Confidence level
α_w	Temperature coefficient in water phase
α_{Sff}	Temperature coefficient for sulphide formation
αr	Temperature coefficient for reaeration
γ	Fraction of dissolved sulphide present as hydrogen sulphide
σ	Standard deviation
%I	Percentage of surface flow as inflow
A	Cross sectional area of flow (m^2)
A_f	Biofilm area (m^2)
c	Corrosion rate (mm/year)
COD	Chemical Oxygen Demand
CCTV	Closed-Circuit Television
d_m	Hydraulic mean depth (m)
EXF	Wastewater exfiltration
ExRate	Exfiltration rate
ENS	Nash Sutcliffe Coefficient
F	Froude number, $u/(g\ d_m)$
FOGs	Fat, Oil, Greases
g	Gravity force (m/s^2)
GR	*Greywater Recycling*
GR-BL	*Greywater Recycling* from Bahtroom & Laundry greywater
GR-B	*Greywater Recycling* from Bathroom greywater
GR-L	*Greywater Recycling* from Laundry greywater
HH	Household
h_L	Head loss (m)
H_2S	Hydrogen Sulphide gas
IWU	Indoor water usage
INF	Infiltration of stormwater into the wastewater system
ISI	Inflow
IRC	Infiltration recess constant
INFS	Infiltration store
IRUN	Impervious surface runoff
K_{Sw}	Saturation constant for readily biodegradable substrate in water phase ($gCOD/m^3$)
K_{Sf}	Saturation constant for readily biodegradable substrate in biofilm ($gCOD/m^3$)
$K_{s,NO3}$	Saturation constant for nitrate ($g\ NO_3/m^3$)
$K_{O,H2S}$	Saturation constant for inhibiting sulphide formation in the presence of oxygen (gO/m^3)
$K_{NO,\ H2S}$	Saturation constant for inhibiting sulphide formation in the presence of nitrate and nitrite (gN/m^3)
K_{SO4}	Saturation constant for sulphate (gS/m^3)

K_{a1}	First dissociation constant for H_2S
K_{H2S}	Saturation constant sulphide oxidation (g S/m^3)
K_La_{O2}	Reaeration coefficient (1/day)
K_{SF}	Saturation constant for fast biodegradable elemental sulphur (g S/m^3)
$K_{O2,SF}$	Saturation constant for oxygen in the oxidation of fast biodegradable elemental sulphur (gO_2/m^3)
$k_{1/2}$	Half-order rate constant for aerobic growth in biofilm, $gO_2^{0.5}/m^{0.5}/d$
$k_{S(-II)Soxb}$	Rate constant for sulfide oxidation by the biofilm (g $S/m^2/d$)
$k_{S(-II),pH}$	Inhibition factor for pH dependency of biological sulphide oxidation
$k_{S(-II)Woxb}$	Sulfide bulk water oxidation rate, biological (g $S/m^3/d$)
k_{H2Swc}	Rate constant for chemical oxidation of H_2S ((g $S/m^3)^{1-mc}$/(g $O_2/m^3)^{nc}$/d)
$k_{HS\text{-}wc}$	Rate constant for chemical oxidation of HS^- ((g $S/m^3)^{1-mc}$/(g $O_2/m^3)^{nc}$/d)
k_{H2S}	Hydrogen sulphide production rate constant (g S/m^2d)
$k_{S(-II)ff}$	Sulphide biofilm formation rate (1/(g $O_2)^{0.5}$.g $S/m^{1.5}$/d)
$k_{H,pH}$	Inhibition factor for pH dependency of heterotrophic biological processes
L	Pipe lifetime (years)
mfb	Reaction order of biological sulfide oxidation in biofilm with respect to sulphide (0-1)
mwb	Reaction order of biological sulfide oxidation in bulk water with respect to sulphide (0-1)
mc	Reaction order, S_{H2Stot}
mwc	Reaction order of chemical sulphide oxidation in bulk water with respect to sulphide (0-1)
n	Sample size
n	Manning roughness coefficient
nfb	Reaction order of biological sulphide oxidation in biofilm with respect to oxygen (0-1)
nwb	Reaction order of biological sulphide oxidation in bulk water with respect to oxygen (0-1)
nc	Reaction order
nwc	Reaction order of chemical sulphide oxidation in bulk water with respect to oxygen (0-1)
OF	Overflow
OF_{dry}	Dry weather overflow
OF_{wet}	Minimum wet weather overflow
PC-SWMM	PC-Storm Water Management Model
Q	Flow (m^3/s)
R	Hydraulic radius (m)
R^2	Coefficient of Determination
RDII	Rainfall-Derived Inflow & Infiltration
RH	*Rainwater Harvesting*
RH-T	*Rainwater Harvesting* supplies Toilet water demand
RH-B	*Rainwater Harvesting* supplies Bathroom water demand
RH-L	*Rainwater Harvesting* supplies Laundry water demand
RMSE	Root Mean Square Error
S_O	Concentration of dissolved oxygen (gO_2/m^3)
S_{NO3}	Nitrate concentration (gN/m^3)

$S_{S(-II)}$	Dissolved sulphide concentration (gS/m^3)
S_{H2S}	Hydrogen Sulphide concentration (gS/m^3)
S_{NO3-N}	Total nitrate concentration (gN/m^3)
S_{OS}	Dissolved oxygen saturation concentration (gO_2/m^3)
$S_{S(-II),eq}$	Dissolved sulfide concentration in equilibrium with the gas phase concentration (gS/m^3)
S_{Sf}	Concentration of fast biodegradable elemental sulphur (gS/m^3)
S	Slope (m/m)
$S_{(-II)}$	Total Sulphide concentration (gS/m^3)
S_f	Slope of the water surface
SD	Septic disposal
SM	*Sewer Mining*
SP	*Sustainable Practice*
SRUN	Pervious surface runoff
TSS	Total Suspended Solids
U	The mean velocity (m/s)
UVQ	Urban Volume & Quality
V_w	Bulk water volume, m^3
$\overline{X}$	Sample mean
WATS	Wastewater Aerobic-Anaerobic Transformation in Sewer
WDM	*Water Demand Management*
WDM-RH	Highest *Water Demand Management* & *Rainwater Harvesting* supply Toilet water demand
WDM-GR	Highest *Water Demand Management* & *Greywater Recycling* from Bahtroom & Laundry greywater
WDM-SM	Highest *Water Demand Management* & *Sewer Mining* supplies to 100% households in study area
WSUD	Water Sensitive Urban Design
WMP	Water Management Practices
Ww	Wastewater discharge
z	Pipe wall thickness (mm)
$Z_{\alpha/s}$	Confidence coefficient

1. INTRODUCTION

CONTENT: *Background; Motivation for this Study; Objectives of this Study; Research Scope; Method in Brief; Research Significance; Thesis Structure*

1.1 Background

Increased urbanisation leads to higher population densities and global climate change alters the earth's water balance and triggers the problem water shortages worldwide. World population is projected to grow from 6.1 billion in 2000 to 8.9 billion in 2050, increasing therefore by 47%. The historical data collected by IPCC on global surface temperature shows an increased average temperature by 0.78 (0.72 to 0.85)^oC between 1850-1900 and 2003-2012. Further, it is likely that the number of cold days and nights has decreased and vice versa. Due to the global warming, the surface temperature and the water cycle is predicted to change and the contrast between wet and dry seasons would increase. The IPCC projection through several models has shown the global surface temperature could rise by 1.5^oC to 3.5^oC and more than 62% population in the world would live in water stressed countries by 2050.

As an impact of changes of global water cycle, many regions have experienced mild to severe water shortages; therefore there is a worldwide effort to reduce potable water consumption (Anderson 1996; Bertrand 2008; Chung & White 2009; Dixon et al. ; Radcliffe 2006). Potable water reduction is achieved through the integration of Water Demand Management and potable water substitution with *Alternative Water Sources* (e.g. rainwater, greywater or blackwater). The Integration of water demand management and potable water substitution into urban development is one of strategies in urban planning and design approach which is called as Water Sensitive Urban Design (WSUD) if the approach is implemented in Australia. There are similar concept of WSUD which is popularly known worldwide such as Low Impact Development (LID) that is known in United States of America and Sustainable Urban Drainage System (SUDS) that is known in United Kingdom. While WSUD integrates all design and management aspect of the water cycle including the stormwater, wastewater, ground water and water supply, LID dan SUDS are more intended to manage only the stormwater. WSUD offers the key principle which considers cities as water supply catchment. To support this key principle, it is very important for a city to have flexibility and adaptability to its water sources (Otterpohl et al. 1997). A city that has flexibility and adaptability to its water sources was characterized by the diversity of its water source (desalinated water, recycled water, rainwater, stormwater) to supply the city's water demand (Anderson 1996; Butler & MacCormick 1996; Ghisi & Ferreira 2007). Furthermore, the city should also have centralized and decentralized infrastructure to supply water for the city's inhabitants. The disadvantage of a centralized water supply such as the long transport and large volume of water supply carried to the houses potentially increases the leakage during transport. Moreover, large volume of water supply needs huge water pipe dimension. Reduction of water pipe size dan leakage during the water transport could be handled if the city implements mixed centralized and decentralized infrastructure (Butler & MacCormick 1996; Crites & Tchobanoglous 1998; Guest et al. 2010). To create a city with high flexibility and adaptability to its water source, the concept of diversity of water source and diversity of infrastructure in urban development is introduced. The former concept requires a city to use alternative water sources for non-potable water demands, while the latter concept promotes centralised or decentralised systems to match water consumption with water quality (Melbourne Water 2008). Potable water demand reduction is one of the benefits of using the alternative water. However, potable water demand reduction is not only achived through the implementation of alternative water but it is also can be done by the people awareness of water conservation. Many campaigns have been introduced to reduce the potable water demand such as increased tariff, usage of water efficiency appliances and provision of rebates. Potable water demand reduction strategy is more likely to be implemented in a decentralised manner (e.g. in household scale or cluster scale) rather than in centralized manner. The term of sustainable practice has been labelled in a variety of ways, but in this study is referred to as 'Water Management Practices (WMP) or Decentralised Servicing Options' as it specifically relates to in source water and wastewater management. In WMP, water and wastewater are managed, treated and used at their source, hence maximum benefits of water saving and environmental protection can be achieved. These practices are also considered to be technically, economically and environmentally feasible in the long-term to secure water supply (Sharma et al. 2010). Some water technologies that are classified as WMP are Water Demand Management, Greywater Recycling, Rainwater Harvesting and Blackwater Recycling.

In high population density areas, residential households are the highest users of urban water, accounting for 60-75% of total potable water (Butler et al. 1995; Radcliffe 2004). For example, during 2011 to 2012, Melbourne residential water consumption was about 65% of the total urban water consumption (Melbourne Water 2012). In Southern California coast, the residential water consumption was the largest use, accounting for 66% of the total urban water consumption (Water Resource Management Group 2010). This means that households have the greatest potential to save water. Due to this reason, many WMP are designed to be implemented in residential areas. It has been mentioned in several studies that WMP application in residential areas offer some benefits including saving potable water, minimising costs associated with the expansion of water supply networks, reducing the environmental impact of discharged wastewater as well as providing infrastructure savings for sewerage systems (Radcliffe 2010; Tjandraatmadja et al. 2009a). While reducing water consumption and substituting potable water demand with alternative water sources are considered to provide positive impacts, many stakeholders admit that some barriers and negative impacts of the adoption of WMP might occur, particularly the impact on downstream infrastructure such as sewer pipe networks (Blanksby 2006; Radcliffe 2010) and also the cost associated to the implementation of WMP. Some WMPs are still connected to existing centralised sewerage networks (Brown et al. 2010; Melbourne Water 2008). These practices are suspected of discharging lesser wastewater and sludge, originating from local treatment plants, to sewerage networks which could triggers problems in sewer networks such as sewer odour and corrosion. Furthermore, the cost of

WMP implementation is also one of challenges for its use. The cost of WMP implementation depends on the operation and maintenance of the technology selected for the WMP. In addition to that the externalities factors such as public acceptance need to be valued in order to achieve the appropriate tariff of water produced from WMP approach. For the rainwater harvesting system, the cost depends upon the volume of storage tank required. The volume of storage tank is calculated based on the size of the roof area, rainfall level and number of household occupants. The cost to establish this system is relatively expensive which ranges from \$1700 to \$4200 for tank size 1.5 m^3 and 10 m^3. The operational cost is mostly about the electricity demand which is known to be very little (1 kWh/day). For greywater recycling, typical installation cost between \$ 2900 to \$ 3600. The operation cost for this system is usually including the demand of the chemical electricity demand. Since the greywater recycling is a technology which involves the treatment then the item of maintenance cost sould be considered too. Among existing technologies for WMP, only the impact of water demand management on sewer pipe networks has been widely studied. However, some metropolitan cities, such as Melbourne, Sydney, Perth and some metropolitan cities in the world aready have a Metropolitan Sewerage Strategy, which is aimed at providing sustainable sewerage services for the future by incorporating WMP technologies (Brown et al. 2010).

Residential wastewater typically has characteristics of highly biodegradable organic matter that varies with flow and diurnal flow patterns (Butler et al. 1995). The changes in wastewater characteristics can be caused by the introduction of WMP technology, which in turn adversely affects sewer networks (Cook et al. 2010; DeZellar & Maier 1980; Gormley & Campbell 2006; Parkinson et al. 2005). Many studies have found that implementation of WMP can reduce wastewater flow which subsequently increases its strength (concentration), thus causing sewer problems such as blockages, odour and corrosion. A study from Yarra Valley Water (YVW), one of the water retailers in Melbourne, Australia, has shown that the advancement of water saving policies exacerbated the problem of sewer blockages (Marlow et al. 2011). The impact of WMP adoption on odour and corrosion in sewers has thus far not been widely studied due to the complexity of estimating the extent of these problems.

In separate sewer systems, the sewer processes which involve biological, chemical and physical process usually occur more intensely compared to combined sewer networks. Sewer problems such blockage, odour and corrosion are caused by the products derived from physical and biochemical processes occurring along the sewer network (Boon 1992). It is important to note that sewer networks not only function as a means of transportation for sewage, but it also functions as a physical, chemical and biological reactor (Hvitved-Jacobsen et al. 2001). Hydrogen sulphide gas is a product of biochemical transformation processes that are responsible for causing odour and corrosion (Boon 1992). Hydrogen sulphide gas is a dissolved sulphide that is released to the sewer atmosphere under certain sewer circumstances. Dissolved sulphide can be released to the sewer atmosphere if there is highly turbulent flow, high wastewater pH and/or temperature (Jensen et al. 2009). Odour caused by hydrogen sulphide gas can endanger sewer workers because the fumes cause illness if the concentration is more than 10 ppm and can be lethal at concentrations above 500 ppm (Hvitved-Jacobsen & Vollertsen 2001). The cost for corrosion rehabilitation or maintenance is high. In Los Angeles county, for example, rehabilitation of 10% of the sewer network cost approximately $420 million and in Belgium, the maintenance cost for preventing corrosion amounts to $6 million per year (Zhang et al. 2008).

Recently, several studies investigated the generation of hydrogen sulphide in residential areas (Kristensen & Staunsbjerg 2006; Nielsen et al. 2008a; Raunkjaer et al. 1995; Vollertsen et al. 2011) since it has less complex wastewater characteristics compared to other wastewater. Furthermore, residential wastewater mostly consists of easily biodegradable organic matter which triggers hydrogen sulphide generation in sewers. However, the hydrogen sulphide generation in residential areas is usually an intermittent sewer problem. Hydrogen sulphide generation occurs mostly during dry weather conditions where the sewer flow is low and the biochemical processes are highly active (Hvitved-Jacobsen et al. 2001). However, a rapid increase in adoption of WMP in the future could potentially shift the current trend, leading to a continuous hydrogen sulphide generation, and consequently it will be an issue that is not affected by the weather but which is a persistent issue requiring greater attention.

Hydrogen sulphide concentration in sewerage networks is known to vary spatially and temporally. Spatial variability is more dependent on pipe geometry while temporal variation is determined by wastewater flow patterns. Most hydrogen sulphide studies have attempted to estimate spatial and temporal variability of hydrogen sulphide concentration (Nielsen et al. 2008a; Sharma et al. 2008; Vollertsen et al. 2011). However, in studies related to scenario analysis for existing and future urban development, both spatial and temporal variability are not the focus. Scenario analysis considers changes in the average concentration between the benchmark condition and the developed scenarios (Cook et al. 2010; Devesa et al. 2009).

Since WMP are considered as future practices, scenario analysis via modeling is required to predict the impact of WMP on sewerage networks. This requires modeling tools that can conduct scenario analysis. However, to develop a reliable modeling tool for scenario analysis, sufficient and suitable data are always needed. Unfortunately, most of the time, the data available for flow and wastewater quality modeling is scarce, because data collection for this kind of modeling is time-consuming and costly (Obropta & Kardos 2007; Willems 2008). Hydrogen sulphide gas modeling, however, involves flow and wastewater quality modeling (Almeida 1999; Hvitved-Jacobsen et al. 2002; Vollertsen & Hvitved-Jacobsen 2000). Therefore, the complexities of flow and wastewater quality modeling as well as difficulty in data collection are factors that limit hydrogen sulphide modeling.

1.2 Motivation for this Study

This study was motivated by the following issues and seeks to address them:

1. There is a lack of research concerning the impact of WMP on sewer pipe networks. As water businesses, society and government continue to reduce their water demand and encourage people to use *Alternative Water Sources*, flow reduces and wastewater

strength increases, and these changes can affect the performance of sewer pipe networks.

2. Many households which install WMP technology are still connected to centralised sewer pipe networks. Therefore, they tend to discharge residual WMP technology (e.g. sludge to sewer pipe networks). This exacerbates existing sewer problems.
3. Current discussion of WMP and their impact on sewerage networks mostly focuses on *Water Demand Management*, but neglects the impact of other WMP including *Greywater Recycling*, *Blackwater Recycling* and *Rainwater Harvesting*. Therefore, this study considered WMP for alternative water source use along with *Water Demand Management*.
4. Current investigation of sewer problems due to WMP is limited to blockages, with less attention being paid to odour and corrosion issues. Therefore, this study attempts to investigate hydrogen sulphide production as the main cause of odour and corrosion problems.
5. There is a lack of knowledge about the limits of reduction in water demand and how much household wastewater volume can be recycled, thus the program of water reduction and wastewater recycling can still be sustained by existing sewer pipe networks.
6. The scaling up of WMP adoption is an important factor that determines the deterioration level of sewer pipe networks. Unfortunately, not many studies explore this causal factor in relation to pipe deterioration.
7. Currently, hydrogen sulphide build-up in residential areas is considered to be an intermittent problem. Several studies found the implementation of WMP exacerbated sewer blockages, hence there is high possibility WMP implementation also will exacerbate sewer odour and corrosion.
8. Lack of available data and complex wastewater quality modeling makes the study of odour and corrosion due to WMP rare.

The issues above are the driving factors that led to the importance of investigating the impact of residential WMP on odour and corrosion problems in sewer networks. Thus, the preventive measures or appropriate policies can be formulated in the early stages of WMP adoption.

1.3 Objectives of this Study

The primary objective was to quantitatively establish and develop an understanding of the impact of WMP technology adoption in residential areas, in terms of propensity to produce sewer odour and corrosion on existing sewer pipe networks. As discussed, extensive data and highly complex modeling techniques are required to model hydrogen sulphide gas due to WMP adoption. Therefore, in addition to the primary objective, this study also attempts to develop a modeling framework that models WMP from the initial point where the wastewater is produced to biochemical process in sewer networks that are responsible for the formation of hydrogen sulphide gas. Furthermore, the other secondary objective in this study is to develop various WMP scenarios which represent existing and future urban development to demonstrate the approach. These scenarios cannot consider all possible questions that arise around WMP adoption and their impact on sewers, but the examples given provide a basis for demonstrating the approach and the outcomes.

For the scenarios considered in this thesis, the investigation of WMP focuses on reducing water demand and adoption of recycled wastewater, as well as increasing the number of households that adopting WMP technology. Weather is another factor that affects the generation of odour and corrosion. Therefore, the effects of weather were considered by varying the volume of both potable water demand and from alternative water sources for every developed scenario in dry weather and wet weather conditions. Furthermore, the investigation also predicted the impact of WMP adoption in future dry weather conditions to reveal impact of scaling up of number of households adopt WMP in study area.

Therefore, the research problems that were identified for this study are:

1. Can a modeling approach that considers local hydraulic issues and changes in wastewater quality be developed to allow scenario analysis to be performed for hydrogen sulphide generation as WMPs are implemented?
2. Can the modeling framework be tested on a case study site to examine hydrogen sulphide generation as WMPs are implemented?
3. What would be the detrimental impact of introducing of source control technology named as WMP?
4. What WMP that was considered as best and worst in terms of reducing the imported water supply and causing sewer odour and corrosion which triggers by the presence of hydrogen sulphide ?
5. What would be the concentration of hydrogen sulphide in studied sewer considering the global climate change effect in 2060 as recommended by the Melbourne Sewerage Strategy ?
6. What would be the impact of increasing number of households adopting source control technology ?

1.4 Research Scope

The scope of this study is limited to the following:

1. Sewer odour and corrosion exclusively caused by hydrogen sulphide gas. In sewers, the source of odour is not only caused by hydrogen sulphide build-up. Ammonia and volatile organic compounds (VOC) gases also contribute. However, in this study, only hydrogen sulphide gas was considered because it is more problematic than other gases. Hydrogen sulphide is not only known as an odour gas, but it also leads to corrosion of sewers.
2. WMP in residential areas. The main source of waste inflow is obtained from domestic wastewater; therefore the WMP in residential catchments greatly affect wastewater quantity and quality in sewer networks.
3. This study will mainly focus on existing sanitary sewer networks. More problems due to implementation of WMP arise from existing sanitary sewer networks since they were

not properly planned and designed to accommodate WMP. New sewer networks usually incorporate aspects of water conservation in their planning and design, which makes new sewer networks less susceptible to the occurrence of sewer problems. Furthermore, this study only focus on separate sanitary sewer system rather than combined sewer since more biochemical transformation process related to odour and corrosion occurred in the sanitary sewer.

4. Water – energy nexus of the WMP is not a focus in this study since this study investigates the impact on sewer odour and corrosion.
5. The study was conducted by using Australian demographic composition and an Australian sewer network. Therefore the results produced in this study are representative of Australian conditions, although the approach may be applied at other locations.

1.5 Method in Brief

To analyse the impact of scenarios for WMP on sewerage networks, the following tasks in Figure 1.1 were conducted. The tasks were conducted sequentially from Development of Modeling Framework to Scenario Analysis.

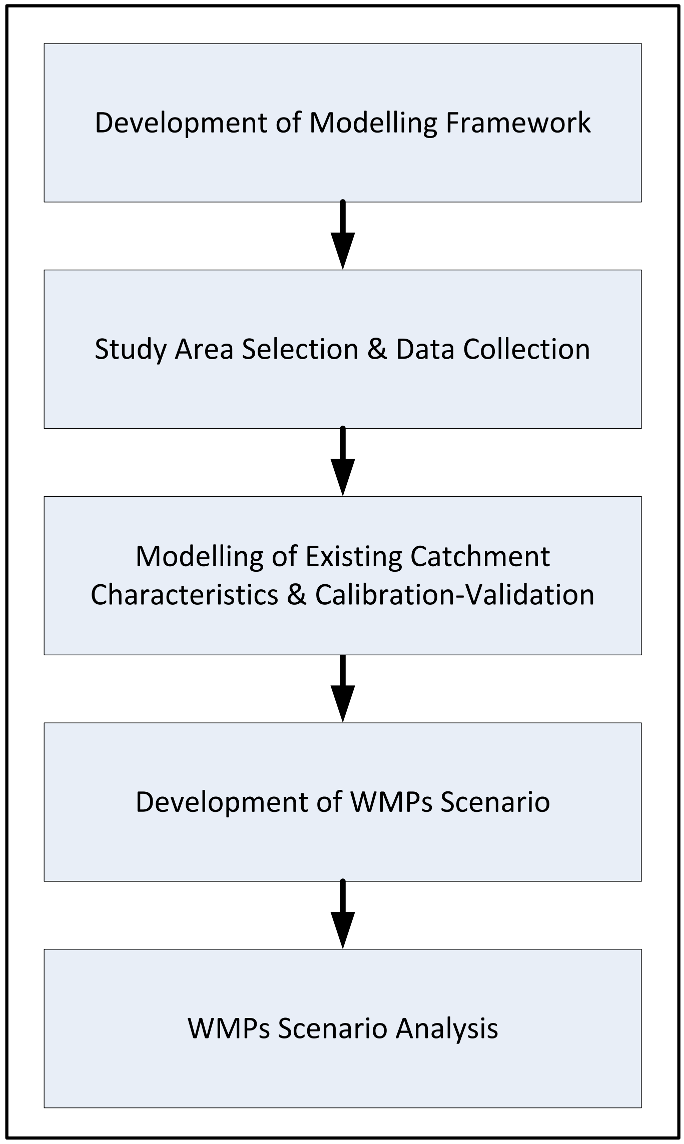


Figure 1.1. Method Flowchart

Task 1 – Development of Modeling Framework

As indicated earlier, a modeling approach for predicting the impact of residential WMP on hydrogen sulphide concentration with minimal data requirements was needed. The modeling approach was initially developed by identifying the data that is required for hydrogen sulphide modeling and data that may reasonably be obtained by water authorities. Existing modeling tools were classified as per their capability for considering wastewater production, sewer flows and sewer process modeling. A model was required for estimating wastewater production from its source, which begins with indoor water demand (i.e. toilet, laundry, bathroom/shower and kitchen), because WMP mostly affect the volume of water consumed. This model should also be able to simulate not only traditional practice, but also non-traditional practices, which include the use of alternative sources (e.g. rainwater, greywater and blackwater). The other requirement was to have a technique or model with strong capabilities to simulate sewer flows and physical and hydrogen sulphide build up, since sewer odour and corrosion are dependent on sewer flows and hydrogen sulphide build up.

Task 2 – Study Area Selection and Data Collection

A case study was selected for testing the developed modeling framework. The selected study area was residential, since many WMP are implemented within households. Detail criteria to select the case study are detailed in Chapter 3, Sub-Section 3.2.1 and 3.2.2. The catchment also had a simple sewerage network and had sewer odour and corrosion problems during low flow, drought conditions. Data that were collected for the residential area consisted of sewer geometry, online monitoring data (flow and hydrogen sulphide in gas phase) as well as water quality sampling. The sampling and experimental data were required in order to estimate wastewater quality and site-specific model parameters. Data from the selected study area was used to calibrate and validate a model which represents existing sewerage networks.

Task 3 – Modeling of Existing Catchment Characteristics (Existing Urban Development) and Calibration-Validation

The existing catchment characteristics are presented as a *Base Case* in this study. A *Base Case* was designed to consider 2010 urban development, population growth, weather conditions and sewer pipe conditions in the study area. Urban development consists of several components including house type, house occupancy and the use of WMP in the study area. Population growth consists of three factors: number of people, population density and household occupancy. So far, the weather is an important factor in hydrogen sulphide build up. Rainfall is an indirect factor that triggers rainfall derived inflow and infiltration (RDII) in sanitary sewers. Existing sewer network conditions in this study area are represented by sewer pipe wall roughness and volume of RDII entering the system. 2010/2011 was selected because the field data was collected during some months in these years. A *Base Case* was presented as a reference point, and the developed scenario was the comparison.

In the initial stage, the *Base Case* setup required data for water demand in the selected study area. Total water demand was obtained from Melbourne Water weekly reports, which subsequently brokdown water demand per total water demand end-use. The breakdown was conducted by assuming that all households used the same rating of water saving appliances and the demand was that described on the Water Efficiency and Labelling Scheme (WELS) website. Wastewater contaminant concentration was derived from literature values, while residential catchment and sewerage network characteristics and historical rainfall records were obtained from Yarra Valley Water (YVW) and the Bureau of Meteorology. The collected data was then entered into the model and hydrogen sulphide production simulated by using the framework developed in Task 1. To affirm the reliability of the model, the framework was calibrated and validated using field study data in 2010.

Calibration was conducted by manually adjusting model parameters until it fitted the observed value. Goodness of fit values (coefficient of determination and root mean square error (RMSE)) were generated to easily compare model predictions to observed values. Once parameters were defined, the model was validated using data from another period or from another sampling point. Details of calibration and validation process are described in Chapter 3, Section 3.3 and the results are presented in Sub-Section of 3.4.2.

Task 4 – Development of Water Management Practices (WMP)

There are three steps in WMP scenario development. They are: main scenario development by inductive approach, selection of Alternative Water Source's technology and further development for each WMP scenario, which includes volume variation, weather variation and future urban development. There are three steps in WMP scenario development, they are establish the focal issue, identify the driving factors and finally build the WMP scenario. The detail process of WMP scenario development is described in Chapter 4.

The selection of Alternative Water Source was based on the following three criteria:

a. Can be implemented in a decentralised manner.
b. Have high public acceptance, mainly based on studies from Australia.
c. Have the potential to exacerbate the current sewer problem.

The selection processes commenced by reviewing all potential water source technology intended to reduce water demand on a household or neighbourhood scale. These alternative sources were then sequentially evaluated based on the three criteria listed above. Detailed selection processes are described in Chapter 4. A ranking table for alternative source selection is also provided to simplify the selection process of WMP.

WMP scenario for existing urban development (2010/2011) was aimed to investigate the changes in the volume of water demand reduction and the volume of recycled wastewater uptake in dry weather and wet weather conditions. WMP scenario for future urban development was aimed at investigating the impact of scaling up of household adoption of WMP technology. Therefore, each of generated main scenarios has sub-scenarios which include the variations on volume of water demand or recycled wastewater. For future simulation, the main scenarios including the Base Case were projected to 2060. The projection in 2060 includes the projection of urban development (house type and occupancy), population growth and climatic condition (rainfall). Main scenarios in 2060 also have sub-scenarios which include the number of households adopting WMP technology. This year was selected in this study based on the Melbourne Metropolitan Sewerage Strategy, which included a planning forecast to 2060.

Task 5 – WMP Scenario Analysis

Scenario analysis compared the *Base Case* and all developed WMP scenarios. Scenario analysis in 2010 (existing urban development) focused on relating independent variables (reduced water demand, greywater uptake, rainwater uptake and extracted sewage for WMP scenario) to five dependent variables (imported water volume, contaminant load, sewer flow, hydrogen sulphide concentration and rate of corrosion). Scenario analysis in 2060 (future urban development) highlighted the impact on scaling up of WMP adoption in terms of the number the households adopting these WMPs and relating it to the dependent variable of imported water in the study area, contaminant load, sewer flow, hydrogen sulphide concentration and corrosion rate. Analysis was presented as the daily total value for discharged wastewater, contaminant load and sewer flow, while for sulphide concentration and corrosion rate, the daily average value was used.

Imported water reduction examines the indoor water demand with WMP adoption. The wastewater production section discusses the volume of wastewater discharge to sewer pipes. The contaminant load section discusses the crucial contaminant that affects hydrogen sulphide build-up. The sewer flow section will examine the diurnal sewer flow profile and compare the daily total sewer flow with the developed scenarios. The dissolved sulphide and hydrogen sulphide gas concentration section also discusses the diurnal profile and compares the Base Case and developed scenarios as well as analysing dissolved sulphide and hydrogen sulphide gas concentrations based on the concentration classification from Hvitved-Jacobsen's (1998) study. Corrosion rate analyses will show the sewer pipe corrosion rate per year. In the discussion chapter, this will be linked to sewer pipe lifespan analysis.

1.6 Research Significance

Due to global climate change, rapid population growth and limited water supplies, lowering household water demand is crucial. Residential areas are the main focus for potable water saving practices, because these areas dominate urban water demand, and they are the most significant areas for growing cities. However, the impact of water saving practices through WMP adoption has not been studied yet, and therefore some unknown outcomes have the potential to become barriers to future water saving practices.

An investigation of the impact of WMP adoption on sewer odour and corrosion can be used to identify sewer flow and wastewater quality limitations of sewerage networks in residential areas. The results can also be used to identify strategies to minimise the impact on sewer odour and corrosion. Eventually, the results from this study can assist water authorities to investigate early stage solutions, or provide preventive measures to maintain effective sewer networks.

New insights about the side effects of WMP are presented in this study. Many studies only highlight the positive impacts of WMP and tend to ignore possible negative impacts. A thorough investigation of all possible WMP and all problems in sewerage networks has not been previously conducted. Adoption of WMP, without a comprehensive and holistic study, may trigger more problems in the future. Thus, this study attempts to address this knowledge gap by considering the attributes of WMP yet to be investigated.

Furthermore, wastewater quality modeling is often avoided because it requires complex data, simulation and calibration processes. Therefore, the development of a modeling framework that can simulate sewerage processes for scenario analysis is vital. To find the impact of WMP adoption on odour and corrosion, ideally, WMP scenario modeling should be capable of simulating wastewater quality from the initial point of wastewater generation (households) to hydrogen sulphide gas prediction on sewer networks. Once satisfactory results are achieved, this tool may be applied to model WMP in different residential areas.

This study is the first attempt to investigate the impact of WMP on sewer odour and corrosion in existing sewer networks. Service providers need to understand that water saving through *Water Demand Management* or the introduction of *Alternative Water*

Sources will change wastewater characteristics and subsequently affect sewerage system operations.

The results of this study would be beneficial in terms of providing the modeling method for hydrogen sulphide generation due to adoption of WMP. Furthermore, new insight on the effect of WMP on the two of sewer problems would be revealed. The model developed in this study might or might not be similar for other catchments, since another catchment will have different pipe characteristics and different existing conditions, as well as a different demography. Therefore, the model developed here cannot be assumed to be generally applicable to other catchments, although it may be useful as an estimation model to predict hydrogen sulphide in sewer pipes, if the catchment characteristics are similar. However, the method applied in this study can be used to generate models for other sewer catchments.

1.7 Thesis Structure

This thesis is presented in seven chapters as can be seen in Figure 1.2 below.

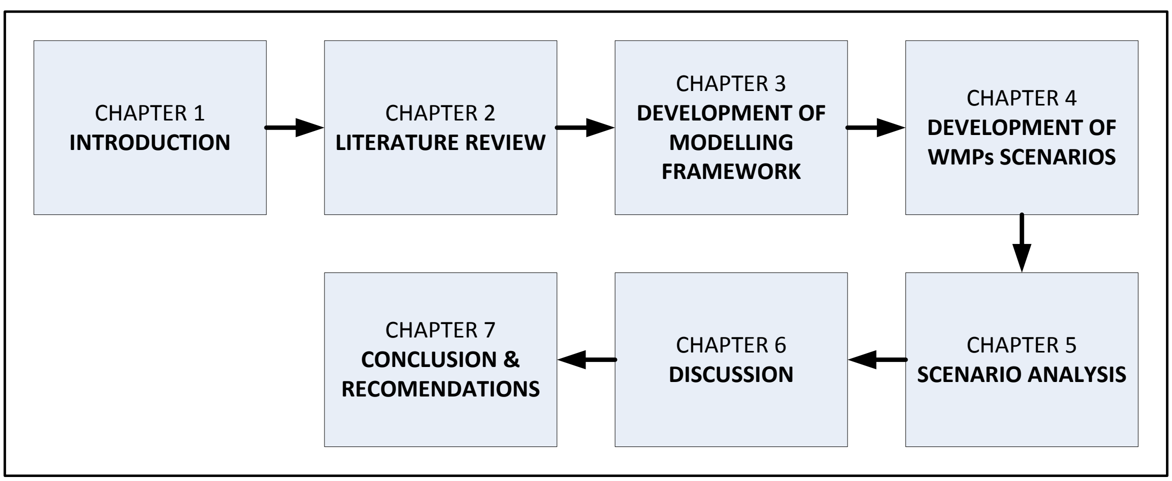


Figure 1.2. Thesis Structure Diagram

Chapter 1 introduces the thesis and comprises the background for the study, the research objectives and scope, as well as presenting the research method and significance of the study. A literature review is presented in **Chapter 2** which highlights the main concept behind the implementation of WMP, and approaches to physical and biochemical processes in sewerage networks. A short review of wastewater generation and sewerage network models for flow simulation and prediction of hydrogen sulphide gas concentrations are also presented. Finally, this chapter summarises the research aims and main objectives of this thesis in the final section. **Chapter 3** describes the development of the modeling approach which includes data requirements, setup of the *Base Case* as well as model parameters for calibration and validation. **Chapter 4** details the WMP selection and scenario development. **Chapter 5** discusses main variables of imported water volume, wastewater volume and contaminant load, sewer flow, hydrogen sulphide concentration and corrosion rate. **Chapter 6** is a discussion of the scenario analysis presented in Chapter 5. Finally, **Chapter 7** summarises the main conclusions and provides recommendations aimed at improving urban wastewater management.

2. LITERATURE REVIEW

CONTENT: *Water Sensitive Urban Design; Water Management Practices; Wastewater Characteristics; Sewerage Network Systems; Available Models to Investigate Impact of-WMP on Sewerage Networks; Objective of this Study*

This chapter cover the review of the literatures which are required to understand this study. Since the study was conducted in Australia, hence section 2.1 provides Australian planning and design approach (WSUD) that are generally adopted as the basis for planning of Water Management Practices (WMP). Other sections in this chapter introduce and discuss wastewater characteristics of WMP, which trigger sewer odour and corrosion, physical and biochemical processes in sewerage networks, hydrogen sulphide as the main component of sewer odour and corrosion, and modeling tools to simulate scenario of WMP. The final section is intended to be a research map that shows the knowledge gaps and the theory to cover the gaps, which eventually leads to the research objectives.

For giving guidance to the reader, this chapter commences with a set of questions in relation to the objectives of this study. These questions are :

1 How does the concept of WSUD used as a basis of WMP implementation in Australia ?
2 What are the Water Management Practice (WMP) that commonly used in Australia ?
3 Fit for purpose concept attempts to match the treatment process and the final water quality which eventually determine the usage of the treated water. What is the characteristics of treated water from WMP application ? What kind of indoor and outdoor end uses that can use the treated water ?
4 Based on previous studies, what are the impacts of WMP on wastewater characteristics?
5 What are the common sewer problems worldwide?
6 What kind of tools can be used to estimate the impact of WMP on sewer problems?

2.1 Water Sensitive Urban Design (WSUD)

"Water Sensitive Urban Design is the application of a wide range of within catchment measures to manage the impacts of urban developments on total water cycle" (WBM Oceanics Australia 1999).

Traditionally, the water and wastewater urban management did not integrate the potential urban water resources such as water, wastewater and stormwater. The water demand was only supplied through centralised, piped water infrastructure, wastewater was transported and treated through centralised infrastructure, the rainwater and stormwater was channelled poured quickly to the nearest natural waterway to avoid floods. Concept of Integrated Urban Water Management (IUWM) attempts to manage all water cycle in the urban context. Water Sensitive Urban Design (WSUD) adopts the concept of SUWM to manage all water cycle in the urban.

Water Sensitive Urban Design (WSUD) is underpinned by the fundamental principle that water supply, wastewater, rainwater and stormwater should be integrated (see Figure 2.1). Initially, WSUD focused more attention on stormwater management, but nowadays that focus has since shifted to water supply and wastewater. WSUD aims to minimise impacts on the natural water cycle and protect the health of aquatic ecosystems by reducing the potable water demand, runoff rate and quality wastewater loads (Sharma et al. 2010). The concepts of WSUD have been widely used because many stakeholders (e.g. water authorities and governments) are concerned with diminishing supplies of potable water and the increasing impact of development on adjacent environments (Melbourne Water 2005).

WSUD incorporates diversity of water sources and infrastructure. This diversity includes all potential sources within an urban catchment that can supply the water demand. There are three urban water sources are identified as (1) piped potable water (from centralised pipe infrastructure), (2) harvested water (i.e. rainwater or stormwater) and (3) wastewater (see Figure 2.2). The strategy of "*Water Demand Management*" and "*Fit for Purpose*" have been implemented in order to supply urban water demand efficiently and effectively

(Melbourne Water 2008). The strategy of *Water Demand Management* is described as reduction in water demand in homes, businesses and industries by installing water efficient appliances, setting up water restrictions and offering financial incentives to the public to replace their old, inefficient water appliances (Australian Government 2005; Tate 1990). Reduction of potable demand, in turn, reduces dependence on remote water sources, possibly allowing more water to be made available for environmental flows or obviating the need for new dams to be constructed. *Fit for Purpose* is the strategy to replace potable water for indoor use i.e. toilet flushing, laundry washing, bathing, and outdoor use i.e irrigation with alternative water that has appropriate water quality and sometimes these water also supply water for public open space irrigation (Tjandraatmadja et al. 2005). This alternative water can be derived through water reuse, recycling or harvesting technologies. Generally wastewater and greywater is reused with secondary treatment system, while rainwater and stormwater are harvested individually or at cluster scale with only primary treatment system.

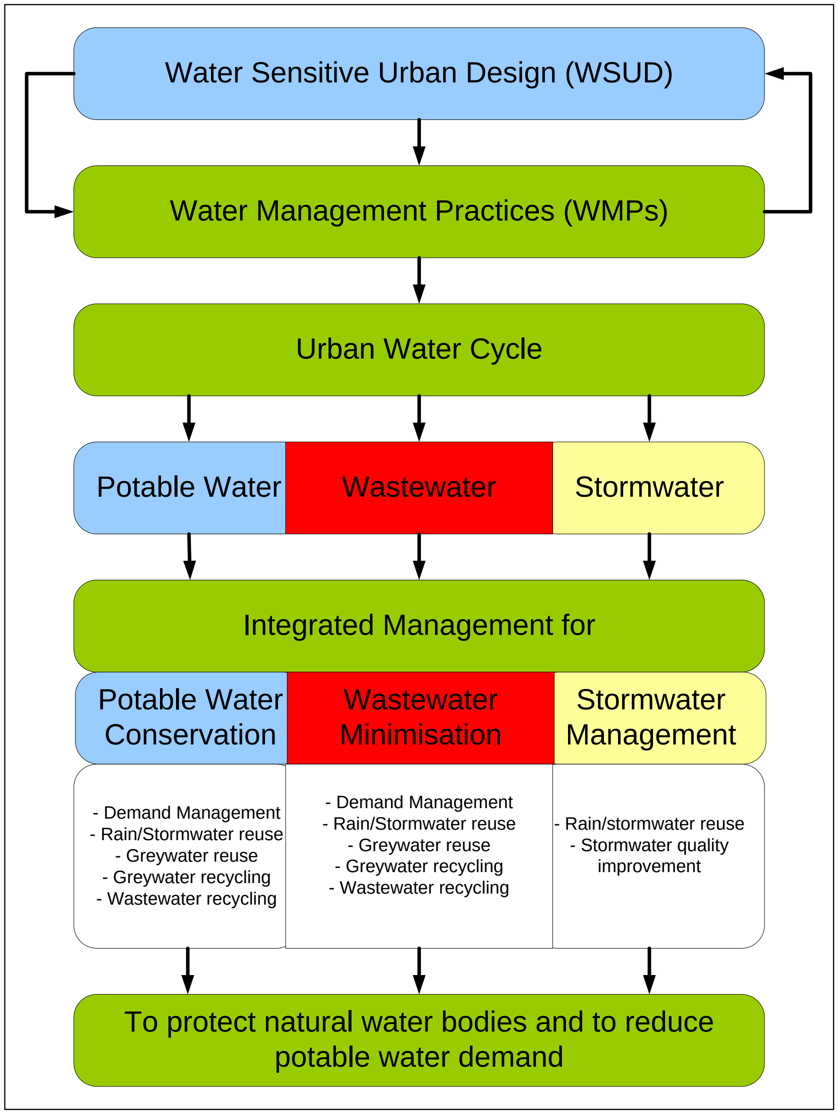


Figure 2.1 Interaction Between WSUD and Integrated Urban Water/Wastewater/Stormwater Management

(Adopted from a figure in Melbourne Water (2008))

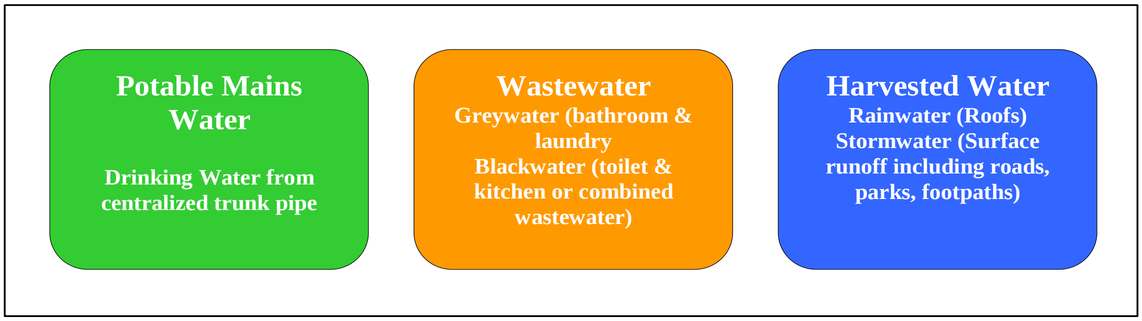


Figure 2.2. Urban Water Resources

Infrastructure diversity includes all infrastructure involved in the urban water cycle from water supply, wastewater collection and drainage systems. The diversity of infrastructure is further classified as centralised and decentralised infrastructure systems. In context of water and wastewater management, centralised infrastructure system is defined as a system that usually far from the point of origin. This system have water source far from the service area and the wastewater is transported to a centralised point for further treatment and reuse (Crites & Tchobanoglous 1998). Decentralised infrastructure system is a water and wastewater system that are managed locally such as individual homes or clustered of homes. The water source of this system is near to the service area and treats the wastewater close to the source (Crites & Tchobanoglous 1998). Each system offers its benefit and weakness, but increasing awareness of water and energy conservation had a consequence that many people prefer decentralised system rather than centralised system (Tjandraatmadja et al. 2009a). Sometimes to maximise the benefit, the decentralised system is integrated with centralised system. However, the integration of these systems subject to the existing infrastructure available in the area. Mostly, the integrated system is conducted in an area that already has sewer networks. Water supply for integrated system is usually supplied by piped potable water and backed up by treated greywater or rainwater, and the wastewater is partially treated and used for backed up water source. Wastewater overflow and treatment residual are usually disposed to centralised sewer networks (Tjandraatmadja et al. 2009a).

Despite all the advantages contained in the adoption of WSUD concept, there are still barriers and impediments to adoption of technology which is based on IUWM and WSUD concepts (Chandler & Eadie 2006). The barriers are lack of knowledge from stakeholders which includes lack of stakeholder awareness, and the availability of policy and legislation to support the adoption of WSUD, the difficulty of technology design and installation, cost and status of the property (Brown & Clarke 2006; Chandler & Eadie 2006; Edwards et al. 2006; James et al. 2006; Marlow et al. 2013). Furthermore, the institutional and personal bias of WSUD technology adoption which leads to the personal and institutional interest is also listed as one of the barriers in research conducted by Marlow et al. (2013). In addition to the barriers above, Sharma et al. (2010) noted that costumer acceptance, type and scale of development, catchment conditions as well as proximity to an existing centralised system are also listed as the barriers of WSUD adoption. However, the key barriers of WSUD adoption are stakeholders knowledge and financial consideration (Sharma et al. 2010). Some studies have mentioned that finance and cost issues could be handled by including incentives and rebates to implement the recommended system and technology (Brown & Clarke 2006; Chandler & Eadie 2006; Edwards et al. 2006; James et al. 2006; Sharma et al. 2010).

Urban water systems are complex and interrelated. Changes to a system will have downstream or upstream consequences that will affect costs, sustainability or opportunities. The adoption of WSUD technologies without holistic assessment can result in conflicting outcomes (Hails et al. 2006). For example, *Greywater Recycling* would decrease the sewage flow velocity in sewer pipe networks (Parkinson et al. 2005), which can potentially contribute to blockages in the network. Increasing use of water efficient appliances, when combined with water consumption restriction, has been proved to cause sewer blockages in the Yarra Valley Water (YVW) catchment (see Figure 2.3). Therefore, a thorough analysis and assessment is needed so that adoption of WSUD achieves outcomes consistent with WSUD goal and passes on the desired benefits to stakeholders.

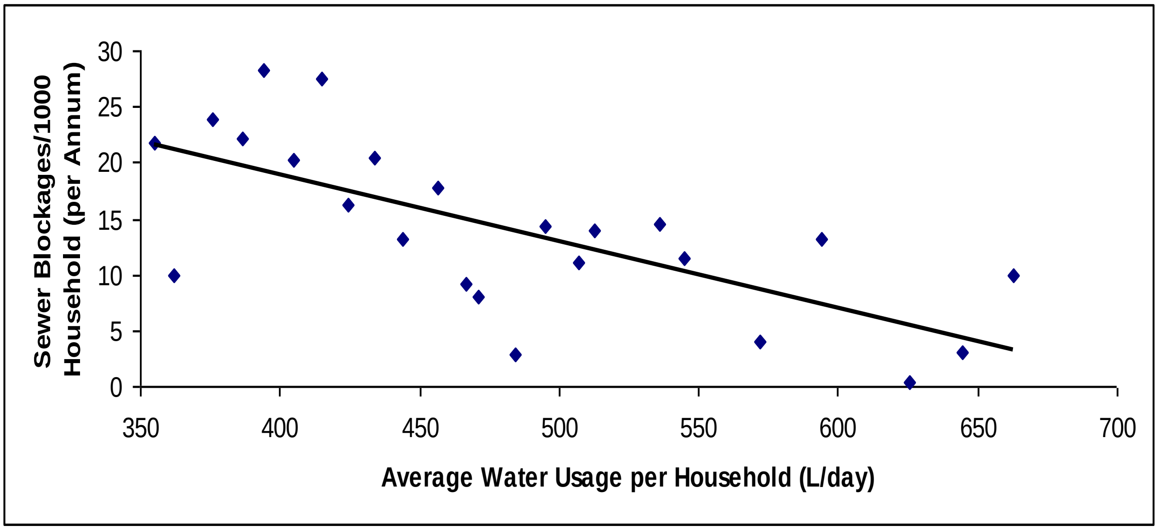


Figure 2.3. Sewer Blockages vs. Water Demand Data (Yarra Valley Water 2011)

2.2 Water Management Practices (WMP)

WMP are the technology or measures to achieve WSUD aims, which are installed in a decentralised manner. The popular WMP are *Water Demand Management*, wastewater (greywater or blackwater) recycling and mining, and Rainwater Harvesting. Mostly due to water scarcity, the adoption of these WMP are increasing due to pressure on the current urban water system (Ghisi & Ferreira 2007; Marks et al. 2006b; Najia & Lustig 2006). This pressure triggers the increasing awareness of the society to save more water by using any WSUD strategies. Residential catchments are responsible for the highest water demand within the urban water system. Thus, having WMP implemented in residential catchments will reduce the pressure on current urban water systems, since WMP fully or partially supply outdoor and indoor water consumption. Though implementation of WMP in residential area considered being beneficial for the current urban system, its implementation at household scale was classified to be untried and unproven yet (Makropoulos & Butler 2010). Therefore, the study of WMP at smaller household scale becomes important to explore its potential in reducing the pressure on current urban water systems.

WMP in residential areas is generally implemented by considering the fit for purpose concept. Reducing the water demand and using alternate the water sources such as recycled water and rainwater, needs to fitted to the most suitable end use within households.

Water demand for end uses differs across regions, and vary with population characteristics, embedded water restriction as well as climate. Table 2.1.presents a comparative summary of end use studies from several areas. Furthermore, Table 2.2 shows the general classification of A*lternative Water Sources* and *Water Demand Management* that can be implemented in a decentralised manner.

Table 2.1. Comparison of End Use Demand Studies

End Uses	Perth (2003)		Melbourne (2005)		Auckland (2007)		Goldcoast (2008)	
	L/cap/day	%	L/cap/day	%	L/cap/day	%	L/cap/day	%
Clothes Washer	42	13	40.4	19	39.9	24	30	19
Shower	51	15	49.1	22	44.9	27	49.7	33
Tap	24	7	27	12	22.7	14	27	17
Dishwasher	N/.A	N/A	2.7	1	2.1	1	2.2	1
Bathtub	N/A	N/A	3.2	2	5.5	3	6.5	4
Toilet (total)	33	10	30.4	13	31.3	19	21.1	13
Irrigation (total)	180	54	57.4	25	13.9	8	18.6	12
Leak (total)	5	1	15.9	6	7	4	2.1	1
Other	N/A	N/A	0	0	0.8	0	0	0
Total Demand	335	100	226.2	100	168.1	100	157.2	100

Table 2.2. General Classification of A*lternative Water Sources* and *Water Demand Management*

WSUD strategies	Type of Supply Infrastructure	Type of Water	Source	Measure/ Technology Use	Type of Use
Water Demand Management (WDM)	Decentralised (Household)	Piped potable water	Treated natural water	Usual WDM	All indoor use
				High WDM	
Fit for Purpose through *Alternative Water Sources*	Centralised or Decentralised (onsite)	Reclaimed Water	Blackwater	Recycling	1.Park Irrigation 2.Toilet
	Decentralised (Neighbourhood)			*Sewer Mining*	1.Park Irrigation 2.Toilet 3.Laundry (*rare case)
	Decentralised (Household/ or Neighbourhood)		Greywater	*Greywater Recycling*	1 Park Irrigation 2 Toilet 1.Laundry
	Decentralised (Household/ or Neighbourhood)			Greywater Direct Use	Park Irrigation
	Decentralised (Household/ or Neighbourhood)	Rainwater	Roof Runoff	*Rainwater Harvesting*	1.Park Irrigation 2. Toilet 3. Laundry 4.Shower 5.Kitchen (*rare case)
	Decentralised (Neighbourhood)	Stormwater	Road/Roof Runoff	Stormwater Harvesting	Park Irrigation

2.2.1 Water Demand Management (WDM)

Water Demand Management is an intervention to reduce water demand through either financial, structural/operational, or socio-political arrangements or a mixture of these arrangements (Australian Government 2005; Tate 1990). Financial incentives for *Water Demand Management* comprise rebates for installing water efficient appliances, penalties for high water consumption, and higher water prices for using water excessively (Tjandraatmadja et al. 2009a). Moreover, it is strengthened by structural/operational and socio-political strategies including reduction in losses due to leaks and implementation of water consumption restrictions as well as regulations. Average daily residential water consumption varies from country to country, for example, in the USA and Canada it is around 350 L/cap/day; in European countries (Italy, Sweden and France), it has been reduced to 250-150 L/cap/day; for Middle Eastern countries (Israel and Jordan) it is around 150 L/cap/day, while in Australia, it is around 100-180 L/cap/day. Managing water demand by *Water Demand Management* strategies has proven to be successful, particularly in reducing water demand in residential areas (Howe & Goemans 2002; Kenney et al. 2008). The implementation of these arrangements has successfully reduced water demand by around 22% to 40% in many countries such as Australia, France, Canada and Jordan. To save more water, nowadays more stringent management demands have been implemented. This policy is well known as high *Water Demand Management*, where government and water authorities encourage people to use the most water efficient appliances in their house. Significant water consumption reduction is achieved (up to 40%) when implementing high *Water Demand Management*. Table 2.3 was sourced from Sharma et al. (2009) and shows water supply scenarios under two conditions: usual WDM and high WDM. Usual WDM refers to the condition where water consumption is not managed and incorporates past practice. High *Water Demand Management* adopts the most water efficient appliances in the household.

Table 2.3. The Scenarios of Melbourne Residential Water Demand (Sharma et al. 2009)

	Usual WDM (L/cap/day)	High WDM (L/cap/day)
Toilet	23	15
Laundry	37	16
Kitchen	16	14
Bathroom	89	52
TOTAL	**165**	**97**

2.2.2 Alternative Water Sources

According to Hurlimann and Dolnicar (2010) and Marks et al. (2006a), there are different alternative sources of water that are mostly used in urban areas: reclaimed water (blackwater), greywater, rainwater, stormwater and desalinated water. Desalinated water is not discussed in this study, since it is considered as centralised supply infrastructure, so it does not fall into the category of local water/wastewater management or WMP. In this review, only *Alternative Water Sources* used for indoor demand and/or considered to alter wastewater characteristics will be discussed.

2.2.2.1 Blackwater

Blackwater is defined as the wastewater that comes from toilets and kitchens. This kind of wastewater mostly contains a mixture of urine and human excreta. The reuse of blackwater is increasingly seen as a sustainable approach to the provision of water. There are two options for *Blackwater Recycling* or *Sewer Mining*. *Blackwater recycling* is a term used for the reuse of blackwater that originates from toilet and kitchen wastewater. Water reuse can be implemented at household or neighbourhood scales, or at a larger centralized wastewater treatment plant. *Sewer Mining* is technology where wastewater (combined wastewater from every end uses) is extracted from the sewer system, treated and reused, and can be implemented at various scales, most commonly regional scale. Hence, sewer mining is actually a variant of blackwater recycling, the only difference being the location where the wastewater is extracted, whether it is taken from a main sewer (sewer mining) or it is derived from households (blackwater recycling). The complex and costly household installation of *blackwater recycling* makes them less desirable to be installed.

Several studies have investigated blackwater to reclaim its nutrients. If blackwater is source separated, approximately 90% nitrogen, 74% phosphorus and 79% potassium can be reclaimed (Jenssen et al. 2003). For countries with limited water resources, blackwater is not only seen as a natural fertiliser, but also as a potential, alternative water source (Otterpohl et al. 2002). Recycled blackwater sourced from sewer mining and other wastewater treatment plant is usually used to reduce potable water demand for flushing toilets and irrigation. According to a study, which investigated the public preference for recycled blackwater use in Australia, treated blackwater is mostly preferred for irrigation water. The second preference is toilet flushing. These preferences are related to people's perception of blackwater rather than its actual quality (Marks et al. 2006b). Blackwater treatment usually involves advanced technology, especially if it is used indoors. This advanced treatment is needed because blackwater contributes a high concentration of nutrients during daily operation. Nowadays, treatment plant by using multiple membrane processes like microfiltration with a suspended growth bioreactor (membrane bioreactors) are usually selected as *blackwater recycling* treatment plants.

The reclaimed water from *Sewer Mining* is usually used for toilet flushing, laundry and irrigation (Hadzihalilovic 2009; McGhie et al. 2009; Sydney Water 2006). The initiative of *Sewer Mining* is intended to be managed and served in a decentralised manner. This practice is not intended for single household applications, but rather to be implemented in collective/cluster scale developments. These systems are often managed by private sector organisations rather than government authorities/ water utilities through a licensing arrangement. A number of *Sewer Mining* initiatives are already in place, mostly in Australia (McGhie et al. 2009; Sydney Water 2006) such as in City Council House (C2H) building, Albert Park and Flemington Racecourse in Melbourne. Some *Sewer Mining* initiatives are also conducted in other states in Australia (e.g. New South Wales and Western Australia). Most of the existing *Sewer Mining* operations use their reclaimed water for irrigation and toilet flushing, and a *Sewer Mining* initiative at Flemington Racecourse not only supplies the racecourse but also supplies the residential area around it. Some households in residential areas use reclaimed water for toilet flushing and laundry water.

2.2.2.2 Greywater

Greywater includes wastewater from the bathroom/shower, washing machine, and bathroom and laundry taps. Sometimes, kitchen wastewater is also included in greywater, but this has less preference, since kitchen wastewater is more polluted and is lower in volume. The reclaimed water from greywater treatment is preferred for non-body contact use, and Marks et al. (2006a) noted that treated greywater is preferred for toilet and laundry use.

Countries pioneering greywater reuse and recycling are the USA, Australia and Japan. Rebates are often offered to encourage the uptake of greywater systems, the amount varying from one country to another. For example, the US offers up to $3000 for establishment of *greywater reuse* and *recycling* systems while in Australia, the government provides rebates of $500 as part of purchasing and installing greywater systems (Australian Government 2010a; Chung & White 2009). In Japan, no incentive or rebate is offered, but the residents choose to install *greywater reuse* and *recycling* systems due to high water prices. The capacity for using greywater reuse systems in Japan is smaller, compared to the US and Australia, since they only use reclaimed water for toilet flushing (Chung & White 2009). In Spain, local regulations are making greywater reuse obligatory (Domenech & Sauri 2010).

2.2.2.3 Rainwater

Rainwater in the context of the urban water system refers to the rainwater that flows as roof runoff and collected in rainwater tanks. The collection of rainwater, or as it is popularly called *Rainwater Harvesting* (RH), is considered to be a *Sustainable Practice*. The collected rainwater can be used for any indoor or outdoor purposes. Hurlimann and Dolnicar (2010) even stated that rainwater is the most publically acceptable water alternative in Australia. However, for the urban catchment that has centralised water supply pipe infrastructure, rainwater is usually used only for laundry, shower, toilet and irrigation, but not for water supply to the kitchen.

The adoption of *Rainwater Harvesting* has been increasing in many countries due to uncertain and prolonged droughts. *Rainwater Harvesting* has been known to offer the benefits of potable water saving and a reduced pollutant load to the drainage system. Governments have setup regulations, standards or guidelines for use and installation of rainwater tanks as well as incentives or rebates. In Australia, rebates of up to $500 are given for the installation of a rainwater tank (Australian Government 2010a; Beal et al. 2011a). In Canada and the US, installation of rainwater tanks must follow local regulations and guidelines for installation and operation of rainwater systems (Fewkes 2006). In New South Wales, Australia, the state government created the BASIX initiative (Building Sustainability Index) to ensure that homes are designed to use less potable water, and reduce greenhouse gas emissions by setting energy and water reduction targets for households. Consequently there has been an increase in *Alternative Water Sources* such as rainwater (New South Wales Government 2011).

2.3 Wastewater Characteristics

This section discusses wastewater characteristics only from residential WMP since residential areas are the major contributor of urban wastewater. As mentioned in several studies, the load of residential wastewater is dependent on the characteristics used to supply the water demand for indoor use and the existence of external water contaminants (e.g. detergent, soap, toothpaste), human input (human excreta, dirt from used clothes and so on) and transmittance pipe contaminant (Almeida et al. 1999b; Eriksson et al. 2002; Tjandraatmadja et al. 2009c). In urban catchments, water consumption for indoor use is usually supplied by pipe mains that belong to the water authorities. When this water is used for any activity, it will be contaminated. Finally, wastewater will contain used water, the contaminant from its source and external contaminants. In the case of WMP implementation, some indoor water demand is supplied by alternative water, such as rainwater or treated wastewater, or the introduction of water saving appliances triggers less used water and subsequently reduces wastewater production.

The next section is divided into two subsections; the first subsection describes household indoor uses that contribute to residential wastewater contaminants. The water source is assumed solely from pipe mains. Thus, the review importantly determines wastewater parameters that might change due to WMP. The second subsection presents wastewater characteristics from WMP based on past studies as well as the approximation of wastewater characteristics based on water supply characteristics.

2.3.1 Residential Wastewater Characteristics from Traditional Practice

Household wastewater contaminant sources are potable water from pipe mains and commercial products used and human contributions which are presented in Table 2.4 (Almeida et al. 1999b; Tjandraatmadja et al. 2009c). Segregation of wastewater quality enables identification of pollution contributions by source, and the level of pollution from each source is summarised and ranked in Table 2.5.

Table 2.4 and Table 2.5 present results from Almeida et al. (1999b), Tjandraatmadja et al. (2009c), Beat et al. (2011b), Willis et al. (2009b) and Keener et al. (2008). Table 2.4 summarises the origin of wastewater quality within households and the percentage load from each source for residential wastewater. Wastewater contaminants are mostly contributed by humans and commercial products. Potable water has the least contribution to wastewater quality loads, with the exception of showers. The highest load of iron and copper are from showers, mainly from potable water. Table 2.5 summarises and ranks the wastewater quality load from household sources. The toilet and washing machine trigger many sewer problems. Other sources, such as the kitchen sink, vanity unit, dishwasher and shower, also contribute wastewater pollutants but in lesser quantities. As per studies conducted in Australia, maximum wastewater volume is contributed by shower/bath use followed by the washing machine (Beal et al. 2011b; Talebpour et al. 2011; Willis et al. 2009b).

There are many contaminants that exist in the wastewater where the main pollutants in the domestic wastewater mostly dominated by organic matter, nutrients, and minor amounts of metals and micropollutants. However, there are only several wastewater quality parameters that affect downstream infrastructure, such as sewerage networks, because of their capacity to produce dangerous or beneficial substances in sewer transformation processes. In this sub-section, the parameters which are considered to significantly contribute to common sewer problems (i.e. blockage, odour and corrosion) are discussed in detail. .

Table 2.4. Source of Wastewater Quality Loads in Household Appliances

	Toilet		Kitchen sink		Shower		Vanity Unit		Washing Machine		Dishwasher	
	Potable water (%)	**Human input+ products (%)**	**Potable water (%)**	**Human input+ products (%)**	**Potable water (%)**	**Human input+ products (%)**	**Potable water (%)**	**Human input+ products (%)**	**Potable water (%)**	**Human input+ products (%)**	**Potable water (%)**	**Human input+ products (%)**
COD*	0	100	0	100	0	100	0	100	0	100	-	-
Nitrate**	33.87	66.13	1.43	98.57	1.98	98.02	4.92	95.08	8.91	91.09	-	-
Sulphur	4.3	95.7	7.1	92.9	10.5	89.5	5	95	17.6	82.4	43.5	56.5
Iron	20.8	79.2	78.7	21.3	99.99	0.01	2.98	97.02	77.2	22.8	63.8	36.2
Copper	23.4	76.6	40	60	89.74	10.26	8.9	91.1	99.5	0.5	15.5	84.5
Zinc	0.9	99.1	23.9	76.1	58	42	1	99	95.4	4.6	1.3	98.7
TSS***	0.08	99.92	0.27	99.73	0.49	99.51	1.27	98.73	0.86	99.14	-	-
FOGs	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

*According to Australian Drinking Water Guidelines, there is no organic matter allowed in drinking water.
**Taking an assumption that nitrate content in potable water is following typical concentrations of ADWG (Australian Government 2004)
***Taking an assumption that potable water has turbidity following the minimum value of turbidity at major Australian reticulated supplies turbidity which is 1 NTU. The relationship between turbidity and TSS is taken from the model provided by Packman et al. (1999).

Table 2.5. Ranking of Household Appliances Based on Its Contribution to the Selected Wastewater Parameters

Reviewed parameters	Ranking (with 1 being highest and 6 being lowest rank)						References
	1	2	3	4	5	6	
Waste water Vol.	Shower	Washing machine	Tap	Toilet	Dishwasher	-	(Beal et al. 2011b; Willis et al. 2009b)
COD	Toilet	Washing machine	Kitchen sink	Shower	Vanity unit	-	(Almeida et al. 1999b)
Nitrate	Kitchen sink	Shower	Kitchen sink	Vanity unit	Washing machine	-	(Almeida et al. 1999b)
Sulphur	Toilet	Washing machine	Shower	Kitchen sink	Vanity unit	Dishwasher	(Tjandraatmadja et al. 2009c)
Iron	Toilet	Washing machine	Shower	Kitchen sink	Vanity unit	Dishwasher	(Tjandraatmadja et al. 2009c)
Copper	Washing machine	Toilet	Vanity Unit	Dishwasher	Shower	Kitchen sink	(Tjandraatmadja et al. 2009c)
Zinc	Toilet	Vanity unit	Dishwasher	Shower	Kitchen sink	-	(Tjandraatmadja et al. 2009c)
TSS	Toilet	Kitchen sink	Shower	Vanity unit	Washing machine	-	(Almeida et al. 1999b)
FOGs	Kitchen	Shower	-	-	-	-	(Keener et al. 2008)

2.3.2 Impact of WMP on Wastewater Characteristics Based on Existing Studies

Some studies have attempted to predict the wastewater characteristics from WMP (DeZellar & Maier 1980; Parkinson et al. 2005). Many discuss common parameters, such as wastewater volume and organic, solid and nitrogen contents, while in fact many wastewater parameters still need to be considered, since they can affect downstream infrastructure. In regard to these, Table 2.6 presents a comparison between wastewater characteristics of traditional and non-traditional practices (WMP). This clearly indicates significant changes in wastewater characteristics from WMP compared to current practices.

The following sub-subsections describe the change in wastewater characteristics due to several WMP.

2.3.2.1 Water Demand Management

The use of water saving appliances within households has become normal practice, particularly in water stressed areas. Therefore, this study focuses on implementation of the highest *Water Demand Management* practices, such as those which occur when all household appliances are of the highest rating. A study conducted by Sharma et al. (2009) considered developments intwo areas in Australia, and different water saving alternatives including highest *Water Demand Management* in residential, commercial, industrial and community precincts. Assuming highest *Water Demand Management* was implemented in residential areas, a total saving of 97 litres/capita/day or 43% of the per capita water demand was predicted. The laundry and bathroom were responsible for the greatest indoor water savings, which concurs with the studies conducted by Tjandraatmadja et al. (2009c), DeZellar & Maier (1980) and Parkinson et al. (2005). DeZellar & Maier (1980) also emphasised that water reduction leads to a reduction of wastewater flow and subsequently increases wastewater strength.

DeZellar and Maier (1980) estimated that reductions of 30-55% in water consumption caused wastewater flow reductions of 15- 16%. The reduction between the water consumption and wastewater flow was not similar because not all the water consumption by the household becomes wastewater. According to Metcalf & Eddy (Metcalf & Eddy 1997), only 60-90% of the per capita water demand becomes wastewater. As wastewater flow decreased, the concentration of BOD and TSS generally increased (25-40%); however their loads remained nearly the same. Though this research did not focus on nitrogen, sulphur or phosphate loads, the grab samples taken in DeZellar and Maier's study indicated that nitrogen, sulphur and phosphate concentrations increased while loadings remained constant. Parkinson et al. (2005) confirmed that due to the use of water saving toilets, the concentration of TSS, BOD, COD and Ammonium N increased by 10% for a change from a 9L to a 6L flush toilet, and increased by 24% for a change from a 9L flush toilet to a 4/2L dual flush toilet.

2.3.2.2 Blackwater Recycling (Sewer Mining)

Blackwater is the source of almost all pathogens and nutrients. Blackwater characteristics are mainly dominated by organic matter, nitrogen and phosphorus compounds, oil and grease, solids and coliform bacteria. A study from Atasoy et al. (2007) presents the effluent from a blackwater membrane bioreactor plant reused for toilet flushing or irrigation. According to that study, the percentage removal of COD, TSS, total Nitrogen and NH_4^+ was 96%, 98%, 99% and 89% respectively. Thus, all effluent concentrations are below those suggested by US.EPA for reclaimed water.

The other important parameters in *blackwater recycling* are nitrates, nitrites, sulphur compounds and iron. Domestic wastewater generally contains no more than 3% nitrates and nitrites, while sulphur compounds are present in human excreta and nearly 90% are sulphate. The other sulphur compounds found in excreta are esters of sulphuric acid and neutral sulphur compounds (Larsen & Gujer 1996; Udert et al. 2006). According to a study conducted by Tjandraatmadja et al. (2009c), sulphur and iron are mostly contributed from the toilet, which is the main component of blackwater. As mentioned in Table 2.4, dominant contaminants in the toilet are contributed by humans and products used in the toilet, while potable water provides little contribution to toilet contaminants. Similarly, contaminants from the kitchen are mostly derived from humans and products used in the kitchen, except for iron which is primarily contributed from potable water.

Sewer Mining is allowed in locations where there is sufficient wastewater flows in sewer networks to flush out any solids that may have been deposited during low flow periods. Swamee et al. (1987) described the approach for estimating minimum flow requirements. The flow is deemed sufficient when minimum sewer operational flow is calculated by considering diurnal flow pattern and other *Sewer Mining* which extract sewage upstream or downstream of the proposed *Sewer Mining* extraction point. Generally, *Sewer Mining* does not use conventional wastewater treatment plants, but typically a compact, sometimes portable advanced treatment plant. This practice allows the treatment residuals (e.g. treatment sludge) to be discharged back to the sewer as long as it does not substantially increase the load in the sewer (Sydney Water 2008). According to Sydney Water (2008), the residual discharge of *Sewer Mining* is more likely to contain grit, more concentrated wastewater and some additives from treatment such as iron, aluminium and sulphate. For example, in Sydney they set the acceptance standard for the concentration of suspended solids in the receiving sewer to 600 mg/L and no grit is allowed to be discharged back to the sewer. Problems will arise from a *Sewer Mining* operation if the treatment residuals (treatment sludge which consist of suspended solid, grit and chemicals) are discharged back to the sewerage networks. Unfortunately, the setup of regulations was intended only to overcome the solid problem in sewerage networks, while neglecting organic and chemical problems that can lead to sewer odour and corrosion.

2.3.2.3 Greywater Recycling

Use of greywater in residential appliances will not only reduce the demand on drinking water, but also reduce the quantity of wastewater discharged to the environment. *Greywater Recycling* is usually used for reducing water demand associated with toilet and outdoor use.

However, in some places, for example in Australia, greywater is treated to Class A water and then reused in washing machines (New South Wales Government 2008).

Greywater contains micro pollutants, small amounts of nutrients, pathogens and quite high organic matters. Organic matters are found largely in wastewater. It is also stated by Jenssen et al. (2003) where organic matters load holds around 50% of the total pollutant load in the wastewater. Organic matter contains organic micro-pollutants, such as XOCs (Xenobiotic organic compounds) which originated from the chemical product such as detergent, soap, shampoo, etc. Micro-contaminants are not considered to have a major influence on sewer processes because of their minor concentrations, although there is no known study of micro-contaminants on sewer processes. The study by Hocaoglu et al. (2010) showed that greywater has relatively high readily biodegradable organic matter and contains more soluble COD compared to blackwater, which has more particulate COD. The nutrient compounds in the greywater can vary significantly and depends on the type of the chemicasl used as detergents, soap, and shampoo,. Christova-Boal et al. (1996) reported that if greywater is reused for toilet and garden, it can save 31% of total water consumption and reduce total wastewater by 47%. However, the wastewater quality loads (organic and TSS) would be lowered by around 40% (DeZellar & Maier 1980). Furthermore, if greywater is also reused for washing machines, then the wastewater volume will be additionally reduced by 13-16% (Almeida et al. 1999b; Butler et al. 1995).

Parkinson et al. (2005) modelled WMP of greywater reuse, combinations of greywater reuse and installation of water saving appliances in a household to predict the characteristics of wastewater effluent. In his model, the reference condition (which is called *Base Case* or traditional practice) was set by using a household without a greywater reuse facility and with a 9L flush toilet. This study assumed that all greywater from household appliances was completely reused, so the sewer discharge was mainly from toilets (excreta, water flushing and urine). For residential households that implement only *Greywater Recycling*, the concentration of TSS, BOD, COD and Ammonium N in wastewater discharge to the sewerage network increased by 23%. For households that implemented the combination of *Greywater Recycling* and water saving appliances (7.5L flush toilet), the concentration of TSS, BOD, COD and ammonium N in wastewater increased by 42%.

2.3.2.4 Rainwater Harvesting

The water collected from rainwater tanks is usually used for garden irrigation, toilet, laundry, shower and bath purposes (Victorian Government 2006). This technology has been reported to save up to 60% of main’s water supply (Villarreal & Dixon 2005), depending on the storage size. Recent studies by Kim et al. (2007) and Najia & Lustig (2006) have identified that organic, total nitrogen and total phosphorus concentrations in rainwater range from 76-345 mg/L, 1.33-2.0 mg/L and 0.087-0.13 mg/L respectively.

However, rainwater from roof runoff contributes significantly to the metal content in wastewater, especially lead. Type of roof, gutter and tank material and its condition as well as the background air pollution is suspected to contribute to metal content in wastewater (Foerster 1999; Magyar et al. 2008; Yaziz et al. 1989). Cook et al. (2010) showed that metal content in wastewater from *Rainwater Harvesting* was significantly higher compared to areas without *Rainwater Harvesting*. Iron and lead were the two metals that had the highest increase of around 300% and 500%, and it was assumed that rainwater was used to replace the potable water source for laundry and toilet applications. The scenario modeling by Cook et al. (2012) assumed household roofs were glazed tiles with lead flashing, which was confirmed by study from (Magyar et al. 2008) as the roof type that most contribute to the increase of iron and lead in collected rainwater.

The sulphate content of rainwater is also a potential issue because sulphate (SO_4^{2-}) is one of the most common anions occurring in rainfall, especially in air masses encountered in metropolitan areas. D’Innocenzio and Ottaviani (1988) analysed sulphate concentrations of rainwater in the urban zones of Rome (Italy), and stated that monthly variation in sulphate concentration varied from 3-27 mg/L. Coombes et al. (2002) in Australia revealed that sulphate concentration in the rainfall collected from roofs was 1.79-14.50 mg/L and that collected from rainwater tanks was 1.7-5.3 mg/L. The concentration variation depended on rainfall intensity.

Table 2.6. Wastewater Characteristics of Reviewed Parameters from Various Studies of WMP

	Population (Cap)	W.W volume (m^3/day)	TSS (mg/L)	Organic (mg/L)		%increase of Sulphate conc. from the *base case*	Metal (mg/L)			Reduced nitrogen (mg/L)		Oxidized nitrogen (mg/L)	Total nitrogen (mg/L)	Reference
				BOD	COD		Fe	Cu	Zn	TKN	Ammonium N	Nitrite/ Nitrate		
Existing household practice (Ref)**	86000 (not including the pop. for commercial, industrial & community)	31287.67	140.24*	31.61*	148.43*								7.35*	(Sharma et al. 2005; Sharma et al. 2009)
Rainwater tank, untreated greywater re-usereuse, highest demand management		14854.80	248.35*	86.12*	306.89*								9.77*	
Existing 9 L flush (Ref.)**	21434	2893.59	391	400	751					82	40			(Parkinson et al. 2005)
Reduced 7.5 L flush		2764.99	409	419	786					85	42			
Reduced 6 L flush		2636.38	429	439	825					90	44			
4/2 L flush		2314.87	486	498	934					102	50			
Greywater re-usereuse (9 L flush)		2207.70	509	522	978					106	52			
Greywater re-usereuse (7.5 L flush)		2057.66	549	562	1056					115	57			
Existing household practice (Ref.)**	1694	270.15					0.26	0.12	0.16	41.71				(Cook et al. 2010)
Water Demand Management		168.76					0.36	0.17	0.19	66.54				
Greywater Recycling (direct diversion)		226.32					0.26	0.13	0.16	48.92				
Greywater Recycling (treatment & storage)		139.48					0.24	0.09	0.09	75.03				
Rainwater Harvesting		269.21					1.13	0.12	0.33	44.33				
Existing practice (Ref.)**	2389500	886504.5	310.07	261										(DeZellar & Maier 1980)
Practice with Water conservation		678618	350.5	338.29		+31%					increase	decrease		

*Some of the wastewater concentration was calculated from their load

** Reference condition /*base case*/Business as usual/traditional practice

2.4 Sewerage Network Systems

This section first discusses the wastewater transformations in sewer networks that lead to or reduce the common problems of blockage, odour and corrosion, followed by a discussion on factors that lead to these problems. Understanding the changes in residential wastewater characteristics due to the implementation of WMP is essential to study the impact of WMP on sewer networks, because different wastewater characteristics trigger various problems in sewerage systems. This section focuses on gravity based separate sewer systems because it is the most common system in Australia and is the system considered in the case study area.

2.4.1 Wastewater Transformation in Sewerage Systems

During transportation wastewater undergoes some characteristic changes (transformation), particularly with regard to the characteristics of organic matter and some important parameters in biological processes such as nitrate, sulphate, oxygen, sulphide and ammonium. The transformation processes occurring in the pipe create intermediate and end products that can either result in benefits or problems for the sewerage system, wastewater treatment plant as well as for the option for wastewater reuse. Hydrolysis of sewerage is beneficial for wastewater treatment because it produces readily biodegradable substrates that can be easily treated. However, some products of the transformation processes, such as hydrogen sulphide and volatile organic compounds, potentially contribute to odour and corrosion in sewerage systems.

Sewer pollutant transformation is classified into four processes; they are (1) sulphide generation, (2) chemical and biological oxidation of sulphide, (3) sulphide emission, and (4) sulphide precipitation (see Figure 2.4). The formation of the transformation products depends on a range of factors including temperature, wastewater flow or residence time in the sewer, type of sewer pipe (pressurised or gravity), wastewater quality, sewer structure (i.e., slope) and nature of the biochemical processes (bulk water, biofilm or sediment) (Almeida et al. 1999a; Nielsen et al. 2008b; Nielsen & Hvitved-Jacobsen 1988; Nielsen et al. 1992; Tanaka et al. 2000). Hydrogen sulphide in wastewater exists in three forms; they are elemental sulphur, metal sulphide and dissolved sulphide. Combination of these sulphide forms is usually called as total sulphide in wastewater.

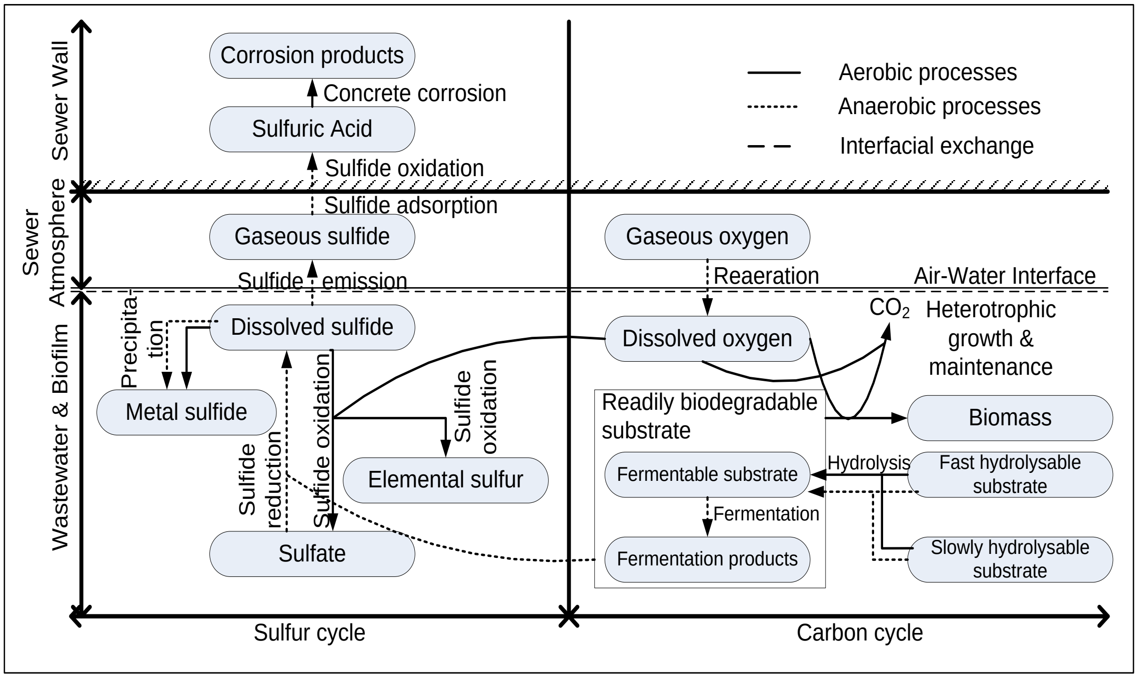


Figure 2.4. Transformation in Sewer System (Nielsen et al. 2008a)

2.4.2 Sewer Problems Associated with Wastewater Quantity and Quality

2.4.2.1 Blockage

Sewer blockage is considered to be the number one cause of loss in sewer serviceability (Ashley 2004). The most common causes are build-up of fats, oils and greases (FOGs), debris, or other solid deposition, tree root intrusion and sewer line collapse (Arthur et al. 2008; Ashley et al. 2003; Geyer & Lentz 1966; Randrup et al. 2001). Build-up of FOGs and solids deposition are likely to be influenced by wastewater characteristics that enter the sewer network, whereas sewer line collapse results from hydraulic and physical factors such as large flows, pipe age as well as pipe condition (Arthur et al. 2008). This review considers blockage problems triggered by parameters originating from wastewater characteristics.

FOGs in sewer systems mostly originate from kitchens (food production) and showers (the use of soap) (Keener et al. 2008). FOGs are very slowly digested and degraded by microorganisms (Cammarota & Freire 2006; Wakelin & Forster 1997). High FOGs have an adhesive character and they generally solidify when cooled. The combination of high FOGs and solids in the sewer can create blockage problems (Keener et al. 2008), and some studies also identified that high FOGs alone can lead to sewer blockage problems (Marvin & Medd 2006; Southerland 2002; U.S. E.P.A 2003). According to Keener et al. (2008), the deposition problem, due to FOGs, does not occur spontaneously after they are discharged to the sewer. Generally, deposits will form between 50 and 200m downstream of their point of discharge. The same study also revealed that average FOG accumulation rates in sewer pipes were 0.10 cm/day and generally FOG cleaning frequencies in pipes varied from 3 months to 2 years using hydrojet cleaning.

The most widely used technology to reduce the impact of FOGs is pre-treatment systems, such as grease-traps that intercept most FOGs and large particulate solids before they enter sewerage systems. After passing the trap, most of the remaining solids will be suspended. The suspended solids in sewage contain soluble organic matter and the remaining FOGs which make the solids cohesive (Crabtree 1989). Sewer pollutant transformations also contribute to the formation of cohesive solids (Verbanck et al. 1994; Williams et al. 1989). Experimental research by Mitchener & Torfs (1996) and Torfs (1994) showed that the greater the content of cohesive solid in the sewage, the greater its resistance to erosion. Greater resistance means that cohesive solids will not be transported by wastewater flow. To conclude, the presence of FOGs, organic matter and solids trigger the occurrence of cohesive solids that can create blockages in sewer pipes.

2.4.2.2 Odour

It is well known that malodorous compounds in sewerage systems can create nuisance problems and sometimes threaten public health, if released into urban atmospheres. Malodorous compounds can be classified as organic and inorganic. Inorganic gases consist of carbon dioxide (CO_2), ammonia (NH_3), methane (CH_4) and hydrogen sulphide (H_2S), and the organic gases (VOCs-Volatile Organic Compounds) consist of products from fermentation such as volatile fatty acids, skatole, indole, ketone, mercaptan and amines (Hwang et al. 1995; Thistlethwayte & Goleb 1972). Not all gases mentioned above contribute to odour problems. Carbon dioxide and ammonia are gases that are typically released under aerobic or anoxic conditions and are considered odourless (Hvitved-Jacobsen & Vollertsen 2001). Ammonia is considered an odourless gas because it has a high recognition threshold value (≈ 40 ppb) and at typical neutral pH, ammonia has a low tendency to be released from wastewater. Methane (CH_4) is also an odourless gas and forms under anaerobic conditions. Methane is considered less important, since it forms in the absence of sulphate and in typical residential wastewater, sulphate is usually present. Residential wastewater usually has sulphate concentration in the range of 40-200mg/L (Araujo et al. 2000).

A study by Hwang et al. (1995) found that malodorous compounds in sewerage systems are dominated by hydrogen sulphide and volatile organic compounds. Hydrogen sulphide is recognised by its characteristic rotten egg odour and can be detected by human senses at a concentration level of 0.001 ppm-0.002 ppm, cause an unpleasant and strong smell at 0.5-10 ppm, has sublethal effects (nausea and eye, nose and throat irritation) at 10-50 ppm, endanger the human eye and respiratory system at 50-300 ppm, be life threatening at 300-500 ppm and cause instant death in concentrations higher than 500 ppm (Hvitved-Jacobsen 2002). The volatile organic compounds are recognised from many different sensory perceptions, for example: dimethyl sulphide and ethyl mercaptan are recognised by their decayed cabbage odour, dymethyl amine by a fishy odour and formaldehyde by a pungent odour (Cheremisinoff 1992). Little information is available about the limit threshold value of each volatile organic compound but Hwang et al. (1995) have indicated that the greatest malodorous volatile organic compound is indole and skatole. These two compounds originate from the breakdown of human discharge from the toilet (Alison 2001).

Generally, potable wastewater, particularly residential wastewater, produces a musty odour and does not produce any odour problems (Water Environment Federation 2008). After entering the sewer, wastewater undergoes a transformation process and potentially forms malodorous compounds when conditions are anaerobic. Factors that support odour formation are mostly similar to those that encourage biochemical transformation processes, except for pipe material (Hvitved-Jacobsen & Vollertsen 2001). Pipe material is a very important factor for odour generated by H_2S because if the pipe is made of plastic/PVC, it has slower surface reactions, leading to low H_2S adsorption in the surface material. This results in greater accumulation of hydrogen sulphide gas in the sewer pipe and thus increases odour problems (Nielsen et al. 2008b). Odour problems are more frequently found in large intercepting sewers with low slope, downstream of pressurised sewer mains, and in pipe sections where high turbulence occurs (Vollertsen et al. 2008).

2.4.2.3 Corrosion

Besides causing odour, hydrogen sulphide gas is also known corrosion causing compound. Corrosion occurs when the free water surface releases hydrogen sulphide gas into the atmosphere and absorbed by moist sewer pipes. The most severe case of corrosion is usually found in the section where high turbulence occurs, at the change from pressurised sewers to gravity sewers and in pumping stations (Aesoy et al. 1997). With respect to the total sulphide concentration, minor corrosion has been found in wastewater that has sulphide concentration in the range of 0.1-0.5 mg/L. Dissolved sulphide concentration higher than 2 mg/L causes severe corrosion in sewerage pipes (Hvitved-Jacobsen et al. 2002). Rehabilitation and restoration of corroded sewers can cost millions. For example in the USA, the rehabilitation of corroded pipelines are estimated to be $1.91 million/km rehabilitated pipe (Sydney et al. 1996).

Through biological and chemical oxidation in the moist pipe surface, hydrogen sulphide is converted to sulphuric acid (H_2SO_4) which corrodes the pipe. The oxidation is triggered by the presence of corrosion causing bacteria, humidity, temperature, pipe age and pipe material. The most common bacteria for biological oxidation are *acidithiobacillus thiooxidans* (Okabe et al. 2007). Though biological and chemical oxidation produce the same product of elemental sulphur, biological oxidation however dominates the production of elemental sulphur since it has a higher oxidation rate compared to chemical oxidation (Jensen et al. 2009).

Furthermore, as mentioned earlier, the corrosion causing process is also determined by the pipe material and age. Corrosion is most extensive in concrete or metal pipes because these pipes have faster surface reactions compared to plastic pipes. Witherspoon et al. (2004) have shown that the corrosion causing process in corroded concrete sewers occurs faster than in new pipes. This is because the new sewer pipe usually has high alkalinity (with pH ranging from 11-13) and bacteria such as *acidithiobacillus thiooxidans* which cannot survive at pH values higher than 7. Generally, ageing of concrete sewers results in a decrease of pH to around 6-7 because ageing concrete sewers have adsorbed hydrogen sulphide which is oxidised to sulfuric acid. At pH 6-7, these bacteria colonise concrete sulphide, further reducing the surface pH to less than 5, which increases the rate of corrosion. These bacteria are very robust since they can survive hydrogen sulphide starvation for longer than 6 months (Jensen et al. 2008). This finding is very important for cold areas and other areas where H_2S corrosion is found to be an intermittent rather than a permanent problem.

The corrosion process involves the reaction of sulphuric acid and cementitious material of the pipe. This reaction causes the pipe lifespan to decrease and eventually it will cause collapse of the sewer. The pipe lifespan can be calculated by dividing the allowable penetration due to corrosion with the rate of penetration into the pipe. The allowable penetration due to corrosion is simply defined as the thickness of the pipe and the rate of penetration is defined as corrosion rate. The equation to determine pipe lifetime is shown in Equation 2.1.

$$L = \frac{z}{c} \qquad \text{……} \textbf{2.1}$$

2.4.2.4 Summary

Figure 2.5 classifies the parameters which support the problems of blockage, odour and corrosion in sewers. Low wastewater volume, high solids (TSS) and high FOGs are the main contributors to blockage, while odour and corrosion are triggered by long residence time, which can be caused by combinations of low wastewater flows and low slope, high organic content and sulphate loads, as well as high temperature and low pH. Figure 2.6 shows the wastewater parameters that decrease the release of hydrogen sulphide and inhibit the generation of hydrogen sulphide. Metal content will bind with sulphide and form a metal sulphide precipitate; therefore, hydrogen sulphide gas generation will be inhibited. Nitrate/nitrite and dissolved oxygen are electron acceptors in anoxic and aerobic conditions, and also act to inhibit hydrogen sulphide generation.

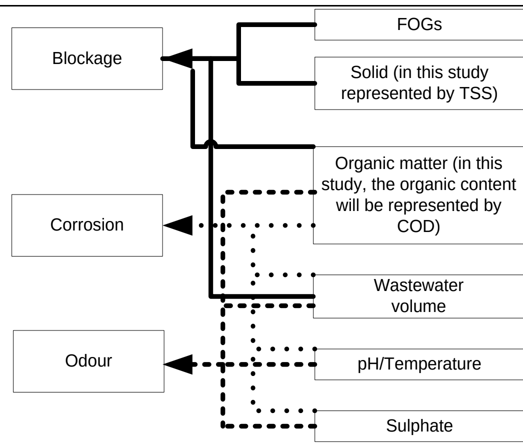


Figure 2.5. Parameters that Support Blockages, Odour and Corrosion

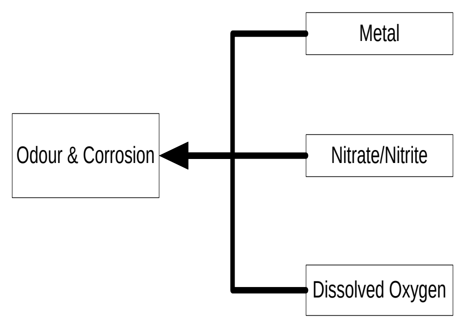


Figure 2.6. Parameters that Inhibit Odour and Corrosion

2.5 Available Models to Investigate the Impact of WMP Adoption in Sewerage Networks

Models are used for several purposes (Mulligan & Wainwright 2004) including:

1. An aid for research
2. A tool to understanding
3. A tool for simulation and prediction
4. A virtual laboratory
5. An integrator of knowledge within and between disciplines
6. A research product
7. A means of communicating science and the results of science.

Models have a significant role in water resources management, especially in managing future uncertainties in water availability. Moreover, climate change and rapid population growth have further added uncertainties in modeling urban water resources.

Since the middle of the 1980s, models have been widely employed by both researchers and practitioners for assessing hydrological and hydraulic aspects of water resources, and during the second half of the 1990s for assessing pollutant loads and concentration. In comparison to flow modeling, the history of sewer water quality modeling is relatively short and the knowledge on water quality processes is still developing (Freni et al. 2008). Moreover, water quality modeling involves many complex equations and a large number of input and output variables, which are acting as impediments in the development of a water quality model. Data collection for wastewater quality modeling from field study are often limited in practice as they are considered expensive and time- consuming (Nguyen et al. 2007). The following subsection presents some available models for simulating wastewater flow and quality from the initial point of generation. Furthermore, it classifies those models based on their main functions.

This study identified 10 models for urban water and wastewater system from previous reviews, journal, model webpage, conference proceedings, etc. Model presented here were firstly introduced for the name (or its abbreviation), the latest available model, the model references, organisation which created the model and finnaly the cost of the model. The comparison between this attributes can be seen in Table 2.8.

Table 2.8. Introductory Information of Urban Water-Wastewater Models

Model	Version	References	Primary author/ organisations	Cost
UVQ	First: 2000 Latest:2005	http://www.csiro.au/Outcomes/Water/Water-for-cities-and-towns/UVQ.aspx	CSIRO	Non-commercial software
Aquacycle	First: 2000	http://www.toolkit.net.au/tools/Aquacycle (Mitchell et al. 2001)	CRC for Catchment Hydrology, Department of Civil Engineering	Available for small charge. Not contaminant modeling
WBM	First: 2004	http://www.waterbalance.ca/	Greater Vancouver Regional District	Web-based, basic model is free; ongoing licence payment for full model
WaterCress	First: 1995	http://www.waterselect.com.au/watercress/watercress.html (Clark et al. 2002)	WaterSelect P/L Richard Clark & David Cresswell	Free
SWMM; Proprietary versions are XPSWMM; PCSWMM and MIKE-SWMM	First: 1971 Latest: 2005	http://www.epa.gov/nrmrl/wswrd/wq/models/swmm/	US EPA	US EPA (SWMM5) version is free including code but the Proprietary versions are available at cost
MIKE URBAN (MU) - MOUSE	First: 1985 Latest: 2004	http://www.crwr.utexas.edu/gis/gishyd98/dhi/mouse/mousmain.htm	DHI Water and Environment	Commercially available at cost
Infoworks CS		http://www.innovyze.com/products/infoworks_cs/	Wallingford Software UK	Commercially available at cost
WATS	First: 2008	www.sewer.dk/TheWATSmodel.htm	Aalborg University, Denmark Jes Vollertsen	The model is still in enhancement stage
MU - MOUSETRAP	First: 1985 Latest: 2004	http://www.crwr.utexas.edu/gis/gishyd98/dhi/mouse/mousmain.htm	DHI Water and Environment	Commercially available at cost
SeWex	First: 2009	http://www.sewex.com.au/	UQ Advanced Water Management Centre (AWMC).	Commercially available at cost

Further, the model was evaluated in relation to the following attributes and summarizes in Table 2.9:

1. Potential Uses - The intended uses of the model including research, education, design and planning.
2. Model Capability - The capability of the model in urban water and wastewater system. In this point, the models were evaluated based on the specific capability offered by the model. The particular capability highlighted in this study are wastewater generation, sewer flow modeling and contaminant and gas modeling capability.
3. Model Resolution - Temporal and spatial resolution of the model is very important factor to run the model temporal resolution refers to the smallest computational timestep of the model. The spatial resolution refers to the size of the modelled area, whether it is only for one catchment or it can be used for multi catchment.
4. Model Calibration - The type of calibration in this model refers to the calibration capability of the model, whether it has to be manually adjusted calibration or automatic calibration has been embedded in the model. Manual calibration becomes harder as the number of model parameters increases. Alternatively, automatic calibration methods are available to deal with large, complex models. Key factors in evaluating an automatic calibration method are the ability to locate global optima, numerical stability and computational burden.
5. Model Input and Output - Input and Output of the model explains what type of input data and what kind of output data obtained from the model. The input data also included the requirement of input data for calibration process. Supposing that more complex models are applied, the problem of data collection remains a major challenge. Zoppou (2001) and Rauch et al. (2002) argued that lack of data is a greater hindrance to any model particularly water quality models. Monitoring and sampling are expensive, leaving many catchments with sparse data (Rodriguez et al., 2000). When data are collected, sampling techniques are often inconsistent, and different urban runoff studies cannot always be easily compared (Leecaster et al., 2002; Kanso et al., 2003). Certain parameters can be highly specific to location or region and are not transferable to studies in dissimilar areas (Driver and Troutman, 1989; Hoos, 1996).

Table 2.9 compares the model in relation to the attributes described above.

Model	Uses	Model Capability				Resolution	Type of Calibration	Input & Output
		Wastewater generation	Water/ Wastewater Management Practice	Sewer Flow	Sewer Contaminant & Gas			
UVQ	Research	Indoor and outdoor water demand, infiltration, exfiltration and leakage in a household. Simulate wastewater quality (wastewater concentration & load per person).	Rainwater harvesting, stormwater harvesting, greywater recycling in a household, neighbourhood and study area scale.	Have no routing of sewer flow (lumped wastewater reservoir in each subcatchment).	-	Daily time step. The maximum time period of a single simulation is 100 years. 3 spatial components: land block, neighbourhood and study area	Manual	Input : historical rainfall, water demand, pollutant load, properties size. Output: Wastewater and stormwater flow and quality, reliability of WMP.
Aquacycle	Research	Indoor and outdoor water demand, infiltration, exfiltration and leakage in a household.		Have no routing of sewer flow (lumped wastewater reservoir in each subcatchment).	-	Same as UVQ	Manual	Input : historical rainfall, water demand, properties size. Output: Wastewater and stormwater flow, reliability

Model	Uses	Model Capability				Resolution	Type of Calibration	Input & Output
		Wastewater generation	Water/ Wastewater Management Practice	Sewer Flow	Sewer Contaminant & Gas			
								of WMP.
WBM	Research	Indoor and outdoor water demand, infiltration, exfiltration in a household. Simulates wastewater quality (sediment)	Rainwater harvesting in a household, neighbourhood and study area scale.	Have no routing of sewer flow (lumped wastewater reservoir in each subcatchment) .	-	Hourly or sub-hourly time steps 3 spatial components: land block, neighbourhoo d and study area	Manual	Input :Historical rainfall, water demand, evaporation and soil catchment characteristics. Output : Wastewater and stormwater flow
WaterCress	Research/ design/ planning	Water demand, infiltration, exfiltration in lumped sub-catchment (not individual household) Wastewater quality is limited to salinity..	-	Have sewer flow routing from the sub-catchment generation to the outlet of the catchment.	-	Daily, hourly or sub-hourly time steps. Spatial : City to regional scale.	Automatic Calibration	Input : Water demand data, historical rainfall and evaporation. Output : Wastewater and stormwater flow

Model	Uses	Model Capability				Resolution	Type of Calibration	Input & Output
		Wastewater generation	Water/ Wastewater Management Practice	Sewer Flow	Sewer Contaminant & Gas			
SWMM; Proprietary versions are XPSWMM; PCSWMM and MIKE-SWMM	Research/ design/ planning	Water demand, infiltration, exfiltration in lumped sub-catchment (not individual household) Any contaminant in wastewater can be generated	-	Have sewer flow routing by using approach of steady state or kinematic or dynamic wave equation.	Basic contaminant modeling by assuming decay coefficient or fraction of other contaminant. No sewer gas modeling	Annual to sub-hourly time steps. Spatially distributed with link-node sewer networks.	Manual/ SRTC (Sensitivity Radio Tuning Calibration), Automatic calibration	Input : Pipe network characteristics, land use, average water demand and some RDII parameters. Output : Stormwater and wastewater flow, contaminant concentration
MIKE URBAN (MU) - MOUSE	Research/ design/ planning	Same as SWMM	-	Flow routing was conducted by using approach of steady state or kinematic or diffusive, dynamic wave equation.	-	Same as SWMM	Manual & Automatic Calibration	Input : Pipe network characteristics, land use, average water demand and some RDII parameters. Output : Stormwater and wastewater flow

Model	Uses	Model Capability				Resolution	Type of Calibration	Input & Output
		Wastewater generation	Water/ Wastewater Management Practice	Sewer Flow	Sewer Contaminant & Gas			
Infoworks CS	Research/ design/ planning	Same as SWMM	-	Same as SWMM	Same as SWMM	Same as SWMM	Manual	Same as SWMM
WATS	Research/ design	Water demand in lumped sub-catchment (not individual household). Sulphide related contaminant (metal-iron, nitrate, nitrite, organic) in wastewater can be generated.	-	Flow routing was conducted by using approach of steady state and dynamic wave equation.	Contaminant related to hydrogen sulphide generation; Hydrogen sulphide gas modeling, corrosion rate.	Distributed hourly simulations for a maximum simulation time of 14 days. Spatially distributed link-node based sewer networks.	Manual	Input : Pipe network characteristics, land use, average water demand and sulphide related contaminant concentration. Output : Sulphide related contaminant concentration after transformation process, hydrogen sulphide gas and bulk water concentration, corrosion rate, wastewater flow.

Model	Uses	Model Capability				Resolution	Type of Calibration	Input & Output
		Wastewater generation	Water/ Wastewater Management Practice	Sewer Flow	Sewer Contaminant & Gas			
MU-MOUSETRAP	Research/ design/ planning	Water demand, infiltration, exfiltration in lumped sub-catchment (not individual household) Any contaminant in wastewater and sulphide related contaminant can be generated.	-	Flow routing was conducted by using approach of steady state or kinematic or diffusive, dynamic wave equation.	Complex contaminant modeling in sewer, including the sediment transport. Sewer gas is modelled by using limited mathematical model of wastewater transformation (aerobic & anaerobic tranformation).	Annual to sub-hourly time steps. Spatially distributed with link-node sewer networks.	Manual & Automatic Calibration	Input : Pipe network characteristics, land use, average water demand and contaminant concentration. Output : Contaminant concentration after transformation process, hydrogen sulphide gas and bulk water concentration, wastewater flow.
SeWex	Research/ design	Water demand in lumped sub-catchment (not individual household). Sulphide	-	Flow routing was conducted by using approach of steady state and dynamic wave equation.	Contaminant related to hydrogen sulphide generation; hydrogen sulphide gas	Distributed hourly simulations. Spatially distributed link-node	Manual	Input : Pipe network characteristics, land use, average water demand and sulphide related

Model	Uses	Model Capability				Resolution	Type of Calibration	Input & Output
		Wastewater generation	Water/ Wastewater Management Practice	Sewer Flow	Sewer Contaminant & Gas			
		related contaminant (metal-iron, nitrate, nitrite, organic) in wastewater can be generated.			modeling, chemical dosing modeling to inhibit hydrogen sulphide	based sewer networks		contaminant concentration. Output : Contaminant concentration after transformation process, hydrogen sulphide gas and bulk water concentration, wastewater flow.

2.6 Objectives of this Study

The primary aim of this study was **to quantitatively establish and to develop an understanding of the impact of WMP technology adoption in residential areas, in terms of propensity to sewer odour and corrosion on existing sewer pipe networks**. Odour and corrosion in sewer networks is caused by several chemical and biological compounds; however in this study odour and corrosion due to hydrogen sulphide formation is considered. WMP are mostly adopted in residential catchments to reduce the potable water demand because urban water demand is dominated by residential demand. Therefore, this study focuses exclusively on adoption of WMP in residential catchments. The above mentioned aim is achieved through several sub-aims, as presented below.

SUB-AIM ONE: Development of Integrated Water/Wastewater Quality Modeling Framework

Modeling wastewater quality from adoption of WMP requires extensive data, most of which is usually unobtainable. This study firstly aims to develop an Integrated Water/Wastewater Quality Modeling Framework. The Integrated Modeling Framework comprises urban catchment and sewerage networks. Section 2.5 presents details of available modeling tools to conduct integrated water/wastewater quality modeling.

SUB-AIM TWO: Development of WMP Scenarios

The second sub-aim of this study is to develop WMP scenarios to thoroughly investigate their impact on sewer odour and corrosion. The first step to develop these scenarios is to select suitable WMP, which are widely accepted by the public and based on feasibility of implementation in residential catchments. The scenarios are developed for each of the selected WMP by considering current and possible future developments. Sections 2.2 and 2.3 highlighted the basic knowledge of existing WMP and their particular water and wastewater characteristics, which were derived from previous studies.

SUB-AIM THREE: WMP Scenario Analysis

To finalise this study, the analysis of developed WMP scenarios was conducted. The analysis is derived from the simulation results of selected WMP scenarios, which is undertaken to assess the impact of WMP on odour and corrosion in existing sewerage networks. Details of common sewer network problems and their cause were presented in Section 2.4.

3. DEVELOPMENT OF MODELING FRAMEWORK

CONTENT: *Introduction; Field Data Collection; Integrated Urban Water model Framework; Existing Urban Development Model Setup; Summary*

To predict hydrogen sulphide build up on sewer networks, it is essential to have powerful modeling tool capable of modeling the complex process of wastewater generation, transportation and transformation. The following sections describe the steps incorporated in the design of a modeling framework to enable the prediction of hydrogen sulphide build up in sewer networks. Extensive data requirement was an obstacle to model hydrogen sulphide build up accurately. Therefore, the developed modeling framework was not designed only to model hydrogen sulphide build but it also has the advantage of generating scenarios by the use of simulation models.

3.1 Introduction

Integrated Urban Water model is a model or combined models that have been used to incorporate the concept of Integrated Urban Water Management (IUWM). Different definitions and interpretations of IUWM were listed in the literature, but the most general definition of IUWM is a practice of managing freshwater, wastewater, and storm water within an urban settlement. Hence, the Sustainable Urban Water model is a model that is capable of simulating all urban water (freshwater, wastewater, stormwater) from its source to its end fate. As can be seen in Figure 3.1, the component of IUWM comprises urban water catchments, sewerage networks, and wastewater treatment plants (WWTP), stormwater infrastructure and water intake. Among the IUWM components, urban catchment–sewer system relations are considered the least developed (Freni et al. 2009). The urban catchment as the generator of urban wastewater plays an important role in urban water management, while the sewer system is known as both the wastewater transportation means as well as a preliminary treatment system. The relations between urban catchment and sewer system is important to study since the sustainability of sewerage networks is dependent on urban wastewater quality (Erbe & Schütze 2005; Fronteau et al. 1997).

The IUWM model can involve several models to represent the various components of IUWM. The application of several models is required, since there has not been a single one that can model all the components of IUWM. The complexity of sustainable urban water models is due to the high level of detail in individual models and operational connections between different models (Rauch et al. 2002; Vanrolleghem et al. 2005). Although these connections have been calculated; in most cases, problems are still present regarding prohibitive computational requirements, especially in the case of long-term analysis (Nguyen et al. 2007; Willems & Berlamont 2002).

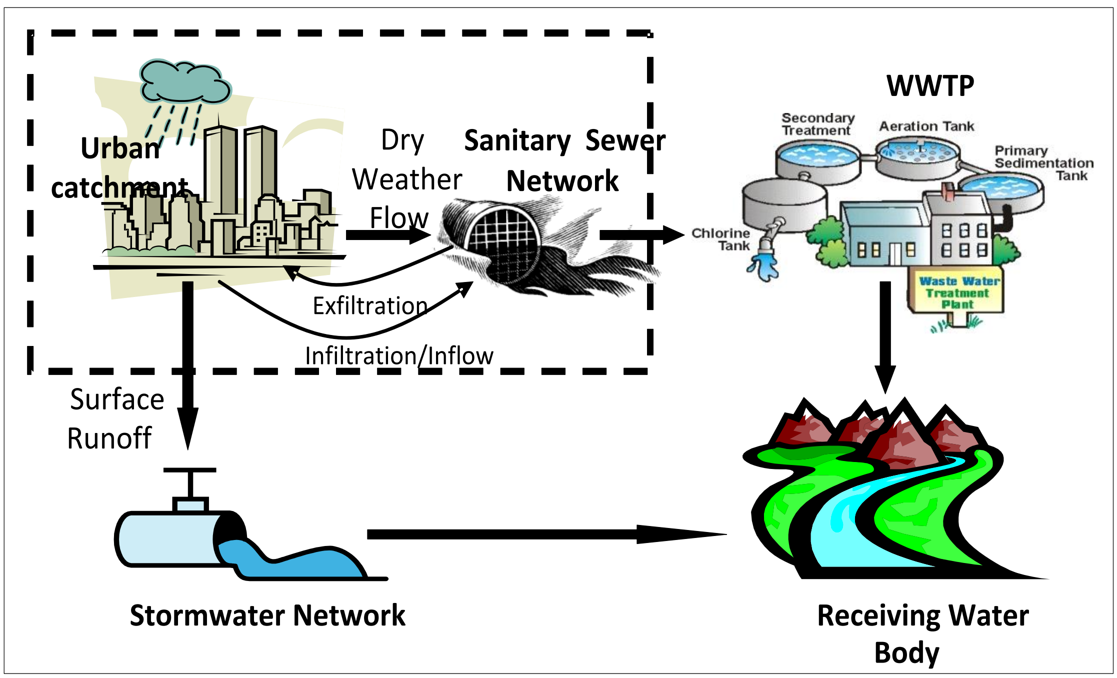


Figure 3.1. Schematic Representation of the Integrated Urban Water Management with Separate Sewer Networks (Focus on Urban Catchment and Sewer network System Relations)

In this study, the Integrated Urban Water model framework was developed to relate to the urban catchment and sewerage network system (as depicted in Figure 3.1 within dotted lines). To support Integrated Urban Water model framework development for hydrogen sulphide prediction, the main tasks and associated tasks required are listed below:

1. Integrated Urban Water model Framework Development
   a. Data Identification
   b. Modeling Tool Selection
   c. Integrated Urban Water model Simulation
   d. Model Parameter Estimation through Calibration and Validation
2. Current Catchment Characteristics Setup
   a. Data Collection
   b. Model Setup

Figure 3.2 depicts links among the main tasks and associated tasks in modeling framework development.

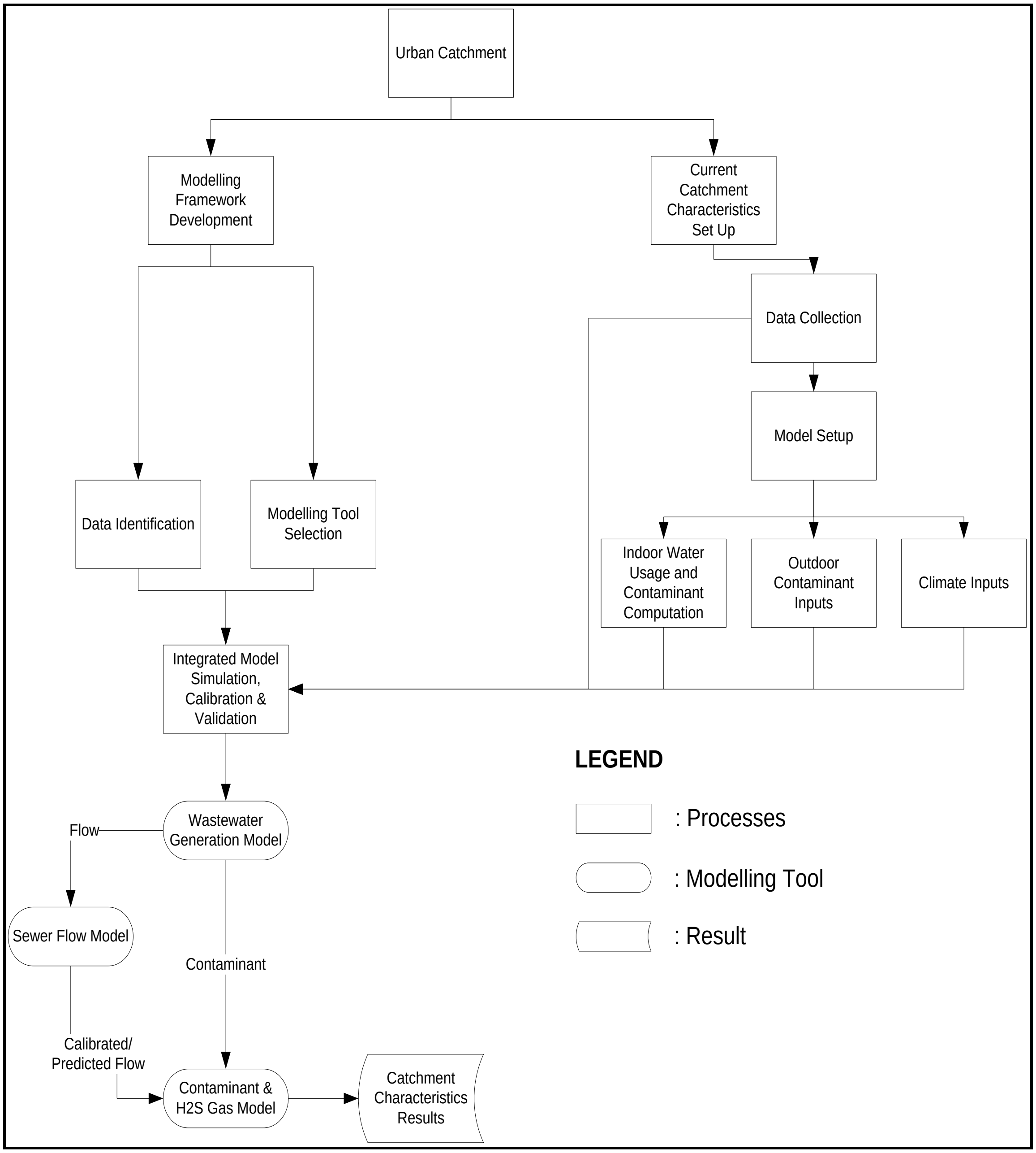


Figure 3.2. Summary of Steps to Develop a Modeling Framework and Existing Development Setup

The following sections will describe detailed processes in each task and associated tasks. Furthermore, this section follows the flows described in Figure 3.2.

3.2 Field Data Collection

The main issue in this study is hydrogen sulphide build up due to increasing adoption of WMP. These practices in urban areas are encouraged, particularly in residential areas, since these areas dominate urban water demand and contribute to a high volume of wastewater production. Therefore, this approach accommodated all requirements to model hydrogen sulphide build up in the residential area. Subsection 3.2.1 describes the criteria for selecting a case study area, with confidence intervals for the data collected are shown in Table 3.6.

3.2.1 Study Site Criteria

– *Catchment type:*

The impact of Water Management Practices (WMP) is likely to be the greatest in urban areas, particularly in urban residential areas, since many WMP have been applied here. Residential catchment contributes more than 60% of total urban wastewater. Thus, an exclusively urban residential catchment was preferred for this study.

– *Sewer pipe type:*

Hydrogen sulphide production occurs primarily in the sewer network network rather than stormwater collection network (Hvitved-Jacobsen & Vollertsen 2001; U.S. E.P.A 1974). The sewer network networks have lower flows and higher concentrations of contaminants as compared to stormwater networks. Thus, this study should require a residential catchment served by a separate sewer system.

– *Data availability:*

The crucial issue for this case study is hydrogen sulphide build up, hence a residential catchment with a record of hydrogen sulphide incidence from the sewer network system is required. However, it is not easy to find exclusively residential catchments with an on-going hydrogen sulphide problem, since it is more likely to be an intermittent problem in this catchment. Hydrogen sulphide build up is more likely to occur during dry weather conditions. Therefore a residential catchment that has hydrogen sulphide build up issue is necessary for a case study.

3.2.2 Selected Study Site

The selected case study site was located in one of Melbourne's largest water utility servicing areas: Yarra Valley Water (YVW). The selected subcatchment, the Glenroy branch, is located within the larger Pascoe Vale catchment in northern Melbourne, as can be seen in Figure 3.3. Glenroy sewer sub-catchment consists mainly of residential blocks with only few schools and some commercial precincts. Based on data provided by YVW, the Glenroy sewer sub-catchment has about 3750 sewer connections (YVW 2010a). This sub- catchment drains sewage to the Pascoe Vale Road sewer networks. Glenroy sewer sub-catchment serves residential areas in Glenroy with a 40-year-old wastewater reticulation pipe. According to the information provided by Moreland City Council (2007) and YVW (2010a), there is only a small possibility that the residential area in this sewer subcatchment will develop more than current levels. Current residential development in Glenroy is taking place in the north-west, which is served by another sewer subcatchment.

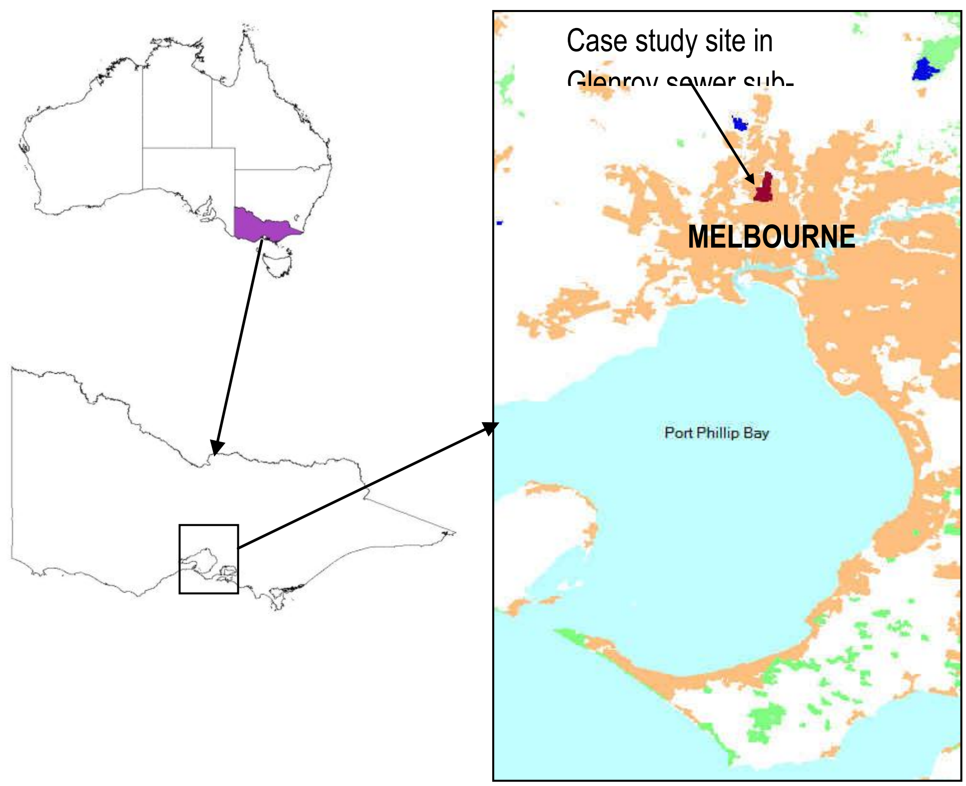


Figure 3.3. Case Study Site Sewer Subcatchment

In an earlier investigation of the Pascoe Vale catchment, hydrogen sulphide related degradation of the sewer pipes caused sewer collapses in 1999 and 2004. The investigation found that the slope of upstream stretch in the Glenroy branch varied between being too flat to being too steep, developing conditions for hydrogen sulphide build up and release. From CCTV examination by water utility, it was also found that the structural grading of a total of 1283m sewer pipe in this area was classified as moderate to worse deterioration (YVW 2010b).

The existing WMP implemented in the Glenroy sewer subcatchment are *Rainwater Harvesting* and *Greywater Recycling*. According to personal information from YVW and Moreland City Council, around 30% of households in this area have a rainwater tank, with 3% using collected rainwater for toilet and or laundry purposes. It is also reported that 3% of households have *Greywater Recycling* facilities (Moreland City Council 2011; YVW 2011).

3.2.3 Available Data

A summary of available data and their sources are listed in Table 3.1. Available data provided by YVW were quite limited and some important data was not available. Therefore to deal with this problem, a field study was conducted. However, due to the limitation of proper sampling and monitoring instrument, as well as the lack of personnel to undertake field research, some targeted data could not be obtained.

Field study was conducted from November to December, 2010. The sampling days were based on Bureau of Metrology (BoM) rainfall forecasting, thus the days with no rainfall were selected as sampling days (29-30 November, 5-6 December and 7-8 December. From the field study, approximately 300 samples were collected.

Table 3.1. Available Data and Their Source of Origin

DATA OBTAINED	PROVIDED BY
• Population and number of sewer connections • Household occupancy size • GIS map which consists of total catchment area, road area, open space area and residential area • Percentage of households installing rainwater tanks and *Greywater Recycling* tanks 2010 • Excel Spreadsheet from Infoworks CS model contains all subcatchment, manhole and pipe properties. The Infoworks model was built based on September, 2007 data • Sewer air temperature April 2010 (See Appendix 1, Figure A.2) • Wastewater flow September 2007 (from calibrated Infoworks CS model) (See Appendix 1, Figure A.1) • Hydrogen sulphide gas concentration April 2010 (See Appendix 1, Figure A-2)	Yarra Valley Water (YVW)
• Sewer flow November /December 2010 • Continuous measurement data for sewer air and wastewater temperature, pH, Dissolved Oxygen November/December 2010 • Hydrogen sulphide gas concentration in November/December 2010 • Total sulphide in wastewater concentration in November/December 2010	Field study
• Maximum heterotrophic growth rate • Sulphide Production • Sulphide Oxidation	Laboratory Experiment → wastewater taken from field study • Successful • Failed • Failed

3.2.4 Location of Collected Data

Figure 3.4 shows the major sewer pipeline and its contributing pipes and nodes in Glenroy sewer sub-catchment. This figure also shows the location of the manholes that were used for field study. YVW conducted flow monitoring in September 2007. This data were used to calibrate and validate their flow model. In the Glenroy sewer branch, flow monitoring was conducted at manholes GLN1 and GLN31. In November and December 2010, the field study conducted by Victoria University and CSIRO was conducted. For this field study, YVW recommended two manholes in the downstream stretches, they are GLN8A and GLN23. Unfortunately, later on it was known that manhole GLN8A was not safe to be used as monitoring and sampling location, therefore only manhole GLN23 was used for field study. For the purpose of calibration of Integrated Urban Water model framework developed in this study, the sewer flow at manholes GLN8A and GLN23 derived from YVW's calibrated model were used to calibrate the simulated flows derived from Integrated Urban Water model framework that is developed in this study. Appendix 1, Figure A.1 shows the sewer flow at manholes GLN8A and GLN23 from YVW's calibrated model.

In different time period, YVW had also conducted an investigation of hydrogen sulphide gas in April, 2010. Hydrogen sulphide monitoring was conducted at manhole GLN2 (see Figure 3.4). The result of hydrogen sulphide monitoring from YVW's field study was plotted in Appendix 1, Figure A.2.

Field study that was conducted by Victoria University and CSIRO consisted of flow monitoring and contaminant sampling activity. The three manholes selected for this study were GLN23, GLN17 and GLN8. Some manhole characteristics are described in Table 3.2. These manholes were located at Gavin Park and Austin Crescent Reserve. Manhole GLN8 was selected to replace manhole GLN8A. The pipe length between manholes GLN23 and GLN8 is 991.7 m and this is a separate gravity sewer consisting of concrete pipes.

Table 3.2. Characteristics of the three selected manholes (YVW 2010a)

	GLN23	**GLN17**	**GLN8**
Pipe diameter (mm)	300	300	375
Distance from pipe bottom to ground level (m)	3.4	3.9	4.5
Average model flow weekday (L/s)	10.6	-	13.9
Average model flow weekend (L/s)	10.7	-	14.7

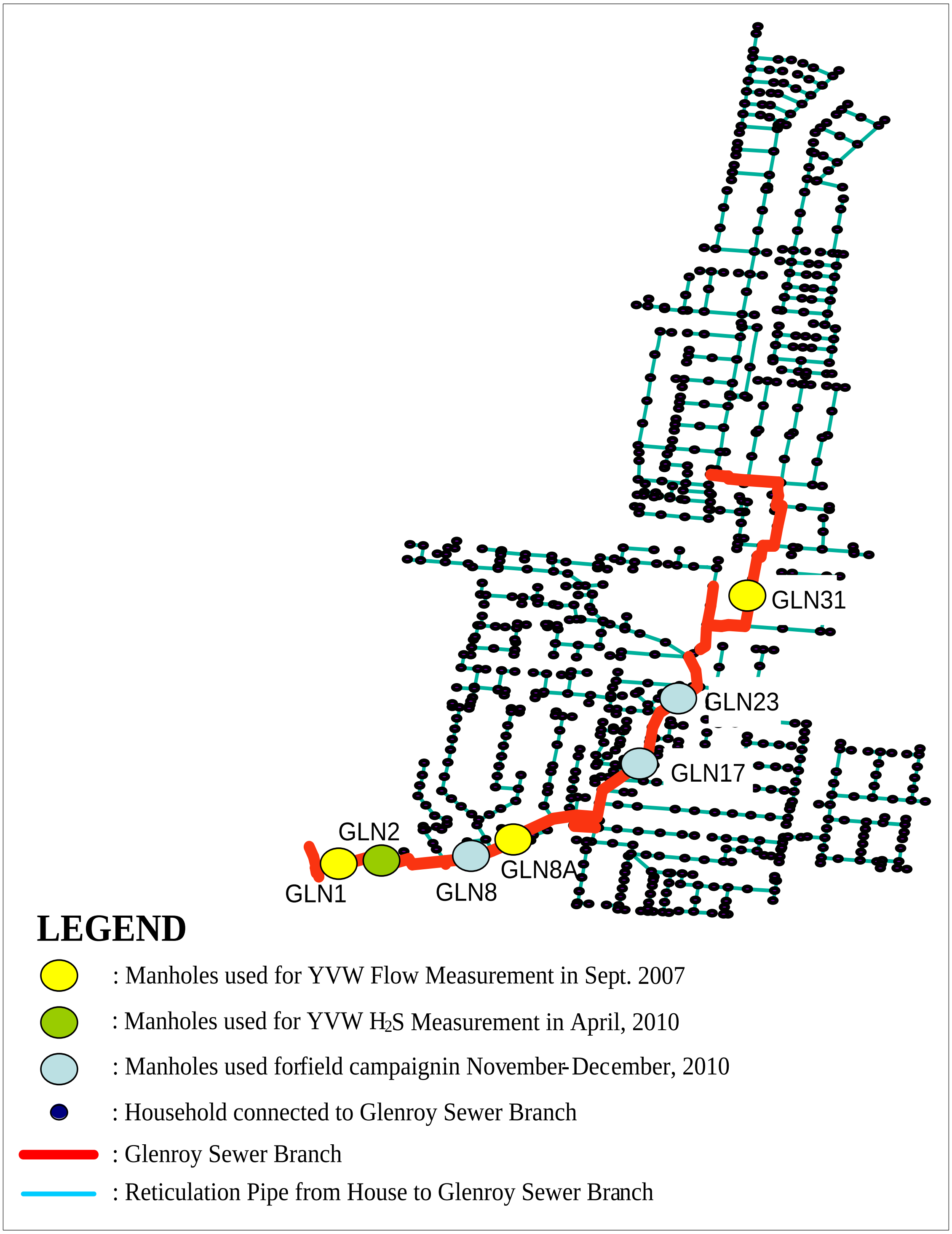


Figure 3.4. Sewerage Networks in Glenroy Sub-Catchment with the Sampling Manholes

3.2.5 Measured Parameters in Field Campaign

From the sewer pipe stretch, several wastewater parameters were investigated. Some parameters were measured continuously, some by sample analysis and some by laboratory experiments. Dissolved oxygen (DO), temperature, pH, hydrogen sulphide gas and flow were measured continuously using a WTW multi-meter with an optical DO-probe and pH-probe (WTW, Germany), three OdaLog gas loggers (App-Tek, Australia) and three Sigma 940 flow meters (Hach, USA). Flow and hydrogen sulphide gas were also measured continuously in each manhole (GLN23, GLN17 and GLN8) while DO and pH were measured only at the upstream manhole (GLN23). The location for each measured parameter is summarised in Table 3.3. Some of the sampling instruments can be seen in Figure 3.5.

Wastewater samples were collected using three automatic wastewater samplers (Teledyne Isco Inc., Lincoln, Nebraska, USA). Two autosamplers were positioned at the upstream manhole (GLN23) and samples collected were analysed for COD and total sulphide, while the third autosampler was positioned at the downstream manhole (GLN8) and samples were analysed for total sulphide only. This installation arrangement was designed to be able to take representative samples for every parameter needed. Total sulphide in bulk wastewater was the primary parameter to be investigated, while COD, pH and temperature were supporting parameters to the hydrogen sulphide occurrence. Further, the wastewater was also collected for the purpose of laboratory experiment, where it was expected some of model parameters would be obtained. Details of these parameters are provided in Table 3.3.

A weir was installed in the downstream part of the manhole to avoid the autosampler taking sediment and to maintain the minimum flow depth of wastewater for sampling under low flow conditions. The probes for the DO/pH meter were installed in a float to avoid tilting. The instrument arrangement inside the manholes can be seen in Figure 3.6.

Table 3.4 listed the volume and frequency of wastewater sampling during field study. To capture the diurnal variation of wastewater parameters wastewater was collected every 12 minutes by using the automatic sampler. The volume of each sample was 50 ml. These samples were combined to form hourly composite samples with a total volume of 250 ml (50 ml x 5 times sampling). During 24 hours, 24 composite samples were ready to be analysed. The COD samples were not preserved before they were collected, while the samples for total sulphide were fixated immediately in bottles prepared with 1 mL 10% zinc acetate. The resulting Zn/S molar ratio was between 1-10, for up to 30 mg S/L.

For the laboratory experiment, wastewater was taken by grab sampling technique using an autosampler. The parameter of pH and temperature was measured directly in the field for this grab sample. Two litres (2 L) of wastewater sample were collected each time. The collected sample was used to determine the sulphide production rate, sulphide oxidation rate and biodegradability. Grab sampling was conducted in the morning or afternoon around 11 am or 12 pm.

Table 3.3. Measured Parameters

	Parameters	**Purpose**	**Location**
Monitoring	pH, dissolved oxygen, water temperature, air temperature, Sewer flow, hydrogen sulphide gas	Input data Calibration	GLN23 GLN23 GLN17 GLN8
Sampling analysis	Total COD, dissolved COD Total sulphide in wastewater	Input data Calibration	GLN23 GLN23
Laboratory experiments	Hydrogen sulphide in wastewater production rate, biological and chemical Hydrogen sulphide oxidation rates, Biodegradability	Input model parameters	GLN23

Figure 3.5. The OdaLoggers and Autosampler inside the Cabinet

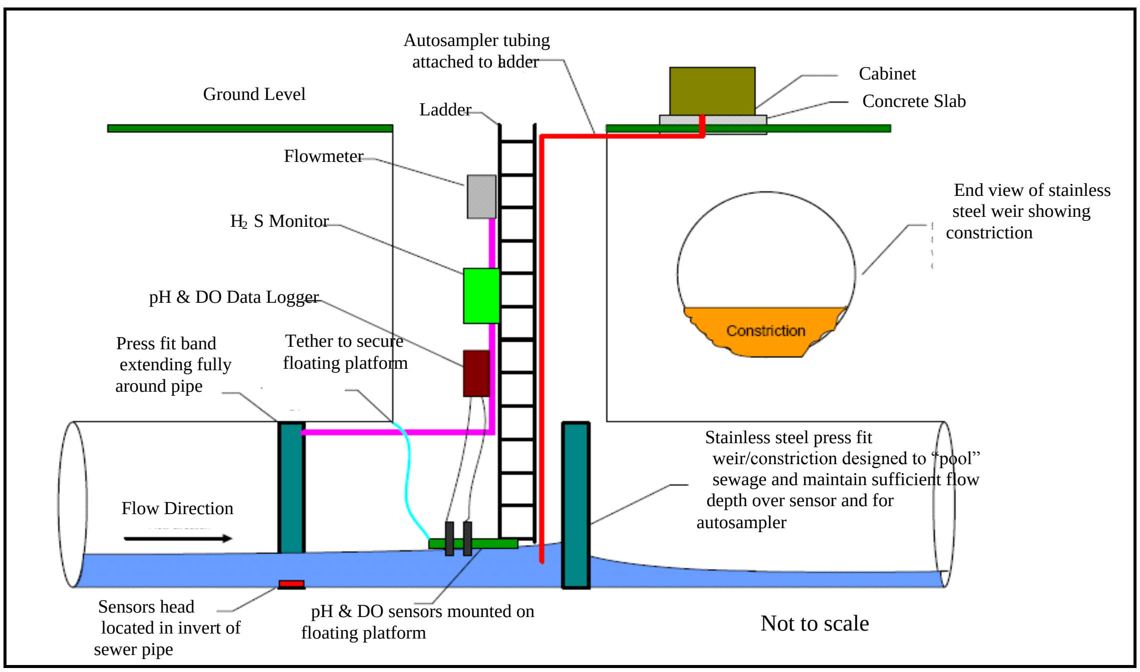


Figure 3.6. The Instrument Arrangement inside the Manhole

(Source : ALS (2010))

Table 3.4. Setup for Composite and Grab Sampling

	Composite Sample	Grab Sample
Sample size [mL]	50	2000
No samples per bottle	5	1
Total sample size [mL]	250	2000
Sampling frequency [min]	Every 12 min within 1 hour per sampling bottle. Therefore for 1 day there were 24 sampling bottles	Single sample at specific time

Table 3.5 gives the online monitoring frequency for each observed parameters. The instrument in GLN8 was installed 13 days after the installation in GLN23 and GLN17. This was due to a leakage problem in manhole GLN8A, which was originally intended to be one of the study manholes. The sampling frequency for every parameter was set up differently, depending on instrument capability.

Table 3.5. Monitoring Frequencies in the Field Study

Parameter	DO	pH	$H_2S_{(g)}$	Flow
Sampling frequency	5 min	5 min	1.5 min	1 min

3.2.6 Sample Handling, Storage and Analysis during Field Campaign

From the monitored sites, all samples were brought back to the laboratory in cool boxes in less than 2 hours and all samples were transferred to another sample bottle in the laboratory. The fresh samples were split into 3 groups of storage bottles for total COD, dissolved COD and total sulphide measurements. Each group contained 24 storage bottles which represented the diurnal variation. The wastewater sample for COD was not preserved during its field collection, while wastewater samples for total sulphide were preserved with 1 ml of 10% zinc acetate during field collection. According to Standard Methods (American Public Health Association et al. 2005), COD and metal samples can be collected without any preservation chemical for a maximum of 48 hours. COD samples were preserved by using 10 ml 4 M H_2SO_4/L per sample. Dissolved COD was found by filtering samples through a GF/C filter before COD digestion.

The total sulphide analyses used the methylene blue method (Cline 1969). The analysis of total sulphide samples was initiated by diluting the sample 5 times and filtering through GF/C paper to avoid solid hindrance after colour development.

Both COD and dissolved COD totals were measured by a closed reflux method using a high range COD determination (American Public Health Association et al. 2005) . COD determination required a standard curve, which was made in each analysis run to ensure that all procedures, reagent and equipment were conducted and used correctly. The standard curve was produced from a stock solution of 1000 mg O_2/L corresponding to 0.8500g $KHC_8H_4O_4$ (potassium hydrogen phthalate) diluted in 1000 mL DI water. This curve was based on 5 concentrations of 20, 200, 500, 750 and 1000 mg O_2/L. The relative standard deviation (RSD) for this method ranged from 57% and 67% for total COD and dissolved COD respectively.

3.2.7 Field Campaign Results

3.2.7.1 Flow Monitoring

From the graph of flow measurement results (see Figure 3.7), it was clearly noticed that sewer flows were influenced by rainfall, even though only separate sewer networks are provided in the area with no stormwater connection. The existing sewer network was usually characterised by pipe cracks and leakages, which allows for external flow entering the pipe network and vice versa. The external flow is strongly dependent on weather variability. The reasons for these different measuring periods for manholes were some start-up problems and weather conditions preventing the simultaneous ending of the field study. To obtain the average dry weather flow, the sewer flow affected by rainfall was excluded; therefore, only the sewer flow which was not affected by rainfall was computed. The rainfall induced flow exclusion was conducted by simply selecting the flow, which had suddenly increased and subsequently matched rainfall data. If there was a sudden increase in the flow, confirmed by the presence of rainfall, these flows were excluded. From the computation, average sewer flows were 19.44 L/s and 49.33 L/s for GLN23 and GLN8 respectively. The flows in downstream manholes (GLN17 and GLN8) showed higher rates because of wastewater inputs from downstream households.

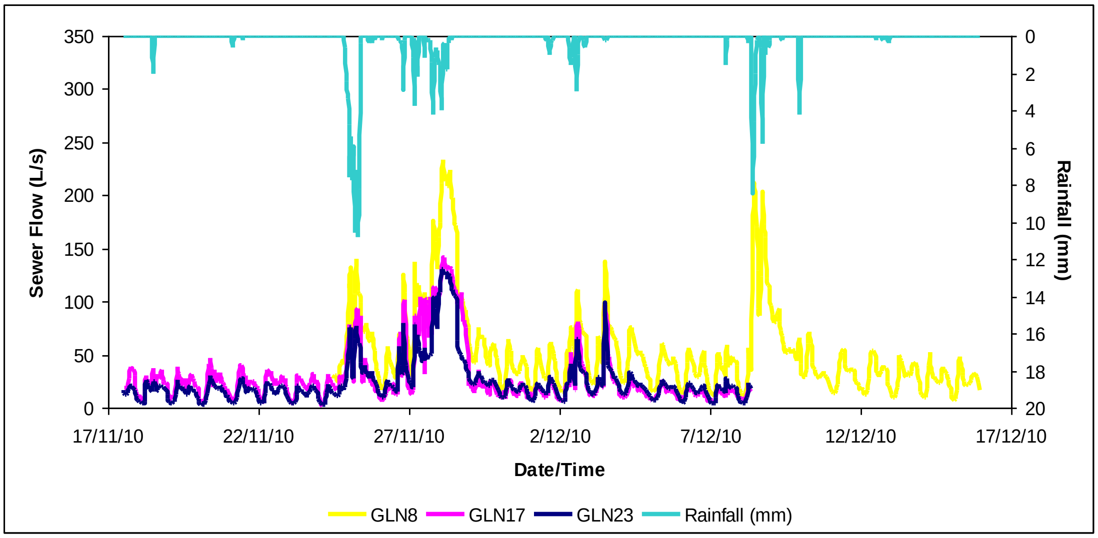


Figure 3.7. Flow Measurement during the Sampling Period

3.2.7.2 Air Temperature and Hydrogen Sulphide Gas Monitoring

Due to pipe ageing, it was expected that the sewer pipe in Glenroy subcatchment had some cracks and joint defects, therefore all hydrogen sulphide gas phase measurements were recorded as 0 ppm during the monitoring period (Figure 3.8). Zero ppm concentration of hydrogen sulphide may occur due to high wastewater dilution by the inflow from rainwater and surface runoff, as well as the infiltration from groundwater through the pipe cracks and joint defects. The limit of detection from the OdaLog instrument was 0-200 ppm hydrogen sulphide with 0.1 ppm resolution, and the range of detected temperature was -20^{o}C to +50^{o}C. The accuracy of the instrument was ±2 ppm at 20 ppm gas in STP (Standard Temperature and Pressure) conditions.

The air temperature seemed to be constant for all manholes, around 17^{o}C. The outside temperature pattern seemed to have no effect on sewer air temperature (see Figure 3.10) and this was also confirmed by the YVW measurement in April 2010 (see Appendix 1, Figure A.2), where sewer air temperature tended to be flat while the outside temperature varied.

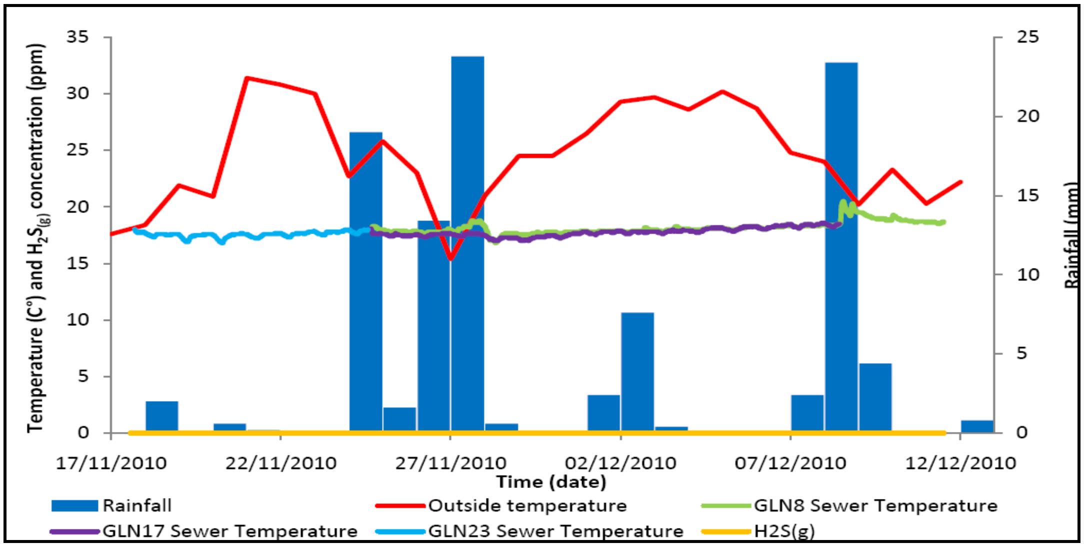


Figure 3.8. Hydrogen Sulphide Gas and Air Temperature from the Monitoring Program

3.2.7.3 Water and Air temperature and Dissolved Oxygen

Wastewater temperature was recorded as 2°C higher than measured air temperature. From Figure 3.9, it can also be seen that the pH was relatively constant. The average pH 7.44 was within the typical interval for wastewater, that is, between 7-8 as suggested by Henze et al. (2002), which matches the pH of 7.4 measured by Raunkjær et al. (1995) in an intercepting gravity sewer receiving almost no industrial discharge. The measured DO concentration was higher for 25 and 26 November 2010 (monitoring period), compared to other days in the study; this was expected, due to rainwater inflow and infiltration, as these were high rainfall days. The average DO concentration from the online measurement was 2.79 ppm, which was similar to the study by Raunkjær et al. (1995) and Gudjonsson et al. (2002).

The measurement range of the instrument was 0 to 19.99 mg/L for Dissolved Oxygen; 0 to 50°C for temperature; and -2 to +19.99 for pH. The accuracy of the probes was ±0.5% of DO value, ±0.2°C for temperature and ±0.004 for pH.

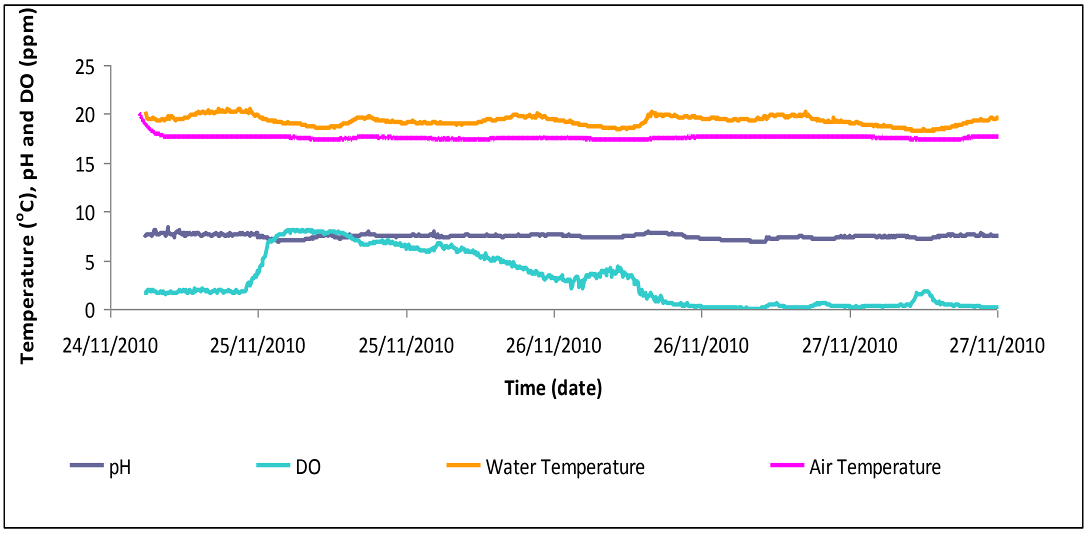


Figure 3.9. Wastewater Temperature, pH and Dissolved Oxygen from Monitoring Program

3.2.7.4 Sampling analysis

There are three main parameters that were analysed in the laboratory and they will be presented here.

1) Total and Dissolved COD

Examining the daily variation of total COD, the individual data shows a great variability, while the average from the 3 days shows a morning and evening peak, where COD concentrations were on average highest in the morning (see Figure 3.10). Unfortunately, some samples were not collected for some hours (7am to 9am) during 2 days of measurement (6 December and 8 December) due to some autosampler errors. As a result, these time only have data from the 1-day measurement, (30 November) and consequently the average value of COD at these times cannot be calculated.

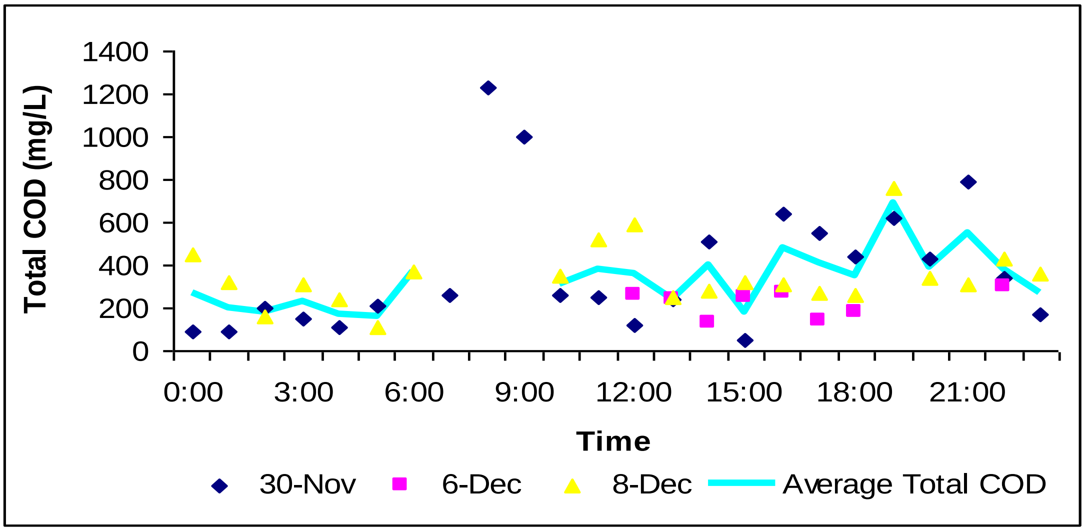


Figure 3.10. Total COD Measurement for 3 days and Their Average

Even though the dataset for the dissolved COD was smaller compared to total COD, the daily variation can also be seen in the dissolved COD for every sampling date. Unfortunately, some samples could not be obtained due to instrument error, hence the average dissolved COD was calculated only for a few hours. Comparing the two averages, the dissolved COD is about half of the total COD (see Figure 3.11). The analysis for total COD gave an average COD-value of 331.83 mg O_2/L, which is comparable to COD concentrations measured by Raunkjær et al. (1995) in September 1992, on an intercepting gravity sewer receiving primarily residential discharge from a population of 4350, which varied between 200-370 mg O_2/L. As for the dissolved COD, the average value of 102.19 mg O_2/L and dissolved COD for every sampling date 30 November, 6 December and 8 December) was 85 mg O_2/L, 45 mg O_2/L and 137 mg O_2/L. Those concentrations are similar to the 75-175 mg O_2/L found by Raunkjær et al.(1995) for the same period.

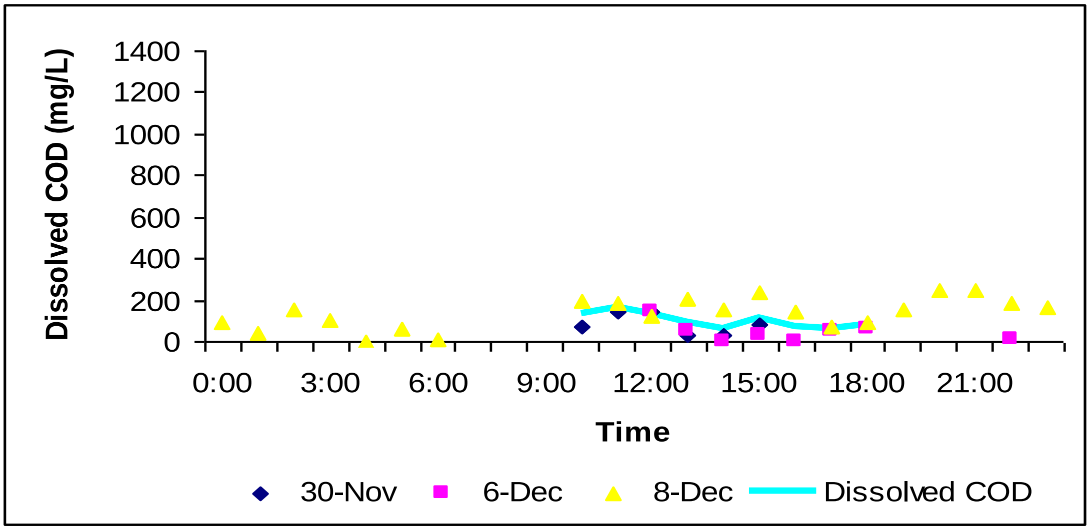


Figure 3.11. Dissolved COD for 3 days and Their Average

2) Total Sulphide

The total sulphide plot can be seen in Figure 3.12. The sampling result for total sulphide showed relatively low concentrations over a 24 hour sampling period. As previously mentioned, the measurement was conducted in sewer manhole GLN23 on 30 November, 6 December and 8 December 2010. The total sulphide in this study ranged between 0.10-0.80 mg/L with an average of 0.46 mg/L. Standard deviation, which shows the variability of average total sulphide, was 0.2. This value was considered to be a normal concentration in a residential area**.** Nielsen et al's (2008a) study in a residential area in Denmark had a total sulphide concentration of < 5 mg/L.

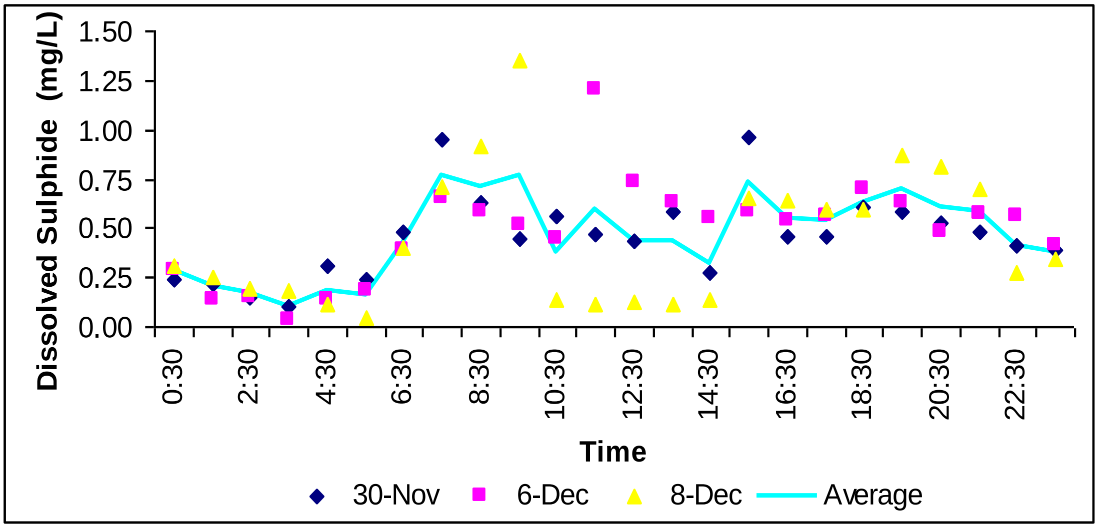


Figure 3.12. Total Sulphide Concentration and Their Average

3.2.7.5 Statistical Analysis of Data

Data gathered in this study was obtained both from monitoring (online measurement) and sampling. Some data has very large population that appeared due to the sampling time interval is very short (less than 10 minutes) and ithe data collected for more than a month. These kinds of data usually belong to online monitoring data where the automatic logger saved the tool's reading. While the data obtained from sampling analysis had limited amount of population, mostly within the duration of 24 hours. To estimate high precision of data, it is important to measure the standard deviation and the confidence intervals of the data. Hence, the data used in this study can be assured to represent the value in the whole population. In this study, the 95% confidence interval was selected. It means that the statistical confidence of the sample collected from this study to estimate the true value of the population is 95%. To calculate the confidence interval, some statistical data of sample mean, standard deviation and confidence interval table (Z-table) were used. The confidence interval was calculated by the formula in Equation 3.1 below :

$$\overline{X} \pm \mathbf{Z}_{\alpha/s}\ \mathbf{x}\ \frac{\sigma}{\sqrt{n}} \qquad \textbf{3.1}$$

Where :

$Z_{\alpha/s}$ = Confidence coefficient

$\bar{X}$ = sample mean

α = confidence level

σ = Standard deviation

n = sample size

As can be seen in Table 3.6, there are 9 data sets collected during the monitoring and sampling period. From the calculation of a 95% confidence interval, it can be seen that most of the monitoring data has little variability, which means that most of the collected data represents the population. The data derived from the sampling analysis has higher variability. It could be due to limited number of samples collected during the field campaign period. As mentioned above, the on-line monitoring data (such as wastewater pH, temperature) has abundant data due to the monitoring interval being less than 5 minutes. On the other hand, the interval of wastewater sampling time at the smallest was every one hour.

Table 3.6. The confidence interval of the collected data

Data	Unit	Average			Standard Deviation			95% Confidence Intervals		
		GLN 8	GLN 8A	GLN 23	GLN 8	GLN 8A	GLN 23	GLN 8	GLN 8A	GLN 23
Sewer Flow :	L/s									
Dec., 2010		77.32		27.27	51.38		26.36	3.85		1.37
Sept., 2007		-	13.90	10.61	-	6.74	4.71	-	1.23	0.86
Sewer Air Temp.	^oC	-	-	17.68	-	-	0.81	-	-	0.02
Water Temp.	^oC	-	-	19.31	-	-	0.72	-	-	0.05
pH		-	-	7.43	-	-	0.23	-	-	0.02
Dissolved Oxygen	mg/L	-	-	2.81	-	-	2.71	-	-	0.18

Data	Unit	Average			Standard Deviation			95% Confidence Intervals		
		GLN 8	GLN 8A	GLN 23	GLN 8	GLN 8A	GLN 23	GLN 8	GLN 8A	GLN 23
Total COD	mg/L	-	-	331.83	-	-	134.31	-	-	54.89
Dissolved COD	mg/L	-	-	102.19	-	-	34.87	-	-	13.95
Total Sulphide in bulkwater	mg/L	-	-	0.46	-	-	0.20	-	-	0.08
H_2S Gas :	ppm									
Dec., 2010		0	-	0	0	-	0	0	-	0
April, 2010				3.94			0.88			0.25

3.3 Integrated Urban Water model Framework

This study attempts to develop an integrated wastewater system model that can predict hydrogen sulphide build up with limited data problem. The process of Integrated Urban Water model development is described in the following subsections.

3.3.1 Data Gap Identification

The following subsection describes the required data sets for hydrogen sulphide prediction and available data sets obtained from YVW and from a previous field study. From these two data sets, the data gaps for hydrogen sulphide prediction were identified. Table 3.7 provides the list of required and available data sets and highlights the gaps.

Table 3.7. Data Identification to Support the Development of a Modeling Framework

DATA NEEDED	DATA OBTAINED	PROVIDED BY	DATA GAP IDENTIFICATION
Data Input			
Data Input for Urban Catchment			
Indoor Water Usage (L/c/d) & Contaminant Load (mg/c/d) (COD, Sulphide, Nitrate, Sulphate, Iron)	Total water demand Indoor water breakdown percentage Population and number of water/sewer connections Household occupancy size Contaminant load for kitchen, laundry, bathroom and toilet	Melbourne Water weekly report Literature YVW YVW Literature	
Outdoor contaminant concentration (mg/L)	Contaminant load for imported water, rainfall, roof runoff, roof first flush	Literature	
Subcatchment and residential area	GIS map which consists of total catchment area, road area, open space area and residential area	YVW	
Existing WMP	Percentage of households that installed rainwater tanks and *Greywater Recycling* tanks in 2010	YVW	
Data Input for Sewer network Networks			
Pipe diameter, shape, slope, type, material	GIS map and Excel spreadsheet from Infoworks CS model containing all pipe properties. The model was	YVW	

DATA NEEDED	DATA OBTAINED	PROVIDED BY	DATA GAP IDENTIFICATION
Data Input			
	developed in 2007		
Manhole ground level and roof level, width, depth	Same as above	YVW	
Contributing subcatchment to sewer network networks	Same as above	YVW	
Sewer air and wastewater parameters (pH, Temperature, Dissolved Oxygen)	Sewer air temperature on April, 2010 Continuous measurement data for sewer air and wastewater temperature, pH, Dissolved Oxygen Nov-Dec, 2010	YVW Field study	
Rainfall Data	Hourly rainfall data February 2003-December 2010	BoM	
Calibration			
Flow Calibration & Validation			Model calibration in this study required 2 parameters: sewer flow and H_2S gas. Further, there are 2 calibration periods for sanitary flow in wet weather (November-December, 2010) and a dry weather period. For dry weather calibration (April, 2010), only H_2S data was available, therefore sewer flow data for the dry month calibration was predicted, based on model parameters obtained from sanitary flow calibration in wet month (November-December, 2010) and
Sewer Flow	Sewer flow September 2007 (from calibrated Infoworks CS model) Sewer flow November-December 2010	YVW Field study	
Water and gas Contaminant Calibration			
Hydrogen sulphide gas concentration	Hydrogen sulphide gas concentration on April, 2010 Hydrogen sulphide gas concentration on November-December, 2010	YVW	
Total sulphide concentration	Total sulphide concentration on Nov-Dec, 2010	Field study	

DATA NEEDED	DATA OBTAINED	PROVIDED BY	DATA GAP IDENTIFICATION
Data Input			
			sanitary flow calibration (September, 2007).
Model parameters (Sulphide production rate, maximum heterotrophic growth rate, sulphide oxidation)	Maximum heterotrophic growth rate Sulphide production Sulphide oxidation	Laboratory experiment Was conducted in laboratory but failed, so data was finally taken from the literature Same as Sulphide production	Not all site specific model parameters were available
Scenario Development			
Urban development Plan	Urbanisation plan (number, size of houses and population); maps for future development	Moreland City Council	

3.3.2 Modeling Tools Selection for Integrated Framework

Modeling tools are needed to predict both sewer flow and hydrogen sulphide builds up in the sewer system for every WMP scenario including the *Base Case*. This study uses three modeling tools to simulate sewer flow and hydrogen sulphide occurrence in urban wastewater system. The integration of these modeling tools was designed to handle the problem of limited data of sewer flow. In this case, there was a lack of sewer flow data in dry weather of April 2010. Furthermore, the Integrated Urban Water model also has the capability to predict hydrogen sulphide in existing sewer networks. To achieve the aims of Integrated Urban Water model development the following modeling tools were selected:

3.3.2.1 Urban Wastewater Generation

UVQ was selected as a modeling tool in this study because it is relatively user-friendly in operation, models the interactions that occur in wastewater and stormwater systems and has free open access. In addition to model capability to analyse flow paths and contaminants concentration/load from source to discharge point through an urban area, UVQ can also be used to investigate the impact of conventional and non-conventional water management practices on flow and contaminant concentration/load (Mitchell & Diaper 2005).

In the UVQ model, water balance and contaminant balance operations occur sequentially for each daily time step. The water balance program loop calculates flows through the urban water system. Contaminant balance operations are based on water volumes calculated in the water balance and user specified concentrations, loads and performance criteria. UVQ uses model simplification approach, where all contaminants are modelled conservatively, with no conversion or degradation within the existing infrastructure, and with simple mixing and removal processes as the basis for calculations. This model does not consider any decay kinetics and temporal variations in water quality.

In the UVQ representation, imported water supplies and rainwater are the major inflows to the urban water cycle, while wastewater, stormwater and evaporation are the main outflows. Water sources can be used for indoor and outdoor end - uses. Specific end - uses are: kitchen, bathroom, laundry, toilet, garden irrigation and public open space irrigation. UVQ has a three - level hierarchy to represent the different spatial scales of an urban area: the land block, neighbourhood and study area. The land block represents a single dwelling or other building type, while a neighbourhood is an aggregation of land blocks that have identical characteristics. Neighbourhoods can be used to describe different land use types making up the study area that will have different characteristics such as physical layouts of pervious and impervious surfaces, water demand and contaminant profile of end - uses (Mitchell & Diaper 2005).

The calculation of wastewater generation in UVQ is represented by the following equation:

<u>Wastewater Generation</u>

$$Ww = IWU + INF + ISI - EXF - OF \quad \text{......3.2}$$

This main equation consists of five sub-processes; they are wastewater exfiltration (EXF), overflow (OF), infiltration (INF), inflow (ISI) and septic disposal (IWU). The equations for wastewater generation processes can be seen from the following equations:

<u>Wastewater Exfiltration</u>

$$EXF = Ex_{Rate} \times (IWU + ISI + INF - SD) \quad \text{......3.3}$$

<u>Overflow</u>

$$OF = OF_{dry} + OF_{wet} \quad \text{......3.4}$$

<u>Dry Weather Overflow</u>

$$OF_{dry} = \%OF \times (IWU + ISI + INF - EXF) \quad \text{......3.5}$$

<u>Wet Weather Overflow</u>

$$OF_{wet}^{min} = ([(IWU + ISI + INF - EXF) - Ww_{cap}],0) \quad \text{......3.6}$$

Infiltration

INF = IRC x $\sqrt{INFS}$ **……………………………………………………………3.7**

Inflow

ISI = %I x (SRUN + IRUN)……………………………………………………………3.8

Septic Disposal

IWU model components for septic tanks and leach fields is not required in this study.

3.3.2.2 Sewer Flow and Rainfall-Derived Infiltration and Inflow (RDII) Simulation

PC-SWMM was used to analyse the sewer flow which is influenced by the external flow called RDII. PC-SWMM is also equipped with a GIS feature, which reduces the time required for data input. It also uses a simple calibration tool called SRTC (Sensitivity Radio Tuning Calibration), allowing easy calibration through use of a moving slide bar, similar to radio tuning. The calibration parameter graph is instantly updated when the slide bar is moved.

❖ **Flow Routing**

SWMM as the basic engine of PC-SWMM has powerful capability to route sewer flow. Flow routing in SWMM is governed by the conservation of mass and momentum equations for gradually varied, unsteady flow (i.e., the Saint Venant flow equations) (U.S. E.P.A 2006). There are three routing approaches to solve the Saint Venant equation: Steady Flow, Kinematic Wave and Dynamic Wave (U.S. E.P.A 2006).

Steady Flow routing represents the simplest type of routing possible by assuming that within each computational time step flow is uniform and steady. To route the flow, it simply translates inflow hydrographs at the upstream end of the conduit to the downstream end, with no delay or change in shape. The Manning equation (Equation 3.9) is used to relate flow rate to flow area (or depth). Unfortunately, this form of routing is insensitive to the time step employed, and is really only appropriate for preliminary analysis using long-term continuous simulations.

Manning Equation

$$Q = \frac{1}{n}.R^{2/3}.S_f^{1/2}.A \text{ ....} \mathbf{3.9}$$

Kinematic Wave Routing assumes uniform flow but unsteady state condition. This routing method solves the continuity equation along with a simplified form of momentum equation in each conduit (See Equations 3.10 and 3.11). This routing is considered to be an efficient routing approach for long-term simulation, if the effects of backflow, entrance/exit losses, flow reversal or pressurised flow are not expected to occur in the simulation.

Dynamic Wave Routing takes into account the non-uniform and unsteady state condition. This routing solves the complete one-dimensional Saint Venant flow equations (Equation 3.11) and therefore produces the most theoretically accurate results. These consist of continuity and momentum equations for conduits and a volume continuity equation at nodes. With this form of routing, it is possible to represent all the effects that cannot be simulated in Kinematic Wave Routing.

Continuity Equation

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \text{ ....} \mathbf{3.10}$$

Momentum Equation

$$\frac{\partial Q}{\partial t} + \frac{\partial \left(Q^2 / A \right)}{\partial x} + g.A\frac{\partial H}{\partial x} + \underbrace{g.A.S_f + g.A.h_L}_{\text{Kinematic wave}} = 0 \text{ ....} \mathbf{33.1}$$

1

In the case of sanitary flow, many researchers model flow routing by using kinematic wave routing, as the sewer network is assumed to have unsteady state flow and it is uniform across the pipe. This assumption is applicable to new sewer systems where the pipe bottom disturbances (e.g. sediment) are not yet formed and pipe defects are relatively small. In the case of 'old sewer network pipes' (existing sewer pipes), the sewer condition is completely different as the bottom of the pipes, which may be occupied by sediment or a thick biofilm. Furthermore, pipe defects occur mostly due to pipe ageing and as result form pipe corrosion. All the above mentioned causes make the kinematic wave routing method unreliable for modeling sanitary flow routing in 'old sewer network pipes'. Dynamic wave routing is the best approach to route existing sewer flow, since it takes into account varied and unsteady state flow.

❖ **RDII**

Excess of rainfall that does not permeate into the soil was called as runoff. RDII represents the percentage of runoff enters the sewer network during and after the storm event. RDII is calculated as a function of time to reach and enter the sewer and the physical condition of sewer pipe. RDII varies for each sewer network and depends on the defects that exist in the sewer. It also depends on the soil type in the vicinity of sewer network. It is difficult to determine RDII through physical calculation, since most of the variables of RDII were not known (such as number of defects on the pipe, soil condition etc.). A method to monitor RDII can be achieved by installing a CCTV in the sewer and inspecting the sewer network. However, these methods cannot capture the response of RDII. Accordingly, due to the difficulties in determining the RDII response, most hydrology and hydraulic models rely on the data of sewer flow hydrographs to estimate RDII response. In PC-SWMM, RDII response was generated from the estimation of time to travel and leakage due to defects. There are three main parameters to represent the response time which is slow (K), medium (T) and fast. (K). These parameters were represented by hydrograph triangles as can be seen in Figure 3.16, each triangle represent the RDII response (slow or medium or fast). Each response time parameter contained three calibration factors that were calibrated through trial and error until the best fit parameter set is obtained.

3.3.2.3 Contaminant and H_2S Gas Analysis

For analysis of wastewater contaminant and hydrogen sulphide gas formation, this study uses the WATS model. WATS offers more features to analyse sulphide as compared to other sulphide prediction modeling tools. It is able to analyse hydrogen sulphide formation as well as predict the temporal and spatial corrosion rate in sewer pipes, which is beneficial for this study. Further, WATS incorporates non-steady state hydraulic and sulphide routing.

However, WATS is known for its complex processes and employs detailed equations of wastewater transformation processes, which require calibration for a large number of model parameters and initial concentrations of model components (Table 3.8 lists governing equations in WATS). WATS does not consider crude parameters like BOD, COD or Volatile Solids, which are traditionally used in wastewater quality modeling to characterise organic matter in wastewater (Hvitved-Jacobsen et al. 1998). These crude parameters which provide a measure of the total concentration of organic matter and biodegradable organic matter do not give detailed information on the composition of fractions of biodegradable organic matter (Vollertsen & Hvitved-Jacobsen 2002), which is required for hydrogen sulphide modeling. Therefore, WATS introduces a holistic approach to wastewater quality modeling by taking into account the fractions of wastewater biodegradability and more detailed processes in sewer pipe networks.

Table 3.8. Equations of Wastewater Transformation in Sewer Pipes Adopted in WATS Modeling Tool

Reaction	References	Equations	
Aerobic Bulk Water Growth	(Tanaka et al. 2000)	$\mu_{HO_2} \frac{(S_F+S_A)}{K_{Sw}+(S_F+S_A)} \frac{S_O}{K_O+S_O} X_{Bw}\alpha_w^{T-20}k_{H,pH}$. ……	**3.12.**
Anoxic (NO_3) Bulk Water Growth	(Yang et al. 2004)	$\mu_{H,NO_3} \frac{S_{NO_3}}{K_{S,NO_3}+S_{NO_3}} \frac{S_F+S_A}{K_{Sw}+(S_F+S_A)} \frac{K_o}{K_o+S_o} f_n X_{Bw}$ ……	**3.13.**
Anoxic (NO_2) Bulk Water Growth	(Yang et al. 2004)	$\mu_{H,NO_2} \frac{S_{NO_2}}{K_{S,NO_2}+S_{NO_2}} \frac{S_F+S_A}{K_S+(S_F+S_A)} \frac{K_o}{K_o+S_o}(1-f_n)X_{Bw}$ ……	**3.14.**
Aerobic Biofilm Growth	(Tanaka et al. 2000)	$k_{½O}\sqrt{S_O}\frac{Y_{HfO}}{1-Y_{HfO}}\frac{A_f}{V_w}\frac{(S_A+S_F)}{K_{Sf}+(S_A+S_F)}\alpha_f^{T-20}k_{H,pH}$ ……	**3.15.**
Aerobic Energy maintenance in bulk water	(Tanaka et al. 2000)	$q_{mO2}\frac{S_O}{K_O+S_O}X_{Bw}\alpha_w^{T-20}k_{H,pH}$ ……	**3.16.**
Anoxic (NO_3) Energy maintenance in bulk water	(Yang et al. 2004)	$q_{m,NO_3}\frac{S_{NO_3}}{K_{NO_3}+S_{NO_3}} f_n X_{Bw}$ ……	**3.17.**
Anoxic (NO_2) Energy maintenance in bulk water	(Yang et al. 2004)	$q_{m,NO_2}\frac{S_{NO_2}}{K_{NO_2}+S_{NO_2}}(1-f_n)X_{Bw}$ ……	**3.18.**
Fast (X_{Sfast}) Aerobic Hydrolysis	(Tanaka et al. 2000)	$k_{h,fast}\frac{X_{S,fast}/X_{Bw}}{K_{X,fast}+X_{S,fast}/X_{Bw}}\frac{S_O}{K_O+S_O}\left(X_{Bw}+\varepsilon_{Bf}X_{Bf}\frac{A_f}{V_w}\right)\alpha_w^{T-20}k_{H,pH}$ ……	**3.19.**
Medium ($X_{SMedium}$) Aerobic Hydrolysis	(Tanaka et al. 2000)	$k_{h,med}\frac{X_{S,med}/X_{Bw}}{K_{X,med}+X_{S,med}/X_{Bw}}\frac{S_O}{K_O+S_O}\left(X_{Bw}+\varepsilon_{Bf}X_{Bf}\frac{A_f}{V_w}\right)\alpha_w^{T-20}k_{H,pH}$ ……	**3.20.**
Slow (X_{SSlow}) Aerobic Hydrolysis	(Tanaka et al. 2000)	$k_{h,slow}\frac{X_{S,slow}/X_{Bw}}{K_{X,slow}+X_{S,slow}/X_{Bw}}\frac{S_O}{K_O+S_O}\left(X_{Bw}+\varepsilon_{Bf}X_{Bf}\frac{A_f}{V_w}\right)\alpha_w^{T-20}k_{H,pH}$ ……	**3.21.**
Fast (X_{Sfast}) Anoxic Hydrolysis	(Mourato et al. 2003)	$\eta_{h,anox}k_{h,fast}\frac{X_{S,fast}/X_{Bw}}{K_{X,fast}+X_{S,fast}/X_{Bw}}\frac{K_O}{S_O+K_O}\frac{S_{NO_3}+S_{NO_2}}{K_{NO}+(S_{NO_3}+S_{NO_2})}\left(X_{Bw}+\varepsilon_{Bf}X_{Bf}\frac{A_f}{V_w}\right)\alpha_w^{T-20}k_{H,pH}$ …	**3.22.**

Reaction	References	Equations
Medium ($X_{Smedium}$) Anoxic Hydrolysis	(Mourato et al. 2003)	$\eta_{h,anox} k_{h,med} \frac{X_{S,med}/X_{Bw}}{K_{X,med}+X_{S,med}/X_{Bw}} \frac{K_O}{S_O+K_O} \frac{S_{NO_3}+S_{NO_2}}{K_{NO}+(S_{NO_3}+S_{NO_2})} \left(X_{Bw}+\varepsilon_{Bf} X_{Bf} \frac{A_f}{V_w}\right) \alpha_w^{T-20} k_{H,pH}$ ... **3.23.**
Slow (X_{Sslow}) Anoxic Hydrolysis	(Mourato et al. 2003)	$\eta_{h,anox} k_{h,slow} \frac{X_{S,slow}/X_{Bw}}{K_{X,slow}+X_{S,slow}/X_{Bw}} \frac{K_O}{S_O+K_O} \frac{S_{NO_3}+S_{NO_2}}{K_{NO}+(S_{NO_3}+S_{NO_2})} \left(X_{Bw}+\varepsilon_{Bf} X_{Bf} \frac{A_f}{V_w}\right) \alpha_w^{T-20} k_{H,pH}$ ... **3.24.**
Fast (X_{Sfast}) Anaerobic Hydrolysis	(Tanaka et al. 2000)	$\eta_{h,ana} k_{h,fast} \frac{X_{S,fast}/X_{Bw}}{K_{X,fast}+X_{S,fast}/X_{Bw}} \frac{K_{NO}}{K_{NO}+(S_{NO_3}+S_{NO_2})} \frac{K_O}{K_O+S_O} \left(X_{Bw}+\varepsilon_{Bf} X_{Bf} \frac{A_f}{V_w}\right) \alpha_w^{T-20} k_{H,pH}$ ... **3.25.**
Medium ($X_{SMedium}$) Anaerobic Hydrolysis	(Tanaka et al. 2000)	$\eta_{h,ana} k_{h,med} \frac{X_{S,med}/X_{Bw}}{K_{X,med}+X_{S,med}/X_{Bw}} \frac{K_{NO}}{K_{NO}+(S_{NO_3}+S_{NO_2})} \frac{K_O}{K_O+S_O} \left(X_{Bw}+\varepsilon_{Bf} X_{Bf} \frac{A_f}{V_w}\right) \alpha_w^{T-20} k_{H,pH}$ ... **3.26.**
Slow (X_{Sslow}) Anaerobic Hydrolysis	(Tanaka et al. 2000)	$\eta_{h,ana} k_{h,slow} \frac{X_{S,slow}/X_{Bw}}{K_{X,slow}+X_{S,slow}/X_{Bw}} \frac{K_{NO}}{K_{NO}+(S_{NO_3}+S_{NO_2})} \frac{K_O}{K_O+S_O} \left(X_{Bw}+\varepsilon_{Bf} X_{Bf} \frac{A_f}{V_w}\right) \alpha_w^{T-20} k_{H,pH}$ ... **3.27.**
Anaerobic Fermentation	(Tanaka et al. 2000)	$q_{fe} \frac{S_F}{K_{fe}+S_F} \frac{K_O}{K_O+S_O} \frac{K_{NO}}{K_{NO}+(S_{NO_3}+S_{NO_2})} \left(X_{Bw}+\varepsilon_{Bf} X_{Bf} \frac{A_f}{V_w}\right) \alpha_w^{T-20} k_{H,pH}$ .... **3.28.**
Biofilm Sulphide Formation	(Nielsen et al. 2005b)	$k_{S(-II)_{ff}} \sqrt{S_F+S_A+X_{S,fast}} \frac{K_{O,H_2S}}{K_{O,H_2S}+S_O} \frac{K_{NO,H_2S}}{K_{NO,H_2S}+S_{NO_3}+S_{NO_2}} \frac{A_f}{V_w} \alpha_{Sff}^{T-20} k_{H,pH}$ ... **3.29.**
Bulk water Sulphide Formation use fermentable substrate	(Sharma et al. 2008)	$k_{H_2S} \frac{(S_F+S_A)}{K_{S_F}+(S_F+S_A)} \frac{S_{SO_4}}{K_{SO_4}+S_{SO_4}} \frac{K_O}{K_O+S_{O_2}} \frac{A_f}{V_w} \frac{S_F}{S_F+S_A}$ .... **3.30.**
Bulk water Sulphide Formation use fermentation products	(Sharma et al. 2008)	$k_{H_2S} \frac{(S_F+S_A)}{K_{S_F}+(S_F+S_A)} \frac{S_{SO_4}}{K_{SO_4}+S_{SO_4}} \frac{K_O}{K_O+S_O} \frac{A_f}{V_w} \frac{S_A}{S_F+S_A}$ .... **3.31.**
Biofilm Sulphide Oxidation	(Nielsen et al. 2005b)	$k_{S(-II)Soxb} S_{S(-II)}^{mfb} S_O^{nfb} \frac{A_f}{V_w} \alpha_{Soxb}^{T-20} k_{S(-II),pH}$ .... **3.32.**
Aerobic-Biological Bulk water Sulphide Oxidation	(Nielsen et al. 2006)	$k_{S(-II)woxb} S_{S(-II)}^{mwb} S_O^{nwb} \alpha_{Soxb}^{T-20} k_{S(-II),pH}$ .... **3.33.**

Reaction	References	Equations	
Aerobic-Chemical Bulk water Sulphide Oxidation	(Nielsen et al. 2006)	$\frac{k_{H_2Swc}+k_{HS^-wc}\frac{K_{a1}}{0.1^{pH}}}{1+\frac{K_{a1}}{0.1^{pH}}} S_{S(-II)}^{mwc} S_O^{nwc} \alpha_{Soxc}^{T-20}$ …………	**3.34.**
Anoxic Sulphide Oxidation	(Mourato et al. 2003)	$p_{S_n} \frac{S_{H_2S}}{K_{H_2S}+S_{H_2S}} \frac{S_{NO_3-N}}{K_{S,NO_3}+S_{NO_3-N}} \alpha_W^{(T-20)}$ …………	**3.35.**
Re-aeration	(Nielsen et al. 2005b)	$K_L a_{O_2} 24(S_{OS}-S_O)$ where $K_L a_{O_2}=0.86(1+0.20F^2)(su)^{3/8} d_m^{-1} \alpha_r^{T-20}$ …………	**3.36.**
Hydrogen Sulphide Emission	(Nielsen et al. 2005b)	$K_L a_{S(-II)} 24(\gamma S_{S(-II)} - S_{S(-II),eq})$ where $K_L a_{S(-II)} / K_L a_{S_o} = 0.86$ …………	**3.37.**
Concrete Biological Sulphide oxidation	(Jensen et al. 2009)	$w_{bio} X_{TS} \frac{S_{H_2S}}{K_{H_2S}+S_{H_2S}} \frac{S_O}{K_{O_2,H_2S}+S_O}$ …………	**3.38.**
Concrete Sulphide oxidation of readily bio-degradable elemental sulphur	(Jensen et al. 2009)	$y_{S_F} X_{TS} \frac{S_{S_F}}{K_{S_F}+S_{S_F}} \frac{S_O}{K_{O_2,S_F}+S_O}$ …………	**3.39.**
Conversion of readily bio-degradable elemental sulphur to slowly degradable sulphur	(Jensen et al. 2009)	$z_s S_{S_F}$ …………	**3.40.**
Concrete Biological oxidation of slowly biodegradable elemental sulphur	(Jensen et al. 2009)	$q_{S_s} X_{TS} S_O^c$ …………	**3.41.**
Concrete Chemical oxidation of hydrogen sulphide	(Jensen et al. 2009)	$v_{abio} X_{TS} S_{H_2S}^{1.17} S_{O_2}^{0}$ …………	**3.42.**

3.3.3 Development of Integrated Urban Water model Framework

In this study, the results from the Integrated Urban Water model will be converted in average daily value (e.g. volume or concentration). Average daily value was considered to adequately describe the changes that occur in the sewer flow and H_2S concentration due to the application of WMP.

Figure 3.13 illustrates the conceptual framework for hydrogen sulphide modeling. The steps to develop the modeling framework and associated assumptions are described in sub-subsections 3.3.3.1 to 3.3.3.3.

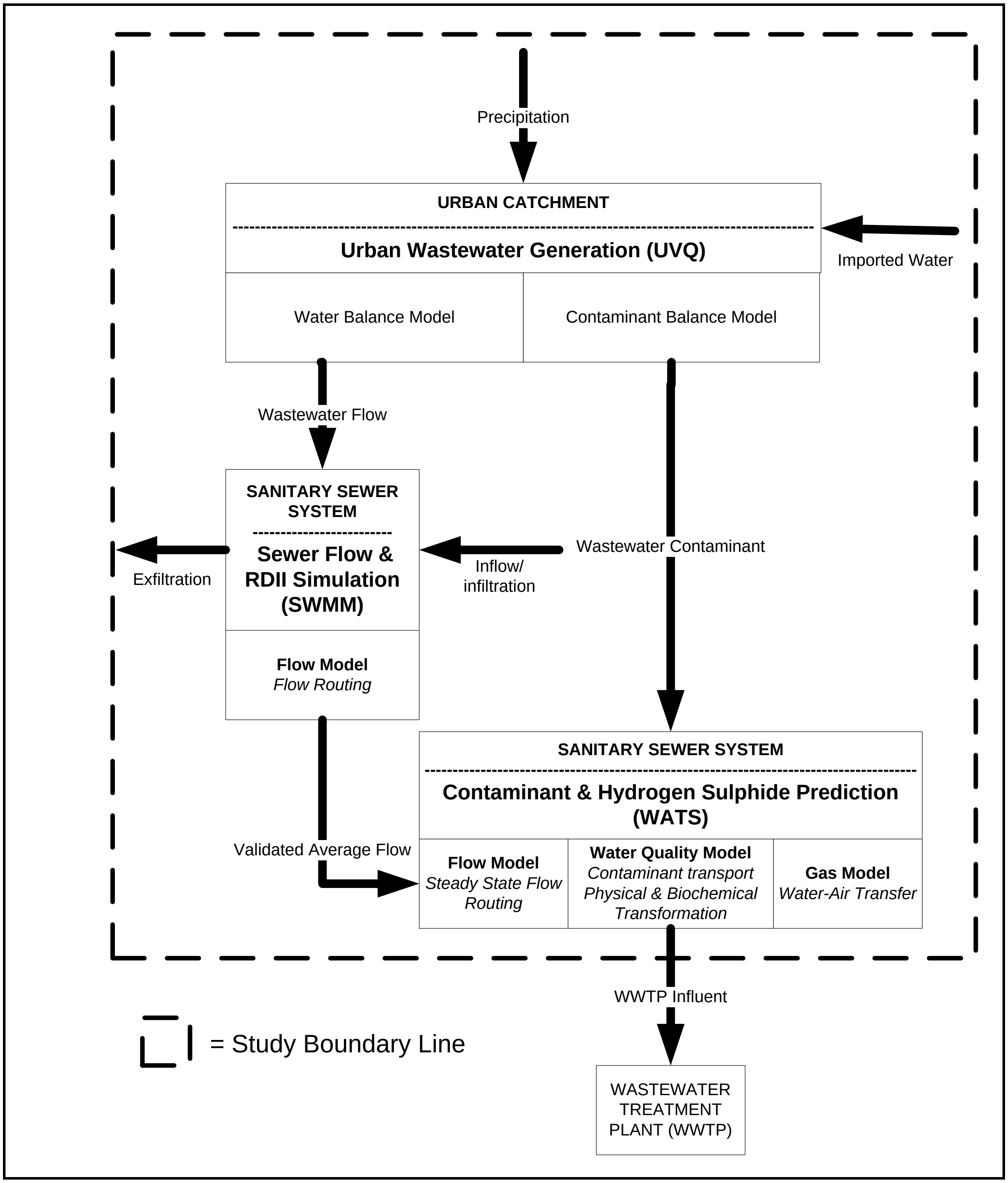


Figure 3.13. Interactions of Urban Wastewater Systems and Modeling Tools Involved in the Integrated Wastewater Model of Urban Catchment and Sewer Networks

3.3.3.1 Description

An Integrated Urban Water model framework consists of three modeling tools which simulate urban wastewater generation: sewer flow and external flow (RDII) connection, contaminants and H_2S gas analysis. The connections allow this modeling framework to overcome the problem of limited sewer flow data for dry weather (April, 2010). The output of Integrated Urban Water model from current condition (*Base Case*) simulation will consist of model parameters from every modeling tool and output variable (e.g. sewer flow and H_2S concentration). While model parameters obtained from *Base Case* simulation were used for subsequent WMP scenario simulation. Output variables from simulation calculations were used to evaluate whether generated model parameters were statistically acceptable. The evaluation process of generated model parameters is called calibration. In order to evaluate goodness of fit between observed data and simulated data, several indicators of goodness of fit were measured: the Nash-Sutcliffe coefficient of efficiency, coefficient of determination and root mean square error (RMSE) (Equations 3.43 to 3.47). These goodness of fit indicators have been used to measure water quality modeling (Daren Harmel & Smith 2007). In those studies, the complexity of water and wastewater quality between the model and the observed value can be captured using the Nash Sutcliffe coefficient, coefficient of determination and root mean square error. Therefore in this study those indicators were applied to simulation output variables of sewer flow and hydrogen sulphide gas concentration.

<u>Nash-Sutcliffe Coefficient of Efficiency</u>

$$E_{NS} = 1 - \left(\frac{\sum_{i=1}^{N} (observed_i - simulated_i)^2}{\sum_{i=1}^{N} (simulated_i - simulated_{average})^2} \right) \quad \text{………………………………..............3.43}$$

<u>Coefficient of Determination</u>

$$R^2 = 1 - \frac{SS_{err}}{SS_{tot}} \quad \text{……………………………………………………………………........…..3.44}$$

<u>Total Sum of Squares</u>

$$SS_{tot} = \sum_i \left(observed_i - observed_{average}\right)^2 \quad \text{3.45}$$

<u>Residual Sum of Squares</u>

$$SS_{err} = \sum_i \left(observed_i - simulated_i\right)^2 \quad \text{3.46}$$

<u>Root Mean Square Error</u>

$$RMSE = \sqrt{N^{-1} \sum_{i=1}^{N} \left(observed_i - simulated_i\right)^2} \quad \text{3.47}$$

3.3.3.2 Steps to Generate Model Parameters

Within the framework, the most important task is to generate the model parameters. For this study, generated model parameters were finally used to estimate sewer flow in April 2010 and used in WMP scenario simulation. The details of the model parameters generation steps are described below:

1) Use sewer flow data from November-December 2010 and September 2007 to obtain sewer flow model parameters which finally will be used to estimate the sewer flow for April 2010.
    a. Data for November-December 2010 were used to obtain the sewer flow model parameters, where the sanitary flow (wastewater flow from household) is affected by RDII. RDII consists of six model parameters: R, T, K, maximum storage depth, recovery rate and initial uptake rate. Based on input data for PC-SWMM software, R, T and K were classified as unit hydrograph parameters, while maximum storage depth, recovery rate and initial uptake rate were grouped into Initial Abstraction parameters. The unit hydrograph parameter was calibrated in November-December 2010 flow simulation until simulated flow matched the observed flow.

   b. Data for September 2007, which represents sanitary flow without the influence of RDII, were used to calibrate Initial Abstraction parameters. This task was conducted by adjusting storage parameter, while keeping the unit hydrograph parameter the same as the November-December 2010 calibration until simulated flow matched the observed flow.
   c. The RDII parameter (unit hydrograph and initial abstraction parameter) from September 2007 was finally used for predicting flow in April 2010.
2) Sewer flow data in November-December 2010 and predicted sewer flow in April 2010 was later used to obtain H_2S model parameters in WATS.
3) WATS model consists of two group model parameters, namely biofilm and bulk water. The calibration of biofilm and bulk water model parameters was conducted in the wet months (November-December 2010), since data available were more sufficient compared to other periods. After getting a good fit between observed and simulated data in the wet months, the obtained model parameters were tested/validated for the dry month (April 2010) simulation.

Figure 3.14 illustrates detailed connection links between modeling tools used in this study.

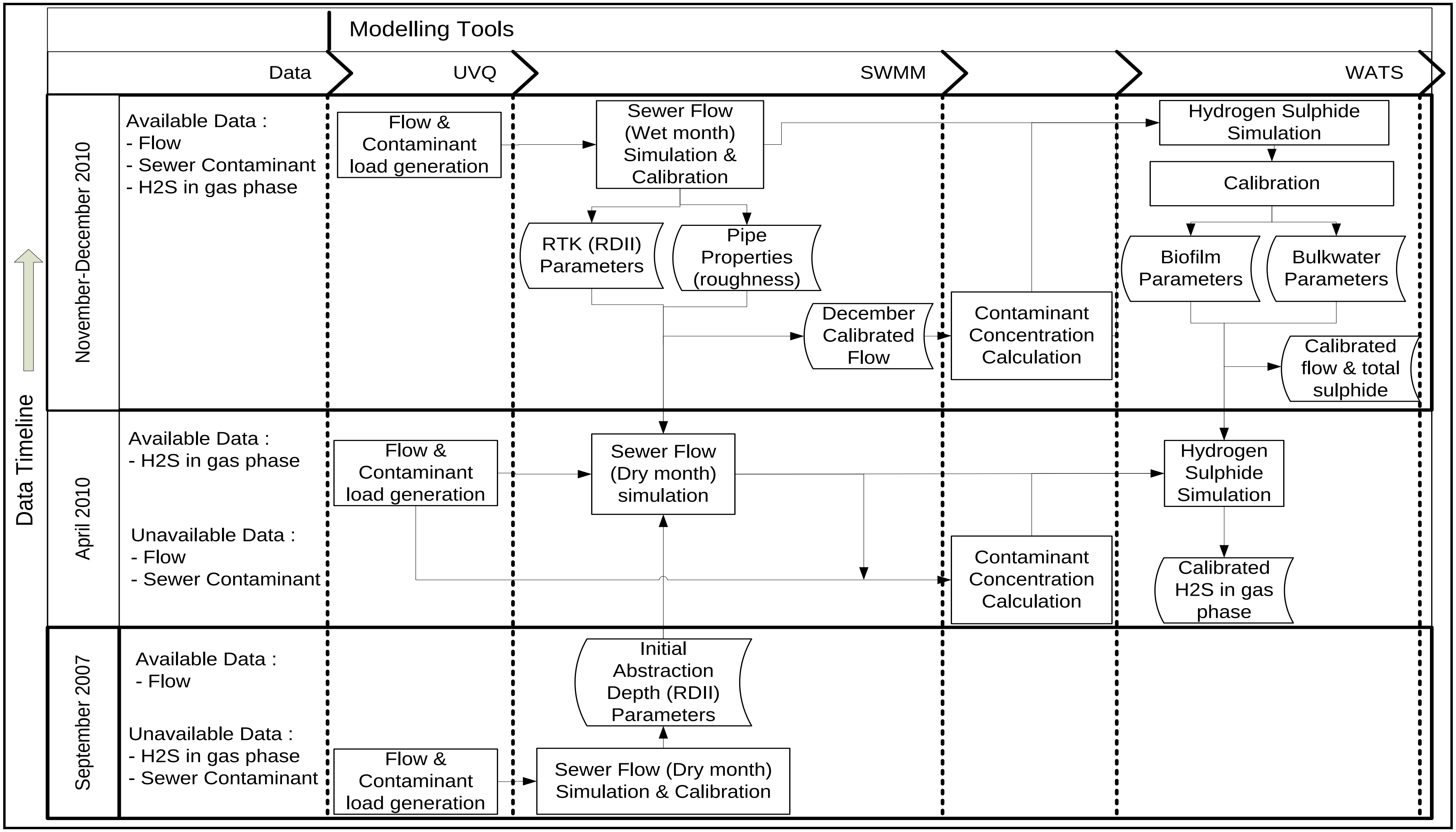


Figure 3.14. Modeling Framework Diagram

3.3.3.3 Assumptions

The assumptions used in this modeling framework were mostly to simplify the integration processes and to avoid overlapping processes between the individual modeling tools. The assumptions in this study are classified for every modeling tool.

1) Assumptions in the Wastewater Generation Model (UVQ)
   a. In UVQ, it was assumed that 0.1% of wastewater flow ends up as exfiltration; 0.1% of stormwater runoff flows into the wastewater system. Those proportions were kept constant during the simulation of all scenarios. These assumptions were set up to represent the aging factors from house connection pipe to sewer discharge point. However, pipe ageing within the house property was considered to be quite small, hence the small percentage of exfiltration and inflow were selected for this study.
   b. The unaccounted water in the households was set at 4% of total water demand in the household.
   c. All households in the study area were 100% detached houses with family households (no single persons). This assumption was based on the data from Moreland City Council, which stated that currently Moreland City Council (Glenroy is a suburb in Moreland City Council) is dominated by detached houses and family households.
   d. The dynamic infiltration and inflow only occurs in Glenroy Sewer Branch but not in household connections.
2) Assumption in Sewer Flow Model (PC-SWMM)
   a. The pipe properties (diameter, length and slope) were assumed not to have changed since the pipes were installed.
3) Assumption in Sewer Contaminant and Hydrogen Sulphide Gas Model (WATS)
   a. Same assumption as sewer flow model (2a above).
   b. Not all model parameters were derived from model calibration; some of them adopted the parameter values from Uni Emirates Arab's study (Vollertsen et al. 2011). The generation of hydrogen sulphide very much depends on the temperature and pH. Domestic wastewater pH worldwide is known usually to be in the range of

normal pH (6.5 – 8). A UEA study conducted an investigation of domestic wastewater in which the pH was approximately 7.7. This study also was conducted with domestic wastewater of pH 7.5. Hence, from the pH point of view, the wastewater between these two locations is comparable. In regard to the temperature, the UEA investigation was conducted in an arid area where the temperature might be as high as 31^{o}C. This situation mimics the condition in Australia in April 2010, which later was set as time period for the Base Case. Therefore, the parameter values from the UEA study were selected to be used in this study due to its similarity for hydrogen sulphide study in a catchment area located in a warmer climate.

3.4 Existing Urban Development (Existing Catchment Characteristics) Model Setup

To model the existing condition in a study area, several steps need to be taken according to Figure 3.2. Firstly, data were collected based on data identification processes in Table 3.6. Secondly, the collected data were inputted and simulated in Integrated Urban Water model tools. Section 3.4.1 describes the processes to obtain data that were not collected in the field study, while section 3.4.2 presents the simulation results, including the obtained model parameters, through model calibration and predicted flow for the dry month in April 2010.

Base Case represents the existing or current urban development scenario, which consists of 30% of households with a rainwater tank and 3% utilising rainwater for toilet or laundry. In addition, 3% of the households in the case study site already had a *Greywater Recycling* facility. Most household water demand is met from piped water. The current WMP configuration can be seen in Table 3.9. The wastewater produced within the household is discharged directly to the sewer network.

Table 3.9. WMP in *Base Case* (Existing Urban Development)

Development	***Sustainable Practice***		**Scheme Scale**
Existing Urban Development 2010/2011	*Rainwater Harvesting*	30%	Individual house
	Rainwater connect to Toilet/Laundry	3%	Individual house
	Greywater Recycling	3%	Individual house

The storage tank sizes were assumed to be 4 m^3 for rainwater and 1 m^3 for *Greywater Recycling*. The size selection for rainwater tanks was based on the 'Guidance on use of Rainwater from Australian Government Department of Health and Ageing' for 90% security of supply (Australian Government 2010a). Tank size for *Greywater Recycling* was selected based on the calculation of 2 days retention storage, which is the minimum storage time (Australian Government 2010a).

3.4.1 Input Data

3.4.1.1 Spatial Dimensions

In the study area of 425 Ha, a typical residential size block was computed to be in the range of 125-790 m^2, comprising a roof area of 63-467 m^2, garden area of 43-274 m^2 and it was assumed that all households have a paved area of 50 m^2. The road area in the study area was calculated at 41.6 Ha and the open space area was 271 Ha. All computations above were derived from GIS spatial analysis, which roughly calculates the block size and roof area, while the garden area was obtained by subtracting the total block size with the roof area. The paved area was assumed, based on a study by Cook et al. (2010). The occupancy rate in the study area was adopted from Robert's (2005) study, which stated that the average household size in Yarra Valley Water's service area was 2.55 people.

3.4.1.2 Climate Inputs

Wastewater generation within a household can also be determined by rainfall and outdoor water consumption. The dependence of rainfall occurs for households which installed the *rainwater tank* and for the households that installed Wastewater or Greywater Recycling facility. In the case of *Rainwater Harvesting*, the reliability of this system to supply indoor and outdoor water demand was greatly affected by rainfall. On the other hand, the wastewater recycling facility is more reliable to continuously supply the indoor and outdoor water demand. Treated water derived from wastewater recycling facility is mostly used to supply toilet flushing (for indoor use) and garden irrigation (for outdoor use). However, the supply of outdoor water consumption depends on the degree of soil wetness. For example, in dry weather, the soil mostly will dry out, therefore a lot of water is needed to wet the soil, while in wet weather, the soil most probably is already saturated with water, therefore outdoor water consumption for watering the garden will reduce significantly. Reduction of outdoor water consumption triggers more treated water from wastewater recycling facility to be diverted to sewer pipe networks; hence this will increase sewage volume.

Since the existing current catchment consist of some households with WMP of *Rainwater Harvesting* and wastewater recycling (see Table 3.8) the climate becomes one of the input data in this study. Figure 3.15 shows the rainfall plot for 2003 to 2011. The climate files used for this study were daily rainfall values from the Essendon Airport station, available for download from the Bureau of Meteorology website. The data used in this study however covers 2003 to 2010. Seven years duration has been selected for this study because the water restriction and practices of potable water substitution are more stringent and boomed after prolonged drought in 2002.

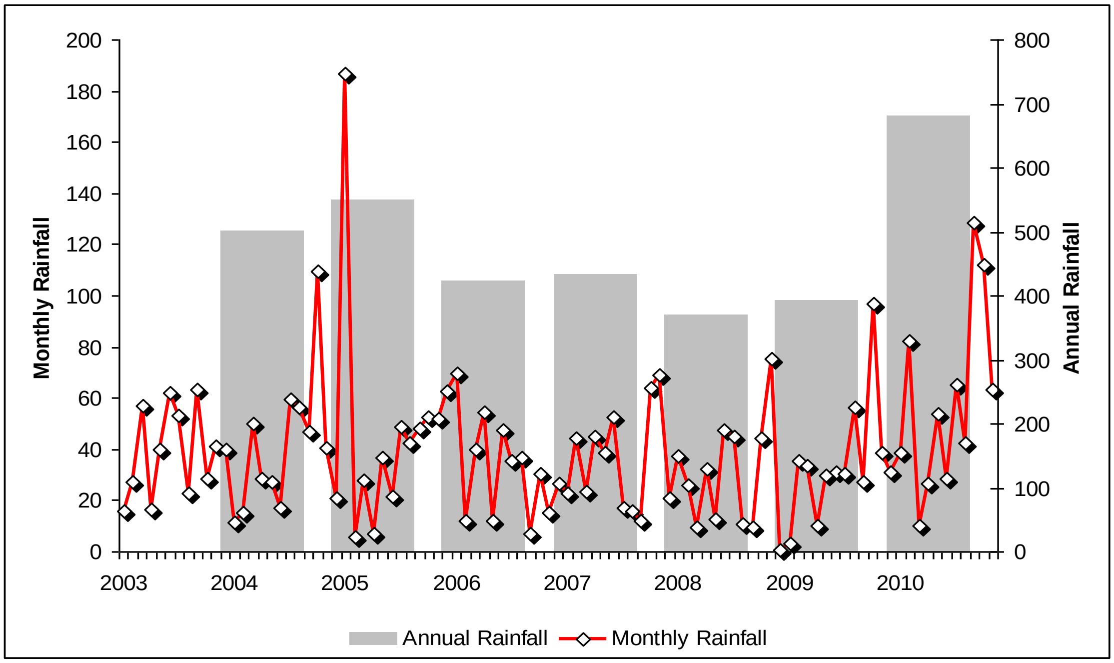


Figure 3.15. Annual and Monthly Rainfall from 2003-2011

3.4.1.3 Water Demand

Water demand is an important input data to calculate the wastewater produced within a household. Based on location, water demand is divided into indoor and outdoor demand. Wastewater discharge to sewer pipes originates from the total indoor water that has been used for indoor activities. The main contributions to indoor water demand come from human uses like bathing, cooking and so on. It was an assumption that indoor water demand does not change over time. However, some studies support this assumption. These studies show the indoor water demand could change depending on location and time (Beal et al. 2010; Roberts 2005; Tjandraatmadja et al. 2009b). For example, indoor water demand during the dry weather is higher than during wet weather (Beal et al. 2010). This is because in the summer people tend to drink more water and take frequent showers to cope with the heat. Furthermore, indoor water demand was also assumed to vary from year to year because of factors such as the recent campaign to reduce water consumption (Target 155) through the installation of water saving appliances, changes to water consumption behaviour and installation of alternative water sources (Tjandraatmadja et al. 2009b).

Therefore in this study, indoor water demand during dry and wet weather was discussed separately. Furthermore, indoor water demand was also differentiated every year. The next sub-subsections will discuss different water demand over different weather and years in this study.

3.4.1.3.1 Total Water Demand for Every Selected Month

Total indoor water consumption can be allocated to several indoor end-use i.e. laundry, kitchen, bathroom/shower and toilet water consumption. It is important to know how much water is consumed for each indoor end-use because it subsequently affects the volume of wastewater discharge. Most of indoor end-uses do not require water with potable water quality. In fact this water demand can be replaced by alternative water such as rainwater and treated wastewater. This concept is known as “Fit for Purpose”, which means quality of water supplied depends on quality required for the specific end-use. For example, for drinking water, the potable water is needed. While for flushing the toilet; this can be supplied from collected rainwater or treated wastewater/greywater.

The next sub-subsection describes the indoor end-use’s water demand for different weather and years. The percentage of each end-use’s water demand was derived from many studies (Beal et al. 2011b; Eriksson et al. 2002; Roberts 2005). The indoor water breakdown which is the breakdown of total daily indoor water demand per capita per day to end uses, was further investigated to reveal the level/rating of water saving appliances for every indoor activity that were likely to be used by most residents in the study area. To identify the current water saving rating, data from the Water Efficiency and Labelling Scheme (WELS) website, owned by the Victorian Government, was used. WELS is Australia's water efficiency labelling scheme that requires certain products to be registered and labelled with their water rating efficiency in accordance with the standard set under the national Water Efficiency Labelling and Standards Act 2005. Water rating labels help residents choose water efficient products, which results in conservation of water supply and reducing water bills. The water saving rating found for *Base Case* will then be used as a reference to establish the water saving rating using WMP scenario simulation. Sub-subsection 3.4.1.3.2

describes the process to breakdown the total indoor water demand and predicts the level/rating of water saving.

- **Water Demand in September 2007**

The water demand for the study site was calculated from total water demand in Melbourne from 30 August to 5 September 2007, which recorded at 999 million L/day (MW, 2007). The Melbourne population on 30 June 2007 was 3,805,800 (ABS 2008). Hence, the water demand was 999,000,000L/day / 3,805,800 cap = 262 L/cap/day.

- **Water Demand in April 2010**

For April 2010, the Melbourne Water weekly report showed the average water demand per capita per day within a week. Since hydrogen sulphide (gas) monitoring was conducted from 1 to 15 April 2010, therefore the average water demand was taken from 26 March to 16 April, as listed in Table 3.10 representing the values used in this study. The water demand provided here was taken from fortnightly water demand data. Therefore, the seasonal variation of water demand should also be reflected in these data. The substantial differences are mostly due to seasonal water demand as well as the water restrictions applied during that period.

Table 3.10. Daily Water Demand in Melbourne in April 2010 (YVW's Monitoring Period)

Date	Average Daily Water Demand
26 March - 2 April 2010	144 L/cap/day
3 - 9 April 2010	141 L/cap/day
10 - 16 April 2010	138 L/cap/day
Average	**141 L/cap/day**

- **Water Demand in November-December 2010**

The wastewater sampling/monitoring period for this study was conducted from 17 November to 8 December 2010. Melbourne Water recorded water demand for every week in November and December 2010 and then reported as the average daily water demand over the week. Table 3.11 lists the average daily water demand over the week which covers the sampling and monitoring period. Since the sampling and monitoring period for this study started on 17 November and ended on 8 December 2010, the water demand for the field study period in November/December 2010 was derived by averaging daily water demand over the week from 12 November to 10 December 2010.

Table 3.11. Daily Water Demand in Melbourne in November-December 2010 (Field Study Period)

Date	Average Daily Water Demand
12 - 19 November 2010	152 L/cap/day
20 - 26 November 2010	174 L/cap/day
27 November - 3 December 2010	140 L/cap/day
4 - 10 December 2010	155 L/cap/day
Average	**155 L/cap/day**

3.4.1.3.2 End-use Water Demand

The breakdown of the total daily water demand per capita into various end uses was carried out by multiplying total water demand with the percentage of water demand for end-use. The selected breakdown percentage from various studies, location and calculation for water demand for end-use is presented in Table 3.12. Water demand is spatially and temporally different from one location to another, depending on many factors, such as environmental conditions, climate, human behaviour and other interventions (water restriction). For this study, the breakdown percentage was taken from several studies and it was assumed that those percentages were also valid for this study (Beal et al. 2011b; Roberts 2005; Willis et al. 2009a). The considerations in selection from other existing studies are climate similarity, study location and similarity of urban profile. For example, November-December 2010 was the autumn–summer season; therefore the breakdown percentage was taken from the study conducted in late autumn or early summer. Since the study area is located in YVW's servicing area in Melbourne, Australia, the data for water usage breakdown from Roberts (2005) was utilised. The other consideration was available urban water demand profiles data and their similarity with the study area. Since the study area is located in Glenroy, a suburb of Melbourne, data taken from a study conducted in a city which has a similar profile to Melbourne would be beneficial to this study (Roberts 2005).

Table 3.12. Summary of Water Demand and Its Breakdown Percentage

	Sep-07	**Apr-10**	**Nov-Dec 2010**
Total Water demand (L/cap/day)	**262**	**141**	**155**
End Use Breakdown Percentage (%)			
Washing Machine	24%	19.5%	19.5%
Irrigation	8%	25%	25%
Toilet	19%	13%	13%
Other/leaks	4%	6%	6%
Bath tub/shower	30%	23%	23%
Tap	14%	12%	12%
Dishwasher	1%	1%	1%
	Autumn 2007=Auckland Winter 2007 (Willis et al. 2009a)	Summer 2010 = Summer Melbourne 2004 (Roberts 2005)	Autumn-summer Melbourne 2010 = Summer Melbourne 2004 (Roberts 2005)
End-use demand (L/cap/day)			
Washing Machine	44.4	27.5	30.2
Irrigation	14.8	35.3	38.8
Toilet	35.2	18.3	20.2
Other/Leaks	7.4	8.5	9.3
Bath tub/shower	55.5	32.4	35.7
Tap	25.9	16.9	18.6
Dishwasher	1.9	1.4	1.6
Indoor Use	**162.9**	**96.6**	**106.2**

The water demand for every time period was derived from the Melbourne Water Weekly Report (Sub Section 3.4.1.3.1)

After calculating the water demand for every use, it was necessary to approximate the current state of water saving behaviour among those inhabitants in the study area. To undertake this activity, the following two tasks were conducted:

1) Predict the water saving rating of indoor water appliances used by inhabitants in the study area by looking at the survey study about the most of appliances used by Melbournian (Cook et al. 2010; Roberts 2005). The scale of rating in WELS varies depends on the appliances and as the consequence, it will brings different water

demand. Every appliance has their rating and the water volume use for every appliance is also determined by the appliances brand.

2) Multiply the water volume (from Point 1) with the frequency and duration of water appliance use. Frequency and duration of water appliances were taken from the study conducted by Roberts (2005).

Tables 3.13, Table 3.14, and Table 3.15 present water appliances rating and water consumption in the study area. Based on the current water usage profile, future scenarios for increased use of water saving appliances were designed. Since this study attempts to generate sewer flow for three different time periods (September 2007, April 2010 and November-December 2010), there were three estimations conducted for water usage for different household appliances. The approach by using three different estimations for different time period was based on study conducted by Beal et al. (2010) study. The study of Beal et al. (2010) confirmed that the water demand is different seasonally, therefore there should be different estimation of water demand for different time period.

Table 3.13. Assumed WELS Ratings and Estimated Water consumption from Water Appliances in Study Area in September 2007

End-use		Appliance Water Demand		WELS Rating	Frequency[1]		Duration[1]		Total Water Demand (L/cap/day)		
									Flow based on WELS rating	Flow based on percentage (Table 3.13)	
Bathroom	Shower and Bath	8.5	L/mins	3 (>7.5 but <=9)	0.85	Times pCpD (shower combined with bath)	7.1	mins	51.3		
Hand Basin (basins/HH)	1.7	9	L/mins	**3**	5.5	Times/day	0.42	mins	14.0		
									65.3	**55.5**	**+Tap**
Laundry	Washing Machine	137	L/load	**3**	6.4	Loads/week			43.5		
	Laundry through bucket	50	Bucket vol. (L)		2	Times/week			3.4		
		60	Average fill level (% full)								
									46.9	**44.4**	**+Tap**
Kitchen	Dishwasher	14	L/load	**3**	4	Loads/week			2.3		
	Kitchen sink	20	L/mins (for cooking)		9	Meals/week			10.7		
		20	Sink Vol. (L)		8	Times/week					
		70	Average fill level (% full)								
									13.0	**1.9**	**+ Tap**
Toilet	Toilet	6/3	L/flush (average flush)	**3**	4	Time flushes pCpD			**36.0**	**35.2**	
Total Indoor Use									**161.3**	**162.9**	

Table 3.14. Assumed WELS Rating and Water consumption from Water Appliances in Study Area in November-December 2010

End-use		**Appliance Water Demand**		**WELS Rating**	**Frequency[1]**		**Duration[1]**		**Total Water Demand (L/cap/day)**		
									Flow based on WELS rating	**Flow based on the percentage (Table 3.13)**	
Bathroom	Shower and Bath	5 (>4.5 <6)	L/mins	**3**	0.85	Times pCpD (shower combined with bath)	7.1	mins	30.2		
Hand Basin (basins/HH)	1.7	5	L/mins	**5**	6	Times/day	0.5	mins	10.2		
									40.4	**35.7**	**+Tap**
Laundry	Washing machine	86	L/load	**3.5**	6.4	Loads/week			27.3		
	Laundry through bucket	50 50	Bucket vol. (L) Average fill level (% full)		3	Times/week			4.3		
									31.6	**30.2**	**+Tap**
Kitchen	Dishwasher	12	L/load	**4**	3.4	Loads/week			2.4		
	Kitchen sink	19.4 20 54	L/mins (for cooking) Sink Vol. (L) Average fill level (% full)		9 9	Meals/week Times/week			10.5		
									12.9	**1.6**	**+ Tap**
Toilet	Toilet	4.5/3	L/flush (average flush)	**4**	2.8	Time flushes pCpD			**21.0**	**20.1**	
Total Indoor Use									**105.9**	**106.2**	

Table 3.15. Assumed WELS Rating and Water consumption from Water Appliances in Study Area in April 2010

End-use		Appliance Water Demand		WELS Rating	Frequency[1]		Duration[1]		Total Water Demand (L/cap/day)		
									Flow based on WELS rating	Flow based on the percentage (Table 3.13)	
Bathroom	Shower and Bath	5	L/mins	**3 (>4.5 but <=6)**	0.85	Times pCpD (shower combined with bath)	7.1	mins	30.2		
Hand Basin (basins/HH)	1.5	5	L/mins	**5**	5	Times/day	0.5	mins	7.50		
									37.7	**32.4**	**+Tap**
Laundry	Washing Machine	86	L/load	**3.5**	6.4	Loads/week			27.3		
	Laundry through bucket	50 50	Bucket vol. (L) Average fill level (% full)		2	Times/week			2.9		
									30.2	**27.5**	**+Tap**
Kitchen	Dishwasher	12	L/load	**4**	3.4	Loads/week			2.3		
	Kitchen sink	20 20 50	L/mins (for cooking) Sink Vol. (L) Average fill level (% full)		7 7	Meals/week Times/week			8.0		
									10.3	**1.4**	**+ Tap**
Toilet	Toilet	4.5/3	L/flush (average flush)	**4**	2.6	time flushes pCpD			**19.2**	**18.3**	
Total Indoor Use									**97.4**	**96.6**	

3.4.1.4 Contaminant Inputs

The contaminant inputs in the wastewater generation model (UVQ) are comprised of several data input, but in this chapter, only four main contaminant inputs were listed:, drinking water supply (piped water), indoor use, rainfall and roof runoff. Other contaminant sources, such as groundwater, road runoff, pavement runoff, were also listed, but since they did not provide much contribution to wastewater contaminants, they were not included here. Nevertheless, the contaminants other than the four main contaminants are listed in Appendix 2, Table A.1. Four contaminant inputs, which are considered to be important in this study, will now be described.

- **Drinking Water Supply**

The piped water contaminant data was obtained by assuming that all contaminant parameters fall within the range of Australian Drinking Water Guidelines (ADWG) (Australian Government 2004).

- **Indoor Use**

Table 3.16 lists the contaminant load for indoor use, rainfall and runoff. Household indoor water contaminants are in the unit of load per person per day in UVQ. However, in most literature, water contaminants are mostly represented by concentration. Therefore, in this study, a load was obtained from the concentration multiplied by average water demand. A literature review on blackwater was used to estimate the proportion of contaminants derived from human excreta, urine, human excreta + urine and toilet paper (Almeida et al. (1999b). In addition, a worldwide review of past greywater studies (Butler et al. 1995; Eriksson et al. 2002) was also used to represent greywater quality. Those wastewater/greywater studies considered relevant for Australia wastewater conditions was based on the consideration that all studies were conducted in metropolitan cities from advanced countries, hence the pattern of demand and habit was assumed to be similar to this study. Metal contaminant load was taken from the study conducted by Cook et al. (2010). This metal study was originally derived from a Melbourne study, therefore it is strongly relevant to this study (Cook et al. 2010).

❖ **Rainfall and Roof Runoff**

The contaminant data for rainfall and roof runoff were obtained from the studies of Coombes et al. (2002), Yaziz et al. (1989) and Wong (2006a). Specific data for some metals were obtained from Coombes et al. (2002) and Magyar et al. (Coombes et al. 2002; 2008). The data collected from those studies were considered to represent contaminant data needed in this study. Some studies were all conducted in Australia (Coombes et al. 2002; Magyar et al. 2008; Wong 2006b), The only figure taken from the study conducted not in Australia is a study by Yaziz et al. (1989). Yaziz et al (1989) presents the rainfall's contaminant concentration which was considered to be general in any places.

Table 3.16. The Contaminant Load from Piped Water, Blackwater and Greywater, Rainfall and Roof Runoff

Contaminant	COD	Nitrate	Sulphide	Sulphate	Iron
Piped Water					
Conc. (mg/L)	0	2	0	2	0.06
Blackwater					
Toilet (mg/cap/day)	51600	14.7	7.7	1200	8.5
Greywater					
Kitchen (mg/cap/day)	13100	1.8	5.2	430	0.2
Bathroom (mg/cap/day)	1750	2.2	5.2	64.3	16
Laundry (mg/cap/day)	12300	24	7.7	1290	1.9
Rainfall					
Conc. (mg/L)	76	0.15	0	3.5	0.005
Roof Runoff					
Conc. (mg/L)	100	0.1	0	14.5	2.1

3.4.2 Model Parameter Estimation

Three Integrated Urban Water model tools were used in this study. Each modeling tool requires model parameters. Most parameters were obtained by trial and error through the calibration process. However, some were derived from laboratory experiments and the literatures.

In this study, calibration was conducted in the sewer flow model (PC-SWMM) and hydrogen sulphide model (WATS). Calibration in the wastewater generation model (UVQ) was not conducted because the observed flow and contaminant data at the point of origin was not available. Moreover, the model development in UVQ is not sensitive to short temporal variations (sub-daily) and does not take into account physical, chemical and biological wastewater degradation. However, UVQ has a strong capability to simulate practices of water management from household scale to city or study area scale. It also has powerful capability to generate wastewater flow and contaminant estimates. It is important to note that all the observed data was collected from sewer pipes in which the wastewater had undergone some physical, chemical and biological processes during transport.

Chapter 2 described the PC-SWMM model, which consists of 4 computational blocks, each with different model parameters: the runoff block describes runoff estimation; the transport and extended transport block describes routing of the runoff or sanitary flow; and the storage block and treatment block describe runoff or sanitary flow mixing in a receiving water body. The last block is more intended for contaminant modeling.

For modeling sewage flow, it is crucial to calibrate the transport block. Sewer flow routing has three major model parameters to calibrate: RDII parameters, pipe roughness and loss coefficient (Baffaut & Delleur 1989). The RDII parameters are considered to be important, particularly for calibration in existing sewer network pipes, since these pipes usually already have cracks or defects, where runoff can infiltrate and exfiltrate from the pipes. The other minor parameters are diameter, pipe length and slope which were obtained from YVW. These parameters remained fixed during the simulations, although pipe diameter could change over time, due to sediment and biofilm build-up.

3.4.2.1 PC-SWMM Model Parameters for Sewer Flow Calibration

❖ Pipe Roughness and Loss Coefficient

The pipe roughness estimation was derived from the E.P.A (2005) literature which states the Manning roughness for concrete pipes are 0.011 – 0.015. The initial value used in the modeling is 0.015, because it was considered that the older pipes would have rougher surfaces compared to new pipes.

The loss coefficient in SWMM consists of entry, exit and average losses. Entry loss coefficient is the entry loss coefficient associated with energy losses at the entrance of the conduit, while exit loss coefficient is the energy losses at the exit of the conduit. Meanwhile, the average loss coefficient takes into account the energy losses along the length of the conduit including the pipe accessories. The approximation value of these losses can be estimated from Larrock et al's (1999) study, which listed entry and exit losses as 0.1 and 1 respectively. The losses due to pipe accessories were considered to be 10% of the total loss along the pipe length.

❖ RDII Parameters

RDII is calculated per unit of rainfall per unit time. It assumes that RDII from one unit of rain is in triangle shape, which is defined by three parameters R, T and K (see Figure 3.16). T is time to peak, T, K is the ratio of recession limb to time to peak, and R is the area of the triangle which is the percentage of RDII volume from excess rain. The time from the recession limb to time to peak is calculated equal to T(1+K). SWMM allows up to three triangles to describe RDII. The first triangle represents the fast response from direct runoff that enters the sewerage network from foundation drains, downspouts and other types of direct connections. The second triangle represents the delayed response from pipe defects or cracked manholes. The third triangle represents the delayed response from increased groundwater level, which enters the sewer pipes from the pipe cracks and defects. In PC-SWMM, to calculate the excess rainfall that enters the sewer network, the initial abstraction depth (I_a), which consists of maximum storage depth (S_{max}) and starting storage depth (Do), were introduced to the RDII parameter. Further, to anticipate the variety of storm events in continuous simulation, a storage recovery rate (Rec) between storms was introduced (Gheith 2009). The procedure for determining RDII parameters (R, T, K, S_{max}, I_a and Rec) is summarised in Appendix 3.

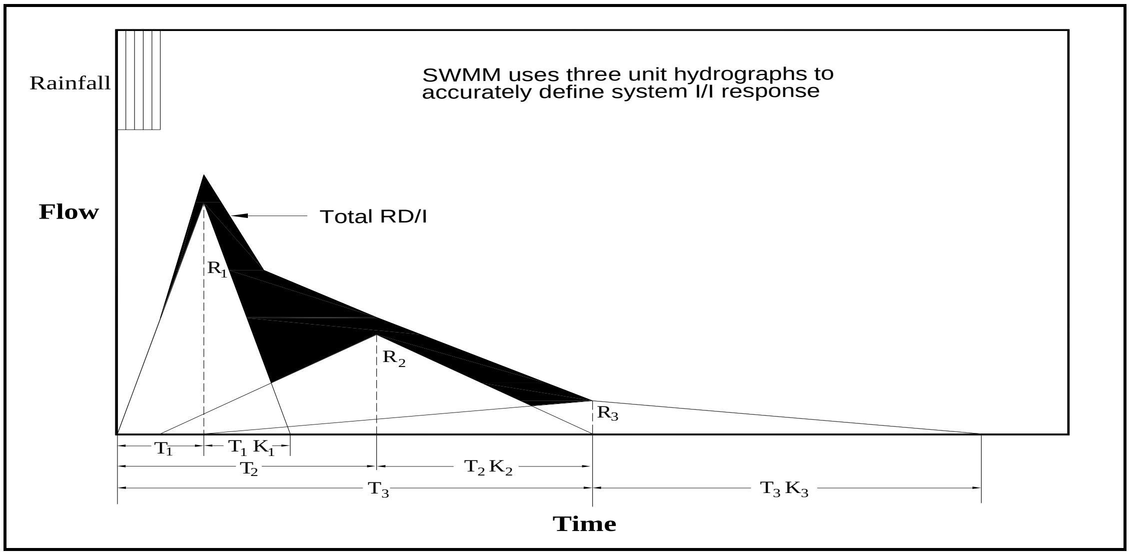


Figure 3.16. RTK triangle to RDII response (Adopted from Gheith (2009))

3.4.2.2 Flow Calibration and Validation

The calibration process aims to adjust the parameter set of a model in order to minimise the difference between model predictions and observed data of the real system by looking at the parameter of goodness of fit. Type and details of goodness of fit parameters were described in Section 3.3.3.1. For this study, the sewer flow simulation is calibrated by using the Sensitivity Radio Tuning Calibration (SRTC) technique. Model validation is also an important step to ensure that models and their outputs resemble the real world context as accurately as possible. Details of SRTC calibration are described in Appendix 4, while results of simulated flow and obtained model parameters from calibration and validation process in PC-SWMM are presented here.

In this study, the calibration was conducted in both wet and dry months. In the wet months, the simulated flow was calibrated and compared to sewer flow in December 2010. Further, the calibrated model was tested (validated) to simulate the flow in November 2010. Calibration in dry months was conducted by comparing simulated flow with sewer flow in September 2007. The flow calibration in September 2007 was conducted by using the RTK parameters from December, 2010 calibration and adjusting the initial abstraction depth parameters (part of RDII parameters). Finally, all RDII parameters obtained for dry month calibration were used to predict sewer flow in April 2010, in which the record of H_2S gas measurement was available.

❖ **November-December 2010 Calibration and Validation**

The calibration and validation in wet month was conducted by calibrating the RDII parameter and pipe losses coefficient. In the old, existing sewer network in this study, there is likely to be a significant influence from RDII, due to pipe ageing and corrosion which can lead to pipe defects.

As can be seen in Figure 3.17, there were several extreme events within November-December 2010 used to obtain RDII parameters. The calibration was carried out for two December 2010 events, as the prediction of R,T and K is best undertaken for a storm event immediately after another large storm event (Gheith 2009) (see Appendix 4 for RDII parameter calibration). The calibration after a large storm event means a high groundwater level and saturated soil conditions are likely to be maintained. The calibration was carried out in two locations in the study area, in manholes GLN8 and GLN23.

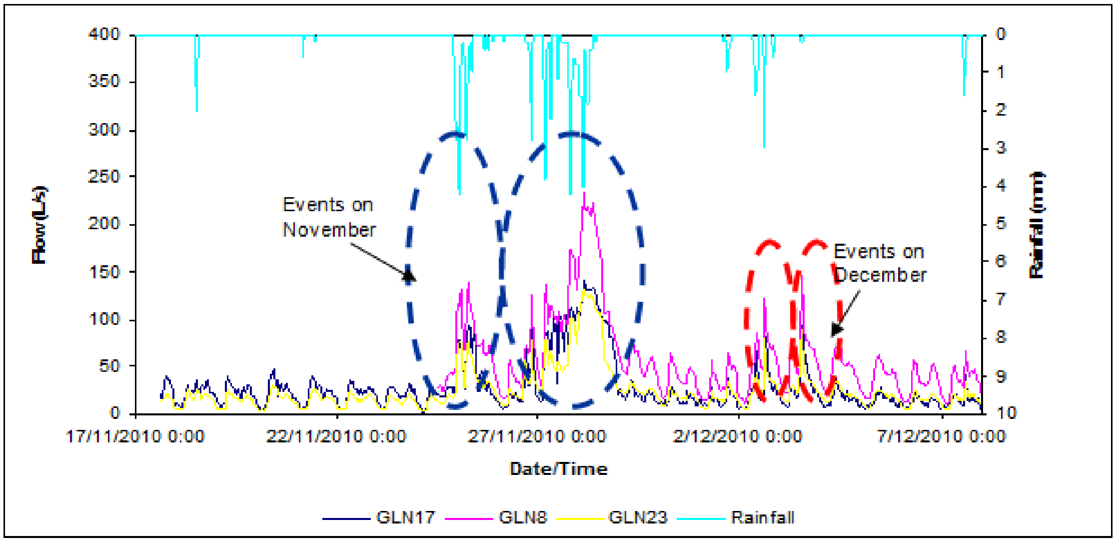


Figure 3.17. Storm Events in November-December 2010 (calibration in December 2010; validation in November 2010)

Figures 3.18, Figure 3.19, Figure 3.20 and Figure 3.21 compare the simulated and observed total daily wastewater volume from PC-SWMM simulation. It can be observed that the model is mostly underestimating sewer flows for large rainfall events.

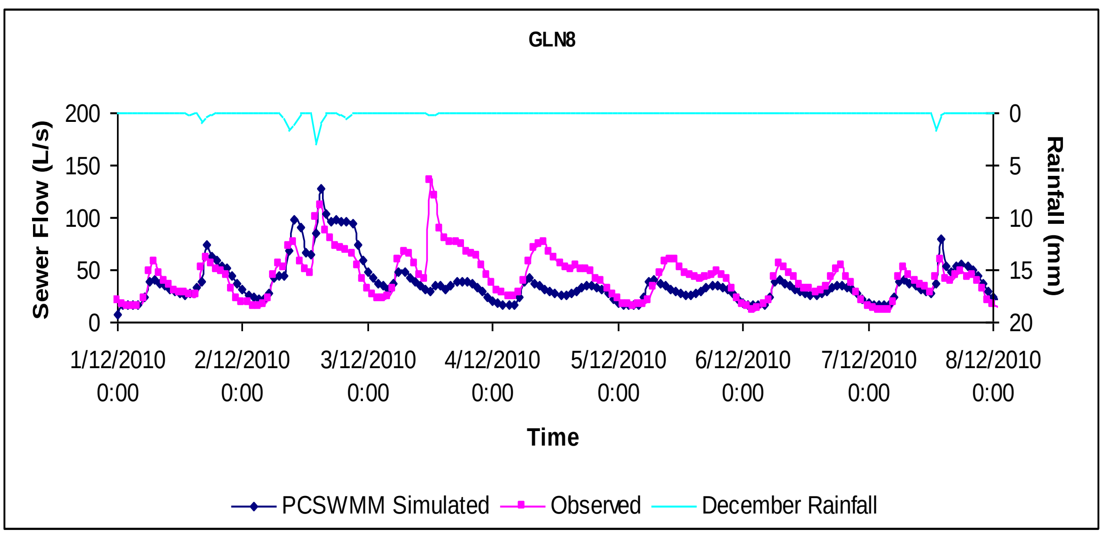


Figure 3.18. Sewer Flow Calibration in December 2010 at Manhole GLN8

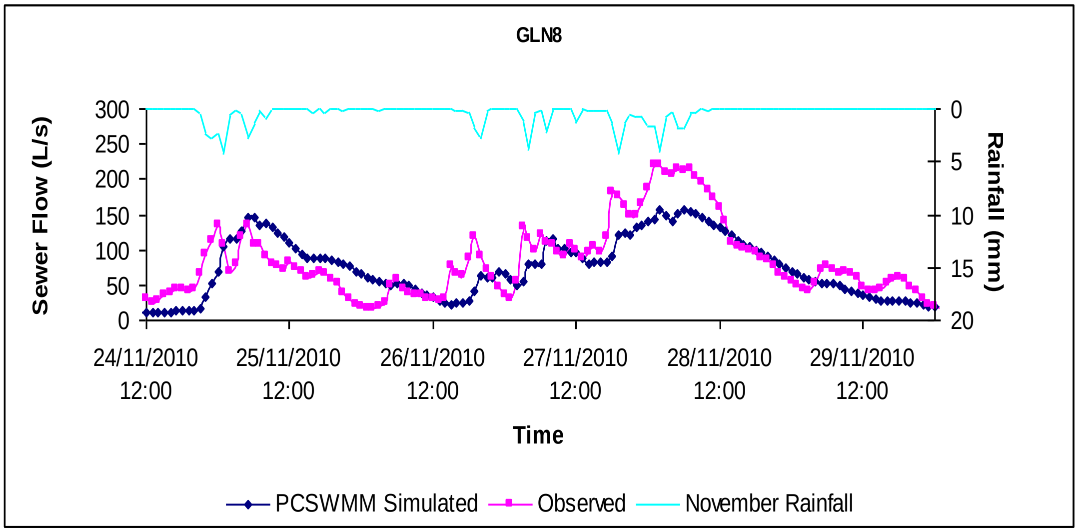


Figure 3.19. Sewer Flow Validation in November 2010 at Manhole GLN8

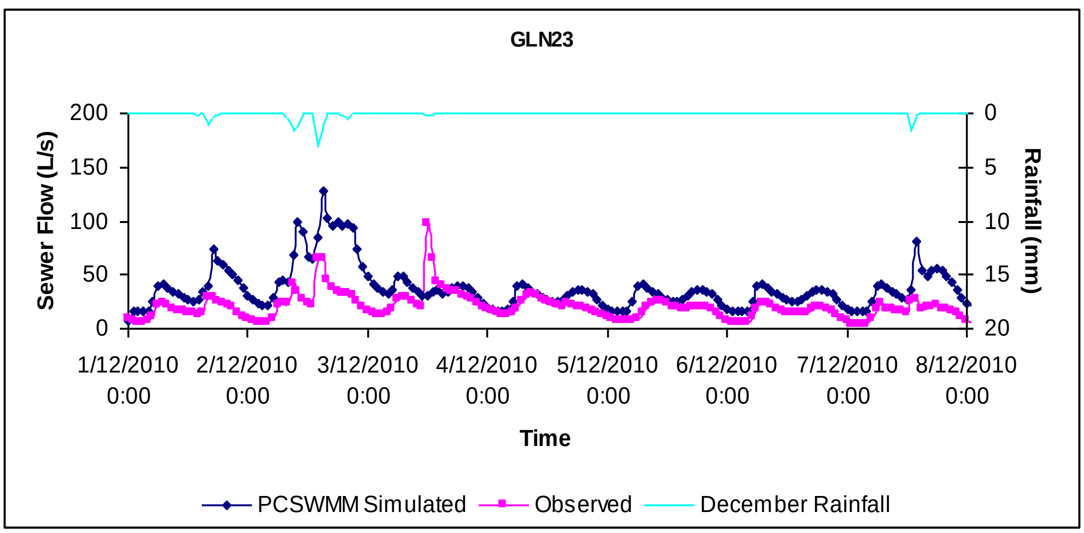


Figure 3.20. Sewer Flow Calibration in December 2010 at Manhole GLN23

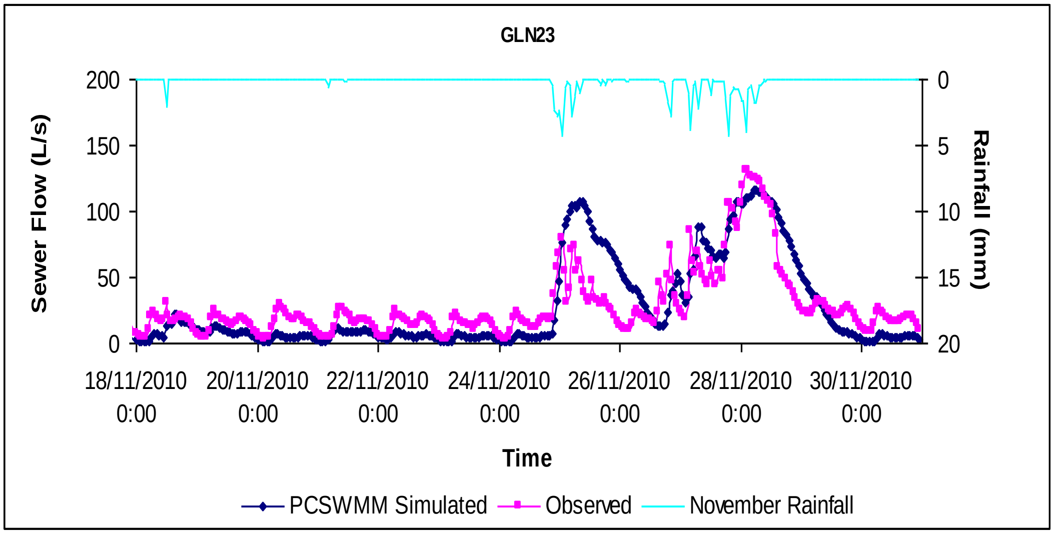


Figure 3.21. Sewer Flow Validation in November 2010 at Manhole GLN23

In order to evaluate the goodness of fit between observed and simulated data, the indicators of the Nash-Sutcliffe coefficient of efficiency, coefficient of determination and root mean square error (RMSE) have been estimated for each flow simulation. Table 3.17 compares goodness of fit indicators in calibration and validation stages.

Table 3.17. Goodness of Fit Indicators at GLN8 and GLN23

	Calibration (December Data)			Validation (November Data)		
	E_{NS}	R^2	RMSE	E_{NS}	R^2	RMSE
GLN8	0.65	0.75	17	0.50	0.70	32
GLN23	-0.40	0.45	23	0.70	0.80	18

It can be seen in Table 3.17 that the sewer flow calibration for two manholes obtain relatively acceptable agreement with the observed data, particularly for calibration in manhole GLN 8. Poorer agreement for manhole GLN 23 was obtained due to RDII parameters that could be maximally optimized in the manholes. It is shown in Figure 3.20 that most of the deviation was in the duration of high rainfall. However, better agreement showed in validation stage for manhole GLN 23. It was predicted that the soil condition, the level of ground water table and the level of defects were different; hence the RDII response behaves differently. In November, 2010 the soil condition was dry due to a long period without rain, while in December the soil had been saturated with water due to continuous heavy rain since mid of November 2010.

Table 3.18 to Table 3.21 shows the RTK and initial abstraction depth parameters for calibration in December 2010. The storage maximum storage depth, recovery rate and starting depth parameters were all maintained at a zero value as representative of a saturated soil condition. The adjusted R, T, K parameters from December, 2010 calibration is used for calibration processes for sewer flow in September, 2010.

Table 3.18. RTK Parameters at Manhole GLN 8 in December 2010 Calibration

	R	T	K
Short Term	0.025	0.2524	0.1908
Medium Term	0.05	6	0.572
Long Term	0.25	28.4693	11.9064

Table 3.19. Initial Abstraction Depth Parameters at Manhole GLN 8 in December 2010 Calibration

	D_{max}	D_{rec}	D_o
Short Term	0	0	0
Medium Term	0	0	0
Long Term	0	0	0

Table 3.20. RTK Parameters at Manhole GLN 23 in December 2010 Calibration

	R	T	K
Short Term	0.025	0.1262	0.0954
Medium Term	0.0375	3	0.74
Long Term	0.2	4.8417	6.8714

Table 3.21. Initial Abstraction Depth Parameters at Manhole GLN 23 in December 2010 Calibration

	D_{max}	D_{rec}	D_o
Short Term	0	0	0
Medium Term	0	0	0
Long Term	0	0	0

❖ **September 2007 Calibration**

Flow calibration in September 2007 was intended to represent the condition where the sanitary flow was not influenced by RDII. This approach was supported by the fact that in September 2007, the rainfall was minimal and the soil was unlikely to be in a saturated condition (see Figures 3.22 and Figure 3.23). If the soil was not saturated, then the values of initial abstraction depth parameters, such as storage maximum depth, recovery rate and starting depth, are not zero. The calibration was carried out by keeping the same R, T, and K parameter values as November-December 2010, assuming that the pipe defects did not change from September 2007 to December 2010. Because these values are fixed, the calibration in this period only adjusted the storage maximum depth, recovery rate and starting depth. The complete set of RDII parameters and other calibrated parameters (i.e. pipe roughness and losses) were then used to predict the sewer flow in April 2010.

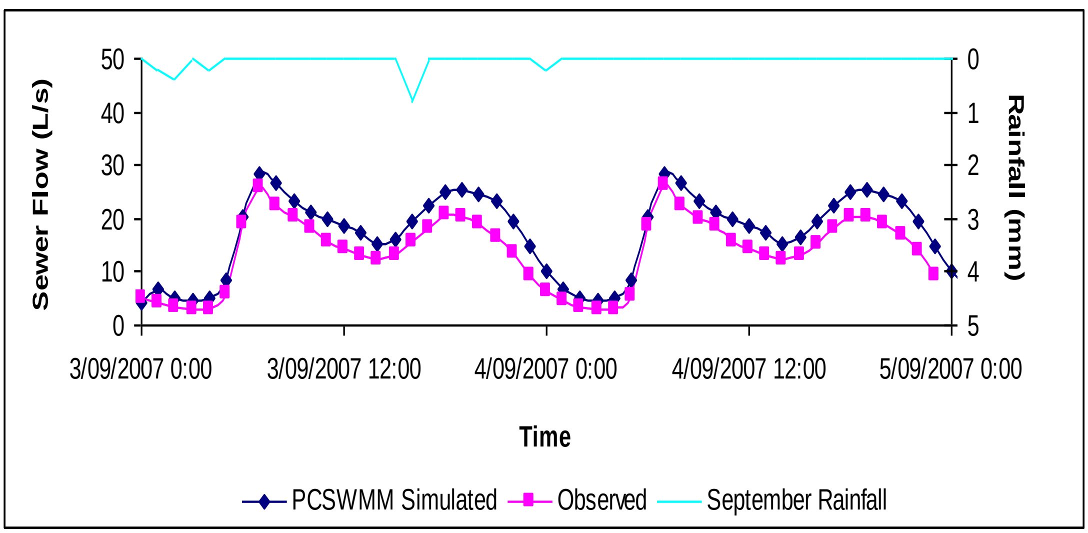


Figure 3.22. Sewer Flow Calibration in September 2007 at GLN8

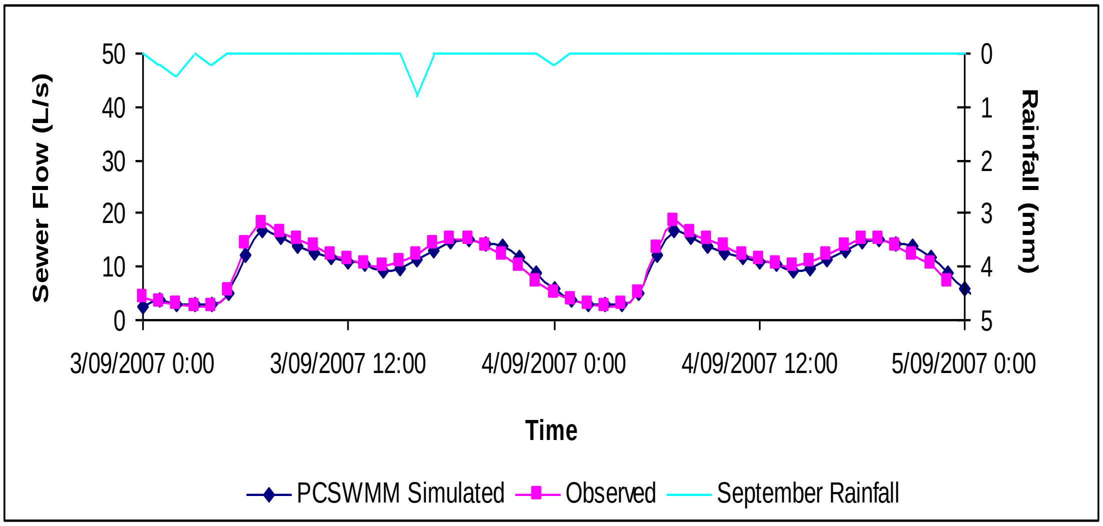


Figure 3.23. Sewer Flow Calibration in September 2007 at GLN23

The flow calibration in September 2007 was quite good at manhole GLN23; however, further downstream at GLN8A, the simulated flow mostly underestimated the actual flow, particularly when high flow occurred. Table 3.22 presents goodness of fit indicators for both manholes. The correlation between simulated and observed values in the two manholes is reasonable with a coefficient of correlation (R) more than 50%. The RTK paraemetrs and the adjusted storage maximum depth (Dmax), recovery rate (Drec) and starting depth (Do) in initial abstraction depth can be seen in Table 3.23 to Table 3.26.

Table 3.22. Goodness of Fit Indicators at GLN8A and GLN23

	Calibration in September 2007		
	E_{NS}	R^2	RMSE
GLN8A	0.75	0.80	3.8
GLN23	0.95	0.96	0.93

Table 3.23. RTK Parameters at Manhole GLN 8A in September 2007 Calibration

	R	T	K
Short Term	0.025	0.2524	0.1908
Medium Term	0.05	6	0.572
Long Term	0.25	28.4693	11.9064

Table 3.24. Initial Abstraction Depth Parameters at Manhole GLN 8A in September 2007 Calibration

	D_{max}	D_{rec}	D_o
Short Term	50	10	0
Medium Term	400	30	0
Long Term	500	50	0

Table 3.25. RTK Parameters at Manhole GLN 23 in September 2007 Calibration

	R	T	K
Short Term	0.025	0.1262	0.0954
Medium Term	0.0375	3	0.74
Long Term	0.2	4.8417	6.8714

Table 3.26. Initial Abstraction Depth Parameters at Manhole GLN 23 in September 2007 Calibration

	D_{max}	D_{rec}	D_o
Short Term	50	10	0
Medium Term	400	30	0
Long Term	500	50	0

❖ **Flow for April 2010**

After defining all the RDII parameters (R, T, K, maximum depth, recovery rate and starting depth), the sewer flow for April 2010 was estimated. Those RDII parameters were important parameters to provide an estimation for the April flow, since there were few rainfall events during this month (see Figure 3.24). However, rainfall events occurred on some days in April 2010, which seems to have had no effect on sewer flow. It is because the soil condition in the study area was dry (unsaturated condition), hence the rainfall excess (runoff) quickly permeates into the soil. .

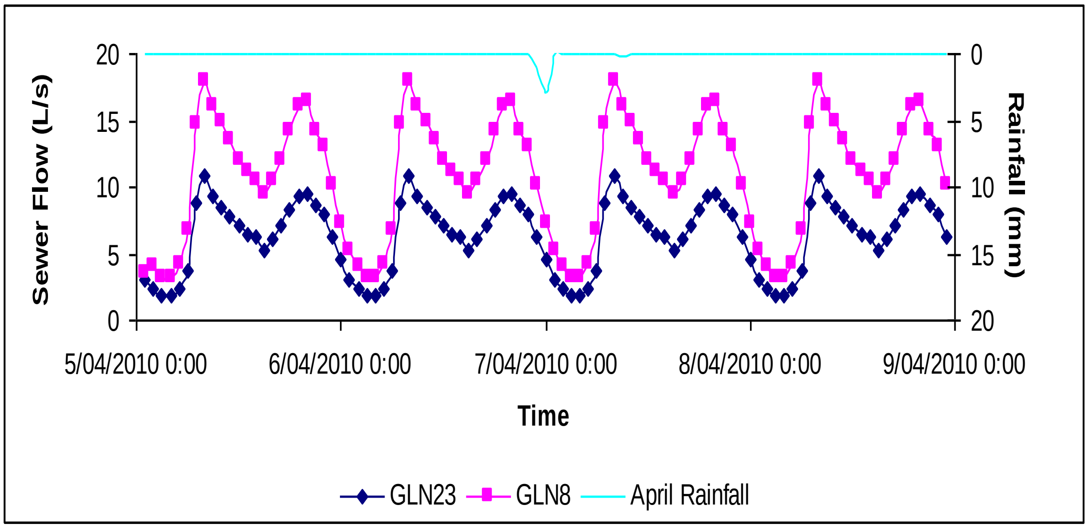


Figure 3.24. Estimated Sewer Flow for Weekdays in April 2010

3.4.3 Sewer Contaminants and Hydrogen Sulphide model (WATS)

WATS requires large number of model parameters for model calibration. Naturally, such parameters vary from case to case and hence need to be determined for every model application. This is often difficult when facing practical engineering problems of data collection. In this study, not all field data parameters were available, and consequently, only the key parameters were selected to be calibrated and determined by laboratory experiments. For other model parameters, the values were obtained from the literature. The procedure of laboratory experiments was briefly described in Appendix 5 and the other model parameters for WATS simulation can be found in Appendix 6, Table A.2. This section presents key model parameters and calibration results from the contaminants and hydrogen sulphide gas model simulation.

3.4.3.1 WATS Model Parameters for Wastewater Quality and Sulphide Gas Calibration

The WATS model was calibrated by using the data set for the wet month (November-December 2010) and then tested or validated by using data from the dry month (April 2010). The input data of wastewater composition is different between dry and wet weather. The WATS model was simulated, based on the BOD or COD fractionation. Total COD for dry and wet weather are 864 mg COD/l and 452 mg COD/L respectively. Since the laboratory experiment to determine the fraction of COD failed, hence the percentage fraction was taken from Vollertsen et al. (2011). The wastewater composition and COD fraction for dry and wet months can be seen in Table 3.27. All the key parameters were manually (trial and error) adjusted to fit the simulation for the observed data. The key model parameters for model calibration are listed in Table 3.28.

Table 3.27. Wastewater Composition Input in WATS

Wastewater Composition	Fractionation of COD value	Dry Month	Wet Month
Temperature (^oC)	-	23	20
pH	-	7.0	7.4
S_F (mg COD/L)	5.3%	46	24
S_A (mg COD/L)	5.3%	46	24
X_{Bw} (mg COD/L)	3.4%	30	16
X_{Sf} (mg COD/L)	13%	113	60
X_{Sm} (mg COD/L)	20%	173	91
X_{Ss} (mg COD/L)	53%	459	240

Table 3.28. WATS Model Parameters

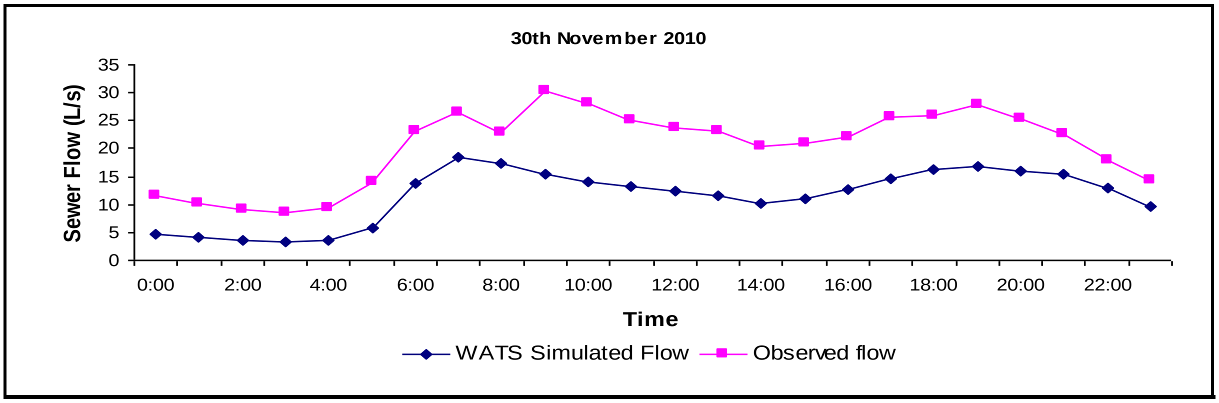
Model Parameters	Possible or accepted range	Calibrated values	Method of Determination
Bulkwater			
Maximum growth rate of the heterotrophic biomass at 20°C (my);1/d	2 – 15	9.6	Measurement
Yield constant for bulkwater aerobic heterotrophic biomass	0.3-0.8	0.41	Model calibration
Maximum growth rate of het. biomass utilizing NO_3 at 20°C (my);1/d	2 – 15	2	Model calibration
Maximum growth rate of het. biomass utilizing NO_2 in the presence of NO3 at 20°C (my);1/d	2 – 15	2	Model calibration
Maximum growth rate of het. biomass utilizing NO_3 in the absence of NO3 at 20°C (my);1/d	2 – 15	2	Model calibration
Maintenance energy rate constant at 20°C (qm);1/d	0.1 – 2	1.2	Model calibration
Saturation constant for het. growth on nitrate (KNO_3)	0.2 – 10	0.2	Model calibration
Saturation constant for het. growth on nitrite (KNO_2)	0.1 – 10	0.1	Model calibration
Saturation constant for KS, bulk water (g COD m^{-3})	0.1 – 10	0.1	Model calibration
Biofilm			
½ order rate constant for biolfilm, aerobic conditions (k½O_2);(gO_2/m)½ 1/d	2 – 100	10	Model calibration
Yield constant for biofilm, aerobic condition	0.4 – 0.8	0.4	Model calibration
Saturation constant for biofilm organic substrate; gCOD/m^3	0.1 – 20	0.1	Model calibration
H_2S formation rate constant; (gH_2S/m^2h)^0.5	2 - 100	40	Model calibration

3.4.3.2 Wastewater Quality and Hydrogen Sulphide Gas Calibration

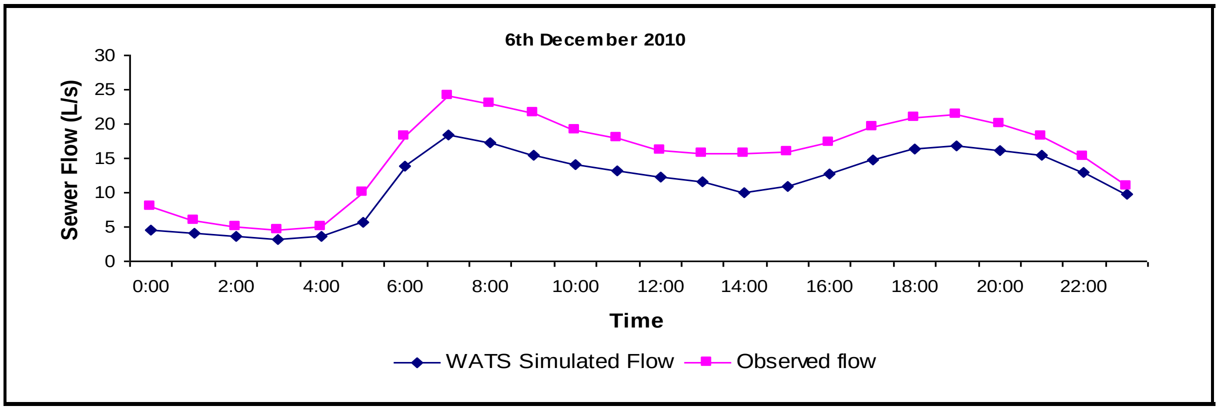
The calibration was conducted in GLN23 because the observed bulk water sulphide was measured in this manhole. Measurement of sulphide was carried out over three days (30 November, 6 December, 8 December 2010). The flow calibration follows the time framework for sulphide calibration. As can be seen in Figures 3.25 and 3.26, the fit between the model predicted, and observed flow and bulk water sulphide at GLN23 generally, followed the pattern of observed flow and sulphide concentration. However, it seems that the WATS model most of the time underestimated the sewer flow, particularly on the 30 November simulation. For two others dates, looking at the parameter of goodness of fit (Nash Sutcliffe, RMSE and R^2), the sewer flow is found to be fit reasonably well, though some flow discrepancies still occurred. For bulk water sulphide, the fit between the observed and predicted sulphide model was good. However, calibration for bulk water sulphide on 8 December gave less accurate results, compared to the other two days. There are two possible reasons behind the underestimated flow and some discrepancies between observed-model predicted sulphides: firstly, it was possibly due to the manual calibration procedure and secondly, it was probably due to equations used in the WATS model.

With regard to the manual calibration procedure, it has been mentioned before that the calibration period is conducted on three different dates. As a consequence, the calibration was initiated for only one date before other dates were tried. When the discrepancies were high in other dates, re-adjustment was made. This process was conducted continuously until the best fit was obtained for all dates. The only solution to reduce the hassle of manual calibration and to produce a better fit will be automatic calibration for the WATS model. Unfortunately, this kind of calibration is not as yet incorporated by the WATS developer.

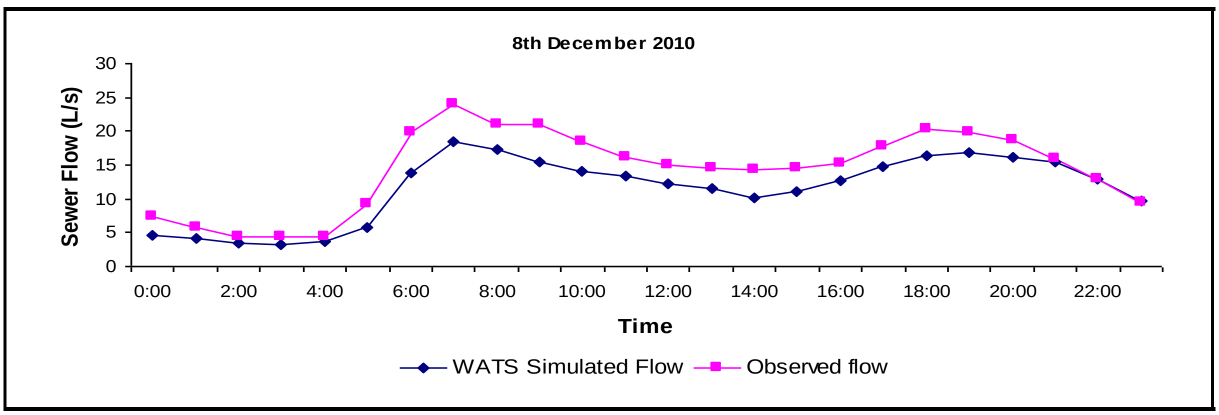
Related to the calibration result discrepancies due to internal equation of WATS, it is mainly for highlighting the flow calibration. The most plausible explanation regarding the underestimated flow could be due to the influence of inflow and infiltration. The WATS model is not designed to simulate flow, which is mostly under the influence of RDII. It is designed mainly to model dry weather flow, which is considered to be the most responsible flow for all physical, biological and chemical sewer processes. To cover this weakness in WATS model related to sewer flow simulation, the mean flow output of PC-SWMM model was used as an input to the WATS model. By using this strategy, the RDII contribution to the case study (Glenroy sewer branch) was accounted for. However, since WATS's hydraulic prediction equations did not cover up the dynamic of RDII, therefore nearly all observed flow points, particularly high flow, were greater than simulated flow.



(a)



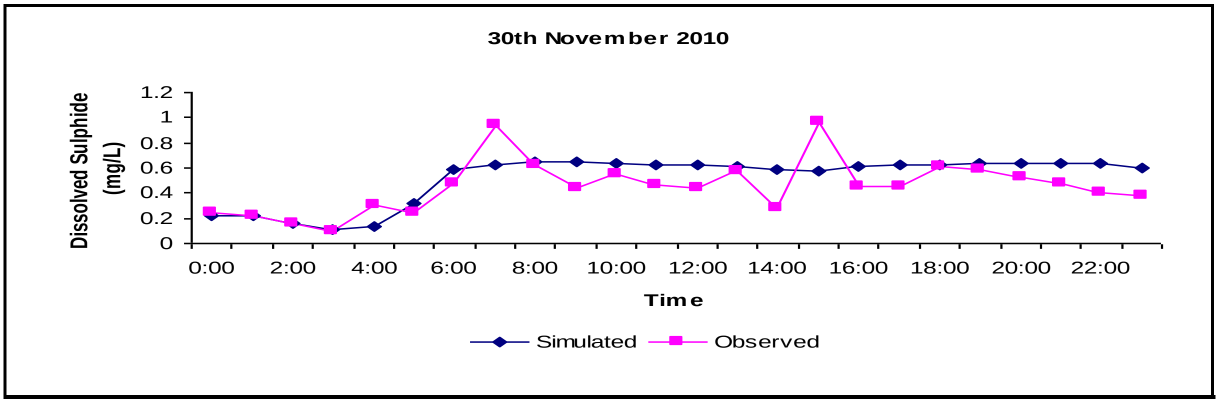
(b)



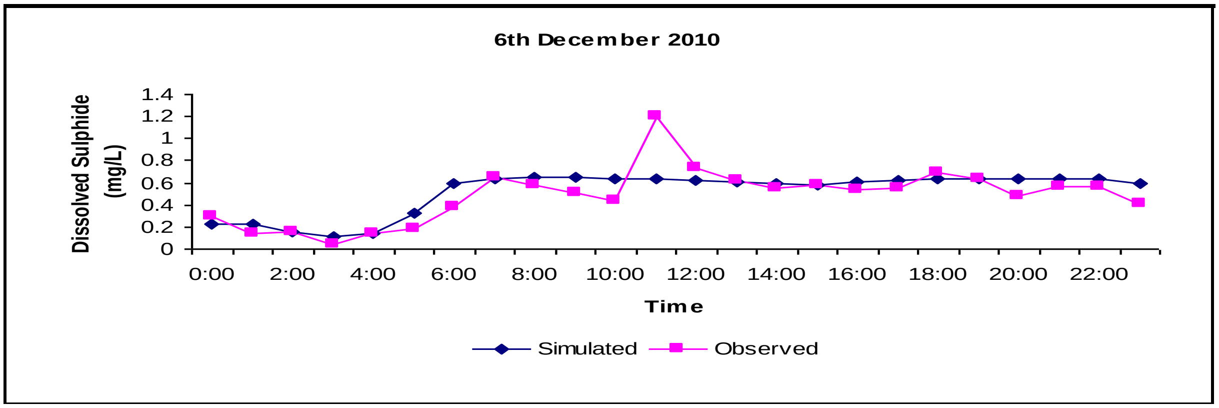
(c)

Figure 3.25. Model Calibration for Sewer Flow for (a) 30 November 2010, (b) 6 December 2010 and (c) 8 December 2010

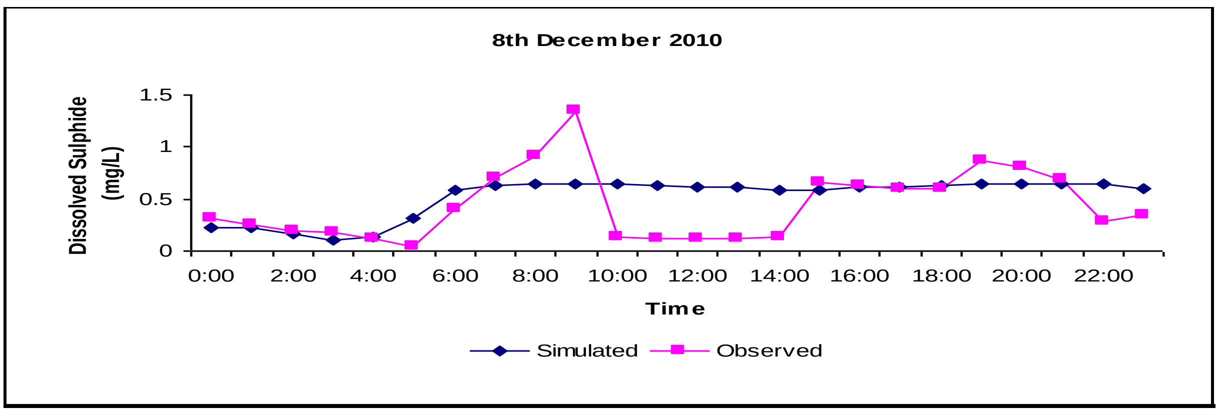
Looking at Figure 3.28, the predicted bulk water total sulphide concentration mostly coincided. However, it seems that the model was not sensitive to high/peak. It missed the peak for three days and tended to flatten after 6am. From Figures 3.27 and 3.28 it can also be seen that the bulk water sulphide was affected by flow reduction in the early morning but not in the afternoon, though this was a time of lower flow. It can be interpreted that the formation of sulphide will start when the flow is higher than 10 L/s and the formation will be less when the flow is lower than 10 L/s. This is due to the fact that less flow means less contaminant, which supports sulphide formation.



(a)



(b)



(c)

Figure 3.26. Model Calibration for Total Sulphide for (a) 30 November 2010, (b) 6 December 2010 and (c) 8 December 2010

Table 3.29 summarised goodness of fit indicators for flow simulation in WATS and total sulphide. For flow calibration the results gave relatively good value except for 30

November 2010. In total sulphide, the predicted sulphide resembles the observed sulphide except for 8 December 2012. E_{NS} negative indicators show that the model is not really a good predictor. The coefficient of determination also has a similar meaning to E_{NS} indicators. However, from three calibration days, only one day is considered to have low goodness of fit indicators, while the other days gave quite good results. To test or validate the model parameters from the wet month calibration, this set will be tested to predict hydrogen sulphide in the gas phase in the dry month of April 2010.

Table 3.29. Goodness of Fit indicators for WATS Flow and Bulk Water Total Sulphide for Wet Month Calibration

	Flow Calibration			Total Sulphide Calibration		
	E_{NS}	R^2	RMSE	E_{NS}	R^2	RMSE
30th Nov.	-2.5	0.25	9.2	0.20	0.60	0.17
6th Dec.	0.30	0.60	4.0	0.35	0.60	0.15
8th Dec.	0.55	0.70	3.2	-1.50	0.30	0.30

Since there was no observed data at other time period for WATS model validation, hence the validation of WATS model was carried out by simulating hydrogen sulphide gas on April 2010. The result of validation process shows the simulated hydrogen sulphide gas matched well with the observed hydrogen sulphide gas particularly on 12th April 2010 as can be seen in Figure 3.27. On the second day, the simulated hydrogen sulphide gas shows poorer results, though in some of the simulated values are close to the observed values, but most of the time the simulation is underestimated. It might be due to the complicated processes behind the formation of hydrogen sulphide gas. Many factors are involved in this process including flow, total sulphide, other contaminants such as metal, and supporting pipe conditions, such as flow depth, wastewater turbulence and the absorption rate of hydrogen sulphide gas by pipe wall. Regardless, the plot between the observed and predicted hydrogen sulphide gas coincides in many hours too. Looking at goodness of fit indicators in Table 3.30, the coefficient of determination (R^2) was 0.4, which is quite reasonable value for wastewater quality modeling.

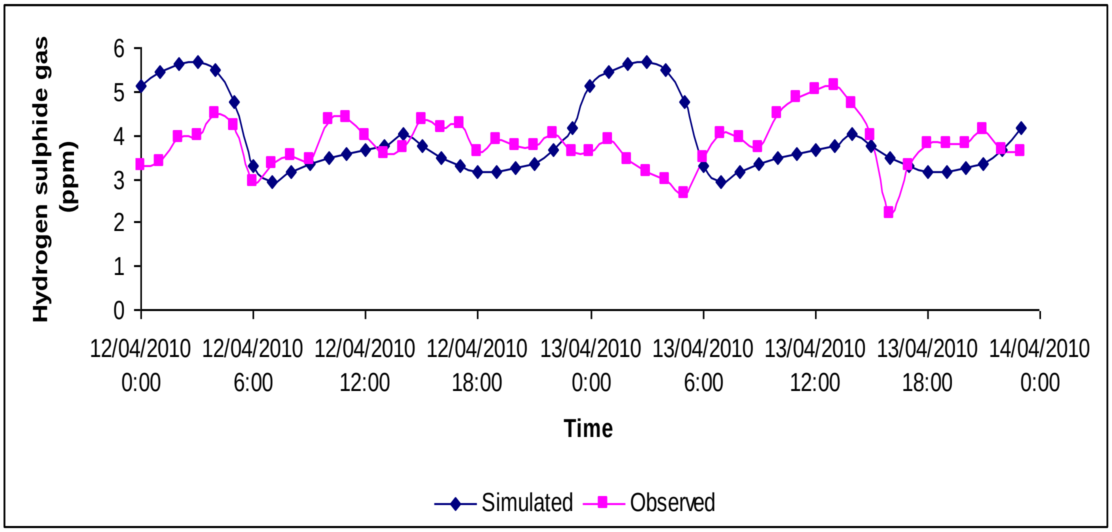


Figure 3.27. Model Calibration for Hydrogen Sulphide Gas

Table 3.30. Goodness of Fit Indicators for Hydrogen Sulphide Gas in Dry Month Calibration

	Hydrogen Sulphide Gas Calibration (December Data)		
	E_{NS}	R^2	RMSE
GLN2	-0.60	0.40	1.00

3.4.4 Sensitivity Analysis

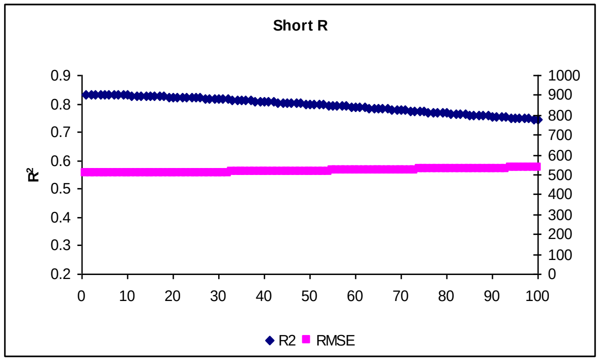
Wastewater quality model requires a relatively large numbers of parameters to define their functional relationship. Unfortunately, information on the parameters is not easily obtained. Therefore, it is common to find models calibrated by comparing modelled output data to observed data. Manual calibration could trigger high uncertainties in the model's output. It is important to conduct the sensitivity analysis on the model parameters, so that the sensitiveness of the model due to parameter changing can be estimated. The sensitivity analysis for this study was conducted by running the model for 100 times. Every run uses different model parameters. The model parameter which was used in every run was derived from the reange of model parameter values. The modelled output data for every model parameter was compared to observed data. The R^2 and RMSE was calculated by comparing modelled data and observed data. Finally they were plotted to the graph against the sequence number of model parameters. Number 1 in the plot means the lowest value in parameter range while number 100 represent the highest value in parameter range.

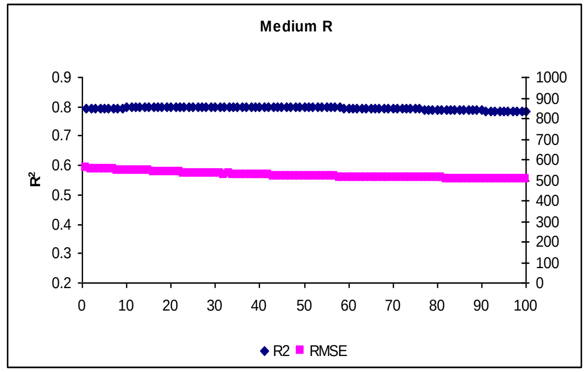
Figure 3.28 presents the sensitivity analysis for model parameters that were used to calibrate the sewer flow. Figure 3.29 presents the sensitivity analysis for model parameters that were used to calibrate wastewater contaminant and sewer gas. For flow calibration, there are RTK parameters and roughness parameters as main parameters that were calibrated in the models. For wastewater contaminant and sewer gas calibration, they were 13 model parameters that were calibrated.

Sensitivity analysis for sewer flow calibration in Figure 3.29 shows that the sewer flow was more sensitive to changes in fast RTK parameters. It was shown by the rapid changing on the R^2 and RMSE when the model parameters were changed. The calibration results tend to be better (smaller RMSE, higher R^2) by increasing the value of the model parameters. Looking at the component of RTK, parameter R is actually the most sensitive parameter compared to T and K parameters. R in the RDII triangle was expressed as the percentage of RDII volume from the excess rain. Hence, it is quite obvious that the runoff as an excess of the rainfall was actually the highest contributor of sewer flow in the wet weather flow.

Sensitivity analysis for wastewater contaminants and sewer gas calibration shows higher uncertainties compared to flow calibration. Some model parameters such as growth rate of heterotrophic biomass yield constant for bulk water aerobic heterotrophic biomas, hydrogen sulphide formation rate constant and ½ order rate constant for biofilm show general patterns of decreasing R^2 with increasing of model parameter values. However, there were two patterns in the graph which means that at some points there were model parameters values that affect performance of the model more than other parameter values. The complexity of the relationship function between the sewer flow, sediment, contaminant and gas could be the reason why the goodness of fit parameter had several patterns of R^2 or RMSE. From the simulation, the most sensitive parameters was measured by looking at the changes on the model parameters below :

1. The parameters of growth rate of heterotrophic biomass
2. yield constant for bulk water aerobic heterotrophic biomass
3. hydrogen sulphide formation rate constant
4. ½ order rate constant for biofilm
5. Maintenance energy rate


Short R
R²
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1000
900
800
700
600
500
400
300
200
100
0
0 10 20 30 40 50 60 70 80 90 100
R2 RMSE


Medium R
R²
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1000
900
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600
500
400
300
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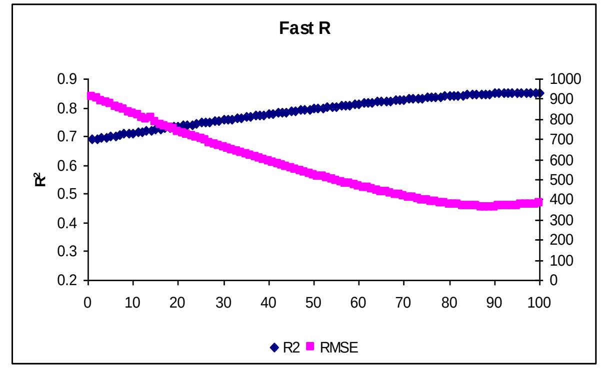
100
0
0 10 20 30 40 50 60 70 80 90 100
R2 RMSE


Fast R
R²
0.9
0.8
0.7
0.6
0.5
0.4
0.3
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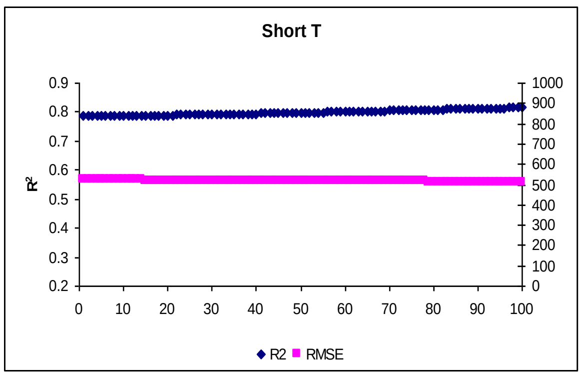
100
0
0 10 20 30 40 50 60 70 80 90 100
R2 RMSE


Short T
R²
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
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900
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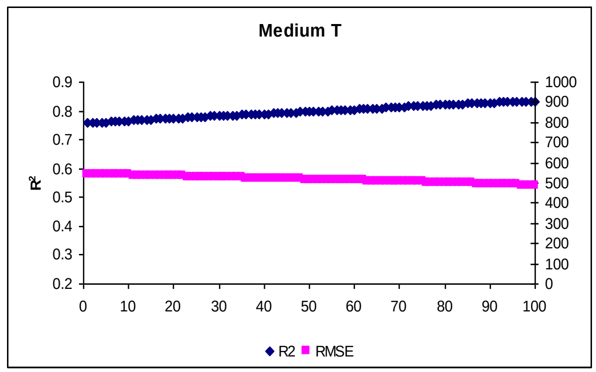
400
300
200
100
0
0 10 20 30 40 50 60 70 80 90 100
R2 RMSE


Medium T
R²
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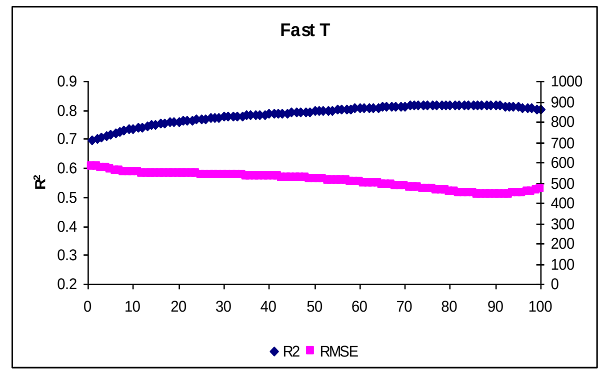
R2 RMSE


Fast T
R²
0.9
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0 10 20 30 40 50 60 70 80 90 100
R2 RMSE

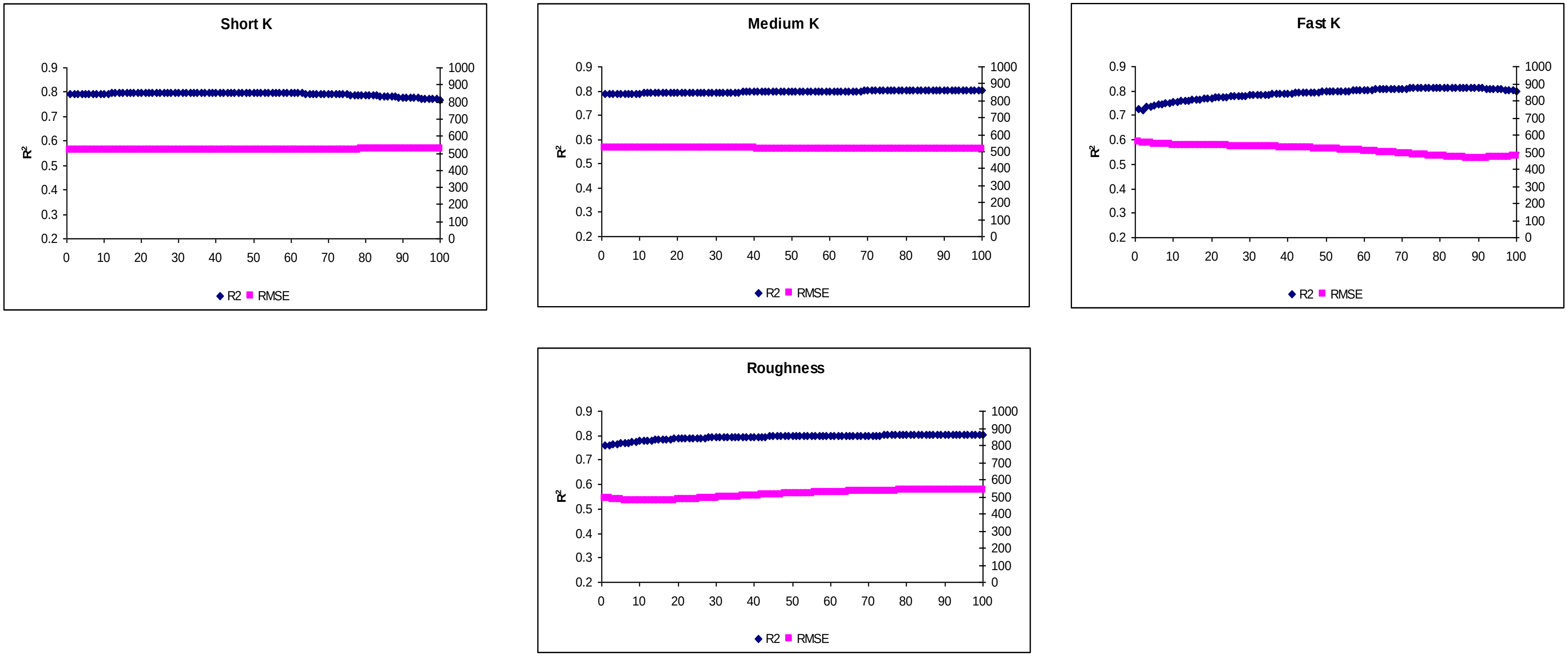
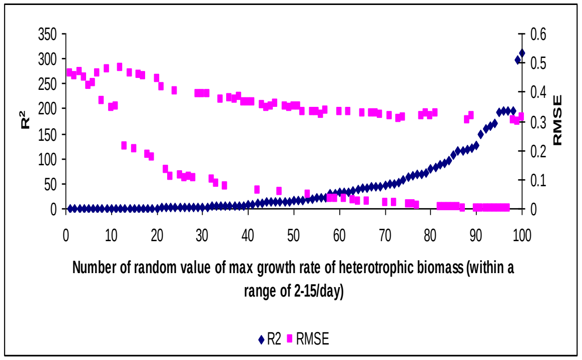
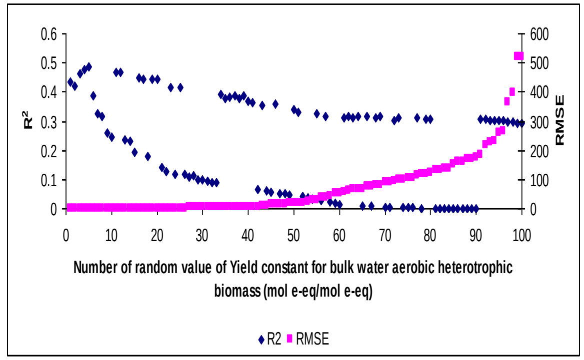
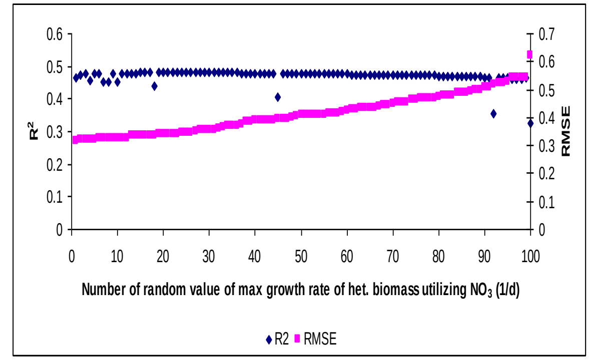
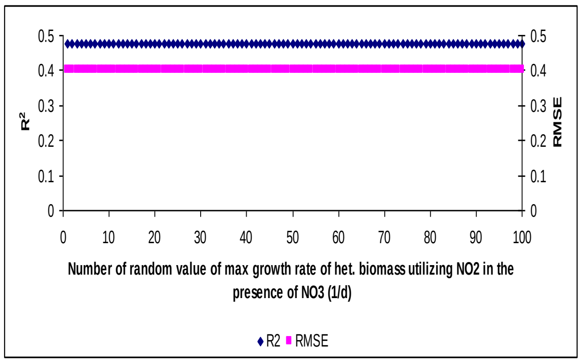


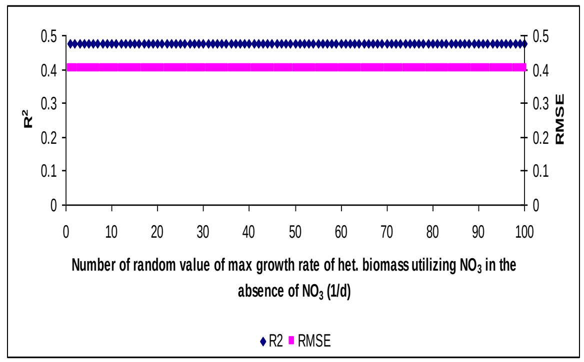
Figure 3.28. Sensitivity analysis for flow calibration

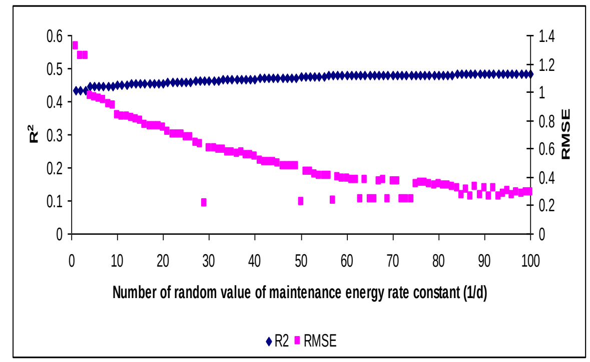

R²
RMSE
Number of random value of max growth rate of heterotrophic biomass (within a range of 2-15/day)
R2 RMSE

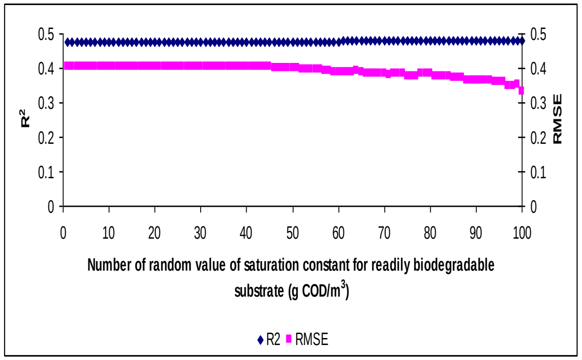

R²
RMSE
Number of random value of Yield constant for bulk water aerobic heterotrophic biomass (mol e-eq/mol e-eq)
R2 RMSE

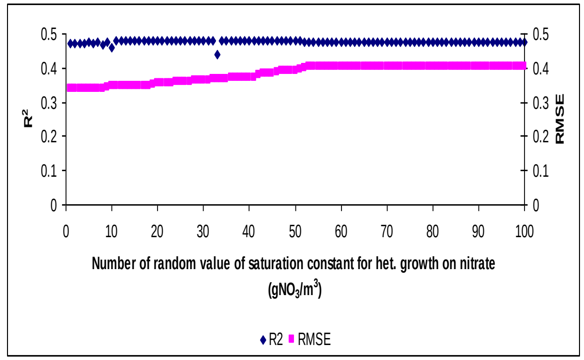

R²
RMSE
Number of random value of max growth rate of het. biomass utilizing NO3 (1/d)
R2 RMSE

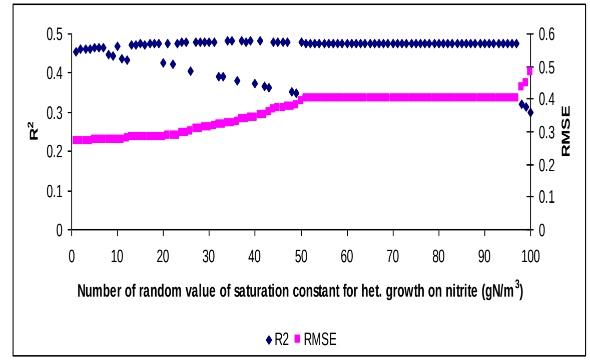

R²
RMSE
Number of random value of max growth rate of het. biomass utilizing NO2 in the presence of NO3 (1/d)
R2 RMSE

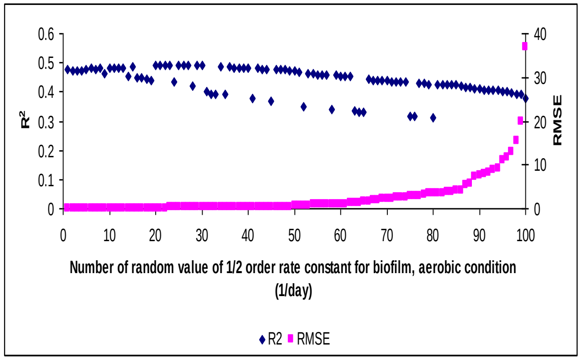

R²
RMSE
Number of random value of max growth rate of het. biomass utilizing NO3 in the absence of NO3 (1/d)
R2 RMSE

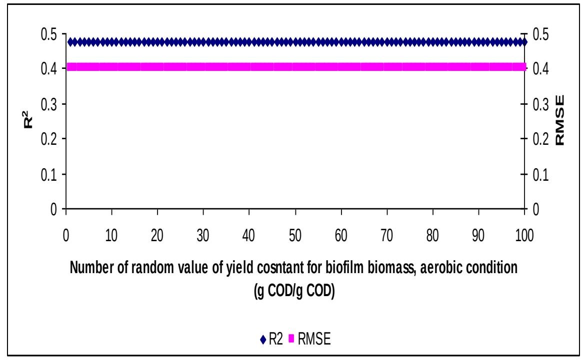

R²
RMSE
Number of random value of maintenance energy rate constant (1/d)
R2 RMSE

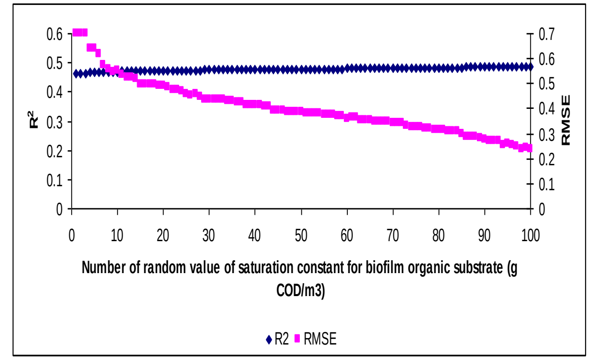

R²
RMSE
Number of random value of saturation constant for readily biodegradable substrate (g COD/m³)
R2 RMSE


R²
RMSE
Number of random value of saturation constant for het. growth on nitrate (gNO3/m³)
R2 RMSE


R²
RMSE
Number of random value of saturation constant for het. growth on nitrite (gN/m³)
R2 RMSE


R²
RMSE
Number of random value of 1/2 order rate constant for biofilm, aerobic condition (1/day)
R2 RMSE


R²
RMSE
Number of random value of yield cosntant for biofilm biomass, aerobic condition (g COD/g COD)
R2 RMSE


R²
RMSE
Number of random value of saturation constant for biofilm organic substrate (g COD/m3)
R2 RMSE

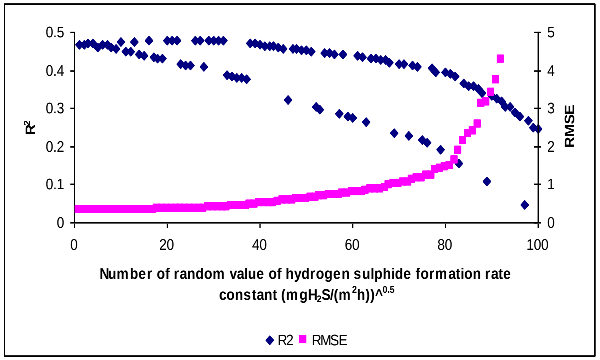


Figure 3.29. Sensitivity analysis for wastewater contaminant and sewer gas calibration

3.5 Summary

This chapter describes the methodology used to develop a modeling framework under the limitation of data availability. The developed framework was tested in a case study site. Eventually, the tested modeling framework can be used to simulate WMP scenarios in any urban development to predict hydrogen sulphide concentrations.

Unlike other Integrated Urban Water model approaches, where a single tool can be used to simulate an urban water component (i.e. one model for urban catchment and one model for sewerage network), this study integrated multiple tools to simulate urban wastewater networks and its catchment to predict hydrogen sulphide concentrations. In this Integrated Urban Water model approach, one tool is used to simulate the urban catchment and two tools are used to simulate sewerage network systems. This arrangement was designed to tackle the problem of limited data availability and to simulate existing and ageing sewerage networks. The integration of three models (UVQ, PC-SWMM and WATS) simulation required input data, model parameters, and output data, which are summarised in Table 3.31.

Table 3.31. Summary of Model Data Requirement

Type	Description
(a) Wastewater Generation Model	
Input Data	Number of connected households, individual land use area (road, park, roof, garden, paved area), household occupancy
Model Parameter	End-use flow rate (volume/person/time), End-use contaminant (mass/volume), external factors affecting wastewater (infiltration and inflow)
Output Data	Expected Inflow to sewerage network (volume/time), expected contaminant to sewerage network (mass/volume)
(b) Sewer Flow Model	
Input Data	Expected inflow to sewerage network (volume/time), sewer diameter, sewer length, sewer gradient
Model Parameter	Loss coefficient, sewer roughness, sewer infiltration and inflow rate
Output Data	Mean daily sewer flow
(c) Sewer Contaminant and Gas Model	
Input Data	Mean daily flow (volume/time), expected contaminant to sewerage network (mass/volume), sewer diameter, sewer length, sewer gradient
Model Parameter	Hydrogen sulphide formation rate, hydrogen sulphide oxidation rate (chemical and biological), maximum growth rate for heterotrophic biomass, wastewater biodegradability, fermentation rate, saturation constant and efficiency constant
Output Data	Sewer flow (volume/time), total sulphide in bulk phase (mass/volume), hydrogen sulphide in gas phase (mass/volume)

The calibration output from the model was split into three categories: model parameters, output flow and contaminant (total sulphide) and hydrogen sulphide gas. Three indicators of goodness of fit (i.e. Nash-Sutcliffe coefficient, coefficient of determination (R^2) and root mean square error (RMSE)) were used to measure how well a simulated value from the model simulation fits with the observation value by summarising the discrepancy between observed values and the values expected under the model. The results from model calibration are good for flow estimation both from PC-SWMM and WATS. The calibration of the contaminant (total sulphide) in bulk water gave quite a good result, while the calibration of hydrogen sulphide in gas phase shows poorer agreement compared to total sulphide calibration. However, the pattern between the modelled and observed data of H_2S

gas was similar, as can be seen in Figure 3.29. Table 3.32 summarises the coefficient of correlation for each calibration process.

Table 3.32. Summary of Goodness of Fit Indicators

		TOOL					
		PCSWMM			WATS		
Month	**Manhole**	**E_{NS}**	**R^2**	**RMSE**	**E_{NS}**	**R^2**	**RMSE**
Flow							
November 2010	GLN8	0.5	0.7	32	-	-	-
	GLN23	0.7	0.8	18	-2.5	0.25	9.2
December 2010	GLN8	0.65	0.75	17			
	GLN23	-0.4	0.45	23	0.3 (6 Dec) 0.55 (8 Dec)	0.6 (6 Dec) 0.7 (8 Dec)	4 (6Dec) 3.2 (8 Dec)
September 2007	GLN8A	0.75	0.8	3.8	-	-	-
	GLN23	0.95	0.96	0.93	-	-	-
Total Sulphide in bulk phase							
November 2010	GLN23				0.2	0.6	0.17
December 2010	GLN23				0.35 (6 Dec) -1.5 (8 Dec)	0.6 (6 Dec) 0.3 (8Dec)	0.15 (6 Dec) 0.3 (8 Dec)
H_2S in gas phase							
April 2010	GLN2				-0.6	0.4	1

4. DEVELOPMENT OF WATER MANAGEMENT PRACTICES (WMP) SCENARIOS

CONTENT: *Technique for Scenario Development; Selection of WMP; Projection in Study Area; Developed Scenarios; Summary*

Global climate change and population growth are two main drivers which increase the pressure on our urban water supplies, and many studies have predicted that current water sources are insufficient for the increasing population (Brown & Clarke 2006; Hurlimann & Dolnicar 2010; Radcliffe 2010; Radcliffe 2006). Prediction of insufficient water brings the consequences of tighter water management, and greater use of alternative water sources and water efficiency appliances, in order to reduce the pressure on current sources of urban water supply. To model these potential changes in urban water management, several future scenarios are developed in this study, in addition to the existing development scenario (or *Base Case 2010/2011*). Scenario design includes reduction of potable water demand and recycled wastewater, as well as the number of households implementing WMP technology in the future.

4.1 Technique for Scenario Development

This study uses a scenario development technique introduced by Henrichs et al. (2009). A scenario is a structured discussion that addresses an uncertain future. The aims of scenario development can vary, dependent on the science or research context, and scenarios are constructed to explore possible urban developments. A scenario should be plausible, internally consistent and meet the goals of the study. There are a number of different approaches that can be used to develop scenarios (Duinker & Greig 2007; Gausemeier et al. 1998; Henrichs et al. 2009; Jarke et al. 1998; Westhoek et al. 2006) as follows:

1) Deductive approach: Linear approach based on narrowing down uncertainty. This approach describes processes of scenario development explicitly.
2) Inductive approach: Non-linear approach or Focused Events based on loosely discussing critical uncertainties. By using this approach, many scenarios are easy to produce, but unfortunately it cannot guarantee causality.
3) Incremental approach: Questioning approach, which defines what must become reality in the 'official future'.

This study uses an inductive approach to generate the WMP scenarios. This approach is selected because the existence of WMP is triggered by the fact that the population in urban areas is growing rapidly, but water resources are declining, both in quantity and quality. This condition is more severe nowadays due to global climate change. Water shortages which trigger WMP implementation is considered to be a focused event which comes from the uncertainties of climate and population growth in the future. In general, the processes of scenario development using an inductive approach are initiated by identifying focal issues of the main concern. The next step is to identify the driving factors of WMP and build many scenarios based on the driving factors. Some assumptions in the context of limitation of this study for developing WMP scenarios are presented and discussed in this section.

The steps involved in the scenario development process are described below:

1) *Establish the Focal Issue*

The main focal issue in this study is the possible change in sewer transformation processes due to the adoption of WMP. These changes in turn can subsequently change the level of hydrogen sulphide concentration in sewer pipes which subsequently lead to sewer odour and corrosion. The key objective was to investigate a set of factors in the adoption of WMP that influence wastewater characteristics associated with problems of odour and corrosion in sewers. Finally, the outcome of this study was expected to identify the maximal volume of recycled wastewater and water demand reduction from WMP that do not lead to a significant increase in sewerage pipe deterioration in the study area. Finding the impact of scalling up of WMP adoption on sewer odour and corrosion is also the outcome of this study.

2) Identify Driving Factors

Since scenarios are created to examine the implications of potential and plausible options, driving factors were selected and set such that they would affect wastewater characteristics. Within the scope of WMP, there are three direct driving factors: source of water supply, utilisation of water saving appliances and number of households adopting WMP. The adoption of WMP is also triggered by population growth, and global climate change. These two factors are classified as indirect driving factors that contribute to a shift in wastewater characteristics.

3) Build Scenario

At this stage, the scenario was developed by using a matrix constructed from two main WMP scenarios, which are *Water Demand Management* (i.e., reduced water demand) and the type of water source (alternative and traditional urban water source) (Figure 4.1). *Water Demand Management* and Type of Water Source were considered to be independent and unrelated WMP. By using this matrix cross, scenario logic is built for the four quadrants and each quadrant is labelled by considering the type of WMP used (i.e. *Base Case*, *Alternative Water Source*, *Water Demand Management*, and *Sustainable Practice).*

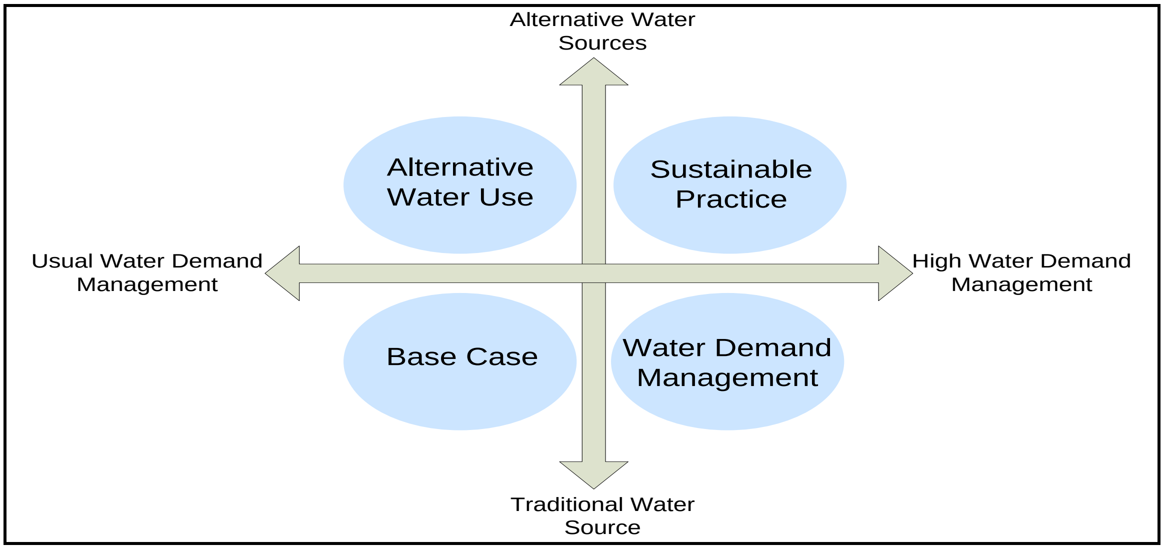


Figure 4.1. Matrix Cross to Establish The Scenario Logic

The descriptions for each scenario are presented below:

- *Base Case*

  Base Case is a scenario that describes a conventional household based on monitoring data and the literature. This scenario considers that *Water Demand Management* has currently been adopted at a set level for water saving. In this study, normal *Water Demand Management* refers to a condition where mostly three-star water saving appliances has been installed within a household. The water source is assumed to be supplied by piped water. Based on information from YVW, WMP of *Rainwater Harvesting* and *Greywater Recycling* have been adopted by several households. Therefore, the *Base Case* has been set up to include existing WMP in the study area (see subsection 4.4.2).

- Water Demand Reduction/*Water Demand Management*

  To reduce potable water demand, many people have been encouraged to decrease their water consumption through installation of water saving appliances. Many methods (e.g. rebate, incentive, disincentive, etc.) have been introduced by water authorities and government to promote the use of water saving appliances (Tate 1990). The use of water saving appliances is now common practice throughout the world. In this study, *Water Demand Management* is described as an action to reduce water demand without the utilisation of *Alternative Water Sources*. This scenario assumes that households in the study area have installed high water saving appliances (above three-star water rating). Water was still supplied by the piped water (see subsection 4.4.3).

❖ Alternative Water consumption

In this scenario, some *Alternative Water Sources* replace piped water. *Alternative Water Sources* were introduced in this scenario including greywater, rainwater and sewage (wastewater from sewer pipe). These water sources required different levels of treatment before use, and the selection of *Alternative Water Sources* and their treatment technologies were based on criteria explained in section 4.2 (also see subsection 4.4.4).

❖ *Sustainable Practice*

This scenario combines water demand reduction and alternative water utilisation, intended to obtain maximum water saving within a household (see subsection 4.4.5).

Every main scenario mentioned above was further split into several sub-scenarios. The sub-scenarios detail the variation in every main scenario such as variation of water volume reduced, volume uptake and number of households that adopted WMP. The volume variation is intended to find the volume limit of water reduction, wastewater uptake and wastewater discharge in the study area (see scenarios and sub-scenarios in Figure 4.6).

4.2 Selection of Alternative Water Source Technology

Table 2.1 in Chapter 2, described several WMP that is widely implemented today. For this study, existing WMP were assessed using the following three criteria:

1) Wide public acceptance. Water or reclaimed water from WMP technology is publicly accepted for at least one indoor water consumption (for toilet flushing or laundry) or for all indoor uses that contribute to sewer flow.
2) Ease of installation or retrofit to an existing dwelling or installed in a decentralised manner.
3) Impact on wastewater flow and contaminant load associated with sewer odour and corrosion.

A recent study in Australia has shown that *Rainwater Harvesting* is the most accepted method that provides alternative water source for supplying all indoor water consumptions including kitchen (Hurlimann & Dolnicar 2010). In the urban water system, rainwater (collected from roof runoff) is mainly used indoors for toilet flushing and laundry use. Rainwater harvesting is different to stormwater harvesting, as rainwater harvesting collects the rainwater from the roof runoff while stormwater harvesting collects water from road runoff. Different locations of runoff collection have consequences on the quality of collected runoff. Rainwater harvesting has been tested to have better water quality compared to stormwater harvesting (Coombes et al. 2002; Yaziz et al. 1989).

Treated greywater and wastewater are also considered to be two sources to replace potable water for indoor water demands. However, the acceptability of these sources is generally lower compared to rainwater. They are more acceptable if they are a water supply for non-body contact purposes (toilet flushing and irrigation) (Hurlimann & Dolnicar 2010; Hurlimann et al. 2007; Hurlimann & McKay 2006).

Wastewater recycling has generally been achieved through large scale centralised treatment plants rather than small scale neighbourhood or household plants. However, application of wastewater recycling technology on a smaller scale (decentralised) is achievable, which may in part be due to the costs of transporting reclaimed water back to the user, the star rating system for environmental impact given to new buildings and increasing interest in integrated water management provision of water services. Thus, there may be an increasing number of households/buildings/neighbourhoods that recycle their wastewater.

This study attempts to select the technology of alternative water source that potentially change the current state of sewer odour and corrosion problems. *Rainwater Harvesting* is the one of the alternative water source's technology which is likely to improve sewer conditions. Collected rainwater from old roof runoff usually contains high metal concentrations because of the roof material (Magyar et al. 2008). Since the rainwater is used for indoor use, the metal content will discharge to the sewerage network. High metal content in sewerage networks is most likely to reduce the release of dissolved sulphide to the gas phase, because metals will bind with sulphide to form a metal-sulphide precipitate (Nielsen et al. 2005a; Padival et al. 1995; Zhang et al. 2008). On the other hand, *Greywater Recycling* is likely to exacerbate sewer problems because it reduces wastewater volumes that go to sewerage networks (Parkinson et al. 2005). In addition, *Greywater Recycling* is likely to discharge wastewater only from kitchens and toilets, which are known to be the most polluted wastewater within households. Compared with *Rainwater Harvesting* and *Greywater Recycling*, wastewater recycling is a technique that often receives more attention regarding its impact on sewer pipes. *Sewer Mining*, which is a form of wastewater recycling, has been proven to increase sewer blockages (Sydney Water 2006). *Sewer Mining* directly extracts the sewage from sewer pipes, which reduces the sewer flow rate and consequently decreases flow velocity. Since flow velocity is slower, sediments are not transported as normal. This condition is made worse by the fact that some *Sewer Mining* facilities discharge their treatment residual (e.g. sludge) back into the sewer system (Sydney Water 2006). As a result, *Sewer Mining* may not only trigger sewer blockages, but also potentially contribute to other sewer problems, such as odour and corrosion (Sydney Water 2006).

To identify potential alternative water source technology that fulfil the criteria and description above, a ranking table of alternative water source's technology was created as can be seen in Table 4.1. This table ranks the technology for every criterion, solely based on the literature review. A score of 1 represents a condition where WMP fulfil all criteria. A score of 2 represents a situation where the criteria are partly fulfilled and a score of 3 represents a situation where all criteria are not met. The total score was then calculated and alternative water source's technology with the least score would be selected. Out of six alternative source technologies, three technologies (rainwater harvesting, greywater recycling, sewer mining) were selected. These technologies were selected to represent different alternative water consumptiond by residents. The WMP ranking based on predetermined criteria is shown in Table 4.1.

Table 4.1. Ranking of Alternative Water Source's Technology Based on The Predetermined Criteria

Measure/ Technology Use	Widely Accepted as water for…				Installed in Decentralized Manner	Caused Odour & Corrosion Problem	Total Score
	Toilet	Laundry	Bathroom/ Shower	Kitchen			
Blackwater Recycling	1	2	3	3	2	2	13
Sewer Mining	1	2	3	3	2	1	12
Greywater Recycling	1	1	2	3	1	1	9
Greywater Direct Use	3	3	3	3	1	1	14
Rainwater Harvesting	1	1	1	2	1	2	8
Stormwater Harvesting	1	3	3	3	3	3	16

Note :
1 = Most accepted/household scale/high effect on odour & corrosion
2 = Accepted/cluster scale/small-medium effect on odour & corrosion
3 = Not accepted/cannot install in decentralized manner/no effect on odour & corrosion

4.3 Future Condition in Study Area

As discussed in Chapter 1, this study analyses existing and future conditions of the Glenroy sewer subcatchment. Period of 2010-2011 was selected to be used as the *Base Case* for existing urban development while 2060 was the scenario used for future urban development. This section describes the possible future (2060) of the Glenroy sewer subcatchment. Year of 2060 was selected based on the target of the Melbourne Water Metropolitan strategy that stated at 2060, the usage of alternative water should be included to supply for water demand in Melbourne. Four development factors are considered to contribute to future urban development of the Glenroy sewer catchment: catchment area and population profile, environmental sustainability practices and climate change.

4.3.1 Catchment Area and Population Profile

The population in Glenroy is projected to increase by around 18% by 2021, which is higher than the overall population increase in Moreland City Council of around 8% (Moreland City Council 2007). Glenroy's predicted population growth contradicts the overall trend for the greater Melbourne area, as the population in older, inner city suburbs is stable or declining (ABS 2008). The main growth in Melbourne is mostly occurring on the rural urban fringes (ABS 2008). Currently, the majority of households in Glenroy are 'family households' (66%), but in the future this figure is predicted to slightly reduce. According to the Melbourne Census in 2001 and 2006, the proportion of single-person households, single-parent households and group households is increasing. Currently, a high proportion of detached houses dominates Glenroy's housing profile; however, there has been an increase in flats, units and apartments; semi-detached, row or terrace houses and townhouses identified during the 2001 and 2006 Census (Moreland City Council 2007).

4.3.2 Environmental Sustainability

Efficient water consumption is managed in Glenroy's Sustainable Water Management Plan (Moreland City Council 2007), which provides the strategic direction for improved water management throughout council operations and the community. The most significant outcome for this plan is council's water reduction. The reduction is intended to decrease use of reticulated water and encourage use of *Alternative Water Sources*. An expected outcome from use of *Alternative Water Sources* is not only reduced reticulated water but also healthy waterways via reduced stormwater flows.

The strategies to reduce use of reticulated water include encouraging citizens to capture rainwater from the roof and to recycle greywater for a range of purposes. It also expects to reduce water and contaminant load in waterways. On a neighborhood scale, the council encourages the use of rainwater and reclaimed water from *Greywater Recycling* and also the use of reclaimed water from wastewater recycling plants. There are no specific studies which reveal specific development plans for rainwater tanks, greywater or blackwater treatment plant (or *Sewer Mining*) installation in the future. Nevertheless, since the council encourages *Sustainable Practice* (or WMP) to improve environmental sustainability, it can be assumed that *Rainwater Harvesting*, *Greywater Recycling* and *Sewer Mining* will increase in the future and that council will not be an impediment to such schemes.

In this study, all extended scenarios (excluding the *Base Case* scenario) were assumed to have uptake of WMP at three different levels. The first development scenario assumed that 30% of households install water saving appliances and use alternative water that originated either from rainwater, treated greywater or reclaimed sewage. The second and third scenarios apply the same arrangement as the first scenario, but increase percentage of households installing water saving appliances and use of *Alternative Water Sources* to 60% and 100% respectively.

4.3.3 Future Climate Condition

The climate variables of rainfall and temperature are those which most affect changes in water demand and sewer processes (Brown & Clarke 2006; Zhou et al. 2000). However based on the results of the field study, supported by other studies, it is unlikely that atmospheric temperature influenced sewer processes. Mohseni & Stefan (1999) and Kinouchi et al (2007) reveal that sewage temperature is mainly influenced by anthropogenic causes such as domestic activities (washing, bathing, toileting and cooking) and sewage travel time rather than atmospheric (outside) temperature. Therefore, this study uses temperature obtained from the field study rather than the forecast atmospheric temperature. Rainfall is one of the important components in the sewer network, and the amount of rainfall that enters the sewer system needs to be forecasted for simulation of 2060. Climate change projections available in the SILO website (Enhanced Climate Database for Australia) is limited to 2050, hence this study generates a simple climate model for rainfall in 2060. Since hydrogen sulphide is generated mostly in dry weather conditions, the data of the month that has lowest rainfall in 2060 is necessary for this study. The lowest future rainfall month could be determined by simple inferential statistics test to determine which month has the lowest mean rainfall, or by counting the frequency with which each month has the lowest rainfall within a given year across a range of years, and using the month with the highest frequency (greatest probability) as the lowest rainfall month in 2060. Monthly rainfall data from 1950 to 2011 for Essendon Airport were obtained from the SILO website. Figure 4.2 presents the rainfall intensity in Essendon Airport (as the nearest rainfall observation station to the study area). Linear regression of the historical data projects that rainfall intensity will decrease by 35.3% in 2060 relative to 1950. The projection has a similar tendency to that of the IPCC report for southern Australia, which shows decreasing rainfall by 0-40% will occur in 2050 (IPCC 2007).

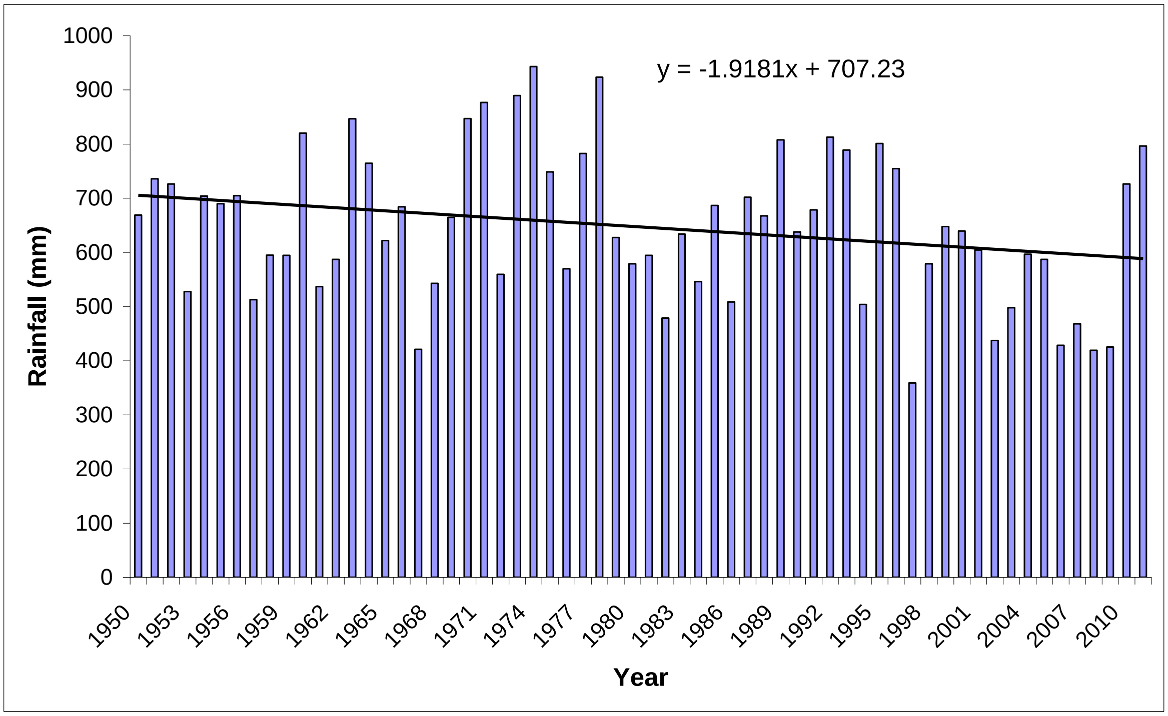


Figure 4.2. Historical Annual Rainfall in Glenroy (1950 – 2011)

Figure 4.3 plots the frequency of the lowest rainfall month from 1950 to 2011. It can be seen that the lowest rainfall mostly occurred in February, January and March. However, February has the highest number of the month that has the lowest rainfall, therefore February was selected for the rainfall projection in 2060.

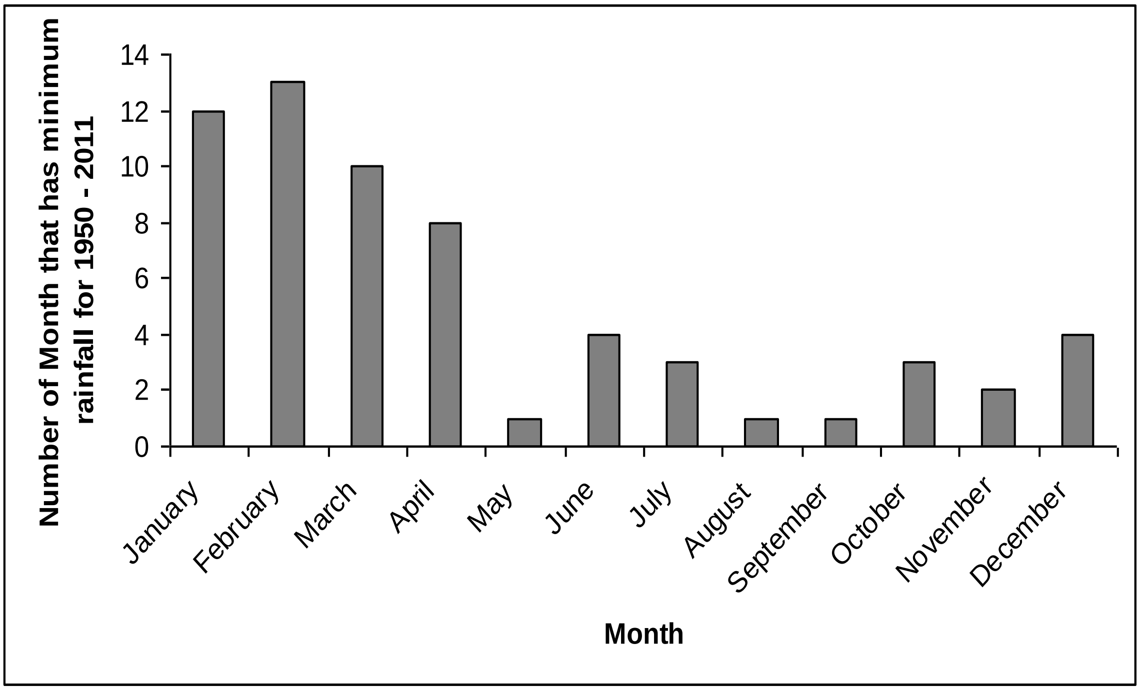


Figure 4.3. Number of Month that has minimum rainfall for 1950 - 2011

4.4 Developed Scenarios

Based on the scenarios development technique described in section 4.1, there are four main scenarios generated in this study. Figure 4.4 illustrates main scenarios and sub-scenarios for existing urban development (2010/2011). Figure 4.5 illustrated the WMP scenario for future urban development (2010). The main WMP scenarios for existing urban development were similar to those for future urban development. However, the sub-scenarios between existing and future urban development are different, depending on the aim for each of them. As mentioned in Chapter 1, the WMP scenarios for 2010/2011 were intended to quantitatively establish the limit of water demand reduction and wastewater recycled and discharged. WMP scenarios in 2060 investigate the impact of scaling up WMP technology adoption in the study area. Every main WMP scenario has three sub-scenarios. Among four main scenarios, only Alternative Water Source experienced further scenario splits, since there are several *Alternative Water Sources's technology* that have been refined in section 4.2. The expected outcome for existing urban development will be limited for water volume reduction and recycled wastewater volume uptake. The expected outcome of future urban development will be a trend of hydrogen sulphide formation due to the increasing number of households adopting WMP.

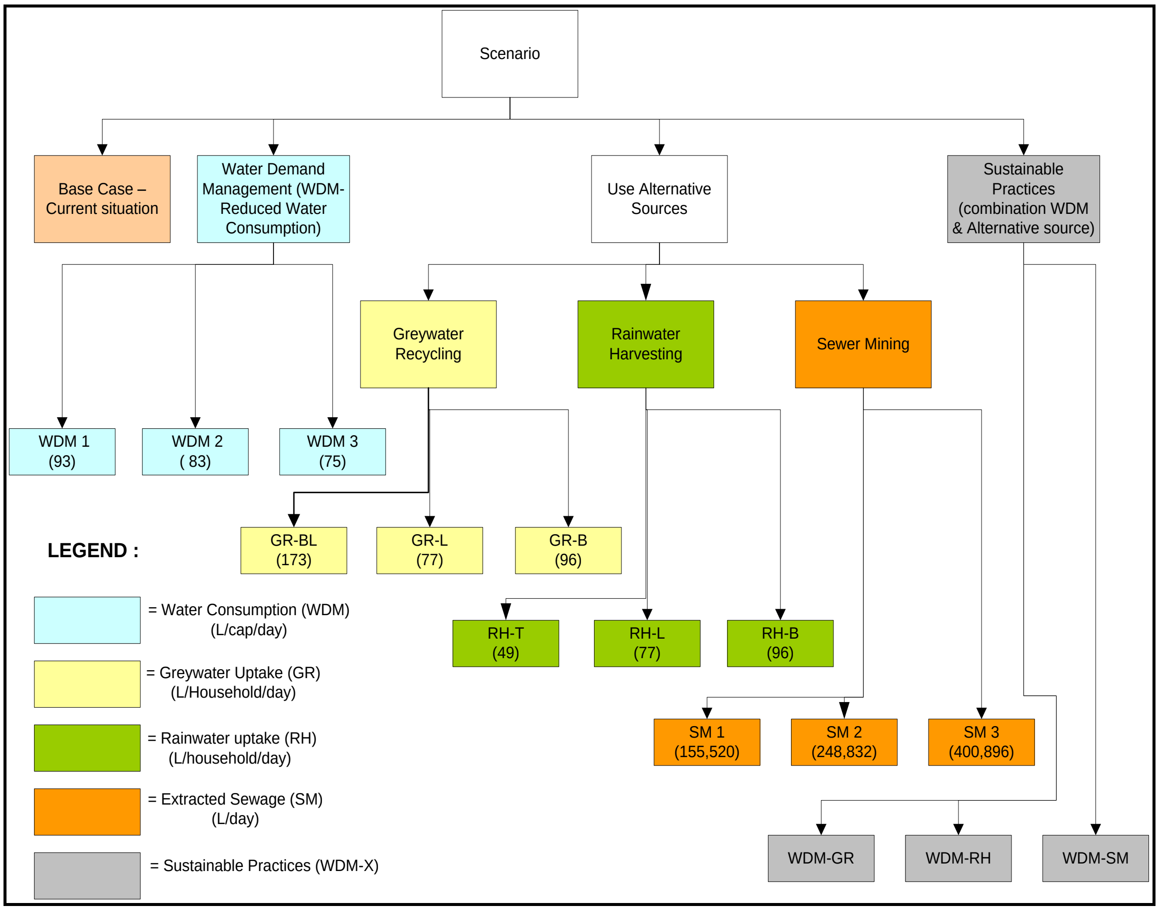


Figure 4.4. Detail of Main Scenarios and Sub-Scenarios for Existing Development in 2010-2011

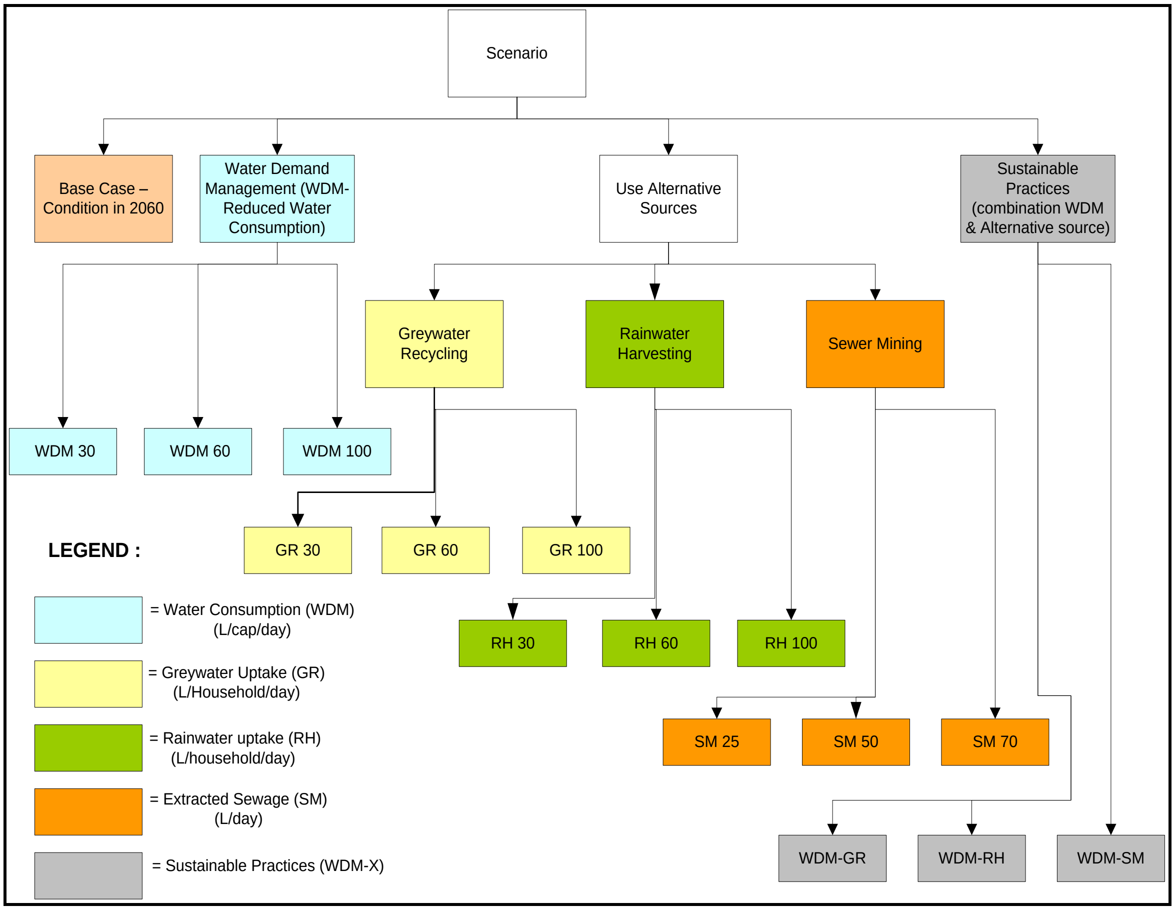


Figure 4.5. Detail of Main Scenarios and Sub-Scenarios for Future Development 2060.

4.4.1 Modeling Assumptions

All scenarios have the following base assumptions in addition to those identified in Chapter 3, subsection 3.4.3.2. The additional assumptions are as follows:

a. For each end - use event (toilet, laundry, kitchen and bathroom), the contaminant load relative to the existing development scenario will remain constant.

b. Water demand (l/c/d) does not change from April 2010 to 2060, except for the high *Water Demand Management* scenario.

c. The kitchen wastewater is not included for greywater.

d. The sludge from greywater treatment plants is assumed to be pumped and disposed of away from households (not to the sewer).

e. The rainwater and greywater tank size represents tank sizes in existing house lots, at 5 m^3 rainwater tank and 1 m^3 greywater tank. Tanks are assumed to be half-full at the start of the simulation.
f. The population growth follows percentage of Australia population projection series C through population densification (total fertility rate of 1.6 babies per woman) (ABS 2008)

4.4.2 Base Case

4.4.2.1 Base Case 2010/2011 (Existing Development)

Base Case 2010/2011 is presented as an existing development within the study area. The existing development represents the conventional household practice in which households were assumed to use three- and four-star water saving appliances. Additionally, the majority of houses in the study area did not use alternative water source. Based on data from YVW, only 30% of houses in the study area have a rainwater tank, with only 3% of houses having rainwater tanks which are used to collect rainwater for bathroom or laundry use. Furthermore, only 3% of houses were equipped with a *Greywater Recycling* facility. Estimation of the input data was taken from many sources including the internal data from water companies (Melbourne Water and Yarra Valley Water), monitoring and sampling data and the literature. Table 4.1 shows the indoor water demand for dry and wet weather. Dry weather water demand was taken from April 2010 data, while wet weather water demand was taken from November and December 2010 data. In regard to outdoor water consumption, the modeling tool calculated this usage based on the watering percentage setup at the beginning of project. For this study, the percentage is kept constant, as 30% of outdoor areas can be watered only by *Alternative Water Sources* such as rainwater or greywater. Thus, there was no piped water supplied for irrigation water.

Table 4.2 presents the indoor water demand for every indoor end-use in dry and wet weather. As has been explained in Chapter 3, indoor water consumption varies with weather. The difference of indoor water consumption per capita between dry and wet weather is triggered by differences in frequency and duration of water appliance use in both dry and wet weather (Beal et al. 2011b). However, the rating of household water appliances did not change. For example, the usage of a dishwasher is more frequent in November-December 2010 compared with April 2010. However, in these months the equipment still has similar water saving appliance stars, which means that the resident did not change their appliances during the months between April 2010 and November-December 2010. Indoor water usage breakdown based on the water saving star, frequency and duration can be seen in Tables 3.13 and 3.14 in Chapter 3.

Table 4.2. *Base Case* Indoor Water Demand for Dry and Wet Weather

Water Appliances and Water Star Rating	Total Water Demand (L/cap/day)	
	Dry Weather	Wet Weather
Washing Machine (***)	30	32
Dishwasher (****)	10	13
Shower (***)	30	30
Tap (****)	8	10
Toilet (****)	19	21
Total indoor water demand	**97**	**106**

To set modeling parameters for the dimensions of residential lots and the ratio of pervious to impervious surfaces, average values from existing residential lots were taken from a GIS map of the Glenroy subcatchment area provided by Yarra Valley Water. The following defines the dimensions used to typify the layout of land blocks for detached houses in the study area:

- Total block area = 525 m^2, comprised of:
  – Garden area = 225 m^2
  – Roof area = 250 m^2
  – Paved area = 50 m^2

4.4.2.2 Base Case 2060 (Future Development)

The *Base Case* in 2060 sees future urban growth in the study area by increased medium density residential dwellings. The Urban Growth Boundary as defined in the Glenroy

Structure Plan predicts that the numbers of detached houses will still dominate, but semidetached houses or flats/apartments will increase in number. The households in the study area are still dominated by family households, but the number of single persons is also increasing. The dimensions used to typify the layout of land blocks for detached houses are similar to *Base Case* 2010/2011. However, since there is an increase of single persons, who are assumed live in flats or apartments, the significance of this style of housing is increased. The dimension of an average flat/apartment is defined below:

- Total area = 300 m^2, comprised of:
  – Garden area = 0 m^2
  – Roof area = 250 m^2
  – Paved area = 50 m^2

Following the trend in urban areas (ABS 2008), the population growth in Glenroy was considered to be slower than the current population growth. Percentage of population increase was derived from Australian population projection conducted by the Australia Bureau of Statistic (ABS 2011). This followed Series C growth, which assumes that the fertility rate is 1.6 babies/woman. Based on this figure, it is projected that in 50 years, the population in the study area will increase by 36%.

The climate profile for 2060 was deduced from a simple projection (subsection 4.3.3). The simple model shows rainfall intensity decreased by 35.3% from 2010 to 2060. The projected rainfall data was used in wastewater generation and sewer flow models.

The level of WMP adoption in 2060 continues at the same level as the 2010/11 *Base Case*. The existing WMP adoption in the case study area comprises 30% of rainwater tank installations with 3% used for indoor use. Furthermore, the study area featured 3% of households with *Greywater Recycling* facilities. The comparison of urban development, which includes population growth and housing development as well as climatic situation for the existing *Base Case* 2010/2011 and the future *Base Case* (2060), are described in

Table 4.3. Figure 4.6 illustrates the arrangement for the *Base Case* in 2010/2011 (existing urban development) and *Base Case* in 2060 (future urban development).

Table 4.3. Comparison Between *Base Case* 2010/2011 (Existing Development) and *Base Case* 2060 (Future Development)

	Existing Development	***Base Case* 2060**
Urban Profile	Household type : 100% Family → occupancy rate = 2.55 person/household. House type = 100% detached house → Garden area = ± 35% from total block area.	Household type : 85 % Family → 2.55 person/household; 15% single person → 1 person/household. House type = 85% detached house → Garden area = ± 35% from total block area; 15% flat/apartment → 0% garden area.
Population	9563 person → 3750 households	13006 → 4335 HH and 766 flats/apartments
Climate	Rainfall from 2002 - 2011	Projected rainfall in 2060 → decreased by 35.3%
WMP Adoption	30% HH installed rainwater tank with 3% used indoor; 3% households had *Greywater Recycling* facility, 100% installed usual water saving appliances (3- star rating)	30% HH installed rainwater tank with 3% used indoor; 3% households had *Greywater Recycling* facility, 100% installed usual water saving appliances (3-star rating)

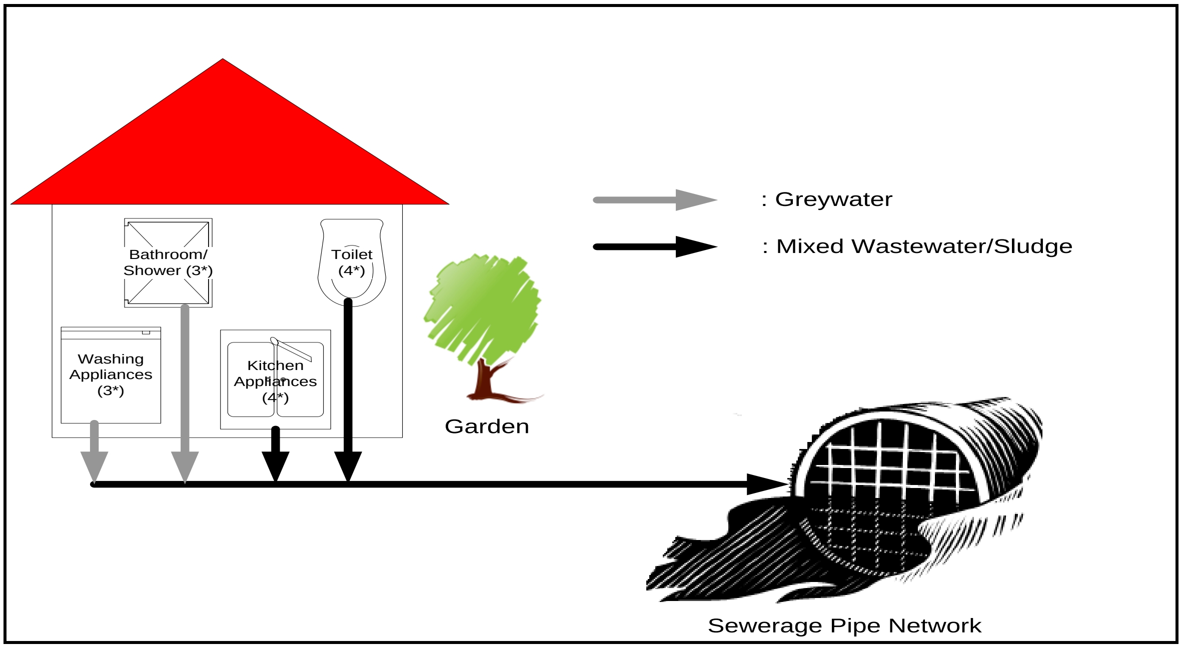


Figure 4.6. ***Base Case*** **Illustration for 2010/2011 and 2060**

4.4.3 Water Demand Reduction/*Water Demand Management* (WDM)

High *Water Demand Management* simulates the uptake of high water efficient appliances. The contaminant loads for each end-use in this scenario are the same as in the *Base Case*. The only difference is in reduced indoor water consumption. The water efficiency assumption for each appliance is based on the Australian Government Water Efficiency Labelling and Standards (WELS) scheme (Australian Government 2010b).

4.4.3.1 Water Demand Management Scenario for Existing Development (2010/2011)

The WDM scenario for existing development was designed to find the impact due to per capita water demand. There are four different water demands including the *Base Case* demand. The reduction of water demand is achieved through the installation of water saving appliances that have higher water star ratings compared to the *Base Case*. Four indoor water demand uses were considered, namely, water demand in the toilet, bathroom, laundry and kitchen. Water demand in the toilet is for the purpose of toilet flushing only. The bathroom comprises showers, baths and hand basins; laundry includes clothes washing and the laundry basin, and the kitchen consists of the kitchen sink and dishwasher. Water demand data was adopted from Roberts (2005). Indoor water demand was estimated from the specific appliances assumed to be installed for each indoor use. The water demand in the toilet was comprised of only water for toilet flushing; in the bathroom by bath, shower and sink use; in the laundry for the washing machine and laundry basin and in the kitchen by kitchen sink and dishwasher use. To determine the water demand from these appliances, the appliances of each indoor use can be categorized as event-based, duration-based and volume-based. For event-based appliances, the water demand was calculated by taking the average volume used per single use of the appliance and then multiplying it by the frequency of that appliance used by the average household in a week. Then it was scaled down to liters per capita per day for each appliance. Event-based appliances include toilet, washing machine and dishwasher. Calculation of water demand based on the duration was conducted by multiplying the average flow rate of the appliance with the average duration of use per person. Duration-based appliances include the shower and running taps. The water demand of volume based appliances was calculated by assuming the fullness level and then multiplying it with the full capacity. It was then multiplied by the frequency of use over a week and scaled down to litres per capita per day by dividing it by the household size. Volume based appliances include the bath and the laundry basin. Since this study focused only on the impact of reduction in residential water consumption on the wastewater flow and contaminant concentration, only indoor water demand was considered in this analysis. Water losses due to leakages were assumed to be 4%. The water demand for *Base Case* and *Water Demand Management* scenarios are summarized in Table 4.4. Figure 4.7 illustrates the configuration for *Water Demand Management* within a household compared to the star rating in the *Base Case*.

Table 4.4. Water Demand for *Water Demand Management* Scenario

	Total Indoor Water Demand (L/cap/day)		**Water Star Rating**									
	Dry Season	**Wet Season**	**Washing Machine**		**Dishwasher**		**Shower**		**Tap**		**Toilet**	
Base Case	97	106	***		****		*** (>4.5 but <=6)		****		**** (4.5/3)	
			30	32	10	13	30	40	8	10	19	21
WDM1	92	101	****		*****		*** (>4.5 but <=6)		****		**** (4.5/3)	
			25	28	10	11	30	33	8	8	19	21
WDM2	83	92	****		*****		****		*****		*****	
			25	28	10	11	29	32	6	7	13	14
WDM3	75	84	*****		******		****		*****		*****	
			21	23	7	8	29	32	6	7	13	14

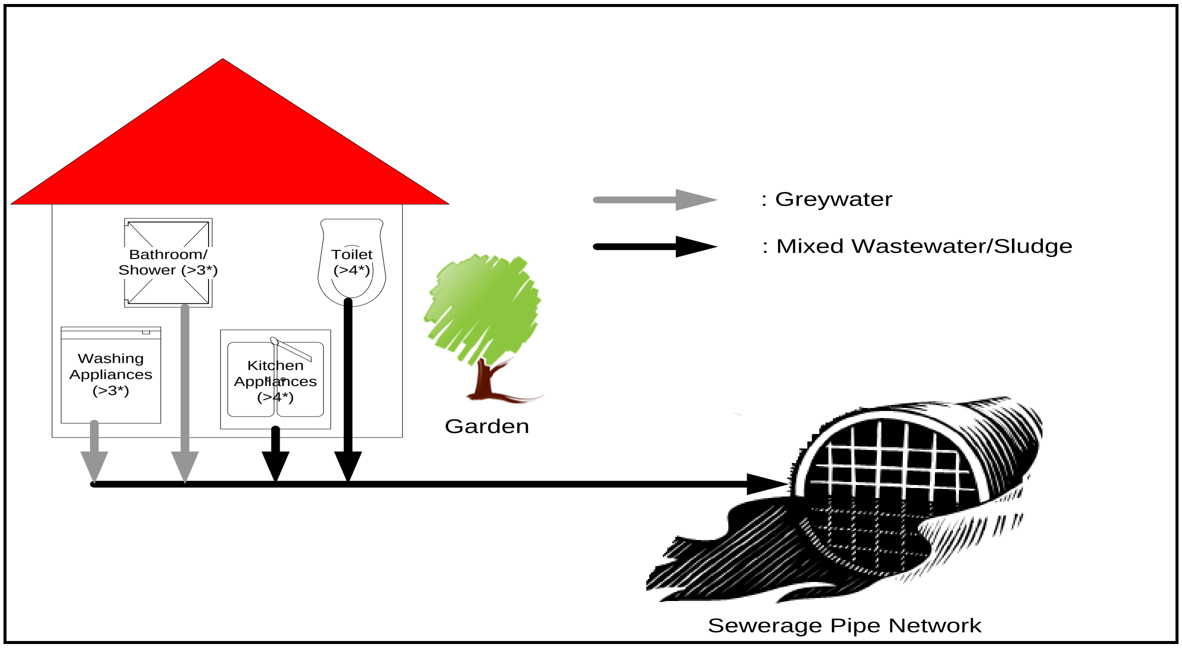


Figure 4.7. Configuration of *Water Demand Management* within a Household

4.4.3.2 Water Demand Management Scenario for Future Development (2060)

The WDM scenario for future development focuses more on the increasing number of households that adopt *Water Demand Management*. Water demand was set by assuming that all households within the study area installed the highest water saving appliances, with a total water demand of 75.13 L/cap/day. The characteristics of the future scenario configuration of high *Water Demand Management* can be seen in Table 4.5. This scenario was modelled on the household scale.

Table 4.5. High *Water Demand Management* Scenarios (household scale)

WMP Scenario	Practices	
WDM30	*Rainwater Harvesting*	30%
	Rainwater connect to Toilet/Laundry/Garden	3%
	Greywater Recycling	3%
	Number of households use highest water saving appliances	30%
WDM60	*Rainwater Harvesting*	30%
	Rainwater connect to Toilet/Laundry/Garden	3%
	Greywater Recycling	3%
	Number of households use highest water saving appliances	60%
WDM100	*Rainwater Harvesting*	30%
	Rainwater connect to Toilet/Laundry/Garden	3%
	Greywater Recycling	3%
	Number of households use highest water saving appliances	100%

4.4.4 Alternative Water Source

The scenario development for several *Alternative Water Sources* will be discussed next. Selected alternative water source's technologies are *Greywater Recycling*, *Rainwater Harvesting* and *Sewer Mining*. In this study, *Greywater Recycling* and *Rainwater Harvesting* were modelled at the household scale, while *Sewer Mining* was the only scenario implemented at the cluster scale.

4.4.4.1 Greywater Recycling (GR)

This scenario treats wastewater from bathroom and laundry and supplies it for toilet flushing and irrigation. The greywater storage tank was set at 1 m^3. This value was chosen based on the calculation of total greywater production and maximum residence time allowed for storing greywater on site. It was assumed that the garden area irrigated constituted only 30% of the total garden area and that excess greywater was directed to the sewer system. The removal efficiency of contaminants during greywater treatment was taken from Tchobanoglous et al. (2003).

4.4.4.1.1 Greywater Recycling Scenario for Existing Development (2010/2011)

Greywater Recycling for an existing development mainly considered the volume of greywater uptake. The variation in greywater volume was achieved by changing the greywater source. Table 4.6 lists the source and volume uptake. Since kitchen wastewater was not included as a component of greywater, 100% greywater uptake meant 100% utilisation of wastewater from the laundry and bathroom. Figures 4.8, 4.9 and 4.10 illustrate the *Greywater Recycling* configurations considered.

Table 4.6. Source and Volume of Greywater Uptake

Greywater Source	Volume of Greywater Uptake (L/Household/day)		Volume percentage (%)
	Dry Weather	Wet Weather	
GR-BL (Laundry and Bathroom)	173	185	100
GR-L (Laundry)	77	87	44
GR-B (Bathroom)	96	116	56

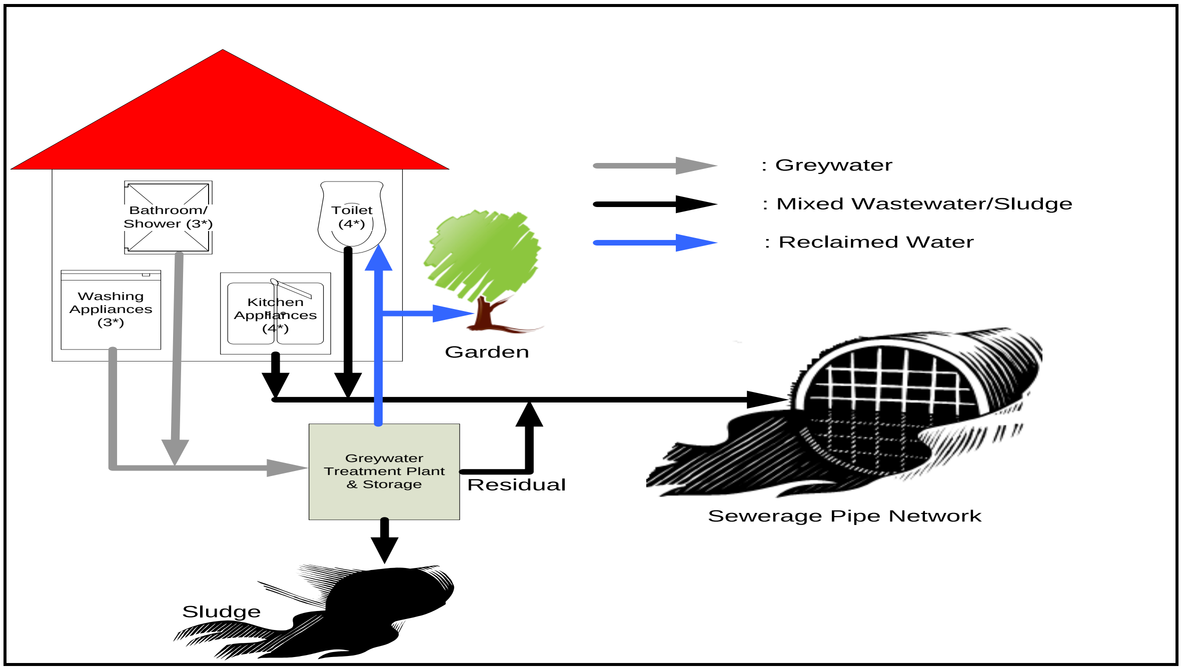


Figure 4.8. ***Greywater Recycling*** **Configuration from Laundry and Bathroom in a Household**

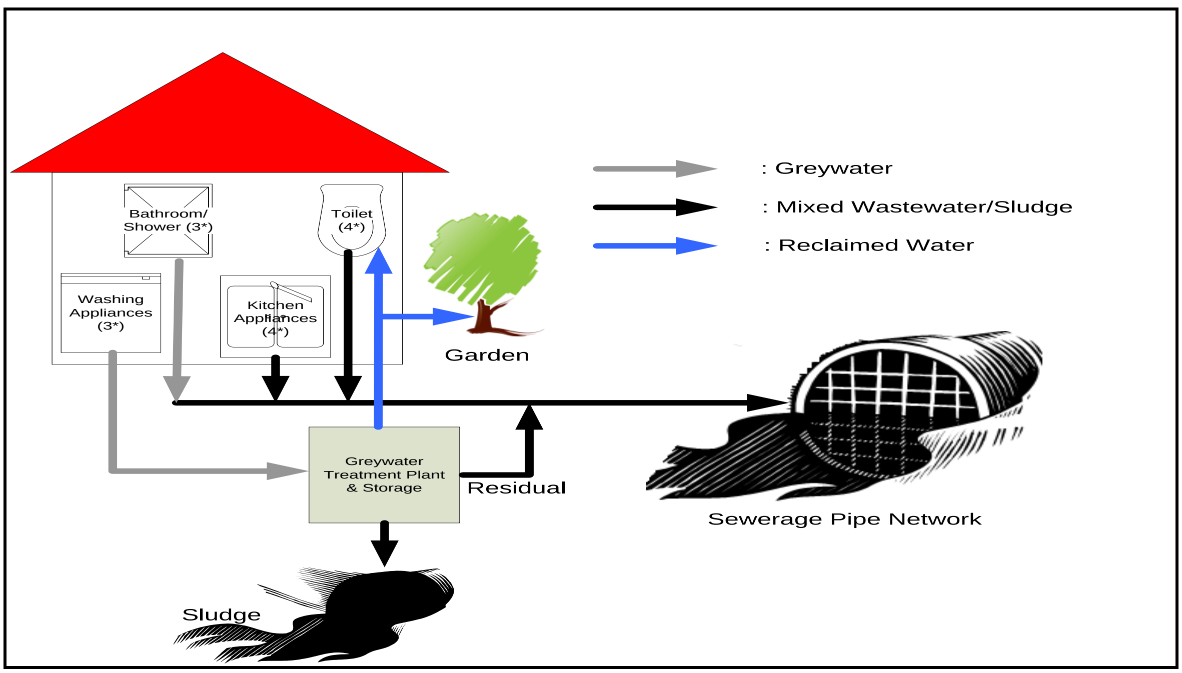


Figure 4.9. ***Greywater Recycling*** **Configuration from Laundry in a Household**

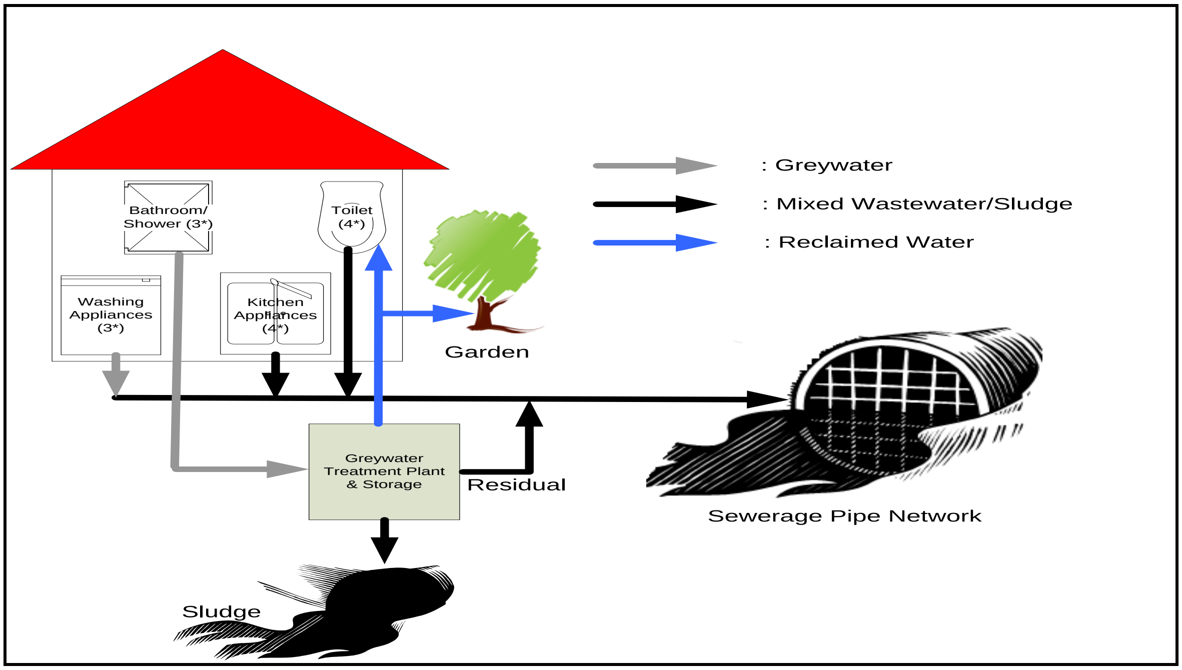


Figure 4.10. ***Greywater Recycling*** **Configuration from Bathroom in a Household**

4.4.4.1.2 Greywater Recycling Scenario for Future Development (2060)

The scenario for future development considered the impact of increasing the number of households that installed a *Greywater Recycling* facility. It was assumed that houses in the study area installed a *Greywater Recycling* facility and used 100% greywater (from the laundry and bathroom) for toilet flushing and garden irrigation. Future scenario details can be seen in Table 4.7.

Table 4.7. ***Greywater Recycling*** **Scenario (household scale)**

Development	Practices	
Scenario GR30	*Rainwater Harvesting*	30%
	Rainwater connect to Toilet/Laundry/Garden	3%
	Greywater Recycling	30%
Scenario GR60	*Rainwater Harvesting*	30%
	Rainwater connect to Toilet/Laundry/Garden	3%
	Greywater Recycling	60%
Scenario GR100	*Rainwater Harvesting*	30%
	Rainwater connect to Toilet/Laundry/Garden	3%
	Greywater Recycling	100%

4.4.4.2 Rainwater Harvesting (RH)

Rainwater Harvesting scenario assumed that the tank capacity was 4 m^3, which is within the range of 2 m^3 – 10 m^3 for rainwater tanks installed in Australian homes (Australian Government 2010a). The first flush volume for a 200 m^2 average roof size was assumed to be equivalent to 0.025 m^3 of roof runoff (Australian Government 2010a). In this scenario, the collected rainwater was assumed to be used either for toilet flushing, laundry use or garden irrigation (see Table 4.4).

4.4.4.2.1 Rainwater Harvesting Scenario for Existing Development (2010/2011)

The scenario of *Rainwater Harvesting* for existing development was set to explore the impact due to rainwater volume uptake. While *Greywater Recycling* focused on the volume uptake variation based on the volume of produced greywater, *Rainwater Harvesting* focused on the volume uptake variation based on the water demands of toilet, laundry and bathroom. Water demand for the garden was not included in this scenario, since it did not affect processes in sewerage pipe networks. Table 4.8 shows the volume of rainwater consumption based on the required water demand for toilet flushing, laundry washing and bath/shower use. Figures 4.11 to 4.13 illustrate *Rainwater Harvesting* configurations supplying different indoor end-uses.

Table 4.8. Indoor End use supplied by rainwater

Indoor End Use	Volume of Rainwater supplied (L/Household/day)	
	Dry Weather	Wet Weather
RH-T (Toilet)	49	60
RH-L (Laundry)	77	89
RH-B (Bathroom)	96	106

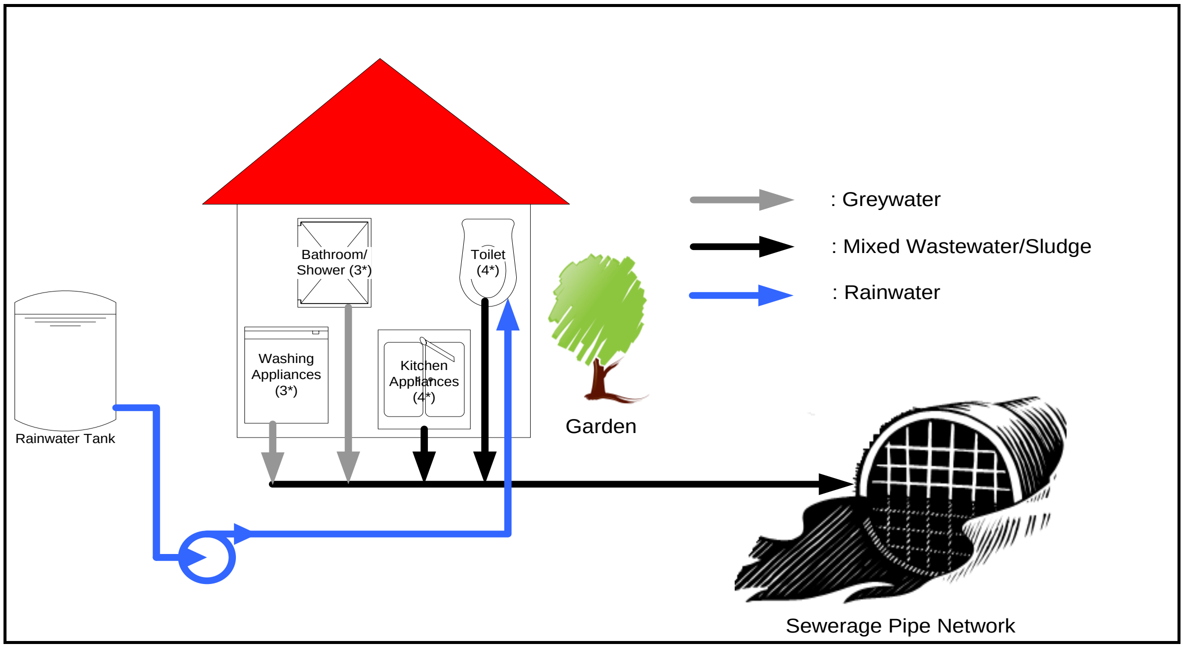


Figure 4.11. *Rainwater Harvesting* Configuration Supplying Toilet

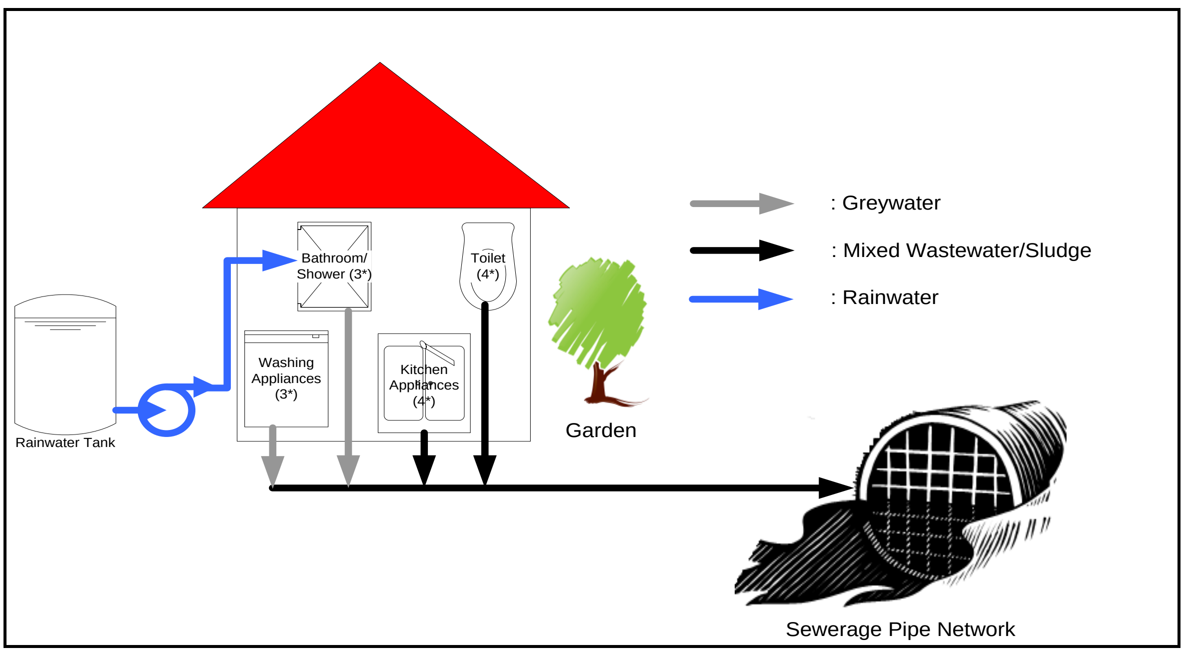


Figure 4.12. *Rainwater Harvesting* Configuration Supplying Bathroom

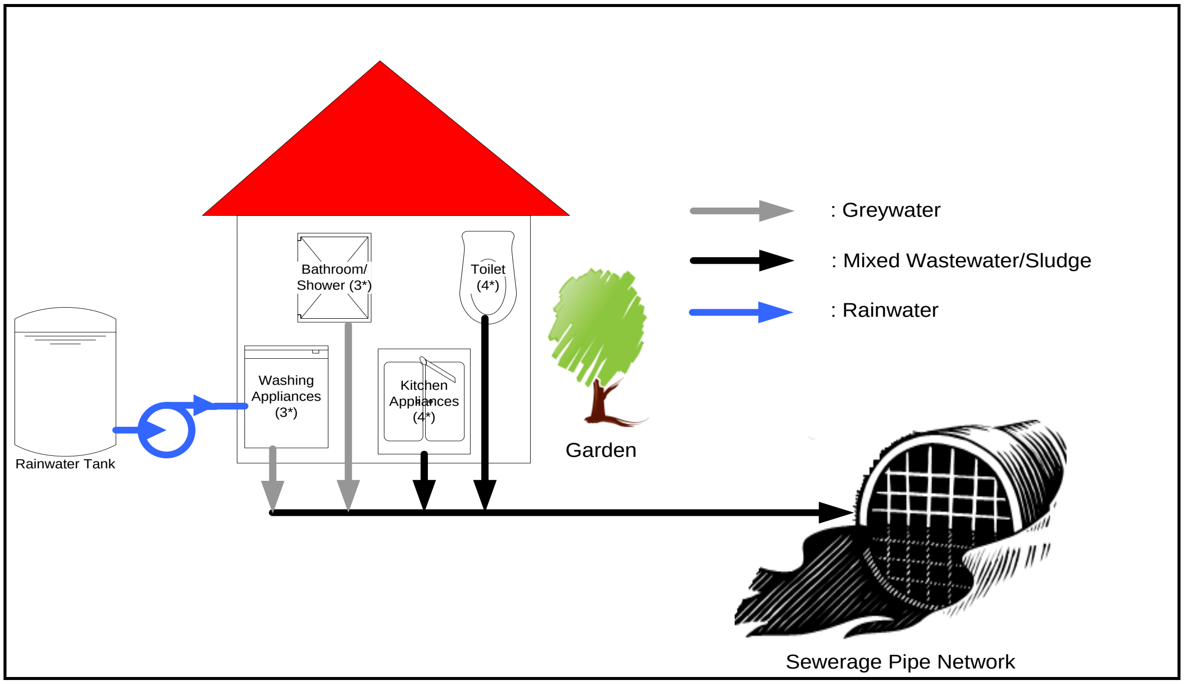


Figure 4.13. *Rainwater Harvesting* Configuration Supplying Laundry

4.4.4.2.2 Rainwater Harvesting Scenario for Future Development (2060)

Similar to the ideas for *Water Demand Management* and *Greywater Recycling* for future development, the *Rainwater Harvesting* scenario also considered there was an increase in the number of households installing rainwater tanks. The selected configuration for this future condition was using rainwater to supply toilet flushing demand. Toilet flushing was selected to receive alternative water because it is the most preferred indoor end-use to receive alternative water source (Hurlimann & Dolnicar 2010). Table 4.9 lists the configuration for *Rainwater Harvesting* in future developments.

Table 4.9. *Rainwater Harvesting* Scenario (household scale)

WMP Scenario	Practices	
RH30	*Rainwater Harvesting*	30%
	Rainwater connected to Toilet	100%
	Greywater Recycling	3%
RH60	*Rainwater Harvesting*	60%
	Rainwater connected to Toilet	100%
	Greywater Recycling	3%
RH100	*Rainwater Harvesting*	100%
	Rainwater connected to Toilet	100%
	Greywater Recycling	3%

4.4.4.3 Sewer Mining (SM)

In this study, *Sewer Mining* involves extracting raw sewage from an existing sewer and treating it on the neighbourhood scale. The recycled water from the plant is used for toilet flushing. Any by products (e.g. sludge) are returned to the sewer main. Based on previous *Sewer Mining* studies, membrane bioreactors are the most common treatment method selected to treat wastewater from sewers (Hadzihalilovic 2009; McGhie et al. 2009). Membrane bioreactors have high treatment efficiency and area compact footprint. Therefore, in this study, a membrane bioreactor was selected as the *Sewer Mining* treatment process and the removal efficiency was taken from Tchobanoglous et al. (2003). The storage tank capacity of treated wastewater was set to 500 m^3, and the initial capacity set to half of the total storage capacity. The contaminant load that discharges to the sewer pipe network was obtained from the summation of wastewater contaminants associated with excess wastewater and sludge production.

The extracted sewage for *Sewer Mining* plant was taken from the 300 mm diameter Glenroy sewer branch. The extraction point was selected based on four main reason which three out of them followed the consideration from Hadzihalilovic (2009)'s study. The reason are below :

1. It is located near with the households that will be supplied by treated water from *Sewer Mining* facility.

2. It is located in residential catchment, since the wastewater quality from residential catchment is fairly uniform quality, hence the treatment process will be relatively simple and reliable.

   The volume of sewage from this location is expected to increase in the future due to population increase.
3. The sewer mining plant is planned to be located in the mid-upper section of main sewer pipe (as can be seen in Figure 4.14). The location of sewer mining plant was selected in order to allow some lower section of main sewer pipe to be impacted by the installation of the *Sewer Mining* plant. The location of Sewer Mining facility is shown in Figure 4.14

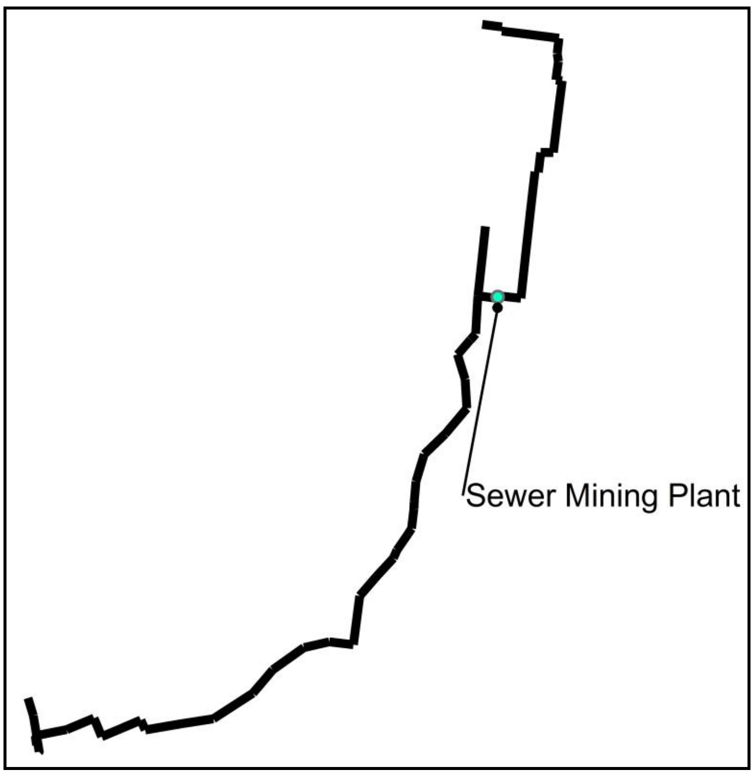


Figure 4.14. Sewer Mining Location

The *Sewer Mining* scenario was set to supply 70% of households because the sewage volume in the location of the sewage extraction point could only supply 75% of households in the study area. However, since there should be some sewage left to maintain minimum sewer flow 70% of households was selected to be the highest percentage supplied by *Sewer Mining*'s treated water.

The extracted sewage volume was the main parameter to be simulated by the *Sewer Mining* scenario. As illustrated in Figure 4.15, the location of extraction was fixed while the extracted sewage volume was varied. The impact of Sewer Mining installation was predicted to occur on downstream of the sewage extraction point. The reclaimed water from the *Sewer Mining* plant was used for toilet flushing and garden watering. *Sewer Mining* arrangement between existing urban development and future urban development are similar. The difference was only the volume of extracted sewage. Tables 4.10 and 4.11 provide details on the *Sewer Mining* scenario for existing urban development (2010/2011) and future urban development (2060).

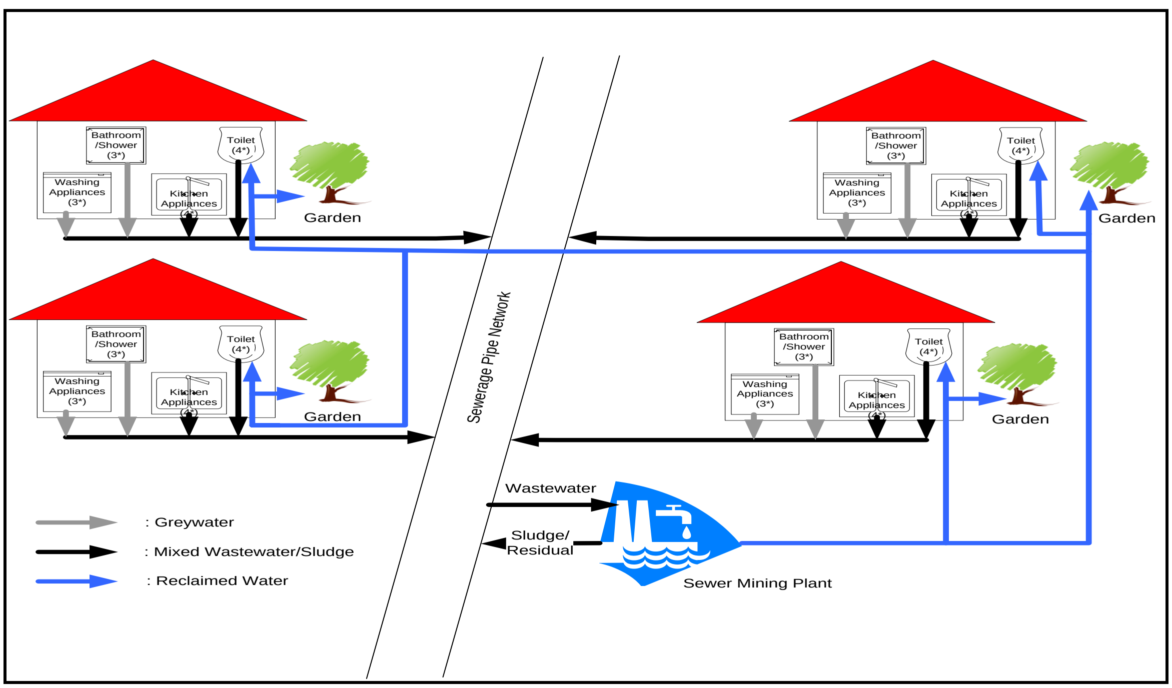


Figure 4.15. ***Sewer Mining*** **Scenario Configuration**

Table 4.10. *Sewer Mining* Scenario (Cluster scale) for Existing Urban Development (2010/2011)

WMP Scenario	Practices	
SM 1	*Rainwater Harvesting*	30%
	Rainwater connect to Toilet/Laundry	3%
	Greywater Recycling	3%
	Volume of Extracted Sewage	69,413 L/day
SM 2	*Rainwater Harvesting*	30%
	Rainwater connect to Toilet/Laundry	3%
	Greywater Recycling	3%
	Volume of Extracted Sewage	152,888 L/day
SM 3	*Rainwater Harvesting*	30%
	Rainwater connect to Toilet/Laundry	3%
	Greywater Recycling	3%
	Volume of Extracted Sewage	214,216 L/day

Table 4.11. *Sewer Mining* Scenario (Cluster scale) for Future Urban Development (2060)

WMP Scenario	Practices	
SM25	*Rainwater Harvesting*	30%
	Rainwater connect to Toilet/Laundry	3%
	Greywater Recycling	3%
	Household connected to *Sewer Mining* plant (Volume of Extracted Sewage)	25% (87,991 L/day)
SM50	*Rainwater Harvesting*	30%
	Rainwater connect to Toilet/Laundry	3%
	Greywater Recycling	3%
	Household connected to *Sewer Mining* plant (Volume of Extracted Sewage)	50% (207,512 L/day)
SM70	*Rainwater Harvesting*	30%
	Rainwater connect to Toilet/Laundry	3%
	Greywater Recycling	3%
	Household connected to *Sewer Mining* plant (Volume of Extracted Sewage)	70% (261,398 L/day)

4.4.5 Sustainable Practice

Sustainable Practice refers to urban development where the strategy of water demand reduction and installation of an alternative source is jointly adopted throughout the study area. There are three combinations for *Sustainable Practice*: the combination between highest reduction of water demand and installation of *Greywater Recycling* treatment; the combination between highest reduction of water demand and installation of *Rainwater Harvesting;* and the combination between highest reductions of water demand with installation of *Sewer Mining*. Figures 4.16, 4.17 and 4.18 illustrate the three scenarios considered for *Sustainable Practice*. Tables 4.12 and 4.13 describe the configuration of Sustainable Practice for existing and future urban development. The configuration of *Sustainable Practice* scenarios between existing and future urban development are similar, the difference being the volume of sewage extracted in the *Sustainable Practice* scenario of *Water Demand Management* and *Sewer Mining.*

Table 4.12. *Sustainable Practice* Scenario for Existing Urban Development (2010/2011)

WMP Scenarios	Practices	
WDM-RH	*Rainwater Harvesting*	30%
	Rainwater connect to Toilet	100%
	Greywater Recycling	100%
	Number of households use highest water saving appliances	100%
	Extracted Sewage volume for *Sewer Mining* plant	0
WDM-GR	*Rainwater Harvesting*	100%
	Rainwater connect to Toilet	100%
	Greywater Recycling	3%
	Number of households use highest water saving appliances	100%
	Extracted Sewage volume for *Sewer Mining* plant	0%
WDM-SM	*Rainwater Harvesting*	30%
	Rainwater connect to Toilet	100%
	Greywater Recycling	3%
	Number of households use highest water saving appliances	100%
	Extracted Sewage for *Sewer Mining* plant	247,373 L/day

Table 4.13. ***Sustainable Practice*** **Scenario for Future Urban Development (2060)**

WMP Scenarios	**Practices**	
WDM-RH	*Rainwater Harvesting*	30%
	Rainwater connect to Toilet	100%
	Greywater Recycling	100%
	Number of households use highest water saving appliances	100%
	Extracted Sewage volume for *Sewer Mining* plant	0
WDM-GR	*Rainwater Harvesting*	100%
	Rainwater connect to Toilet	100%
	Greywater Recycling	3%
	Number of households use highest water saving appliances	100%
	Extracted Sewage volume for *Sewer Mining* plant	0%
WDM-SM	*Rainwater Harvesting*	30%
	Rainwater connect to Toilet	100%
	Greywater Recycling	3%
	Number of households use highest water saving appliances	100%
	Households connected to *Sewer Mining* (Volume of extracted sewage)	100% (299,886 L/day)

4.5 Summary

Chapter 4 described the scenario development process by identifying the driving factors that are likely to change future sewer wastewater characteristics. All scenarios developed in this study were simulated based on existing development (2010/2011) and future development (extended to 2060). The scenario development for existing development also considers climate change (rainfall and temperature), which are known to be the most influential climate variables for ageing sewerage pipe networks. To represent the development in 2060, rainfall and temperature were projected by a simple linear regression method. The scenarios that were developed in this study are summarised in Table 4.14.

Table 4.14. Configuration of Existing Development and Scenarios

	WMP Scenario	Water Demand (L/cap/day)	Greywater Uptake (L/HH/day)	Rainwater Uptake (L/HH/day)	Extracted Sewage (L/day)	% of Household Connected			
						Water Demand Management	*Greywater Recycling*	*Rainwater Harvesting*	*Sewer Mining*
Dry Weather in April 2010	*Base Case* 2010/2011 (Existing Development)	97	0	0	0	0	3	30	0
	Water Demand Management	93 83 75	0	0	0	100	3	30	0
	Greywater Recycling	0	173 77 96	0	0	0	100	30	0
	Rainwater Harvesting	0	0	49 77 96	0	0	3	100	0
	Sewer Mining	0	0	0	69,413 152,888 214,216	0	3	30	25 50 70
	Sustainable Practice								
	* WDM-RH	75	0	49		100	100	0	0
	* WDM-GR	75	173	0		100	0	100	0
	* WDM-SM	75	0	0	247,373	100	0	0	100
Wet Weather in November 2010	*Base Case* 2010/2011 (Existing Development)	106	0	0	0	0	3	30	0
	Water Demand Management	101 92 84	0	0	0	100	3	30	0
	Greywater Recycling	0	185 87 116	0	0	0	100	30	0

	WMP Scenario		**Water Demand (L/cap/day)**	**Greywater Uptake (L/HH/day)**	**Rainwater Uptake (L/HH/day)**	**Extracted Sewage (L/day)**	**% of Household Connected**			
							Water Demand Management	***Greywater Recycling***	***Rainwater Harvesting***	***Sewer Mining***
	Rainwater Harvesting		0	0	60 89 106	0	0	3	100	0
	Sewer Mining		0	0	0	50,778 100,850 145,230	0	3	30	25 50 70
	Sustainable Practice									
	*	WDM-RH	84	116	0	0	100	100	0	0
	*	WDM-GR	84	0	60	0	100	0	100	0
	*	WDM-SM	84	0	0	347,427	100	0	0	100
Dry Weather in August 2060	*Base Case* 2060 (Future Development)		97.4	0	0	0	0	3	30	0
	Water Demand Management		75.1	0	0	0	30 60 100	3	30	0
	Greywater Recycling		97.4	173	0	0	0	30 60 100	0	0
	Rainwater Harvesting		97.4	0	49	0	0	3	30 60 100	0
	Sewer Mining		0	0	0	87,991 207,512 261,398	0	3	30	25 50 70
	Sustainable Practice									
	*	WDM-RH	84	116	0	0	100	100	0	0
	*	WDM-GR	84	0	60	0	100	0	100	0
	*	WDM-SM	84	0	0	299,886	100	0	0	100

5. SCENARIO ANALYSIS

***CONTENT:** Variable of Scenario Analysis; Piped Potable water;*
Discharged Wastewater & Contaminant Load; Sewer Flow;
& Hydrogen Sulphide Gas;
Corrosion Rate; Regression Analysis;
Scaling Up of WMP Adoption by Considering-
Future Urban Development & Climate Change;
Summary

This chapter presents the results from all selected scenarios compared to the *Base Case*. The chapter is divided into seven sections. Section 5.1 presents the variable used for cenario analysis. Section 5.2 reveals the impact of WMP on piped potable water volume. Section 5.3 quantifies the volume of wastewater discharged, contaminant load and percentage changes of WMP scenario from the *Base Case*. Significantly, the impact of WMP in sewerage networks is described in sections 5.4, 5.5 and 5.6. Section 5.4 discusses the impact of WMP on sewer flow, while section 5.5 discusses the impact of WMP on sulphide in wastewater and hydrogen sulphide gas in sewers. Section 5.6 relates the result of hydrogen sulphide gas with the subsequent effect on sewer pipe corrosion rates. Section 5.7 contains regression analysis that relates the independent variable in WMP adoption (e.g. variation of water demand reduction) and dependent variable of the Integrated Urban Water model (e.g. hydrogen sulphide gas). Finding the limits for maximum piped potable water reduction and the uptake of discharged wastewater is also an expected outcome in this study, and will be discussed in section 5.7. Section 5.8 discusses the impact of increasing WMP on the future of sewer networks. Section 5.9 is a summary of the result of scenario analysis.

Old sewer networks have different characteristics compared to new sewer pipes. Deteriorating pipes are mostly found in old sewer networks and they allow external flow to infiltrate to the sewer and vice versa. Therefore, even though sewer network networks are not designed to receive any external flow or to allow exfiltration, these processes are still present in ageing pipe networks. The effect of pipe ageing is enormous during wet weather, where runoff inflow and groundwater infiltration present in sewer networks and flow rates can be five times greater than in dry weather. This incident has been shown to occur in the study area (see Chapter 3, section 3.2.7.1, Figure 3.7).

By using the developed modeling framework, the impacts of WMP on sewer odour and corrosion were quantified. The developed method includes the calibrated model and set of model parameters. Modeling result of *Base Case* or existing urban development was already obtained from the calibration and validation process in Chapter 3. However, the modeling result of *Base Case* for future development of the 2060 will be presented in this chapter.

Chapter 5 will mainly discuss the impact of WMP adoption in dry weather for both current development (2010/2011) and future development (2060). The result of wet weather simulation will also be discussed in this chapter. However, due to lower significance caused by wet weather flow on odour and corrosion problems in sewer pipes, tables and figures associated with wet weather simulations will be placed in Appendix 7, Figure A.12 to Figure A.18.

5.1 Variable of Scenario Analysis

Table 5.1 describes the variables used to analyse the impact of WMP on hydrogen sulphide build-up. The impact of WMP on sewerage networks was analysed based on existing development (2010/2011) and future development (2060). Analysis for existing development aimed to explore the impact of WMP adoption, which considered changes in water demand and introduction of *Alternative Water Sources* on hydrogen sulphide build up in sewers. The analysis was conducted for both dry and wet weather. Analysis on different weather investigated whether rainfall significantly affect the increase or decrease of hydrogen sulphide concentration (gas and water phases) in ageing sewerage pipe networks.

To explore the impact of WMP in future scenarios, all identified scenarios were analysed by considering the conditions in 2060. This year was selected in this study based on the Melbourne Metropolitan Sewerage Strategy. This strategy was aimed at responding to future uncertainty about wastewater production and wastewater reuse (Brown et al. 2010). It is expected that Melbourne Water could provide sustainable sewerage services by 2060. Since the volume of wastewater production very much depend on the urban and population and climate, hence future development scenarios considered altered urban and population growth as well as climate change in study area.

Table 5.1. Variable for Scenario Analysis

General Objective	Selected Season	Specific Objective	Development used	WMP Scenario	Main Analysis Variables
To analyse the effects of volume of water demand reduction; greywater uptake; rainwater uptake, extracted sewage and combined WMP scenario	Dry Weather and Wet Weather	To analyse the reduction of water demand	Existing Development (2010/2011)	*Water Demand Management (WDM1; WDM2; WDM3)*	Reduction of water demand
		To analyse the volume uptake of alternative water source		*Greywater Recycling (GR-L; GR-B; GR-BL)*	Volume of greywater uptake based on greywater production (greywater from bathroom and laundry/ only bathroom/ only laundry)
				Rainwater Harvesting (RH-T; RH-L; RH-B)	Volume of rainwater uptake based on supplied indoor end-use (rainwater consumptiond for toilet flushing/ washing/shower)
		To analyse the volume of extracted sewage		*Sewer Mining (SM1; SM2; SM3)*	Volume of extracted sewage

General Objective	Selected Season	Specific Objective	Development used	WMP Scenario	Main Analysis Variables
		To analyse the effects of combined water demand reduction and application of *Alternative Water Sources*		*Sustainable Practice (WDM-RH; WDM-GR; WDM-SM)*	Type of WMP combination practice
To analyse the effect of future development, which include urban growth change and population increase	Dry Weather	To analyse the scale up effect of WMP scenarios adoption	Future Development (2060)	*Water Demand Management* (WDM30; WDM60: WDM100)	Number of households installing water saving appliances
				Greywater Recycling (GR30; GR60; GR100)	Number of households installing *Greywater Recycling* facility
				Rainwater Harvesting (RH30; RH60; RH100)	Number of households installing rainwater tanks
				Sewer Mining (SM25; SM50; SM70)	Number of households supplied by treated water from *Sewer Mining* plants
		To analyse the effect of combined water demand reduction and application of alternative water source in the future		*Sustainable Practice (WDM-RH100; WDM-GR100; WDM-SM70)*	Type of WMP combination practice

Table 5.2 re-lists the value of variables for WMP scenarios and includes the codes used for current urban development simulation. The detailed value for all variables was listed in Table 4.14. In order to assess to what extent water demand reduction can reduce wastewater flow and alter contaminant load quantity within the study area, scenarios of *Water Demand Management* were simulated using three different water demands, which is smaller than water demand in *Base Case*. Water demand in *Base Case* for dry weather was set to be 98 L/cap/day and water demand for *Water Demand Management* scenarios was set to 93 L/cap/day; 83 L/cap/day and 75 L/cap/day. Details of *Water Demand Management* scenarios were described in section 4.4.3 in Chapter 4.

In Alternative Water Source scenarios, the uptake volume of alternative sources was used as a variable in this study. In the *Greywater Recycling* scenarios, the volume of greywater uptake was selected based on the greywater source. It was assumed that kitchen wastewater was not suitable for reuse; therefore, 100% greywater uptake was represented by recycling all wastewater from the bathroom and laundry. The *Rainwater Harvesting* scenarios collected rainwater for toilet, laundry and bathroom use. *Sewer Mining* was the only scenario that was considered for implementation at cluster scale, by extracting wastewater from a local sewer. The simulation variable for this scenario was the service coverage of the *Sewer Mining* facility, and it was specified that *Sewer Mining* supply the water demand for 25%, 50% and 70% of households in the study area; therefore it extracts 69,413 L/day; 152,888 L/day and 214,216 L/day sewage volumes respectively. The recycled water was considered for use in toilet flushing. *Sustainable Practice* scenarios combine the highest *Water Demand Management* and using alternative sources.

Table 5.2. WMP Scenarios Variable Value & Code for Existing Urban Development (2010/2011)

WMP	Variables		Scenario Code
Base Case	Water Demand (L/cap/day)	98	*Base Case*
Water Demand Management	Water Demand (L/cap/day)	93	WDM1
		83	WDM2
		75	WDM3
Greywater Recycling	Greywater Uptake (L/HH/day)	173	GR-BL
		77	GR-L
		96	GR-B
Rainwater Harvesting	Rainwater Uptake (L/HH/day)	49	RH-T
		77	RH-L
		96	RH-B
Sewer Mining	Extracted Wastewater (L/day)	69,413	SM1
		152,888	SM2
		214,216	SM3
Sustainable Practice	Water Demand/ Greywater uptake / Rainwater Uptake / Extracted Wastewater	75 (L/c/d) / 49(L/HH/d)	WDM-RH
		75 L/c/d) / 173 (L/HH/d)	WDM-GR
		75 (L/c/d) / 247,373 (L/d)	WDM-SM

5.2 Piped Water

The main aim of WMP adoption is to conserve potable water so there will be no more water shortage in many areas. Piped water reduction due to WMP was evaluated through a wastewater generator model (UVQ). All WMP scenarios have similar water demand per person per day except *Water Demand Management*. Water demand setup in the *Base Case* and some WMP scenarios for every end-use in dry weather are 37.7 L/cap/day for bathroom, 30.2 L/cap/day for laundry, 10.3 L/cap/day for kitchen and 19.2 L/cap/day for toilet. In wet weather, water demand set in the *Base Case* and WMP scenarios are 50.6 L/cap/day for bathroom, 31.6 L/cap/day for laundry, 12.9 L/cap/day for kitchen and 21

L/cap/day for toilet. In the bathroom, piped potable water was used for shower, bath and tap use for vanity units. There were two different uses for the laundry: piped potable water for washing machines and laundry troughs. In the kitchen, piped potable water was used for dishwashers and kitchen sinks. For the toilet, piped potable water was only used for toilet flushing. No piped water was used to supply outdoor water consumption such as irrigation. UVQ simulates combined water consumptiond within each end-use (bathroom, kitchen, laundry, toilet) and does not consider single use within end-use (e.g. water demand for dishwashers and kitchen sinks in kitchen end-use). Hence, the calculation to combine every single use within end-use was conducted separately by using Excel spreadsheet. The reliability of the system to supply water continuously for each WMP scenario was set to 100%. This means that WMP scenarios are able to supply intended indoor water demand end-use (e.g. toilet, laundry, kitchen, and bathroom) without any days where the system cannot supply the water demand (failure days).

For scenario of *Water Demand Management*, the water demand per person per day was reduced, as listed in Table 5.3. The highest water reduction was assumed to be in laundry use, followed by kitchen use at WDM1. For WDM2 and WDM3 scenarios, laundry still has the highest water reduction, followed by toilet, bathroom and kitchen. In total, the implementation of WDM1, WDM2 and WDM3 scenarios contribute to a piped potable water reduction of 5 L/cap /day; 15 L/cap/day and 22 L/cap/day respectively. In Figure 5.1, the value of piped potable water reduction is converted to account for the total population in the study area. Therefore, the reduction of piped potable water is presented in Figure 5.1 as Total Households Piped Water Volume.

Table 5.3. Water Reduction in *Water Demand Management* Scenario for Every Indoor Use

Scenarios	Laundry (L/cap/day)	Kitchen (L/cap/day)	Bathroom (L/cap/day)	Toilet (L/cap/day)	Total Reduction/ WDM scenario (L/cap/day)
WDM1	4.8	0.2	0	0	**5**
WDM2	4.8	0.2	3.2	6.6	**15**
WDM3	9.5	3	3.2	6.6	**22**

Results in Figure 5.1 show a water demand reduction of 5 L/cap/day in the study area can contribute to 47 m^3/day water saving. The reduction of water demand by 15 L/cap/day and 22 L/cap /day also contributes to water saving by 136 m^3/day and 209 m^3/day respectively. WDM1 gives very little reduction compared to other WDM scenarios.

In general, reduction in water demand due to replacement of potable water for some indoor use with *Alternative Water Sources* contributes to higher water saving than *Water Demand Management* scenarios. By using alternative water from *Greywater Recycling*, potable water can be saved by up to 123 m^3/day. Low water saving in the *Greywater Recycling* scenario is caused by the UQV model setup that does not allow treated water from *Greywater Recycling* to be used for laundry washing, bathroom or kitchen use. Hence, the treated water produced from *Greywater Recycling* plants was used for toilet flushing and garden irrigation. A similar percentage of piped potable water reduction indicates the reliability of *Greywater Recycling* systems to supply water for toilet flushing and garden irrigation to achieve 100%.

In *Rainwater Harvesting* scenarios, the collected rainwater was used to supply various indoor uses (i.e. toilet, bathroom and laundry water). The UVQ setting allows collected rainwater to be used for any indoor use (kitchen, laundry, bathroom and toilet) and outdoor use (garden irrigation). Therefore, the contribution of these scenarios for piped potable water saving is quite high: reaching 123 m^3/day piped potable water reduction for rainwater supplied toilet flushing water; 205 m^3/day water reduction for the rainwater consumptiond to supply laundry water; and 252 m^3/day piped potable water reduction for rainwater supplied bathroom water. The scenario to supply water demand of many end uses (toilet, laundry and bathroom) using collected rainfall was not included in this study because the reliability of the rainwater harvesting system was less than 100%. Less reliability of *Rainwater Harvesting* system means that the collected rainwater will not be sufficient to supply the water demand for all intended end uses.

UVQ has limited choices for using treated water from cluster scale treatment for various indoor uses. Moreover, it only allows treated water from clustered wastewater treatment, like *Sewer Mining*, to be used for toilet flushing and garden irrigation (household scale) as well as public open space irrigation (clustered scale). Therefore, *Sewer Mining* scenarios were set to use their treated water for toilet flushing and garden irrigation only. Figure 5.1 shows that *Sewer Mining* contributes to 130 m^3/day water saving when extracting sewage for toilet flushing and garden irrigation water demand for 70% of households in the study area. Where 25% and 50% of households were supplied by treated water from *Sewer Mining*, the piped potable water reduction was 46 m^3/day and 92 m^3/day respectively.

Combination scenarios of *Sustainable Practice* contributed the highest piped potable water reduction in the study area. *Sustainable Practice* of WDM-SM gave the highest reduction of piped potable water supply in the study area, reaching 322 m^3/day water reductions, while other *Sustainable Practice* combination scenarios of *WDM-RH* and *WDM-GR* had less water reduction (290 m^3/day).

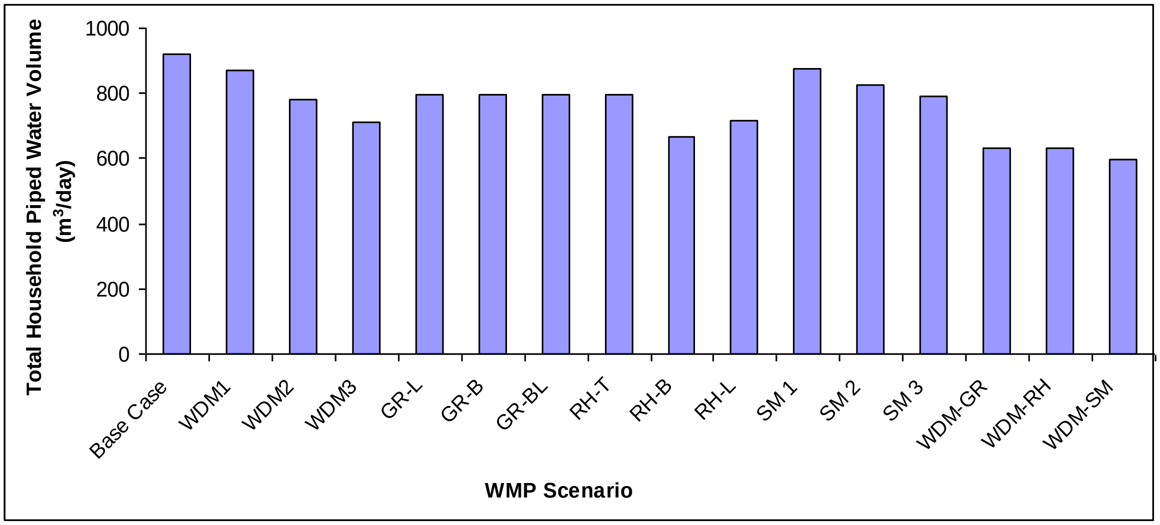


Figure 5.1. Consumed Total Piped Water in Study Area

5.3 Discharged Wastewater and Contaminant Load

Wastewater characteristics in sewer networks depend on discharged wastewater flow and contaminant load produced within a household. Any WMP applied within a household will determine the quantity and quality of wastewater. Similarly, the installation of clustered WMP that take their water source from sewage and discharge the residual treatment back to the sewer pipe is also likely to lead to changes in wastewater characteristics in the downstream sewer pipe.

This section discusses discharged wastewater flows and contaminant loads produced by households in the study area. For WMP installed at the cluster scale, the discussion will highlight discharged wastewater flows and contaminant loads produced within all clusters of the study area. Wastewater volume and contaminant loads produced within a household or clusters were estimated by UVQ. This model uses a mass balance within a study area to predict water flows and contaminant loads.

5.3.1 Discharged Wastewater

Wastewater produced in households depends on the quantity of indoor water consumption, mostly associated with the kitchen, laundry, bathroom and toilet. Outdoor water consumption can also affect household wastewater quantity, but only if WMP divert wastewater for outdoor water consumption (e.g. greywater directed for irrigation). Indoor water consumption for each scenario was presented in Chapter 4 and section 5.1. The production of wastewater flow within a household and cluster that eventually discharges to sewer pipe network will be discussed next.

The wastewater discussion will be divided into two topics: produced wastewater for WMP implemented within a household (household scale) and WMP installed at cluster scale.

5.3.1.1 Discharged Wastewater Flow for Household WMP

Discharged wastewater flow from households to sewer networks will be presented as total discharged wastewater in the study area. In the UVQ model, wastewater produced from a household was calculated from total indoor water demand, with infiltration and inflow added, then reduced by exfiltration and overflow. If no WMP related to wastewater consumption are installed in a household, the discharged wastewater will be equal to produced wastewater that has been affected by inflow-infiltration and exfiltration-overflow. However, if the households that have installed WMP which recycle wastewater, the recycled wastewater has to be reduced from the produced wastewater to get the discharged wastewater. As explained in Chapter 3, the UVQ model in this study has been set up to minimise infiltration, inflow and exfiltration coefficients within a household. Therefore, the main component of produced wastewater in dry weather is for indoor use only.

In a *Water Demand Management* scenario, the produced wastewater was similar to discharged wastewater, since no wastewater was used before it flowed to the sewer pipe network. As can be seen in Figure 5.2, total discharged wastewater in *Water Demand Management* scenarios gradually decreased from WDM1 to WDM3, since WDM1 has the least water reduction, while WDM3 has the highest water reduction (see Table 5.3). Percentage of discharged wastewater reduction corresponds with percentage of water demand reduction. WDM1, WDM2 and WDM3 scenarios have thus successfully reduced wastewater flow by 5%, 15% and 23% respectively. Discharged wastewater in the study area for *Base Case* scenario was 915 m^3/day. After adoption of *Water Demand Management* scenarios the discharged flow reduced to 869 m^3/day; 777 m^3/day and 705 m^3/day respectively for WDM1, WDM2 and WDM3 scenarios.

Among single WMP scenarios, *Greywater Recycling* contributes to the highest discharge wastewater reduction, diverting bathroom and laundry greywater (GR-BL) and it also has the highest reduction. Thus the ranking is as follows: *Greywater Recycling* diverts bathroom greywater (GR-B) followed by *Greywater Recycling* that diverts laundry greywater (GR-L). Discharged wastewater for *Greywater Recycling* was 723 m^3/day, 678 m^3/day and 652 m^3/day respectively for scenarios GR-L, GR-B and GR-BL.

Discharged wastewater for *Rainwater Harvesting* scenarios did not differ from discharged wastewater in the *base case*, because there was no water demand reduction or wastewater reuse. The alternative water consumptiond in this scenario was derived from an external source that did not relate to piped potable water and wastewater.

For *Sustainable Practice*, discharged wastewater was reduced to 705 m^3/day and 488 m^3/day for WDM-GR and WDM-RH respectively. High reduction in WDM-GR was due to the combination effect between WDM-GR and WDM-RH. This reduction mainly occurred due to the effects of *Water Demand Management*.

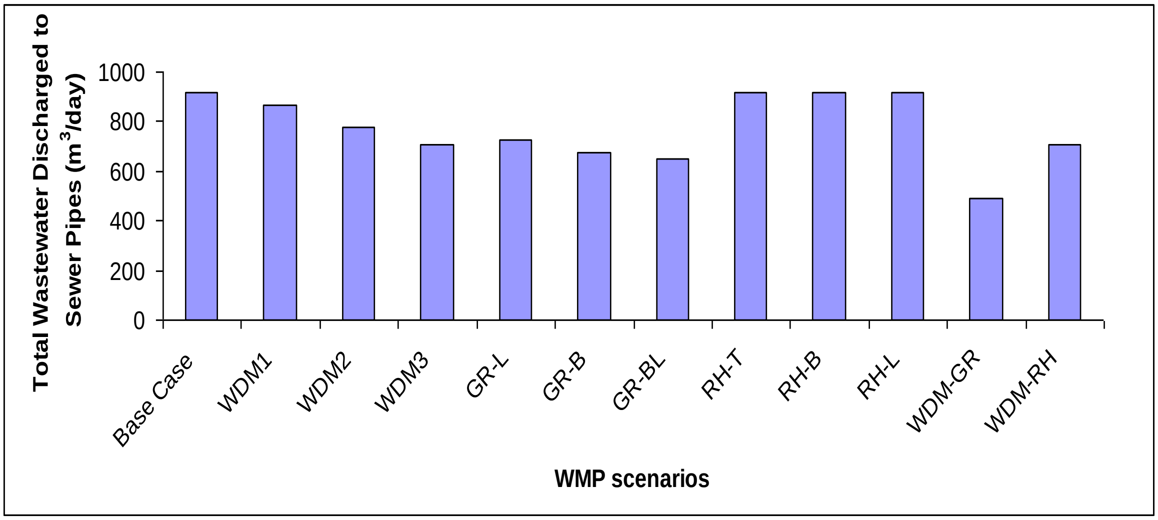


Figure 5.2. Discharged Wastewater for Household WMP

5.3.1.2 Wastewater Volume for Clustered WMP

Discharged wastewater within a cluster was calculated by estimating the discharged wastewater within a household multiplied by number of households in a cluster. Total discharged wastewater was calculated by totalling all discharged wastewater from every cluster, reduced by sewage flow extraction due to *Sewer Mining*. Figure 5.3 depicts WMP if *Sewer Mining* reduced discharged wastewater from 915 m^3/day to 846 m^3/day, 762 m^3/day and 700 m^3/day for SM1, SM2 and SM3. These reductions correspond with a reduction in percentages of 6%, 17% and 23% respectively. *Sustainable Practice* of WDM-SM contributes to the highest discharged wastewater reduction. This practice reduces discharged wastewater from 915 m^3/day to 458 m3/day and corresponds to 50% wastewater reduction in the study area. Some households were set to not receive reclaimed water from a *Sewer Mining* facility. This was because the extracted sewage volume was not sufficient to supply all household toilet water demands. Some households had already adopted other WMP such as rainwater tanks or *Greywater Recycling* treatment. Figure 5.3 illustrates wastewater reduction for clustered WMP.

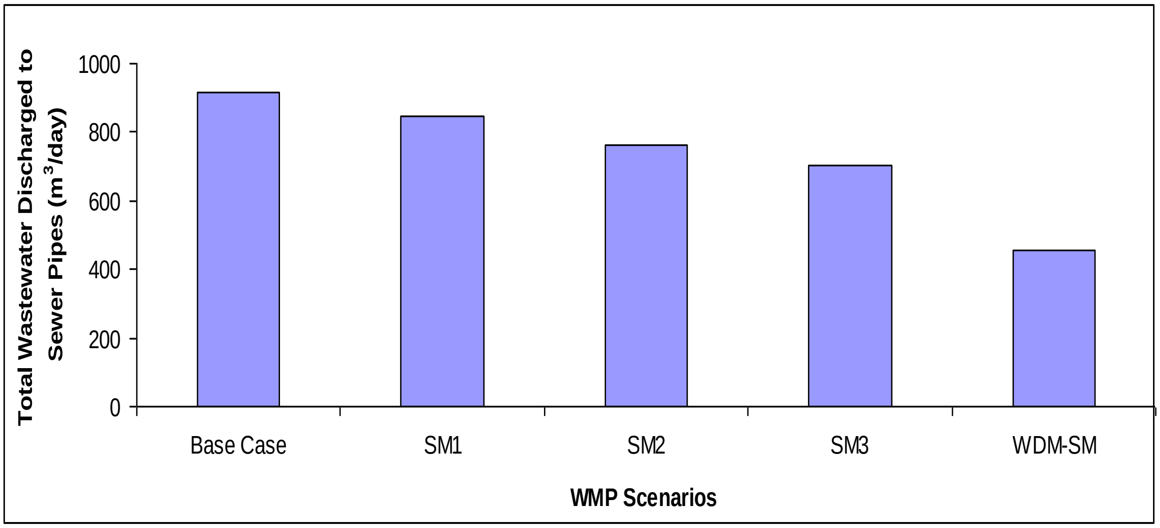


Figure 5.3. Discharged Wastewater for Clustered WMP

5.3.2 Contaminant Load

Five main contaminants associated with sulphide formation in sewer networks are: COD, nitrate, sulphide, sulphate and metals (iron, copper and zinc). These contaminants, apart from copper and zinc, have been incorporated into the WATS model. Therefore only metal contaminants of iron will be discussed here. Contaminant load is a variable that is not affected by weather. Therefore, the result will be similar between dry and wet weather simulation. Five contaminants and how they change in load due to the adoption of WMP scenarios will now be discussed. The changes in percentage of wastewater flow discharged to sewers and the contaminant load will also be presented.

5.3.2.1 COD Load

COD (Chemical Oxygen Demand) is an important parameter in the process of sulphide formation. COD load for each node was derived from the wastewater generation model (UVQ). The loads presented in Figure 5.4 were calculated as total COD loads for the study area. UVQ calculates COD load in wastewater, based on the input data of contaminant loads for every indoor use, as well as any input from *Alternative Water Sources* such as rainwater and greywater.

It is obvious that *Greywater Recycling* and *Sustainable Practice* of WDM-GR had the lowest COD load contribution to discharged wastewater. This is because *Greywater Recycling* includes greywater treatment, which means nearly all contaminants, particularly COD, will be removed from the discharged wastewater. The assumption here is the treatment residual from the *Greywater Recycling* treatment plant, such as sludge, is not disposed to the sewer but separated to other disposal places. Treatment and sludge separation contribute to low COD load discharged to the sewer in the *Greywater Recycling* scenario. However, the COD load which is discharged to the sewer pipe is still high and was only reduced by around 17% from the *Base Case*. This is because greywater does not contain a high COD load. The biggest contributor to COD load in household water is the toilet, followed by laundry, kitchen and bathroom (Almeida et al. 1999b).

COD loads in *Rainwater Harvesting* and *Sustainable Practice* of WDM-RH were slightly increased because rainwater contains a small amount of COD matter, while piped potable water did not contain COD. *Water Demand Management* did not change, because piped potable water demand did not contain a COD load. In *Sewer Mining*, the COD load slightly decreases because the treated water supplied for toilet flushing still contains small amounts of COD. Most of the COD load is contained in sewage overflow and treatment sludge which are disposed back to the sewer.

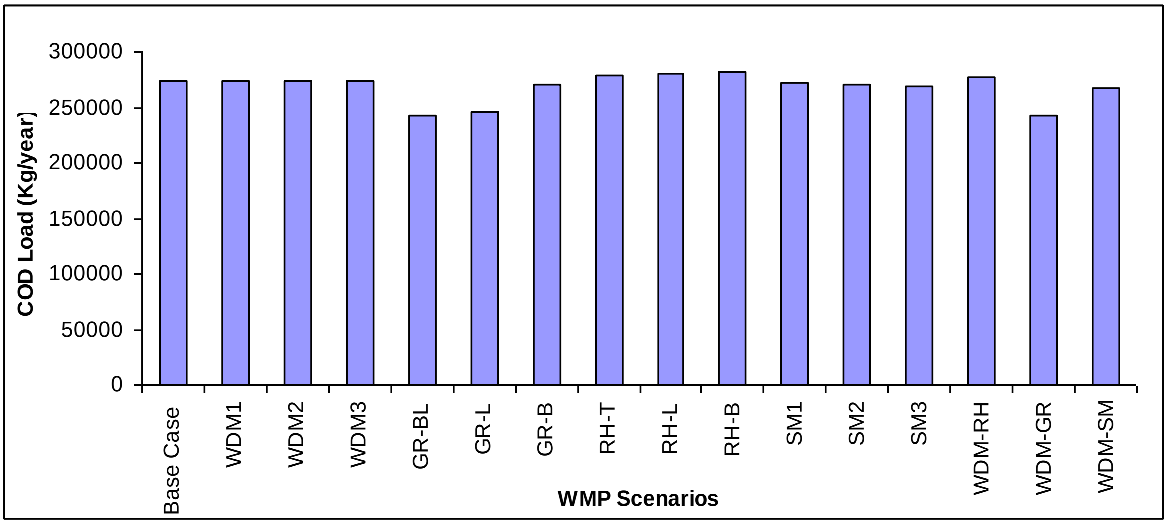


Figure 5.4. COD Load For Every Scenario

In the WATS model, COD is concentrated at a node/point of discharge. The concentration was calculated by dividing the average COD load over a day with the flow from every node. WATS modeling for hydrogen sulphide production considers all COD to be equal, but it also takes into account the biodegradability of organic matter. Biodegradability characteristics (biodegradable percentage) were taken from a study by Vollertsen et al. (2011) for a catchment located in a warm to hot area. Biodegradability was assumed to be similar in all pipe sections based on fixed percentages from the Vollertsen et al. (2011) study. Table 5.4 presents the fraction of biodegradable COD in dry weather assumed for this study. Fraction of biodegradable COD in wet weather is listed in Appendix 7, Table A.3.

Table 5.4. COD Fraction Used in WATS (Dry Weather)

Scenario	**Average COD_{Total}**	**S_A**	**S_F**	**X_{BW}**	**X_{Sf}**	**X_{Sm}**	**X_{Ss}**
	mg/L						
COD Fraction	**100%**	**5.3%**	**5.3%**	**3.4%**	**13%**	**20%**	**53%**
Base Case	864	45.8	45.8	29.4	112.4	172.9	458.1
WDM1	916	48.6	48.6	31.2	119.1	183.3	485.7
WDM2	1024	54.3	54.3	34.8	133.2	204.9	542.9
WDM3	1146	60.7	60.7	39.0	149.0	229.2	607.4
GR-L	994	52.7	52.7	33.8	129.2	198.7	526.6
GR-B	1199	63.5	63.5	40.8	155.8	239.7	635.3
GR-BL	1280	67.8	67.8	43.5	166.4	256.0	678.4
RH-T	879	46.6	46.6	29.9	114.3	175.9	466.1
RH-L	887	47.0	47.0	30.2	115.3	177.4	470.1
RH-B	891	47.2	47.2	30.3	115.8	178.2	472.2
SM1	954	50.6	50.6	32.4	124.0	190.8	505.7
SM2	1228	65.1	65.1	41.8	159.6	245.6	650.9
SM3	1754	92.9	92.9	59.6	228.0	350.7	929.5
WDM-RH	1159	61.4	61.4	39.4	150.7	231.8	614.2
WDM-GR	1893	100.3	100.3	64.4	246.1	378.6	1003.3
WDM-SM	4020	213.1	213.1	136.7	522.6	804.0	2130.5

5.3.2.2 Nitrate Load

Nitrate in wastewater predominantly comes from ammonium to nitrate conversion; however nitrate can also be contributed by fresh wastewater originating from indoor use. Nitrate naturally exists in potable water and other water-related products in a household, but in low concentrations. Indoor sources of nitrate are mainly from the kitchen and the bathroom (Almeida et al. 1999b). Figure 5.5 depicts a declining trend in *Water Demand Management*, which shows that by reducing water demand, a reduction of nitrate load in wastewater will occur. Nitrate is a natural contaminant that exists in potable water, but in minor concentrations. Nitrate is also sourced from human discharge (urine and human excreta) but the proportion is less than 3% of total nitrogen in human discharge. This is why reducing water demand and diverting wastewater (including toilet wastewater) can decrease the nitrate load discharge to the sewer pipe. More water reductions applied in the household will reduce the nitrate load.

The most significant reduction in wastewater nitrate load, relative to the *Base Case*, was contributed by *Greywater Recycling*. This is because the greywater treatment system reduces nitrate by up to 90%. Furthermore, the application of greywater for irrigation means nitrate from the laundry and bathroom, destined for the sewer, will now be applied to the garden (see Figure 5.5). The usage of rainwater in *Rainwater Harvesting* scenarios can reduce nitrate by around 20% for RH-L and RH-B. This is due to the fact that nitrate is unlikely to be found in rainwater. Thus replacing piped potable water that contains nitrate with rainwater that does not contain nitrate will reduce the nitrate load disposed to the sewer pipe. *Sewer Mining* scenarios slightly reduce nitrate load to the sewer pipe for the same reason as COD load. The *Sustainable Practice* of WDM-RH and WDM-SM have quite a high reduction of nitrate load due to the influence of *Water Demand Management*. For *Sustainable Practice* of WDM-GR however the nitrate load is even more reduced because both scenarios contribute to a reduced nitrate load.

Nitrate produced through ammonium oxidation contributes more significantly to nitrate load in sewer pipes compared to nitrate produced by a household. Therefore, if wastewater contains a high ammonium load, it is most possible that the nitrate load will likely increase when the sewage has undergone an ammonium oxidation process in the sewer pipe.

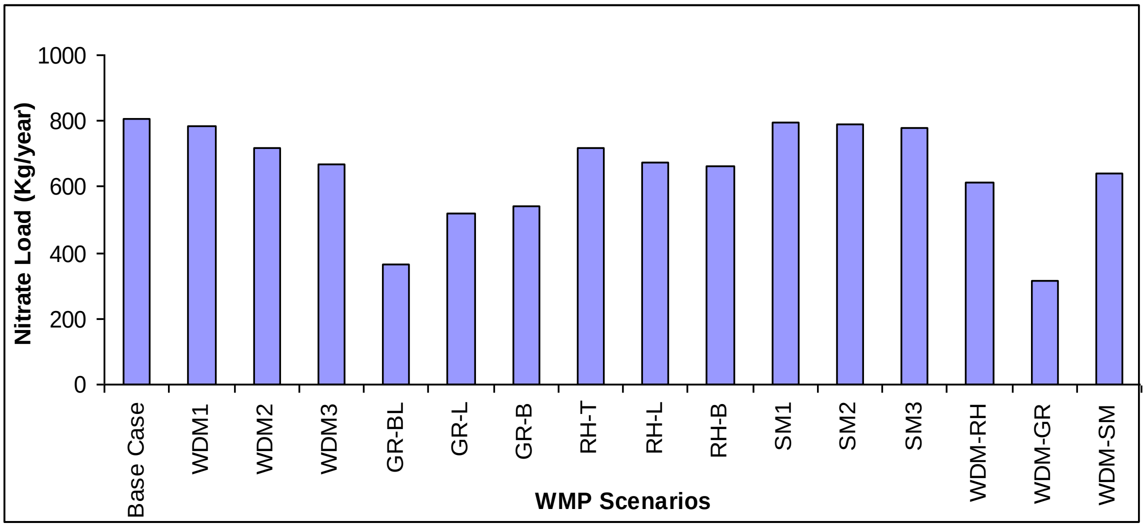


Figure 5.5. Nitrate Load for Every Scenario

5.3.2.3 Sulphide Load

Similar to nitrate, most sulphide is produced in sewer pipes rather than by households through anaerobic heterotrophic degradation of organic matter, with sulphate as the terminal electron acceptor (sulphate reduction). Pipe biofilm and sediment are located where sulphide is formed. Sulphide in biofilm and sediment will finally diffuse to lower sulphide concentrations, which usually belong in sewage streams (Nielsen 1991). As can be seen in Figure 5.6, sulphide will not be formed in piped potable water and sulphide is unlikely to occur in collected rainwater. Therefore *Water Demand Management* and *Rainwater Harvesting* do not change wastewater sulphide load. Sulphide is sourced from human discharge and water-related products used in the household (shampoo, soap, dishwashing detergent, etc.) (Tjandraatmadja et al. 2009c). The *Greywater Recycling* scenario reduced the sulphide load because its treatment was assumed to remove 79% of sulphides in wastewater. Sulphide loads in *Sewer Mining* is slightly decreased because some treated water supplied to the toilet still carries a sulphide load. However, the sulphide load considered here is only sulphide in wastewater discharged from the household rather than the sewer pipe. The sulphide load in the sewer pipe is likely to increase due to the process that involves sulphate in sewer pipe networks.

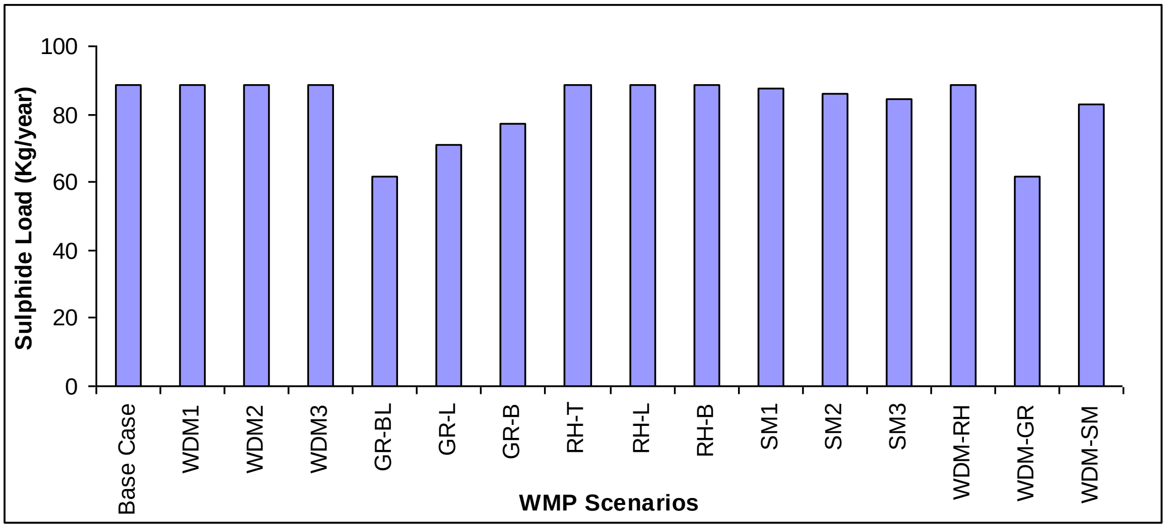


Figure 5.6. Sulphide Load for Every Scenario

5.3.2.4 Sulphate Load

The source of sulphate in residential wastewater is usually from human and water-related products for household use. Therefore, as can be seen in Figure 5.7, there is no significant reduction of sulphate on *Water Demand Management* scenarios compared to the *Base Case*. The percentage reduction of *Water Demand Management* was 1% and this applies to scenario WDM3, which has the highest water reduction. For the other two *Water Demand Management* scenarios the percentage reduction of sulphate load is lower than 1%. *Greywater Recycling* had the lowest sulphate load of all scenarios. GR-BL, GR-L and GR-B were able to reduce sulphate loads by 39%, 35% and 11% respectively. These results indicate that the main sulphate contributor is laundry greywater, since the reduction of sulphate load from GR-B is much smaller, compared to GR-L. *Rainwater Harvesting* had a slightly increased wastewater sulphate load because in the UVQ model rainwater and roof runoff were assumed to have quite a high sulphate concentration of 3.5 mg/L and 14.5 mg/L respectively, while potable water concentration was 2 mg/L. *Sewer Mining* scenarios decrease sulphate load in the study area, since a small amount of sulphate still remains in treated wastewater. The sulphate load is similar to the *Base Case* because in *Sewer Mining* practice, treatment sludge that contains many contaminants, including sulphate, was discharged back to the sewer pipe.

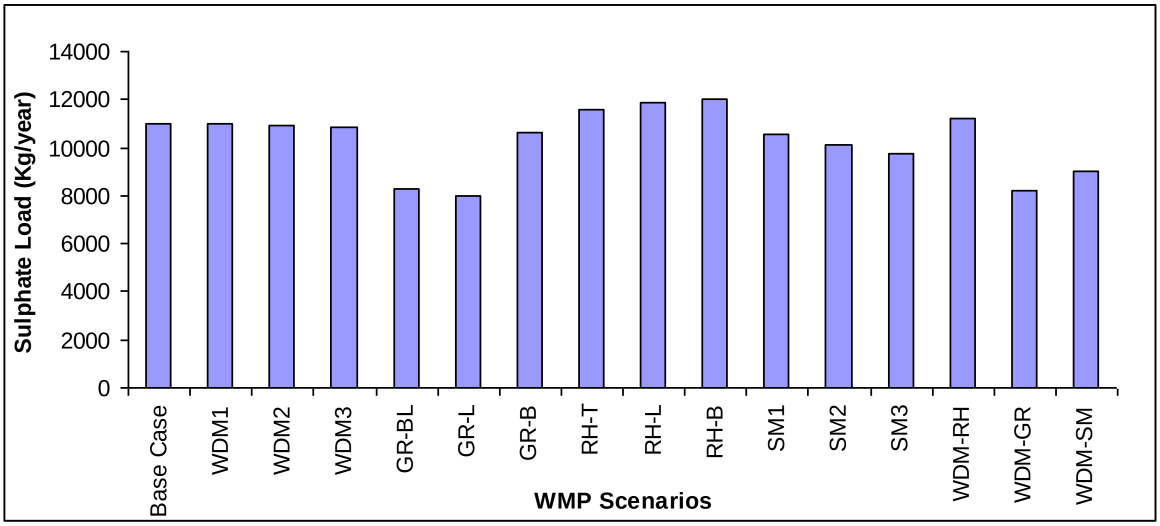


Figure 5.7. Sulphate Load for Every Scenario

5.3.2.5 Iron Load

As can be seen in Figure 5.8, the lowest iron loads belong to *Greywater Recycling* scenarios and *Sustainable Practice* scenario of WDM-GR. GR-L had the highest iron load compared to GR-B and GR-BL. *Greywater Recycling* treatment was set to remove 90% of iron in the wastewater (Cook et al. 2010). Furthermore, greywater from the bathroom was one of the significant sources of iron in wastewater (Tjandraatmadja et al. 2009c). For the *Rainwater Harvesting* scenario, the iron load was quite high compared to the *Base Case*. The increased iron load in the rainwater scenario compared to the *Base Case* was due to piped potable water demand being substituted with rainwater. The modeling assumed an iron concentration of 0.005 mg/L in rainfall and 2.1 mg/L for roof runoff, while potable water has a concentration of 0.06 mg/L. However, the low substitution of potable water with rainwater for indoor demands (only 20-35%) meant the load difference was not very high.

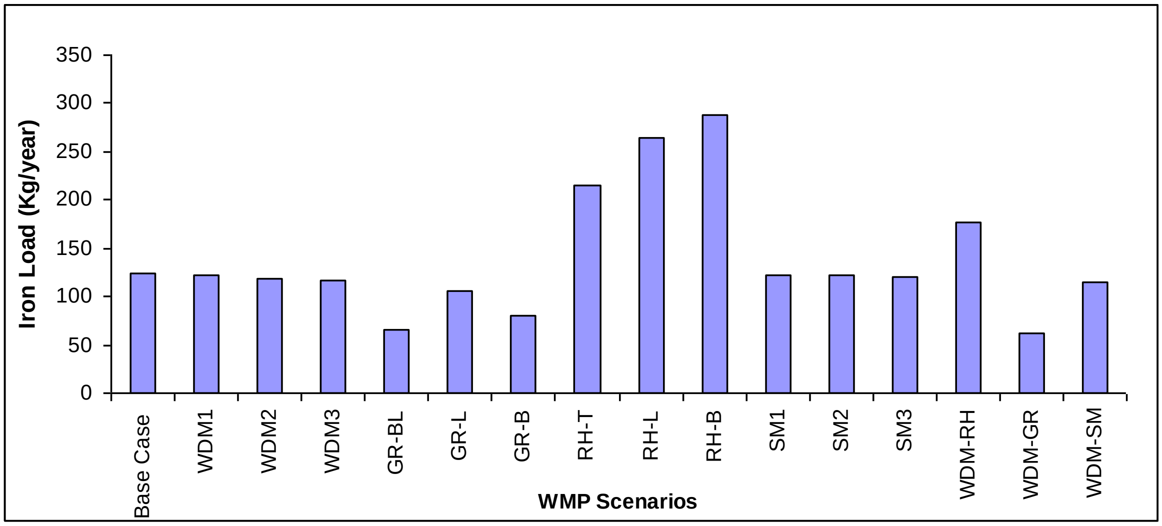


Figure 5.8. Iron Load for Every Scenario

5.3.3 Flow and Contaminant Load Changes

Figure 5.9 shows the impact of WMP in discharged wastewater flow and contaminant loads. Table 5.5 summarises the average percentage change for each WMP scenario. Figure 5.9 and Table 5.5 clearly show significant changes in discharged wastewater flows, but do not impact contaminant loads.

Reduced water demand results in changes in discharged wastewater flow. The nitrate load discharged from households is also affected by the adoption of *Water Demand Management,* but it is important to note that the nitrate load is only a minor source of nitrate in sewer pipes. In fact the presence of nitrate in the sewer is actually due to the ammonium oxidation process. It is obvious that reduced water demand can cause discharged wastewater flow reduction, but previous study argue that conserving water through reducing water demand does not change the wastewater contaminant load (DeZellar & Maier 1980). However, in this case, for nitrate contaminants that already exist in potable water, the efforts to reduce water demand not only reduce wastewater flow, but also reduce the nitrate load. The reduction of discharged wastewater flow was 5%; 15% and 23% for WDM1, WDM2 and WDM3 respectively. In addition, household nitrate load shows 2%; 10% and 17% reduction for WDM1, WDM2 and WDM3. The iron load was reduced by 1%; 4% and 5% for WDM1, WDM2 and WDM3. The sulphate load also decreased by 0.3%; 0.5% and 0.8% for WDM1, WDM2 and WDM3.. The flow and load analysis from *Water Demand Management* scenarios indicate that it is likely that sewer biochemical process will change, due to the adoption of *Water Demand Management*. However, in this analysis, we cannot determine the magnitude of changes that will occur, since many contaminants will be formed or reduced during sewer biochemical processes.

Greywater Recycling shows high reductions for both wastewater flow and contaminant loads. Wastewater flow has been reduced by 21%, 35% and 46% for GR-L, GR-B and GR-BL. Further for contaminants load, COD has been reduced by 10%, 2% and 17% for GR-L, GR-B and GR-BL scenarios respectively. Lesser reduction of COD load in GR-B is due to the bathroom greywater usually contains relatively small COD concentrations. The highest reduction was for the nitrate load for scenario of GR-BL, which has been reduced the load by 77% in wastewater. Iron load also has been reduced much compared to Base Case, which reduced by 14%, 555% and 69% for GR-L, GR-B and GR-BL. High reduction of contaminant load was due to the greywater recycling treatment installed in these scenarios..

Rainwater Harvesting scenarios contribute by 0% discharged wastewater reduction. This is because there is no reduction in water demand or wastewater discharge to the sewer network. The rainwater is simply used to substitute piped potable water demand. However, there is quite a high reduction in nitrate load, by up to 20%. However, the iron load increases significantly in these scenarios by up to 20%. As mentioned earlier, these two contaminants are crucial to eliminate sulphide formation; however since they both contribute in a different direction, sulphide formation will be mainly determined by other contaminants such as sulphide and COD. Analysis of results show there is little increase (less than 10%) of COD and sulphide for *Rainwater Harvesting*. However, all results presented here is more of an indicative analysis, since sewer biochemical processes determine the magnitude of the contaminant load.

In the *Sewer Mining* scenario, wastewater flow is reduced significantly compared to the *Base Case*. However, the contaminant load only slightly decreases. Reduction in contaminant load was triggered by the fact that some of these contaminants still remain in treated water, while the rest are mixed with treatment sludge that will eventually be discharged to sewer pipe networks. Wastewater flow decreases up to 20%, while contaminant loads decrease from 1% up to 15%. The combination of greatly reduced flow and slightly reduced contaminant load could consequently increase the contaminant concentration enormously. High contaminant concentration, particularly COD, sulphide and sulphate, will trigger the formation of sulphide in sewer pipes.

Sustainable Practice of WDM-RH produce results similar to *Rainwater Harvesting*, where wastewater flow did not change significantly compared to the *Base Case*. Changes occurred for nitrate and iron loads, where nitrate from household use reduced by around 20% and iron increased by around 10%. WDM-GR reduced both wastewater flow and contaminant load. The former was reduced by around 50% and the latter was reduced by up to 70% for nitrate—the highest reduction. The other contaminants also reduced their loads by 10% to 30%. WDM-SM is able to reduce discharged wastewater flow up to 50% and slightly decrease the contaminant load by 15%. These combinations can increase contaminant concentration. Hence the scenario of WDM-SM can create the most favourable condition for sulphide formation.

In conclusion, the adoption of WMP has been predicted to change wastewater characteristics of flow and contaminant load. It is not the single action of discharged wastewater flow or contaminant load that will determine the extent of sulphide formation, but the combination of these two parameters. However, contaminant loads in sewer pipes are not only sourced from the household. They are also significantly produced during sewage transport. Hence we cannot estimate the magnitude of sulphide only based on household discharge of wastewater flow and contaminant flow analysis. This analysis needs to be followed by an analysis of hydrogen sulphide formation potential, so that the significance of changes in wastewater flow and contaminant load on the formation of sulphide can be deduced. It is expected that an analysis that accounts for both changes in flow and contaminant concentration and load, will develop a strategy that will eliminate sulphide formation in sewer networks. The following section will discuss sewer flows and sulphide formation in sewer networks.

Table 5.5. Average Wastewater Flow and Contaminant Load Changes

WMP Scenario	Wastewater Flow m^3/day	Contaminant Load (Kg/year)					Average Percentage Change					
							Wastewater Flow	Contaminant Load				
		COD	Nitrate	Sulphide	Sulphate	Iron		COD	Nitrate	Sulphide	Sulphate	Iron
Base Case	915	273851	805	89	11010	124	-	-	-	-	-	-
WDM1	869	273848	785	89	10974	123	-5	0	-2	0	-0.3	-1
WDM2	777	273783	720	89	10904	119	-15	0	-10	0	-0.5	-4
WDM3	705	273780	668	89	10850	118	-23	0	-17	0	-0.8	-5
GR-L	726	245321	522	71	7967	106	-21	-10	-35	-20	-28	-14
GR-B	598	269057	446	73	10541	56	-35	-2	-45	-18	-4	-55
GR-BL	493	227734	182	49	6970	39	-46	-17	-77	-44	-37	-69
RH-T	879	278336	720	89	11565	215	-4	2	-11	0	5	74
RH-L	915	280733	674	89	11862	264	0	3	-16	0	8	113
RH-B	915	281972	662	89	12023	289	0	3	-18	0	9	134
SM1	846	134346	359	41	4272	52	-8	-51	-55	-54	-61	-58
SM2	762	173623	442	52	4805	67	-17	-37	-45	-42	-56	-46
SM3	701	209182	518	61	5355	87	-23	-24	-36	-31	-51	-29
WDM-RH	705	276723	613	89	11214	177	-23	1	-24	0	2	44
WDM-GR	490	242181	314	62	8223	63	-46	-12	-61	-30	-25	-49
WDM-SM	458	271378	550	78	6467	109	-50	-1	-32	-12	-41	-12

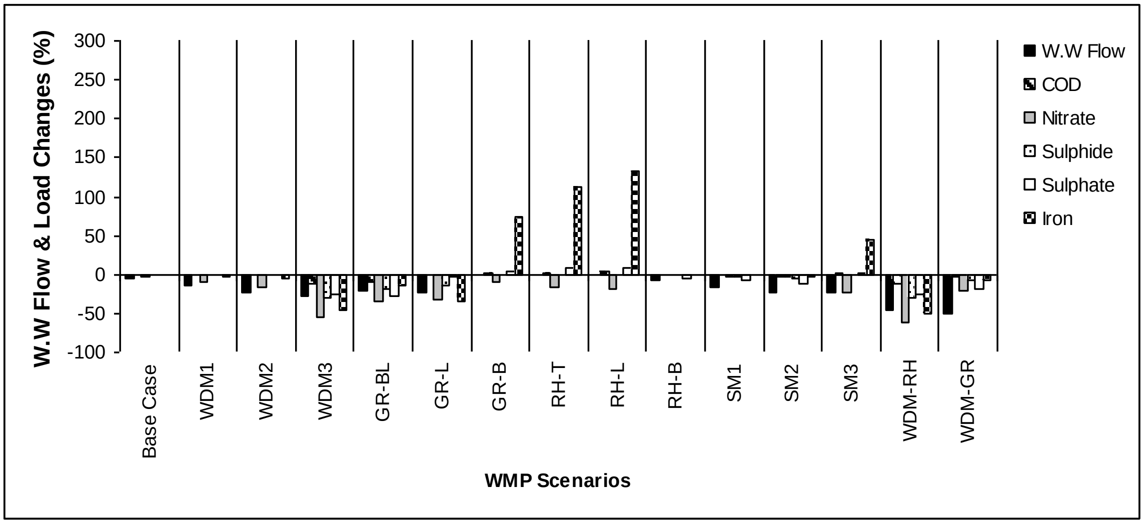


Figure 5.9. Percentage Change WMP Scenarios

5.4 Sewer Flow

The scope of this study is to investigate the propensity of the increase in sewer odour and corrosion due to WMP. The main cause of odour and corrosion is the presence of hydrogen sulphide gas. When considering hydrogen sulphide release into the sewer atmosphere, it is important to consider what sends dissolved sulphide into the atmosphere. There are at least two known factors that contribute to hydrogen sulphide release. Firstly, it is about instability of dissolved sulphide in water and saturation levels that liquid media can hold. The stability of pH is more determined by wastewater pH. Secondly, the turbulence of wastewater is a physical characteristic of sewers that causes hydrogen sulphide to be released into the sewer atmosphere. Wastewater turbulence is influenced by sewer flow. Sewer flow in existing pipes usually consists of discharged wastewater from households/commercial areas/industrial areas and external inflow such as infiltration. There is also the possibility that the existing sewer might reduce its flow because of exfiltration. Any changes in sewer flow will also change wastewater turbulence. Diurnal flow pattern is a driver of sewer flow. The flow pattern mostly relates to human activity.

Sewer flow, in this study, was obtained from PC-SWMM simulation and WATS simulation. PC-SWMM functioned as a tool to estimate sewer flow, which included sanitary flow and inflow-infiltration derived from rainfall. However, since the simulation was conducted in dry weather (April 2010) the effect of rainfall through inflow and infiltration was insignificant. The output of daily average flow per node from PC-SWMM was taken as flow input in the WATS simulation. By using WATS simulation, the hydrogen sulphide and corrosion rate for every scenario can be estimated.

For example, the sewer flow was calculated for each pipe over a 24-hour period using 1-hour time intervals. In this section, sewer flow will be analysed based on diurnal sewer flow and daily average sewer flow. These were obtained from data recorded in the outlet node located downstream as part of the last pipe in the sewer network (pipe GLN54). Daily average sewer flow was derived by taking the average hourly flow in the downstream part of pipe GLN54. Analysis of the diurnal sewer flow profile is helpful in understanding when sewer flow can potentially trigger the formation of hydrogen sulphide, since hydrogen sulphide formation is likely to have formed in low flow conditions. Analysis of daily average flow plots is beneficial to practically comparing the *Base Case* with WMP scenarios.

Figure 5.10 presents the diurnal plot of total sewer flow in the study area. As can be seen, almost all WMP scenarios have reduced total sewer flow over a 24-hour period. Early morning is the time when sewer flow is at its lowest value. The second lowest value was in the afternoon around 3 pm. However, WMP are most likely to influence sewer flow in the early morning (before 4 am), while the sewer flow from WMP is only slightly different compared to the *Base Case*. In addition, the diurnal flow pattern of each WMP scenario is similar to the *Base Case* flow pattern. Relating diurnal flow with the formation of hydrogen sulphide, it is likely that sulphide forms during the early morning and mid-afternoon when the sewer flow is low. However, in this study, hydrogen sulphide formed mostly in the early morning.

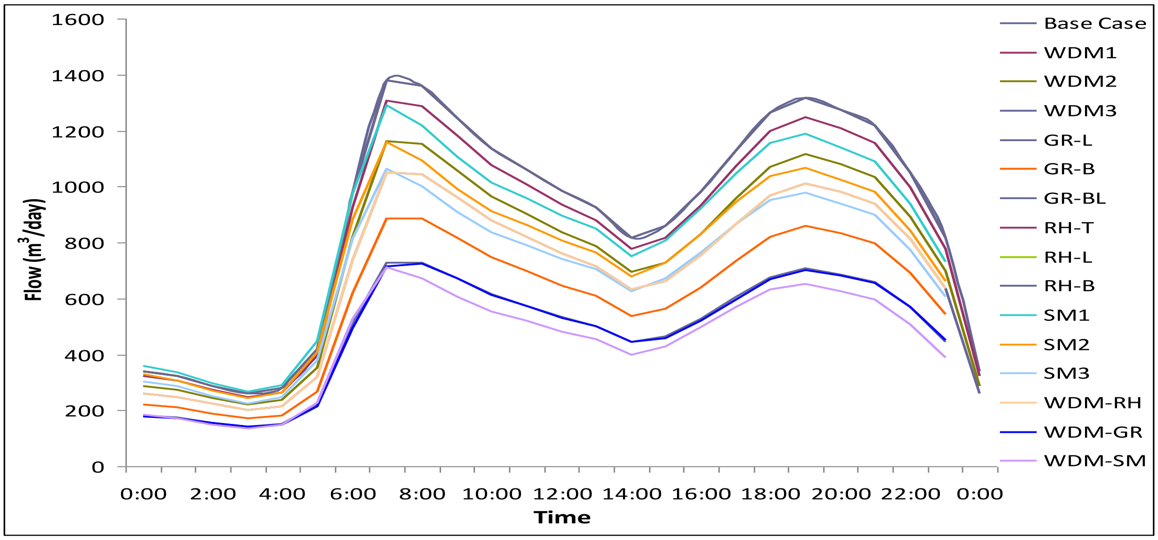


Figure 5.10. Diurnal Profile of Sewer Flow

Figure 5.11 clearly shows that the total sewer flow reduced due to *Water Demand Management*, *Greywater Recycling*, *Sewer Mining and Sustainable Practice*, notably combinations between the highest reduction in water demand and installation of *Alternative Water Sources*. The highest sewer flow reduction was contributed by *Sustainable Practice* (WDM-SM), followed by greywater scenarios (GR-BL). This is consistent with the fact that greywater contributed around 60% of the total wastewater volume. The use of recycled water from *Greywater Recycling* plants for toilet flushing and irrigation reduces wastewater by redirecting water from sewer discharge to irrigation use. Sewer flow in *Rainwater Harvesting* constitutes zero reduction, which means that sewer flow is similar to the *Base Case*. Introducing rainwater through *Rainwater Harvesting* as a substitute for piped potable water for indoor end-use did not affect sewer flow. This is because rainwater is an external water source which is not included in household water-wastewater balance. Therefore, potable water substitution with rainwater will not affect the sewer pipe but it will affect contaminant balance.

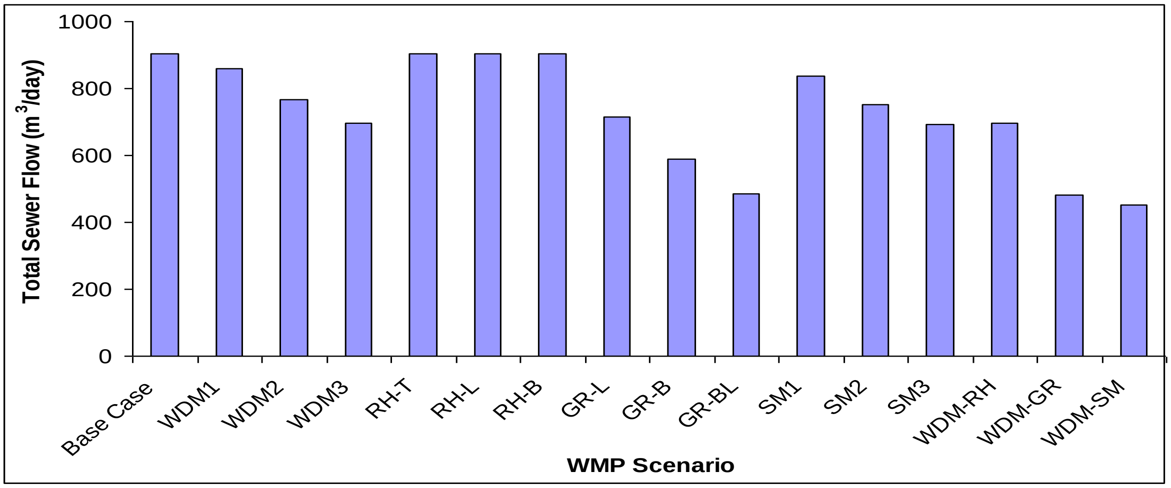
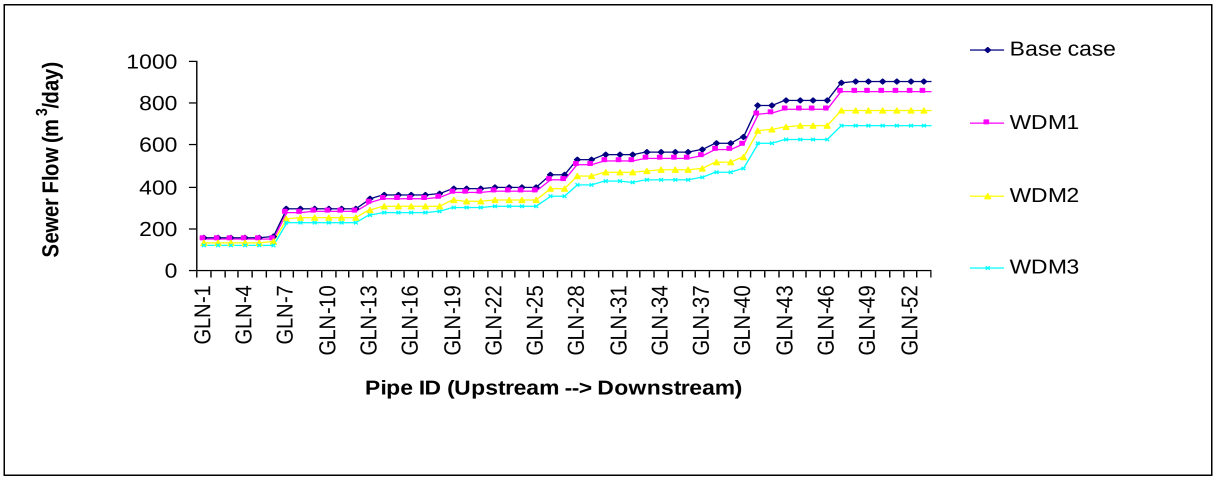
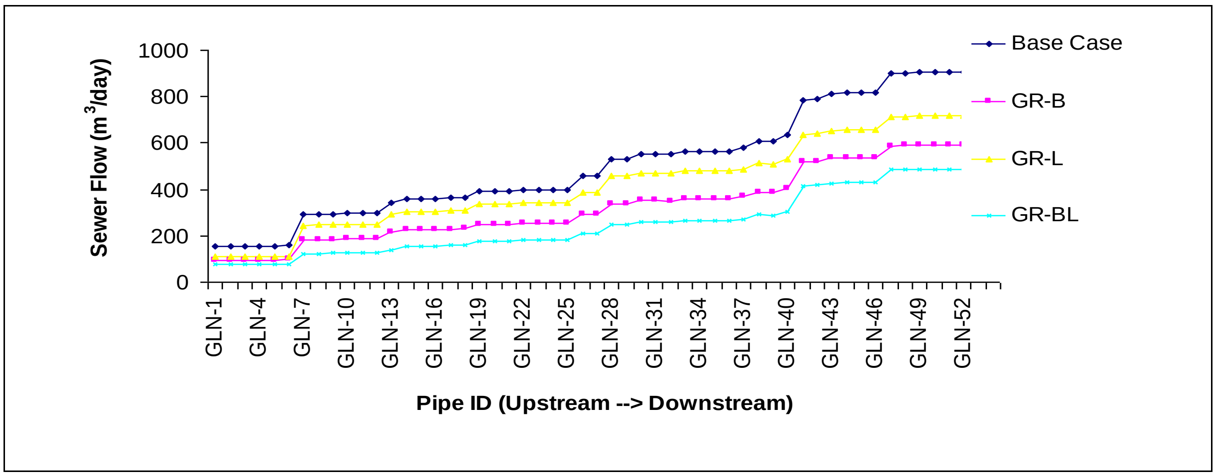


Figure 5.11. Total Sewer Flow for Every Scenario

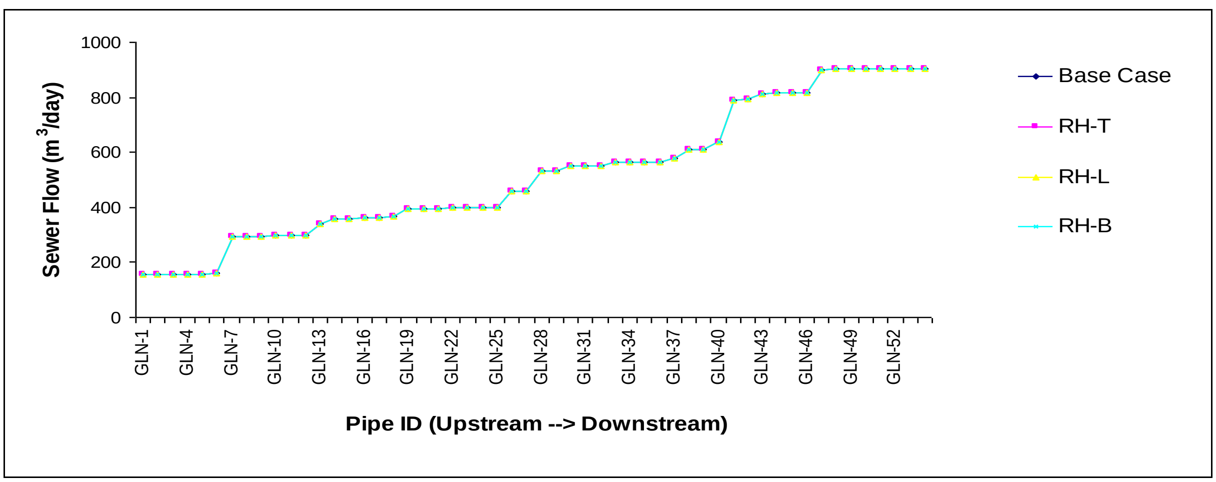
Figure 5.12 (a) to (e) shows the daily average sewer flow plot for every pipe in the sewerage network, hence we can see sewer flow changes due to additional flow from nodes as well as sewer flow reduction due to sewage extraction in the *Sewer Mining* scenario. The greatest reduction of sewer flow was caused by *Sustainable Practice*, particularly WDM-SM. Sewer flow was dropped after the extraction point, but at the end of the sewer pipe, the sewer flow of WDM-SM was similar to WDM-GR. *Greywater Recycling* was the second main scenario that can greatly reduce sewer flow. GR-BL reduces sewer flow followed by GR-B and GR-L scenarios. Sewer flow in *Sewer Mining* initially coincided with sewer flow in the *Base Case*, but after the sewage extraction point (*Sewer Mining* facility), the flow dropped significantly. For *Rainwater Harvesting*, the sewer flow does not change since there is no water demand reduction or wastewater reduction. *Rainwater Harvesting* collects rainwater for supplying indoor use and the rest of the rainwater is used for garden irrigation.


Sewer Flow (m^3/day)
1000
800
600
400
200
0
GLN-1
GLN-4
GLN-7
GLN-10
GLN-13
GLN-16
GLN-19
GLN-22
GLN-25
GLN-28
GLN-31
GLN-34
GLN-37
GLN-40
GLN-43
GLN-46
GLN-49
GLN-52
Pipe ID (Upstream --> Downstream)
Base case
WDM1
WDM2
WDM3

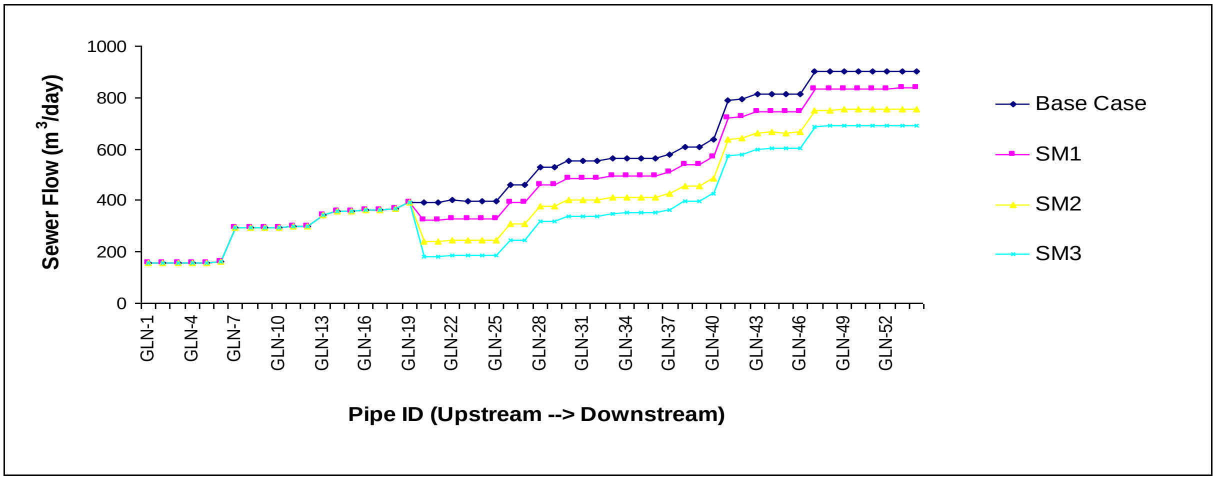
(a)


Sewer Flow (m^3/day)
1000
800
600
400
200
0
GLN-1
GLN-4
GLN-7
GLN-10
GLN-13
GLN-16
GLN-19
GLN-22
GLN-25
GLN-28
GLN-31
GLN-34
GLN-37
GLN-40
GLN-43
GLN-46
GLN-49
GLN-52
Pipe ID (Upstream --> Downstream)
Base Case
GR-B
GR-L
GR-BL

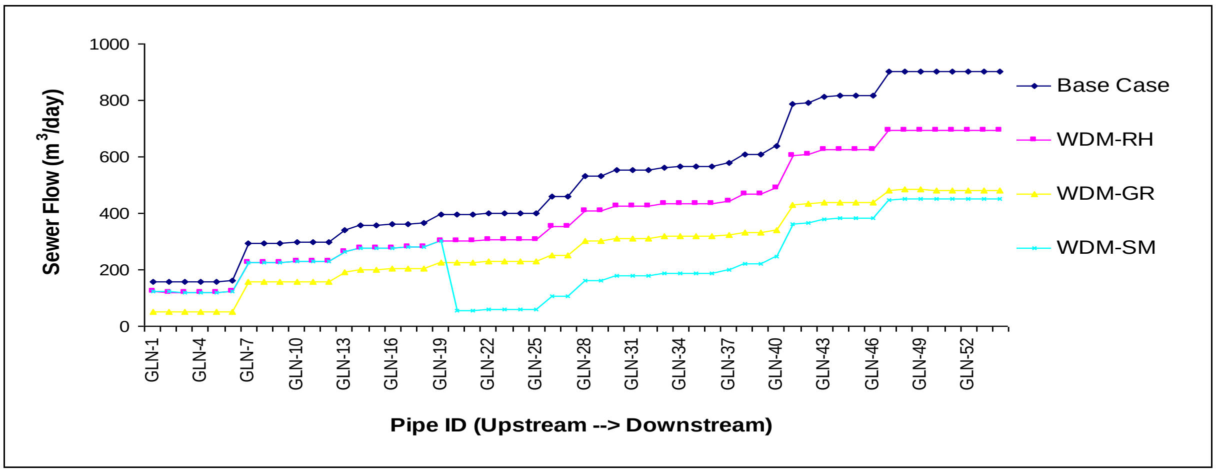
(b)


Sewer Flow (m^3/day)
1000
800
600
400
200
0
GLN-1
GLN-4
GLN-7
GLN-10
GLN-13
GLN-16
GLN-19
GLN-22
GLN-25
GLN-28
GLN-31
GLN-34
GLN-37
GLN-40
GLN-43
GLN-46
GLN-49
GLN-52
Pipe ID (Upstream --> Downstream)
Base Case
RH-T
RH-L
RH-B

(c)



(d)



(e)

Figure 5.12. Wastewater Plot per Pipe (a) *Water Demand Management*, (b) *Greywater Recycling*, (c) *Rainwater Harvesting*, (d) *Sewer Mining*, and (e) *Sustainable Practice* Scenarios

5.5 Dissolved Sulphide and Hydrogen Sulphide in Gas Phase

The formation of sulphide in the water phase is affected by many trigger factors such as wastewater characteristics, sewer pipe geometry and existing conditions of sediment and biofilms. The formation of hydrogen sulphide gas is mostly affected by wastewater characteristics (sewer flow, sulphide concentration, other contaminant concentration, such as iron), pipe geometry and pipe material (Nielsen et al. 2008a; Nielsen et al. 2008b).

Wastewater characteristics are represented by the wastewater volume and contaminant load, which have been discussed in section 5.3.

Sulphides in bulkwater and hydrogen sulphide gas are two main components from this study, which can determine the impact of WMP adoption on odour and corrosion. Therefore, this section provides three different graphs for a detailed investigation of dissolved sulphide and hydrogen sulphide gas. The first graph illustrates sulphide and hydrogen sulphide gas diurnal profiles. These profiles of dissolved sulphide and hydrogen sulphide gas use a daily average concentration, which is obtained by averaging each variable (sulphide and hydrogen sulphide) recorded in each pipe at each time step.

The second graph is a plot of sulphide and hydrogen sulphide per pipe from upstream to downstream pipes. By looking at these graphs, it is expected that we can determine the critical point where dissolved sulphide is formed, and where hydrogen sulphide will be released. The third graph presents classification of dissolved sulphide and hydrogen sulphide gas based on a threshold value determined by Hvitved-Jacobsen’s study (2002). The threshold value for dissolved sulphide illustrates pipe corrosion severity related to sulphide concentration found in wastewater, while the threshold value for hydrogen sulphide gas was classified based on its effect on human health. The classification of sulphide and hydrogen sulphide gas gives insight into how many pipes have changed their concentration due to WMP adoption. The fourth figure gives the location of pipes that have exceeded the critical threshold value for dissolved sulphide and hydrogen sulphide gas.

5.5.1 Diurnal Profile

Figure 5.13 depicts the diurnal profile of dissolved sulphide. As can be seen, the diurnal plot of sulphide corresponds to sewer flow. The sulphide concentration is high when the sewer flow is low. This profile occurs early in the morning (from 12:00 am to 4:00 am). The concentration of sulphide during the day is the reverse of sewer flow plot. The sulphide concentration of *Sustainable Practice* of WDM-SM, WDM-GR and *Greywater Recycling* of GR-BL show extremely high concentrations compared to other scenarios because less wastewater discharges to sewer network.. However, the concentration difference between WDM-SM and WDM-GR was quite obvious early morning, but then the concentration of sulphide later in the day was closer to WDM-GR and WDM-SM. The diurnal profile of hydrogen sulphide gas, as shown in Figure 5.14, presents a similar trend to dissolved sulphide; but in the hydrogen sulphide plot, the gap between peak concentration around 1 am and the concentration at other times is relatively small. The only obvious peak belongs to the *Sustainable Practice* scenario of WDM-SM. This scenario has a distinctively higher peak of dissolved sulphide and hydrogen sulphide gas compared to other WMP scenarios early morning, because low flow due to the application of high *Water Demand Management* worsens by sewage flow extraction at the *Sewer Mining* facility.

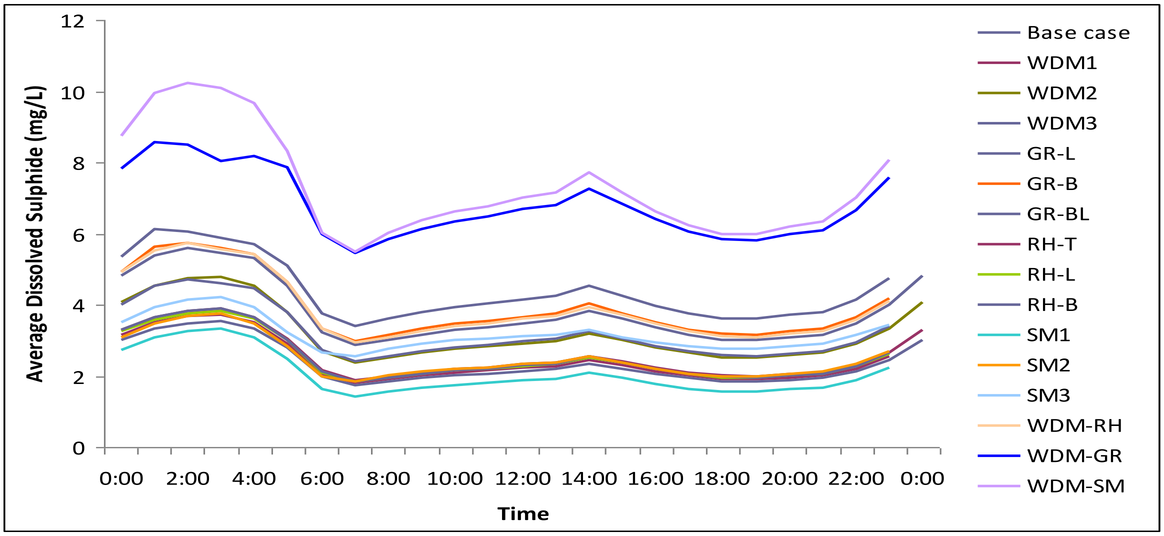


Figure 5.13. Diurnal Profile of Dissolved Sulphide

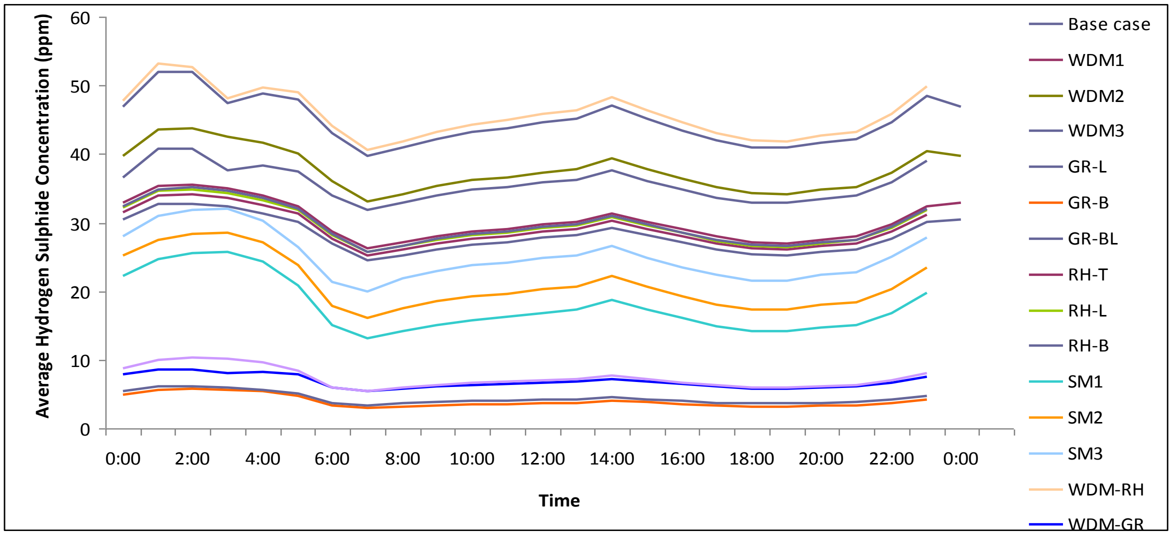


Figure 5.14. Diurnal Plot of Hydrogen Sulphide Gas

5.5.2 WMP Scenario Comparison

Figures 5.15 and 5.16 clearly show that *Sustainable Practice* which is a combined practice between water demand management and the usage of alternative sources (WDM-SM and WDM-GR) has the highest formation of dissolved sulphide and hydrogen sulphide gas in the sewer pipe. Only sustainable practice scenario of WDM-RH does not contribute much to the formation of dissolved sulphide and hydrogen sulphide. Lesser contribution of dissolved sulphide and hydrogen sulphide in WDM-SM due to *Rainwater Harvesting* does not reduce the sewer flow; hence the sewer flow reduction is solely obtained from WDM scenarios. For single practice scenario, the scenario of *Greywater Recycling* that reused greywater from the bathroom and laundry (GR-BL) has the highest concentration compared to other single practice scenarios. From these WMP comparisons, we can clearly see that *Sewer Mining* contributes best to lowest sulphide and hydrogen sulphide formation. However, this plot cannot exactly show the formation of sulphide and hydrogen sulphide due to *Sewer Mining* scenarios. *Sewer Mining* scenarios affect most downstream pipes after the node of *Sewer Mining* facility, while this plot gives the average value of sulphide and hydrogen sulphide from most upstream pipes to most downstream pipes. Moreover, after sewage extraction, sulphide and hydrogen sulphide gas drops to zero level, because they were released to the *Sewer Mining* facility. To recover the level of sulphide and hydrogen sulphide to the *Base Case* level, a certain pipe length is needed.

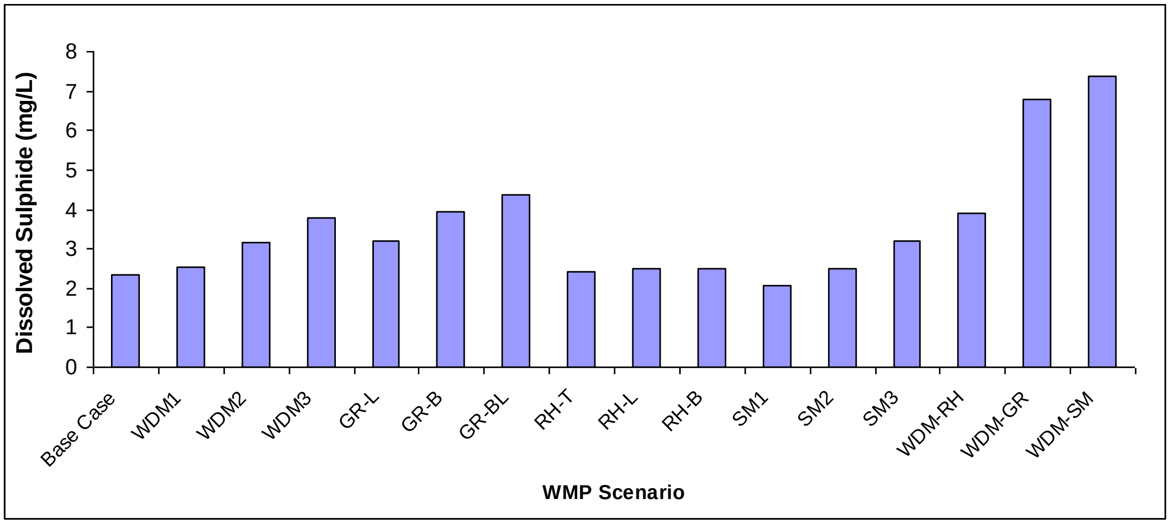


Figure 5.15. WMP Scenarios Comparison For Dissolved Sulphide

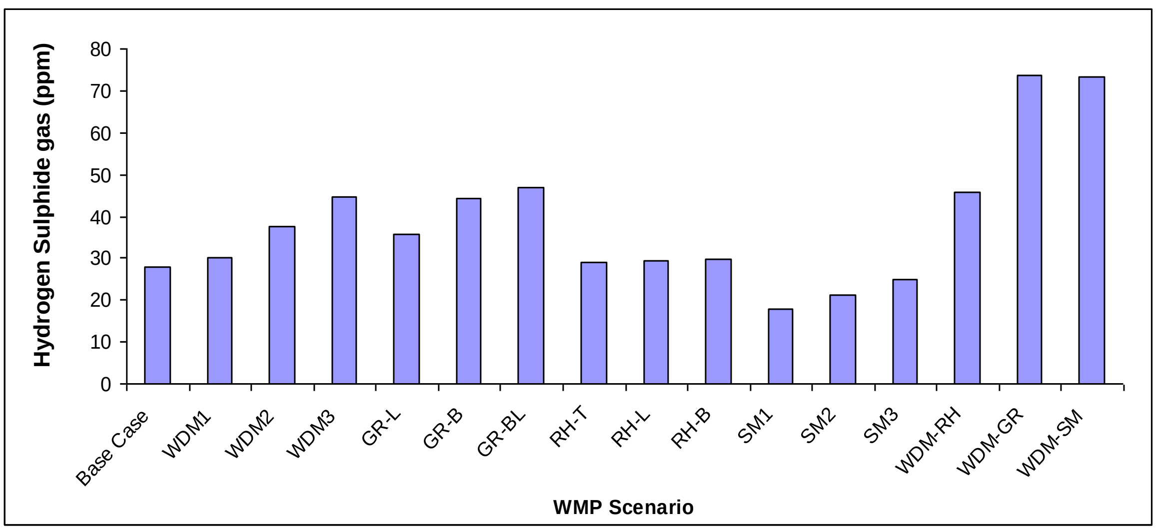
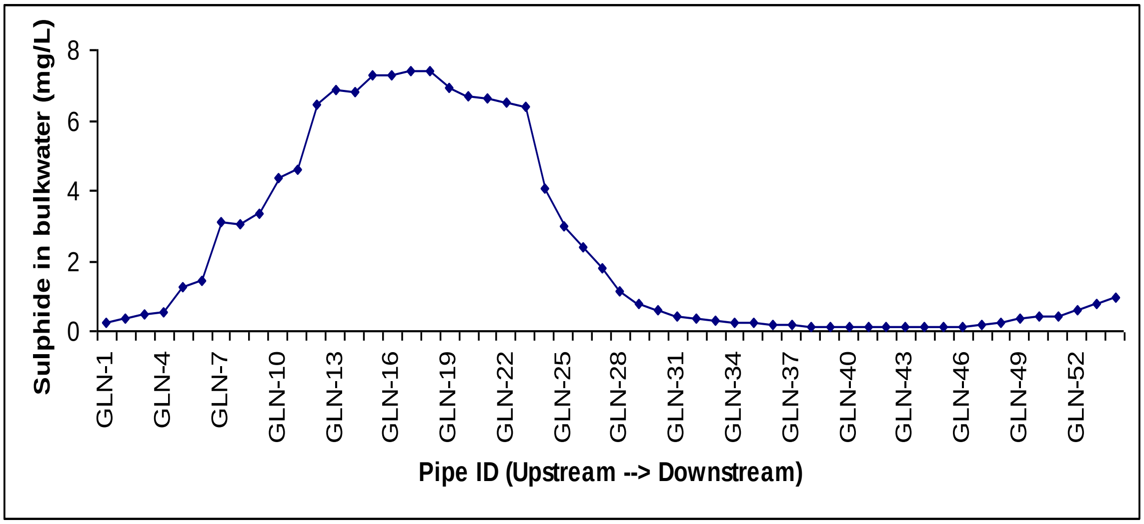


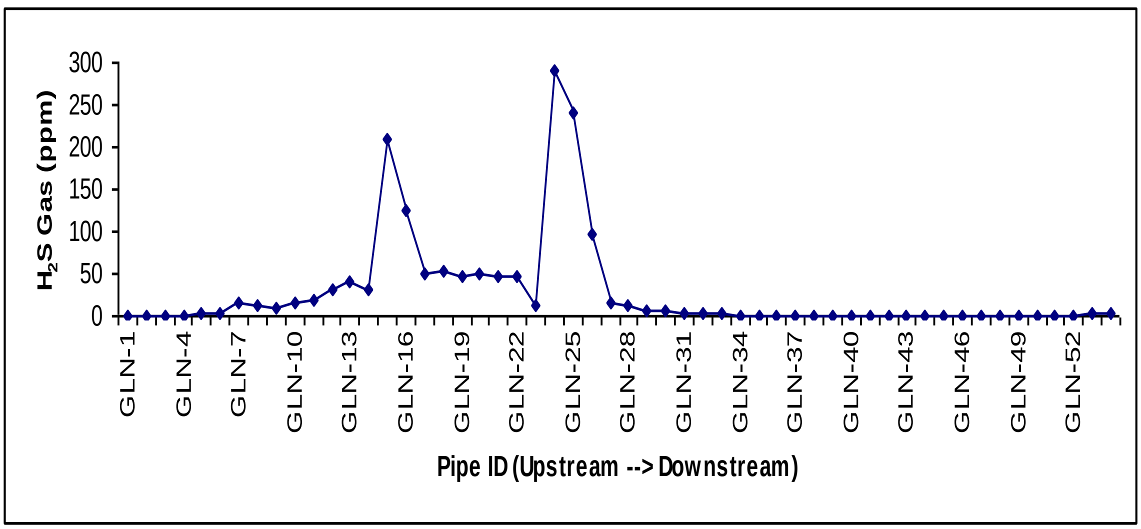
Figure 5.16. WMP Scenarios Comparison For Hydrogen Sulphide Gas

5.5.3 Plot of dissolved sulphide and hydrogen sulphide gas from upstream to downstream

In Glenroy sewer pipe, the formation of dissolved sulphide and release of hydrogen sulphide was very high. Dissolved sulphide began to form on low slope pipe stretches and hydrogen sulphide gas was highly released in high slope stretches. As can be seen in Figure 5.17 (a) and (b), sulphide concentration in bulkwater and hydrogen sulphide concentration vary from low concentration (< 0.5 ppm up to extremely high concentration (> 100 ppm). *A Base Case result presented below is* a result of calibrated model that explained in Chapter 3. Unfortunately, from 54 pipe stretches in Glenroy sewer sub-catchment, only one pipe stretch (at node GLN2 which belong to pipe stretch GLN54) that has its hydrogen sulphide confirmed through model calibration and validation.



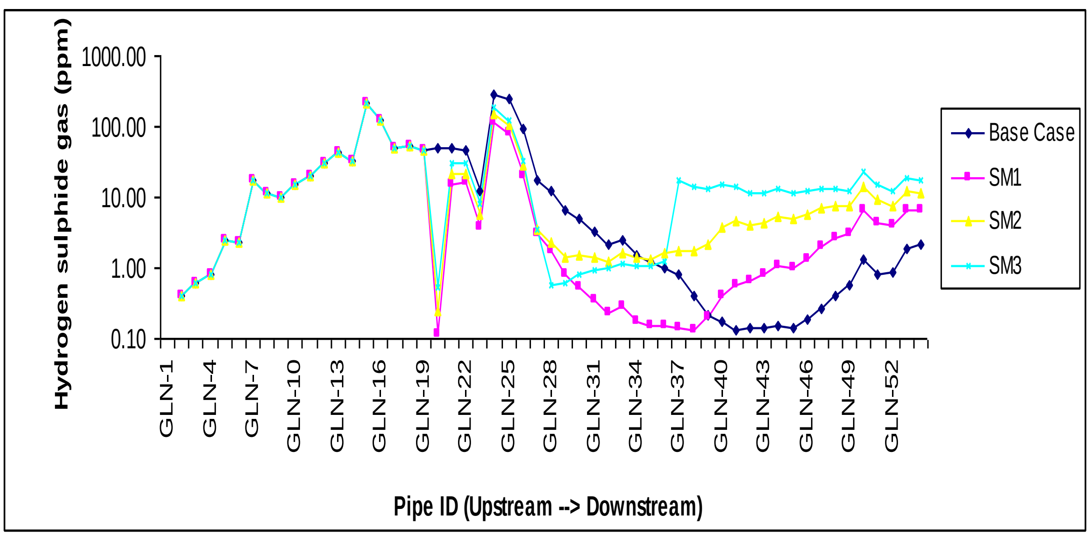
(a)



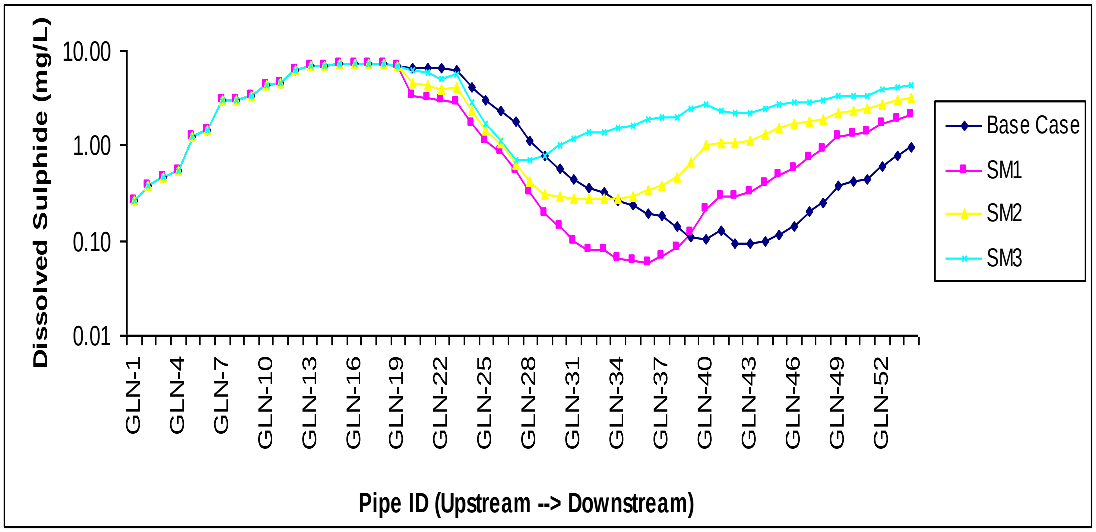
(b)

Figure 5.17. ***Base Case*** **Concentration of (a) Dissolved sulphide, and (b) Hydrogen Sulphide Gas in *Base Case***

The adoption of WMP does not change the location of lowest and highest concentrations of dissolved sulphide and hydrogen sulphide gas. The formation of dissolved sulphide is initiated at the beginning of the pipe network and increases up to the middle of upper pipes. Sulphide decreases up to the middle of downstream pipes and again increases up to the outlet of the Glenroy sewer pipe. The same pattern also shows for hydrogen sulphide gas concentration, where the highest concentration was found in the middle of upper pipes. However, *Sewer Mining* scenarios are the only exception for this pattern, since they extract sewage in the middle of the pipe networks, hence the sulphide and hydrogen sulphide pipe stretch pattern plot is different after the point of extraction compared to the *Base Case*. A drop in sulphide and hydrogen sulphide gas concentration occurs due to the model assuming that sulphide and hydrogen sulphide was released when wastewater was extracted. However, after the point of extraction, the hydrogen sulphide from *Sewer Mining* scenarios was predicted to quickly reform and after a certain pipe length, will exceed *Base Case* hydrogen sulphide concentrations. Figure 5.18 illustrates the pipe stretch plot from *Sewer Mining*. The pipe stretch plot for other WMP scenarios can be found in Appendix 8, Figure A.19a to A.19d (dissolved sulphide) and Figure A.20a to A.20d (hydrogen sulphide gas). These pipe stretch graphs are plotted in logarithmic scale, so they show the concentration variation.



(a)



(b) Hydrogen sulphide gas

Figure 5.18. Concentration of (a) Sulphide in Water Phase, and (b) Hydrogen Sulphide Gas in *Sewer Mining* Scenario

Concentration variation from highest to lowest concentration of the *Base Case* is very high. The lowest concentration of dissolved sulphide is located at the most upper pipe stretch and several pipe stretches in the middle of the downstream pipe with a sulphide concentration of 0.26 mg/L. The highest sulphide concentration of 9.2 mg/L is located in the middle of the upper pipe. The lowest concentration of hydrogen sulphide gas is found at two pipe stretches in the most upper pipe and in the middle of downstream pipes (< 2 ppm). The highest hydrogen sulphide concentration is found in the middle of the upper pipe (pipe stretch GLN-24) with a concentration of 224 ppm. Table 5.6 presents the lowest and highest concentrations of WMP scenarios of dissolved sulphide and hydrogen sulphide gas.

Table 5.6. Concentration Range of Dissolved Sulphide and Hydrogen Sulphide Gas

WMP Scenario	Dissolved Sulphide (mg/L)		Hydrogen sulphide gas (ppm)	
	Min.	Max.	Min.	Max.
Base Case	0.1	7.4	0.1	290
WDM1	0.1	8.1	0.2	301
WDM2	0.1	10.0	0.3	353
WDM3	0.2	12.0	0.4	401
GR-L	0.1	9.5	0.2	323
GR-B	0.2	11.2	0.4	373
GR-BL	0.2	11.9	0.4	377
RH-T	0.1	7.6	0.1	296
RH-L	0.1	7.7	0.1	299
RH-B	0.1	7.7	0.1	300
SM1	0.1	7.4	0.0	209
SM2	0.3	7.4	0.0	209
SM3	0.4	7.4	0.2	209
WDM-RH	0.2	12.2	0.4	406
WDM-GR	0.3	19.1	0.9	547
WDM-SM	0.6	26.4	0.1	638

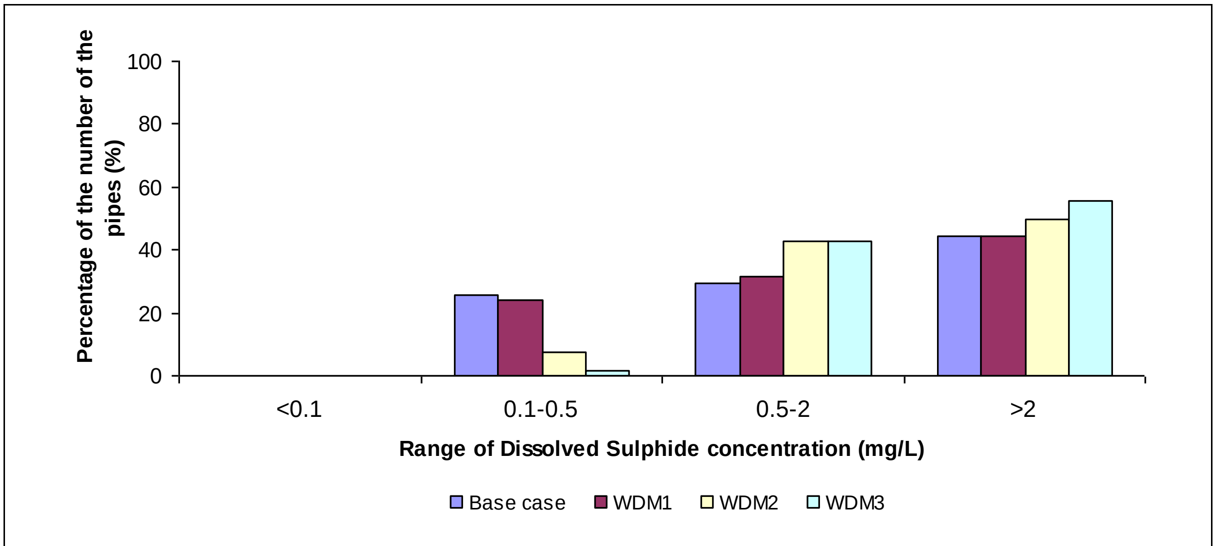
5.5.4 Classification of Dissolved Sulphide and Hydrogen Sulphide Gas Concentration

Hvitved-Jacobsen (2002) observed that pipes will experience severe corrosion when the concentration of sulphide in wastewater exceeds 2 mg/L, major corrosion will occur when the dissolved sulphide concentration ranges between 0.5 mg/L to 2 mg/L, and minor corrosion can be identified when the dissolved sulphide concentration in the wastewater at around 0.1-0.5 mg/L. The corrosion is not detected when the concentration of dissolved sulphide is less than 0.1 mg/L. The finding of Hvitved-Jacobsen (2002) was later used for classifying maximum sulphide concentration that could cause severe pipe corrosion in this study.

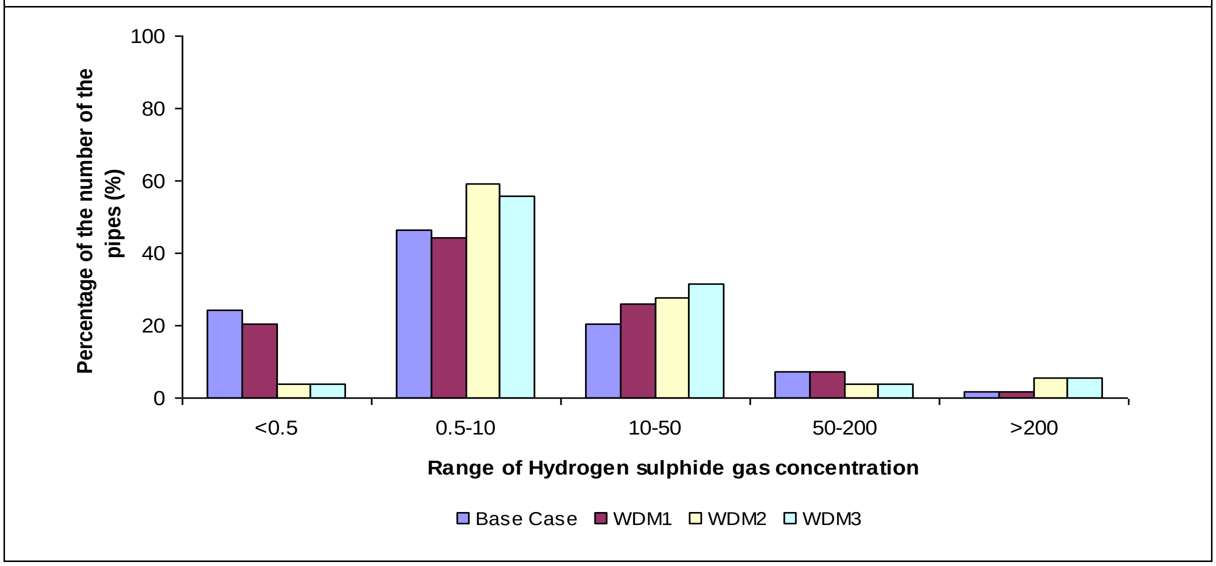
In order to predict the impact of WMP on odour formation due to hydrogen sulphide gas, a threshold value has been set based on values from Hvitved-Jacobsen (2002) that classified the concentration of hydrogen sulphide based on human health effects. Hydrogen sulphide gas will be a nuisance at concentrations above 0.5 ppm; above 10 ppm it will cause irritation and nausea, above 50 ppm respiratory and eye injuries will occur, and above 200 ppm hydrogen sulphide will have lethal effects. Figures 5.19 to 5.23 depict concentration distribution in the sewer network. The distribution looked at the number of pipes as a percentage in the study area. The figure classifies the number of pipes based on concentrations of dissolved sulphide and hydrogen sulphide gas that have been mentioned above. By looking at the figures, we could determine the concentration that dominates the sewer network for every scenario and determine how many pipes are classified as "at risk" following the implementation of WMP.

Figure 5.19 shows the *Base Case* scenario has many pipes (44%) that have sulphide concentration above 2 mg/L. It indicates that those pipes might have severe corrosion. *Water Demand Management* scenarios do not seem to change this proportion much. After the implementation of WDM1, the number of pipes which have concentrations higher than 2 mg/L do not change; however after the implementation of WDM2 and WDM3, these pipes with concentrations of higher than 2 mg/L have increased to 50% and 56% respectively. This means there were increasing risks of severe corrosion in some pipes if the water demand reduction is higher than 15 L/cap/day.

For hydrogen sulphide gas concentration, many pipes (46%) in the *Base Case* scenario have a concentration of 0.5-10 ppm. In this concentration range, nausea, eye and throat irritation can occur. After the adoption of WDM1, there was a reduction in pipe numbers that had a concentration of 0.5-10 ppm because some pipes increased their concentration to above 10 ppm. For WDM2, some pipes that previously had a concentration of <0.5 ppm, after adoption of WDM2 those pipes have increased to 0.5-10 ppm (59%); and further the concentration of 10-50 ppm also increased (28%). Similarly to WDM3 the concentration of 0.5-10 ppm and 10-50 ppm increased. For a concentration of 50-200 ppm, WDM1 had a similar pipe number as the *Base Case*, while WDM2 and WDM3 had lesser pipes for a concentration of 50-200 ppm. However, Base Case and WDM1 do not have pipes that had concentration higher than 200 ppm, while WDM2 and WDM3 had.



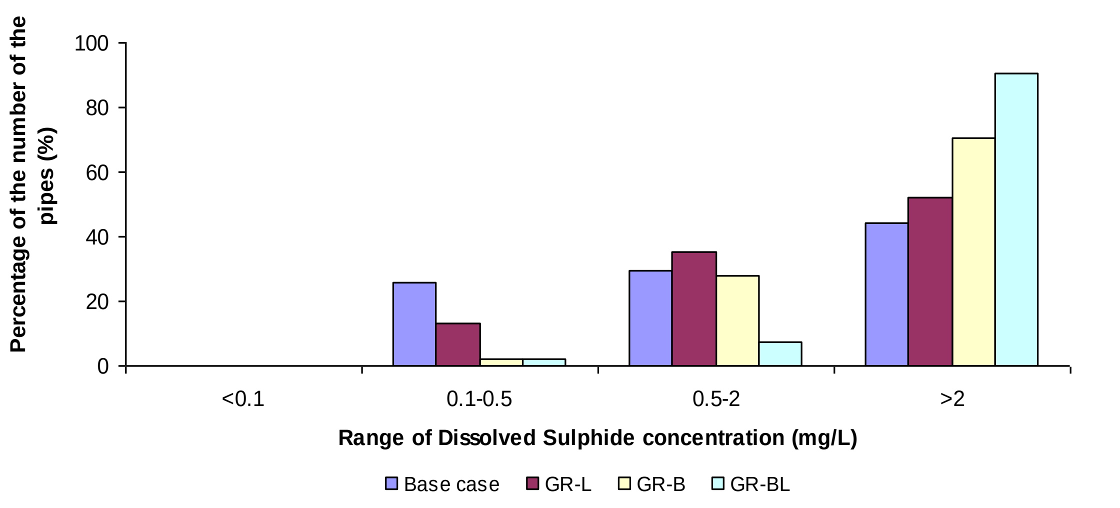
(a) Dissolved Sulphide



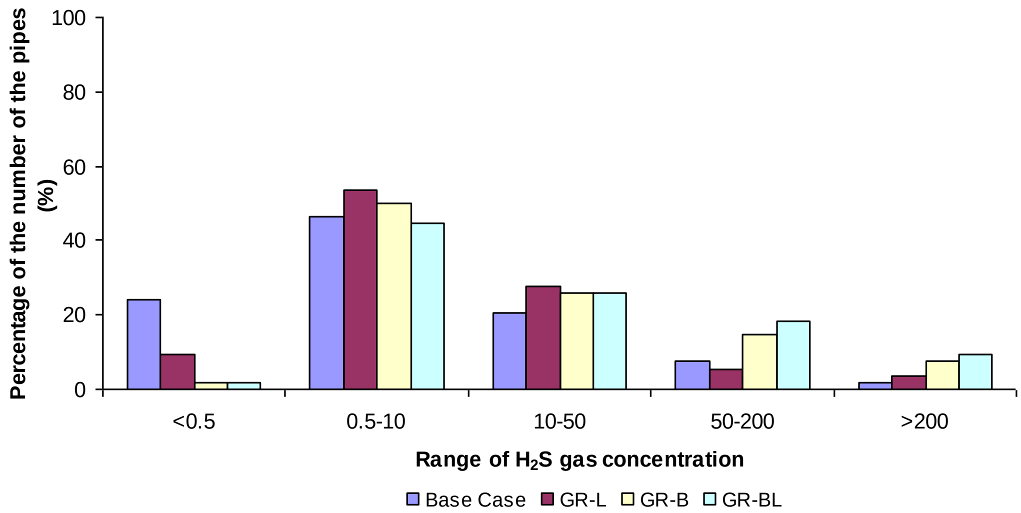
(b) Hydrogen sulphide gas

Figure 5.19. Percentage of Pipes number Based on Classification of Dissolved Sulphide and Hydrogen Sulphide Concentration for scenario of *Water Demand Management*

Based on Figure 5.20, many pipes in the *Base Case* and scenarios of *Greywater Recycling* had concentrations higher than 2 mg/l sulphide. The proportion of pipes that had a concentration of more than 2 mg/L in GR-L, GR-B and GR-BL was 52%, 72% and 91% respectively. Nevertheless, the proportion of pipes in GR-L is distributed to all sulphide concentrations, compared to the other two scenarios, which are likely to be almost all pipes with a concentration higher than 2 mg/L. This indicates that the adoption of *Greywater Recycling* scenarios, particularly scenarios that recycled greywater more than 96 L/HH/day, can potentially cause severe corrosion in most pipes in the study area. For hydrogen sulphide gas concentration in study area, many pipes had concentration of 0.5-10 ppm. For *Greywater Recycling* scenarios, the proportion as follows, GR-L, GR-B and GR-BL have 54%, 50% and 44% respectively. GR-B and GR-BL had a smaller concentration of 0.5-10 ppm compared to GR-L, but both scenarios have a large number of pipes at concentrations greater than 10 ppm.



(a) Dissolved Sulphide

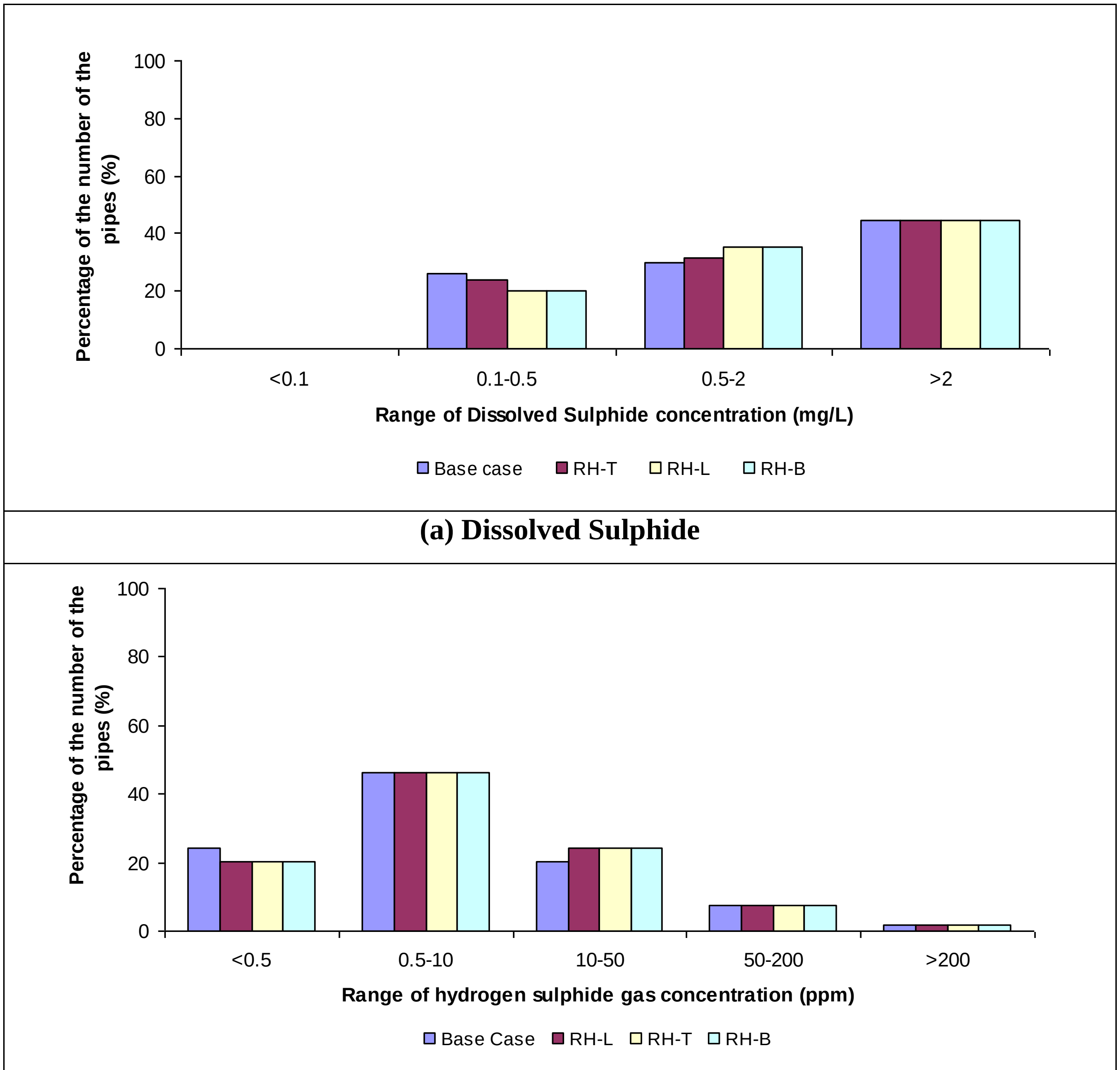


(b) Hydrogen sulphide gas

Figure 5.20. Percentage of Pipes number Based on Classification of Dissolved Sulphide and Hydrogen Sulphide Concentration for scenario of *Greywater Recycling*

Figure 5.21a quite clearly shows that after the adoption of *Rainwater Harvesting* scenarios, many pipes still had the same concentration as the *Base Case*. Few pipes have changed their concentration, but if so, it was minor. The *Rainwater Harvesting* scenario RH-T shows 24% of pipes have a concentration of 0.1 – 0.5 mg/L sulphide, which had decreased compared to the *Base Case*, and 31% of pipes have concentration of 0.5-2 mg/L which had increased compared to the *Base Case*. The rest of the pipes are distributed as the *Base Case* scenario. Similarly, as for the *Rainwater Harvesting* scenario RH-T, RH-B and RH-L the concentration of 0.1-0.5 mg/L applies to 20% of pipes, which have decreased by 6% compared to the *Base Case*, while the concentration of 0.5-2 mg/L have increased by 5% compared to the *Base Case*. Thus 35% of pipes in the study area have 0.5-2 mg/L sulphide. The pipes that have a sulphide increase are relatively small in number. And further, no pipe had increased its concentration to higher than 2 mg/L after the adoption of the *Rainwater Harvesting* scenario. Therefore, this scenario is predicted not to have a significant change in terms of corrosion levels in sewer pipes in the study area. A similar trend occurred for hydrogen sulphide gas concentration. Figure 5.21b shows that most pipes in *Rainwater Harvesting* scenarios have similar concentrations as per the *Base Case*. Therefore, by looking at these figures, we can understand that the implementation of *Rainwater*

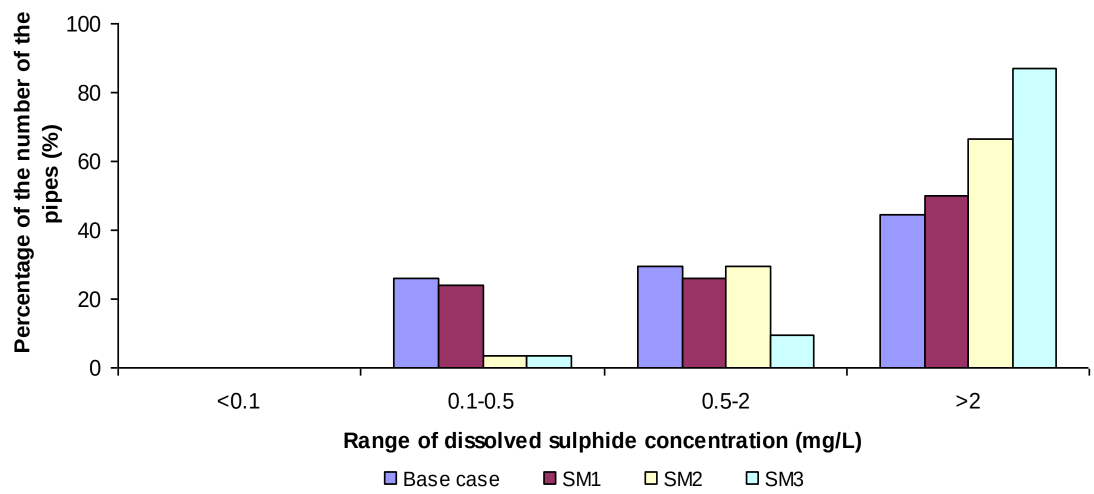
Harvesting will not greatly influence the current corrosion and odour level in the study area.



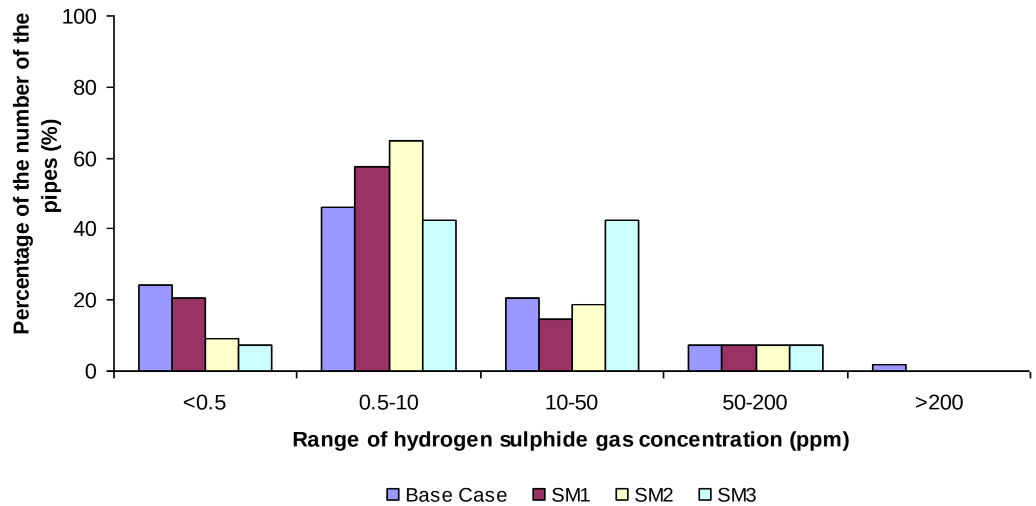
(b) Hydrogen sulphide gas

Figure 5.21. Percentage of Pipes number Based on Classification of Dissolved Sulphide and Hydrogen Sulphide Concentration for scenario of *Rainwater Harvesting*

Sewer Mining scenarios implement clustered treatment which discharges treatment residual, such as sludge, back to the sewer network. However, the average overall result from *Sewer Mining* presented in Figures 5.15 and 5.16 could not capture the increasing potential risk by implementing these scenarios, since the average value of hydrogen sulphide gave a lower concentration of sulphide and hydrogen sulphide gas compared to the *Base Case*. Only Figure 5.18 captures how many downstream pipes will be at risk when *Sewer Mining* is implemented. This section also cannot thoroughly capture the complete figure of sulphide and hydrogen sulphide gas concentrations due to *Sewer Mining*, but Figures 5.22 contributes to the information about the overall number of pipes that have certain concentrations. According to Figure 5.22, many pipes in *Base Case* have a sulphide concentration higher than 2 mg/L; however implementing *Sewer Mining* has increased the risk of more pipes having a concentration higher than 2 mg/L. In the *Sewer Mining* scenario SM1, the proportion of pipes which have concentrations higher than 2 mg/L is 50%. This percentage has increased by 6% from the *Base Case*. In *Sewer Mining* scenarios SM2 and SM3, the proportion is 67% and 87% of pipes with sulphide concentrations higher than 2 mg/L, which means these pipes have increased corrosion risk due to *Sewer Mining* scenarios. For hydrogen sulphide gas, many pipes have hydrogen sulphate gas concentrations of 0.5-10 ppm. The exception is SM3 which has a distributed proportion of pipes between concentrations of 0.5-10 ppm and 10-50 ppm.



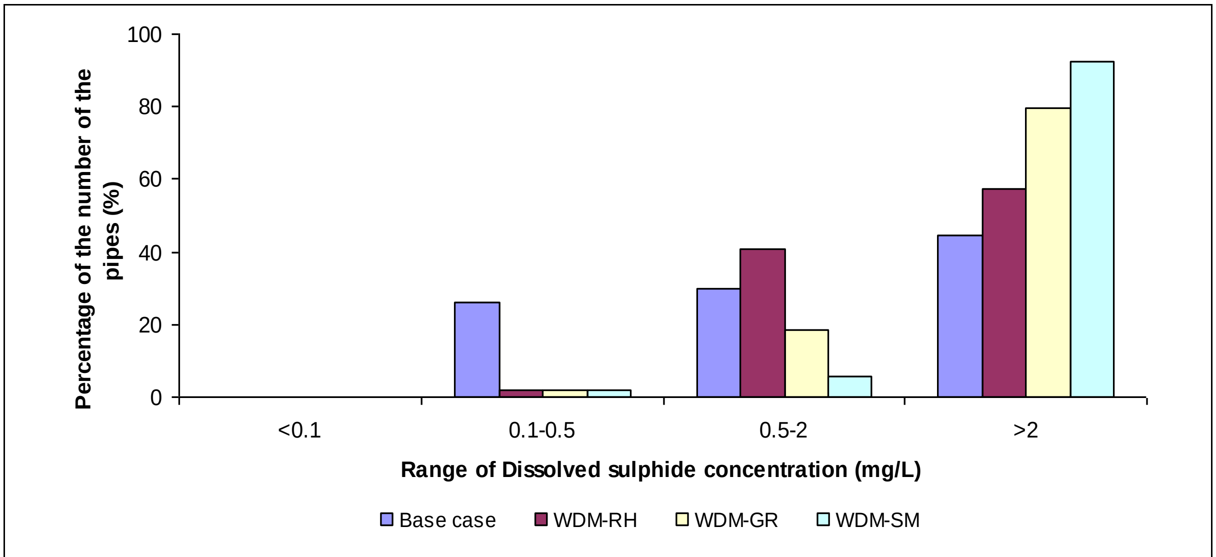
(a) Dissolved Sulphide



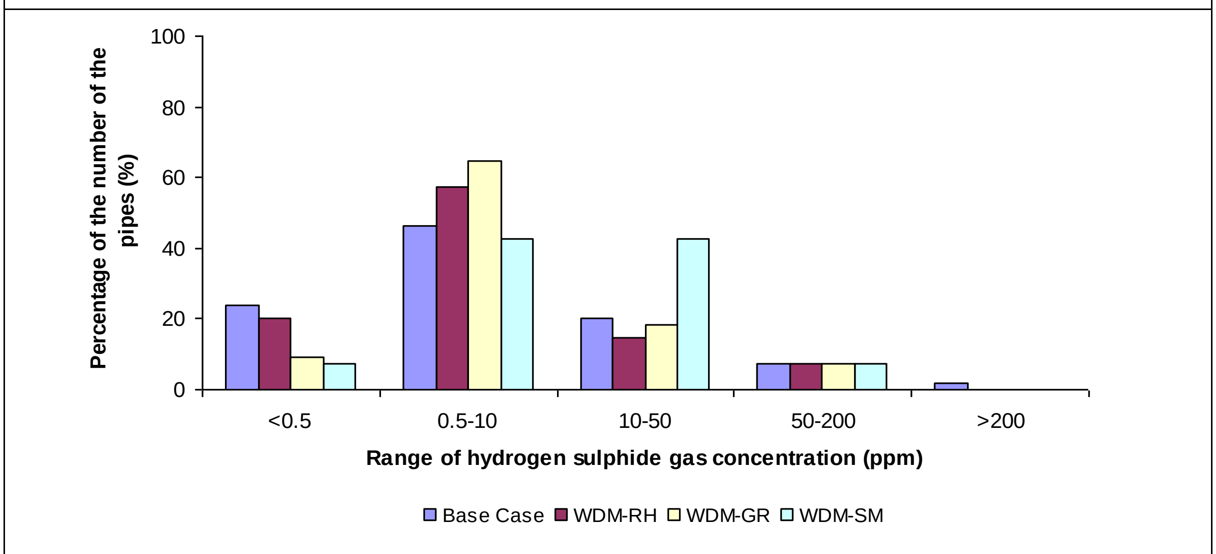
(b) Hydrogen sulphide gas

Figure 5.22. Percentage of Pipes number Based on Classification of Dissolved Sulphide and Hydrogen Sulphide Concentration for scenario of *Sewer Mining*

For *Sustainable Practice* scenarios, Figure 5.23a depicts many pipes that have sulphide concentrations higher than 2 mg/L, especially WDM-SM with a concentration higher than 2 mg/L in 95% of pipes. For hydrogen sulphide gas in Figure 5.23b, many pipes have concentrations of 0.5-10 ppm, except for WDM-SM that has the same proportion (39%) of pipes with concentrations of 0.5-10 ppm and 10-50 ppm. By looking at these figures, it can be concluded that every *Sustainable Practice* scenario could potentially affect corrosion and odour levels in sewer pipes, but among these three scenarios, WDM-SM is predicted to have the worst effect on sewer corrosion and odour.



(a) Dissolved Sulphide



(b) Hydrogen sulphide gas

Figure 5.23. Percentage of Pipes number Based on Classification of Dissolved Sulphide and Hydrogen Sulphide Concentration for scenario of *Sustainable Practice*

5.5.5 Location of Sulphide bulkwater and Hydrogen Sulphide Gas Exceed Threshold Value

This section discusses the location of pipes identified at high risk after the implementation of WMP scenarios. High risk was assessed when concentrations of sulphide were predicted to be higher than 2 mg/L and H_2S greater than 10 ppm. Most WMP result in an increase in pipes at risk, except for *Rainwater Harvesting* scenarios, where all sulphide concentration was below 2 mg/L and few pipe stretches increased their hydrogen sulphide to more than 10 ppm. However, sulphide concentration increases to 2 mg/l and hydrogen sulphide gas concentrations to 10 ppm do not directly relate to each other because increases in hydrogen sulphide concentration to 10 ppm can be caused by an increase in sulphide concentration of less than 2 mg/L, depending on the initial hydrogen sulphide concentration.

Figure 5.24a and Figure 5.24b depict dissolved sulphide and hydrogen sulphide gas that exceeded 2 mg/L and 10 ppm in the *Base Case*. The figure of dissolved sulphide and hydrogen sulphide gas location for other WMP scenarios was not included in this chapter, but they are attached in Appendix 9, Figure A.21 to Figure A.30. However, discussion about the location of pipe stretches that exceed predetermined concentration (2 mg/L for dissolved sulphide and 10 ppm for hydrogen sulphide) is still presented here. As can be seen in Figures 5.26a and 5.26b, pipe stretches in the study area will be divided into four main stretches: upstream stretch ***(1)***, middle upstream stretch ***(2)***, middle downstream stretch ***(3)***, and downstream stretch ***(4)*** (see Figure 5.24 for number's explanation). As can be seen in Figure 5.24, the critical stretch for both sulphide and hydrogen sulphide gas in the *Base Case* are located at upstream to middle upstream segment. This stretch has a very high pipe slope. Adoption of WMP scenario will potentially add critical pipes in these stretches. The lowest concentration of dissolved sulphide and hydrogen sulphide was found in the middle downstream stretch. Therefore, an increase exceeding the predetermined concentration is not likely to occur unless the adopted scenario impacts the formation of dissolved sulphide and hydrogen sulphide gas in sewer pipes.

There was no change in pipes with a concentration of sulphide higher than 2 mg/L in the *Water Demand Management* scenario of WDM1; however for WDM2 and WDM3, there were some pipes that exceeded 2 mg/L. These concentrations were located in upstream segment and middle upstream stretch pipes. For hydrogen sulphide concentration in WDM1 scenario, few pipes in the upstream stretches exhibit an increase in hydrogen sulphide concentration to higher than 10 ppm. While for *Water Demand Management* scenarios of WDM2 and WDM3, the increase of hydrogen sulphide concentration to higher than 10 ppm occurs in some pipes located in the middle upstream stretch and upstream stretch.

For *Greywater Recycling*, the increase of sulphide was located in upstream stretch, middle upstream stretch and downstream pipe stretch. Even in GR-BL, increased concentrations of dissolved sulphide also occurred in a few pipes in the middle downstream stretch. For hydrogen sulphide gas, GR-L and GR-B have few pipes in the upstream and middle upstream stretch with concentrations higher than 10 ppm. For GR-BL, concentration exceeded 10 ppm, which occurred not only on those two stretches above it, but also in the downstream segment.

Due to adoption of *Rainwater Harvesting* scenarios, there were no pipes with changed sulphide concentration higher than 2 mg/L. However, for hydrogen sulphide concentration, two pipes in the upstream and middle upstream stretches had hydrogen sulphide concentrations higher than 10 ppm.

Sewer Mining scenarios decrease the dissolved sulphide concentration to lesser than 2 mg/L in some pipes which are located in the middle upstream segment. This is also the case for hydrogen sulphide concentration, where some pipes in the middle upstream segment have decreased their hydrogen sulphide concentration to lower than 10 ppm after adoption of *Sewer Mining* scenarios. However, Sewer Mining scenarios of SM1 and SM2 increased the sulphide concentration in the downstream segment. SM3 contributes to worse condition, because it increased the sulphide concentration to more than 2 mg/l in the middle downstream segment to downstream segment. The same case also occurs for hydrogen sulphide gas concentration, where the increase mostly occurred in the downstream segment, but SM3 has some additional pipes in the middle downstream segment that have increased concentration to more than 10 ppm.

An increase of sulphide concentration to more than 2 mg/L in *Sustainable Practice* scenarios of WDM-RH and WDM-GR occurred in the middle upstream and downstream stretches. For WDM-SM, the increase occurred in all pipes located in two stretches above the middle downstream segment. For hydrogen sulphide gas concentration in WDM-RH, the increase occurred in the upstream segment, for WDM-GR the increase occurred in upstream and middle upstream stretches, while for WDM-SM, the increase was in all pipes in all stretches.

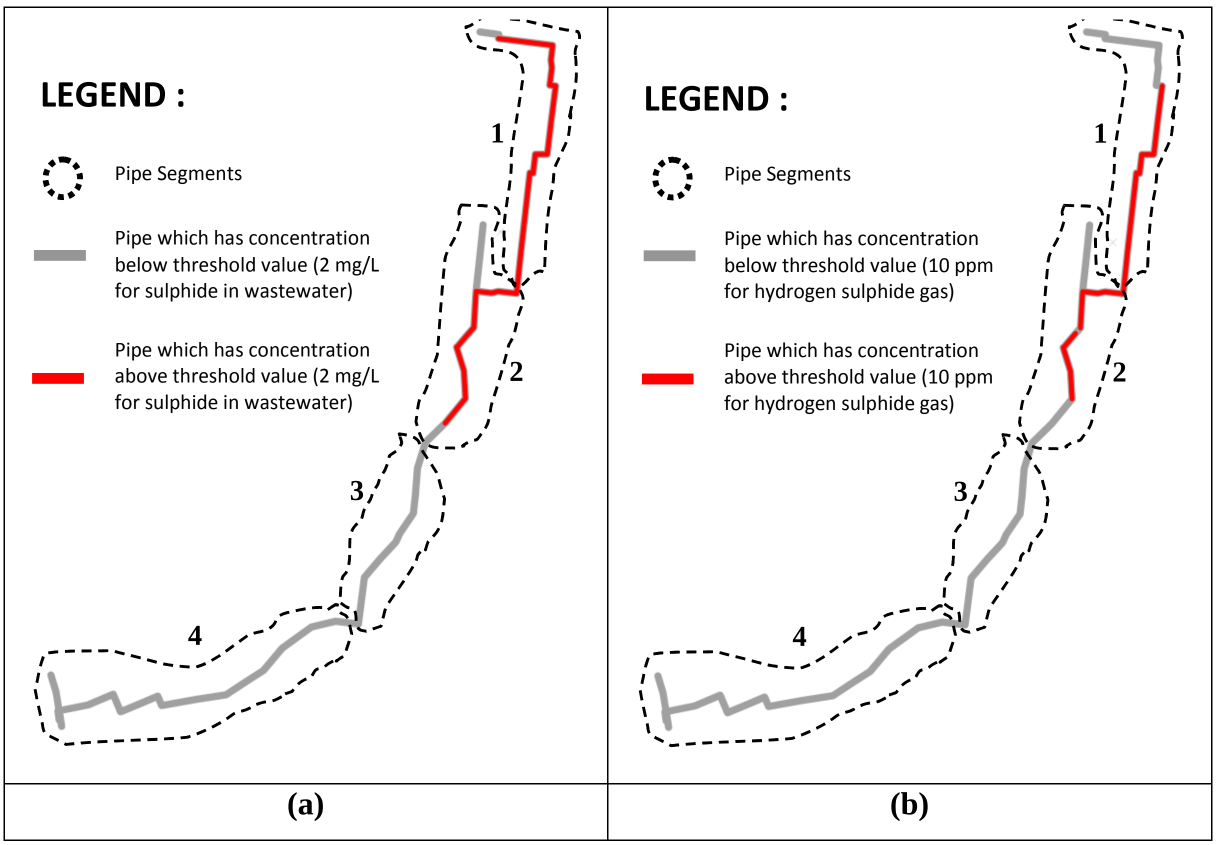


Figure 5.20. Location of pipes that have concentration of (a) ≥ 2 mg/L and (b) hydrogen sulphide gas ≥ 10 ppm in *Base Case*

5.6 Corrosion Rate

Sulphide and hydrogen sulphide formations in sewers affect pipes through corrosion. The WATS model has the capability to simulate individual pipe corrosion rates expressed as a unit of mm/year. Similar to dissolved sulphide and hydrogen sulphide gas, the corrosion rate was also produced by the model by following the diurnal pattern; however in this study, the diurnal corrosion rate was simplified to the average corrosion rate for each pipe. Further, the average corrosion rate from all pipes was averaged to get the daily average corrosion rate in the study area. Eventually, this corrosion rate will be used to calculate the lifespan of the pipe in the study area. Lifespan will be discussed in Chapter 6. The rate obtained in this study was considered to represent the approximate corrosion rate in the sewer pipes in the study area. However, it is important to note that the corrosion obtained here is only an average rate which can not represent the corrosion rate per pipe. The corrosion rate for each pipe would vary, depending on the dissolved sulphide and hydrogen sulphide release in that pipe.

From Figure 5.25, the highest corrosion rate was dominated by *Sustainable Practice* scenarios (WDM-RH, WDM-GR and WDM-SM). The corrosion rates are 1.6 mm/year, 2.1 mm/year, and 2.6 mm/year respectively. This means that in one year, there will be 1.6, 2.1 or 2.6 mms of pipe wall corroded, depending on the implemented scenario. Pipe lifespan depends on the thickness of the wall. If the pipe wall is quite thick, the lifespan might be longer compared to a thinner wall. *Greywater Recycling* scenarios, particularly GR-BL and GR-B, also have high corrosion rates around 1.6 mm/year and 1.5 mm/year respectively. WDM3 has a similar corrosion rate to GR-B, around 1.5 mm/year, while RH-T has little increase in the corrosion rate. It means that the effect on the *Sustainable Practice* scenario WDM-RH corrosion rate was mostly contributed by *Water Demand Management* scenarios rather than *Rainwater Harvesting* scenarios. *Sewer Mining* scenarios SM1 and SM2 contribute to lower corrosion rates compared to the *Base Case*, while SM3 contributes to a small increase compared to the *Base Case*. However, as this plotting shows, the average value cannot capture the increasing risk of corrosion rates due to *Sewer Mining* scenarios. Moreover, since these scenarios were installed in the middle of the sewer network, which had high sulphide and hydrogen sulphide concentration, nearly all the sulphide and hydrogen sulphide was released, which resulted in a significant decrease in sulphide, hydrogen sulphide and corrosion rates. Table 5.7 presents maximum and minimum corrosion rates from pipes in the Glenroy sewer subcatchment.

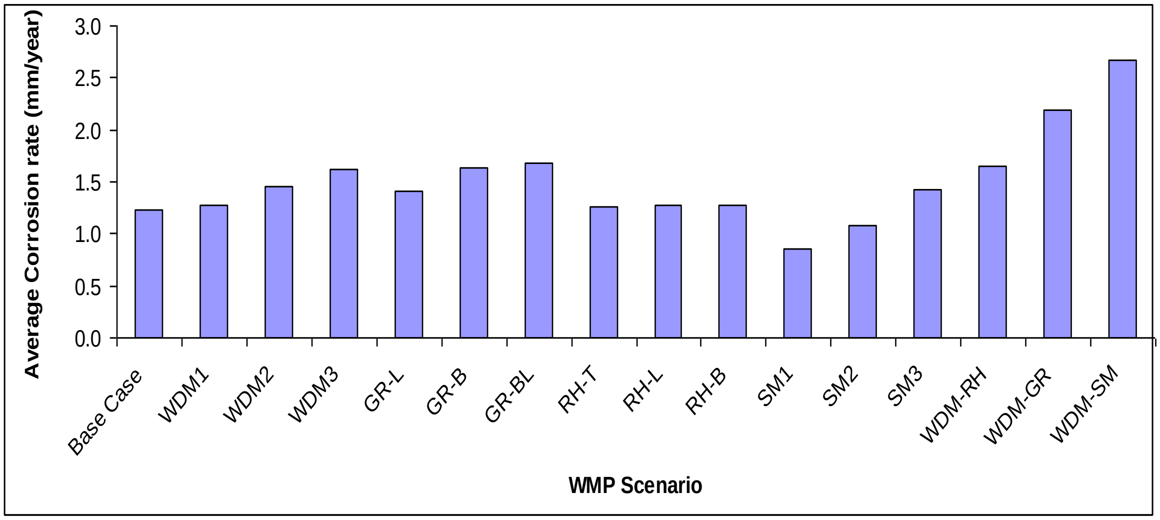


Figure 5.25. Average Corrosion Rate

Table 5.7. Range of Corrosion Rate

	Corrosion Rate (mm/year)	
	Max.	**Min.**
Base Case	0.08	14.21
WDM1	0.08	14.42
WDM2	0.09	15.73
WDM3	0.10	16.82
GR-L	0.09	14.88
GR-B	0.13	16.11
GR-BL	0.13	16.38
RH-T	0.08	14.39
RH-L	0.08	14.48
RH-B	0.08	14.51
SM1	0.04	7.43
SM2	0.07	8.63
SM3	0.08	9.43
WDM-RH	0.10	16.95
WDM-GR	0.22	18.69
WDM-SM	0.10	16.79

5.7 Regression Analysis

This study analysed several independent variables (multi variate analysis) for their effect on flow, sulphide concentrations in the in bulk water and hydrogen sulphide gas production. However, to make the presentation of the graph clear, these variable were presented individually. The linier regression model presented in this section determines a direct relationship between the main independent variables of WMP including water demand, greywater/rainwater uptake, sewage extraction, quantity and quality of sewer wastewater and hydrogen sulphide gas and dissolved sulphide. Regression analysis was used to understand which independent variables from different WMP scenarios related to the dependent variable of sewer flow, sulphide in water phase and hydrogen sulphide gas, as well as explore the forms of these relationships. Furthermore, the regression equation gives insight on how changes in the independent variables impact on resultant dependent variables. In this case, the impact due to changes in water reduction volume, uptake of greywater and rainwater volume, as well as sewage extraction volume on sewer odour and corrosion, can be predicted through dissolved sulphide concentration, hydrogen sulphide gas concentration and corrosion rates, which are eventually useful in planning and policy making. However, the changes of water reduction, greywater and rainwater uptake and sewage extraction volume cannot be concluded as the only trigger factors that change the concentration of dissolved sulphide and hydrogen sulphide gas.

In the case of sewer flows, changes may occur due to source flow changes, and pipe and joint defects that allow infiltration, inflow and exfiltration. Effects due to pipe and joint defects have been considered constant during the *Base Case* and WMP scenarios simulations. This has allowed the modeling to consider the impact of WMP adoption in isolation, and the influence of changes in inflow and infiltration has not been considered.

In the case of sulphide formation in bulk wastewater, the trigger factors of sulphide concentration changes are more complex compared to sewer flow. Many factors have been listed from various studies that can affect the level of sulphide in wastewater. Some of those factors are source flow, source contaminant load, which eventually forms contaminant concentration, pipe characteristics such as diameter, slope and length, as well as the existing condition of sewer pipes including the existence of sediment and biofilm. All of these factors have been considered in the WATS model and produced the results presented earlier in section 5.5. However, the WATS model is complex and does not directly link changes in WMP variables and sulphide formation. By using regression analysis, the direct relationship between independent and dependent variables can be determined.

The formation of hydrogen sulphide in the gas phase is triggered by a combination of factors including sewer flows and sulphide formation. Additionally, sewer material also determines hydrogen sulphide concentration in sewer networks. However, only independent variables associated with WMP adoption were considered.

Regression analysis conducted in this study presents the variable as a percentage of reductions or increases rather than plotting the absolute value. The percentage values represent the ratio of desired value to total value (how much water volume was reduced to total water demand, or how much greywater/rainwater volume was taken up to total greywater volume/total indoor use of rainwater or how much sewage volume was extracted to total sewage volume at the point of extraction). Regression analysis was conducted for single scenarios only, hence *Sustainable Practice* scenarios which are combinations of single scenarios between *Water Demand Management* and *Alternative Water Sources* (e.g. *Rainwater Harvesting*, *Greywater Recycling* and *Sewer Mining*) are not included in this analysis.

5.7.1 Water Demand Management

As can been seen in Figures 5.26, 5.27 and 5.28, regression analysis was used to relate reduced water demand with sewer flows, sulphide concentrations in water and hydrogen sulphide concentration in the gas phase. The changes in water demand show strong linear correlation with changes in sewer flow, sulphide concentrations in wastewater and hydrogen sulphide concentrations in the gas phase, with all correlation coefficients being higher than 0.99. The high coefficient of determination indicates that the linear regression model is quite reliable.

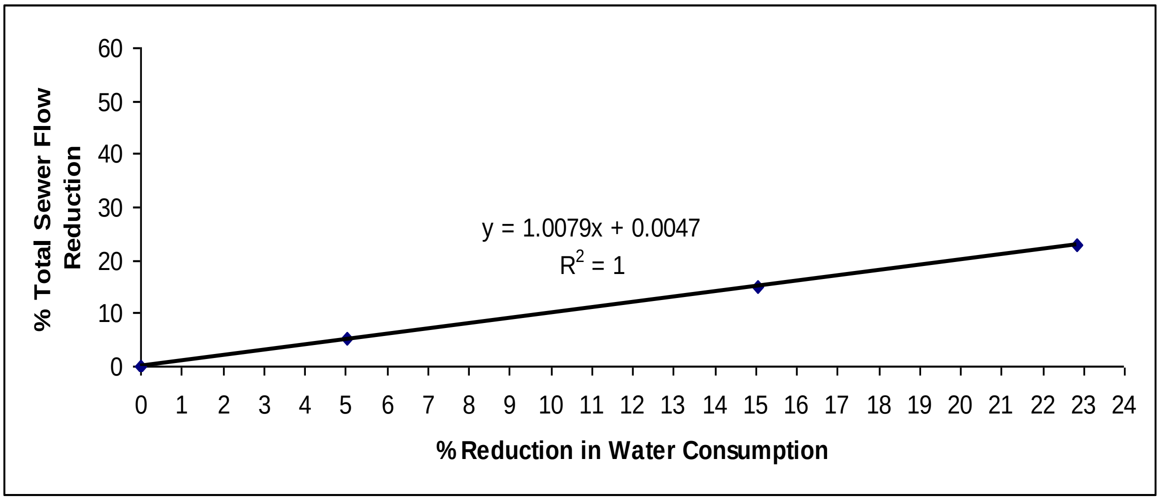


Figure 5.26. Regression Analysis for Sewer Flow vs Water Demand for *Water Demand Management* Scenarios

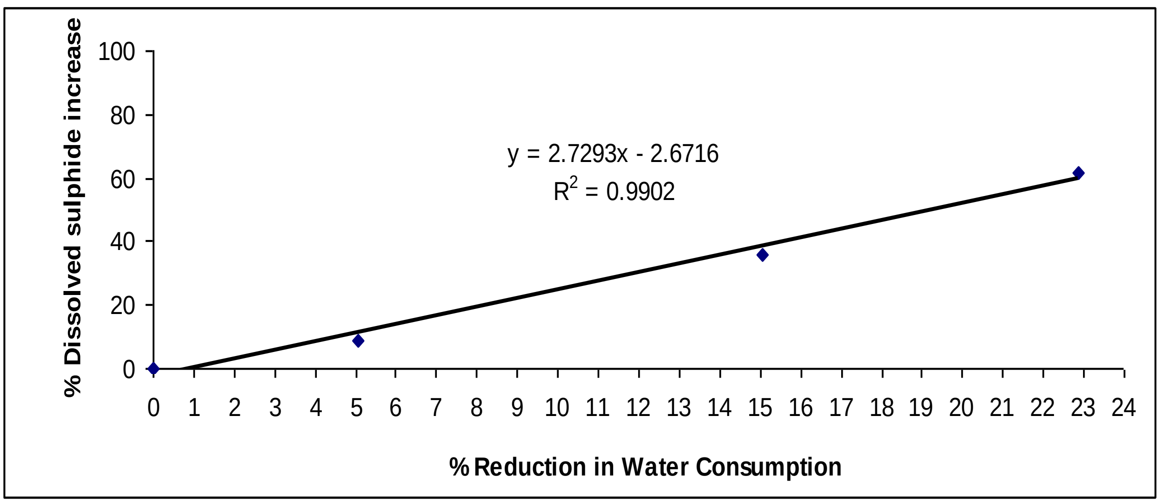


Figure 5.27. Regression Analysis for Dissolved Sulphide Concentrations for *Water Demand Management* Scenarios

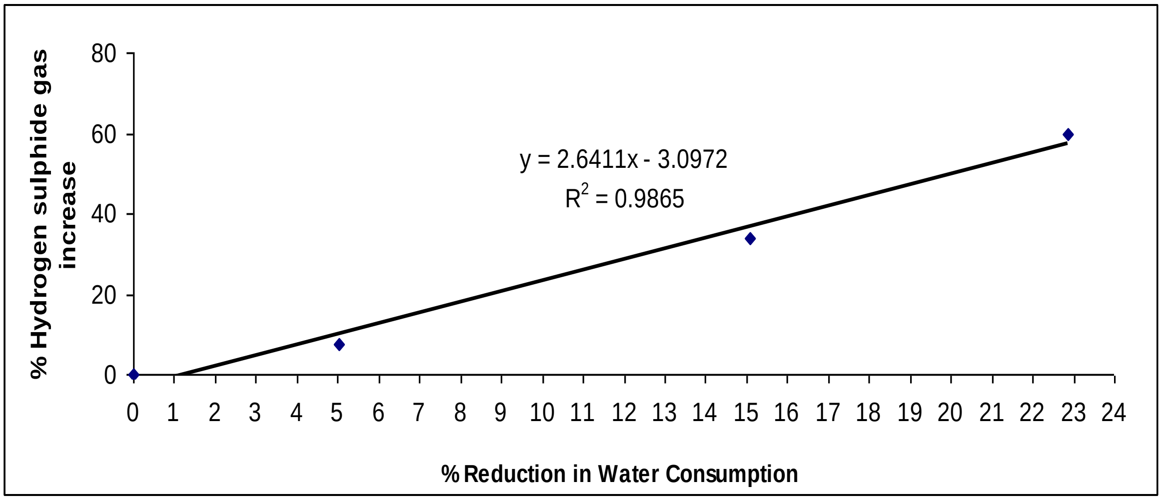


Figure 5.28. Regression Analysis for Hydrogen Sulphide Gas Concentrations for *Water Demand Management* Scenarios

5.7.2 Greywater Recycling

Linear regression between greywater volume uptake and sewer flows, dissolved sulphide concentrations and hydrogen sulphide gas concentrations for *Greywater Recycling* scenarios are shown in Figures 5.29, 5.30 and 5.31. The correlation coefficients were lower than for *Water Demand Management* scenarios; however, the coefficient of determination was still reasonable and varied between 0.87 and 0.95. The lower coefficient of determination compared to the *Water Demand Management* scenarios was expected because part of reclaimed water from *Greywater Recycling* treatment is used for garden irrigation, and only excess reclaimed water was assumed to be discharged to the sewer. Since the garden irrigation requirement varies, depending on precipitation and evaporation, there is variability in the excess volume discharged to the sewer. Even though the effect of garden irrigation was minimised by simulating the scenario in dry weather conditions, where it was expected to have only small excesses of greywater flows to the sewer, there was still increased variability in the regression model compared to *Water Demand Management* model.

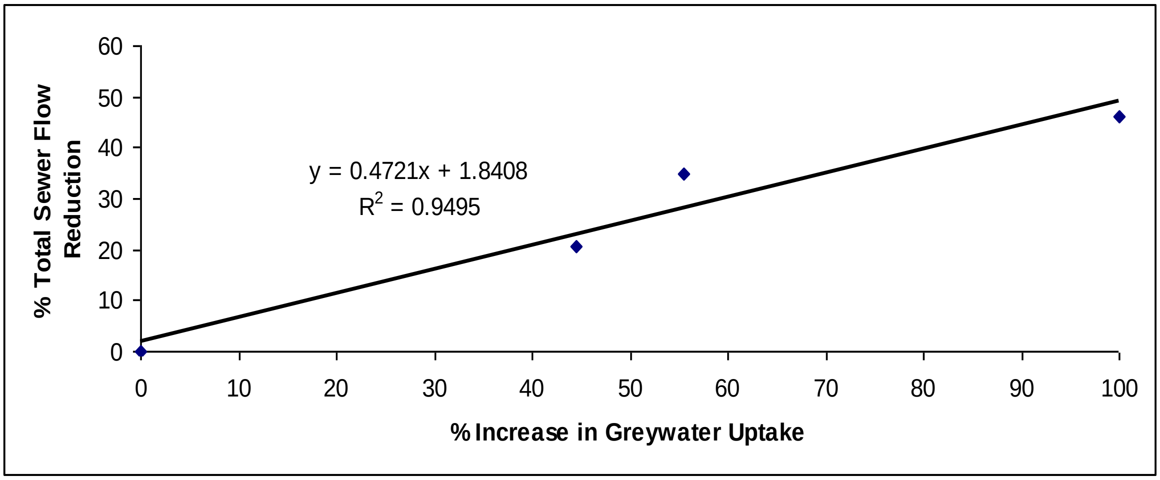


Figure 5.29. Regression Analysis of Sewer Flows for *Greywater Recycling* Scenarios

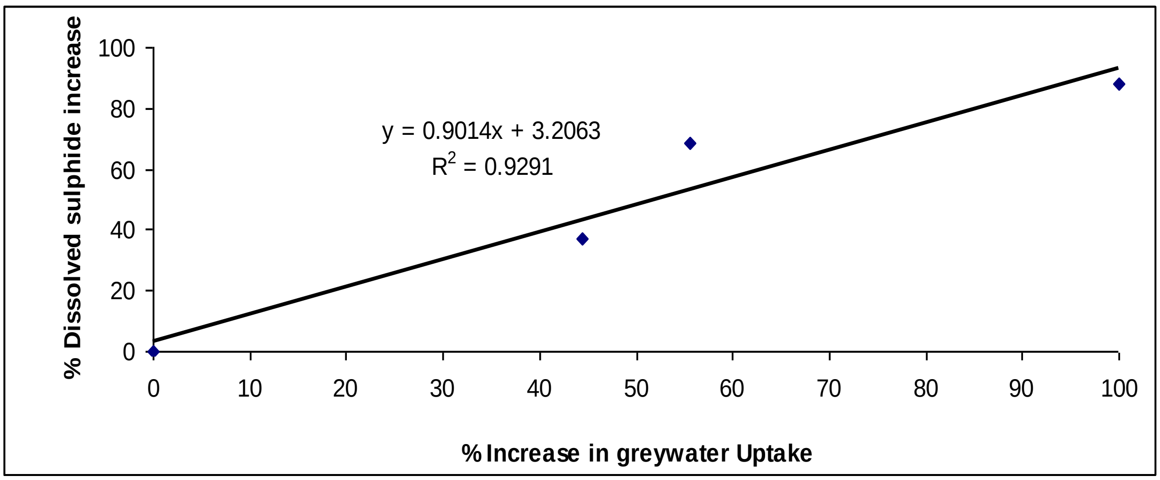


Figure 5.30. Regression Analysis of Dissolved Sulphide for *Greywater Recycling* Scenarios

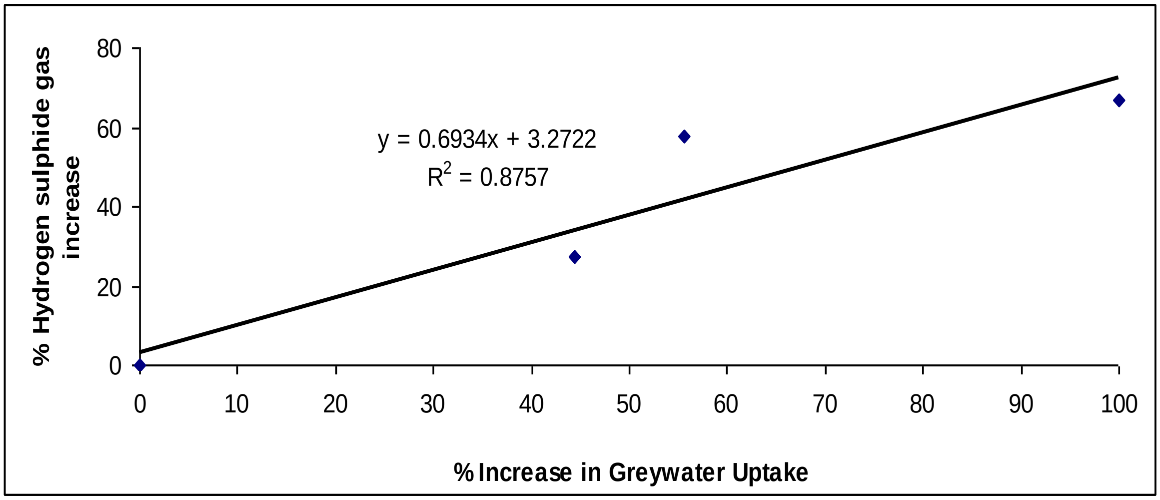


Figure 5.31. Regression Analysis of Hydrogen Sulphide in Gas Phase for *Greywater Recycling* Scenarios

5.7.3 Rainwater Harvesting

Figures 5.32, 5.33 and 5.34 regarding the coefficient of determination for *Rainwater Harvesting* show no relation between using rainwater and sewer flow. This was shown by a relatively low coefficient of determination, which is 0.74. The dissolved sulphide and hydrogen sulphide gas linier regression show better results of the coefficient of determination (R^2 = 0.99). Looking at coefficients of determination, they reflect that rainwater volume uptake relates to changes in sulphide and hydrogen sulphide gas. However, though the relationship between sewer flow reduction, sulphide and hydrogen sulphide and percentage of rainwater volume uptake is quite strong, but the small extent of sewer flow reduction, dissolved sulphide and hydrogen sulphide increase can be interpreted as the increase can be neglected

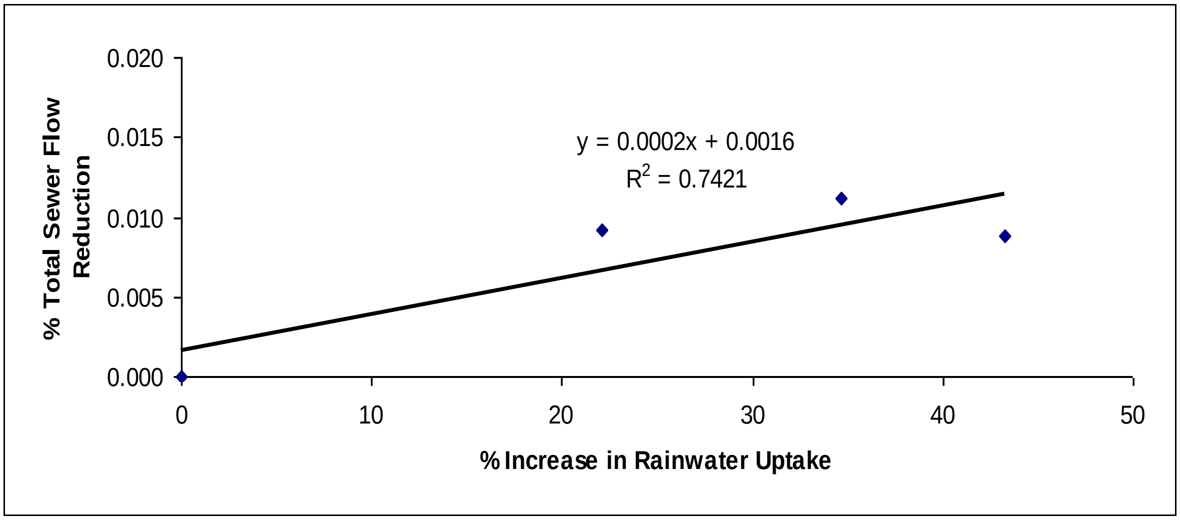


Figure 5.212. Regression Analysis for Sewer Flow in *Rainwater Harvesting* Scenarios

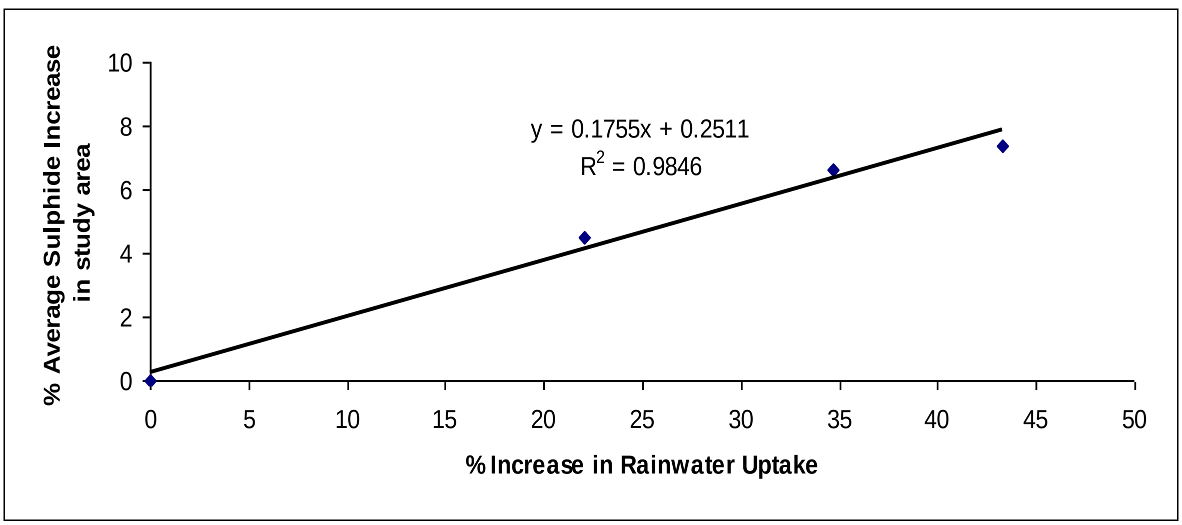


Figure 5.22. Regression Analysis for Dissolved Sulphide for *Rainwater Harvesting* Scenarios

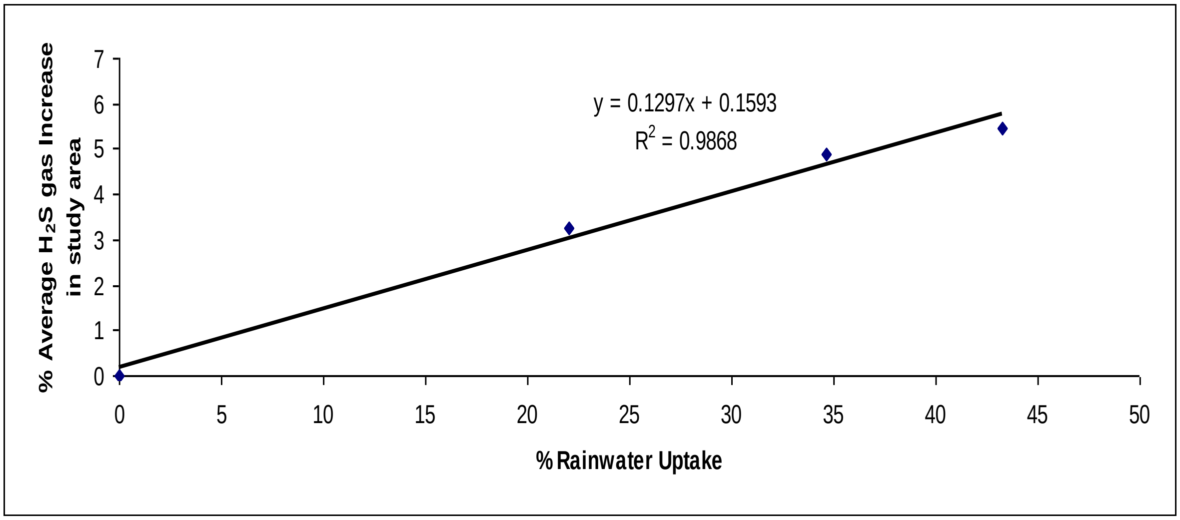


Figure 5.23. Regression Analysis for Hydrogen Sulphide in Gas Phase for *Rainwater Harvesting* Scenarios

5.7.4 Sewer Mining

Figures 5.35, 5.36 and 5.37 show the linear regression for sewer flow reduction and sulphide and hydrogen sulphide increase for *Sewer Mining* scenarios. The linear regression model was only applied to relate the sewage volume extracted with downstream total sewer flow. The coefficients of determination for sewer flow reduction were high (R^2 = 0.98), which indicates a high relationship between two variables. However, the relationship between the sewage volume extracted and dissolved sulphide-hydrogen sulphide gas concentrations have poorer coefficients of determination (R^2 = 0.88 for dissolved sulphide and R^2 = 0.86 for hydrogen sulphide gas). For dissolved sulphide, only scenario SM1 has negative increase while two other scenarios of SM2 and SM3 have positive concentration increase. For hydrogen sulphide gas, all *Sewer Mining* scenarios have negative increase. Negative increase in dissolved sulphide and hydrogen sulphide gas plot was produced as a consequence of a sulphide concentration drop after sewage extraction and the concentration recovery process is slow therefore the average concentration of this scenario is lower than the Base Case (negative increase). For the positive concentration increase, these scenarios have re-gained their dissolved sulphide quickly hence the average concentration is higher than the Base Case.

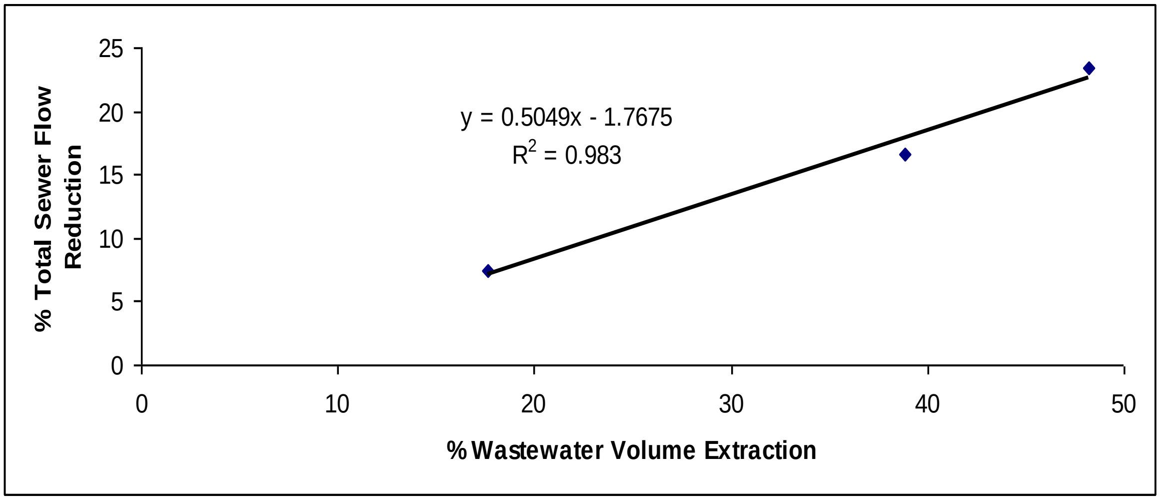


Figure 5.35. Regression Analysis of Sewer Flow for *Sewer Mining* Scenarios

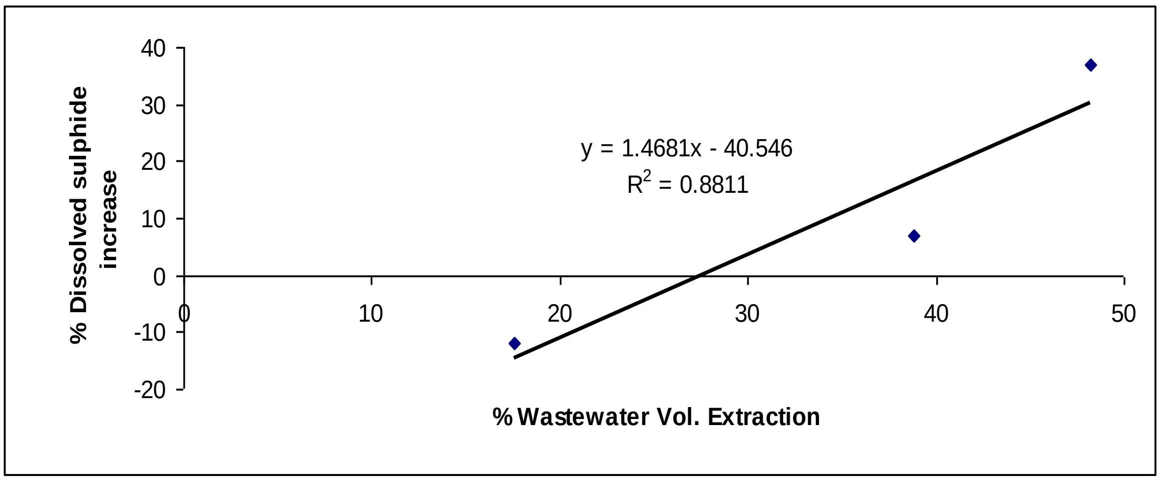


Figure 5.36. Regression Analysis of Dissolved Sulphide Concentrations for *Sewer Mining* Scenarios

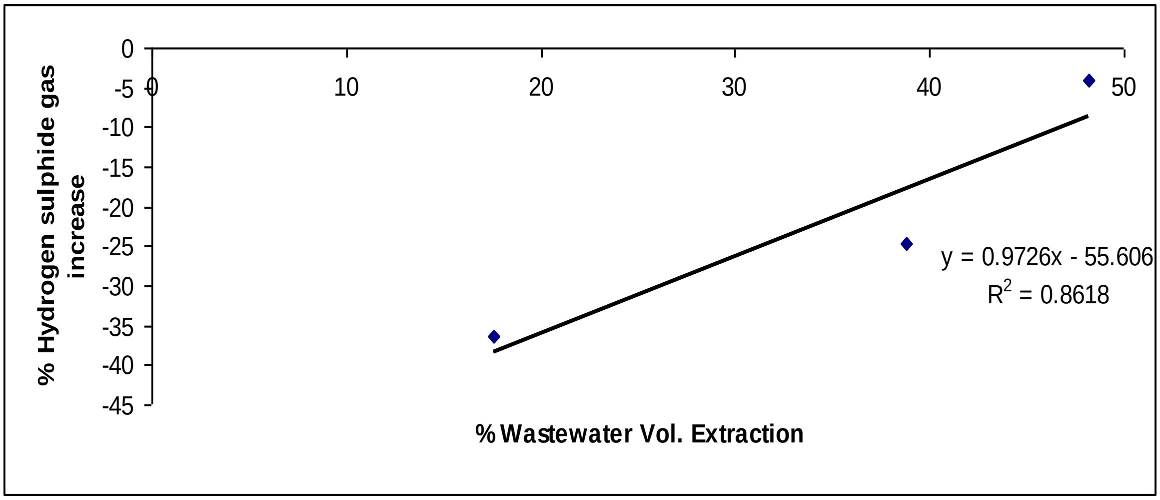


Figure 5.37. Regression Analysis for Hydrogen Sulphide Gas Concentrations for *Sewer Mining* Scenarios

Sewer Mining is mostly conducted by extracting sewage in the main pipe and discharging the sludge back to the sewer. The effect on sewers after the point of extraction has not been widely considered or studied. Here I present predictions for sulphide and H_2S gas concentrations after the point of extraction. The results are presented in terms of a "recovery" pipe length, which determines the pipe length needed to recover the sulphide and hydrogen sulphide concentrations beyond those of the *Base Case* at the same location. As can be seen in Figures 5.38 and 5.39, the lower the ratio of extraction, the longer the distance required to surpass the sulphide and hydrogen sulphide concentrations at the same locations for the *Base Case* scenario.

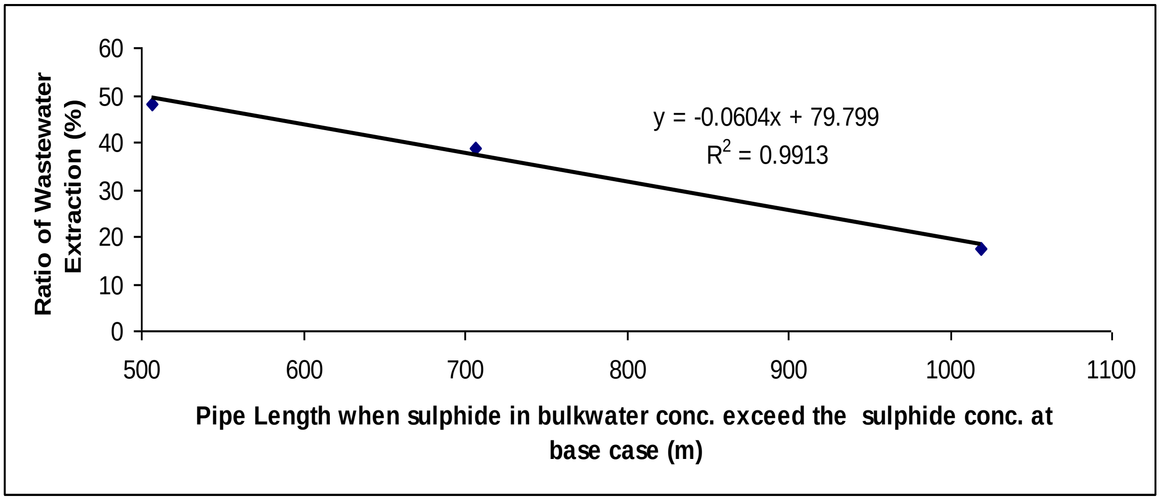


Figure 5.38. Pipe Length When Dissolved Sulphide Concentration Exceeds The *Base Case*

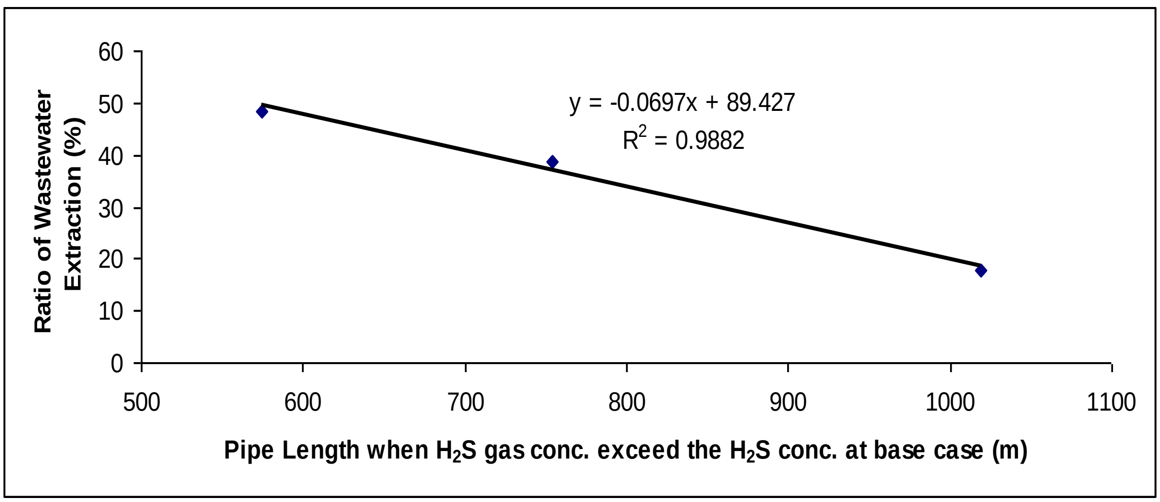


Figure 5.39. Pipe Length When Hydrogen Sulphide Gas Concentration Exceeds The *Base Case*

5.8 Scaling Up of WMP Adoption by Considering Future Urban Development and Climate Change

Changes in wastewater characteristics are affected by many factors including the number of households implementing WMP. Since WMP is being promoted by a range of financial incentives and regulatory changes, their adoption in future is predicted to increase. This section illustrates the effect of future development (2060), including climate change, urban growth and population increase, as well as increasing the extent of WMP adopted within households. How these changes affect wastewater flow and hydrogen sulphide concentrations in the case study sewer network is considered.

The first subsection discusses total wastewater discharge and total contaminant loads from all households in the study area. This is followed by a discussion of total sewer flow, sulphide concentrations in wastewater and hydrogen sulphide gas concentrations. Finally, the relationship between the number of households implementing WMP and sewer flow, sulphide concentrations in wastewater as well as hydrogen sulphide gas concentrations is presented.

5.8.1 Wastewater Discharge

Figure 5.40 depicts the average daily wastewater flows discharged to the sewer network for the WMP scenarios installed in household scale. The total wastewater flow discharges from *Water Demand Management* and *Rainwater Harvesting* scenarios was derived by summing total produced wastewater from all households in study area after incorporate the reduction of water demand and replace the potable water with collected ranwater. For *Greywater Recycling* scenarios, the total wastewater flow discharges to sewer networks was derived by subtratcting the total produced wastewater with the volume of recycled wastewater in individual household then summing all the individual household's wastewater discharge in study area. *Greywater Recycling* scenarios (GR100) and *Sustainable Practice* scenarios (WDM-GR and WDM-RH) had the most impact on reducing the quantity of wastewater discharged to the sewer compared to the *Base Case*. The reduction in *Sustainable Practice* scenarios WDM-GR, WDM-SM and the *Greywater Recycling* scenario GR100 achieved nearly 50%. *Rainwater Harvesting* scenarios had no impact on decreasing wastewater flows compared to the *Base Case*. Wastewater flow discharge to sewer flow in *Water Demand Management* was reduced from 10%, 16% and 22% of the *Base Case* scenario for WDM30, WDM60 and WDM100 respectively.

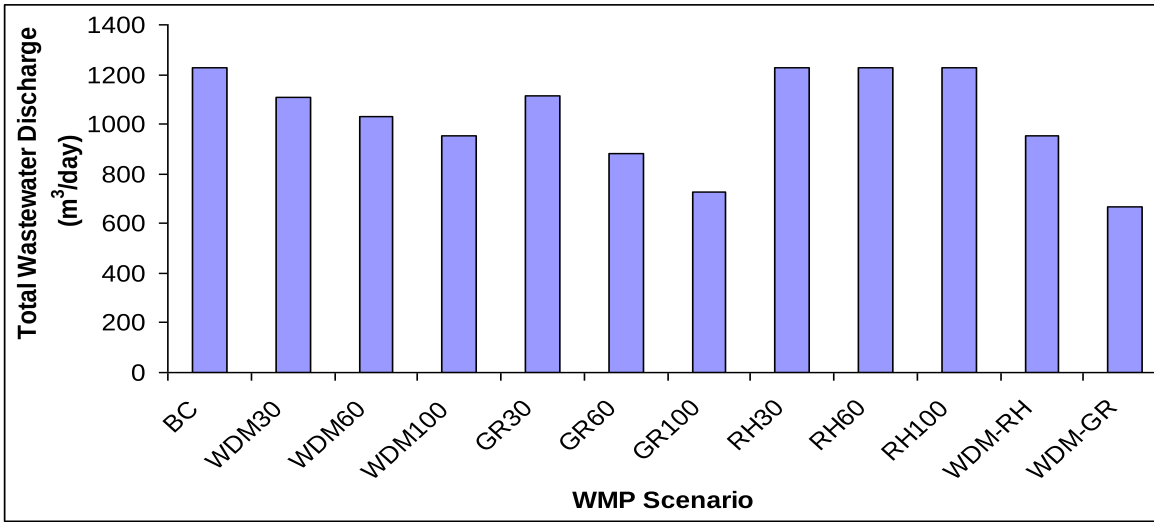


Figure 5.24. Wastewater Discharge From Household's WMP Scenarios In Year 2060

Figure 5.41 depicts wastewater discharge from clustered WMP scenario i.e. *Sewer Mining* scenarios and *Sustainable Practice* scenario of WDM-SM. The total wastewater discharges to sewer network was derived by summing the produced wastewater from all cluster in study area then subtracting the total wastewater with the extracted wastewater. As expected scenario which has the smallest extraction volume (SM25) has highest wastewater volume. The wastewater volume continues to reduce as the extraction volume is getting higher.

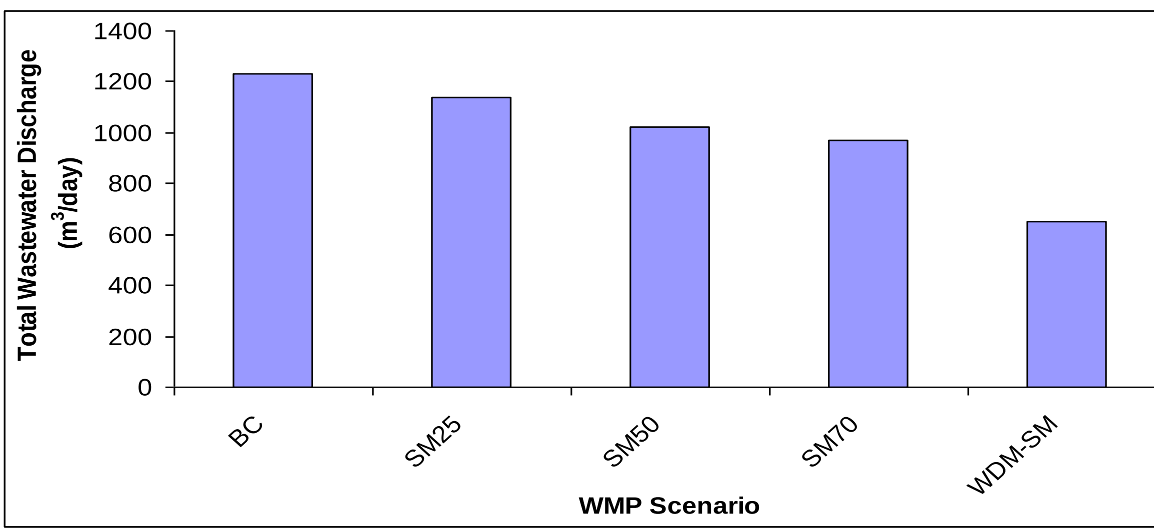


Figure 5.25. Wastewater Discharge From Clustered's WMP Scenarios In Year 2060

5.8.2 Contaminant Load

5.8.2.1 COD Load

Figure 5.42 shows that the *Greywater Recycling* scenario and Sustainable Practice scenario resulted in the highest reductions of approximately 10% to 30% of the *Base Case*. Toilet and kitchen effluent contributed the most COD to the wastewater stream. Hence diverting greywater from the total wastewater stream did not reduce the COD load. Since *Greywater Recycling* contributes most to the reduction of COD, WDM-GR also has less COD load compared to other WMP scenarios. The *Water Demand Management* scenarios did not reduce any COD load because the COD concentration in piped potable water was set to 0 mg/L. *Rainwater Harvesting* increased COD load marginally, since rainwater was assumed to contain some traces of COD.

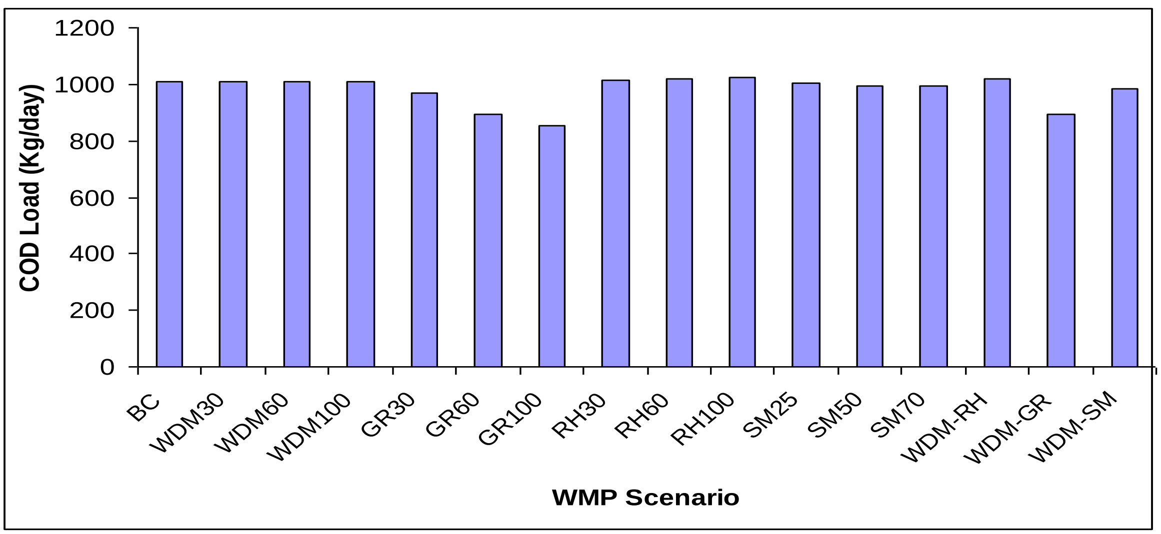


Figure 5.26. COD Load in Year 2060

To simulate hydrogen sulphide production in the sewer network, the biodegradability of COD based on COD concentration is required. Table 5.8 lists the concentration of COD in different biodegradability fractions as modelled in WATS. The same percentage used in subsection 5.3.2.1 was used to break down the average COD total.

Table 5.8. Biodegradability of COD in 2060

Scenario	Average COD_{Total}	S_A	S_F	X_{BW}	X_{Sf}	X_{Sm}	X_{Ss}
	mg/L						
COD Fraction	**100%**	**5.3%**	**5.3%**	**3.4%**	**13%**	**20%**	**53%**
Base Case	833	44.1	44.1	28.3	108.3	166.6	441.4
WDM30	900	47.7	47.7	30.6	117.0	180.0	477.1
WDM60	938	49.7	49.7	31.9	122.0	187.7	497.4
WDM100	1084	57.5	57.5	36.9	141.0	216.9	574.7
GR30	954	50.6	50.6	32.4	124.0	190.8	505.6
GR60	1171	62.1	62.1	39.8	152.3	234.3	620.8
GR100	1262	66.9	66.9	42.9	164.0	252.4	668.7
RH30	835	44.3	44.3	28.4	108.5	167.0	442.5
RH60	840	44.5	44.5	28.6	109.2	168.0	445.1
RH100	846	44.9	44.9	28.8	110.0	169.3	448.6
SM-25%	891	47.2	47.2	30.3	115.8	178.1	472.0
SM-50%	1022	54.2	54.2	34.8	132.9	204.5	541.8
SM-70%	1111	58.9	58.9	37.8	144.4	222.2	588.8
WDM-RH	1117	59.2	59.2	38.0	145.2	223.4	592.0
WDM-GR	1661	88.0	88.0	56.5	215.9	332.2	880.2
WDM-SM	1811	96.0	96.0	61.6	235.4	362.2	959.8

5.8.2.2 Nitrate Load

Figure 5.43 depicts the nitrate load from all WMP scenarios for future development. The reduction of this load was quite high for *Greywater Recycling* scenarios, particularly GR60 and GR100. For GR30, the load decreased by approximately 10% (from 2.75 Kg/day in *Base Case* to 2.25 Kg/day in GR30). The load drastically decreased as the number of houses adopting *Greywater Recycling* increased (1.25 Kg/day in GR60 and 0.65 Kg/day in GR100). This high reduction was due to the nitrate content mostly being found in bathroom and laundry wastewater. In addition, the *Greywater Recycling* treatment has efficiency of 99% nitrate removal. *Water Demand Management* scenarios also reduced their nitrate loads because nitrate was a natural contaminant in potable water, and therefore reducing water demand reduced the nitrate load. *Rainwater Harvesting* reduced the nitrate load marginally. The reduction in *Rainwater Harvesting* scenarios was due to the replacement of the potable water source containing nitrate with rainwater that did not contain nitrate. However, it needs to be highlighted that the main production of nitrate in sewer pipes did not originate within a household. Its production is mainly in sewer pipes as a result of ammonia conversion through nitrification.

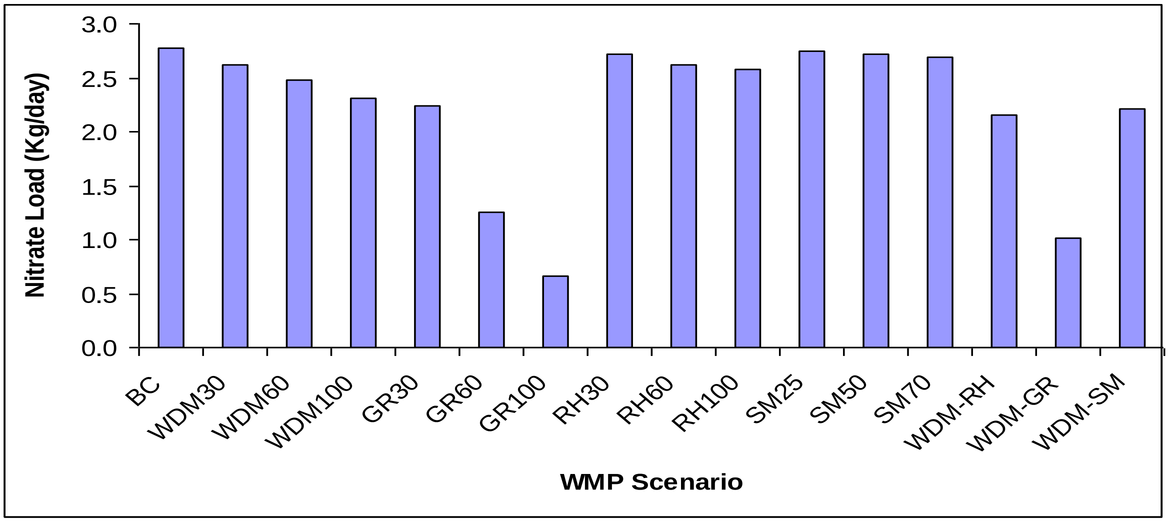


Figure 5.27. Nitrate Load in 2060

5.8.2.3 Sulphide Load

Similar to COD load, sulphide was also not found in piped potable water. Therefore, the increasing number of houses that implemented *Water Demand Management* scenarios did not change the sulphide load in wastewater. *Rainwater Harvesting* scenarios also did not contain sulphide. Therefore, increasing the number of houses implementing *Rainwater Harvesting* scenarios did not significantly change the sulphide load. Sulphide in residential wastewater is contributed from greywater. Water-related product and human contamination are two of the main sulphide contributors in residential wastewater. Therefore Figure 5.44 shows that the *Greywater Recycling* and *Sustainable Practice* scenario of WDM-GR has the least sulphide concentration among other WMP, since the greywater was taken to supply indoor water consumption and garden irrigation. However, the main source of sulphide in sewer pipes actually originated from sulphate reduction in anaerobic conditions. Therefore, many studies about residential wastewater neglected sulphide existence, due to human or water-related product contribution, since it contributes very little compared to sulphide formation due to sulphate reduction.

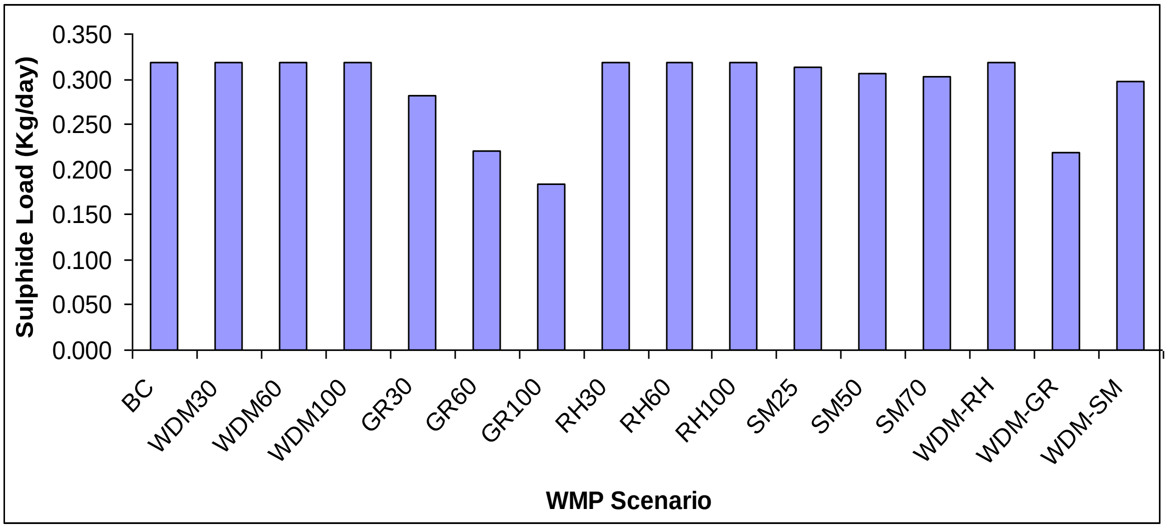


Figure 5.28. Sulphide Load in 2060

5.8.2.4 Sulphate Load

Sulphate can be categorised as a natural contaminant in urban rainwater, since urban areas mostly have a high number of industrial areas and vehicles. Sources of sulphate in urban rainwater originate from smelting operations in industrial areas or burning of coal or fuel emissions from vehicles. As can be seen in Figure 5.45 based on the above facts, the concentration of sulphate in the wastewater from *Rainwater Harvesting* scenarios are slightly increased compared to the *Base Case*. *Water Demand Management* scenarios did little to reduce sulphate loads because sulphate was assumed to be contained in only small concentrations in piped potable water. Various scenarios of *Greywater Recycling* reduce sulphate loads from 5% to 30% of the *Base Case*. This reduction comes from the treatment removal efficiency being set to 54%.

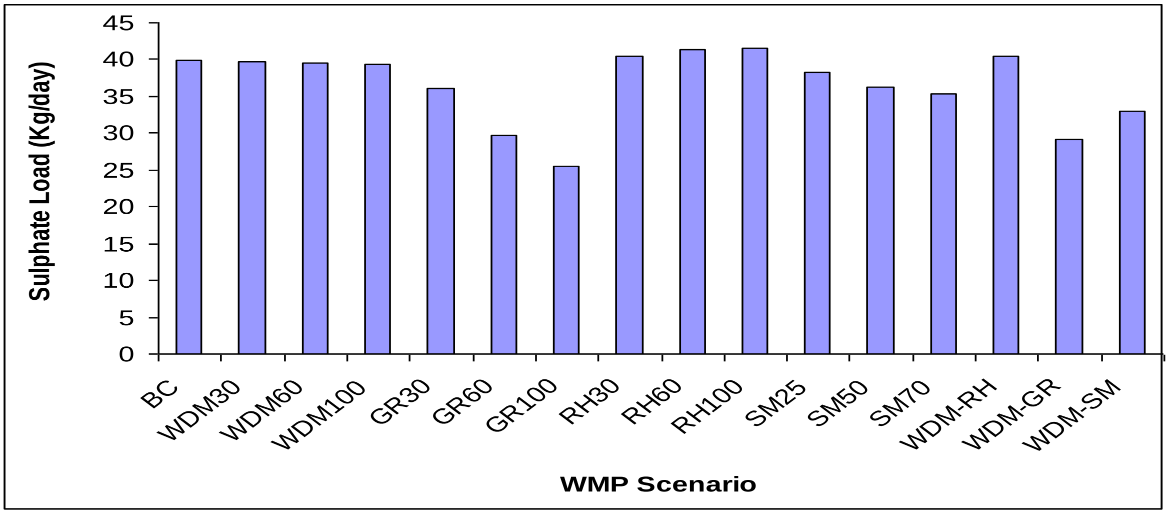


Figure 5.45. Sulphate Load in 2060

5.8.2.5 Iron Load

High increases of iron were found for *Rainwater Harvesting* scenarios. As can be seen in Figure 5.46, increasing the number of households that installed rainwater tanks resulted in an increased iron load. Iron was assumed to be sourced from roof runoff, which then collected in rainwater tanks. Increases of around 20% to 80% were found in *Rainwater Harvesting* scenarios. In *Water Demand Management* scenarios, the iron load remained relative unchanged, while for *Greywater Recycling* scenarios there were reductions of approximately 10% to 70% of iron compared to the *Base Case*.

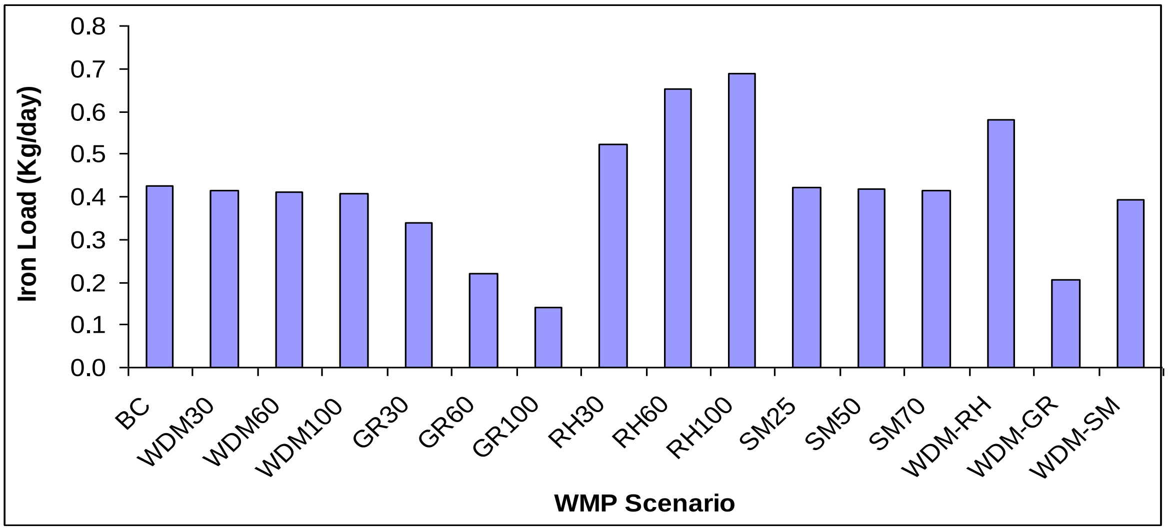


Figure 5.46. Iron Load in 2060

5.8.3 Sewer Flow, Dissolved Sulphide and Hydrogen Sulphide gas Concentration

5.8.3.1 Sewer Flow

Figure 5.47 depicts total sewer flows for the scenarios simulated. There are three scenarios that impact the most on sewer flow compared to the *Base Case*. They are WDM-GR and WDM-SM and GR100. They reduce the sewer flow by approximately 40% to 45%. *Water Demand Management*, *Sewer Mining* and *Greywater Recycling* scenarios installed in 30% and 60% of households in the study area had a relatively marginal impact on decreasing sewer flow compared to the *Base Case*. In the *Rainwater Harvesting* scenarios, there is no change in the sewer flow. For WDM-RH, there is a marginal impact on reducing sewer flow. In this scenario, the sewer flow reduction mainly occurred due to implementation of *Water Demand Management* scenarios and little impact from *Rainwater Harvesting*.

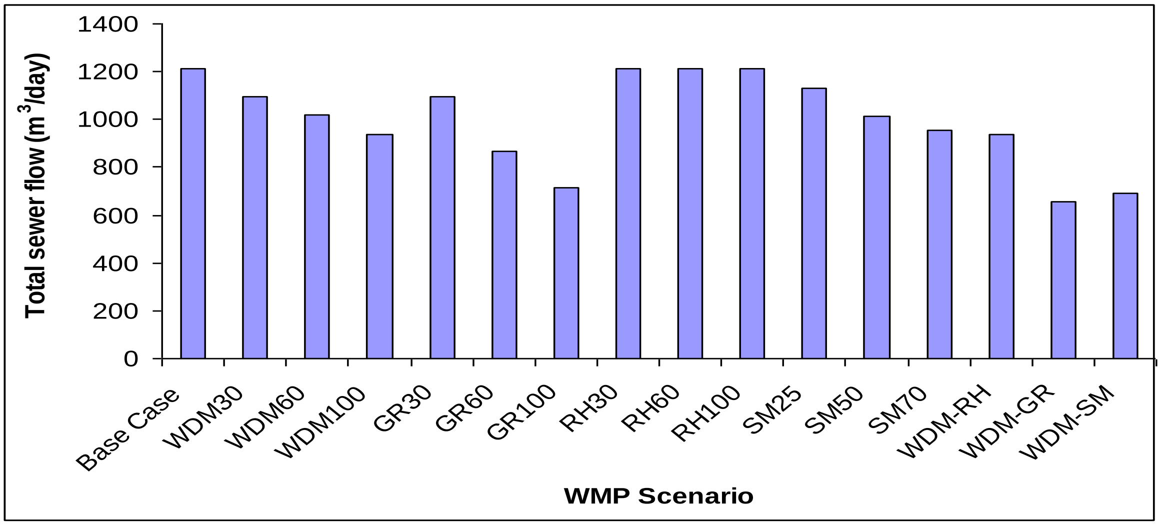


Figure 5.47. Sewer Flow Comparison in 2060

5.8.3.2 Dissolved Sulphide & Hydrogen Sulphide Gas

Figure 5.48 shows that the most extreme increase of dissolved sulphide was contributed by WDM-GR followed by WDM-SM, increasing the dissolved sulphide concentration to around 167% and 111% of the *Base Case*. A sulphide increase of 108% is also contributed by GR100, and GR60 contributed to a sulphide increase by around 70%. Implementation of *Greywater Recycling* scenario of GR30 will only marginally increase sulphide in sewer pipes by 17%. This is the second smallest increase of dissolved sulphide for WMP scenario installed in single households. As can be seen from Figure 5.48, adoption of the *Water Demand Management* scenario WDM100 has increased dissolved sulphide by 51% of *Base Case* concentration. The other *Water Demand Management* scenarios of WDM30 and WDM60 increased the concentration of dissolved sulphide by 16% and 30% respectively. Scenarios of *Rainwater Harvesting* do not impact sulphide concentration much; even two scenarios of *Rainwater Harvesting*, RH30 and RH60, do not impact sulphide formation. The only *Rainwater Harvesting* scenario that has impact is RH100 that increases sulphide formation by only 1%. This increase is due to some organic content collected in rainwater tanks and carried together with collected rainwater for indoor uses. A slight sulphide reduction was found in *Sewer Mining* scenarios, particularly SM25. However, the plot in Figure 5.49 cannot really capture the effect *of Sewer Mining* scenarios, since it was a plot of the sulphide average from all pipe sections in the study area. The effect of *Sewer Mining* scenarios can be compared at the outlet of Glenroy sewer subcatchment, where the concentration of dissolved sulphide exceeded the *Base Case* concentration by 1.5 times, 2 times and 2.3 times for SM1, SM2 and SM3 respectively. For *Sewer Mining*, some pipes decrease their sulphide because it is released to the *Sewer Mining* plant; however, the sulphide was rapidly recovered because this practice discharges residual sludge back to the sewer pipe. At the outlet of the sewer subcatchment, it was found that *Sewer Mining* scenarios SM25, SM50 and SM70 had increased sulphide concentration to around 75%, 135% and 175% respectively.

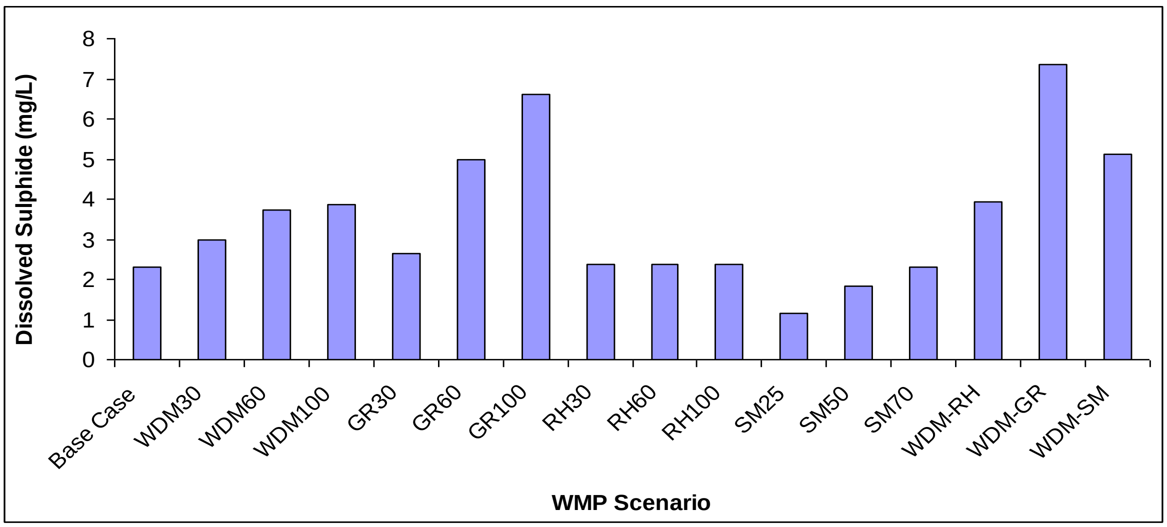


Figure 5.48. Dissolved Sulphide comparison in 2060

Figure 5.49 shows hydrogen sulphide gas concentrations released into the sewer atmosphere. WDM-GR still has the most impact on hydrogen sulphide gas and it is followed by GR100 and WDM-SM. The increase in proportion for these two scenarios is higher than the dissolved sulphide percentage increase, which is around 160% of the *Base Case* for WDM-GR. An increase of 98% and 82% was contributed by GR100 and WDM-SM respectively. WDM-RH, GR60 and WDM100 increase hydrogen sulphide gas concentration by 55%, 65% and 52% respectively. The rest of WMP scenarios have hydrogen sulphide gas increase of less than 30%.

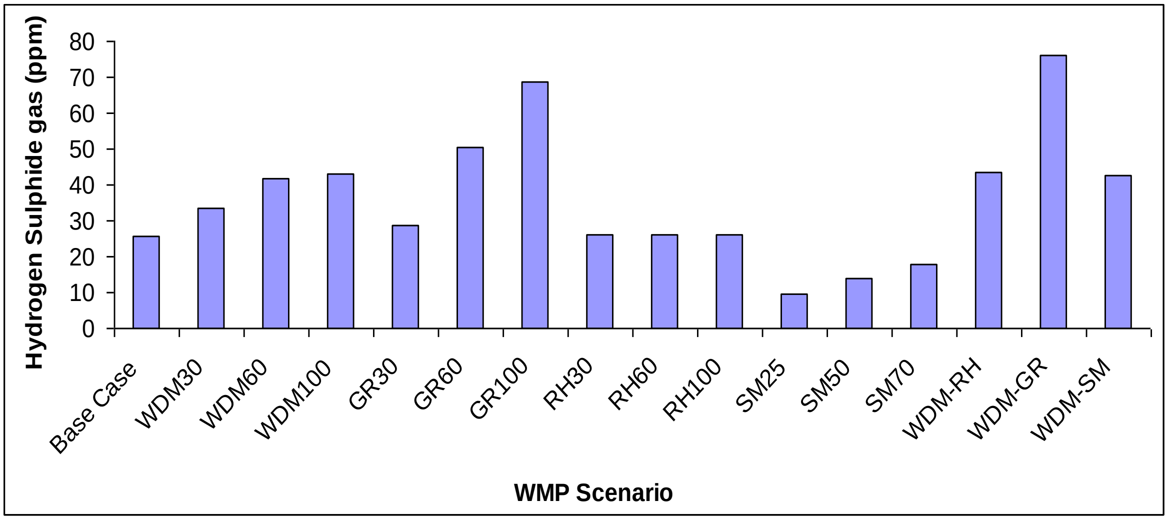


Figure 5.49. Hydrogen Sulphide gas comparison in 2060

5.8.3.3 Corrosion Rate

Corrosion is found from the mass of sulphuric acid (H_2SO_4) consumed per m^3 of concrete corroded. It depends on the volume of gas and area of concrete corroding biofilm in the gas phase. The determination of these two factors is very much affected by wastewater flow. Therefore, the corrosion rate is a function of both hydrogen sulphide, which has been converted to sulphuric acid, and also those factors depending on wastewater flow such as volume of gas and biofilm area in gas phase. Figure 5.50 depicts the corrosion rate found in every scenario. Assuming that pipe geometry and material are the same between the *Base Case* and all WMP scenarios, WDM-GR and WDM-SM as well as GR100 most impact on corrosion rates. The two WMP scenarios have the lowest wastewater volume and the highest hydrogen sulphide gas in the sewer pipe. The increase in corrosion rates for WDM-GR was around 100% of the *Base Case*. WDM-SM and *Greywater Recycling* have similar increased proportions around 50% of the *Base Case*.

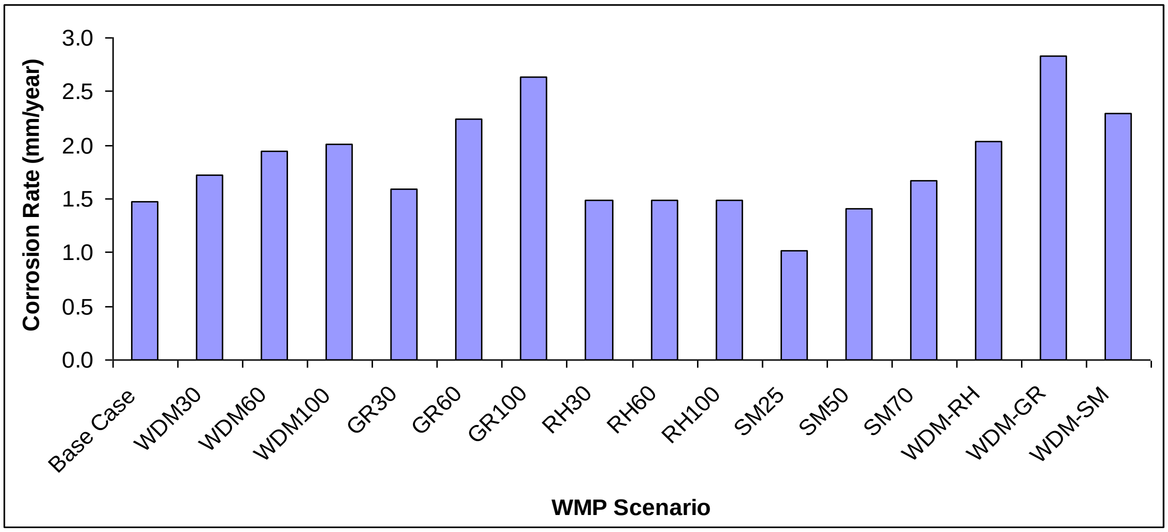


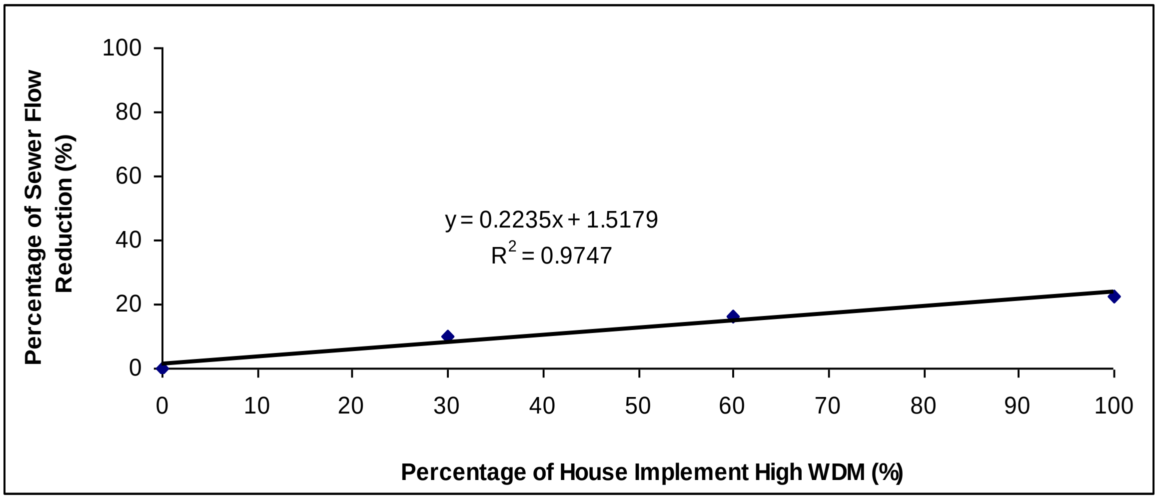
Figure 5.29. Corrosion Rate Comparison In 2060

5.8.4 Regression Analysis for Urban Development in 2060

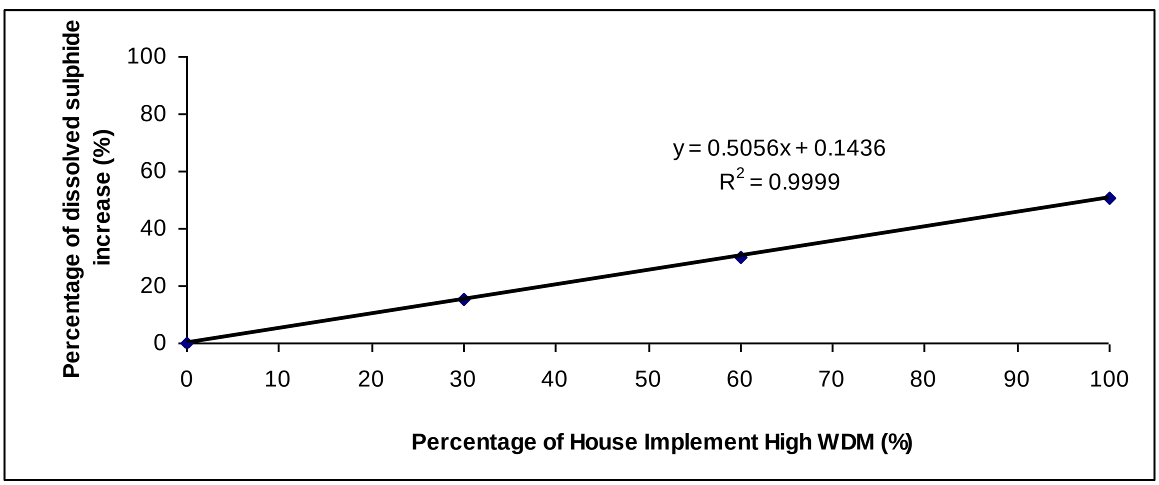
In order to predict the impact of increasing the number of WMP in the study area in 2060, the plots between percentage of households connected to WMP and sewer flow, sulphide concentration in wastewater and hydrogen sulphide gas concentration in the gas phase were created. These plots also show regression lines and equations relating to the variables, and the strength of the relationship provided by regression analysis is given by the R^2 value. The establishment of such relationships is useful to quantify the volume of daily wastewater flows and potential hydrogen sulphide gas concentrations expected to be produced by additional new blocks.

5.8.4.1 Water Demand Management

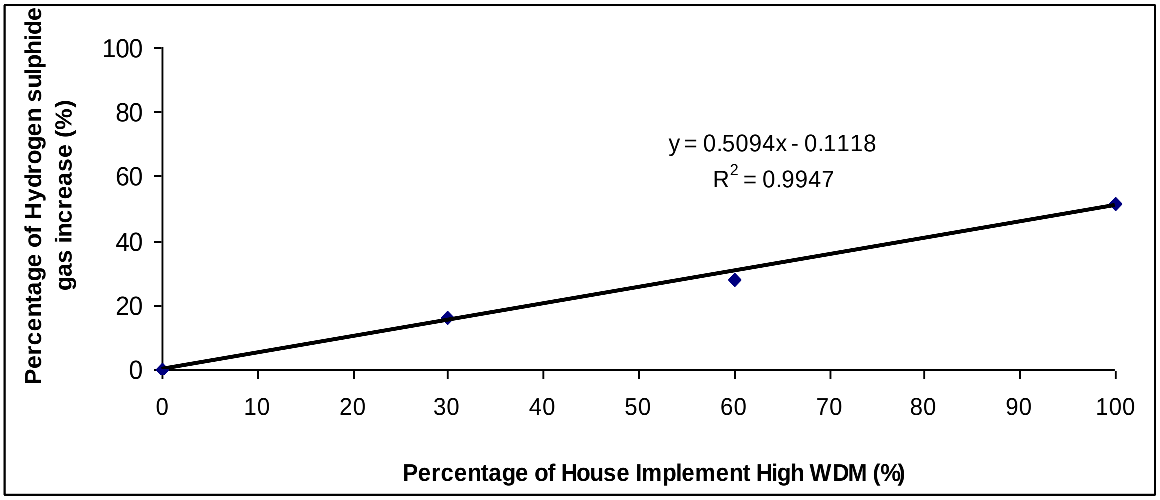
Figure 5.51(a) and the regression equation describe the proportional reduction in wastewater volume as a function of the number of households connected to WMP for *Water Demand Management* scenarios. As can be seen in Figure 5.51a, there is high correlation between the number of households implementing *Water Demand Management* scenarios and reduction of total sewer flow. The implementation of high *Water Demand Management* in 100% households in the study area (GR100) is able to reduce sewer flow by 25%. Consequently, the dissolved sulphide and hydrogen sulphide gas increases by around 70% from the initial (*Base Case*) concentration. As can be seen in Figures 5.51b and 5.51c, the coefficient of determination for dissolved sulphide and hydrogen sulphide gas is very high, reaching 0.999 and 0.9947 respectively. Figure 5.51b and Figure 5.51c indicate that adoption of *Water Demand Management* scenario could worsen the current state of odour and corrosion sewer problems.



(a)



(b)

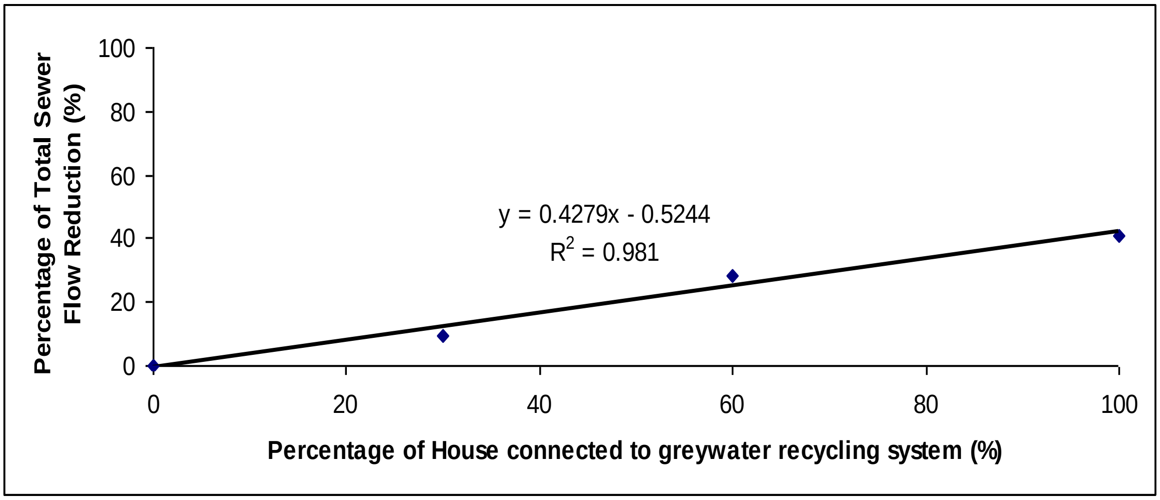


(c)

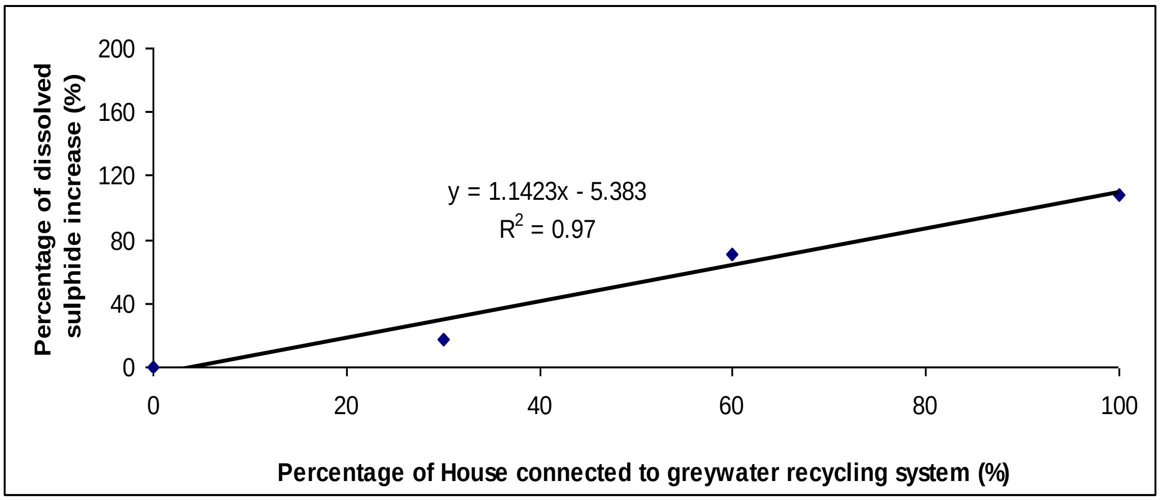
Figure 5.30. ***Water Demand Management*** **Regresion Analysis for (a) Sewer Flow, (b) Dissolved Sulphide, (c) Hydrogen sulphide gas**

5.8.4.2 Greywater Recycling

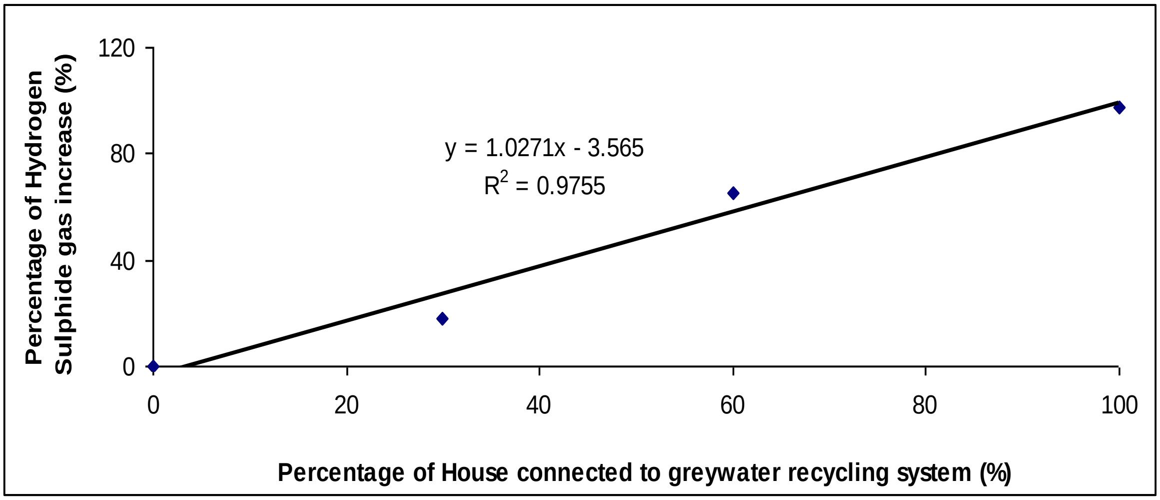
The relationship between sulphide concentration in wastewater and the number of households adopting WMP for *Greywater Recycling* scenarios are relatively high for sewer flow (R^2 = 0.98), dissolved sulphide and hydrogen sulphide gas with R^2 higher than 0.97 (see Figure 5.52a, b and c). Implementation of *Greywater Recycling* in 100% households in the study area (GR100) definitely reduces 40% sewer flow, which consequently increases dissolved sulphide and hydrogen sulphide gas to nearly 120%. Extreme increases in sulphide and hydrogen sulphide gas were due to the fact that the *Greywater Recycling* plant took greywater, which contained less organic pollutants and solids compared to wastewater from the kitchen and toilet. Therefore, with much less sewer flow, the organic concentration becomes very high, and subsequently triggers sulphide and hydrogen sulphide gas formation. The effect of *Greywater Recycling* scenarios could be worse in terms of causing odour and corrosion, if sludge as a residual of the *Greywater Recycling* treatment plant was disposed to the sewer pipe network.


Percentage of Total Sewer Flow Reduction (%)
100
80
60
40
20
0
y = 0.4279x - 0.5244
R^2 = 0.981
0
20
40
60
80
100
Percentage of House connected to greywater recycling system (%)

(a)


Percentage of dissolved sulphide increase (%)
200
160
120
80
40
0
y = 1.1423x - 5.383
R^2 = 0.97
0
20
40
60
80
100
Percentage of House connected to greywater recycling system (%)

(b)

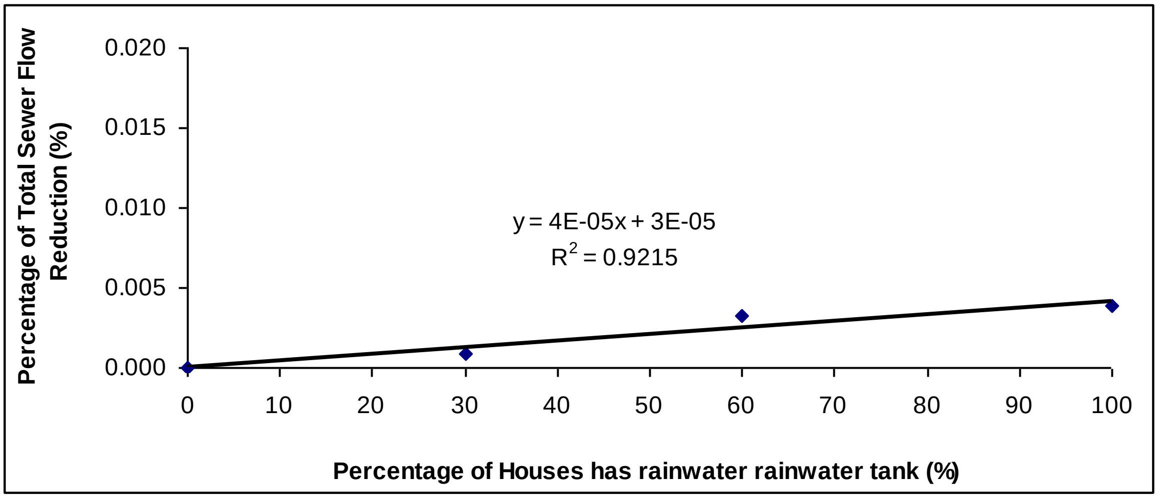


(c)

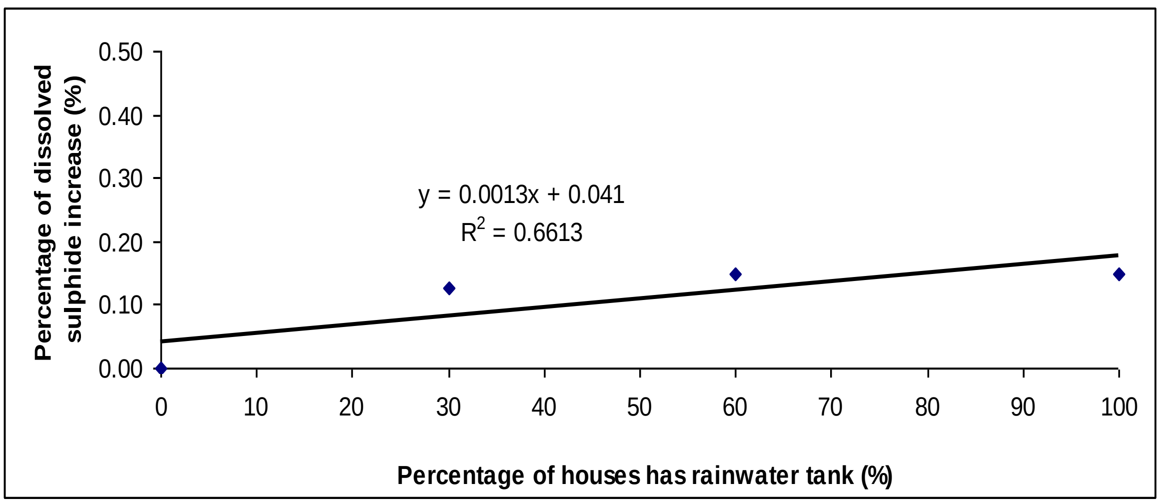
Figure 5.31. ***Greywater Recycling*** **Regresion Analysis for (a) Sewer Flow, (b) Dissolved Sulphide, (c) Hydrogen Sulphide gas**

5.8.4.3 Rainwater Harvesting

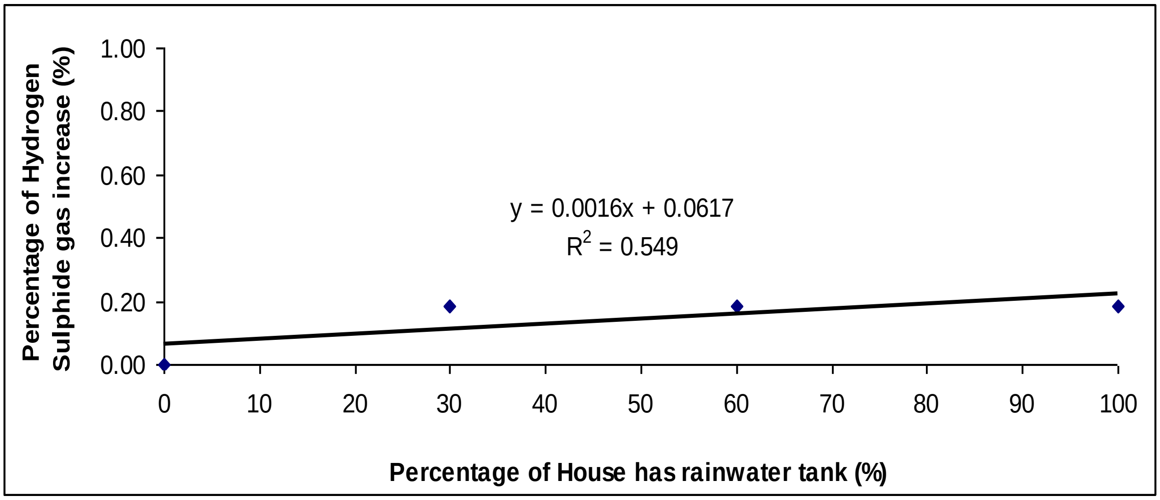
Figures 5.53a, Figure 5.53b and Figure 5.53c present regression analysis for *Rainwater Harvesting* scenarios, though the relationship is quite strong for total sewer flow (R^2 = 0.92), but relatively small for dissolved sulphide (R^2 = 0.66) and hydrogen sulphide gas (R^2 = 0.55). The small extent of flow reduction means this reduction can be neglected. The changes of dissolved sulphide and hydrogen sulphide gas due to different percentages of households adopting *Rainwater Harvesting* scenarios were again not significant since the increase of dissolved sulphide and hydrogen sulphide gas are around 0.1%..


Percentage of Total Sewer Flow Reduction (%)
0.020
0.015
0.010
0.005
0.000
y = 4E-05x + 3E-05
R2 = 0.9215
0
10
20
30
40
50
60
70
80
90
100
Percentage of Houses has rainwater rainwater tank (%)

(a)


Percentage of dissolved sulphide increase (%)
0.50
0.40
0.30
0.20
0.10
0.00
y = 0.0013x + 0.041
R2 = 0.6613
0
10
20
30
40
50
60
70
80
90
100
Percentage of houses has rainwater tank (%)

(b)



(c)

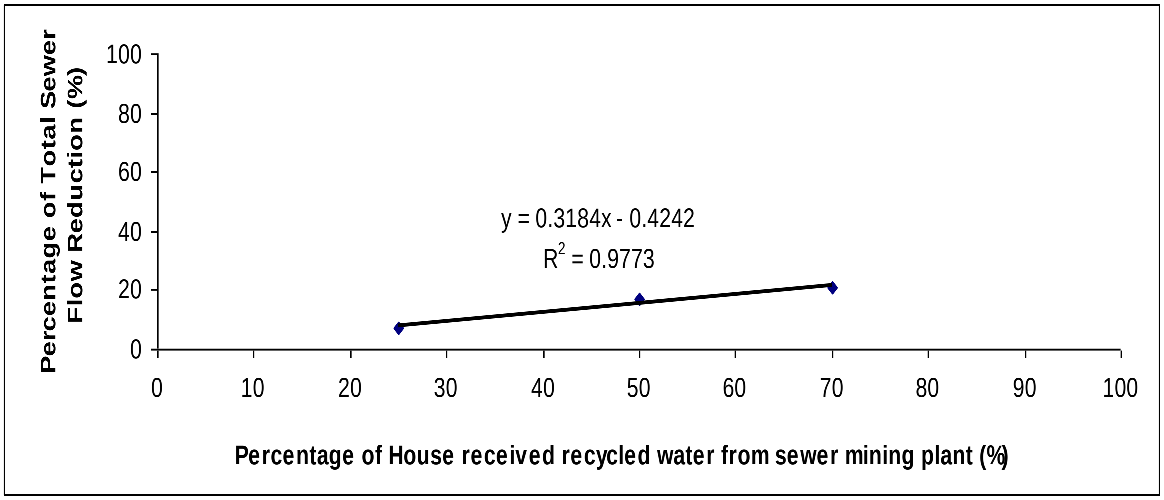
Figure 5.32. *Rainwater Harvesting* Regresion Analysis for (a) Sewer Flow, (b) Dissolved Sulphide, (c) Hydrogen Sulphide gas

5.8.4.4 Sewer Mining

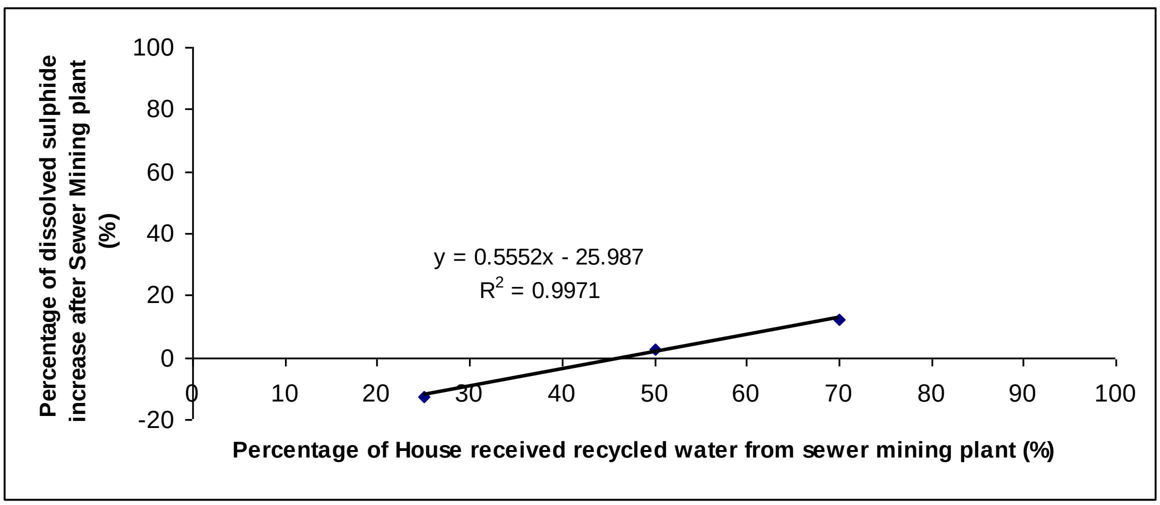
Figure 5.54a clearly shows there is strong relationship between the number of households supplied by reclaimed water from the *Sewer Mining* plant and sewer flow reduction. The strong correlation is illustrated by a coefficient of determination of 0.98. The coefficient of determination is high due to the fact that the extraction volume of sewage depends on the number of households supplied by treated sewage.

The plot for sulphide and hydrogen sulphide gas in Figures 5.54b and 5.54c were calculated based on the average concentration for pipes in the study area (before and after the point of sewage extraction of *Sewer Mining* plant). After the sewage extraction location some pipes have lesser sulphide and hydrogen sulphide gas concentration than the *Base Case*, but after a certain distance, the sulphide and hydrogen sulphide gas will again exceed the *Base Case* concentration. However, since the incidence of sulphide and hydrogen sulphide gas concentration exceed the *Base Case*, concentration was located in the downstream pipes that have relatively small sulphide production and low slope, hence the hydrogen sulphide gas was not easily released, which makes the average concentration of sulphide and hydrogen sulphide gas become lower compared to the *Base Case*. As a result, the percentage increase in both abovementioned figures shows negative percentages.

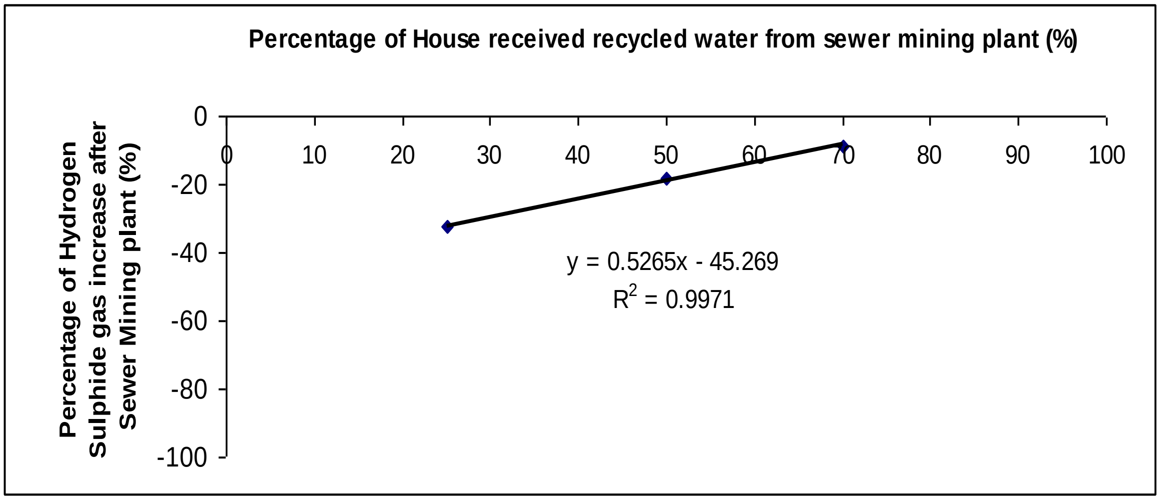
Figures 5.54b and 5.54c show the relation between the number of households supplied by treated water from *Sewer Mining* plants and that the increased percentage of dissolved sulphide and hydrogen sulphide gas are quite strong. It indicates that the volume of sewage extracted is very much determined by sulphide and hydrogen sulphide gas concentration in sewage, since the volume of sewage extraction is dependent on the number of households supplied by treated water from the *Sewer Mining* plant. However, the effect of sulphide and hydrogen sulphide is not solely due to sewage extraction. Treated sludge disposal to sewer networks also contribute to the formation of hydrogen sulphide gas. Unfortunately, this study does not cover the separate effect from each cause (sewage extraction and sludge disposal). As can be seen in Figure 5.54b, the average concentration of dissolved sulphide was lesser than the *Base Case* in the low percentage of supplied household scenario (SM25) but the increase of dissolved sulphide become positive when the *Sewer Mining* supplied to 50% (SM50) and 100% (SM100) of the households in the study area. This indicates that due to sewage extraction and sludge disposal, dissolved sulphide in *Sewer Mining* scenarios was re-established rapidly, thus their concentration becomes higher than the *Base Case*. In contrast, hydrogen sulphide concentration (Figure 5.54c) had negative increases in all scenarios, which means that *Sewer Mining* scenarios had lesser hydrogen sulphide concentration compared to the *Base Case*. This indicates that low pipe slope in downstream sewer pipes affects the process of hydrogen sulphide gas release. Instead of releasing sulphide into the sewer atmosphere, low slope pipes tend to keep the sulphide in the wastewater and biofilm. In the gravity sewer, such as the sewer pipes in the study area, the release of hydrogen sulphide gas depends more on the slope, while for sewer pipes dominated by pressurised gravity pipes, the release of hydrogen sulphide gas is more determined by the changing of pressurised pipe to gravity pipe.


Percentage of Total Sewer Flow Reduction (%)
100
80
60
40
20
0
y = 0.3184x - 0.4242
R^2 = 0.9773
0 10 20 30 40 50 60 70 80 90 100
Percentage of House received recycled water from sewer mining plant (%)

(a)


Percentage of dissolved sulphide increase after Sewer Mining plant (%)
100
80
60
40
20
0
-20
y = 0.5552x - 25.987
R^2 = 0.9971
0 10 20 30 40 50 60 70 80 90 100
Percentage of House received recycled water from sewer mining plant (%)

(b)



(c)

Figure 5.33. ***Sewer Mining*** **Regresion Analysis for (a) Sewer Flow, (b) Dissolved Sulphide, (c) Hydrogen sulphide gas**

5.9 Summary

This chapter has predicted wastewater volumes, sulphide concentrations in wastewater and hydrogen sulphide concentrations in the gas phase when WMP such as *Water Demand Management*, *Greywater Recycling*, *Rainwater Harvesting*, *Sewer Mining* and *Sustainable Practice* which combined single WMP scenarios (i.e. WDM-RH, WDM-GR and WDM-SM) are adopted to various extents. Some WMP were assumed to be implemented in individual houses (*Water Demand Management*, *Greywater Recycling* and *Rainwater Harvesting*, *Sustainable Practice* of WDM-RH and WDM-GR) while the others (*Sewer Mining* and *Sustainable Practice* of WDM-SM) were assumed to be implemented at cluster scale.

The computer model used in this study was not designed for simulating clustered WMP such as *Sewer Mining*. Therefore some modifications had to be made in order to describe *Sewer Mining* practice. These modifications included the amount of extracted wastewater being determined by water demand for toilets and garden irrigation. These volumes were estimated using UVQ. *Sewer Mining* also required modification in the sewer pipe network modeling tool. In this tool, additional nodes have to be added as a *Sewer Mining* node. One node was set to receive only sewage from the main pipe and the other node was set to discharge little flow with high contaminant, representing sludge. The sewage extraction and sludge disposal to sewer networks followed the diurnal flow pattern. However, by using this modification, there was no continuous relation between the extracted sewage and sludge disposal. The volume of sewage extraction and sludge disposal during the day was solely based on the average extracted flow and disposed sludge computed at single time. The reality of sewer mining process from the sewage extraction to sludge disposal to sewer networks might involve more complex time-based process. It means that the sludge will not immediately produce at the same time as sewage was extracted. There will be some time allows sewer mining to produce sludge and this phenomenon can not be capture by using the modification technique to model the sewer mining plant.

Tables 5.9 and 5.10 summarise the results of main analyses. In these tables, several practical parameters directly related to sewer odour and corrosion were listed (piped potable water, sewer flow, hydrogen sulphide gas and corrosion). Table 5.10 did not list piped potable water because the research focus of scaling up of WMP adoption is only to find the impact on sewer odour and corrosion. Dissolved sulphide was not listed in this table since it was considered as a parameter of hydrogen sulphide gas and corrosion rate calculation, but it was not directly related to sewer odour and corrosion. A similar reason was also applied to wastewater discharge from individual households and clusters as well as the contaminant load. These parameters were not included in the abovementioned tables since these parameters were not directly related to sewer odour and corrosion. But it is the components of sulphide formation subsequently released as hydrogen sulphide that cause odour and corrosion in sewer pipes. A summary of Chapter 5 is provided to enable the reader to have a brief overview of the issues that were covered during the study and to subsequently provide a basis for further discussion relating to relative sewer sustainability of each WMP scenario as will be described in Chapter 6.

The result presented in Table 5.9 is based upon averaged results. The impact of WMP adoption on piped potable water is probably the most expected impact compared to other scenarios. A simple analysis of frequency of water appliance usage and the volume of water consumed enable the value of total piped potable water consumed within a household to be calculated. Subsequently, the individual household's piped potable water volume was calculated by the number of households within a study area. The results suggest that even relatively small reductions in household piped potable water demand and replacement of piped potable water can contribute to noticeable reductions of piped potable water demand in the study area.

The simulation results show that *Greywater Recycling* has the greatest impact for reducing sewer flows, as well as the build-up of hydrogen sulphide gas. Recycling greywater from bathrooms was the most influential factor that triggered sulphide build-up for *Greywater Recycling* scenarios. *Water Demand Management* of up to 5% reduction of water demand will not contribute to increased sulphide in wastewater, but the impact is large for reductions in water demand above 5%. *Rainwater Harvesting* seems not to influence the reduction in sewer flows and is a very minor impact on sulphide build-up. *Sewer Mining* affects sewer pipes downstream at the point of extraction. The sulphide concentration and hydrogen sulphide gas concentration decreased significantly after the point of extraction, as sulphide was assumed to be released from the sewer network. However, sulphide and hydrogen sulphide gas concentrations recover quickly after the extraction point. The recovery time depend on the quantity of extracted wastewater. *Sustainable Practice* which combines high *Water Demand Management* and *Alternative Water Sources* (i.e. *Rainwater Harvesting, Greywater Recycling and Sewer Mining*) contributes quite significantly to wastewater reduction and sulphide build-up. The effect of WDM-SM was the most extreme for increasing sulphide and hydrogen sulphide concentrations compared to other WMP scenarios.

The impact of WMP adoption on sewer pipes in wet weather flow seems minor. Only WMP of *Sustainable Practice* contributed quite a significant impact on total sewer flow and sulphide build-up. The rest of the WMP scenarios have contributed to minor impacts on total sewer flow and sulphide build-up. For future development in 2060, overall impact is slightly lower than current development (by comparing current and future *Base Cases*). Related to the scaling up of WMP in the study area, the impact on sewer flow and sulphide build-up shows linear relationships with number of households adopting WMP in the study area, where the greater adoption of WMP contributes to higher reduction of sewer flow and increase of sulphide build-up with the exception of *Rainwater Harvesting*, which did not affect sewer flow.

Finally, all the results in this chapter are significant only to the specific study area. As mentioned, other catchment areas might have not the same characteristics as this catchment, since they are likely to have different pipe geometries, source wastewater characteristics and demography. However, the approach and procedures conducted in this study can be used for other sewer catchments to investigate sulphide build-up due to the adoption of WMP.

Table 5.9. Summary of WMP Adoption Impact in Current Urban Development (2010/2011) – Percentage of Changes as compared to the Base Case

WMP Scenario	Potable water (%)	Sewer Flow (%)	Hydrogen Sulphide Gas (%)	Corrosion Rate (%)
WDM1	-5	-5	7	4
WDM2	-17	-15	25	16
WDM3	-29	-23	37	24
GR-L	-15	-21	21	14
GR-B	-15	-35	37	25
GR-BL	-15	-46	40	27
RH-T	-15	0	3	2
RH-L	-38	0	5	4
RH-B	-29	0	6	4
SM1	-5	-7	-57	-42
SM2	-11	-17	-33	-13
SM3	-16	-23	-4	14
WDM-RH	-46	-23	39	26
WDM-GR	-46	-47	62	44
WDM-SM	-54	-50	62	54

Table 5.10. Summary of WMP Scale Up Impact in Future Urban Development (2060) – Percentage of Changes as compared to the Base Case

WMP Scenario	Sewer Flow (%)	Hydrogen Sulphide Gas (%)	Corrosion Rate (%)
WDM30	-10	31	17
WDM60	-16	61	33
WDM100	-23	67	37
GR30	-10	11	8
GR60	-28	96	53
GR100	-41	167	79
RH30	0	0.1	0.1
RH60	0	0.1	0.1
RH100	0	0.1	0.1
SM25	-7	-63	-30
SM50	-17	-45	-4
SM70	-21	-31	13
WDM-RH	-23	69	38
WDM-GR	-46	196	93
WDM-SM	-43	65	56

6. DISCUSSION OF SCENARIO ANALYSIS

CONTENT: *Summary;*
Impact of WMP on Potable water Demand Reduction & Contaminant Quality;
Impact of WMP on Sewer Flow; Impact of WMP on Odour;
Impact of WMP on Corrosion; Ranking of WMP Scenario;
Effect of Wet Weather on WMP's Sewer Impact; Limit value;
Implications of Study to Sewer Asset Deterioration Study;
Limitations of this Study

This chapter provides the reader with a discussion of the results presented in previous chapters, summarising the key points. The implication of WMP scenarios on the main issues, such as reduction fresh demand, sewer odour and corrosion, will be discussed. Ranking of WMP scenarios are also given based on their specific objectives. The discussion continues with an exploration of the effects of wet weather and future development on existing sewer systems. Finally, this chapter relates the key findings with sewer asset management and highlights the limitations of this study.

6.1 Summary

In this section, the thesis content is summarised based on the main tasks outlined to achieve thesis objectives. The first subsection will review general and specific objectives of the thesis. The following subsections will briefly describe the summary of Integrated Urban Water model framework and development of WMP scenarios as well as the results of scenario analysis.

6.1.1 Thesis Objectives

The general objective of this study is to investigate the impact of the adoption of WMP on sewer odour and corrosion. This general objective was split into the following specific objectives:

1. Development of an Integrated Urban Water model framework.
2. Development of WMP scenarios particularly designed to investigate the increasing volume of potable water reduction and recycled wastewater in dry and wet weather as well as the number of households that implement WMP technology.
3. Scenarios analysis which specifically discussed the impact of WMP on potable water demand, wastewater discharge and contaminant load, sewer flow, dissolved sulphide and hydrogen sulphide gas as well as corrosion rate. The scenario analysis also discusses the impact of WMP in wet weather and future conditions (see Chapter 5).

6.1.2 Development of an Integrated Urban Water model Framework

There are three main functions of the Integrated Urban Water model framework developed for this study. Firstly, it serves as a scenario prediction tool, secondly, it is able to handle the problem of availability of minimum data, and thirdly, it is developed to handle existing sewer problems and associated problems such as RDII. As a scenario prediction tool, this framework was developed by integrating the modeling tools of wastewater generation in urban catchments, and sewer flow and hydrogen sulphide gas generation in urban sewer network systems. It was expected that this framework would be able to simulate different developed scenarios and predict the impact on sewer pipes. The inclusion of a sewer flow-RDII model was intended to be able to handle the modeling problem of availability of minimum data, and also to model the existing sewer network accurately. This framework was also provided with model parameters, which represent residential wastewater from Australia. The developed Integrated Urban Water model framework is illustrated in Chapter 3 (see Figure 3.13).

6.1.3 Development of Water Management Practices (WMP) Scenarios

In this study, WMP scenarios were developed by using a matrix cross of two water conservation strategies: reducing water demand and replacing potable water with

Alternative Water Sources. From this matrix cross, four main strategies were identified, namely *Base Case*, *Water Demand Management (WDM)*, *Alternative Water Sources* of *Rainwater Harvesting (RH)*, *Greywater Recycling (GR)* and *Sewer Mining (SM)*, and *Sustainable Practice* which combines *Water Demand Management* and *Rainwater Harvesting (WDM-RH)* and *Greywater Recycling (WDM-GR)* and *Sewer Mining (WDM-SM)*. The *Base Case* was designed to represent the current condition and to serve as a reference point for this study with regard to all results obtained. *Water Demand Management* represents the condition when all households in the study have installed water saving appliances, but did not have any *Alternative Water Sources*. *Alternative Water Sources* represent the condition when all households have installed various *Alternative Water Sources* such as *Greywater Recycling*, *Rainwater Harvesting* and clustered wastewater recycling plants called *Sewer Mining*. The strategy of *Sustainable Practice* represents the condition where the two strategies of *Water Demand Management* and *Alternative Water Sources* are implemented in a household. Each of the main scenarios was further developed by varying the reduction of potable water and uptake of *Alternative Water Sources*.

Existing sewer pipes are usually dominated by old and ageing pipes. These sewer pipes have cracks and defects in various parts like pipe joints. These problems allow external flow to enter the sewer pipe and vice versa. Since the sewer flow will change due to external flow, all biotransformation processes inside the pipes will also change. In order to understand the impact of WMP on sewer pipes, which is affected by external flow, the developed scenarios above were re-simulated by using rainfall data from wet weather conditions.

Urban development is also one of the important factors which can affect current odour and corrosion levels. Therefore, this study also includes scenarios that take the future urban development and the future climate in the study area into consideration. This was done by projecting the scenarios developed in the current dry weather to 2060. In the 2060, the main scenarios were further developed into three urban stages. These stages assumed 30%, 60%

and 100% of households in the study area implemented WMP scenarios and service coverage for households supplied by treated water from the *Sewer Mining* facility were 25%, 50% and 70%. The *Sewer Mining* facility was not set to supply 100% households in the study area, since presumably it would be located in the middle of the Glenroy sewer sub-catchment, hence there is no sufficient wastewater to supply 100% households in the study area. Brief details of the scenarios are tabulated in Chapter 4 (see Table 4.13).

6.1.4 Scenario Analysis

All the scenarios were modelled by using the methodology developed. The results of model simulation were classified based on the impact of the adoption of WMP on variables including the:

- impact on piped potable water demand reduction
- impact of total wastewater discharged and contaminant load
- impact on sewer flow
- impact on dissolved sulphide and hydrogen sulphide gas in the sewer network
- impact on sewer corrosion rate.

These simulation results were briefly presented in Section 5.2 to Section 5.7. Wet weather analysis was included in dry weather analysis, but the graph result is presented separately in Appendix 7, Figure A.12 to Figure A.18. Further analysis by considering future urban developments are briefly discussed in section 5.8. The obtained results have been analysed to produce hydrographs, hydrogen sulphide maps and a regression analysis graph.

6.2 Impact of WMP on Water Demand and Contaminant Quality

One of the obvious benefits of WMP scenarios simulated in this study is related to the reduced potable water demand supplied by the water supply system. This has been identified as an important aspect of sustainable development, as it leads to reduction in the demand on reserves of freshwater. All of the WMP analysed in this study offer the potential for reducing water demand in residential areas. In this study, toilet was the only indoor end-use that can be supplied with any type of water (potable, reclaimed water for greywater recycling or sewer mining treatment, collected rainwater). Replacing potable water supply to toilet with alternative water sources was considered to be an effective way to reduce residential potable water demand. Water demand in toilet flushing is around 19 L/cap/day, which is the third largest at a household after water demand in laundry and bathroom.

Figure 6.1 presents the percentage of reduction in piped potable water. *Greywater Recycling*, *Sewer Mining* and *Sustainable Practice* scenarios of WDM-GR and WDM-SM are actually potential contributors to higher reduction of potable water if their treated water can be used to supply some indoor water demand, other than toilet flushing. As stated by Eriksson et al. (2002), total greywater can be up to 75% of the volume of combined residential wastewater. It has been estimated that 49% of total household water demand could be reduced if treated greywater is reused for toilet flushing and laundry, and this percentage will be higher if treated greywater could supply bathroom water demand (Dixon et al. 1999; Karpiscak et al. 1990). However, in this study the maximum potable water saving for *Greywater Recycling*, *Sewer Mining* and *Sustainable Practice* scenarios of WDM-GR and WDM-SM is only 13% because they can only supply water demands for toilet flushing.

Rainwater Harvesting scenarios give different percentages on potable water saving with the highest being RH-B. Water saving up to 25% was achieved after implementation of this scenario, followed by RH-L at 20% and RH-T at 13%. The variation in potable water saving percentage in rainwater harvesting scenario depends on the indoor end uses of collected rainwater. The bathroom has the highest household water demand, followed by the laundry, toilet and kitchen (Tjandraatmadja et al. 2009c). Even though rainwater substantially reduces water demand in households due to its low reliability, particularly in dry weather (Ghisi & Ferreira 2007), in this study collected rainwater was set to supply single indoor water usage, thus the reliability of 100% during a year could be achieved. Increasing the rainwater tank size can be a solution to improving the reliability of the *Rainwater Harvesting* system (Dixon et al. 1999). However, this study emphasises the application in a dense, existing urban area (not new development). Hence 4 m^3 volume of rainwater tanks is considered to be suitable for application in dense area. Larger rainwater tanks are not considered feasible due to limited availability of space.

The policy to reduce water demand through *Water Demand Management* scenarios contributes to various potable water saving percentages. The installation of highest water saving appliances (with star ratings of 4.5, 5, 6) for WDM3 is able to reduce water demand by about 22% in the study area, while WDM2 and WDM1 have lesser water saving percentages (14% and 9%), since they use water saving appliances with less rating. Detail about water ratings used for every scenario of *Water Demand Management* can be found in Chapter 4 (see section 4.4.3). Installing high water saving appliances is only one method of *Water Demand Management* to reduce potable water demand. There are many other methods for water saving such as disincentive, incentive and reward for reducing indoor and outdoor water consumption as well as the regulation of water tariff increase (Tate 1990). Water restriction policy limits water usage for mostly outdoor purposes (Butler & Memon 2006).

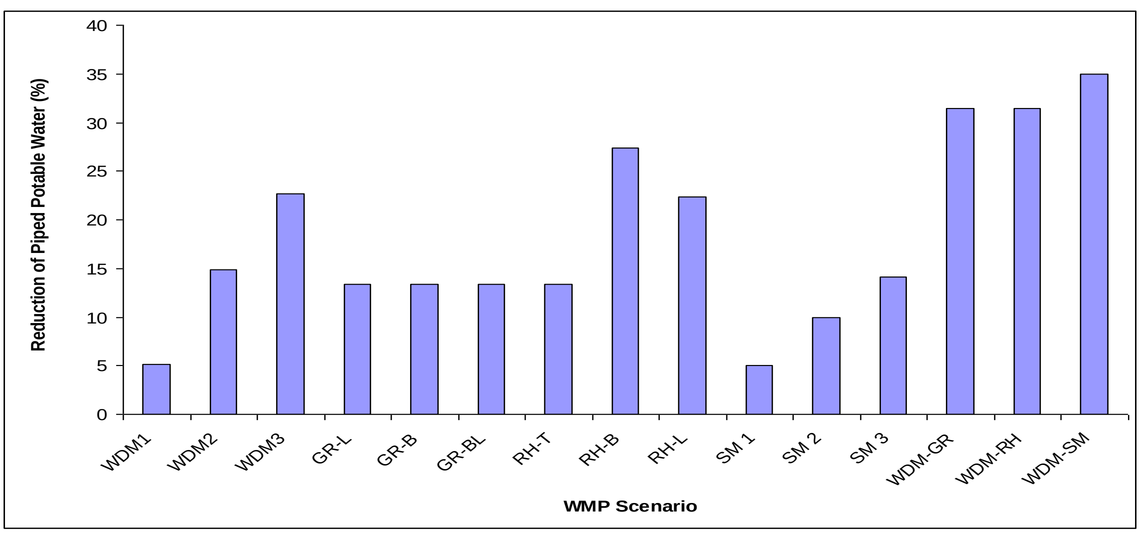


Figure 6.1. Reduction of Imported Potable water from Water Supply System

Due to the reduction in potable water demand, this study indicates that there are significant implications for wastewater flow and contaminant load of households, which result in the change of contaminant concentration in sewer pipes (see Figure 6.2). As can be seen in Figure 6.2, the results for some contaminants are as expected, where the trend is towards reduced wastewater, as water demand is reduced and potable water is replaced by an alternative wastewater source. In contrast, for other contaminants, the concentration increases in some scenarios and decreases in others, as water demand is reduced and potable water replaced by *Alternative Water Sources*.

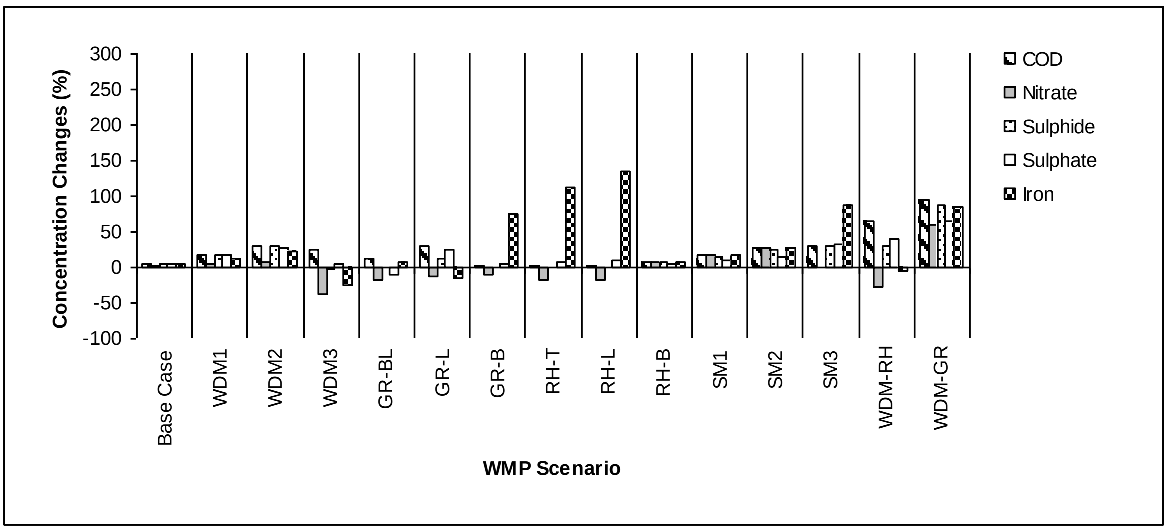


Figure 6.2. Contaminant Concentration change for 2010/2011 Case

The contaminant concentration changes can be due to wastewater reduction, or load change or a combination of wastewater reduction and contaminant load change. COD and sulphide are the only two contaminants with increased concentration in all scenarios. An increase in COD and sulphide concentration in *Water Demand Management* was mainly due to wastewater reduction, since COD and sulphide loads do not change in these scenarios. For other contaminants (sulphate, nitrate and iron), the increase was caused by an increase in contaminant load and reduced wastewater discharge. Higher concentrations of COD, sulphate and sulphide foster sulphide formation.

For *Greywater Recycling*, *Sewer Mining* and *Sustainable Practice* scenarios WDM-GR and WDM-SM, some contaminants (nitrate, sulphate, iron) decrease their concentration while others increase their concentration (COD, sulphide). This occurs because the percentage of contaminant load removal from the *Base Case* was higher than the percentage of wastewater discharge reduction. As a result, the contaminant concentration will be lower than the *Base Case* concentration. As can be seen in Figure 6.2, the contaminant concentration in GR-B is higher compared to other *Greywater Recycling* scenarios. This indicates that laundry greywater contributes to most of the contaminant load in greywater. This is consistent with other study findings (Almeida et al. 1999b; Tjandraatmadja et al. 2009b) (see Table 2.4).

Rainwater Harvesting scenarios have certainly increased the concentration of iron in wastewater by more than 50% increase. This is because many existing residential areas had galvanised iron (GI) which contained iron compounds, hence the collected roof runoff in rainwater tanks has a correspondingly high iron load. Magyar et al's (2008) study also noted that many households in the Melbourne residential area are still using GI roof material. Since it was assumed that all households in the study area had GI, it is likely that roof runoff collected in rainwater tanks has a high iron concentration.

Sewer Mining, the only scenario installed in cluster scale, has increased contaminant concentration in the study area. This is because the extraction of sewage consequently reduces sewer flow and sludge disposal to the sewer network. The increased concentration depends on extracted sewage volume. Therefore the high increase is most significant in scenarios which extract high sewage volume including SM3 and WDM-SM. Even though the increase of concentration in the sewer network was seen as a disadvantage due to its impact on sewer infrastructure, it has an advantage when it comes to the efficiency of downstream treatment processes in the treatment plant.

6.3 Impact of WMP on Sewer Flow

The consequence of reducing water demand and replacing potable water with household greywater or sewage is sewer flow reduction. In existing sewer networks, sewer flow reduction may offer a benefit of excess flow capacity which can later be used to accommodate population expansion, thereby eliminating the need for new construction. However, sewer flow reduction also gives consequence of low flow. Low sewer flow relates to long residence time of sewage in sewer pipes as well as low velocity. Plenty of substrate in fresh sewage can be consumed by biomass that will consume dissolved oxygen. Long residence time allows this process to happen over a long period, however the supply of oxygen through re-aeration mostly does not occur, since sewage velocity is low (Nielsen et al. 2008a; Nielsen et al. 2005b). As a consequence, the sewage becomes anaerobic, which supports sulphide formation. Moreover, sufficient sewage velocity assures a sewer cleansing capacity to help sewers flush down, or clean up deposits of sediment and biofilm that sticks to sewer pipes. Once the velocity is low, the capability of sewers to clean up becomes limited; as a result, much sediment is left in the bottom of pipes (Swamee et al. 1987). The process of sulphide formation mostly occurs in deeper layers of sediment and biofilm (97%), since these layers are mostly anaerobic. Only around 3% of sulphide formation occurs in wastewater (Nielsen et al. 2005b; Nielsen 1991).

The other consequence of long residence time is the possibility of nitrate reduction process will occur (DeZellar & Maier 1980). Nitrate has been known as one of component that can reduce the formation of sulphide in wastewater. In long residence time, nitrate will be reduced to ammonium. In this condition, sulphide in wastewater will be formed and potentially released to sewer atmosphere if there a supportive conditions such as flow turbulence.

Diurnal patterns of sewer flow (see Chapter 5, section 5.5.1) have shown that low flow occurred early morning. This corresponds with less water demand at this time. Low flow is one of the factors which trigger sewer odour and corrosion. Low sewer flow triggers from more turbulence causes the release of hydrogen sulphide gas into the sewer atmosphere.

Afternoons were the second potential low flow time, which can subsequently endanger the sustainability of sewer infrastructure.

Figure 6.3 depicts the percentage of sewer flow reduction due to all WMP scenarios. The highest reduction of sewer flow was contributed by WDM-RH, WDM-GR and WDM-SM which reduced sewer flows by 20%, 47% and 49% respectively. Implementation of *Greywater Recycling* scenarios GR-BL and GR-B also caused high sewer flow reduction (45% and 33% respectively). *Water Demand Management* and *Sewer Mining* also reduced sewer flow, but the maximum reduction of about 20% was contributed by WDM2 and SM3. Other *Water Demand Management* and *Sewer Mining* scenarios reduced sewer flow by less than 20%. *Rainwater Harvesting* is the only scenario that did not affect sewer flow, since there was no reduction in wastewater volume discharged to the sewer. Therefore, based on theory and simulation results above, the most potential WMP that can trigger sewer odour and corrosion are WDM-GR, WDM-SM and GR-BL.

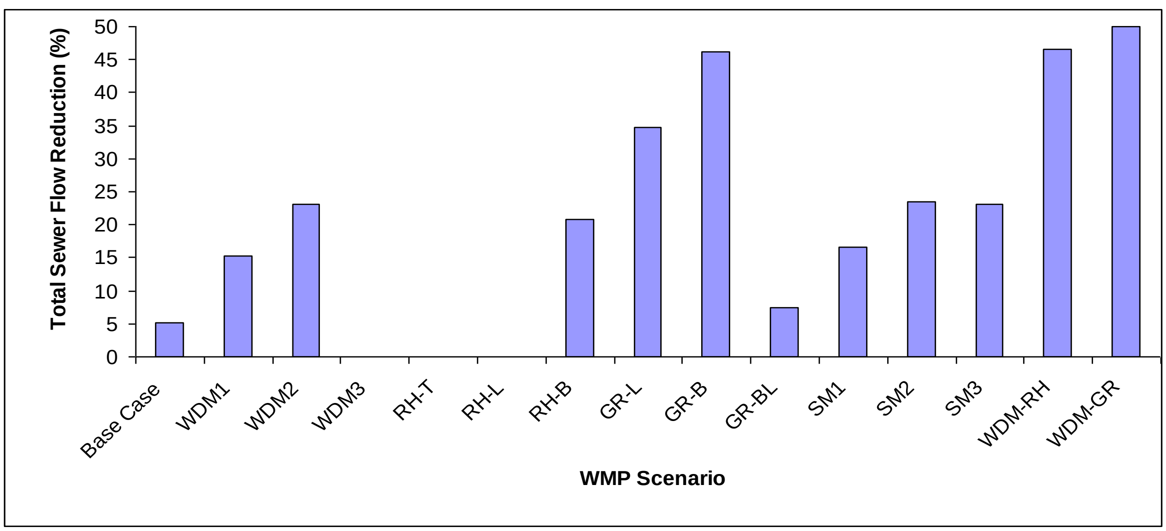


Figure 6.3. Sewer Flow Reduction

6.4 Impact of WMP on Sewer Odour

A consequence of the presence of odorous sewer gas in sewer pipes is the potential danger, mostly to sewer workers, and in some cases, to the public near the odorous site. For hydrogen sulphide, the threshold value of detection is quite low (0.002 ppm). At this concentration, it does not create any harmful effects (Hvitved-Jacobsen 2002). The odour will start to become a nuisance at concentrations of more than 0.5 ppm. Further, when the hydrogen sulphide gas concentration is above 10 ppm, it causes headaches, nausea and eye and respiratory irritations. At higher concentrations (> 200 ppm), it can be fatal and can result in death.

The hydrogen sulphide odour level depends on the condition of wastewater, sewer pipe characteristics and the prevailing temperature. A WMP scenario can trigger a change in wastewater characteristics, which can eventually lead to more hydrogen sulphide build-up in the sewer pipe. COD and sulphate are the most important contaminants in the build-up of dissolved sulphide, which is subsequently released as hydrogen sulphide in instances where supporting factors, such as low flow and aeration, prevail.

The odour formation in the Glenroy sewer subcatchment cannot be avoided, since the sewer pipe has a low slope at the beginning and a very high slope in the middle of the network. The low slope is responsible for the generation of hydrogen sulphide gas in the water phase. When hydrogen sulphide passes the pipe section with a high slope, the gas is released, which eventually causes the odour problem.

As highlighted in Chapter 5, the scenario of highest *Water Demand Management* increases hydrogen sulphide gas concentration to a maximum of 10 ppm, which causes unpleasant odour, but it is not harmful yet to humans. Alarming levels however were shown in WDM-GR and WDM-SM scenarios as well as GR-B and GR-BL. Therefore, many pipes in these scenarios have exceeded the threshold of hydrogen sulphide gas concentration (10 ppm). Therefore these scenarios can endanger humans, who coincidently inhale hydrogen sulphide gas. On the other hand, GR-L has increased hydrogen sulphide gas concentration in many pipes in the study area by less than 10 ppm. It is due to the lesser volume of greywater that was recycled in the scenario of GR-L. Hence it can be concluded that greywater from the bathroom is actually the trigger factor for causing an increase in hydrogen sulphide gas in sewer pipes.

Rainwater Harvesting only causes a slight increase in hydrogen sulphide concentration (1 ppm). This leads to a strong smell of rotten eggs, but does not have any serious impact on humans. This increase can be caused by two factors. Firstly, discharged wastewater from households was not reduced in this scenario; hence the contaminant concentration did not increase. Secondly, iron concentration in collected rainwater was very high; hence it can eliminate the release of hydrogen sulphide gas. For those households which installed GI roofs, it is possible that the iron load could be very high, as observed in this study. High iron concentration in sewers can suppress the release of hydrogen sulphide gas, as the dissolved sulphide reacts with iron to form iron precipitate. The only caution in *Rainwater Harvesting* is the content of organic compounds from roof runoff that can contribute to organic concentration entering the sewer system. In this study, it was assumed that roof runoff contains the organic compound of COD, which eventually adds to COD concentration in wastewater. This assumption causes a slight increase in hydrogen sulphide gas formation.

The impact of *Sewer Mining* scenarios on downstream sewer pipes occurred after sewage extraction and sludge disposal to the sewer pipe. On the upstream sewer pipes (before sewage extraction and sludge disposal) the concentration of hydrogen sulphide is similar to that of the *Base Case.* After sewage extraction some hydrogen sulphide gas concentration decreased due to release of hydrogen sulphide gas to the *Sewer Mining* treatment plant. The reformation of hydrogen sulphide gas occurred after the location of sewage extraction and sludge disposal; however, hydrogen sulphide gas which exceeded the hydrogen sulphide concentration at *Base Case* occurred after some pipe distance, depending on sewage volume extraction. Less sewage volume extraction will cause longer distances to exceed the hydrogen sulphide gas concentration at the *Base Case*, while high sewage extraction will cause shorter distances. The hydrograph plot of the daily average from all pipes in the study area cannot pick up the effect due to *Sewer Mining* scenarios. The daily average from hydrogen sulphide gas concentration will be lower than the *Base Case,* since some pipes after the location of sewage extraction and sludge disposal have lower hydrogen sulphide concentration. The impact of *Sewer Mining* scenarios can be detected at the outlet of the Glenroy sewer pipes. Hydrogen sulphide gas concentration in *Sewer Mining* scenarios was three times higher than the *Base Case* for SM1, five times higher for SM2 and eight times higher for SM3. This shows that the implementation of *Sewer Mining* scenarios can contribute to a loss or gain in order to reduce sewer odour and corrosion due to hydrogen sulphide gas, depending on the location of sewage extraction and sludge disposal of the *Sewer Mining* facility. *Sewer Mining* can be a strategy to reduce the number of pipes affected by hydrogen sulphide gas; however, it can also be a trigger to exacerbate the impact due to hydrogen sulphide presence.

A detailed classification analysis shows that most pipes in the study area show an increased hydrogen sulphide gas concentration in the range of 1-10 ppm when the *Water Demand Management* scenario is implemented. While in the *Greywater Recycling* scenario, most pipes in the study area have an increased concentration in the range of 10-50 ppm. This increase definitely causes problems which lead to harmful effects to human health. The *Rainwater Harvesting* scenario has increased the hydrogen sulphide concentration in most pipes by 0.5-1 ppm. In *Sewer Mining,* most pipes have a daily average hydrogen sulphide gas concentration increase (less than 0.5). However, if we look at the downstream pipes after the *Sewer Mining* point of extraction, the increase is in the range of 0.5-1 ppm.

In many ageing sewer pipe networks, where modifications to control or eliminate the production of odour cannot be made, it will be necessary to resort to other methods such as oxygen injection or addition of chemicals. Of course, the selected method must be determined by a detailed analysis of the local conditions.

6.5 Impact of WMP on Sewer Corrosion

Because of the large capital expenditure each year to correct the effects of hydrogen sulphide corrosion in sewers, it is important to understand the level of corrosion that is likely to occur in changes in wastewater composition due to the adoption of WMP. By fully understanding these changes, preventive measures can be developed to control or eliminate the corrosion.

Hydrogen sulphide corrosion can be controlled by using several methods, one of which is source control of any contaminant that triggered corrosion. In residential areas, the contaminant in sewer networks is derived from each household. Unfortunately almost all WMP, which are implemented within a household or at a cluster scale, tend to exacerbate the corrosion level in sewer pipes. This level is mostly expressed as the corrosion rate. Pipe corrosion can shorten the life of sewer pipes as the corrosion process leads to the pipe material reacting with sulphuric acid obtained from hydrogen sulphide gas conversion. The reaction produces a pasty mass of material, which is loosely bonded to the inert material used to manufacture the pipe. Periodically, as the sewer fills, portions of the pasty mass will be sheared off because of their mass. This process will repeat itself as the ageing pipe continues to corrode. This section calculates the lifetime of sewer pipes in the Glenroy sewer subcatchment by using Equation 2.1.

The corrosion rate of sewer networks is determined by the pipe material and pipe age. Plastic pipe tend to have slow surface reaction compared to concrete pipe. Slow surface reaction means low hydrogen sulphide gas adsorption, thus in this case, corrosion rate will be low and hydrogen sulphide gas will remain high and potentially cause odour problem. The reverse condition is applied for pipe with high surface reaction i.e. concrete pipe. Most of hydrogen sulphide gas will be adsorbed thus corrosion rate will be high while odour problem will be unlikely to occur (Witherspoon et al. 2004). Further, the corrosion rate will be much faster in aging pipes which typically owned by existing sewer networks (Jensen et al. 2008). Therefore, existing sewer networks are very much susceptible to corrosion problem. Moreover, it is worsen by the implementation of WMP which many of them potential to exacerbate problem of sewer corrosion.

As can be seen in Figure 6.4, pipe lifetime at the *Base Case* is 124 years. The simulations show that the decrease in average pipe lifetime is most prominent in *Sustainable Practice* scenarios WDM-SM and WDM-GR, which reduces pipe lifetime by 67 year and 55 years respectively, whereas WDM-RH has a similar pipe lifetime reduction with GR-B and GR-BL (about 34 years). The *Water Demand Management* scenario SM3, which has the highest reduction in water demand (22.25 L/cap/day), can reduce pipe lifetime by 30 years. Further, *Rainwater Harvesting* scenarios RH-B and RH-L only reduce pipe lifetime by 5 years. The other *Water Demand Management* scenarios (SM1 and SM2) and *Rainwater Harvesting* scenario (RH-T) reduce pipe lifetime by less than 20 years and less than 5 years respectively. SM3 that supplied 70% of households in the study area contributed to a reduction of average pipe lifetime by 17 years in downstream pipes after the location of sewage extraction and sludge disposal. Figure 6.4 showed that the average pipe lifetime in SM1 is longer than the *Base Case*. This result can be true for some pipes after the location of sewage extraction and sludge disposal, since the concentration of hydrogen sulphide gas is lower than the *Base Case*. However, after a certain distance, hydrogen sulphide levels have exceeded *Base Case* concentration, which subsequently increases the corrosion rate and shortens pipe lifetime. But because the increase of hydrogen sulphide gas concentration in the downstream pipes is still lower than the released hydrogen gas to the *Sewer Mining* plant, average pipe lifetime in SM1 and SM2 scenarios are 177 years and 140 years respectively. This is a longer pipe lifetime compared to the *Base Case*. While for SM3, due to rapid reformation of hydrogen sulphide gas, the average pipe lifetime becomes slightly longer (107 years) compared to the *Base Case*.

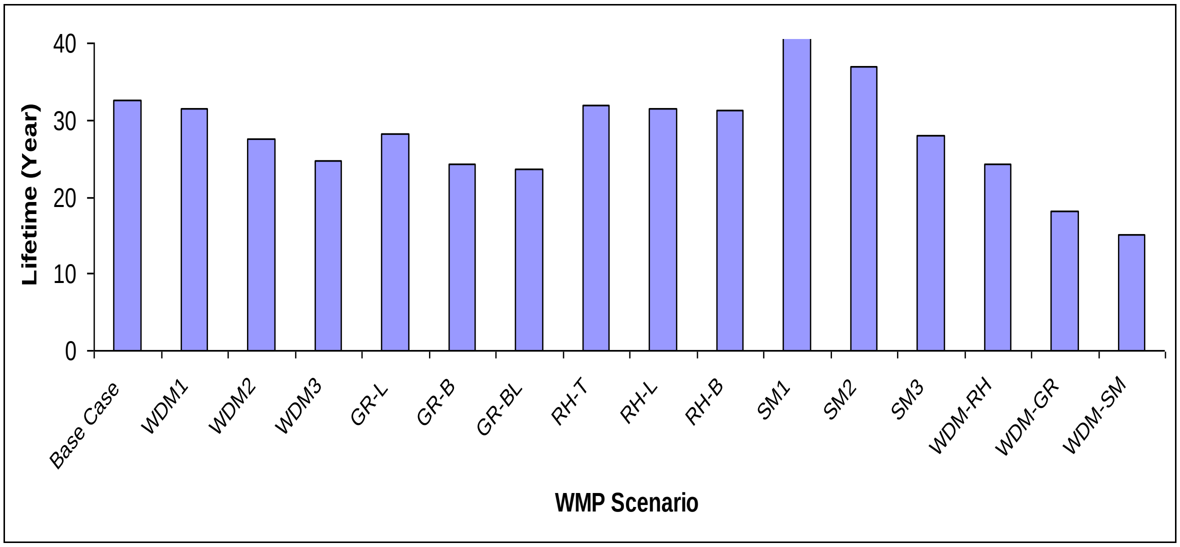


Figure 6.4. Average pipe lifetime for each scenario

When severe corrosion by hydrogen sulphide is anticipated and cannot be eliminated by controlling the contaminant at the source, other control methods need to be implemented to reduce the possibility of increasing pipe deterioration. The most common control methods used in existing systems are aeration, chlorination and mechanical cleaning. The sewer pipe in the study area is dominated by concrete pipes and it is also characterised as systems that have mild or intermittent corrosive condition. Though installing the concrete sewer pipe in a high/mild risk area is not something that is recommended, the use of concrete pipe is still allowable, if the inside of the concrete pipe is covered by limestone or dolomite aggregate to increase the alkalinity of pipe material. The pipe cover will spread the attack of acid over a much greater mass of material, which should prolong the life of the pipe.

6.6 Ranking of WMP Scenario

WMP's scenario ranking is based on various parameters listed in Table 6.1. 1 indicates the best scenario and 4 the worst. For example, the potable water reduction in the study area was minimal in WDM-GR, which ranked 1, while the hydrogen sulphide concentration is high in this scenario, and was thus ranked 4. At the end of the ranking, the score will be totalled and scenarios that have the least total will be regarded as the best scenario based on modeling tool outputs. These WMP scenarios were ranked based on parameters in the study area and not individual households or neighbourhoods. The parameters in Table 6.1 were generated from wastewater generator modeling and sewer processes modeling. The wastewater discharge, contaminant load and dissolved sulphide are not included in this table due to parameters in sewer flow, hydrogen sulphide and corrosion rate calculation. As the aim of the research was to develop an understanding of sewer odour and corrosion implications due to various WMP, no further analysis was conducted. For future study, the inclusion of reliability of the system should be incorporated.

Table 6.1 presents those scenarios of *Rainwater Harvesting* that are generally the best, in terms of the reduction in potable water demand, and have the least impact on the sewer network. Looking at more detailed rainwater scenarios, RH-L and RH-B are the best *Rainwater Harvesting* scenarios compared to RH-T. This is because the toilet has the least water demand compared to other indoor uses within a household. Further estimation concludes that an increase in collected rainwater for indoor water consumption will reduce the score, which in turn will further confirm that *Rainwater Harvesting* is the best scenario based on the modeling output. However, if a reliability study is also considered, *Rainwater Harvesting* scenarios would have a higher score. This is because the *Rainwater Harvesting* system is the most vulnerable alternative source to supply water demand within a household. This is an important point, given that many studies of global climate change agree that rainfall intensity will decrease in future (IPCC 2007).

Greywater Recycling and *Sustainable Practice* are two scenarios classified to give the worst impact overall. *Greywater Recycling* had a high score of reduction of potable water demand because greywater was only accepted for limited indoor (i.e toilet) and outdoor water consumption. Therefore, the potable water demand is still quite high, since only potable water for toilet flushing was replaced by treated greywater. Within *Greywater Recycling* scenarios, GR-B and GR-BL had the highest score compared to all WMP scenarios. It means that they were considered to be worst case scenarios. WDM-GR and WDM-SM are also two worst case scenarios. These scenarios gave the best reduction of potable water demand, which consequently reduces much wastewater, and increases hydrogen sulphide gas formation and corrosion rate.

Based on objective analysis, it can be concluded from Table 6.1 that *Water Demand Management* had various total scores, which were classified from the least impact and worst impact, depending on the volume of potable water reduced from the water supply system. In WDM1, which has the least reduction of potable water, a marginal impact on sewer pipes is likely to occur. WDM2 reduced potable water in significant amounts, which consequently mildly increased hydrogen sulphide gas concentration and corrosion rates. WDM3 gave the worst impact compared to other WDM scenarios, nearly equal to that of the *Greywater Recycling* scenario.

As discussed in Chapter 5 for *Sewer Mining*, the average value used in scenario analysis did not really pick up the effect after extraction of sewage and sludge disposal. Therefore the scenario ranking listed in Table 6.2 underestimated the impact caused by *Sewer Mining* on odour and corrosion. This did not occur directly after extraction, but after some pipe distance. The benefit could be maximised if the location of sewage extraction and sludge disposal occurs at the right location. Or alternatively, the treatment sludge is handled separately and not returned to the sewer pipe. However, this study does not cover analysis of possible location for the *Sewer Mining* facility to optimise *Sewer Mining* benefits.

Table 6.1. WMP Ranking

	Parameters	Specific Objective	WMP Scenarios in Existing Development														
			WDM1	**WDM2**	**WDM3**	**GR-L**	**GR-B**	**GR-BL**	**RH-T**	**RH-L**	**RH-B**	**SM 1**	**SM 2**	**SM 3**	**WDM-RH**	**WDM-GR**	**WDM-SM**
A	**Potable water demand**	**Reduce potable water usage**	4	3	2	3	3	3	3	2	2	1	3	3	1	1	1
B	**Sewer Flow**	**Minimize sewer flow reduction compared to *Base Case***	1	2	3	3	4	4	1	1	1	1	2	3	3	4	4
C	**Hydrogen Sulphide Concentration**	**Minimize hydrogen sulphide concentration increase compared to *Base Case***	1	3	4	3	4	4	1	1	1	1	1	1	4	4	4
D	**Corrosion Rate**	**Minimize corrosion rate increase compared to *Base Case***	1	2	3	2	3	3	1	1	1	1	1	1	3	4	4
Total Score			7	10	12	11	14	14	6	5	5	4	7	8	11	13	13

Note :

WDM : *Water Demand Management*; GR : *Greywater Recycling*; RH : *Rainwater Harvesting*; SM : *Sewer Mining*; L : Laundry; B : Bathroom; BL : Bathroom & Laundry

A :	1 : >30% reduction	2 : 20% - 30% reduction	3 : 10% - 20% reduction	4 : <10% reduction
B :	1 : <10% reduction	2 : 10% - 20% reduction	3 : 20% - 30% reduction	4 : >30% reduction
C :	1 : <10% increase	2 : 10% - 20% increase	3 : 20% - 30% increase	4 : >30% increase
D :	1 : <10% increase	2 : 10% - 20% increase	3 : 20% - 30% increase	4 : >30% increase

6.7 Effect of Wet Weather on WMP's Sewer

The wet weather conditions in this study were simulated by applying input data for a wet weather month. However, the output was selected by looking at the dry days within a wet weather month. In this study, these dry days were taken in November 2010. From data of BoM at Essendon Airport station, Melbourne, November 2010 was the wettest month in 2010. Wet weather simulation aimed to reveal the impact of WMP scenarios adoption under the influence of high flow in sewer pipes. High flow was caused by inflow and infiltration triggered by rainfall.

Findings from this study proved that wet weather affect the formation of sewer odour and corrosion. Compared to dry weather, dissolved sulphide and hydrogen sulphide concentration in wet weather is much lesser. High flow in sewer pipe dilutes contaminants thus their concentrations are reduced. Low contaminant concentration will reduce the build-up of sulphide, which eventually reduces hydrogen sulphide gas concentration released into the sewer atmosphere. High flow is triggered mainly by the infiltration and external inflow to sewer networks. However, the increase of wastewater flow during wet weather is not only caused by infiltration and inflow, but also by unused treated wastewater discharged back to the sewer network. In dry weather conditions, the water demand from indoor and outdoor use is very high; however, in wet weather conditions the total water demand is less due to reduced outdoor demand. Even though the outdoor demand was not discus in detail in this study, it is important to mention the outdoor demand as additional information that will help to comprehend the discussion. For *Greywater Recycling*, part of the treated greywater is used for garden irrigation. However, in wet weather conditions, garden water demand is much less, and hence much of the treated wastewater is discharged back to the sewer, which subsequently dilutes wastewater in the sewer pipe.

Model simulations show there are some hydrogen sulphide build-up during dry days in wet weather but it was much lesser compared to sulphide build up in dry weather. From this finding, it can be clearly noticed that flow contribution from infiltration and external inflow to sewer flow is lesser than the flow reduction because the implementation of WMP. Therefore, from sewer plot in Appendix 7, Figure A.15, the sewer flow from WMP scenarios is still lesser than the *Base Case*. Less flow generates hydrogen sulphide build up in sewer networks. From the model simulation results, it can be concluded that sulphide formation on existing sewer networks was affected by the weather.

Most probably, much better condition of odour and corrosion will occur if simulation is conducted in wet days during wet weather. Because many studies claimed that hydrogen sulphide build-up is typically a sewer problem that presents in dry weather conditions (Hvitved-Jacobsen et al. 2001). In addition, the study about effect of sulphide build-up is rare due to assumption that sewer pipes are “leak free” or tight, where inflow and infiltration can be neglected. However, investigating sulphide build-up in existing residential areas which have ‘old’ sewer pipe networks cannot solely be leak free, since most of the time these sewer pipes are under the influence of external inflow and infiltration, which can be directly influenced by rainfall or as a delayed response to groundwater after rainfall events.

6.8 Effect of Future Development on WMP’s Sewer

Two aspects need to be considered in analysing the impact of WMP on sewer pipes due to future developments. The first aspect is urban development, which includes population growth and future expansion of residential areas. The second aspect is climate, which might influence processes in the sewer pipe in future.

By assuming that in future there is a gradual increase in the number of households that implement WMP, this study also attempted to analyse the impact on the sewer network. Simulation results show that future hydrogen sulphide gas concentration is less compared to current WMP scenarios. This means that the severity of odour and corrosion is expected to be much less compared to current conditions. This is due to the fact that wastewater production increases while atmospheric temperature in the future will only slightly increase. It has been stated by Mohseni and Stefan (1999) and Kinouchi et al. (2007) that sewage temperature is mainly influenced by anthropogenic causes such as domestic activities (washing, bathing, toilet flushing and cooking) and sewage travel time rather than atmospheric (outside) temperature. Moreover, the sewer pipes were laid deep underground with the pipe depth >3 m, thus atmospheric temperature had no effect on sewage temperature. Since the simulation is only conducted in dry weather, future rainfall does not affect sewer processes.

Due to the above facts, wastewater is most likely more diluted due to an increase in population, which subsequently causes smaller contaminant concentration. Thus, hydrogen sulphide production becomes less compared to current conditions. Therefore, it seems that the level of odour and corrosion will not change much in the future, and it is likely that urban development is the most important factor that will influence the presence of odour and corrosion caused by hydrogen sulphide. From WMP scenarios simulation in dry weather and wet weather as well as future conditions, it can be concluded that hydrogen sulphide formation in residential areas will still be a seasonal problem in future.

6.9 Limit Value of Potable water Reduction, Wastewater Recycling and Number of Households Adopting WMP scenarios

From regression analysis, the limit value of exacerbating the problem of odour and corrosion can be established. However, the limit value obtained in this study is specific to the condition of sewer pipes and presented as a percentage value. As highlighted in Chapter 5 (see section 5.5), odour is detected at hydrogen sulphide gas concentrations of 0.02 ppm, but it becomes an odour nuisance at concentrations of 0.5 ppm, and causes serious human health problem at concentrations above 10 ppm. Therefore, the limit value for odour will be established at concentrations of hydrogen sulphide that cause odour nuisance and can endanger public health. Severe sewer corrosion occurs when dissolved sulphide concentration exceeds 2 mg/L. Therefore the limit value established for sewer corrosion will be based on this concentration.

Daily average concentrations of dissolved sulphide and hydrogen sulphide gas in *Base Case* (current condition) are already high, at around 2.34 mg/L for sulphide concentration in bulkwater and 28 ppm for hydrogen sulphide gas concentration. These concentrations already exceed the value of sulphide and hydrogen sulphide that can cause severe corrosion (2 mg/L) and endanger public health (10 ppm). However, they will be used as a datum to obtain the percentage of limit value. It was assumed that increasing the concentration of hydrogen sulphide and sulphide by 2 mg / L and 10 ppm from the datum value (2.34 mg/L and 28 ppm) will increase the risk of more severe corrosion, and consequently will increase the risk of hydrogen sulphide gas becoming more dangerous to human health.

In the *Water Demand Management* scenario, reduction of water demand by 32% will increase the risk of sulphide becoming 4.34 mg/l, an increase of 2 mg/L from the datum value. Reduction of water demand by 32% also leads to reduction of sewer flow by 32%. For hydrogen sulphide, to increase hydrogen sulphide gas concentrations to 10 ppm, water demand should be reduced by about 14%. Reduction of water demand by 14% will reduce sewer flows by the same percentage.

For *Greywater Recycling*, 91% greywater uptake reduced the sewer flow by 45% and subsequently increased dissolved sulphide by 2 mg/L. While hydrogen sulphide increased by 100 ppm requires greywater uptake by 45%, which consequently reduces the sewer flow to about 23%. In the *Rainwater Harvesting* scenario, there is no reduction of sewer flow, but dissolved sulphide and hydrogen sulphide gas can increase by 2 mg/L and 10 ppm, and increase rainwater uptake by up to 465% and 240%, which is incredibly unrealistic. The limit value percentage of *Sewer Mining* tends to be overestimated, since regression analysis cannot really pick the effect of sewage extraction in the middle of the sewer pipe network. Dissolved sulphide concentration increases by 2 mg/L if 86% of sewage in the sewer pipe is extracted by the *Sewer Mining* plant and hydrogen sulphide increases by 10 ppm if there is 93% of sewage extraction. This is considered a high sewage extraction percentage, which will lead to other sewer blockage problems.

The limit value for the number of households that adopt WMP scenarios in the future are described below. For *Water Demand Management* scenarios, an increase of dissolved sulphide by 2 mg/L will not occur, even though 100% of households in the study area implemented *Water Demand Management* scenarios. If 100% of households implemented *Water Demand Management* scenarios, it would only increase sulphide by 1.2 mg/L. However, for hydrogen sulphide gas concentration to increase by 10 ppm, it would only need 66% of households to install high water saving applicances.

Greywater Recycling significantly impacts on hydrogen sulphide and sulphide concentration. Dissolved sulphide increases by 2 mg/L can be contributed to sewer pipe networks if 79% of households have a *Greywater Recycling* facility. While for increasing hydrogen sulphide gas by 10 ppm from the datum, it only needs 37% of households to install a *Greywater Recycling* facility. The result from *Rainwater Harvesting* is not significant and can be neglected. While *Sewer Mining* overestimates the result by giving a high percentage of households that use treated water from the *Sewer Mining* facility.

6.10 Implication of Sewer Asset Deterioration Study

The infrastructure asset of a sewer collection system consists of several primary components, namely, sewer pipes, manholes and pump stations. Sewer asset management can be defined as managing infrastructure capital assets to minimise the total cost of owning and operating them, while delivering service levels desired by consumers. To achieve the abovementioned goal, proactive and preventive maintenance is more likely to be used compared to a traditional approach of reactive maintenance. Fenner (2000) argues that proactive and preventive maintenance has been proven to be more cost effective than both reactive maintenance and avoiding early deterioration of sewer pipes. It is clearly evident that existing pipes have high potential for pipe deterioration. Pipe ageing is considered the main factor for pipe deterioration worldwide. Therefore many deterioration prediction models take pipe age as the most important factor (Ariaratnam et al. 2001; Baur & Herz 2002; Hasegawa et al. 1999; McDonald & Zhao 2001; Najafi & Kulandaivel 2005). However, age-related deterioration of sewers is mostly unclear. In many cases, the failure of pipes can be related to wrong practices at the time of construction or subsequent third party damage, rather than their longevity.

Results from this study also give significant insight as to how pipe age is influenced by many factors; one is the type of waste carried by the pipe. Most researchers studying pipe deterioration prediction models do not consider type of waste, although this study demonstrates that type of waste is an important factor that can influence the deterioration of pipes. Based on the literature review undertaken for this study, only two studies from eleven existing studies considered type of waste as a factor in pipe deterioration models (Baur & Herz 2002; McDonald & Zhao 2001).

Behavioural change in indoor water demand is likely to be more stringent in future. As has been revealed by this study, this change will alter wastewater composition which will eventually affect sewer pipes. All the considered WMP have proven to decrease the lifespan of the sewer pipe due to the problem of corrosion. The findings of this research can assist with future sewer deterioration research to prioritise type of waste as an important deterioration factor. Moreover, sewer asset management for existing sewer pipes can be adjusted to include ways to control the production of hydrogen sulphide. While for new development areas, the sewer pipe network can be designed to be 'smarter' than current sewer pipe designs, which might involve smaller diameter pipes, the installation of pipes at less steep slopes and as sewer wall coating.

6.11 Limitations of this Study

Specific limitations of this study that have implications on the results and conclusions are outlined below.

6.11.1. Modeling Framework Development

The modeling framework developed in this study consists of three modeling tools, which includes wastewater generation, sewer flow and hydrogen sulphide. These models are complex and are mostly calibrated and validated individually. However, in this study, these modeling tools were assumed to be one Integrated Urban Water model engine. Therefore, it leads to a single calibration, which is the final output of the Integrated Urban Water model (combined sewer flow and hydrogen sulphide models). Single calibration for this Integrated Urban Water model means ignoring some complexities that are present within each of the individual models. Moreover, connecting the three models manually was also a time-consuming task.

The default setup of the wastewater generation model, which assumed water demand in every house within a cluster to have similar water demand and contaminant load, was also highlighted as one of the limitations of this study. Moreover, the wastewater generation model selected featured a daily time step as the smallest time step. In reality, the water demand and contaminant load varied within the day. The simplification of daily time step analysis in a wastewater generation model might underestimate the result produced by a hydrogen sulphide prediction model.

Most of the hydrogen sulphide prediction model was simulated at a hourly time step; however, in this study, the time step is adjusted (daily time step), since the wastewater generation model has a daily time step output. This adjustment is also intended to suppress inaccuracy due to different time step output in the individual model that eventually combined as Integrated Urban Water models.

Another crucial limitation of this study is related to the validation of the methodology. As mentioned previously, the problem of hydrogen sulphide formation in a purely residential area is not commonly found. The study area selected for this study was the only residential area in Melbourne known to have odour problems caused by hydrogen sulphide formation. Therefore, it was not possible to validate the developed, Integrated Urban Water model framework to another residential area. It is expected that further research will be able to validate this Integrated Urban Water model framework to another study area.

6.11.2. Scenario Modeling

To model the WMP scenarios using the developed Integrated Urban Water model framework, some adjustments are still needed to mimic the real conditions when WMP are implemented. The adjustments for each of these scenarios will now be briefly discussed.

6.11.2.1 Water Demand Management

There were three scenarios for *Water Demand Management*, which gradually reduced water demand within a household. To determine water demand, star ratings from the current WELS (Water Efficiency and Labelling Scheme) website were used. The water demand based on these ratings has limited the reduction of water demand by a maximum of 22% (less than that in the *Base Case)* in dry weather. As mentioned, these WMP scenarios are most likely to represent the future, rather than the current condition. Therefore, the selection of gradual decreasing water demand based on current WELS will uncover further water demand reduction, which may occur in the future.

6.11.2.2 Greywater Recycling

The *Greywater Recycling* scenario was designed to reuse bathroom wastewater, laundry wastewater, and combined laundry and bathroom wastewater. Unfortunately, the sludge discharged to the sewer network was not simulated in this study. Based on several studies, this practice will most likely occur when the *Greywater Recycling* plant is installed in a household. In a case where the treatment sludge is discharged back to the sewer, the final hydrogen sulphide gas production could be much worse than the current simulated scenario.

Another weakness found in the *Greywater Recycling* scenario is related to the wastewater generation model that provides limited options for indoor water consumption that can be supplied by treated water from *Greywater Recycling*. Although this scenario can recycle and provide alternative water supply in large volumes, its use is limited to toilet flushing and outdoor water consumption. Due to this limitation the savings of potable water for indoor use in *Greywater Recycling* was relatively small compared to other WMP scenarios.

6.11.2.3 Rainwater Harvesting

Scenarios of *Rainwater Harvesting* in this study were simulated in the driest month in 2010 (April). Since *Rainwater Harvesting* scenarios were set up to supply without any failed days (100% reliability), collected rainwater usage should either be toilet, laundry or bathroom. The rainwater storage tank size was 4 m^3 as an acceptable large storage tank for a dense urban area. After trialling some *Rainwater Harvesting* scenarios simulation by using average rainwater tank size of 4 m^3, it became evident that rainfall intensity during the dry months can only supply water for the toilet, the bathroom or kitchen. Simulation from the wastewater generation model shows that the reliability of the *Rainwater Harvesting* system was not 100% when supplying the water demand for laundry, bathroom and toilet use. *Rainwater Harvesting* that only supplies single indoor end-use is not really consistent with reality, since many households use collected rainwater for many indoor non-potable water consumptions. Therefore, the limitation of this study related with modeling the *Rainwater Harvesting* scenario is the *Rainwater Harvesting* system's arrangement that did not supply many indoor water consumptions, so it did not really mimic reality. In future research, the modeling of *Rainwater Harvesting* scenarios can vary the storage tank, hence it can supply multiple indoor water consumptions.

6.11.2.4 Sewer Mining

Sewer Mining and *Sustainable Practice* of WDM-SM are scenarios which are implemented at a cluster scale. None of the individual models had the capability to model the practice of *Sewer Mining* from the point of waste generation until the outlet of the sewer model. In some studies, *Sewer Mining* was mostly conducted as a part of sewer flow modeling (Sydney Water 2006), but none of these models were combined with the wastewater generation model. Since this study was intended to determine the impact of the *Sewer Mining* from the household up to the sewer outlet, some adjustments had to be made. These adjustments will be explained below. They eventually became limitations of *Sewer Mining* scenario modeling and the results generated.

In the wastewater generation model, the wastewater recycling plant, which is represented as the *Sewer Mining* facility, was assumed to be installed in every cluster and the storage tanks were adjusted until the toilet water demand was fully supplied (100% system reliability). Since every cluster has a different number of households the assumption and adjustment above lead to the size of the cluster storage tank being different for every cluster, which eventually leads to difficulties in generating a conclusion based on the storage tank volume. However, since the variation in storage tank volume is not a focus of this study, it can be neglected.

The calculation of total sewage extracted from sewer pipe to supply the toilet water demand for 25%, 50% and 70% of households in the study area was based on the difference in wastewater volume in the *Base Case* and *Sewer Mining* scenario. Moreover, this scenario neglected the additional contaminant load that originated from the alternative water from the *Sewer Mining* plant, used to supply toilet flushing water in a household. This arrangement might underestimate the total contaminant load discharged from a household, since the alternative water from the *Sewer Mining* plant would contain a higher contaminant load compared to that in potable water.

Another modification was also implemented in the sewer pipe modeling tool. Since the modeling tool of hydrogen sulphide (WATS) did not provide any node that had the capability to treat and store wastewater extracted from the sewer pipe, two normal nodes were added to the network. The first additional node was intended to be a sewage receiving node, while the second node functioned as a sludge discharging node. By using this modification, the time lapse from sewage was extracted to sludge was produced was ignored. The modification assumes that the sludge was produced at the same time as sewage was extracted, which is not really correct in reality.

6.11.3. Other Limitations

In this study, the component of industrial and commercial waste was not accounted for. In the Glenroy sewer subcatchment, this was not considered to be significant. But in many urban catchments, commercial waste may contribute to a significant proportion of total contaminant load. Also, the methodology does not account for practical implications and associated engineering requirements, or cost implications of installing water management practices for sustainable wastewater management.

7. CONCLUSIONS AND RECOMMENDATIONS

CONTENT: *Conclusions;*
Recommendations for Future Research

This chapter presents the conclusions drawn from this study and recommendations for future research. The conclusion consists of main discussion points, previously mentioned in Chapter 6.

7.1 Conclusions

This study set out to address a number of questions in relation to future wastewater management and its implications on existing sewer pipe networks. Subsequently, the study undertook to evaluate these implications through the development of a computer-based simulation methodology to quantify the effects of Water Management Practices (WMP), which include reduced water demand, *Alternative Water Sources* and a combination of reduced demand and alternative sources.

All approaches and assumptions used in the computer simulations are constrained by limitations of the models applied; thus there is a possibility of losing sight of the complex nature of wastewater generation and sewer processes. Even though some of the natural complex processes cannot be incorporated in the Integrated Urban Water model simulation, this model can simulate the developed scenarios with acceptable accuracy. Eventually, this will be a versatile simulation tool that will provide the basis for evaluating a number of WMP scenarios. Furthermore, the developed simulation model may play a role in future decision-making. The conclusions from this study are discussed in the following subsections.

7.1.1 Impact on Piped Water

The results indicate that each WMP scenario may offer opportunities for improvement in terms of sustainable use of natural water resources by reducing the demand of potable water. Among all selected WMP, *Sustainable Practice* scenarios of WDM-RH, WDM-GR and WDM-SM have the most potential to reduce potable water demand. However, the saving is mostly contributed from *Water Demand Management* that reduces water demand within a household. The implementation of *Alternative Water Sources* scenarios like *Greywater Recycling* and *Sewer Mining* do not contribute significantly to potable water saving, since their treated water can only be used for toilet flushing and garden irrigation. The only alternative water source that was acceptable for all indoor uses is collected rainwater from *Rainwater Harvesting*. Unfortunately based on many studies addressing the impacts of climate change on rainfall, it is predicted that although extreme rainfall events are likely to increase, the total rainfall will decrease. This will definitely reduce the reliability of *Rainwater Harvesting* for supplying household water. On the other hand, the reliability of greywater or wastewater supply is fixed and is therefore not affected by other factors (climate dependent water sources). Therefore, for sustainable water supply in future, greywater or wastewater is considered to be more reliable as compared to rainwater. Treated greywater and wastewater were considered to be the highest reliability water supply, if their treated water was not limited to toilet flushing and garden irrigation. However, for treated water from greywater and wastewater to be used as main supply to replace potable water for non-potable water consumptions, greywater or wastewater should treated to the highest quality (Class A), to comply with water recycling regulations and acceptable by the community.

7.1.2 Impact on Sewer Flow

Based on this study, the reduction of water demand and potable water replacement by other sources, such as treated greywater and treated wastewater, have proved to be capable of reducing sewer flow at various levels of reduction, depending on reduced water demand and reclaimed greywater and wastewater volumes. The only WMP scenarios in this study that did not affect the level of sewer flow is *Rainwater Harvesting*. There are several negative impacts of sewer flow reduction which advance the problem of sewer odour and corrosion through higher sulphide formation: increasing contaminant concentration discharged to sewer network, lowering sewer velocity and prolonging sewage residence time. Investigation of contaminant concentration by using wastewater flow and contaminant load showed that COD and sulphide concentration constantly increased in all scenarios, while other contaminant concentrations depended on the type of WMP.

The highest reduction of sewer flow occurred in the *Greywater Recycling* scenario of GR-BL and *Sustainable Practice* scenarios of WDM-GR and WDM-SM. The least impact of WMP adoption was contributed by *Rainwater Harvesting* scenarios. *Rainwater Harvesting* did not change the level of sewer flow, since it was an external factor of the wastewater system. Decreasing sewer flow affects the extent of transformation of pollutants in the sewer pipe system. This is noted regarding the possibility of formation of septic conditions, which will give rise to increased sewer odour and corrosion problems related to hydrogen sulphide gas. In conclusion, the study demonstrated that the adoption of WMP, particularly for those related to water reduction and wastewater/greywater recycle, may have a critical impact on sewer pipes due to reduction of sewer flow.

7.1.3 Impact on Sewer Odour

Model simulation results showed that all WMP scenarios can be observed to be potentially detrimental in terms of exacerbating the current condition of odour in sewer pipes. The *Rainwater Harvesting* scenario has the least detrimental impact on odour and corrosion, while WDM-GR and WDM-SM have the most impact. *Sewer Mining* also potentially contributes to worsening the problem of odour and corrosion. However, the effect of hydrogen sulphide build-up due to *Sewer Mining* does not occur immediately after the *Sewer Mining* point of extraction. The hydrogen sulphide build-up becomes extremely high after some distance from the point of extraction. This finding is important, so that preventive action of suppressing hydrogen sulphide by chemical dosing can be undertaken, when the hydrogen sulphide concentration starts to reach levels detrimental to human health as well as to pipe infrastructure. From all WMP scenarios simulation, it can be concluded that hydrogen sulphide gas is able to generate odour problem in low water demand reduction or low greywater volume uptake. It means that problem of odour is sensitive to little changes of wastewater characteristics.

By solely looking at the impact of these WMP scenarios on the problem of sewer odour due to hydrogen sulphide gas, it can be concluded that the best WMP for this study is *Rainwater Harvesting*. Although there is a marginal increase of hydrogen sulphide gas in *Rainwater Harvesting*, it did not change the current state of the hydrogen sulphide gas problem in the sewer network. WDM-GR and WDM-SM however totally changed the hydrogen sulphide problem in the sewer network. Almost all pipes in these two scenarios exceeded 10 ppm, which is a potential danger, if hydrogen sulphide is released above the ground or inhaled by sewer workers. Therefore action should be taken to reduce the formation of hydrogen sulphide gas in adopting *Sustainable Practice* scenarios WDM-GR and WDM-SM. The preventive action of chemical addition can be one of the most feasible options in the existing sewer network.

7.1.4 Impact on Sewer Corrosion

Hydrogen sulphide is also a trigger for pipe corrosion problems. The formation of hydrogen sulphide endangers pipes which are made of metals and reinforced concrete. In the study area, the sewer pipe material is a reinforced concrete, which is highly susceptible to exposure to hydrogen sulphide gas. Without adoption of any WMP scenarios, the corrosion rate is significant and threatened the lifetime of sewer pipes in the study area. WMP scenario adoption increases the corrosion rate, which consequently shortens pipe lifetime.

By analysing the results of this study, it can be found how much potable water can be reduced and how much the alternative water can be up taken so they will not aggravate the sewer problem of odour and corrosion. Further, the impact and the benefit of the WMP implementation was capitalized by using linier regression approach. WDM-GR and WDM-SM reduced initial pipe lifetime by more than 50%. Other WMP scenarios however reduced sewer pipe lifetime less than *Sustainable Practice* scenarios. The consequence of shorter pipe lifetime has impacted earlier pipe replacement or rehabilitation that can cost millions of dollars. *Rainwater Harvesting* scenarios did not greatly affect the current corrosion rate, since only a marginal increase of hydrogen sulphide gas occurred. Some preventative action has been investigated such as providing a vent pipe so there will be oxygen recirculation that can inhibit the formation of anaerobic conditions or some pipe coating. Another example is in green development areas, the pipe size be adjusted to accommodate the flow coming from sources having WMP technology installed on the properties. Many attempts to minimise the production of sulphide and therefore avoid the release of hydrogen sulphide into the sewer atmosphere; the rest are intended to directly protect the pipes through pipe coating.

Overall, *Sustainable Practice* scenarios which combined water demand reduction and use of *Alternative Water Sources* are more advantageous in terms of potable water saving, but the detrimental consequences on sewer pipe networks are much higher. Therefore, *Sustainable Practice* is not really a good option for downstream infrastructure like sewer pipes. Therefore, to obtain both benefits of water saving and minimising the effect on sewer pipes, optimisation of a single WMP scenario is recommended as compared to combined WMP scenarios, for example, *Sustainable Practice*. To conclude, the WMP that can satisfy sustainability demand of water saving without concurrently causing significant detrimental impacts to existing downstream infrastructure, is the preferred option. Further, from analysis of dissolved sulphide concentration in all scenarios, it can be concluded that dissolved sulphide concentration that can trigger severe corrosion will occur in medium to high water demand reduction or medium to high greywater volume uptake. It means that the severe corrosion will not be easily occurred when there is little change in wastewater characteristics.

7.1.5 Impact of WMP Adoption on Odour and Corrosion in Wet Weather

In wet weather, sewer pipes usually have higher sewer flows compared to dry weather. In existing sewer networks, the sewer flow is mostly boosted by some external flows. However, when the external flow is negligible (sewer pipe in perfect condition), the additional flow is obtained from residual water that was not taken up for outdoor use. The external flow for sewer pipes is mainly derived from direct inflow and infiltration, which depends on the season. Pipe cracks, and defects as well as pipe joint defects are the external inflow passage ways that enter the sewer network.

In the study area, the existing sewer pipes have been proved to be very much affected by external inflow in wet weather. High inflow and infiltration in sewer pipes in the study area show they are deteriorating. Pipe and joint defects could be caused by the existence of hydrogen sulphide, which corrodes pipe material, hence moistens pipe surface. The investigation of the impact on wet weather was conducted on dry days in the wettest month of the year. Hence, the impact was assessed based on the wettest dry days, with the expectation that the formation of hydrogen sulphide gas would be very low (zero). It is clearly seen that the influence of WMP adoption on hydrogen sulphide formation in the wettest dry days is significantly reduced, but still marginal hydrogen sulphide formation occurs. This indicates that on other dry days (not necessarily the driest days), hydrogen sulphide will be formed, but in various concentrations, depending on sewage dilution. Thus, it can be concluded that in the future, the significant impact due to sewer odour and corrosion will still be experienced as a seasonal problem, and will only occur in dry weather.

7.1.6 Impact of Scaling Up of WMP Adoption in Future Urban Development

From an investigation of current urban development, it can be shown that each of the observed WMP scenarios exacerbated the problems of odour and corrosion. Climate change studies predict longer, dry days will occur in future, which is likely to lead to the increasing adoption of WMP in years to come. Hence, it is nearly impossible to avoid the detrimental effects of these scenarios in terms of increasing odour and corrosion problems in sewer networks.

From 2060, this study projected that the problem of sewer odour and corrosion in sewer networks will be mainly affected by urbanisation and population growth. Concerning the ability of WMP scenario to influence sewer flow and hydrogen sulphide formation, which subsequently leads to sewer odour and corrosion, this seems to be influenced by the scale at which the technologies are implemented. However, results obtained for scale up *Rainwater Harvesting* will not affect sewer flow, but hydrogen sulphide formation will still occur. The number of households adopting WMP scenarios is proportional to the reduction of sewer flow (except for *Rainwater Harvesting*) and will increase hydrogen sulphide. Hence, more households that implement WMP scenario will thus increase the risk of the occurrence of sewer odour and corrosion.

The only way to reduce the detrimental effects for sewer pipes in the future would be by controlling the production of hydrogen sulphide within acceptable threshold levels, which are not harmful to human health and infrastructure. For existing sewer networks, there are many controlling methods, which include chemical dosing and source control of wastewater. For new sewer systems, more controlling methods are available. These include the two controlling methods mentioned above and also by designing smarter sewer networks. Designing a smarter sewer means optimising sewer design in order to minimise sulphide formation as well as improving sewer pipe resistance to sewer corrosion.

7.2 Recommendations for Future Research

In order to improve the results of the modeling undertaken in this study, and usability of this study for implementation in the real world, several recommendations are provided.

1. The Integrated Urban Water model framework should be validated to another study area, which has the characteristics of a residential area, with separate existing sewer pipe networks and hydrogen sulphide build-up.
2. The simulation should be conducted for several dry and wet months so that the variation of weather and population behaviour on indoor water consumption can be recorded. This is because there is a possibility that the weather influences people's water demand in different ways.

3. In the *Rainwater Harvesting* scenario, simulation should include the usage of collected rainwater to supply multiple indoor water consumptions, such as bathroom, laundry and toilet, therefore the system's arrangement will be similar to the reality.
4. Time series of hydrogen sulphide analysis will be very beneficial for calculating when hydrogen sulphide mostly occurs in sewer pipe networks. However, this recommendation needs more effort in terms of modeling tool development, since so far there is no tool that provides a dynamic model from the source of wastewater generation up to the dynamic sewer system.
5. The physical, chemical and biological processes, and dynamic inflow, infiltration and exfiltration should be taken into account from the wastewater discharge point, which is the household (by using UVQ model). The model used in this study ignored all the physical and biochemical processes in the surrounding location of wastewater production (e.g. household sewer pipe, greywater and rainwater storage tank, etc.). It will be beneficial in a future study, to include more spatial detail to obtain a better idea of when hydrogen sulphide starts to build up.
6. Simulations of wastewater production, wastewater quality produced by the household and sewer processes are inherently stochastic. A mathematical simulation of those items based upon statistical variations would enable improvement in modeling capabilities and subsequently the predictive confidence of simulation results will increase.
7. Many current deterioration models did not include type of waste as indicators. According to this study, a wastewater characteristic is very important to determine the sustainability of sewer infrastructure. Hence, for future study of sewer pipe deterioration models, it is recommended that type of waste be included as the main indicator to build the model.
8. Further research on analysing the whole cost of WMP adoption on the sustainability of water resources and downstream infrastructure is recommended. Hence those WMP can be ranked based on modeling result analysis and cost analysis of potable water saving and downstream infrastructure sustainability (sewer pipe).

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APPENDIXES

- **Appendix 1** : Yarra Valey Water (YVW)'s Field Measurement & Model Data
- **Appendix 2** : Urban Volume & Quality (UVQ) Contaminants Concentration
- **Appendix 3** : Procedure to Determine Rainfall Derived Inflow & Infiltration (RDII) Parameters (R; T; K; S_{max}; I_a; Rec)
- **Appendix 4** : Calibration Procedure by using Sensitivity-based Radio Tuning Calibration (SRTC) Tool
- **Appendix 5** : Procedure & Result of Laboratory Experiment to Obtain "Wastewater Aerobic-Anaerobic Transformation in Sewer (WATS)" Model Parameters.
- **Appendix 6** : Model Parameters of WATS Model
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- **Appendix 8** : Pipe Stretch Plot for WMP Scenario of All WMP Scenario except *Sewer Mining* Scenario
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Appendix 1. Yarra Valey Water (YVW)'s Field Measurement & Model Data

1) Flow Data

   YVW conducted flow monitoring in September 2007. This data were used to calibrate and validate their flow model. In the Glenroy sewer branch, the flow monitoring was conducted at the manholes GLN1, which is located in Subcatchment PAVA25 and GLN31, which is located in Subcatchment PAVA24. Based on the calibrated model, the flows at GLN8A and GLN23 were obtained. The results from this flow monitoring for GLN8A and GLN23 can be seen in Figure A.1. Later in 2010, one of the manholes (GLN23) used as locations to do flow monitoring and contaminant sampling (See Chapter 3 for manholes location).

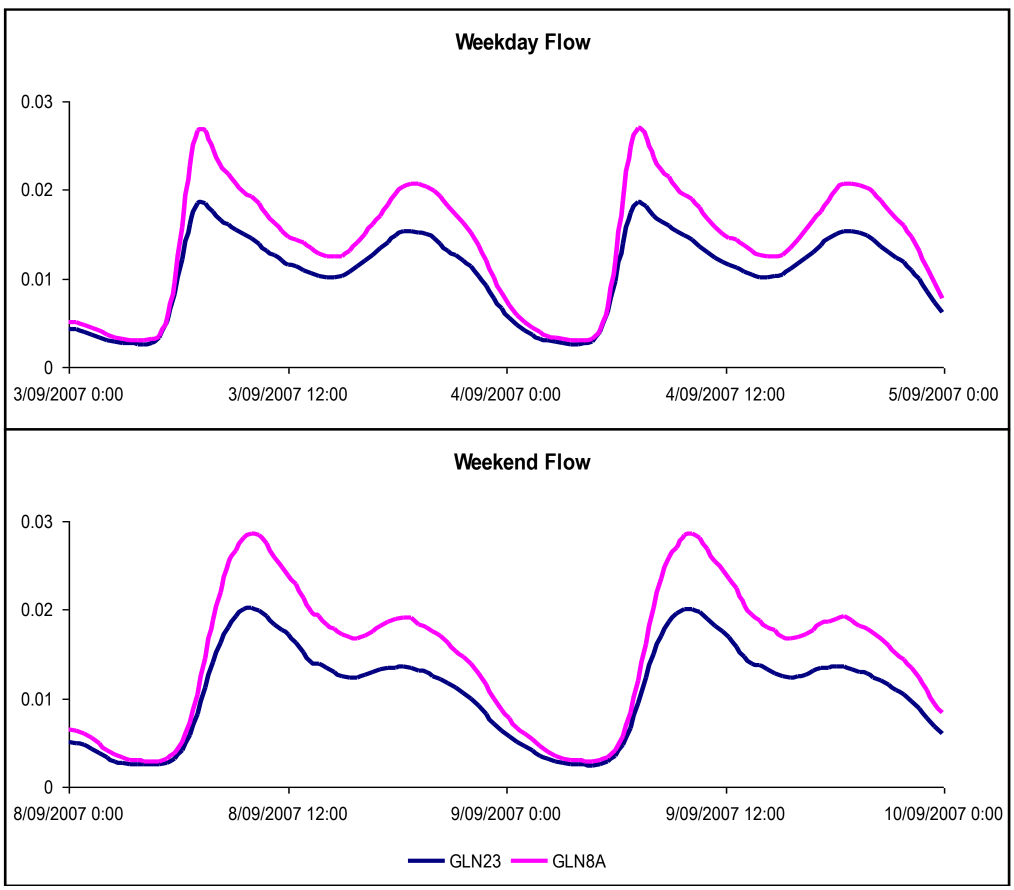


Figure A.1. Weekday And Weekend Flow From YVW's Calibrated Model On September 2007

2) Hydrogen Sulphide Gas

YVW had conducted an investigation of hydrogen sulphide gas in April, 2010. Samples were collected downstream from manhole (GLN2. At that time, hydrogen sulphide gas was detected with low concentrations, between 1-7 ppm hydrogen sulphide gas (YVW 2010b). Examining Bureau of Meteorology (BoM) data for April 2010, the lowest rainfall was identified during the month compared to other months indicating that limited dilution conditions during the month. The hydrogen sulphide gas plot with rainfall and temperature can be seen in Figure A.2.

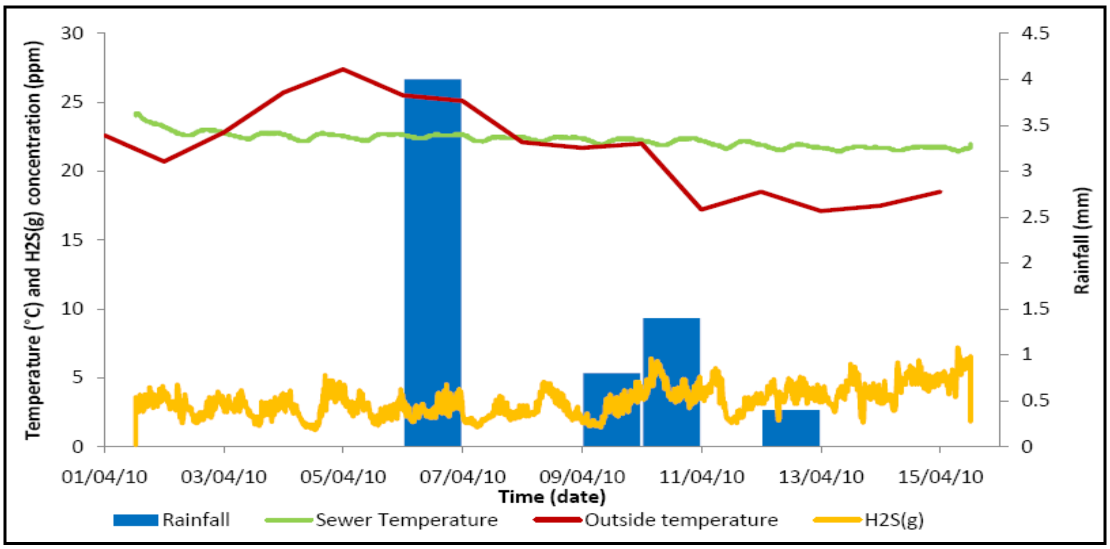


Figure A.2. Sewer Temperatures, Rainfall and Outside Temperatures from The Previous Measurement, April 2010

Appendix 2. Urban Volume & Quality (UVQ) Contaminants Concentration

Table A.1. Contaminant Input Data

Contaminants		**Pavement Runoff**	**Road Runoff**	**Roof First Flush**	**Groundwater**
COD	mg/L	300	300	300	0
Nitrate	mg/L	0.05	0.05	0.05	1.13
Sulphide	mg/L	0	0	0	0
Sulphate	mg/L	7.31	7.31	7.31	161
Iron	mg/L	0.07	0.07	4.2	7.7

Appendix 3. Procedure to Determine Rainfall Derived Inflow & Infiltration (RDII) Parameters (R; T; K; S_{max}; I_a; Rec)

The procedure for determining the RDII parameters (R, T, K, S_{max}, I_a and Rec) follows the approach formulized by Gheith (2010) which can be summarized as follows:

a) Process rain gauge data and flow meter data to identify storms where the soil Antecedent Moisture Condition (AMC) impact on unit hydrograph parameter (R, T and K) is minimal. The best situation is to have a storm event which is shortly preceded by another large storm. Two examples of this type of situation are presented in Figure A.3. If applicable, an event at times where the groundwater level was high and temperature was low would lead to best results. The high groundwater level will minimize the surface runoff to be abstracted and stored in groundwater storage system and the low temperature will reduce evaporation. This will help minimize the effect of storage recovery rate between the events and will keep the initial abstraction depth at a minimum.

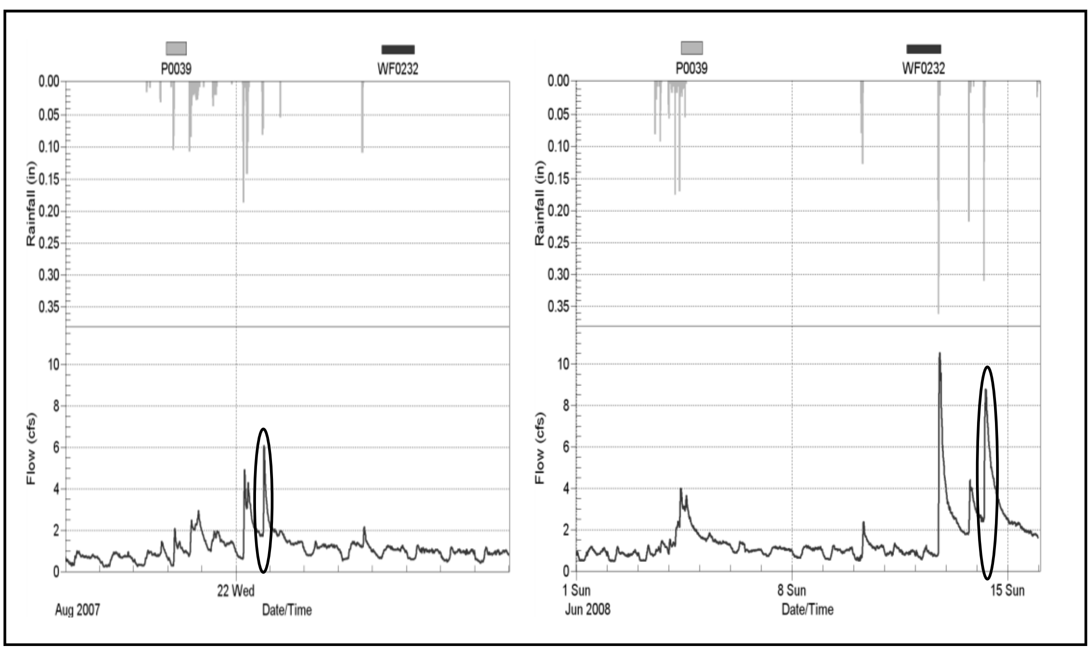


Figure A.3. Examples Of RDII Events Where Initial Abstraction Depth Is Minimal (≈Zero) (Adopted From Gheith (2010))

b) Determine R by assuming that initial abstraction ≈ 0, then the Equation becomes :

Equation A.1

$$R = \frac{RDII}{A_{Serviced} * i_{total\ rain}}$$

Where :

R	: Percentage of excess rain entering the collection system as RDII. The R parameter is a user-defined parameter and is function of size and number of defects. R increases with the number of pipe defects that would allow RDII to enter the collection system. Theoretically, R will be zero for "tight" portions of the collection system regardless of the precipitation volume and climatic conditions.
RDII	: Rainfall-Derived Inflow & Infiltration
$A_{serviced}$	: Serviced portion of the sanitary sewershed area upstream from the flow meter. Only the area expected to contribute to RDII should be considered. This is also a user-defined value which can be obtained using GIS or aerial maps with knowledge of collection system distribution (public and private sewers)
$I_{total\ rain}$	: Precipitation data from rain gauges

Knowing the rainfall intensity ($i_{total\ rain}$) and RDII from the rain gauge and flow meter data for the selected storm event, R can be solved for using Equation A.1.

c) Calibrate for T and K to match simulated peak flow and shape to the observed hydrograph.

d) Use the same R, T, and K in all events and apply appropriate maximum storage and recovery rate to calibrate for the other storm event(s). SWMM4.4 and SWMM5 allow for monthly recovery rate and maximum storage for each of the three triangles used to simulate the three RDII sources.

Appendix 4. Calibration Procedure by using Sensitivity-based Radio Tuning Calibration (SRTC) Tool

Procedure in Sensitivity-based Radio Tuning Calibration

The calibration & verification technique in PC-SWMM was called as SRTC technique. The method is undertaken using a known uncertainty percentage defined by the user and observed time series data in modelled area. When SRTC is run, PC-SWMM completes two computations, one for each extreme high and low percentage of the selected uncertainty range. The value laid between the high and low percentage is called sensitivity gradient. This sensitivity gradient is used to estimate the PC-SWMM computed response. The SRTC calibration actually provides a calibration process that linearly interpolates the value between two extremes in sensitivity gradients. This technique can be used both for calibration and for sensitivity analysis. For sensitivity analysis purposes, the SRTC tool provides insight to the sensitivity of the chosen response function to one or more model parameter. Moreover, sensitivity analysis does not require observed time series data.

There are two important windows which are important in SRTC calibration. These windows are the uncertainty estimate panel and slider bar to adjust the calibrated value. To calibrate a model with SRTC tool, the following steps should be performed :

a) Assign uncertainty estimates to the desired SWMM5 model parameters using the table panel (See Figure A.4).

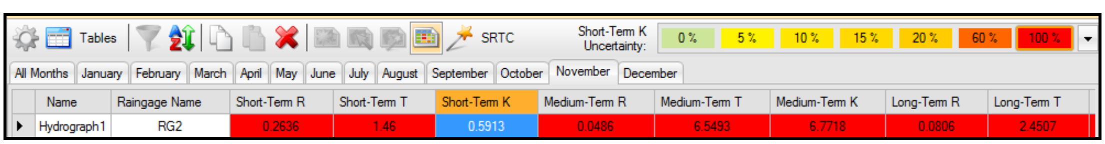


Figure A.4. Uncertainty Estimate Panel

b) Run the SRTC calibration tool.
c) Once it finished computing, then the slider bars will appear.
d) Load observed time series either through Graph panel or SRTC calibration panel.
e) Through Graph panel or SRTC calibration panel, select the events for calibration.

f) Calibrate the model parameter by adjusting the slider (move the slider up and down – See Figure A.5) until it match the observed time series data or by looking at the value of goodness of fit measures (i.e. RMSE & R).

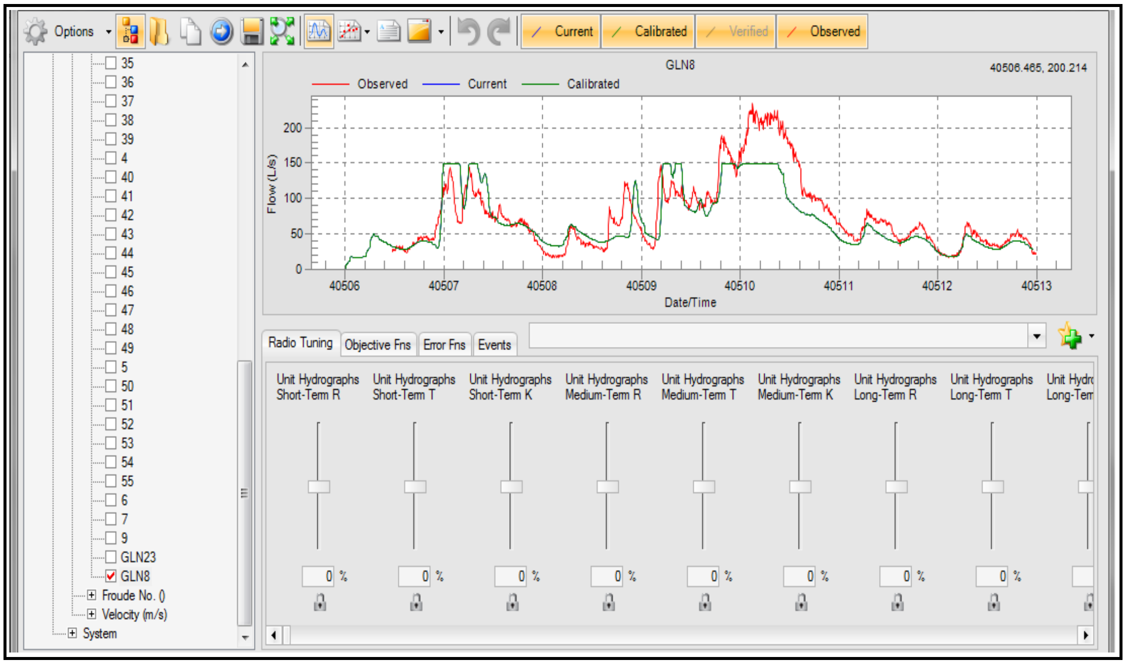


Figure A.5. Slider Bar To Adjust The Calibrated Value

g) Once it fitted to the observed time series data, it can be verified.

h) The new model parameter values can be saved to either current project or new scenario.

i) Re-run the whole model.

j) In Graph panel, select the calibration tab then the plot of the observed and simulated value will appear.

Appendix 5. Procedure & Result of Laboratory Experiment to Obtain "Wastewater Aerobic-Anaerobic Transformation in Sewer (WATS) Model Parameters"

1) **Procedure in Laboratory experiments**

❖ **Determination of kinetic parameters**

The lab experiments were conducted by using three cyclindrical plastic containers as batch reactors with 2 L volume. Each experiment used three reactors to measure: bulk water sulphide production, biological and chemical sulphide oxidation and biodegradability by measurement of the Oxygen Uptake Rate (OUR). The reactor arrangement can be seen in Figure A.6.

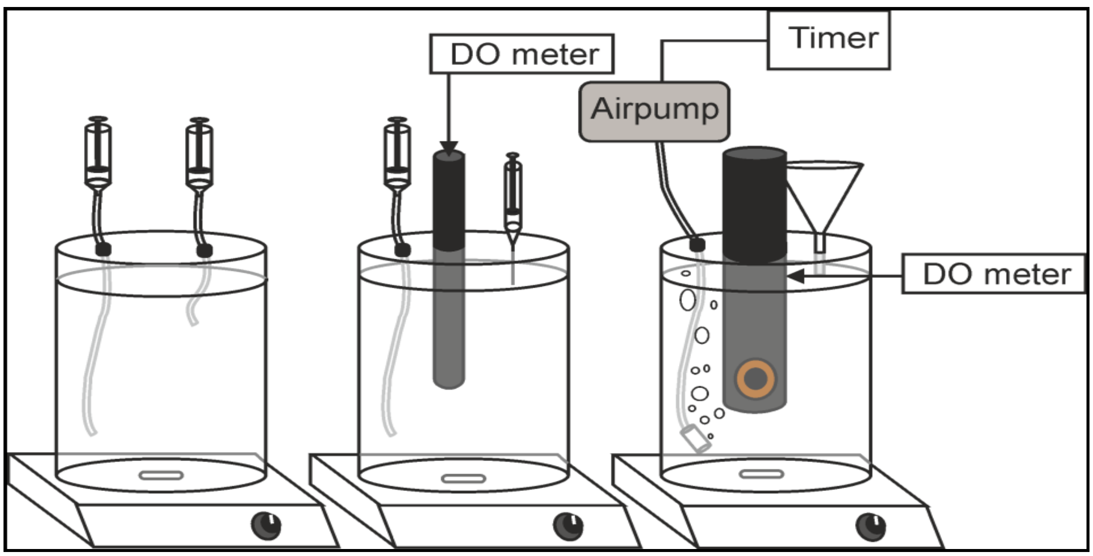


Figure A.6. The 3 Batch Reactors for Sulphide Production (Left), Hydrogen Sulphide Oxidation (Middle) And OUR (Right)

❖ **Sulphide Production**

The reactor was sealed by using resin material to keep it airtight. The wastewater consumptiond for this experiment was stored in a sealed container for 24 hours to create anaerobic conditions. At set intervals of 15 min, 10 mL samples were extracted and analysed to determine the change in sulphide concentration. When the samples were extracted the sample volume was replaced with wastewater from a separate anaerobic container in order to keep the volume constant in the reactor. From the 10 mL sample, a smaller sample of 0.5 mL was immediately preserved in 1 mL 10% zinc acetate and then diluted to 10 mL with DI water before analysis. By diluting the samples 20 times it was deemed unnecessary to filter the samples. The experiment was run for a maximum of 6 hours and was repeated twice.

❖ **Biological and Chemical Sulphide Oxidation**

The procedures for these two analyses were the similar, but for chemical sulphide oxidation, the wastewater was autoclaved first and the analysis container was first disinfected.

For both oxidation experiments, the reactor was filled with wastewater aerated for at least for 24 hours prior to the start of the procedure (Nielsen et al. (2003)). The reactor was set up with a magnetic stirrer, a Hannah Instruments (HI) 9140 DO-probe and two syringes, one for sampling and one for addition of $Na_2S{\cdot}3H_2O$ stock solution. The analysis mixture was constantly stirred with a magnetic stirrer. The 12M $Na_2S{\cdot}3H_2O$ stock solution was made with 100 mL of oxygen stripped deionised water (DI) (nitrogen was used to strip the oxygen from the water) and then adding 0.4182g washed and dried $Na_2S{\cdot}3H_2O$ to the water.

The wastewater was aerated until the DO concentration reached around 7 mg/L, then the aeration was stopped. To find the initial rate of sulphide demand in aerated wastewater, the DO concentration was measured every minute for up one hour and the mixture was left unmixed until the DO concentration fell below 1 mg/L.

The wastewater was re-aerated for 30-60 min by using an aerator that was not connected permanently to the reactor. The DO was then measured for 3 min before adding the 10 mL $Na_2S{\cdot}3H_2O$ stock solution to reach a total amount of 5 mg S/L.

Samples for sulphide analysis were extracted for each 0.5 mg O_2/L decrease in DO. 10-15 mL was extracted from the reactor before each sample was taken to ensure fresh sample from the reactor were extracted (there was a 10-15mL dead space in the sample apparatus). Then 0.5 mL sample was extracted and preserved in 1 mL 10% zinc acetate. Samples were diluted with DI up to 10 mL. This dilution reduced suspended solids concentration so that sample filtration was unnecessary. After each experiment the validity of the DO-probe was checked in a beaker of aerated water. Sulphide will degrade the sensitivity of the probe by formation of silver sulfide on the working electrode. The DO-values showed no significant change.

❖ **Biodegradability (OUR)**

This analysis required the development of an OUR curve (the rate of reduction of DO concentration over time vs time) to determine the biodegradability of the wastewater according to the COD-defractionation method (Vollertsen & Hvitved-Jacobsen 2002)). For this experiment, the reactor was filled with fresh wastewater, and s fitted with an optical DO-probe (D-Opto, New Zealand), an air pump, a magnetic stirrer and an expansion funnel. The reactor was sealed to make it airtight by using resin material. The air pump was connected to a timer which was set to turn on and off at set intervals in order maintain aerobic wastewater. Initial experiments showed that the fresh wastewater was very biologically active and the DO concentration decreased rapidly, to quickly to allow sufficient monitoring. To avoid this issue all subsequent samples were diluted 1:1 with DI water. The experiment ran for up to 48 hours in order to ensure detail of the “tail” of the OUR curve was measured.

2) Result

❖ **Sulphide Production**

The wastewater samples for sulphide production were grab samples which were taken adjacent to the autosampler. Sulphide concentration in the samples declined over the period of the analysis indicating no sulphide production in the water phase during the analysis period, see Figure A.7. According to the study of Pomeroy (1959), sulphide production in bulk wastewater is minimal (<3%) and the biofilm and silt deposits were identified as the two components where major sulphide production occurred. An increase might have been seen if the experiments had been run over several days, but with the described setup the possible production recorded could also be caused by biofilm growing inside the reactor.

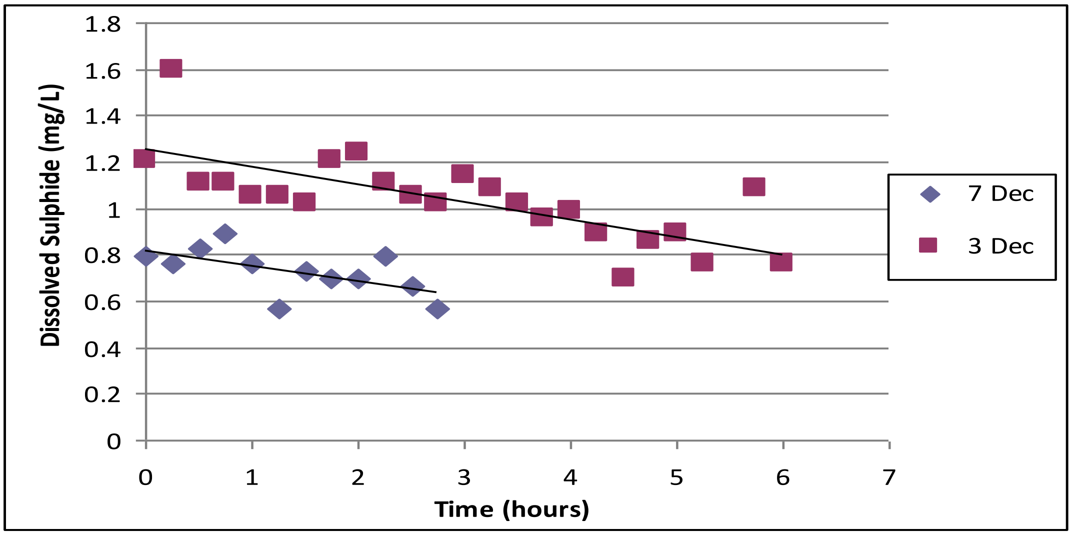


Figure A.7. Sulphide Concentration From Sulphide Production Experiment

❖ **Sulphide Oxidation**

Sulphide oxidation comprises of bio oxidation (or total oxidation) and chemical oxidation. Results from two oxidation experiments showed similar trends in sulphide reduction, see Figure A.8. Chemical oxidation (the blue series in the graph below) was expected to remain constant prior to addition of the stock solution. However, an immediate reduction was observed suggesting interference by biological activity. An explanation for this could be that either the reactor or the aerator stone were not cleaned/disinfected thoroughly before the experiment, allowing biological activity to occur in the reactor. The slopes of the curves for bio or total oxidation are fairly similar (the green and red series in the graph below), though it was expected that the slopes would be significantly steeper after the stock solution was added, see Figure A.9. This could be due to a high biological oxygen use which was also observed in the Oxygen Uptake Rate experiments, but here it is impossible to determine how much of the oxygen removal is due to sulphide oxidation and how much is due to other biological growth. Since the depletion of oxygen concentration was not different between the experiment before and after sulphide stock solution, then the sulphide oxidation rate cannot be estimated.

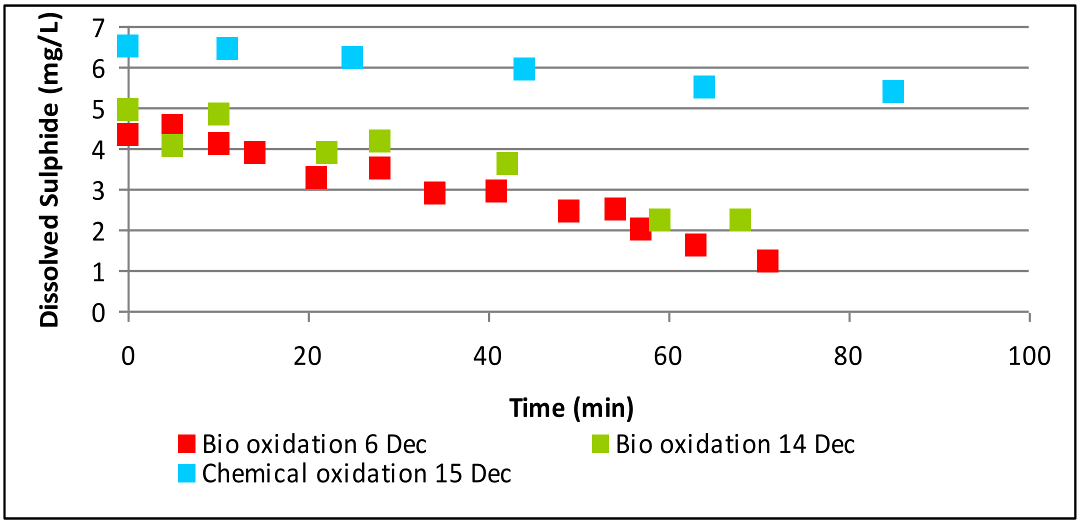


Figure A.8. The Sulphide Concentration After Added The Sulphide Stock Solution

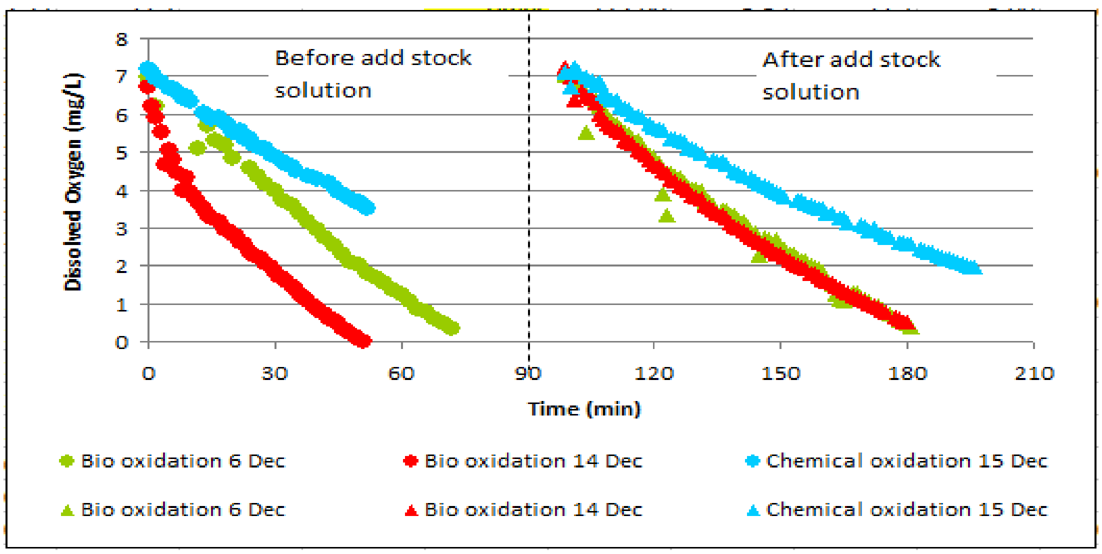


Figure A.9. The Oxygen Concentration Before And After Added The Sulphide Stock Solution

❖ **OUR (biodegradability) / Heterotrophic Maximum Growth Rate**

The result from the biodegradability experiments gave sufficient data to measure the initial OUR concentration and maximum growth rate. However, temperature control at a constant 20^{o}C is required to determine the maximum growth rate and the reactor temperature in this study varied between 18-25^{o}C. Thus the maximum growth rate could not be calculated accurately.

The OUR measurement indicates that the wastewater contains a high concentration of biodegradable matter and this finding is consistent with literature describing organic matter in sewer wastewater (Vollertsen & Hvitved-Jacobsen 2002) (See Figure A.10). In the OUR experiment, the dissolved oxygen concentration should be maintained above zero, as there are difficulties in increasing the oxygen concentration again. However, manual equipment was used in this study and it was not possible to maintain dissolved oxygen at greater than zero.

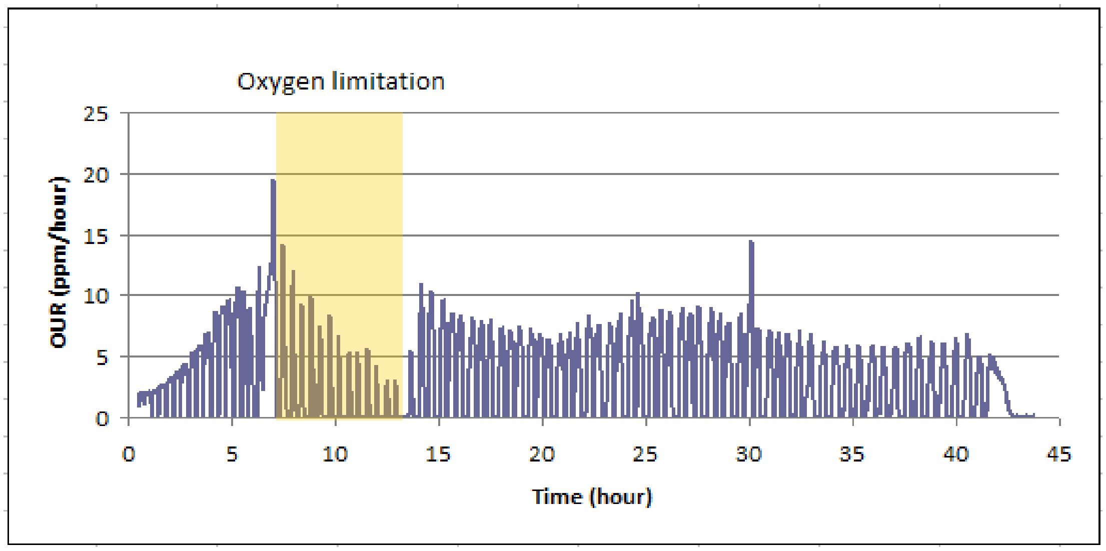


Figure A.10. The OUR Plot For Diluted Wastewater

Despite these difficulties, enough data was collected (see Figure A.10) in order to estimate, the initial OUR, OUR(t_0), and the maximum growth rate, μ_H, to 1.82 ppm/h and 9.61/day, respectively. The maximum growth rate was determined by plotting the natural logarithm of OUR to initial OUR value vs time (Figure A.11).

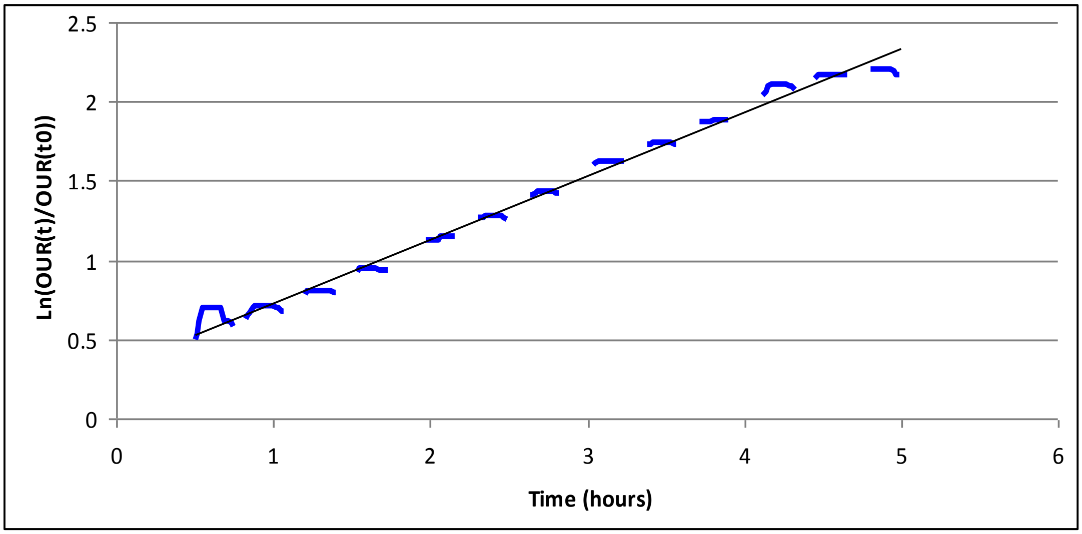


Figure A.11. The Natural Logarithmic Plot Of The Initial OUR

3) Identified Problem in Laboratory Experiment

In conclusion, there were errors in laboratory methods and techniques which meant not all required parameters could be estimated with certainty. Some of the problems with the laboratory experiments were :

1) Sulphide Production : The experiment was not carried out for a long enough period of time to produce good data of sulphide production. This problem is due the manual operation of equipment as sulphide samples needed to be taken at least every 20 mins for more than 24 hour (3 days is suggested duration to do this experiment).
2) Sulphide Oxidation : This experiment provided an indicative result but not accurate estimatation of the oxidation rate. The cause of similar rates of oxygen depletion before and after adding the sulphide stock solution stock was unknown but was potentially impacted by a wastewater with very high biodegradability. Similar reductions in DO for both bio oxidation and chemical oxidation might due incomplete cleaning and disinfection of the reactor vessel and contents.
3) Biodegradability (OUR experiment) : These three experiments provided an estimation of initial OUR and maximum growth rate. The start up problem is due to the equipment such as DO meter. Frequent replacement of the DO probe was required during this experiment in order to maintain DO meter function. The

manual setup of the experiment also hindered operation as maintaining the DO concentration above zero was difficult and short aeration periods did not increase the DO concentration to the previous level. In addition, the reactor was not covered by the water bath so temperature was not maintained at 20^{o}C.

Due to these difficulties not all the site-sensitive parameters were obtained and so data from previous studies was used. A high temperature hydrogen sulphide gas prediction study in Middle East (Vollertsen et al. 2010) was selected to provide the missing parameters. The study in Middle East was selected to fill out the missing parameters due to the same area characteristics which is arid area and weather condition in summer condition (temperature).

Appendix 6. Model Parameters of WATS Model

Table A.2. WATS Model Parameters

WATS Model Parameters	Value
Maximum growth rate of the heterotrophic biomass at 20°C (my);1/d	9.6
Maximum growth rate of het. biomass utilizing NO_3 at 20°C (my);1/d	2
Maximum growth rate of het. biomass utilizing NO_2 in the presence of NO_3 at 20°C (my);1/d	2
Maximum growth rate of het. biomass utilizing NO_3 in the absence of NO_3 at 20°C (my);1/d	2
Yield constant for bulk water aerobic heterotrophic biomass (Y_{HwO2});mol e-eq/mol e-eq	0.3
Yield constant for bulk water anoxic heterotrophic biomass (Y_{HwNO});mol e-eq/mol e-eq	0.1
Saturation constant for readily biodegradable substrate (KS);gCOD/m^3	0.1
Saturation constant for dissolved oxygen (KO);gO_2/m^3	0.01
Saturation constant for het. growth on nitrate (KNO_3);gN/m^3	0.2
Saturation constant for het. growth on nitrite (KNO_2);gN/m^3	0.1
Maintenance energy rate constance at 20°C (qm);1/d	0.5
Maintenance rate during NO3 respiration;1/d	0.33
Maintenance rate during NO2 respiration in the presence of NO_3;1/d	0.42
Maintenance rate during NO2 respiration in the absence of NO_3;1/d	0.42
Rate constant for fast hydrolysable substrate at 20°C (kh,fast);1/d	7.3
Saturation constant (KX,fast) for kh,fast dependents on kh,fast with the slope (no dependency = zero);gCOD/gCOD	0.23
and with the intersection (if no dependency, then this is equal to KX,fast);gCOD/gCOD	-0.5
Rate constant for medium hydrolysable substrate at 20°C (kh,med);1/d	1
Saturation constant (KX,med) for kh,med dependents on kh,med with the slope (no dependency = zero);gCOD/gCOD	0.23
Saturation constant (KX,med) for kh,med dependents on kh,med with the slope (no dependency = zero);gCOD/gCOD	-0.5
Rate constant for slow hydrolysable substrate at 20°C (kh,slow);1/d	0.5
Saturation constant for slow hydrolysable substrate (KX,slow);gCOD/gCOD	0.9
Anaerobic hydrolysis effectivity constant (eta,h,anaerobic);-	0.3
Biofilm biomass effeciency constant (epsilon);-	0.1
Biofilm biomass concentration (XB,film);gCOD/m^2	30
½ order rate constant for biolfilm, aerobic conditions	10

WATS Model Parameters	Value
(k½O_2);(gO_2/m)½ 1/d	
½ order rate constant for biolfilm, NO_3 reduction (k½NO_3);(gN/m)½ 1/d	4
½ order rate constant for biolfilm, NO_2 reduction in the presence of NO_3(k½NO_2I);(gN/m)½ 1/d	5
½ order rate constant for biolfilm, NO_2 reduction in the absence of NO_3(k½NO_2II);(gN/m)½ 1/d	5
Yield constant for biofilm biomass, aerobic conditions (Y_{HfO2});gCOD/gCOD	0.55
Yield constant for biofilm biomass, anoxic conditions (Y_{HfNO});mol e-eq/mol e-eq	0.37
Saturation constant for biofilm organic substrate;gCOD/m^3	4
Rate constant for fermentation at 20°C ($q_{,fe}$);1/d	3
Saturation constant for fermentation (K_{fe});gCOD/m^3	5
Relative hydrolysis under anoxic conditions compared to oxic condition (f_{nyNOh});-	0.8
Saturation constant under anoxic conditions (KNO);gNO/m^3	0.5
Hydrogen sulfide formation rate constant (kH_2S);(mgH_2S/(m2h))^$^{0.5}$	32
Power of concrete corrosion dependency on H_2S gas concentration;ppm H_2S	0.7
Rate constant for concrete corrosion;gH_2S/(m^2 d)	0.864
Difference in reaeration rate, wastewater to clean water (alpha_rea);-	1
Difference in DO saturation concentration, wastewater to clean water (beta_rea);-	1
Saturation inhibition constant for biofilm H_2S formation in the presence of oxygen (KoH_2S);gO_2/m^3	0.3
Saturation inhibition constant for biofilm H_2S formation in the presence of nitrate/nitrite (KNOH_2S);gN/m^3	0.4
Saturation inhibition constant for biofilm H_2S formation with respect to sulfate (KSO_4);gS/m3	1
Fraction of the formed sulfuric acid that acts with the concrete surface;-	0.5
Arhenius constant for the bulk water heterotrophic transformations (alpha_w);-	1.07
Arhenius constant for reaeration (alpha_r);-	1.03
Arhenius constant for the H_2S emission (alpha_rs);-	1.03
Arhenius constant for the biofilm heterotrophic transformations (alpha_f);-	1.05
Arhenius constant for the biofilm H_2S formation (alpha_s);-	1.05
Arhenius constant for the chemical oxidation of sulfide;-	1.07
Arhenius constant for the biological oxidation of sulfide in the bulk water;-	1.07
Rate constant for chemical oxidation of H_2S;gH_2S/(m^3 d)	0.96
Rate constant for chemical oxidation of HS^-;gH_2S/(m^3 d)	12

WATS Model Parameters	Value
Rate constant for biological oxidation of sulfide;$gH_2S/(m^3\ d)$	12
ph optimum for heterotrophic and autotrophic processes;-	7.5
Parameter accouting for the width of the biological sulfide oxidation pH dependency;-	25
Parameter accouting for the width of the biological heterotrophic pH dependency;-	175
Space step of the calculations. A smaller space step reduces noice.;m	1
Max time step of the calculations. A smaller step increases accuracy.;m	10
Stoichiometric reaction coefficient of chemical sulfide oxidation, bulk water;gS/gO_2	0.9
Stoichiometric reaction coefficient of biological sulfide oxidation, bulk water;gS/gO_2	2
Stoichiometric reaction coefficient of chemical sulfide oxidation, biofilm;-	2
H_2S biofilm oxidation rate;$gS/(m^2\ d)$	2.4
H_2S bulk water chemical oxidation order with respect to sulfide;-	1
H_2S bulk water chemical oxidation order with respect to oxygen;-	0.1
H_2S bulk water biological oxidation order with respect to sulfide;-	1
H_2S bulk water biological oxidation order with respect to oxygen;-	0.1
H_2S biofilm oxidation order with respect to sulfide;-	0.5
H_2S biofilm oxidation order with respect to oxygen;-	0.5

Appendix 7. Result of Wet Weather Flow Simulations

Table A.3. Fraction of COD . Biodegradability

Scenario	**Average CODTotal**	**S_A**	**S_F**	**X_{BW}**	**X_{Sf}**	**X_{Sm}**	**X_{Ss}**
	mg/L						
	100%	5.3%	5.3%	3.4%	13%	20%	53%
Base Case	452	24.0	24.0	15.4	58.8	90.4	239.6
WDM1	468	24.8	24.8	15.9	60.9	93.7	248.3
WDM2	501	26.6	26.6	17.0	65.1	100.2	265.5
WDM3	535	28.4	28.4	18.2	69.6	107.0	283.7
GR-BL	425	22.5	22.5	14.5	55.3	85.1	225.4
GR-L	448	23.8	23.8	15.2	58.3	89.7	237.7
GR-B	502	26.6	26.6	17.1	65.3	100.5	266.3
RH-T	458	24.3	24.3	15.6	59.6	91.7	243.0
RH-L	462	24.5	24.5	15.7	60.1	92.4	244.9
RH-B	464	24.6	24.6	15.8	60.3	92.8	245.8
SM1	726	38.5	38.5	24.7	94.4	145.3	385.0
SM2	1057	56.0	56.0	35.9	137.4	211.3	560.0
SM3	1469	77.9	77.9	50.0	191.0	293.9	778.7
WDM-RH	541	28.7	28.7	18.4	70.3	108.1	286.5
WDM-GR	518	27.4	27.4	17.6	67.3	103.6	274.5
WDM-SM	2213	117.3	117.3	75.3	287.7	442.7	1173.1

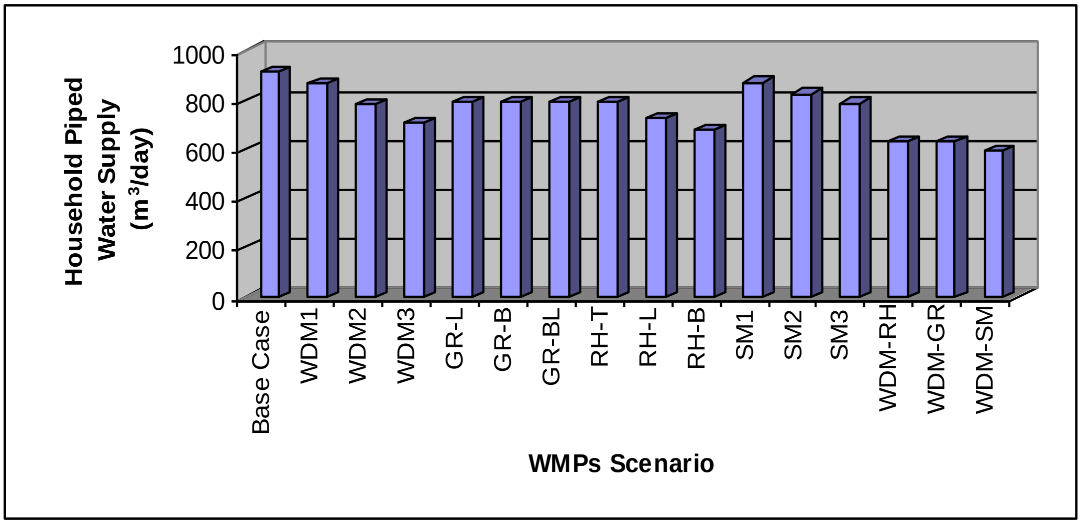


Figure A.12. Total Household Piped Water Supply in Wet Weather

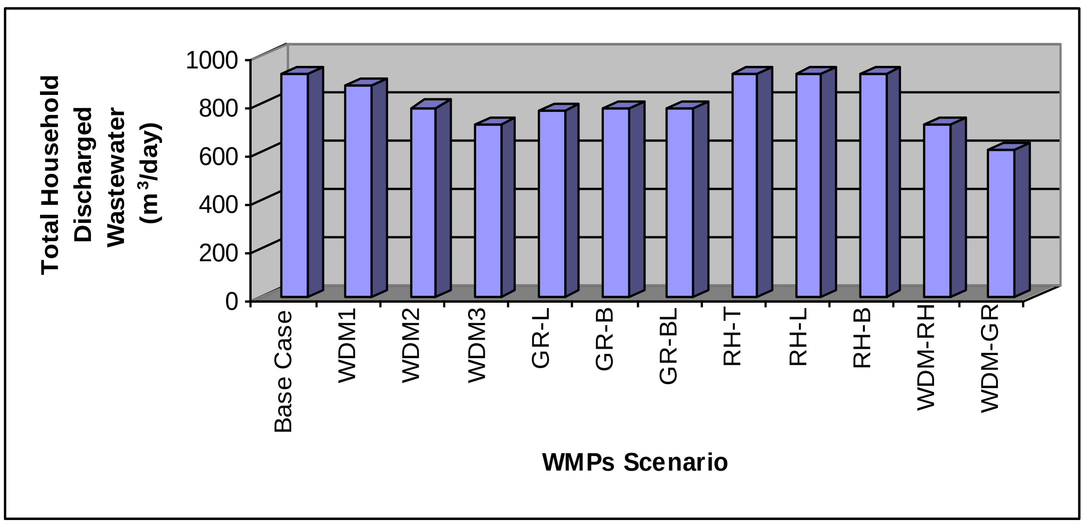


Figure A.13. Total Household Discharged Wastewater in Wet Weather

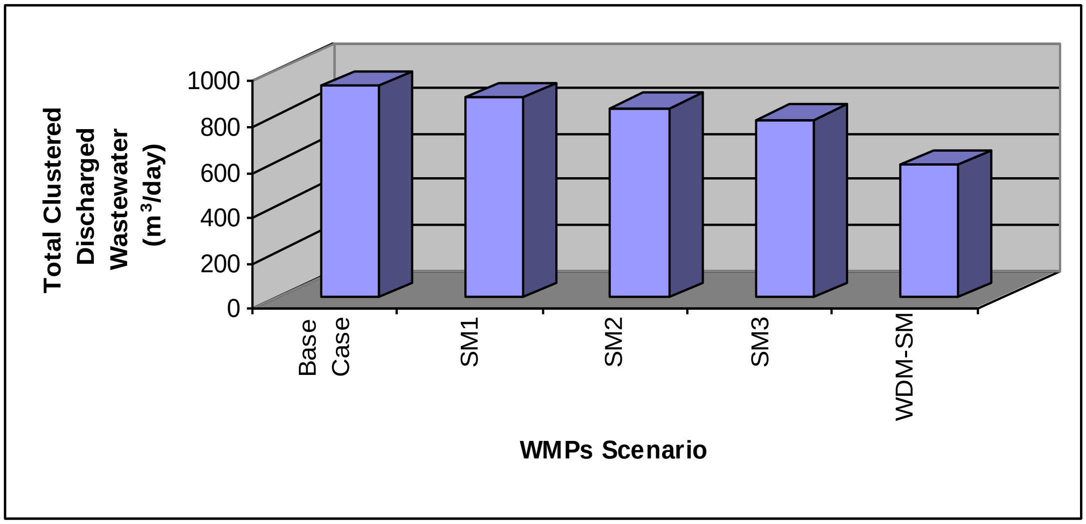


Figure A.14. Total Clustered Discharged Wastewater in Wet Weather

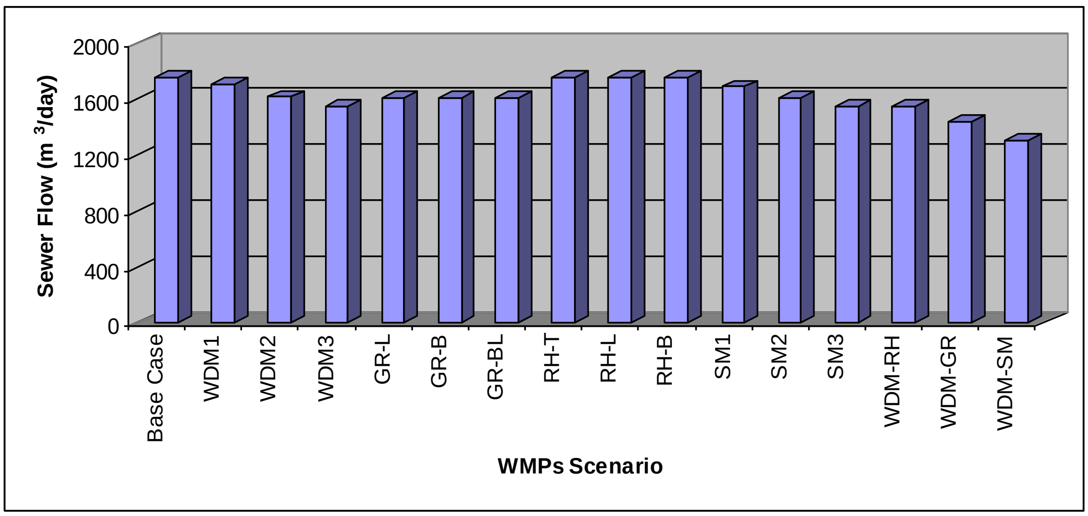


Figure A.15. Total Sewer Flow in Wet Weather

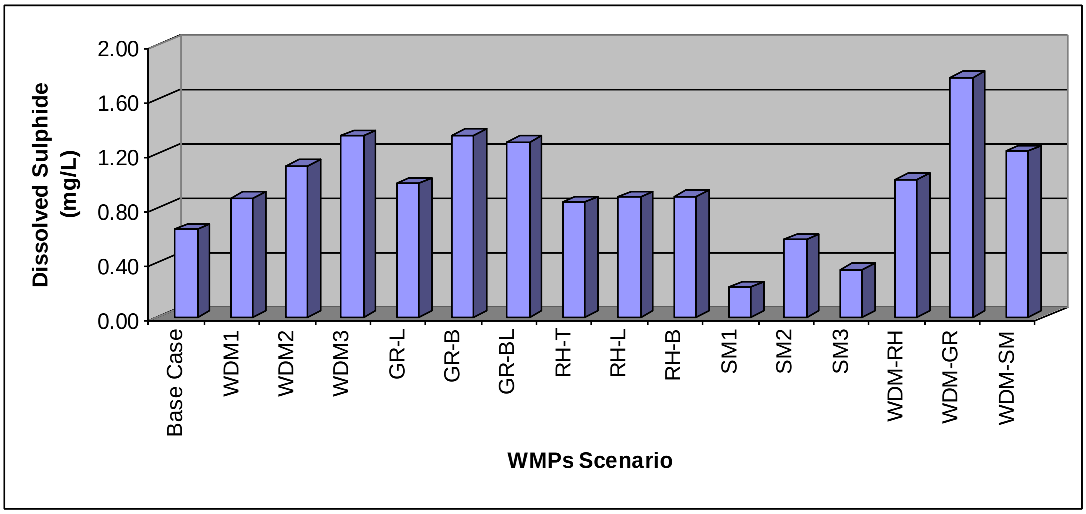


Figure A.16. Concentration in Wet Weather

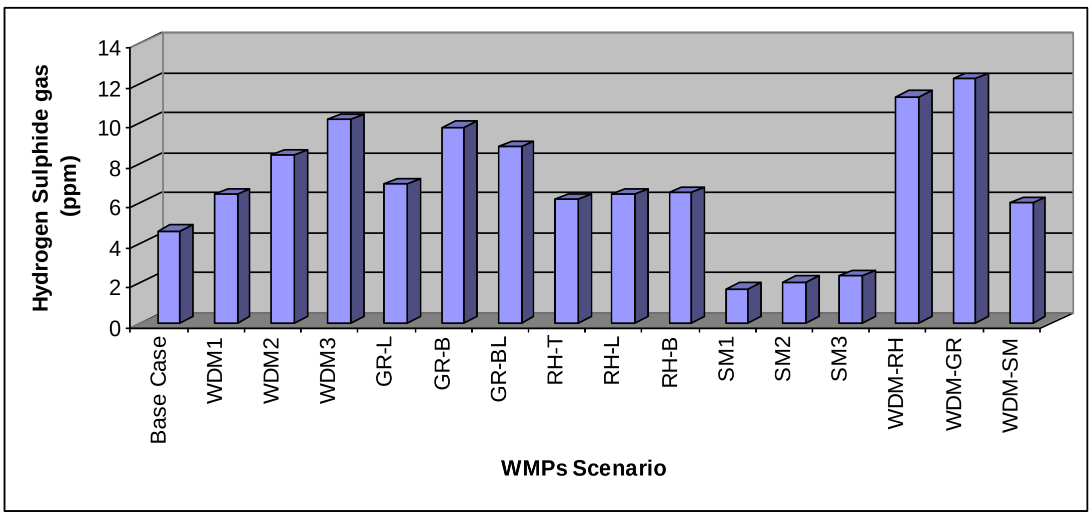


Figure A.17. Hydrogen Sulphide Gas Concentration in Wet Weather

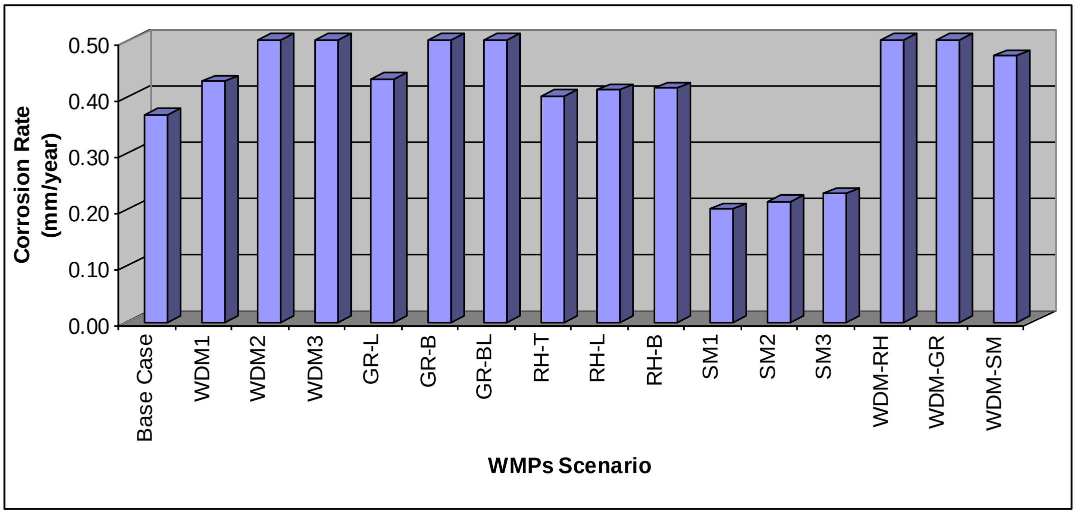
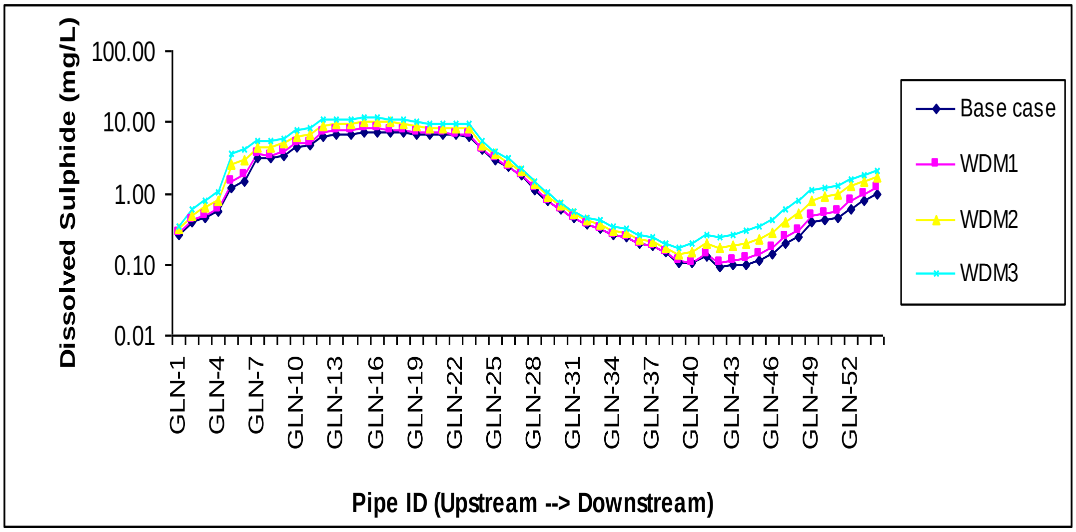
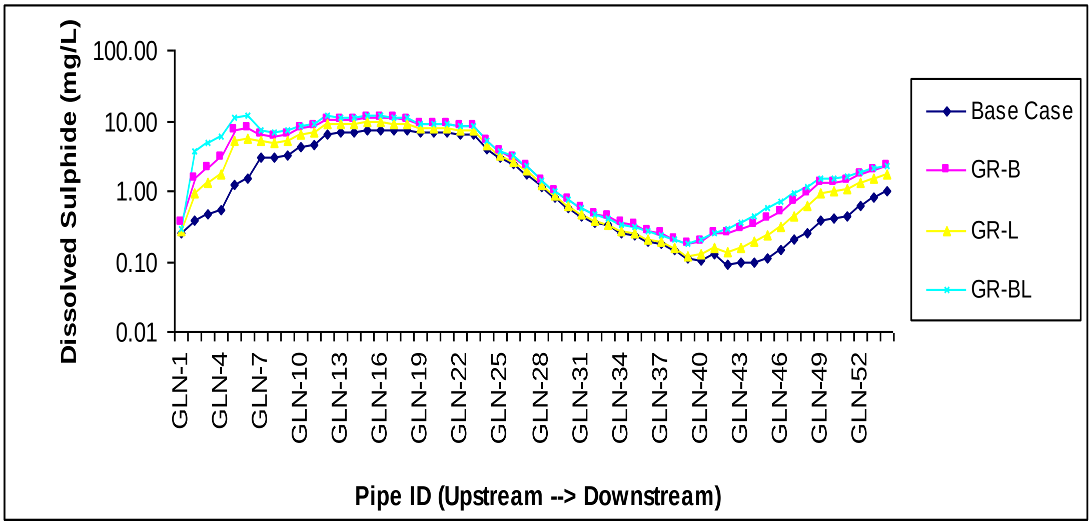


Figure A.18. Corrosion Rate in Wet Weather

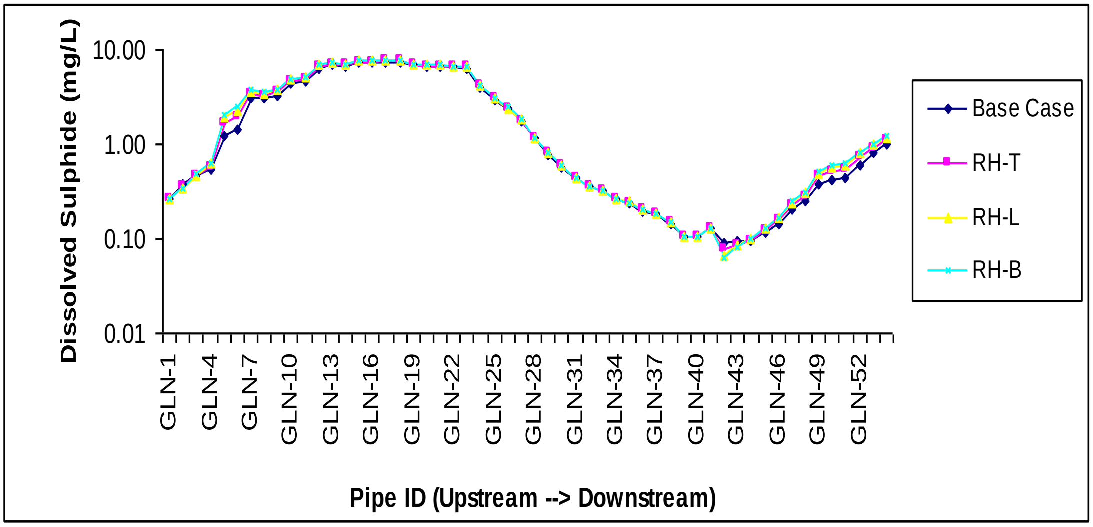
Appendix 8. Pipe Stretch Plot for WMP Scenario of All WMP Scenario except Sewer Mining Scenario



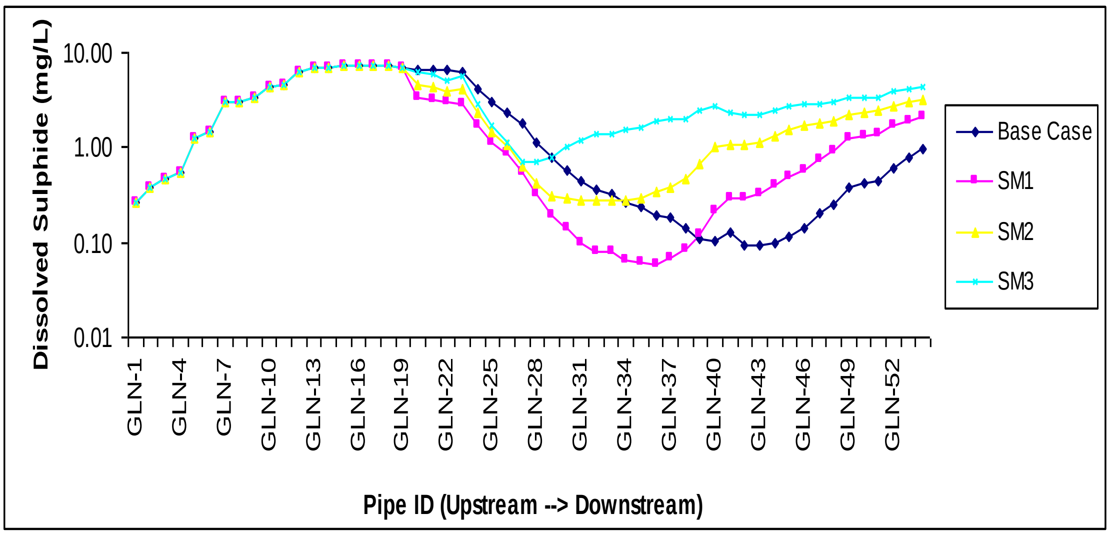
(a)



(b)

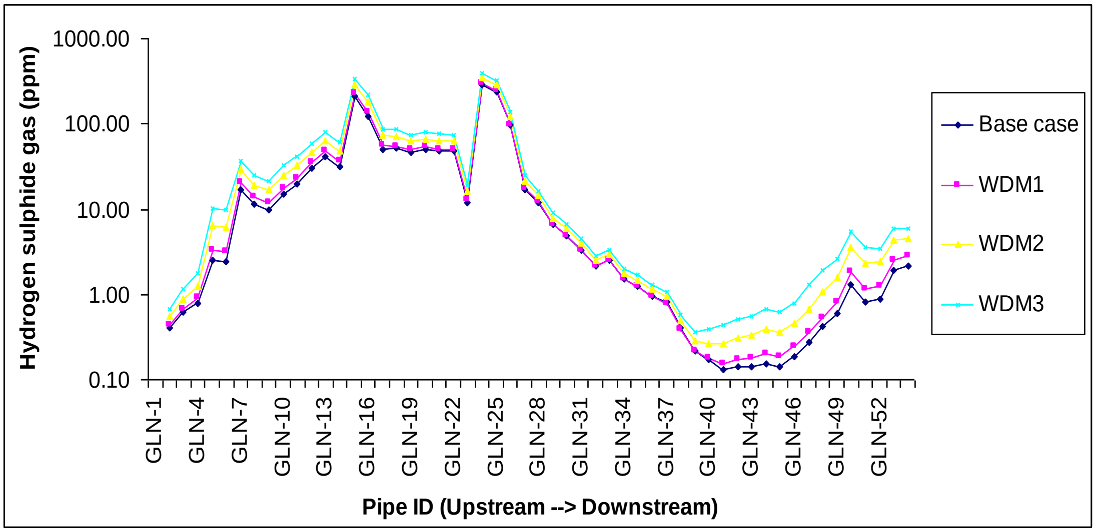


(c)



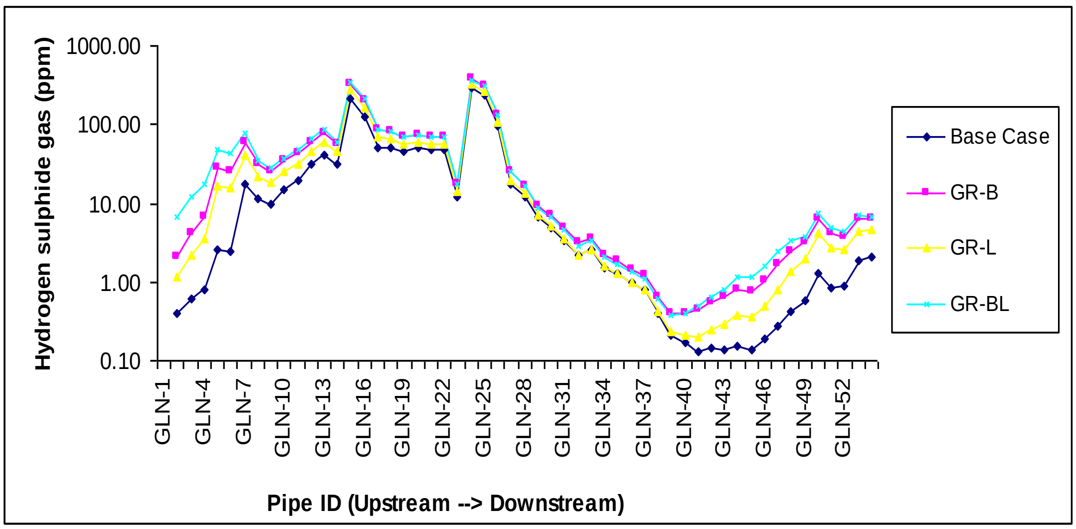
(d)

Figure A.19. Pipe Stretch Plot of Dissolved Sulphide for (a) *Water Demand Management*; (b) *Greywater Recycling*; (c) *Rainwater Harvesting*; (d) *Sustainable Practice*



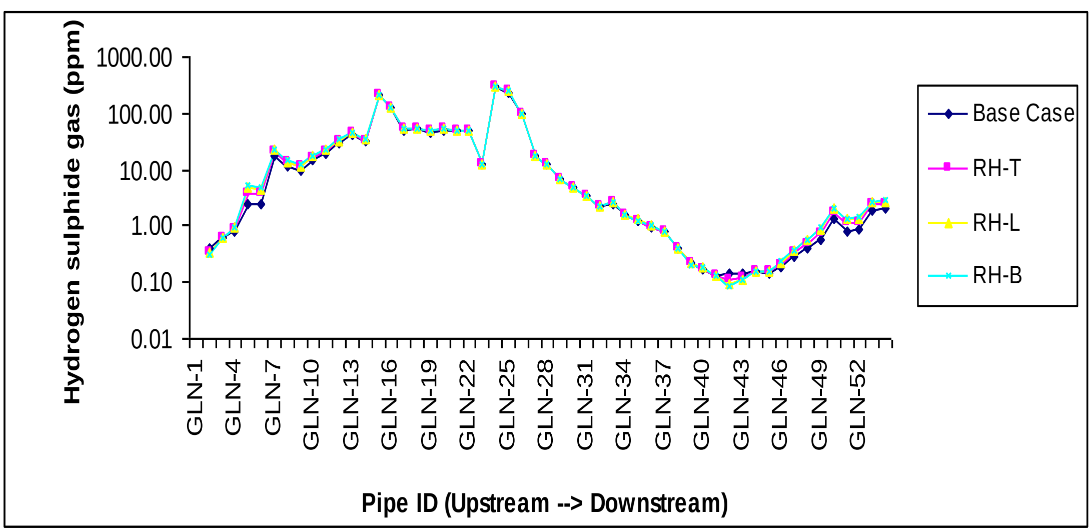
Hydrogen sulphide gas (ppm)
1000.00
100.00
10.00
1.00
0.10
GLN-1
GLN-4
GLN-7
GLN-10
GLN-13
GLN-16
GLN-19
GLN-22
GLN-25
GLN-28
GLN-31
GLN-34
GLN-37
GLN-40
GLN-43
GLN-46
GLN-49
GLN-52
Pipe ID (Upstream --> Downstream)
Base case
WDM1
WDM2
WDM3

(a)



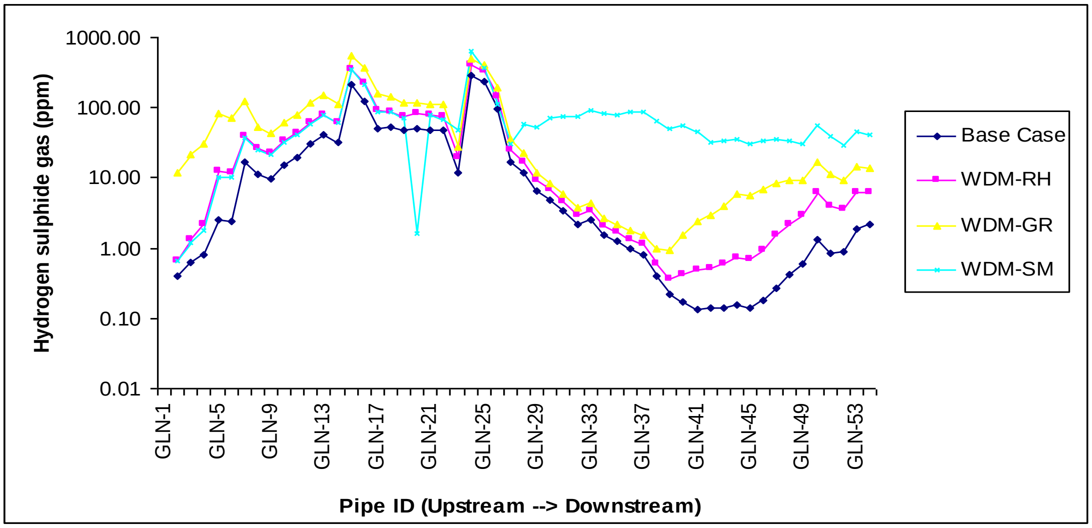
Hydrogen sulphide gas (ppm)
1000.00
100.00
10.00
1.00
0.10
GLN-1
GLN-4
GLN-7
GLN-10
GLN-13
GLN-16
GLN-19
GLN-22
GLN-25
GLN-28
GLN-31
GLN-34
GLN-37
GLN-40
GLN-43
GLN-46
GLN-49
GLN-52
Pipe ID (Upstream --> Downstream)
Base Case
GR-B
GR-L
GR-BL

(b)



Hydrogen sulphide gas (ppm)
1000.00
100.00
10.00
1.00
0.10
0.01
GLN-1
GLN-4
GLN-7
GLN-10
GLN-13
GLN-16
GLN-19
GLN-22
GLN-25
GLN-28
GLN-31
GLN-34
GLN-37
GLN-40
GLN-43
GLN-46
GLN-49
GLN-52
Pipe ID (Upstream --> Downstream)
Base Case
RH-T
RH-L
RH-B

(c)



(d)

Figure A.20. Concentration of Hydrogen Sulphide Gas for (a) *Water Demand Management*; (b) *Greywater Recycling*; (c) *Rainwater Harvesting*; (d) *Sustainable Practice*

Appendix 9. Figures of Pipe Location that have Dissolved Sulphide and Hydrogen Sulphide Exceeded Concentration of 2 mg/L and 10 ppm Respectively

As seen in Figure A.21, due to the adoption of reduced water demand in WDM scenarios, the number of the pipes at high risk because of dissolved sulphide concentration increased with: no pipe stretches for WDM1 (it means it same as B*ase Case*), 3 pipes for WDM2 and 6 pipes for WDM3. For pipes at risk due to changes in hydrogen sulphide concentration, the predicted changes were: WDM1 increased risk at 3 pipes, WDM2 increased risk at 4 pipes and WDM3 increased risk at 5 pipes (see Figure A.22).

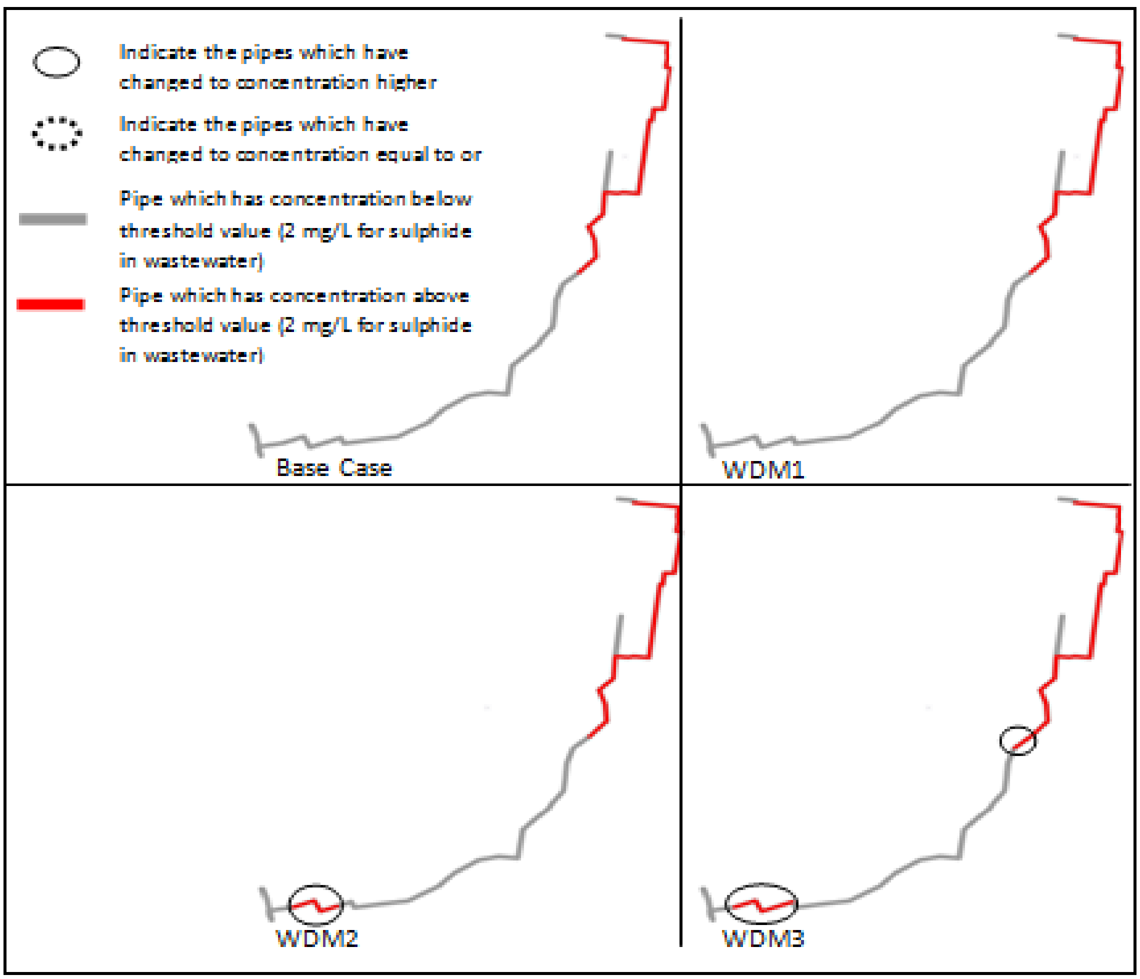


Figure A.21. Location of additional pipes that have concentration of sulphide in wastewater equal to or higher than 2 mg/L in *Water Demand Management* Scenarios

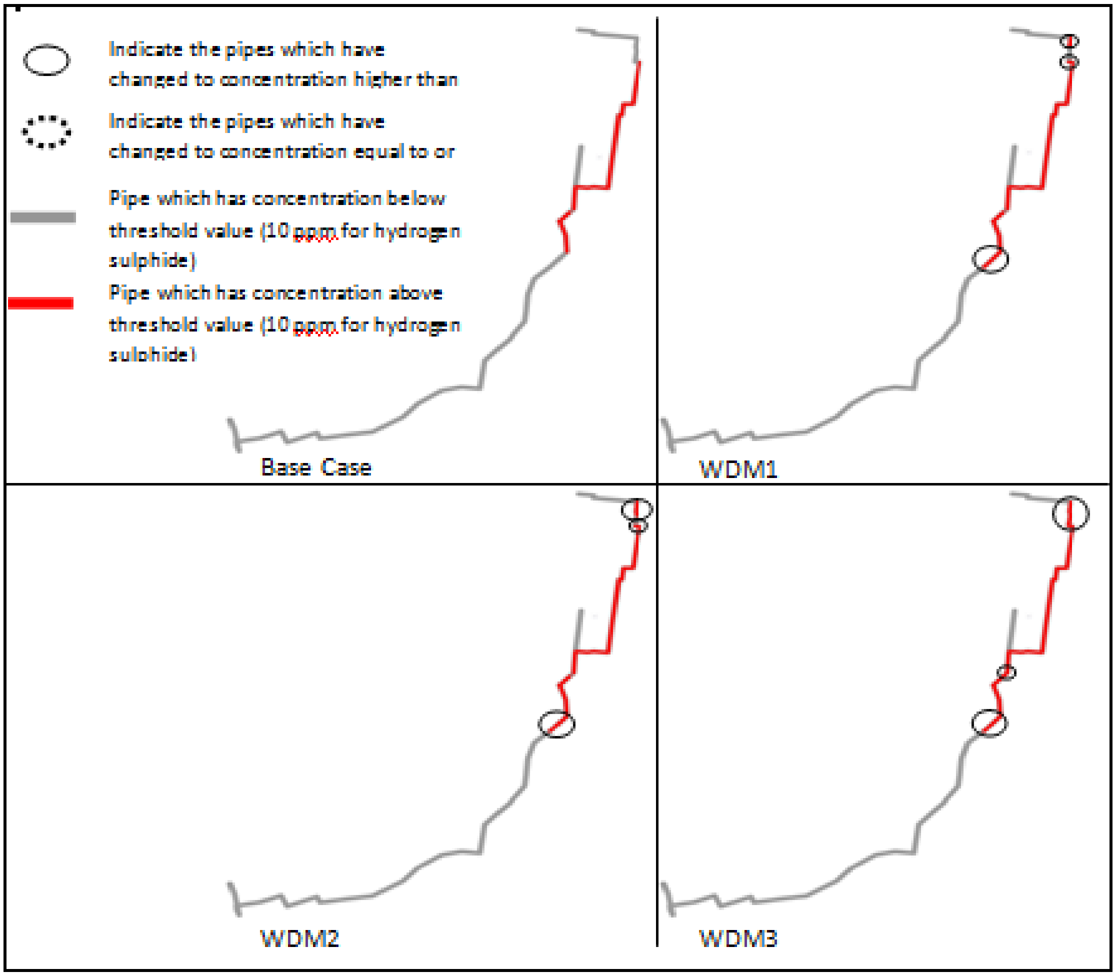


Figure A.22. Location of additional pipes that have concentration of hydrogen sulphide gas equal to or higher than 10 ppm in *Water Demand Management* Scenarios

In *Greywater Recycling* scenarios, the small greywater intake represented by GR-L had 3 pipe stretches that exceeded the threshold value after modeling this scenario while for the GR-B scenario there were 9 pipe stretches that exceeded the threshold. GR-BL scenario had 12 pipe stretches in the sewer pipe network that exceeded the threshold value of dissolved sulphide concentration (see Figure A.23). For hydrogen sulphide concentration, GR-L changed 3 pipes, GR-B changed 6 pipes and GR-BL changed 9 pipes to concentrations higher than 10 ppm (see Figure A.24).

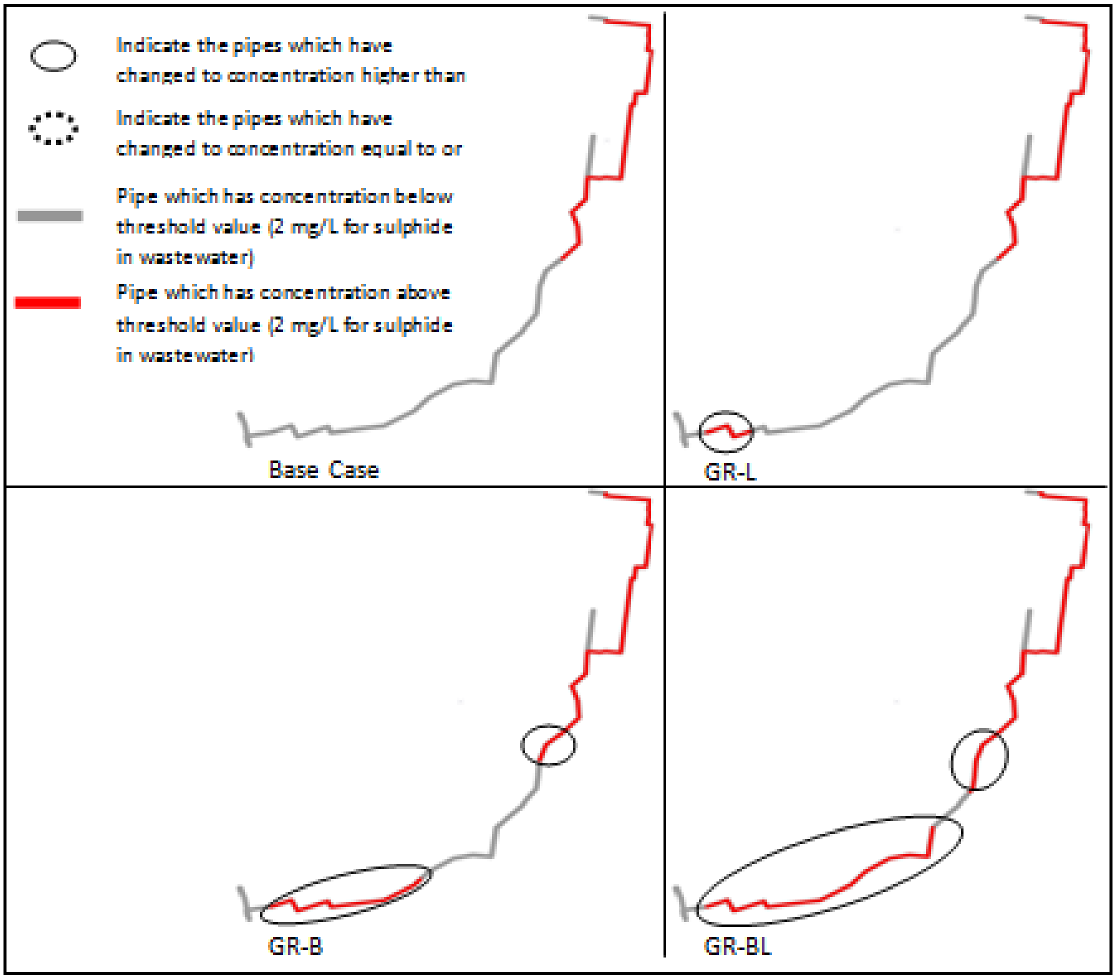


Figure A.23. Location of additional pipes that had concentrations of sulphide in wastewater equal to or higher than 2 mg/L in *Greywater Recyling* Scenarios

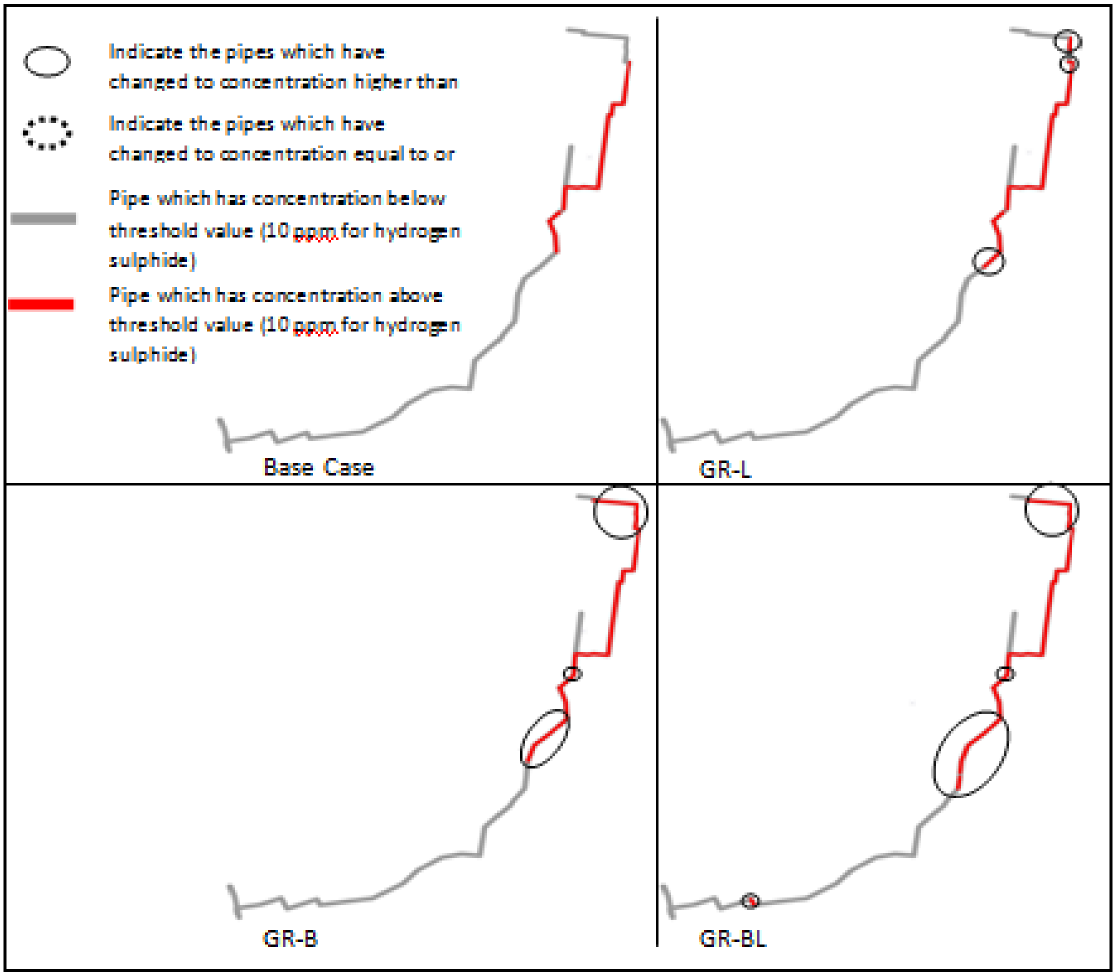


Figure A.24. Location of additional pipes that had concentrations of hydrogen sulphide gas equal to or higher than 10 ppm in *Greywater Recyling* Scenarios

Rainwater Harvesting modeling predicted little effect on dissolved sulphide and hydrogen sulphide concentrations in the study area. While no pipes were modelled as having sulphide concentrations higher than 2 mg/L (see Figure A.25), two pipes in all *Rainwater Harvesting* scenarios increased their hydrogen sulphide concentration to higher than 10 ppm (see Figure A.26).

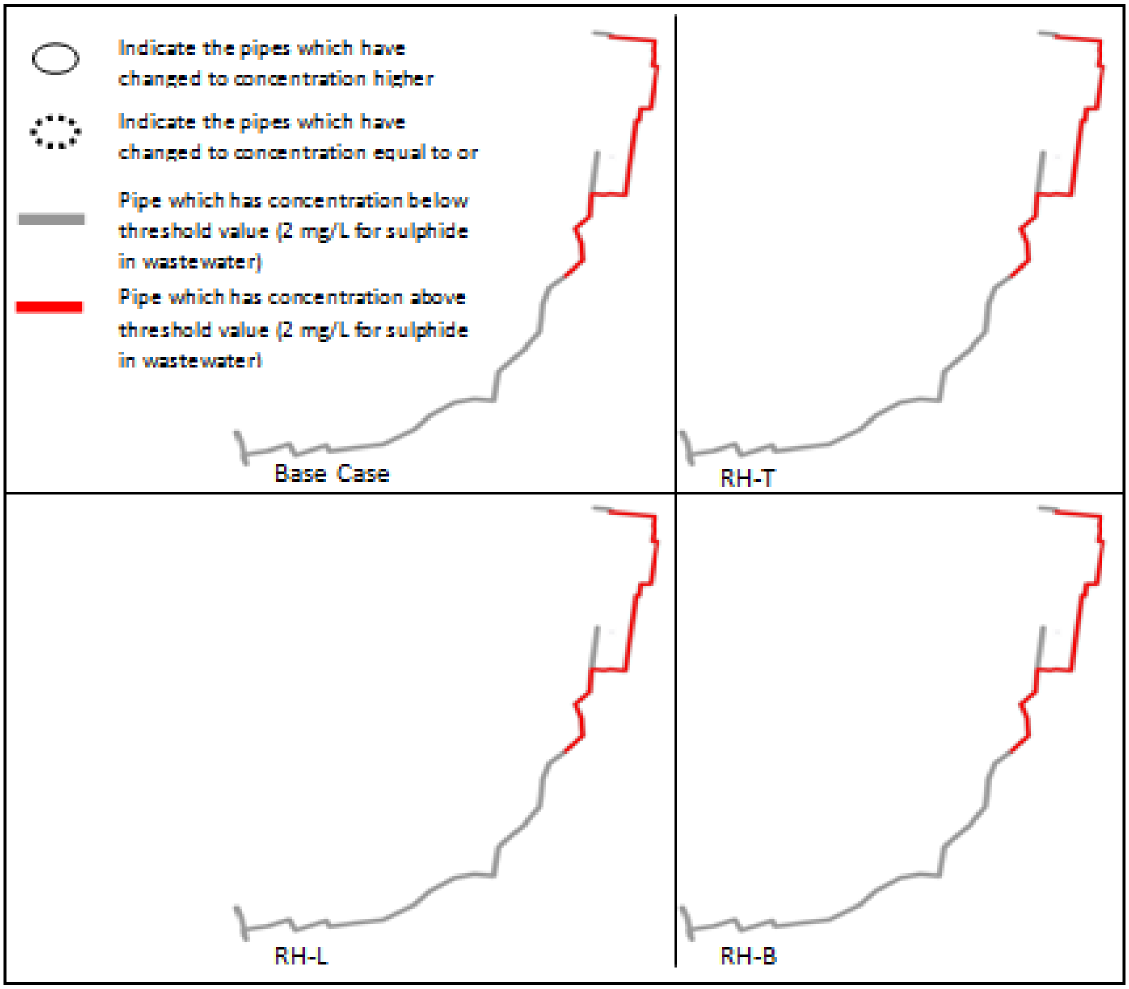


Figure A.25. Location of additional pipes that had concentration of sulphide in wastewater equal to or higher than 2 mg/L in *Rainwater Harvesting* Scenarios

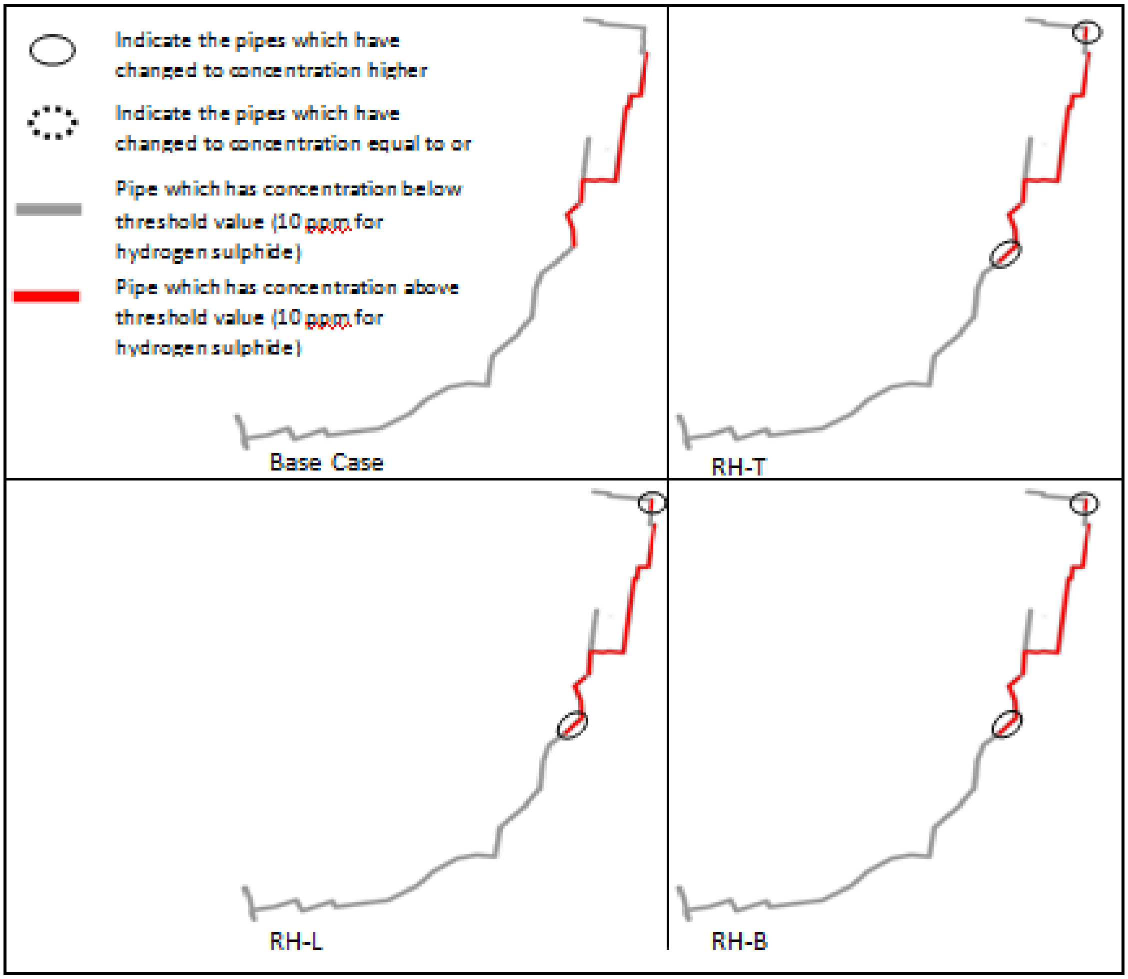


Figure A.26. Location of additional pipes that had concentrations of hydrogen sulphide gas equal to or higher than 10 ppm in *Rainwater Harvesting* Scenarios

In *Sewer Mining*, the number of stretches that exceeded the threshold value of 10 ppm decreased due to the location of the *Sewer Mining* facility. The facility was assumed to be installed in the middle of network where the hydrogen sulphide concentration was relatively high. As has been discussed previously, when there is wastewater extraction from *Sewer Mining* facility, some sulphide and hydrogen sulphide gas were released which leads to a drop in sulphide and hydrogen sulphide concentrations. Decreases in sulphide (see Figure A.27) and hydrogen sulphide concentration (see Figure A.28) after the *Sewer Mining* facility caused some pipe stretches that initially had concentrations equal to or higher than 10 ppm to have concentrations less than 10 ppm.

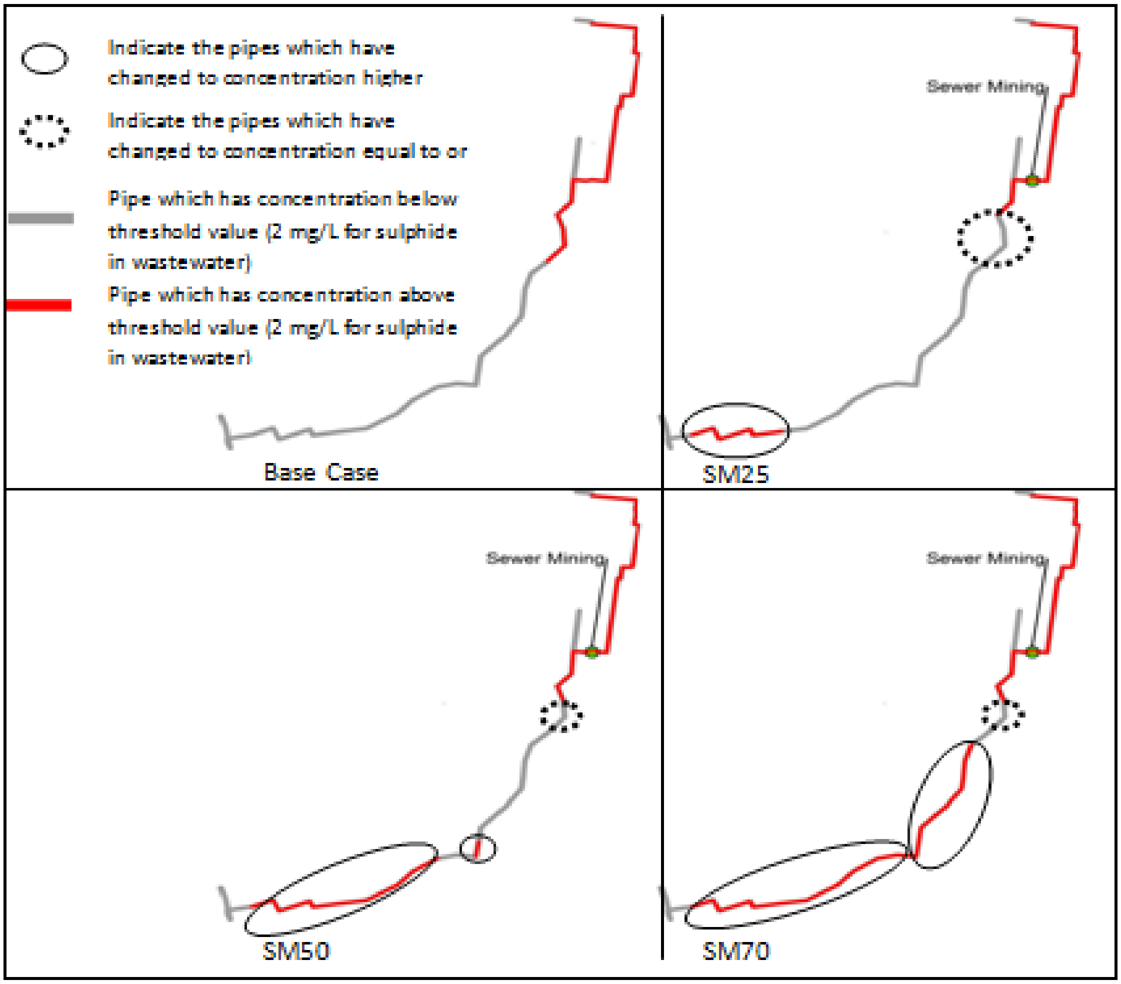


Figure A.27. Location of additional pipes that had concentrations of sulphide in wastewater equal to or higher than 2 mg/L in *Sewer Mining* Scenarios

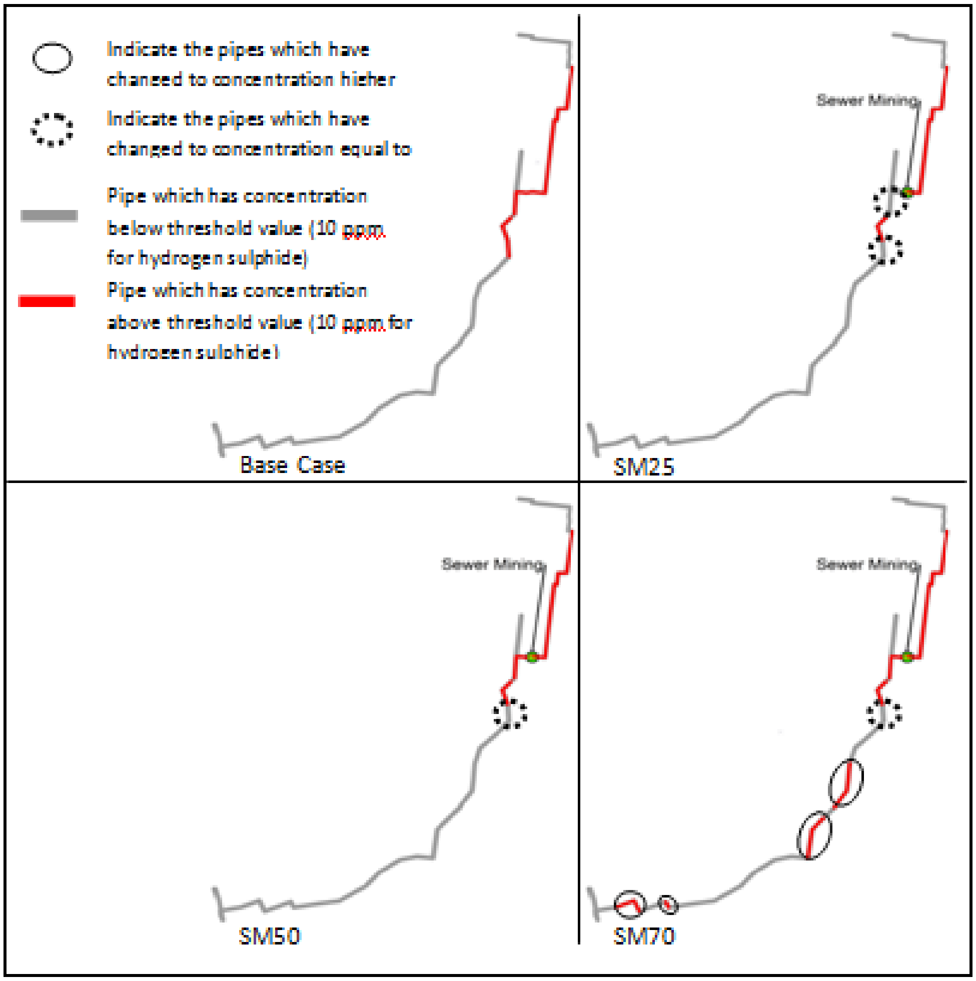


Figure A.28. Location of additional pipes that had concentrations of hydrogen sulphide gas equal to or higher than 10 ppm in *Sewer Mining* Scenarios

All *Sustainable Practice* scenarios had pipe stretches that increased until dissolved sulphide and hydrogen sulphide gas concentrations were equal or higher than to the threshold value. For sulphide concentrations, WDM-RH and WDM-GR changed 6 pipes and 12 pipes respectively to have concentration higher than 2 mg/L (See Figure A.29). For hydrogen sulphide concentrations, WDM-RH scenario changed 4 pipe stretches and WDM-GR changed 6 pipe stretches (See Figure A.30). The location these pipes were mainly in upstream-middle for WDM-RH, and distribute evenly from upstream to downstream for WDM-GR. For scenario of WDM-SM, almost all the pipes in Glenroy sewer branch were predicted to have concentrations above 2 mg/L for dissolved sulphide and 10 ppm for hydrogen sulphide gas.

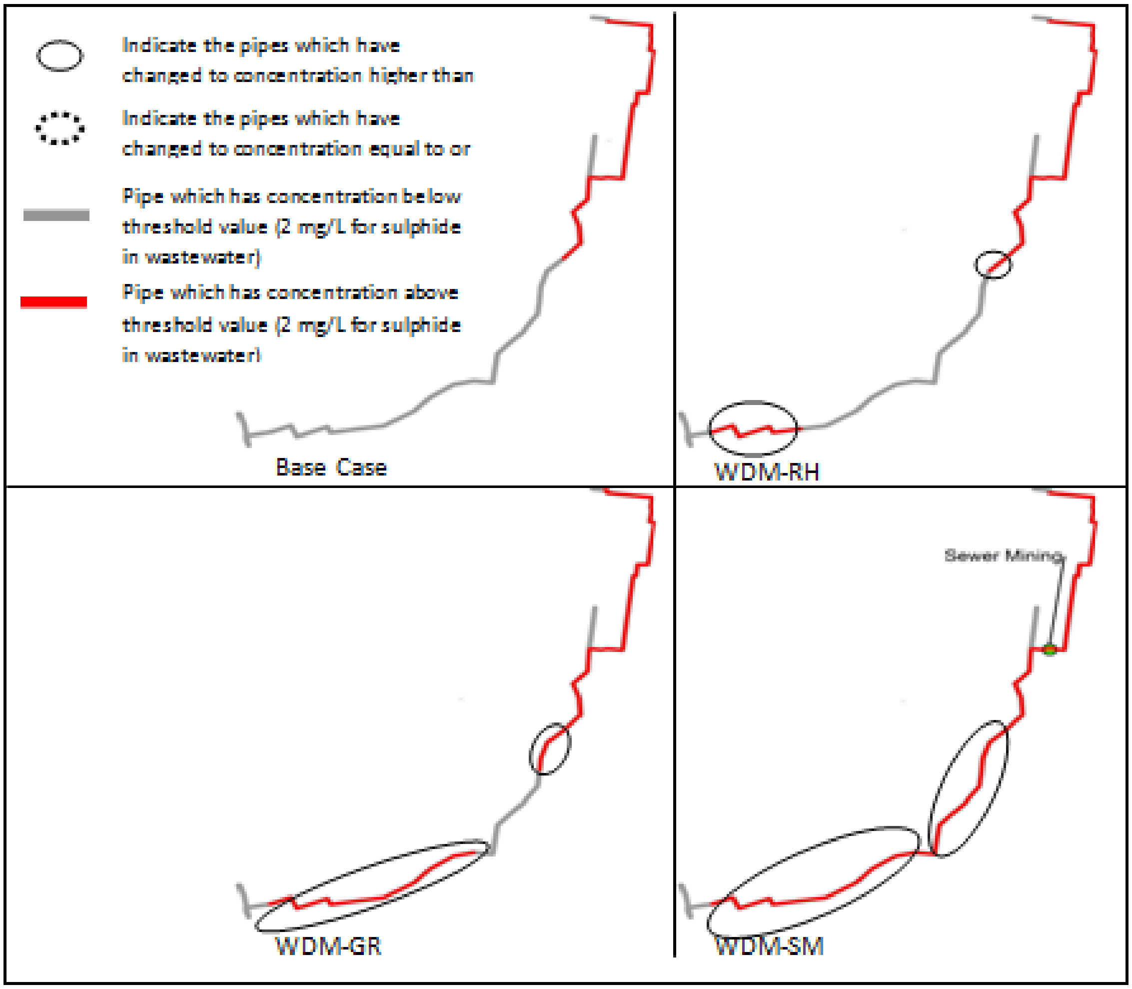


Figure A.29. Location of additional pipes that had concentrations of sulphide in wastewater equal to or higher than 2 mg/L in *Sustainable Practice* Scenarios

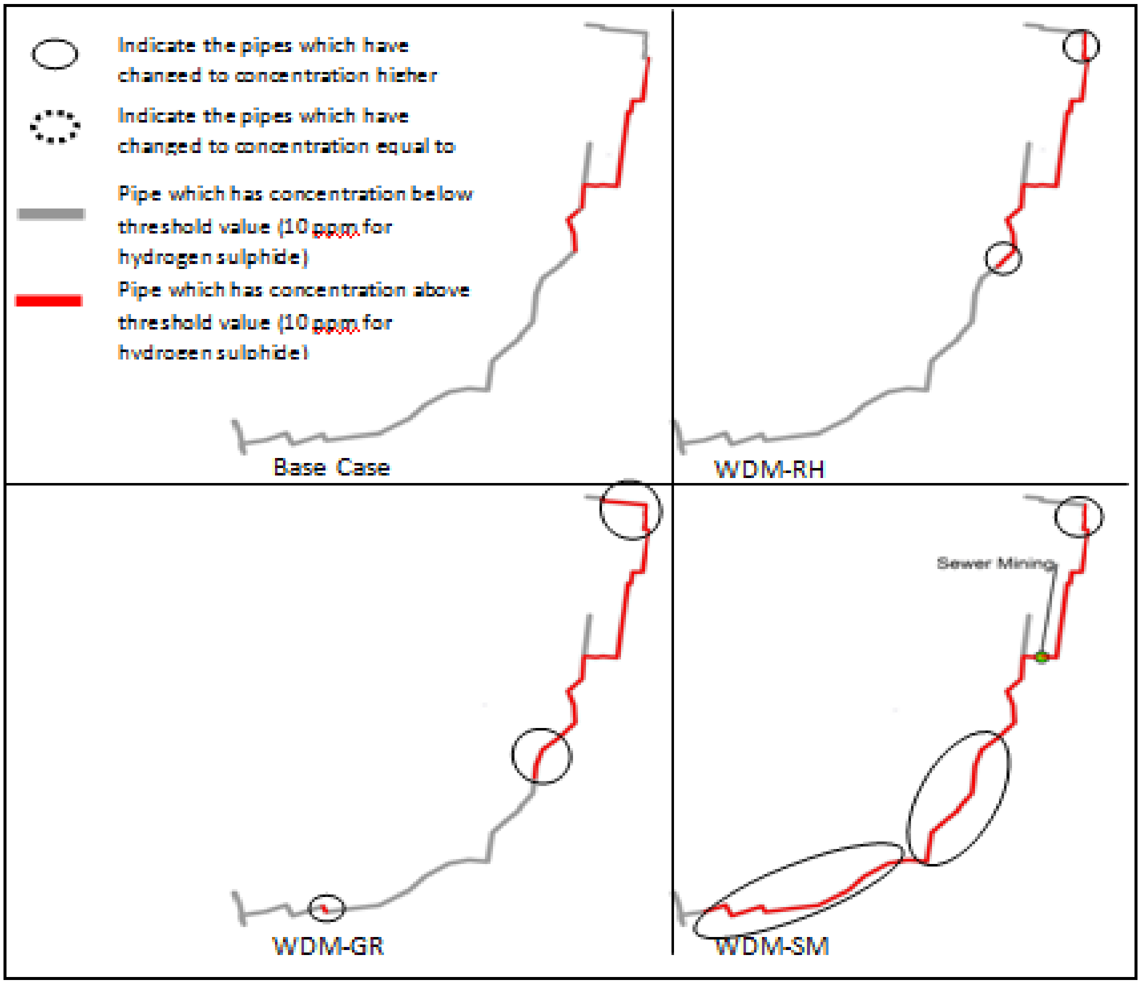


Figure A.30. Location of additional pipes that had concentrations of hydrogen sulphide gas equal to or higher than 10 ppm in *Sustainable Practice* Scenarios