University of Southern Queensland

Faculty of Health, Engineering and Sciences

A Water Sensitive Urban Design approach to mitigate the effects of Rainfall Derived Infiltration and inflow on existing sewerage systems

A dissertation submitted by

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Abstract

Urban developments can cause various detrimental impacts on public health and the environment, primarily due to the modification of the catchment and natural water cycle during rainfall events. Increases in impervious areas across catchments can cause increases in stormwater runoff volumes, discharge rates and pollution, directly resulting in sewage entering flood waters and stormwater networks exceeding their designed capacity.

This research aims to analyse and quantify the benefits of Water Sensitive Urban Design (WSUD) in an urban residential catchment and identify a relationship between WSUD in mitigating Rainfall Derived Infiltration and Inflow (RDII) in existing sewerage systems during high rainfall events. This research, also aims to identify the knowledge gap in this area and encourage further research in mitigating RDII, thus reducing the risk to public health and the environment caused by sewer overflows and sewer releases into waterways. To identify the forementioned relationship, a medium sized urban residential development was designed. Predeveloped and post developed scenarios were analysed in relation to stormwater runoff using MUSIC by eWater, (Model for Urban Stormwater Improvement Conceptualisation) and WSUD approaches were analysed to quantify their mitigating effect on RDII in an existing sewerage system. RDII was estimated for the catchment and a comparative study was created to determine the reduced amount of RDII through implementation of WSUD.

A total of five WSUD strategies were quantified including, a bioretention basin, bioretention swale, street tree pits, permeable pavements and rainwater tanks. A combination of all these strategies, in the residential development, was also investigated and found to produce the most desirable results. RDII in the existing sewerage system was found to be reduced by 0.0079L/s or 28.44L/hr and achieving a total reduction in peak flow by 81.3%, essentially returning stormwater runoff conditions back to predeveloped conditions for the urban development. The most effective individual WSUD was the bioretention basin, reducing expected RDII by 0.0068L/s or 24.48L/hr and achieving a total reduction in peak flow by 71.7% over the catchment.

Assumptions for the WSUD were made in accordance with best management practices and Water by Design guidelines and sewer infiltration and inflow rates were used that were based on previous research in this field. A lack of real-time flow monitoring data has reduced the level of accuracy for this study, although contribution towards the identified knowledge gap is evident. This study intends to promote further research in the development of mitigation strategies for reducing RDII, ultimately benefiting the community and the environment.

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List of Abbreviations

I/I	Infiltration and Inflow
RDII	Rainfall Derived Infiltration and Inflow
SSO	Sanitary Sewer Overflow
WSUD	Water Sensitive Urban Design
SSOAP	Sanitary Sewer Overflow Analysis and planning Toolbox
WSAA	Water Services Association Australia
TSS	Total Suspended Solids
GWI	Ground Water Infiltration
WWTP	Waste Water Treatment Plant
SEQ	South East Queensland
SP	Service Provider
MUSIC	Model for Urban Stormwater Improvement Conceptualisation
BCC	Brisbane City Council
PE	Polyethylene
AC	Asbestos Cement
VC	Vitrified Clay
RC	Reinforced Concrete
PVC	Polyvinyl Chloride
EP	Equivalent Persons

1. Introduction

1.1. Background

Urbanisation is continually on the increase in Australia and transforming the economic and social geography of most countries in the world, with urbanisation on the increase, engineers are continually challenged with maintaining and updating services to meet peak demands. According to McIntosh et al, 2013, "*More than 50% of the world's seven billion people live in cities already and this figure is expected by the United Nations to rise to over 70% by 2050, when the total global population will be just under nine billion people*". In modern times there has been a strong focus on flood mitigation, as more rural land urbanised and changing the natural hydrological behaviour of the landscape, creating an increase in impervious surfaces. Conventional stormwater drainage and sewerage systems are constantly upgraded, the cost of upgrading these systems can be become extremely expensive. In some cases, overloaded stormwater drainage systems are overlooked. When developers subdivide properties, the cost of upgrading a large network of stormwater pipes, inlets and culverts may be too expensive, especially for small subdivisions 1 into 2 lot subdivisions. Recent studies have found, urbanisation has increased the frequency and risk of flooding in major cities and sewerage overflows (Maheshwari et al 2022, Liang et al 2021 & Ronalds & Zhang 2019). Urbanisation can have detrimental public health, environmental and economic impacts if not managed appropriately.

There is the now a strong push from local councils and governing bodies to enforce hydrological mitigation methods and stormwater management in new developments. The main areas of focus for urban stormwater management include, ensuring pollutants are removed or captured and treated before leaving the development and entering in stormwater system, re-use of stormwater for alternative uses and/or water supply and avoiding deviation from the natural ecological stormwater function. McIntosh et al 2013 states, it is through the above areas of focus that these governing bodies are trying to achieve a combination of flood mitigation, water supply and ecological restoration and enhancement.

Water Sensitive Urban Design (WSUD) strategy commenced in Southeast Queensland in 2004 and since then, has been analysed in great depth and put forward as a sustainable, cost effective and reliable approach to help mitigate modern challenges around stormwater management.

According to Water by Design 2007, the purpose of WSUD for stormwater manage consists of the below three objectives.

- **Frequent Flow Management Design Objective** – focuses on capturing and treating the initial portion of runoff, this is considered to contain the highest levels of pollutants. The objective also aims to ensure disturbance to in-stream eco systems is maintained and developed catchments perform in a similar manner to their predeveloped condition

- **Waterway Stability Management Design Objective** – Seeks to prevent downstream erosion by controlling flows through urban developments, in particular the magnitude and duration of the storm event by introducing 'lag time' to slow down/reduce sediment transportation.

- **Stormwater Quality Management Design Objective** – Reducing pollutant runoff from urban developments by ensuring all runoff is directed into treatment systems before exiting the developed site.

WSUD now plays a large part in urban developments in Queensland and is strictly controlled by legislated requirements through the Queensland Environmental Protection Agency (EPA). There are many WSUD strategies can be implemented in developments with steep or undulating topography, flat topography, catchments with multiple open spaces to the public, catchments with street layouts and industrial sites.

These strategies, although not extensively researched, may also be utilised to relieve the presence of Rainfall Derived Infiltration and Inflow (RDII) on existing sewer systems, especially in areas with aged and poorly maintained sewerage. WSUD can reduce peak runoff flows by slowing heavy rainfall events down by capturing and treating runoff and could potentially reduce the risk sewer networks exceeding their design capacity overflowing into public streets or causing wastewater treatment plants to release effluent into water bodies from capacity exceedance.

The research presented within this dissertation will be strongly focused on Southeast Queensland standards and guidelines. This dissertation intends to focus on the direction that local councils and governing bodies are moving towards with new urban developments and intends on exploring knowledge gaps around the detrimental effects of urbanisation, with extra emphasis around flood mitigation and ecological restoration and enhancement. This dissertation also intends to provide a platform for continued research, focusing on how stormwater mitigation by WSUD can change the hydrological behaviour of areas with high impervious surfaces and how WSUD can be used to reduce to impacts of RDII on existing sewer networks.

1.2. Aims and Objectives

This dissertation intends to benefit the engineering community by identifying a knowledge gap around the relationship between WSUD and RDII in existing sewerage systems. It intends to achieve this by highlighting the importance of stormwater mitigation in urban developments and to encourage further research and investigation around achieving a sustainable future. To accomplish this overall aim, the following objectives will be undertaken.

- Complete an in-depth literature review around current, 'best management practices' for WSUD and quantifying the performance of these strategies. Explore the causes of RDII in existing sewerage networks and how this can be reduced by WSUD.
- Create a case study involving an urban residential development, design appropriate WSUD for the catchment and assess the performance of the strategies in relation to a heavy rainfall event.
- Estimate the expected RDII that is a direct result of the urban development and identify how WSUD runoff mitigation can contribute to a reduction in RDII for a residential development.
- Create a method and platform that can be utilised for further research around mitigating RDII by means of WSUD in new urban developments.
- Promote the need for additional research to close the knowledge gap identified, discussing the assumptions made to achieve the results and how increased accuracy can be achieved.

2. Literature Review

2.1. Introduction

This literature review will provide an in-depth analysis on current literature and standards around types WSUD, how to measure the performance of WSUD, how to model WSUD, current industry stands of RDII and how to mitigate RDII. This review will be spilt into multiple sections to assist in the clear understanding of key concepts around WSUD methods and RDII and aims to critically analyse the gathered information to sufficiently narrow down gaps in research, identifying shortcomings.

To evaluate the current knowledge around WSUD and RDII for this field of research, the following pieces of literature have been examined, peer reviewed journals and articles, international and local government reports and standards, previous dissertations, books and similar case studies. To derive current and past knowledge around WSUD and RDII, sources have been selected ranging from 1991 – 2022.

2.2. WSUD Benefits

WSUD is an internationally recognised concept, beginning in Southeast Queensland in 2004, and offers an alternative holistic approach to urban design over traditional stormwater convention. According to the WSUD Technical Design Guidelines for South East Queensland 2006, the key principles of WSUD are as follows.

- To protect existing natural features and ecological processes.
- To maintain the natural hydrologic behaviour of catchments.
- To protect water quality of surface and ground waters.
- To minimise demand on the reticulated water supply system.
- To minimise sewage discharges to the natural environment.
- To integrate water into the landscape to enhance visual, social, cultural and ecological values.

There are many guides available around the design of WSUD that are updated regularly, keep up to date with modern developments and knowledge around water dynamics and hydrology. Two organisations appear to standout above others in WSUD design and have close partnerships with local councils and governments are, Water By Design and Health Waterways.

Both organisations offer a range of technical guidelines and solutions for urban development with a key focus on the above mentioned, WSUD key principals.

Other benefits of WSUD can be summarised in the below flow chart by the Urban Stormwater Quality Planning Guidelines 2010, below in Figure 2.1. This dissertation will be heavily focused on the Wastewater minimisation aspect and Groundwater management with a strong focus on stormwater quantity.

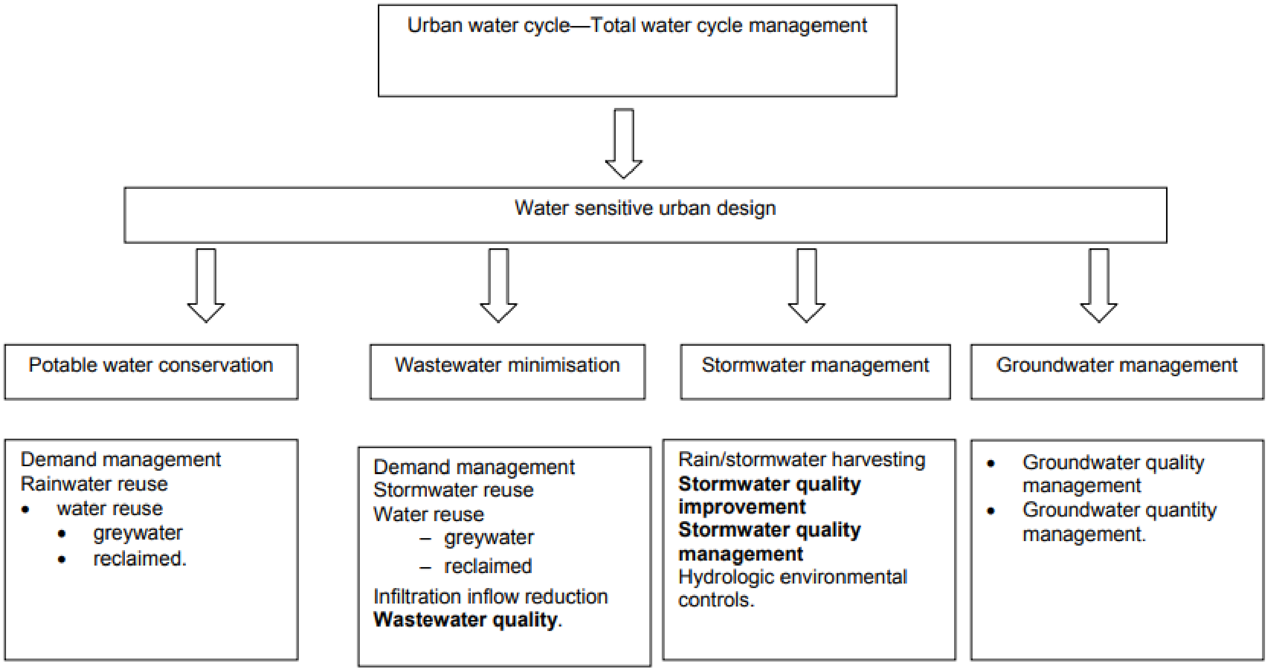

Figure 2.1 - WSUD and the urban water cycle (Urban Stormwater Planning guidelines, 2010)

2.2.1. WSUD Mitigation Strategies

The use of WSUD strategies is widespread today and have been adopted by many local councils and water authorities across Australia, as part of new and existing developments. Although there are many studies available in the literature that investigate how WSUD can be used in a stormwater management sense, there has only been a small number of studies found in this literature review that directly correlates WSUD strategies to mitigate RDII.

The below WSUD strategies have been recommended for use by councils within SEQ, studies for current best management practices using WSUD and through previous research reports. There are many other forms of WSUD not outlined below including buffers, pollutant traps and other forms of bioretention systems that have similar properties.

2.2.1.1. Green Roofs

Green roofs appear in the earliest studies on WSUD and are commonly used overseas. As the name suggests, they are roofs of buildings and housing covered with plants or trees that can grow in a minimal amount of soil, sand and/or gravel over waterproof membrane. Figure 2.2 below displays a typical structure for a green roof.

Figure 2.2 – Green Roof structure (Foster et. al. 2011)

A study by *Foster et. al. 2011*, found that green roofs can reduce annual run-off of stormwater by 50 – 60% on average and can also filter air pollutants. Other advantages of green roofs, include insulating and energy reduction. According to Castleton et al. (2010), green roofs can significantly reduce energy use in existing buildings with poor insulation values, the soil substrate can reduce heat gain/loss into and out of buildings. Although, green roofs can be expensive to install and require ongoing maintenance, they can also add extra weight on the roof of the structure and are vulnerable to large rainfall events. Green roof structures are not commonly found in residential subdivisions and in Queensland, there was not a large amount of design focused on this strategy.

2.2.1.2. Permeable Pavements

Permeable pavements are a porous surface that is typically composed of asphalt, concrete, or open pore pavers. A storage reservoir/tank is often installed below that holds water and conveys it in the stormwater system. As water slowly filters through the permeable pavement, it is filtered and cleaned of pollutants. A study in Auckland, New Zealand by *Frassman and Blackbourn 2010*, monitored a conventional asphalt permeable pavement test site for two years and found the pavement to have excellent hydraulic performance and in many storm events, the catchment with the pavement acted like its originally non-impervious state. The Study concluded that permeable pavements should be given strong consideration for low impact development, assuming particular care is taken during the installation ensuring proper flow. A typical layout of a porous pavement system is shown below in Figure 2.3.

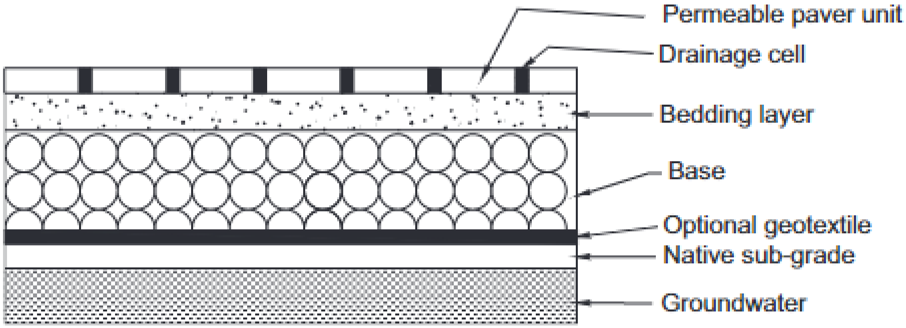

Figure 2.3 – Typical porous pavement (Tota-Mahara et al. 2008)

Some drawbacks for permeable pavements are the cost of installation, ongoing maintenance (permeable pavements are prone to clogging if not drained correctly and become very inefficient) and they tend to lack strength properties compared to traditional asphalt or concrete pavements, therefore may not be ideal in areas with heavy vehicles. Permeable pavements may be a good solution for residential driveways and footpaths to capture stormwater runoff that would usually be directed towards kerb and channel.

2.2.1.3. Vegetated Swales

Vegetated swales are very commonly used to manage roadway runoff and have been found to be effective in removing pollutants and total suspended solids significantly increasing downstream water quality. Swales may not be suitable in areas with below standard road verges, as they are required to be wide enough to convey water at a velocity that will not cause erosion to the outer banks, velocity should also be kept low enough to remove any targeted pollution from sedimentation, infiltration and/or absorption whist avoiding damage to vegetation within the swale that assists in this cleaning process. Other site constrains are steep topography - greater than 4% may cause scour/erosion, very flat topography less than 1% - can cause the swale to become waterlogged and unable to drain efficiently causing undesirable boggy areas for traffic movement, large catchments – swales need to be quite large to suit the desirable velocities, acid sulphate soils – transportation of these soils can be hazardous to the environment.

Vegetated Swales do require maintenance generally in the form of routine inspections to check sediment deposition, scouring, blockages at inlets and outlets, mowing or trimming of turn/vegetation and repair to possible damage caused by vehicles or storms. Refer to the below Figure 2.4 for a typical section of a swale.

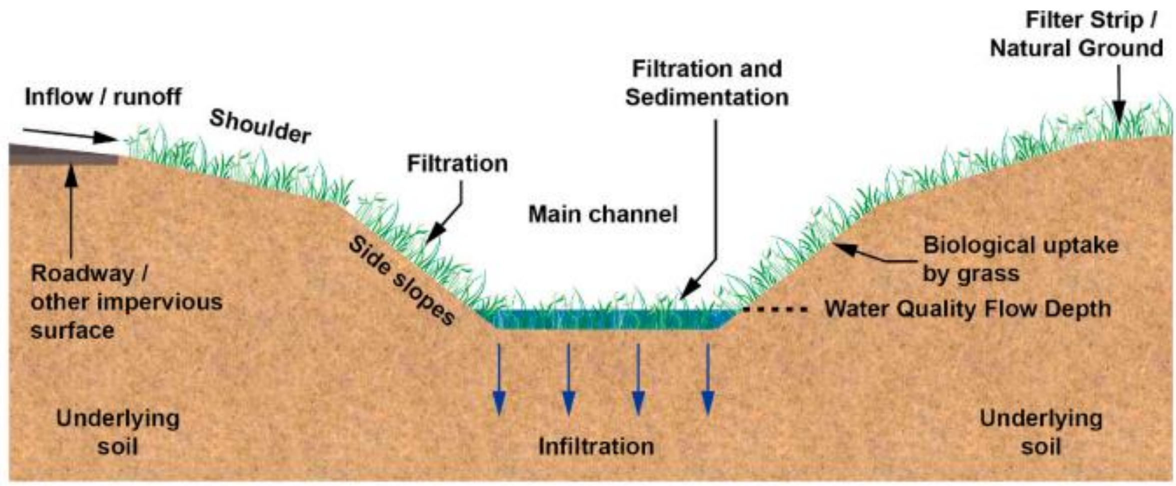

Figure 2.4 – Typical grass swale cross-section (Ekka et el. 2021)

A study by Ekka et al 2021, on a comprehensive approach for swale design found that, swales can accomplish multiple objectives of runoff management including, volume reduction, water quality protection and stormwater conveyance, whilst climate conditions can be considered. Vegetated swales can come in many forms, for stormwater runoff quality and quantity management, swales with underlaying bioretention and pipe drainage provide improved performance over standard swale practices.

2.2.1.4. Bioretention Basins

Bioretention basins are vegetated areas where runoff is typically filtered through a filter media layer, then a layer of sandy loan and/or gravel into perforated underdrains before flowing into the stormwater system. An impermeable geotextile is often used around the base to prevent infiltration and to capture all runoff into the underdrains. Clean out points are provided at every 20 – 30m depending on the local standards and sediment forebays for runoff to settle in are usually provided with vehicular access depending on the size for cleaning and maintenance. Refer Figure 2.5 for a typical section of a bioretention basin.

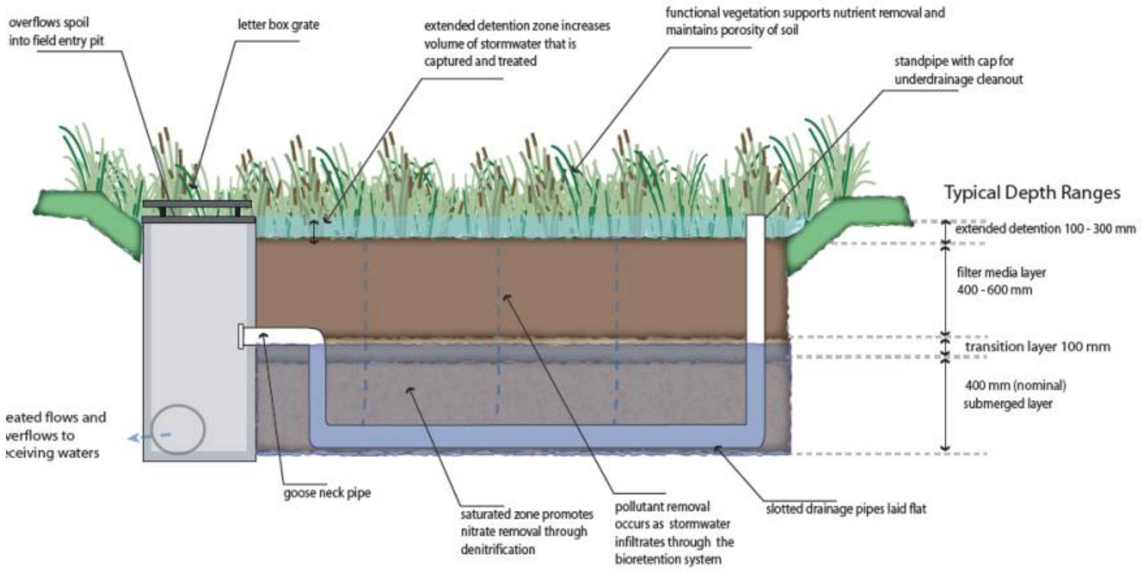

Figure 2.5 – Typical bioretention cross section (Townsville City Council, 2011)

Benefits of bioretention basins include removal of pollutants before entering existing stormwater systems, store runoff especially when paired with detention tanks to slow or lessen the effects of large rainfall events, they can be versatile in means of size, ground conditions and climate and are aesthetically pleasing. According to *Mangangka et al. 2015*, antecedent dry periods can result in low moisture content in bioretention basins and can improve treatment performance, hence high-water absorbing vegetation is recommended. The study also determined some negative effects of bioretention basins such as, having a relatively low ability to treat water with high water depths, nitrification occurring where ammonium nitrogen reduces, but consequently lower nitrite removal and the possibility of pollutant leaching, which can generally be solved by appropriate use of geotextile membranes and appropriate filter media and timely replacement when required.

2.2.1.5. Infiltrations Trenches

Infiltration trenches are simple systems that use permeable soils and gravels to reduce peak flows. Often found in private yards obstructing the natural flow path that may be caused by roof water or impervious surfaces. Microbial biofilms present in the soil help to digest organic pollutants. They can be easy and cost-effective method for reducing flow from adjacent impermeable surfaces and implemented into site landscaping. Like most mitigation strategies, maintenance is required over periods of time to avoid build-up of pollution and they are not recommended for sites with fine clay/silt soils in the upstream catchment. Infiltration trenches are often used for small catchments in private properties. Refer Figure 2.6 for a typical section of an infiltration trench.

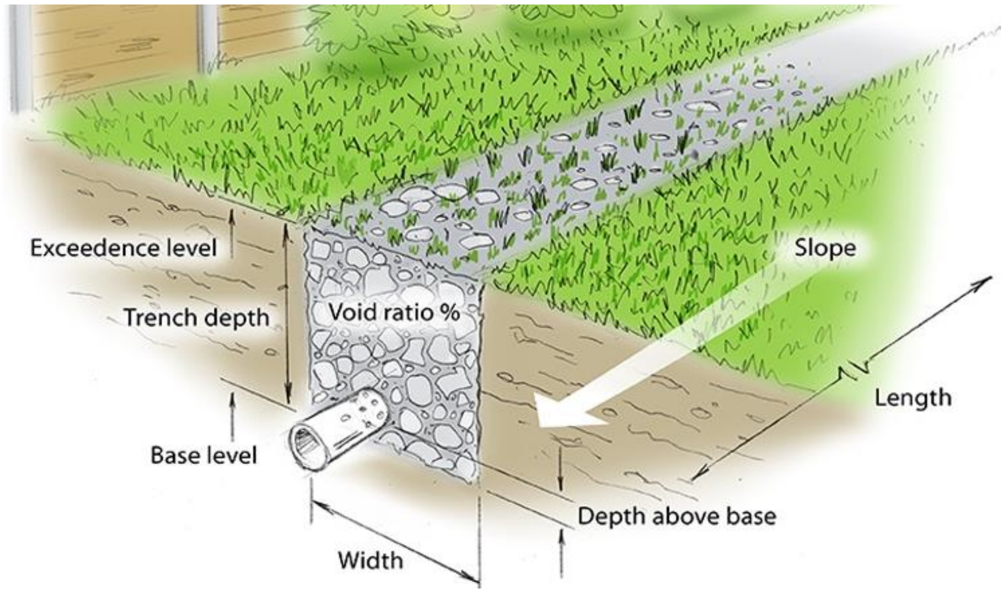

Figure 2.6 – Typical infiltration trench (Autodesk Innovyze 2021)

2.2.1.6. Constructed wetlands

Constructed Wetlands typically consist of three parts, *Wetlandinfo QLD Government 2018.*

- Inlet zone – works like a sediment basin to remove all coarse sediment
- Macrophyte zone – densely planted area and the main body of the wetlands, removes fine particles and dissolved pollutants from the captured runoff
- High flow bypass channel – excess water flows around the wetland during high rainfall events to avoid damage to the wetland.

Wetlands can take up a large amount of area and can be found in new estates where existing flow paths are present, flows through the wetlands are generally detained for 72 hours, using outlet control, although depending on the circumstances these detention time maybe shorted or longer. A wetland is used for relatively large catchments with high flows, the site is needs to be reasonably flat and can be designed to avoid damage from fine clay sediment. According to *Vymazal 2010*, "Constructed wetlands require very low or zero energy input and, therefore, the operation and maintenance costs are much lower compared to conventional treatment systems".

Constructed wetlands can generally be designed as multipurpose ecosystems that may provide for flood control, wildlife habitat and carbon sequestration. Refer Figure 2.7 for a typical set out of a constructed wetland.

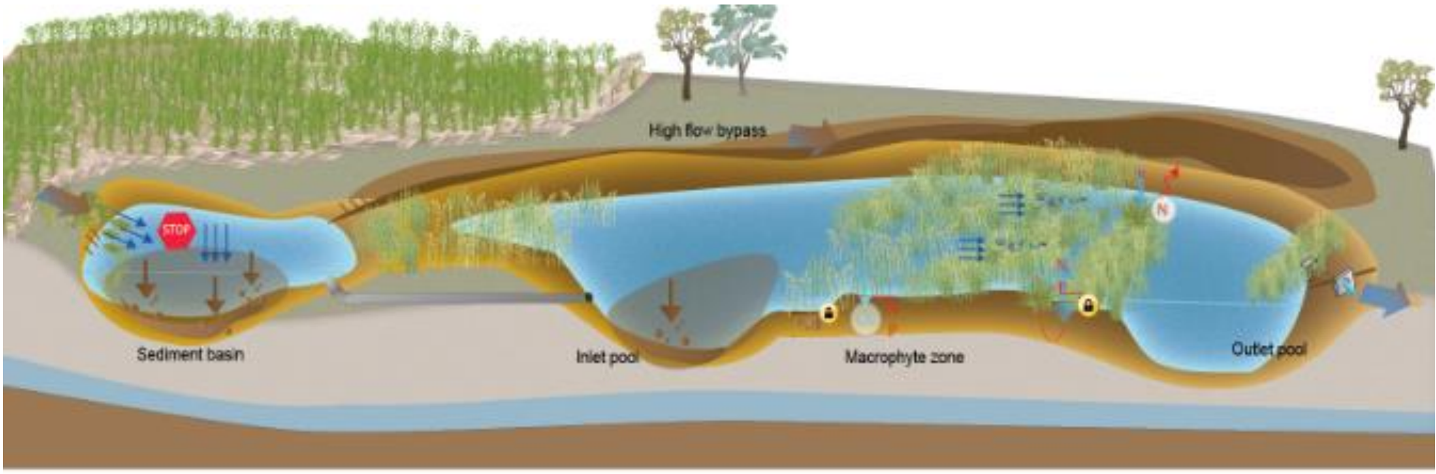

Figure 2.7 – Treatment Wetlands (Wetlandinfo QLD Government 2018)

2.2.1.7. Urban Street Tree Pits

Urban street trees are a smaller form of bioretention system and are usually used to treat and covey run off to a large system. They are also commonly referred to as tree bio-pods or water smart trees and can easily be constructed around urban environments using minimal space and providing appeal to an urban development.

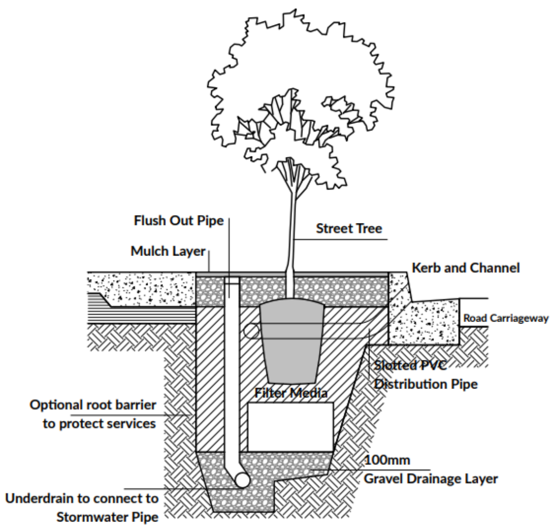

Figure 2.8 - Street Tree Pit (Water by Design - Concept Design Catalogue 2018)

Figure 2.8 above provides a cross-section of a typical street tree pit with under drainage, that is usually directed to kerb and channel or a stormwater network. Urban street trees can be blended into the urban landscape very well and come in different sizes for increased effectiveness.

2.2.1.8. Rainwater Tanks

Rainwater tanks capture and store roof water that can in turn can be reused on-site. They can play a major part in flood and peak flow control in storms by creating an extended lag time in an event and capturing a significant area of impervious area. Water stored in tanks can become a health hazard extended periods of time and there are many standards around mosquito prevention and regular inspects, that fall under regular maintenance, therefore rainwater tanks only provide benefits if water is used frequently. Minimum tank sizes for a single dwelling are usually 5kL and 3kL for attached buildings, units and accommodation buildings are unspecified. Other advantages of rainwater tanks used a WSUD strategy are, retaining water close to source, reducing site run-off and peaks, reducing strain on stormwater systems and minimising household water usage, refer to Figure 2.9 below for a typical rainwater tank solution.

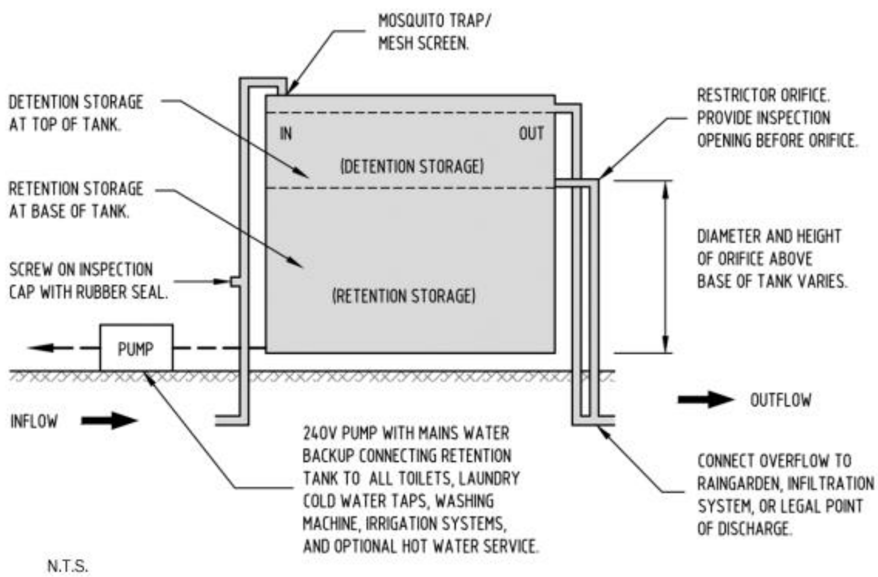

Figure 2.9 – Rainwater tank (Water Sensitive SA, January 2020)

2.3. WSUD Performance Modelling

It has been identified through a study on local planning schemes around Southeast Queensland, that MUSIC modelling is the most used hydrology software for WSUD design and performance measuring. According to *Water by Design – WSUD Modelling Guidelines 2018*, "The Model for Urban Stormwater Conceptualisation (MUSIC) is a software tool that stimulates the behaviour of stormwater in urban catchments. MUSIC is the preferred tool for demonstrating the performance of stormwater quality treatment systems within urban areas".

2.4. Music Modelling Guidelines

The guidelines for using MUSIC are as follows:

- **Create stormwater management objectives -** determine what is required for the catchment in question, what requirements/results are needed for a successful outcome.

- **Catchment model setup –** Identify the preferred meteorological data to be used for the catchment, determine rainfall runoff, create a source node, pollutant parameters and define the catchment properties.

- **Stormwater treatment -** Determine treatment WSUD strategies, configuration and parameters, create treatment nodes.

- **Life cycle cost –** Once nodes have been created meeting desired parameters, a cost estimation can be created for life of the WSUD based on ongoing maintenance.

- **Results –** Run the model, analyse the results and determine if the treatment strategy complies with the stormwater quality objectives

- **Reporting and Assessment –** MUSIC can output result reports and information that can be presented in Stormwater Management Plans for assessment by local authorities.

2.4.1. Stormwater Management Objectives

Stormwater management objectives are generally created by the local authority where the development is proposed. They consist of a criterion that needs to be achieved for an urban development to be approved for construction. It is very consistent between councils within Southeast Queensland for urban developments to create a lawful point of discharge, meaning directing rainfall and runoff from the developed catchment to the stormwater system without affecting neighbouring properties. It is very important that stormwater is conveyed lawfully in a way that is not directing towards neighbouring developments and in not encouraging flooding in any means.

They are also pollutant design objectives to meet with urban developments in Southeast Queensland. The objectives are outlined in the WSUD Technical Design Guidelines for Southeast Queensland and are below.

- **Greater than or equal to 80%** - Reduction in total suspended solids load.
- **Greater than or equal to 60%** - Reduction in total phosphorus load
- **Greater than or equal to 45%** - Reduction in total nitrogen load.
- **Greater than or equal to 90%** - Reduction in total gross pollutant load.

2.4.2. Catchment Model Setup

MUSIC recodes meteorological data for use in model creation, appropriate data can be added that are based on rainfall stations around Southeast Queensland. A modelling climate period and time-step is usually selected, timesteps greater than 6 minutes are generally only selected for predeveloped catchments to reduce run time. Developed models are required to use a time step of six minutes for accurate results.

Catchment properties that are added to the MUSIC model are, total area, percentage of impervious, runoff parameters, pollutant export parameters and a split of the catchment around similar land use, for example: roof areas, free drainage areas and roads. The catchment can also be defined by topography and land use. Refer to Figure 2.10 Below for typical surface types and their nodes.

SURFACE TYPE	MUSIC SURFACE TYPE NODE
House and garage roof to tank	Roof (100% impervious)
House to external drainage	Roof (100% impervious)
Ground level (driveway, shed and yard)	Included as part of ground level surface node with the percentage imperviousness adjusted accordingly
Half of road and verge	Included as part of road surface node with the percentage imperviousness adjusted accordingly. Note that 50% of the road width would generally be modelled with the property on the opposite side of the road.

Figure 2.10 – Surface type and node example *(Water by Design, 2010)*

Other parameters for the catchment such as area, area of impervious, slope and soil types are measured or collected on a site-by-site basis. Slopes and catchment areas can be calculated by GIS software using equal area methods and measurement tools, impervious areas can be determined on site or less accurately by using typical data sets, whereas geotechnical soil data can usually be attained by soil surveys.

2.4.3. Stormwater Treatment Nodes

All stormwater treatment devices have default inlet and storage parameters that are based on council and standard guidelines across Southeast Queensland. Generally, if the parameters cannot be user defined, MUSIC will recommend parameters to be used, although it is up to the designer to specify sizes of the treatment device. The WSUD treatment nodes can be created with limited data available, although the more information that is available the more accurate the results will be and model complexity also increases as shown in the below figure 2.11 by *Grayson et al, 2000*.

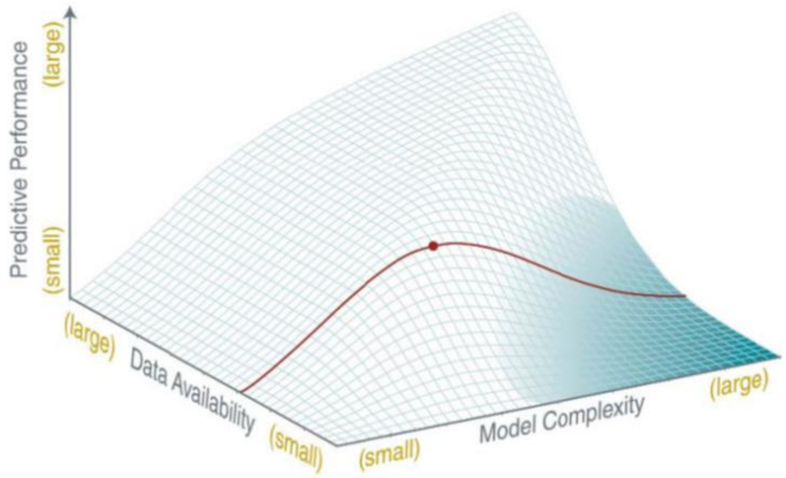

Figure 2.11 - Model – Data availability vs complexity (Grayson et al, 2000)

2.4.4. Life Cycle Cost

MUSIC Version 4 and above have life cycle cost features inbuilt in the software. Once the nodes and parameters are specified the model can calculate the sum of all expenses associated with the project including, acquisition, operation and maintenance, installation, refurbishments and disposal costs.

An annual inflation rate is used with current inflation rate figures and up to date figures used from local stormwater management managers across Queensland.

2.4.5. Results, Reporting and Assessment

Once the model has been run, a load analysis can be output. The analysis will summarise the mean annual load of pollutants and reduction percentage from the treatment notes. Pollutant concentrations and runoff reduction can be output and exported for using in Microsoft excel. These results can be input into creating hydrographs or output for use in Stormwater Management Plans, Integrated Management Plans, Total Water Cycle Management Plans or a standalone MUSIC modelling report. According to *Benito 2015*, hydrographs provide an excellent visual representation of a storm event, the major factors including runoff peaks, volume, duration and shape of the storm. An example of a predeveloped and post developed case hydrograph is shown below in Figure 2.12.

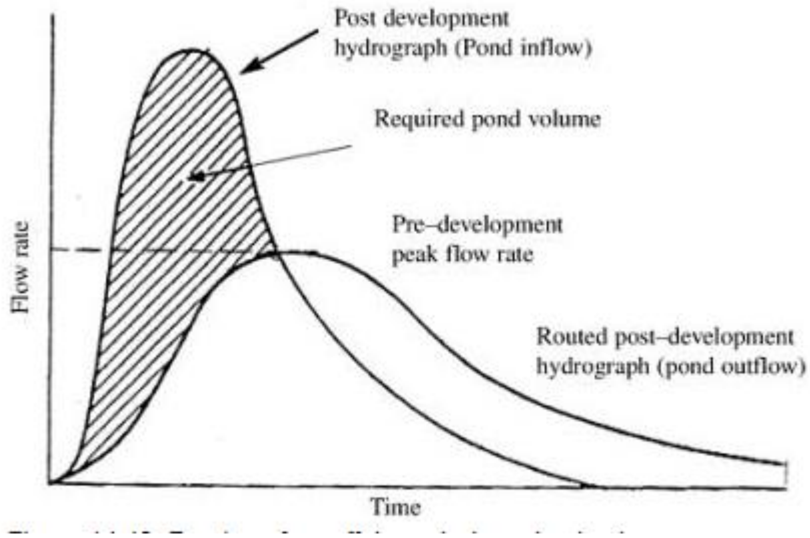

Figure 2.12 – Hydrograph example (Mays, 1999)

Hydrographs consist of plotting measured flowrate or discharge against storm duration and are an efficient method to quantify the performance of WSUD by determining what effect the WSUD has on a storm event. This information can then be utilised to determine how this change in storm event responds to RDII on an existing sewer system.

2.5. RDII Identification and Sources

RDII is the addition of non-sewer water into urban and sanitary sewer systems in direct consequence of a rainfall event and has long been a critical problem for urban water management and infrastructural asset management. It is widely known, RDII can have detrimental social, economic, and environmental impacts on our way of life. Furthermore, climate change and IFD analysis continue to show an increase in frequency of high intense rainfall events that continue to alter hydrologic performances of sewer and drainage infrastructure globally (Yilmaz et al 2014) and indicate the occurrence of high intensity events and flood volumes are also likely to increase in the future (Whitefield 2012).

According to Ellis 2001, infiltration into sewerage systems occur from two principal sources, leakage from the trench (sand/gravel) backfill from old pipework and loose broken pipe connections and by hydraulic leakage into the sewer system by elevated ground water levels, more commonly known as ground water infiltration of GWI.

Both sources of infiltration, are also the likely cause of sewer exfiltration, the leakage of wastewater from the sewer system, that may contaminate ground and surface water causing a large range of problems to public health and the environment, resulting in costly repairs from structure failures and ground subsidence from the erosion of soil support (Bhatia et al 2017). Although, according to an assessment of sewer leakage by means of exfiltration - measures and modelling tests (Rutsch 2006), there is contradiction in case studies that attempt to quantify exfiltrating wastewater and determine its effect on the surrounding environment and it appears apparent, this contradiction is largely dependent on the water table depth, in the case study.

Ellis 2001 also notes, Infiltration can generally be the dominant contributor to peak flow in sewer separate sewer systems where stormwater is diverted away within its own system and not combined with sewer. In many countries and some regions in Australia with old sewer infrastructure, sewage and stormwater are conveyed in a single common pipe network generally known as, combined sewers. However, most combined sewer systems in Australia, have been separated into separate systems since (National Water Quality Management Strategy 2006). Where systems are combined, such as Launceston, Tasmania, it has been found that the contribution of direct runoff known as inflow, is the dominate contributor to peak flow in the system (Jessup 2015). Major sources of inflow are generally caused by illegal rainwater connections into the sewer network, landscaping that directs stormwater into sewer manholes or overflow relief gullies, old or unsealed manholes covers and pump stations or stormwater cross connections (Gladstone Regional Council). Urbanisation and the replacement of natural landscapes with impervious surfaces, such as roads and rooftops, and can substantially change the natural hydrological cycle in the area. Refer to Figure 2.13 below for common Infiltration and Inflow (I/I) sources.

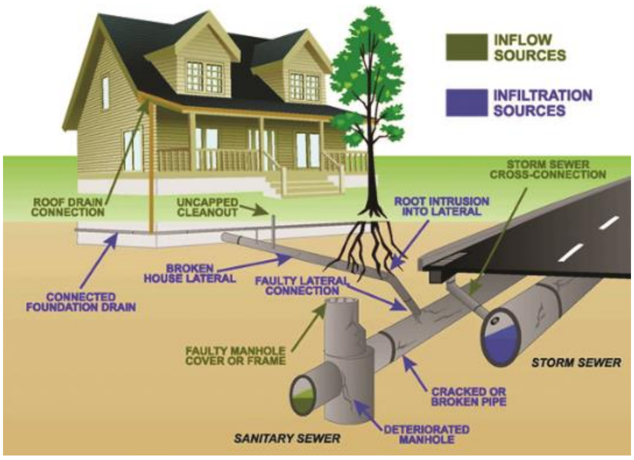

Figure 2.13 – Infiltration and Inflow sources (Kurz, P.E, Dee 2017)

2.5.1. Contributing Factors

There are many factors that contribute to RDII in sewer systems that can cause sewerage overflows at manholes or force wastewater treatment plants to release effluent into adjoining rivers or streams (Water Environment Federation 2017, Jayasouriya et al 2015), these include:

- **Sewer type, size, age, and sewer appurtenances**
  - It is common for infiltration to occur in faulty joints, cracked pipes and manhole covers.
  - Older sewers made from materials, such as Asbestos Cement, Vitrified Clay, Earthenware and Concrete have been found to be more susceptible to RDII, many sewer mains made from these materials have reached their design life and are damaged or can be easily broken down.
  - Pipe flow exceeds the design flow for the pipe size, fractures and failures in the pipe can occur.
- **Soil Type and Soil Properties**
  - Soils with high hydraulic conductivity (a soils susceptibility for fluid to pass through its pores) and large pore spaces tend to have higher infiltration rates.
  - Soils with high moisture contents or saturated soils tend to achieve maximum hydraulic conductivity quickly, resulting in less surface runoff and more infiltration.
  - High permeability of the soil can also promote a higher infiltration rate as there is more air pockets and pores for water to fill. Sewer pipes are generally embedded in granular material, in which can be eroded away causing damage to sewer systems if soil allows for too much infiltration. Different types of pipe embedment is generally used depending on a geotechnical analysis, in some cases piles may be used to avoid movement.
- **Quality of Design, Construction and Upkeep**
  - Poor supervision and site inspection of sewer construction can lead to improper joining of pipes or sealing of manholes, causing high chance of shearing, root intrusion, leaks and failure resulting in high infiltration.
  - Poor or un-enforced standards and codes can lead to a decrease in construction quality, non-suitable materials used or unqualified contractors.
  - Poor materials used or lack of maintenance and rehabilitation. Regular sewer assessments and monitoring can identify defects early and reduce more progressive defects and RDII.

    - Poorly designed or installed sewer systems with lake of cleansing gradient or slope, can cause a 'chemical attack' from stagnate sewer and erode the sewer system.
- **Groundwater and hydrology**
    - High water tables can cause erosion and stresses in the system, from movement in the soil during wet weather events. A high-water table also increases GWI, as the sewer system becomes submerged to a point.
    - RDII from long duration events causing flooding or ponding over sewer systems.
    - Land development and material change of use, the increase in impervious area and connections to the existing drainage system from land development and subdivisions.
- **Community**
    - Private sanitary systems in Australia, are not controlled by local water authorities and are therefore not subject to the same high standards, there is also no authorised control over rectification works.
    - Illegal roof water connections to sewer systems, resulting in large inflow.
    - General population increase and possible overburden of sewer systems.

2.6. Australian Sewer Standards

This chapter reviews current design and construction standards, in Australia to provide a clear understanding of how sewers are designed. It is important to review the industry design and construction standards for sewers to gain an understanding of the primary function of sewer systems, the common failures of sewer systems and what mitigation strategies can be implemented to reduce sewer failures on the environment.

2.6.1. Water Services Association of Australia

The Water Services Association of Australia (WSAA) is Australia's main industry body representing urban water and sewer services for up to 70% of the Australian population. The WSAA provides a means of standardisation of industry performance monitoring, whilst facilitating collaboration, networking, and development of industry codes across Australia (WSAA 2011). The WSAA have five national codes for sewer and water systems, the publications address planning, design, construction, testing and commissioning of water and wastewater. The codes recognised are,

- Gravity Sewerage Code of Australia
- Water Supply Code of Australia
- Sewerage Pumping Station Code of Australia

- Vacuum Sewerage Code of Australia
- Pressure Sewerage Code of Australia

These national codes have been widely adopted by local water authorities and governing bodies around Australia and focus on the broader issues around services such as, environmental management, asset management. These codes have been built and revised around the latest industry knowledge to influence national and state policies on sustainable and environmentally conscience resource management and to provide for improvement in industry performance.

2.6.2. Gravity Sewerage Code of Australia - SEQ Edition

The Southeast Queensland Code is a specific edition of the Gravity Sewerage Code of Australia, with standards for South East Queensland (SEQ) water authorities. These authorities include, City of Gold Coast, City of Logan, Urban Utilities (independent board for Brisbane, Ipswich, Lockyer valley, Scenic Rim, and Somerset Councils), Redland City Council and Unity Water. The primary purpose of the Gravity Sewerage Code of Australia is to document technical best practice for design and construction of quality sewer networks. (WSAA – SEQ Code 2021), although the SEQ Service Providers (SPs) also reserve the right to approve and standardise other design and construction requirements, for other developments and projects. The WSAA SEQ Code is typically used for the design and construction of sewer systems up to DN300 for SEQ SPs, although it also provides concepts that may be used for larger systems. The Code also does not specifically address sanitary/private drainage systems, although is generally used as a 'deemed to comply' solution by engineers and contractors.

2.6.2.1. Smart Sewers

The SEQ Code adopts the use of 'smart sewers' and are the preferred solution for all in-fill developments within the SEQ-SPs. The smart sewer systems are implemented to reduce infiltration and tree-root intrusion at a lower cost to the customer, compared to more convention sewer systems. These systems are split into two categories, 'NuSewers' and Reduced Infiltration Gravity Sewerage systems or 'RIGSS'.

NuSewer systems comprise of fully welded Polyethylene pipes (PE), fitting and maintenance shafts and are a mandatory system for UU and a permitted option for Unitywater. Since NuSewer is a fully PE welded system, it can contain vertical and horizontal bends and the use of maintenance shafts, where other systems may require concrete manholes or maintenance structures. Queensland Urban

Utilities claim, the elimination of rubber ring joints in NuSewers will minimise GWI and RDII compared to traditional sewer system, although infiltration and exfiltration still may occur from undetected construction defects and customer drains, that may not be fully welded PE (Queensland Urban Utilities 2019). The use of maintenance shafts in the sewer system also reduces the amount of infiltration the system receives.

RIGGS are constructed from PVC or Polypropylene and are commonly consist of RRJ PVC sewers and PVC chambers and/or maintenance shafts. Although, in traditional sewer systems, PVC is a commonly used pipe material the only difference between a traditional sewer from PVC and RIGGS is the use of maintenance shafts, thereby reducing the quantity of manholes in the design, a large contributor to RDII. RIGGS also utilises in-line bends to reduce the need for manholes in the system.

Smart Sewers can be designed to include horizontal and vertical curves to minimise the number of maintenance structures. The reduce number of maintenance structures in the systems, it is found RDII is reduced significantly and inspections and blockages in the pipe can be undertaken and resolved using CCTV equipment and jet rodders (WSAA – SEQ Code 2021).

2.7. Hydraulic Capacity

The discharge of industrial, trade or domestic wastewater into any river or waterway is strictly prohibited under Queensland Legislation - *Environmental Protection Act 1994*, with the risk of large fines and catastrophic damage to the environment, design flow of sewer systems is generally designed to cater for certain amounts of RDII, GWI and air space/ventilation (WSAA – SEQ Code 2021).

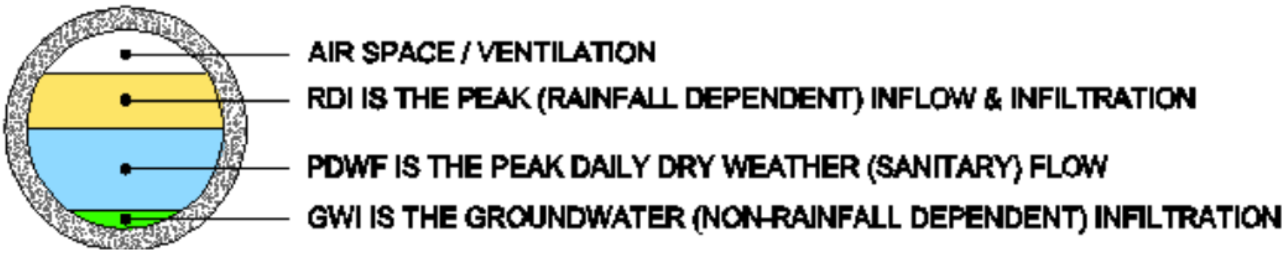

Figure 2.14 – Hydraulic Capacity (WSAA – SEQ Code *2021)*

"The Peak Dry Weather Flow (PDWF) is defined as the most likely peak sanitary flow in the pipe during a normal day. It exhibits a regular pattern of usage with morning and evening peaks related to water usage for toilets, showers, baths, washing and other household activities Hydraulic capacity" (WSAA – SEQ Code 2021).

During intense rainfall events, the hydraulic design capacity can be exceeded, putting the sewer system under pressure and can cause surcharge in manholes and SSOs. These SSOs can pose an inherent risk to the public health of the community and the environment.

The determine the PDWF for a sanitary sewer system within the SEQ water authority's jurisdiction, the below formula is used.

$$PDWF = d * ADWF$$

Where:

"ADWF is the combined average daily sanitary flow into a sewer from domestic, commercial and industrial sources. Based on empirical evidence, ADWF is deemed to be 180 L/d/EP or 0.0021 L/s/EP." (WSAA - SEQ Code 2021) and the value d (dry weather peaking factor) can be determined by using the chart in *Table 2.1*, or by the below formula – where A is a gross plan area of the development's catchment in hectares.

$$d = 0.01(\log A)4 - 0.19(\log A)3 + 1.4(\log A)2 - 4.66\log A + 7.57$$

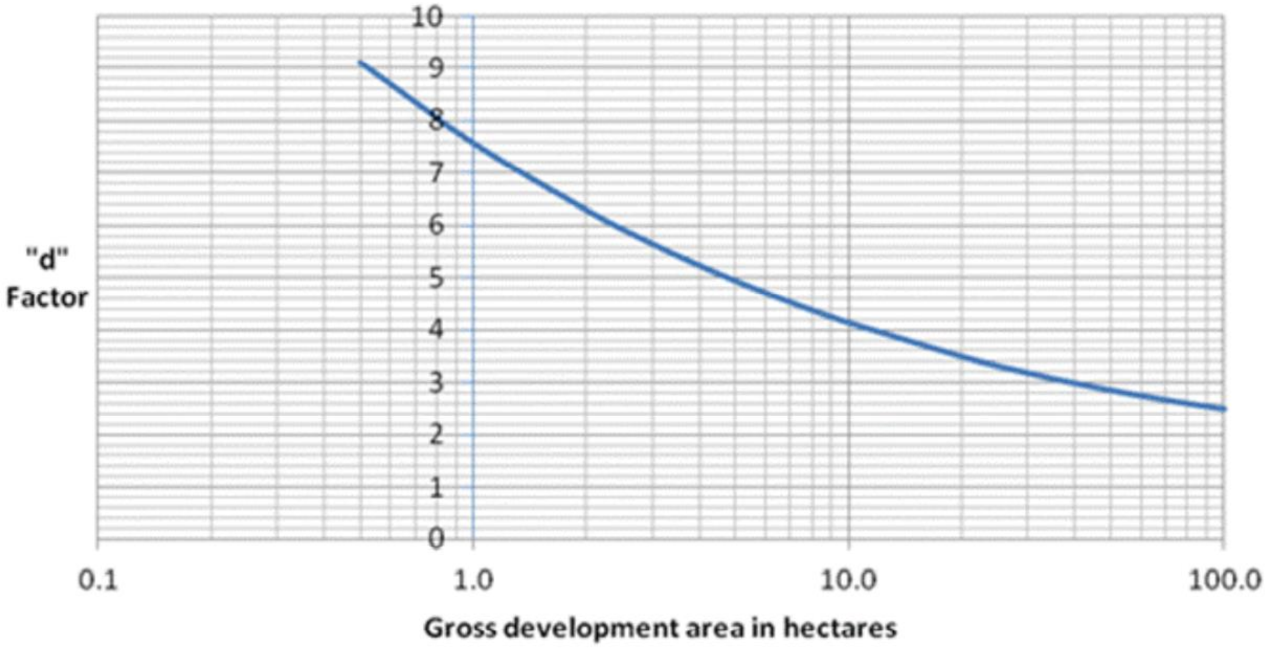

Table 2.1 – Factor 'd' vs Gross development area in hectares (WSAA - SEQ Code 2021)

The GWI is estimated on the assumption that good quality workmanship and materials are used for the sewer system and is calculated using the below formula.

$$GWI = 0.025 * A * PortionWet$$

Where, '*A*' is a gross plan area of the development's catchment in hectares and PortionWet can be summarised as, *"portion of the planned pipe network estimated to have groundwater table levels in excess of pipe inverts. For example, if 70% of the sewer system is below groundwater table levels, then PortionWet = 0.7" (WSASA* - SEQ Code 2021*).*

RDII is estimated by the below formula and is expressed in L/s.

$$RDII = 0.028 * AEff * C * I$$

Where, '*AEff*' is a function of impervious area in relation to the catchment in the design area, that will discharge stormwater runoff. The catchment of the area, being determined generally using contour mapping and in accordance with QUDM.

For residential developments the SEQ Code defines '*AEff*' with the below formulas.

$$AEff = A \times (Density/150)^{0.5} \text{ for Density} < 150 \text{ EP/Ha}$$

Or

$$AEff = A \text{ for Density} > 150 \text{ EP/Ha}$$

With the value for *'Density'* in this case being the development's EP density/gross Ha

For commercial and Industrial developments *'AEff'* can be defined as:

$$AEff = A \times (1 - 0.75\ Portion_{Impervious})$$

Where, '$Portion_{Impervious}$', can be summarised as, "*the portion of the gross plan area likely to be covered by impervious structures that drain directly to the stormwater system e.g. if a development has 20% coverage by such structures, then PortionImpervious= 0.2.*" (WSAA - SEQ Code 2021).

The value '*C*' is known as the Leakage Severity Coefficient and is derived by table 2.2 below. According the WSAA, the Leakage Severity Coefficient takes into account soil aspect of the catchment and aging network infrastructure and defects to derive a coefficient that may be used in the RDI calculation.

Influencing aspect	Low impact	High impact
Soil aspect, S_{aspect}	0.2	0.8
Network defects and inflow aspect, N_{aspect}	0.2	0.8
$C = S_{aspect} + N_{aspect}$	Minimum = 0.4	Maximum = 1.6

Table 2.2 – Leakage Severity Coefficient (C) (WSAA - SEQ Code 2021)

Finally, the value *"I"* is a function of rainfall intensity. A I_1, 37.35% is generally used, which can also be expressed as an ARI of 2 for a one-hour duration. This information is generally sourced from the Bureau of Meteorology, using the coordinates of the development.

Once PDWF, GWI and RDII has been determined, an allowance of at least 40% air space is provided in the pipe, during dry weather flows and when the RDII is determined to be at its minimum.

It is evident in the above design flow estimation that, RDII and GWI have a significant role in hydraulic capacity although, the above calculations do not cover the many contributing factors of RDII such as possible defects, pipe material and jointing methods and aging of infrastructure. The GWI calculation assumes that quality materials a good workmanship is used and appears to negate the many soils type and soil properties that play a large role in GWI. Finally, RDII is calculated using a model very similar to the Rational Method, used in QUDM for stormwater flow. The RDII calculation requires the designer/engineer to determine a percentage of impervious structures in the catchment, quite often this is determined by aerial imagery and can easily be misjudged, skewing the output.

2.8. Estimating and Detection of RDII

Estimating and detecting RDII in sewers may be split into two types of approaches, qualitative and quantitative methods (Thapa et al. 2019). Qualitative methods are based on the classification of sewers and their environmental surrounds in relation to properties and parameters, whereas quantitative is typically based on classification of data based on computable values.

Each method has their advantages and disadvantages when it comes to quantifying RDII and generally require assumptions to predict values.

In a study by *Benedittis & Bertrand-Krajewski 2005*, a comparison of measurement methods analysing traditional qualitative methods used around Europe at the time, found that it was not possible to distinguish or identify a preferred or best method, rather a combination of these methods could be valuable to better define the conditions and reduce uncertainties and assumptions.

Methods applied during dry weather periods, a total wastewater or flow rate is generally necessary. The traditional method for measuring wastewater flows is the use of a flume (specifically shaped, engineered static structure, used to restrict flow) and an ultrasonic monitor (flow monitoring device).

The flow rate of a sewer around Queensland, is captured using these monitoring devices that are setup around several points of interest determined by the water authorities, such as inflow into wastewater treatment plans, pump stations and certain manholes that adjoin or receive sewer to significant areas or a deemed problematic. In contact with most of the SEQ SPs, flow monitoring is only used at Waste Water Treatment Plants (WWTP) and waste water data can be difficult to attain for the public.

2.8.1. Qualitative Methods

Qualitative methods are traditionally used for location/detection of RDII and identifying problem areas within a sewer network. These methods include:

- **Smoke Testing Method**
  - Commonly used by Queensland Urban Utilities and other SEQ SPs, involves blowing non-toxic smoke into sewer manholes, that will then enter the sewerage pipes connecting to a property (Queensland urban Utilities 2019). If the pipe is free of defects, cracks and intrusions, the smoke will be vented out of the household sewer vent. If the pipe does have the above problems or is illegally connected to roofwater drainage, then smoke will escape from the ground or roof guttering.
  - Smoke testing is relatively inexpensive, environmentally friendly, and easy to conduct for the operator, although smoke testing should be used as a basic first step to identify problems and is known to have a low success rate in detection.

- **Dye Testing Method**
  - Can also be used to detect RDII problems in sewer systems. A non-toxic dye is added to the water source, that when is stimulated, the dye leaks into the system. The dye can come in a range of colours to suit different points of suspected infiltration and applied to different plumbing fixtures to narrow down the source.
  - In High flow and turbid conditions, it has been stated that the dyes can be hard to see for the operator (PTSA 2008). It can also be a time-consuming process in low flow environments and can be labour-intensive as entering infrastructure is often necessary.

- **DTS Method (Distributed Temperature Sensing Method)**
  - Utilises long lengths of fibre optic cabling, to measure temperature with a high frequency and resolution. The difference in temperature of the inflow is plotted along a distance vs temperature chart and the indifferences in temperature can be recognised as infiltration, inflow, or exfiltration.
  - This method is widely used and relatively inexpensive in comparison to other methods.
  - A case study by Hoes et. al. 2009, found that using DTS for detecting illegal connections, monitoring results for empty sewers, differed from partially filled sewers, also participation in pipelines can also influence monitoring results.

- **CCTV & 3D optical scanner**
  - This method is most used, especially in newly constructed sewer infrastructure, it is usually the engineer's responsibility to check the constructed sewer for any defects, cracks, splits, obstructions or as what was designed.
  - Queensland service providers use this method as preventive maintenance for possible corrective action can be implemented, such as cleaning.
  - Can be time consuming going over many kilometres of sewer, although criteria are stringent, possibility of human error.
  - Can also be expensive and time consuming.

- **Low Pressure and Vacuum Testing**
    - Another common method used throughout SEQ. The pipeline is 'shut off', all valves are closed, sewer inlets and outlets are plugged, and maintenance structure shafts and risers are sealed for testing.
    - The system is subject to a vacuum pressure (negative pressure) of around 27kPa for RRJ sewers and 50kPa for sewers with welded joints.
    - The pressure is either slowly increased (low pressure testing) or is left to stabilise (vacuum testing).
    - A loss of pressure is recorded, if the losses are greater than the recommended, the sewer system may have leaks or defects.

2.8.2. Quantitative Methods

These are current methods for assessing the magnitude, discharge, and volume of RDII and should be generally used in conjunction with the above Qualitative methods.

Stable Isotopes Method

This method, also known as a tracer method *Kracht et al. 2006*, quantifies infiltration by separating wastewater into two categories. Drinking water that has become sewerage from household, trade or industrial use and extraneous water derived from groundwater infiltration, drainage pipes and public fountains. The function for infiltration is summarised below in Figure 2.15, for a 24hour period:

$$Q_{\text{infiltration, 24h-total}} = \int_{24\text{ h}} X_{\text{infiltration}}(t)\ Q_{\text{wastewater}}(t)\ \mathrm{d}t$$

$$X_{\text{infiltration, 24h-total}} = \frac{\int_{24\text{ h}} Q_{\text{infiltration}}(t)\ \mathrm{d}t}{\int_{24\text{ h}} Q_{\text{wastewater}}(t)\ \mathrm{d}t}$$

Figure 2.15 – Stable Isotopes Method (Kracht et. al 2006)

This method uses isotopic tracers to calculate infiltration in the following steps

- Catchment is surveyed to determine the stable isotope composition of any infiltrating waters that may be present at several measuring points.
- Local drinking water within the catchment is surveyed to determine the stable isotope composition, including means to control the homogeneity of mains water composition
- Wastewater samples are taken from several diurnal cycles at the forementioned measuring points. All discharge can be measured in parallel to determine the isotopic indifference.

This method generally needs to be conducted at a minimum of 24hours during dry weather conditions (Kracht et. al 2007). The drinking water and groundwater sampled should have homogenous, but distinct isotopic signatures and components of drinking water and ground water should interact, (Ellis & Bertrand-Krajewski 2010) and it is important that comprehensive hydrological survey and investigations are accurately documented.

Pollutant Time Series Method

Quantifies infiltration in a sewer system based on a time-varying pollutant concentrations to create palatographs. A model that can represent the time-varying behaviour of contaminate interaction and transport of pollutants within catchment surfaces and a sewer system.

This method is not suitably used in areas that have industrial, commercial, and residential wastewater combined and assumes infiltration into the sewer contains a negligible number of pollutants, in which may not always be the case (Ellis & Bertrand-Krajewski 2010).

Conductivity Monitoring

This method generally uses Fast Fourier Transform, to analyse variations in wastewater flow and quality via different levels of conductivity converted into frequencies over a per a selected period.

According to Zhang. et. al 2018, "The proposed method has distinct advantages over traditional flow-based methods for estimating inflow and infiltration, especially when the events produce backwater, overflow, and abnormal flow data in sewer systems. The method uses very simple conductivity sensors. Thus, the proposed approach can be easily implemented for real-life applications"

Although, it appears evident, this method can only be used in areas with high quality monitoring data available of rainfall and sewer flows and areas with details GIS systems available.

Flow Rate Method

More conventional method used for infiltration assessment, also known as the Constant Unit Rate Method, assumes constant infiltration of groundwater in dry weather flows (Beheshti et. al. 2015). An equation is derived requiring the following parameters to be known - population served, daily average water consumption per capita and daily average industrial effluent flow these parameters are divided by the daily dry weather flows of the system to estimate the total infiltration.

This method has been used as a very broad estimate, based on very simple assumptions. It may be used to determine a difference in flow or provide a requirement for additional analysis to be used in a catchment. It is not recommended, to be used as an accurate assessment of RDII.

Synthetic Unit hydrograph (SUH)

The most used SUH method is known as the RTK Method. This method combines three hydrographs created using parameters R, T and K. Vallabhaneni 2014 describes these values as the below.

R – Fraction of rainfall volume that enters the sewer system.

T – Time from the onset of rainfall to the peak of the SUH.

K – Ratio of time-to-recession to the time-to-peak of the unit hydrograph.

The hydrographs are shown below in Figure 2.16

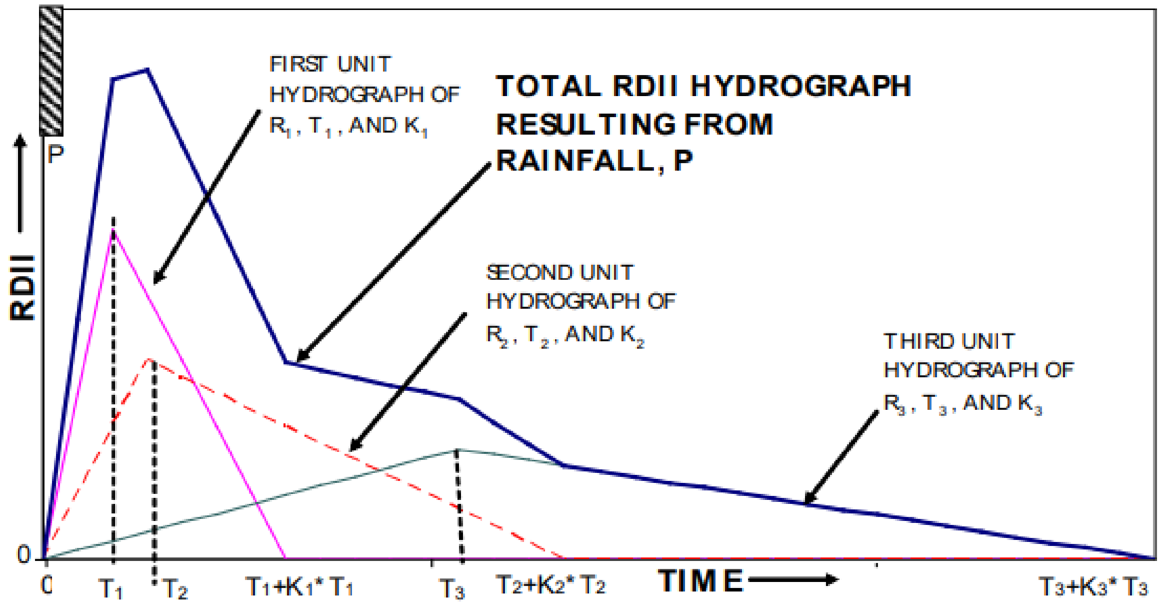

Figure 2.16 – RTK Method Parameters (Vallabhaneni 2014*)*

The three triangles or hydrographs (shown in pink) above indicate fast, medium, and slow responses of RDII flow entering the sewer system almost immediately, during the rain event and after the rain event. Once all three hydrographs are derived, they are added together to determine the total amount of RDII.

The RTK method is generally inbuilt in modelling software such as SewerCAD by Bentley Systems and SSOAP toolbox by the Environmental Protection Agency (EPA).

2.8.3. Estimating and Detecting RDII Overview

Estimating RDII in sewer systems can be complex when RDII and overflow occur simultaneously. The above methods all have their limitations and vary in accuracy depending on available data with the catchment. Due to the likelihood of this uncertainty, multiple methods are generally used. It is important to have a comprehensive and detailed understanding of the locations where RDII may be occurring within a system to aid efficient rectification works on the sewer system.

2.9. Mitigation Strategies

A sewer system that has been correctly designed, maintained, and operated serves a purpose to collect and convey all wastewater flow to the wastewater treatment plant for processing, without causing any harm to the environment or public health of the community. Although, due to the age, past mistakes, and continued development, sewer systems are rarely this efficient. This chapter aims to pose as a guide to the current mitigation strategies and focus on sustainable WSUD strategies that can mitigate the adverse impacts that wet weather events have on existing sewer.

2.9.1. Conventional Mitigation Strategies

The current mitigation strategies to reduce RDII are largely involved with structural rehabilitation measures on existing and aging pipelines and infrastructure. There are also design requirements in SEQ and smart sewers, as previously mentioned to help reduce the effects of RDII for new developments. *Tomczak and Zielinska 2017*, split the current rehabilitation methods into three categories, maintenance and repair, renovation, and replacement.

Maintenance and repair, generally includes chemical grouting to fix cracks and defects in existing concrete manholes and structures, cleaning existing sewer systems and repairing sections from root intrusion or other damage.

Renovation includes performing a corrective action to resolve the defect and/or bring the existing pipe or infrastructure up to a current standard of practice such as relining of a pipe. There are many methods currently used to reline a pipe or manhole such as:

- Relining
  - A smaller pipe is simply pushed/pulled through the old pipeline
- Close fit relining
  - Liner pipe is mechanically deformed/folded for insertion, then returned to its original form with the application of heat or pressure.
- Spray on Lining
  - Liner is applied to a clean and dried pipe wall
- Pipe bursting
  - A larger diameter pipe is installed with the assistance of a hydraulic pipe cracker, gradually breaks the old pipe.
- Cured lining
  - Liner is pushed through the existing pipe and cured with water or steam

Finally, Replacement which simply involves removing the old infrastructure and replacing it with new, up to standard infrastructure. In SEQ it is a requirement for the water authority to replace any old infrastructure fronting the any new development at the developer expense, such as old Asbestos Cement and Vitrified Clay pipe.

Other methods involving mitigation, have been largely based around preventing sewer overflows generally caused by RDII. These include increasing the storage capacity of sewer networks to reduce the effect of overflow hazards, although these methods can be very costly and have adverse aesthetic impacts. Increasing the amount of pump stations present in the network has also been adopted to prevent overflows, although this solution is found to be very expensive and according to *WSAA – SEQ Code 2021*, pumping station failures can cause significant overflows and generally occur due to factors such as interruptions to the power supply or equipment failure.
Overflow Relief Gullies have been installed throughout SEQ to prevent sewer overflows in private properties, although if installed incorrectly also contribute to stormwater inflow into the sewer systems. If the ORG is installed too low or if an illegal roof water connection is installed, this becomes another point of entry of stormwater inflow.

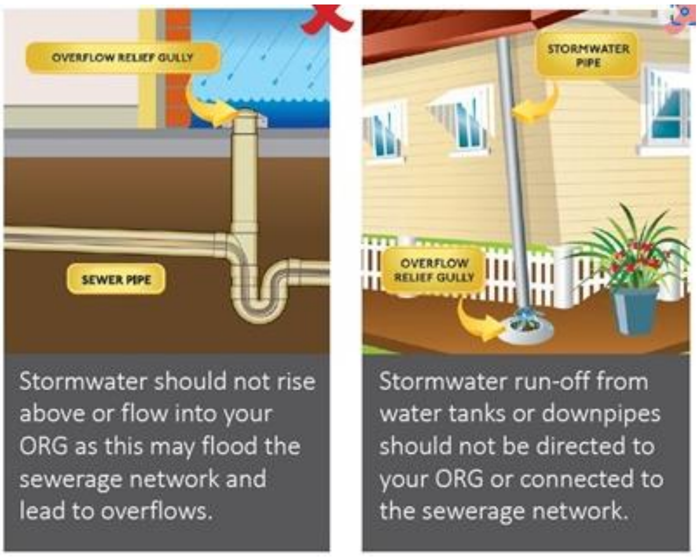

Figure 2.17 - Overflow Relief Gully Installation (Queensland Urban Utilities 2019)

Finally, it is important to note, RDII mitigation strategies can be implemented in the design of sewer systems. Bulkheads and trench stops can be installed in areas of steep gradient to reduce minimise longitudinal and lateral movement in pipelines, prolonging the life of the pipe embedment and preventing damage to the sewer (WSAA SEQ Code, 2021) and final inspection and supervision to ensure correct installation is implemented.

For the most part, it appears these methods involve fixing or preventing RDII in existing networks. Although they do not however, address private drainage sewer or mitigating the increasing water volumes over and around sewer systems from urbanisation or impacts of climate change, that appear to be a leading contributor to RDII. Private sewer mains, especially in built-up areas, can account for a large portion of the sewer network that isn't the responsibility of the local water authority. Private sewer lines are also laid with less ground cover (typical sewer connection point to a property is less than 1.5m from existing surface) then sewer mains, making them far more vulnerable to RDII via damage and intrusion. Regular maintenance and repair are rarely implemented on private drainage as it is the property owners responsibly to maintain this part of the sewer drainage.

According to Robinson et. al (2019) "I/I is increasing *waste water treatment costs, waste water treatment plant expansion costs, reduced capacity in trunk sewers, reduced opportunity for municipal revenues associated with development, increased administration costs for municipalities, reduced lifespan of sewers, and increased risk of insured and uninsured damages associated with basement flooding*.", it appears there is a lack of knowledge around sustainable, cost-effective mitigation measure for reducing the impact of RDII.
Nasrin (2018) states, "structural measures are being less used in recent years and the implementation of sustainable and cost-effective WSUD approaches are on the rise."

2.10. Summary

To complete this literature, review many journals, articles, guidelines, standards and case studies were examined to determine expected results, current literature, current standards and efficient methods to achieve desired results. It was found that quantification methods for WSUD are used quite regularly around Southeast Queensland, there are many in depth guidelines to assist designers choose the correct WSUD for their application and efficiently design the strategy to achieve a level of standard that councils are willing to agree is acceptable for the development to proceed. Although more expensive than most conventional methods of stormwater control, WSUD has become almost compulsory for many developments. MUSIC model was found to be the most used method for quantifying WSUD and can be used in conjunction with other hydrological calculations and data to achieve results that are considered sufficient. MUSIC model can be used to design appropriately selected WSUD for a residential catchment and output results that can be converted into hydrographs to provide a clear understanding on the performance of the WSUD during a storm event.

In the reviewed literature in relation to RDII, it was found that quantitative methods are very reliant on flow monitored sewer networks. It was also found that when contacting local authorities, this data was either non-existent or not available to the public. Methods around reducing RDII were heavily focused on repairing and replacing sewerage mains and structures and local authorities do not have many guidelines in the way of mitigating RDII, like they do with WSUD strategies mitigating stormwater runoff. It is evident there is a knowledge gap around, how WSUD may be used as a tool to mitigate RDII in existing sewer networks. Although quantifying RDII will be difficult without flow monitoring data and other estimation methods will have to be used for this dissertation.

3. Methodology

3.1. Introduction

This chapter intends to outline the body of methods, rules and postulates employed to achieve accurate and constructive results aligning with the aim of this study. In the literature review, it was recognised that a combination of stormwater modelling supplemented by hand calculations would produce the most accurate results. This methodology will utilise information gathered from the literature review to achieve a method that can produce reasonable outcomes.

3.2. Methodology Outline

In the literature review it was found that the most used modelling software for stormwater quality improvement and rainfall-runoff modelling in development within Southeast Queensland is MUSIC by eWater, although several councils also accept AQYALM-XP. In many cases, if an alternative software is to be used, the practitioners are required to demonstrate the suitability of the model. Music Model is accepted as a reliable source to assist developers and consulting engineers by all local councils and governing bodies and will be used to determine stormwater runoff.

A detailed preparation of how music model will be set up and utilised to determine runoff reduction from different WSUD, will be described within this methodology. This rainfall runoff reduction will then be compared to estimated values of RDII within a catchment and a total reduction in RDII as a direct result from design WSUD strategies will be determined. It is important to note, this methodology will not include training or learning of MUSIC, although will include values used for best-practice modelling of WSUD infrastructure, by sources identified in the literature review.

A brief outline of steps that will be included in this methodology that will be explored in greater depth are as below:

- **Site and catchment identification**

A proposed site for this investigation was chosen within Brisbane City Council (BCC) in the suburb of Castledine. Real allotments are designed in accordance with BCC planning schemes and code requirements. There is enough fall through the catchment to be a perfect candidate to assess the performance WSUD and to be used as a typical base scenario. This site location is important to determine input parameters that is used in this investigation, although the specification of the selected location is insignificant to a degree, this investigation could be completed at any location.

- **Catchment analysis**

Existing data for the selected catchment relevant to this investigation can be sourced from the Bureau of Meteorology (BOM) , Geographic Information System (GIS) and surrounding development applications. Generally, for a residential development a survey and geotechnical investigation may be undertaken prior this type of investigation, in these circumstances GIS mapping and existing neighbouring applications can be used. An analysis of existing catchment conditions for rainfall through contour interpretation and ground parameters can be used for investigating surface flow.

- **Pre-development stormwater runoff estimation**

Using data collected in the catchment analysis to identify a best practice method and approach in determine existing runoff estimation in accordance with council guidelines and planning scheme and QUDM. Catchment assumptions can be made to assist calculations and verification through relevant software to simulate pre-developed catchment conditions.

- **Design suitable WSUD for catchment**

Using best management practices from sources identified through the literature review to establish suitable WSUD for the catchment and establish scenarios to identify controlled flow through these systems, for comparative measures. MUSIC model will be used to assist in the design of WSUD.

- **Post-development modelling calibration and validation**

Model development using designed WSUD for the catchment following recommended guidelines, determine balance between data availability and model complexity to achieve accurate results and recordings. Identify model assumptions and calibrate model to determine total mitigate flow rates within catchment.

- **Estimate RDII for catchment**

Use appropriate standardised guidelines for determination of predicted wastewater production from the development and existing conditions and quantify base RDII expected in existing sewer system and for proposed development, using methods determine in the literature review.

- **Compare and analyse reduced RDII potential from post-development modelling**

Analyse identified flow mitigated from design WSUD and conduct comparative analysis with estimated RDII, describe method to identify potential reduction of RDII with in the catchment resulting from the introduction of WSUD methods.

3.3. Site Identification

The site chosen for this case study is in Carseldine, QLD and is within Brisbane City Council's jurisdiction, refer to Figure 3.1 below. Although, the location for this study is mostly irrelevant, this site was chosen due the availability in data, the fall of the land, the size of the developable land and the existing infrastructure surrounding the allotment.

Figure 3.1 – Case Study Area (QLD Globe, imagery 2017)

The site has an area of approximately 4ha and is in a built-up area that does not contain an overland flow path or is contained within a flood area, according to BCC flood awareness mapping and a generated BCC flood wise property report

3.4. Catchment Analysis

The catchment currently has 5 existing dwellings, that for this case study will be assumed to be demolished for the provision of a new estate. The site currently falls towards the north-western corner and is covered by approximately 25% vegetation. The existing road that runs towards the eastern boundary of the site, appears to be in good condition with full kerb and channel and sufficient fall to capture rainfall to the existing stormwater network.

Neighbouring developments exist on the north and western boundaries, and it is assumed for this case study, existing stormwater infrastructure has the capacity to cater for any new development. The land from the south is vacant and existing flow from upstream is to be accounted for in this case study.

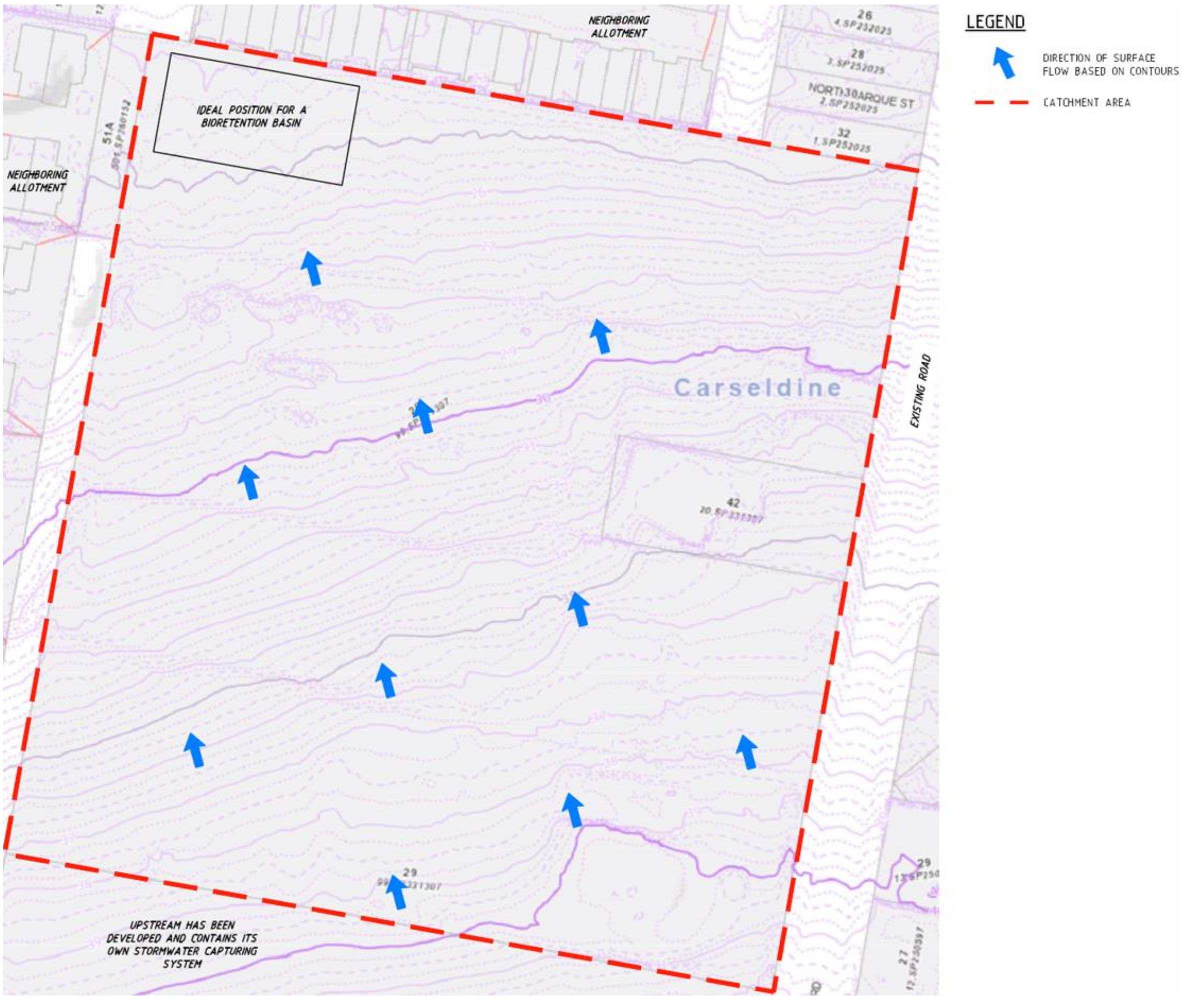

Figure 3.2 – Site Catchment (eBIMAP Brisbane City Council Mapping Service)

Figure 3.2 above shows the catchment for the proposed site, the catchment area is 4.05ha. The existing road to the east has not been included in this catchment as previously discussed, it is well established with current stormwater conveyance infrastructure.

The proposed subdivision will consist of 63 lots, with space in the north western corner for green infrastructure, this area is suitable to capture the most amount of flow. The minimum size for each lot will be 450m^2 in compliance with Brisbane City Council's planning scheme for selected zones and minimum lot sizes.

The dimensions for each lot will be identical, 15m x 30m. A house with an impervious roof area of 250m^2 and concrete driveway area of 35m^2 to the proposed roads. This indicative lot complies with Brisbane City Council's planning scheme and will be used for obtaining catchment data. Refer to Figure 3.3, for a visual representation of a typical house and lot layout.

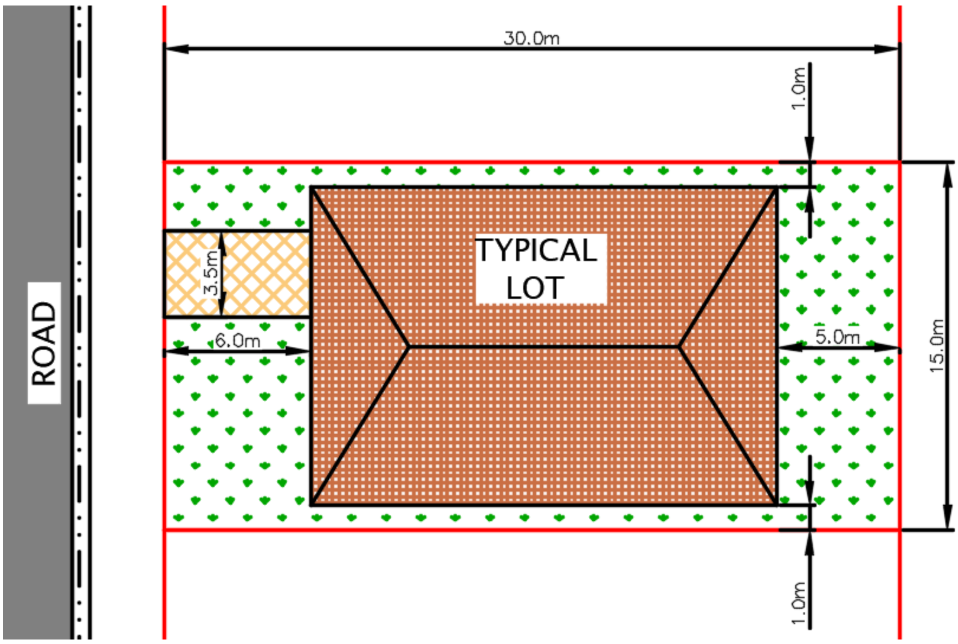

Figure 3.3 – Typical house and lot layout for 1 lot

To accurately represent a generic design that could be seen around Brisbane, each allotment will have access to a road, with a BCC standard 3.75m verge. An estate with 63 allotments and roads connecting to existing roads is shown below in Figure 3.4. The estate has been designed specifically to allow for the maximum number of allotments, whilst maintaining within BCC guidelines.

Figure 3.4 – Developed 63 lot estate

It is required to design a typical estate to be able to split the catchment into categories that will assist in the design of green infrastructure. Below in Table 3.1, the calculated catchment areas for each split zone are calculated for the designed typical estate.

Area (Node)	Catchment Area (ha)	Impervious Percentage
Roof	*1.575*	*100%*
New Road (hardstand 1)	*0.608*	*100%*
Driveway (hardstand 2)	*0.221*	*100%*
Landscaped (Free Drainage)	*1.646*	*30%*

Table 3.1 – Split catchment area types

The catchment area will be defined using the above area nodes defined in Table 3.1, these nodes will be used to output data from the MUSIC model. For this case study the roof, new roads and driveways are assumed to be 100% impervious as a worst-case scenario, although this may not be the case, in a real-world scenario. The landscaped free drainage areas are areas that will be turfed/landscaped i.e., road verges, has assumed these areas will be 30% impervious.

This value can be assumed in this case study, as neighbouring developments within the area have found this impervious percentage appropriate and have used 30% in their stormwater management plans, after geotechnical investigation of the local soils. This assumed conservative value is also appropriate for a residential subdivision where post development conditions may find sheds, footpaths and other impervious surfaces constructed and therefore altering the amount of impervious catchment.

Stormwater management plans for the development to the north and to the west of the selected site are available on Brisbane City Council's Development I website for public viewing. Each of these developments have their own stormwater management designs and make it clear that it is not expected for the subject site chosen above, to experience any surface runoff from either neighbouring development.

The surrounding developments have implemented green infrastructure for water quantity and quality control. This infrastructure consists of individual rainwater tanks for each townhouse or allotment, grass buffer strips to provide discontinuity between impervious surfaces and designed drainage systems, gully pit filters have been provided in all gully pits to provide an 'at source' water treatment and finally bio-retention basins to treat all expected surface flow from the development and create a lag time, thereby reducing the overall impact of stormwater discharge.

3.5. Pre-developed Stormwater Runoff Estimation

It is common practice for residential subdivision of this size to determine peak discharges for the existing catchment for event-based simulation and to consider total reduction of overland flow. BCC requires a hydraulic assessment and code assessed application. According to the Brisbane City Council's City Plan 2014, The stormwater drainage system must:

a) Prevent or minimise adverse social, environmental, and flooding impacts on the city's waterways, overland flow paths and constructed drainage network

b) Ensure that the design of channel works as part of development maximises the use of natural channel design principles where possible

c) Achieve acceptable levels of stormwater run-off quantity and quality by applying total water cycle management and water sensitive urban design principles

If a new development does not seem fit for one of the above code requirements, it will not be approved for development. It is important for this case study to adhere to these requirements where possible to ensure the real-world feasibility of this study.

BCC City Plan 2014, states that for flow estimation guidance, “Council refers the designer to QUDM and Australian Rainfall and Run-off. Council will accept flow estimations using the rational method, calibrated run-off routing models, calibrated time-area routing models and calibrated direct rainfall hydraulic models”. Therefore, in accordance with the City Plan, QUDM and the ARR 2019 will be followed. Using of the rational method has been found to provide reasonable peak flow estimates for small urban catchments, although current standards suggest this method should only be used as a ‘checking tool’ of numerical models. Runoff-routing models are more widely accepted to produce accurate results, QUDM identifies the use of XP-RAFTs as a suitable model in this instance. Flood Frequency Models can also be used to determine peak discharge, although are often used for rural catchments.

For this case study, the Rational Method calculation will be undertaken and validated by XP-RAFTS to determine peak flow predictions.

3.5.1. Rational Method

To estimate the peak discharge for a catchment using the Rational Method the below formula is used.

$$Q_y = (C_y \,.\, {}^{t}I_y \,.\, A)/360$$

Where, Q_y is the peak flow rate in m^3/s for an AEP of 1 in ‘y’ (years).

C_y – Is known as the coefficient of discharge and is an adjustment factor that can be determined by the following steps.

- Fraction impervious (f_i) for the catchment is determined using *Table 4.5.1 - Fraction Impervious vs Development Category (*QUDM 2016), where different f_i values have been categorised for different modes of development.

- Determine the 1-hour rainfall intensity (${}^{1}I_{10}$) for a 10% AEP for the catchment location, this information can be found using the IFD data for 2016 on the BOM website.

- F_y can be determined using *Table 4.5.2 – Table of Frequency Factors* in QUDM (2016)

- The 10% AEP coefficient (C_{10}), may then be determined using *Table 4.5.3 – Table of C_{10} Values* (QUDM).

- A C_y value can then be determined using the below formula, with the found forementioned values.

$$C_y = F_y \,.\, C_{10}$$

$^{t}I_{y}$ – Is the average rainfall intensity for a provided time of concentration (t_{c}.). QUDM (2016) defines the time of concentrations as,

"The time, measured from the start of a design storm, for surface runoff to collect and flow from the most remote part of the catchment to the point at which a design discharge is bei ng calculated." To determine an appropriate time of concentration it is important to consult, *Table 4.6.1 – Summary of typical components of time of concentration* (QUDM 2016). This table provides direction on which factors are to be accounted for in the development. The catchment condition for this case study will be under category (a), which describes a catchment that is predominately piped/channelised urban catchment that is less than 500ha with the top of the catchment being urbanised, this category is the best fit and the components will be used to determine the time of concentration.

The minimum design storms for residential developments (low-medium to high density) in BCC to be considered are a 10% AEP and a 2% AEP, the calculated time of concentration will be used with the average rainfall intensity for these design storms to determine the $^{t}I_{y}$.

It is also important to note, the partial area effect does not need to be used in this catchment. These calculations are not required as the time of concentration can be calculated as the landscape is a typical drainage catchment. Developments that may have built up areas and structure upstream, significant change in slope and out of proportion catchment shapes, that may affect the time of concentration' in upstream catchments, it is important to consider the partial area effect that allows for 'unusual' drainage conditions.

The results and calculated rational method for this case study can be found in Chapter 4 – Results of this research document.

3.5.2. Runoff-Routing Model

The runoff-routing model used in this case study is XPRafts by Innovyze. This software has been selected as it is a widely used model for developments, within Brisbane and is also mentioned in QUDM 2016. XPRafts can be effectively utilised to develop stormwater hydrographs from design storms or actual events using Intensity Frequency Diagram (IFD) data with temporal patterns to Australian Rainfall & Runoff (AR&R) 2019.

The loss models inbuilt are

- Continuing/Initial Loss
- Proportional/Initial Loss
- ARBM water balance model

The hydrographs generated can be transferred to other hydraulic stimulation programs for a detailed hydraulic analysis such as, XPSWIMM or XPStorm. Although for this catchment, it is not necessary for this level of detail.

There are five parameters required for XPRafts.

- Catchment area
- Slope of catchment (equal area method can be used), in this case an average will suffice
- Degree of urbanisation (calculated from fraction of impervious for the catchment)
- Expected Losses
- Rainfall data

XPRafts by default will divide the catchment in equal areas or isochrones for accuracy. The XPRafts input information determined for this catchment is displayed in the below Table 3.2 below.

Parameter	Catchment
Initial Loss (mm)	*10*
Continuing Loss (mm/hr)	*2*
Catchment Area (ha)	*4.05*
Fraction Impervious (%)	*20*
Vectored Slope (%)	*8*
Manning's (n)	*0.045*
IDF Coefficient (location)	*Brisbane*
Storage	*1*

Table 3.2 - XPRafts Input Data

The IL and CL has been determined using AR&R 2019 for this catchment. The fraction impervious of 20% has been used, as there are existing houses in the catchment and without a site inspection, a conservative figure can be determined by aerial imagery. The vectored slope was calculated using the GIS mapped contours and length of the catchment. A conservative Manning's Roughness Coefficient (n) of 0.045 has been used as recommended by Water by Design. The results from the runoff-routing model can be found in Chapter 4 – Results.

3.6. Design Suitable WSUD for the Catchment

WSUD features a range of different strategies and come in many different shapes, sizes and forms that can be implemented on almost all catchments. The main objects for WSUD on a development scale according to, Water Sensitive Urban Design – Developing design objectives for urban development in South East Queensland (Water by design 2007), are as follows.

- Protect existing natural features and ecological processes.
- Maintain the natural hydrologic behaviour of catchments
- Protect water quality of surface and ground waters
- Minimise demand on the reticulated water supply system
- Minimise sewage discharges to the natural environment
- Integrate water into the landscape to enhance visual, social, cultural and ecological values

The types of WSUD that will be considered for this case study are outlined below in Table 3.3 (WSUD Technical Design Guidelines 2006) and will be determined on their suitability and practicability. Constraint 'C' may preclude use, Constraint D can be used with appropriate design and a tick means there is no constraint.

WSUD Measure	Steep site	Shallow bedrock	Acid Sulfate Soils	Low permeability soil (eg. Clay)	High permeability soil (eg. sand)	High water table	High sediment input	Land availability
Swales and buffer strips	C	D	D	✓	✓	D	D	C
Bioretention Swales	C	C	C	✓	✓	C	D	C
Sedimentation basins	C	✓	✓	✓	✓	D	✓	C
Bioretention basins	C	D	D	✓	✓	C	C	C
Constructed wetlands	C	D	C	✓	D	D	D	C
Infiltration measures	C	C	C	C	✓	C	C	C
Sand filters	D	✓	✓	✓	✓	D	C	✓
Aquifer storage and recovery	C	C	C	C	✓	C	C	C

Table 3.3 – Site Constraints for WSUD Measures (WSUD Technical Design Guidelines 2006)

The above table can be used as a guide for designing WSUD strategies around catchment parameters. Although it does generalise the WSUD measure, for example 'Infiltration Measures' can consist of any WSUD strategy that is designed control runoff volume and typically consists of a holding pond or tank designed to promote infiltration. This may include permeable pavement, tree pits and green roofs.

The below Table 3.4, can be used to determine a suitable application for the WSUD strategy.

WSUD Measure	Allotment Scale	Street Scale	Precinct or Regional Scale
Swales and buffer strips		✓	
Bioretention Swales		✓	✓
Sedimentation basins			✓
Bioretention basins	✓	✓	✓
Constructed wetlands		✓	✓
Infiltration measures	✓	✓	
Sand filters	✓	✓	
Aquifer storage and recovery			✓

Table 3.4 – WSUD Application in Urban Catchments (WSUD Technical Design Guidelines –2006)

Using the above guides, we can filter out which WSUD strategies may not be suitable for the parameters of our case study site. As we are particularly concerned with runoff volume in this case study the WSUD strategies that will be examined in detail are, bioretention swales, a bioretention basin, infiltration measures in the means of – tree pits and permeable pavement and storage in the form of rainwater tanks. A constructed wetland in this case would not be appropriate as wetlands typically take up large amounts of space and are more suited around parks, other measures such as sand filters are not considered in this case study as their main purpose are quality treatment and do little in the means of reducing runoff volumes.

3.6.1. Design Objectives for WSUD

WSUD is largely implemented for water quality and environmental protection, therefore once suitability of WSUD is determined, the WSUD strategy is often designed to achieve a target reduction in mean annual pollutants from the proposed development. These reduction in loads are a requirement for an urban development in BCC and can be found in the below Table 3.5.

Target Pollutant	Total Reduction
Total Suspended Solids	*> = 80%*
Total Phosphorus	*>= 60%*
Total Nitrogen	*>=45%*
Total Gross Pollutant	*>= 90%*

Table 3.5 – Total pollutant reduction targets

For this case study the WSUD implemented will be sized accordingly to meet these requirements, i.e., if the bioretention basin doesn't not achieve the total reduction in all target pollutants, then it will be increased until the total areas meet these requirements.

3.7. Post-development Modelling Validation and Calibration

MUSIC (Model for Urban Stormwater Improvement Conceptualisation) by eWater will be used to determine the volume and quality of water flowing from the site catchment. According to eWater's website MUSIC has been, "Grounded in decades of Australian research, we developed MUSIC's simple and tailored workflow to make design and analysis of water sensitive urban design (WSUD) systems easy and meet best practice.". MUSIC model has been selected as an appropriate model for this study as it is widely used across Australia by urban developers, local governments, engineers, water authorities and town planners to evaluate conceptual stormwater management measures, in particularly WSUD.

MUSIC is a user-friendly stormwater modelling software that is often used as a conceptual tool in the design of WSUD for stormwater quantity and quality calculations. Similarly, to most models the more information about the catchment, the more accurate you can expect the outputs to be, although with calibration, sufficient results can still be achieved on catchments with limited information. The model has standard parameters added to each WSUD strategy that are inbuilt in accordance with BMP and can be altered to suit different scenarios, although it has been identified that the model is very sensitive to the percentage of impervious selected for the catchment. Total percentage of impervious for a catchment can be a challenging task to accurately estimate, reducing accuracy. MUSIC can also be used as a life-cycle cost module platform to encourage WSUD. Figure 3.5, below displays the BCC guidelines to the design of WSUD and is used to promote WSUD in Brisbane, aligning with Brisbane's '*water smart*' strategy. It is also used as a clear guideline to provide developers an understanding on how a proposed development can be assessed. It can be noted that if the WSUD does not meet performance targets, then generally the proposal will not be accepted.

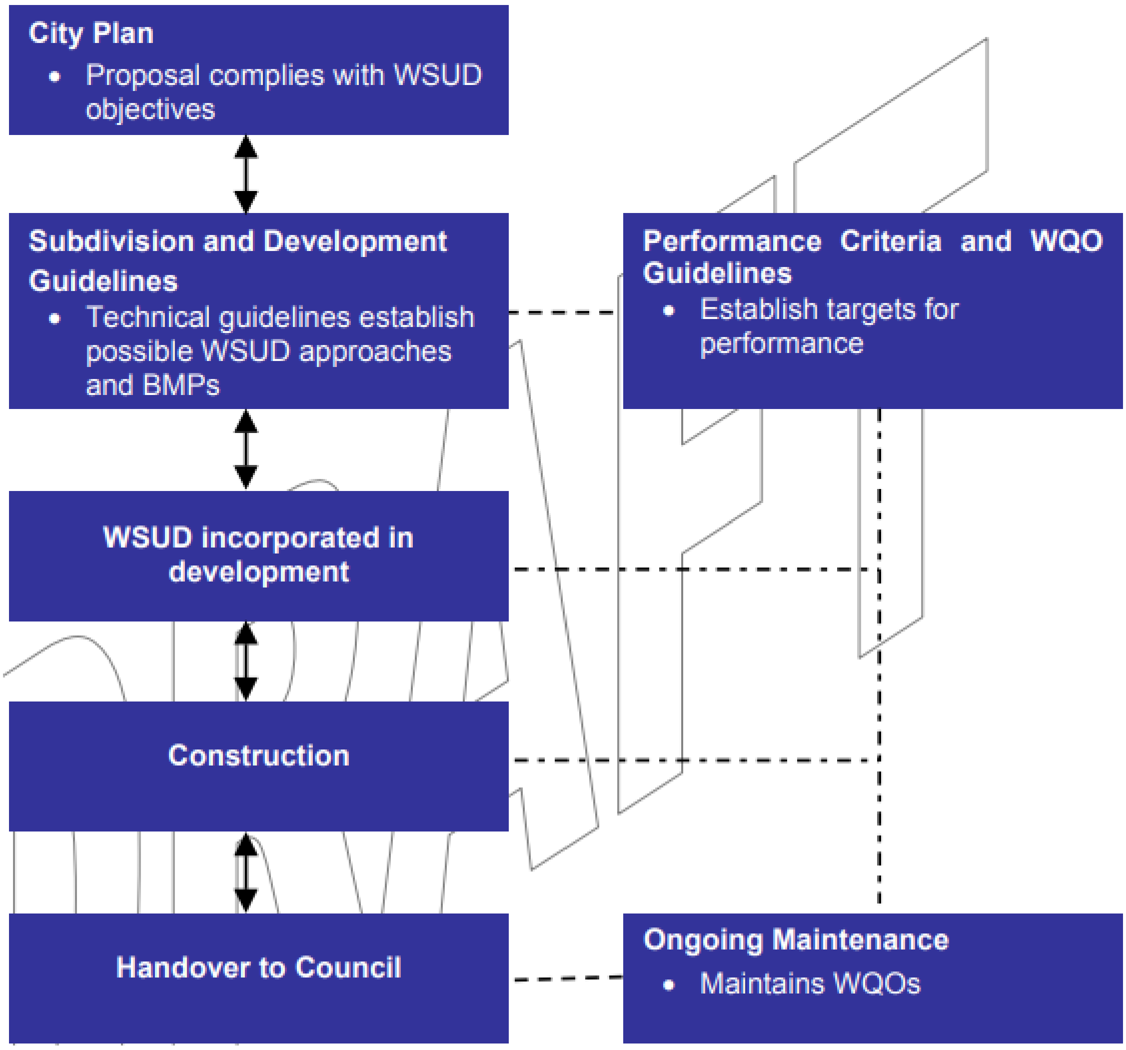

Figure 3.5 –Brisbane City Council WSUD plan (Practice Note 1a Water Sensity Urban Design 2019)

To create a consistent model to BCC guidelines, preserving quality assurance, MUSIC-link will be used. MUSIC-link is a two-step process inbuilt in MUSIC,

- Model creation and simulation of the MUSIC model
- Secondly, validate the model against pre-defined standards for BCC

The MUSIC-link tab shown below in Figure 3.6 is used to validate the model.

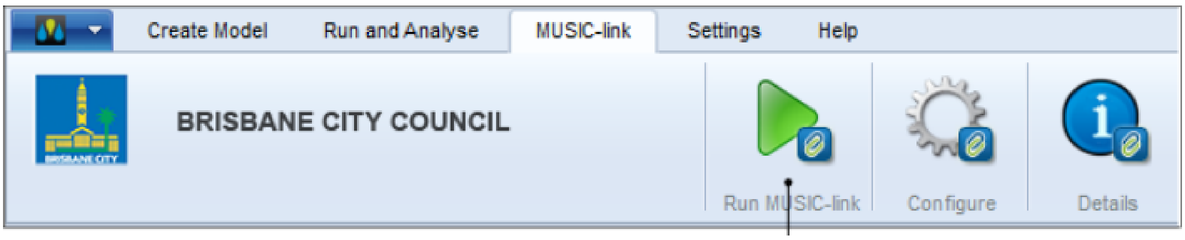

Figure 3.6 MUSC-Link for Brisbane (Brisbane City Council – Toolkit 2019)

In some cases, a Brisbane City Council MUSIC-link validation report is required to be generated and submitted along with the required development application documents. The validation report steps for BCC are shown below in Figure 3.7

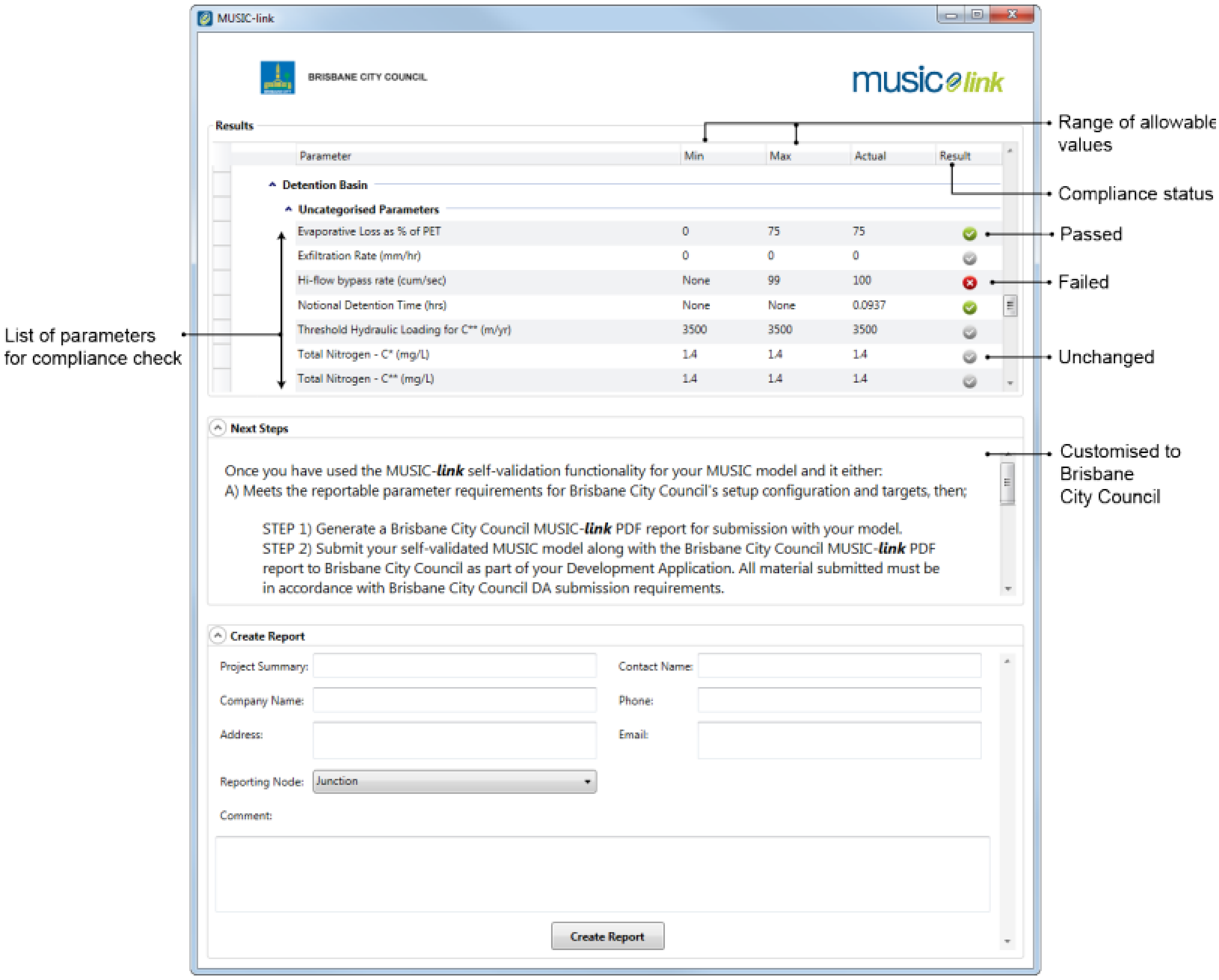

Figure 3.7 MUSC-Link guide (Brisbane City Council – Toolkit 2019)

Historical rainfall and evapotranspiration data have been used from gauge 40214 – Brisbane Regional Office for the MUSIC Model during the period of 01/09/1990 – 31/12/1990. This is the standard meteorological data template is fit for use. A hyetograph for the rainfall event and the average potential evapotranspiration can be found in Results chapter 4.2.

3.7.1. Pre-developed Case Nodes

To capture the change in run-off for the catchment, the natural existing run-off will be modelled. This will not only provide data to compare change in a pre-developed case to a post-developed case but will ultimately, provide a clear understanding on how the implementation of WSUD strategies can affect the run-off flow, which could contribute to infiltration and inflow over existing sewer systems. Ideal results for this study, may find the post-developed scenario with increased impervious areas exhibiting natural or pre-developed run-off behaviour and resulting the urban development not increasing RDII.

Recommended MUSIC modelling parameters for urban residential can be found below in Table 3.6, these parameters are generally used in BCC area unless there is a comprehensive calibration of local stream records in the area or BCC supports alternative parameters to be used. In this case study, these recommended parameters will be used.

PARAMETER	LAND USE			
	URBAN RESIDENTIAL	COMMERCIAL AND INDUSTRIAL	RURAL RESIDENTIAL	FORESTED
Rainfall threshold (mm)	1	1	1	1
Soil storage capacity (mm)	500[10]	18	98	120
Initial storage (% capacity)	10	10	10	10
Field capacity (mm)	200	80	80	80
Infiltration capacity coefficient a	211	243	84	200
Infiltration capacity exponent b	5.0	0.6	3.3	1.0
Initial depth (mm)	50	50	50	50
Daily recharge rate (%)	28	0	100	25
Daily baseflow rate (%)	27	31	22	3
Daily deep seepage rate (%)	0	0	0	0

Table 3.6 – Recommended MUSIC rainfall-runoff parameters (Water By Design 2010)

To assist in the design of WSUD strategies that are in accordance with BCC Planning Scheme's and development codes, the below figures in Table 3.7 are the recommended pollutant parameters that will be used. The WSUD strategies can be sized to achieve the recommended pollutant reduction.

FLOW TYPE	SURFACE TYPE	TSS log^{10} values		TP log^{10} values		TN log^{10} values	
		Mean	St. dev.	Mean	St. dev.	Mean	St. dev.
	Urban residential						
Baseflow parameters	Roof	N/A	N/A	N/A	N/A	N/A	N/A
	Roads	1.00	0.34	-0.97	0.31	0.20	0.20
	Ground level	1.00	0.34	-0.97	0.31	0.20	0.20
Stormflow parameters	Roof	1.30	0.39	-0.89	0.31	0.26	0.23
	Roads	2.43	0.39	-0.30	0.31	0.26	0.23
	Ground level	2.18	0.39	-0.47	0.31	0.26	0.23
	Industrial						
Baseflow parameters	Roof	N/A	N/A	N/A	N/A	N/A	N/A
	Roads	0.78	0.45	-1.11	0.48	0.14	0.20
	Ground level	0.78	0.45	-1.11	0.48	0.14	0.20
Stormflow parameters	Roof	1.30	0.44	-0.89	0.36	0.25	0.32
	Roads	2.43	0.44	-0.30	0.36	0.25	0.32
	Ground level	1.92	0.44	-0.59	0.36	0.25	0.32
	Commercial						
Baseflow parameters	Roof	N/A	N/A	N/A	N/A	N/A	N/A
	Roads	0.78	0.39	-0.60	0.50	0.32	0.30
	Ground level	0.78	0.39	-0.60	0.50	0.32	0.30
Stormflow parameters	Roof	1.30	0.38	-0.89	0.34	0.37	0.34
	Roads	2.43	0.38	-0.30	0.34	0.37	0.34
	Ground level	2.16	0.38	-0.39	0.34	0.37	0.34

Table 3.7 – Average MUSIC pollutant parameters (Water By Design, 2010)

The pre-developed source nodes can then be setup, aligning with the recommended parameters to meet guidelines. Refer to Figure 3.8 below for the steps involved in creating the source node in MUSIC.

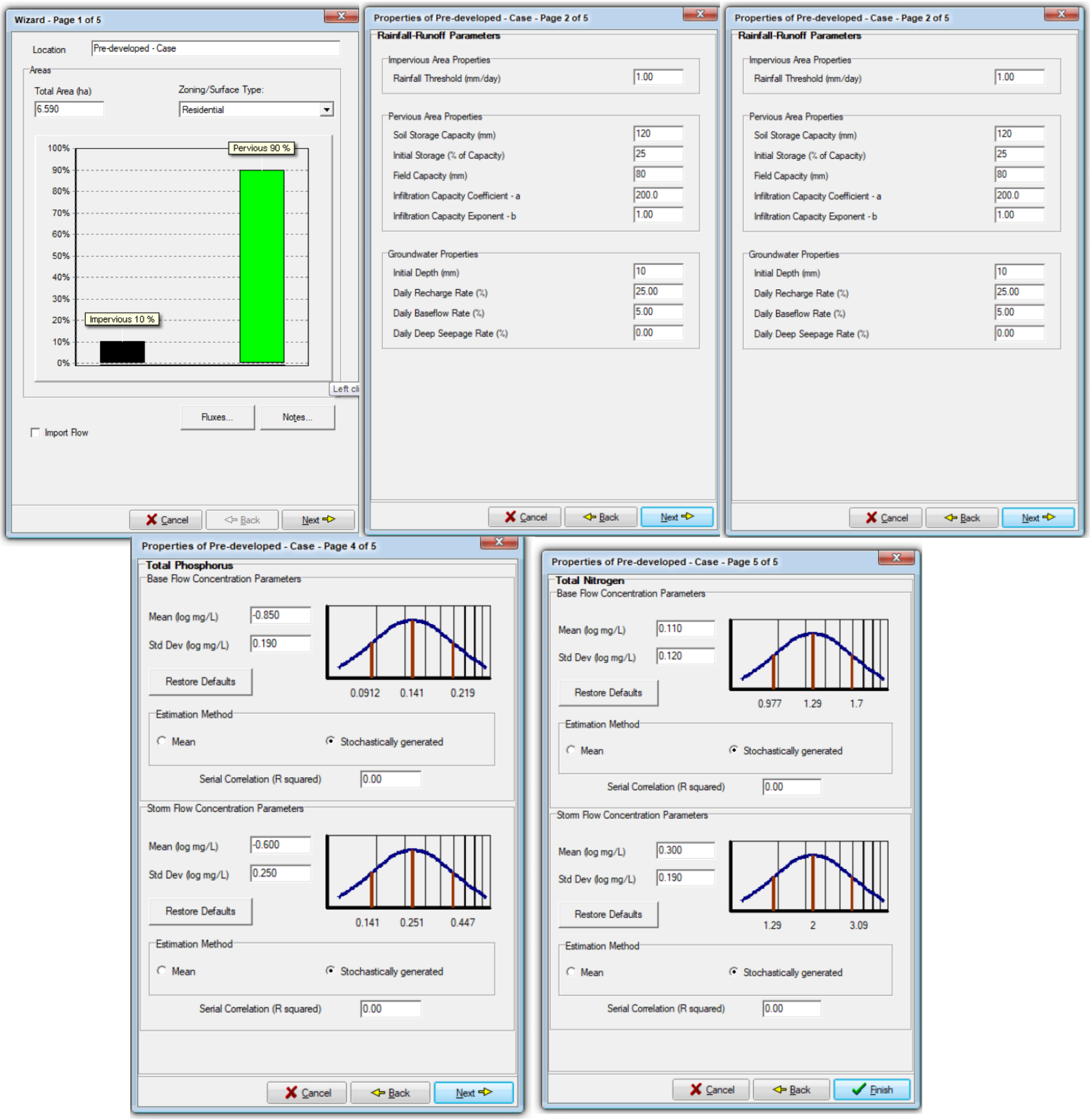

Figure 3.8 – Pre-development source node (MUSIC)

3.7.2. Developed Case Nodes

The developed case nodes input into MUSIC, have been split into four different catchment categories as forementioned and shown in *Table 3.1*. This is an important step to increase the accuracy of the model, impervious percentage has increase drastically in the catchment with the construction of housing, roads and other pavement surfaces. The roof, driveways and roads will be modelled as 100% impervious, all other areas such as allotment yards and road verges will be modelled as 'free drainage' areas at 30% impervious. The percentage has been used in surrounding developments and counts for initial and continuing losses, therefore is suitable to be used for this case study.

The rainfall station, rainfall period and modelling time step used in the MUSIC model can be found in the Figure 3.9 below. This rainfall station is the closest to the case study and the rain period and time step are the default and recommended properties used in BCC.

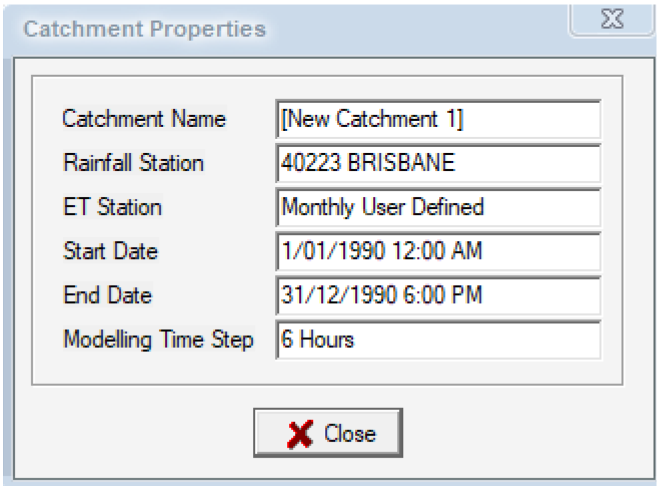

Figure 3.9 – MUSIC catchment properties (MUSIC)

3.7.3. Roof Areas Source Node

A roof area of 250m^2 for all 63 proposed houses has been calculated and the total area is 1.575ha. This area is 100% impervious. The parameters used for these nodes are in accordance with MUSIC guidelines and recommendations. It is important to create a separate node for the roof areas, as this is an area that will likely change parameters to suit different WSUD strategies and the flow indifferences can then be captured. Refer to Figure 3.10 below, for the source node setup and parameters used in MUSIC.

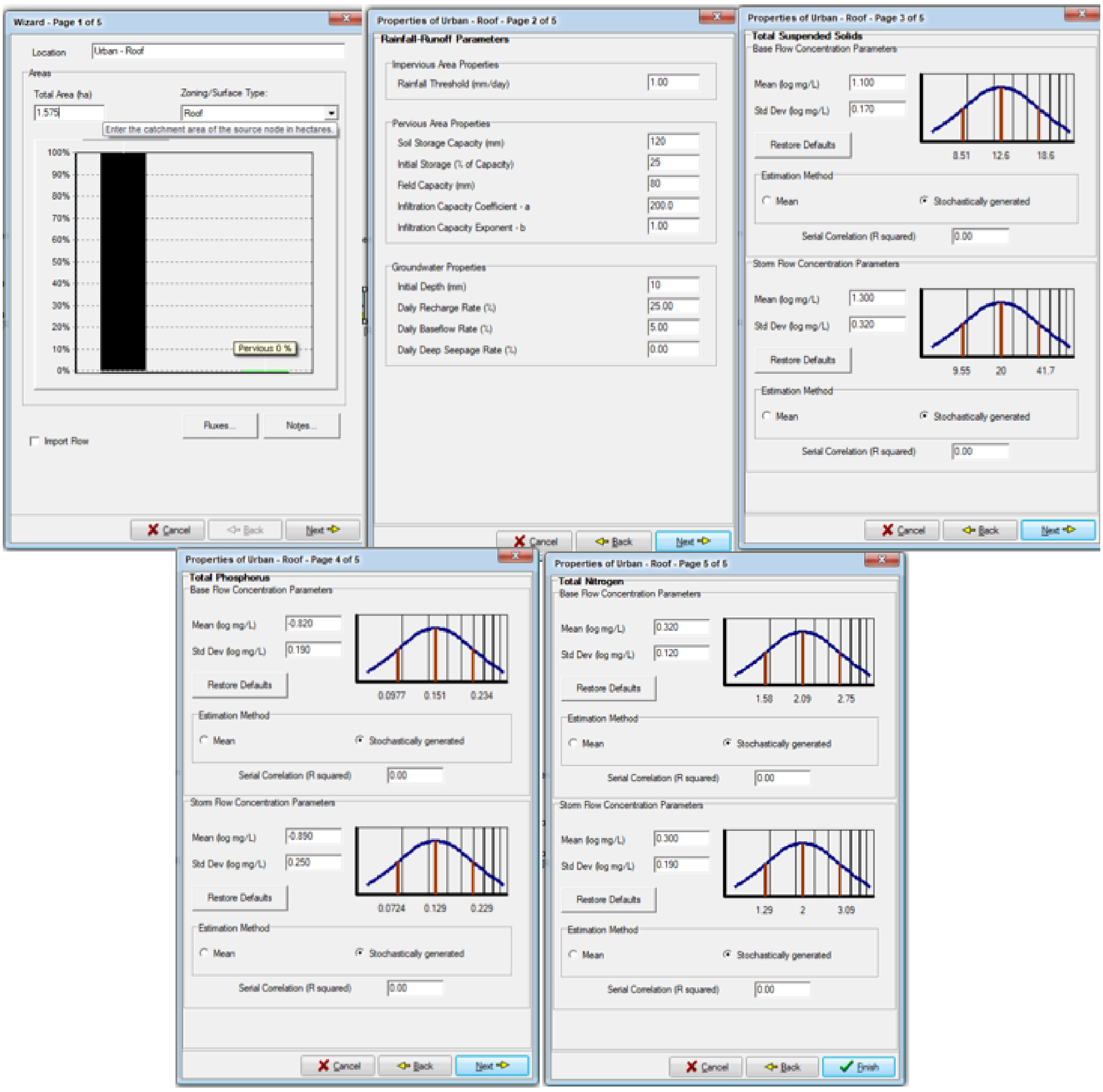

Figure 3.10 – Urban Roof area source node (MUSIC)

3.7.4. New Roads Source Node

Similarly, to the roof source node, the roads are calculated as 100% impervious. Although this may not be the case. The new roads have been calculated to have a width of 7.5m to the nominal face of the kerb, this road width is common for urban residential areas in BCC and the total area 0.608ha has been calculated. It is important for this case study, to understand and analyse the flow changes between a sealed road and with the introduced of permeable pavement. A source node for the existing road has also been considered for the potential use of a swale, it has been assumed there is a one-way crossfall for the swale to capture the majority of runoff. The parameters used for these nodes are in accordance with MUSIC guidelines and recommendations, refer to Figure 3.11 below, for the source node setup and parameters used in MUSIC.

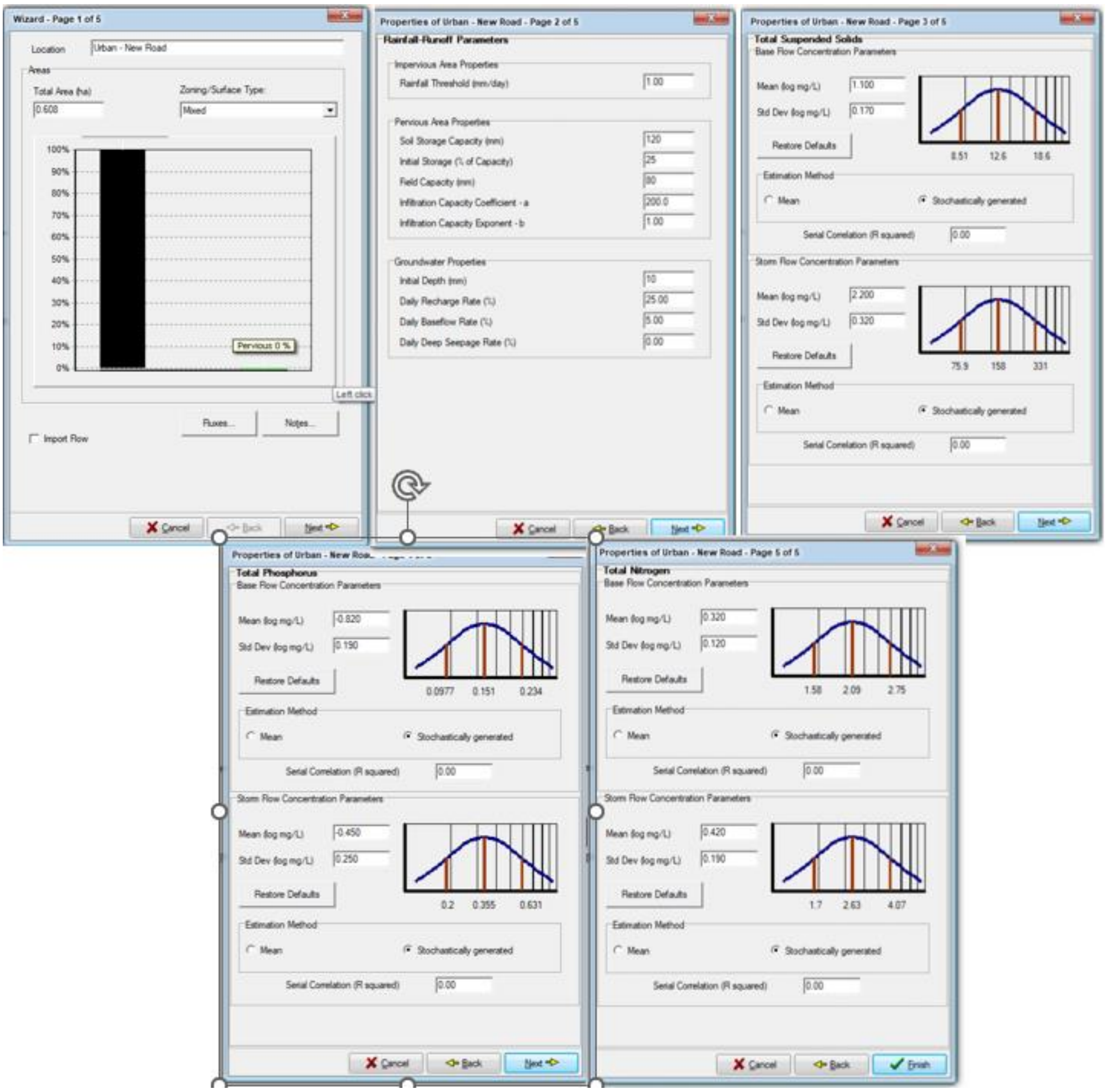

Figure 3.11 – Urban Road area source node (MUSIC)

3.7.5. Driveway Source Nodes

The driveway for all allotments has a total area of 0.221ha for the developed catchment. This has been calculated using a standard 3.5m wide driveway on a BCC standard 4.25m wide road verge for all 63 lots. The driveways have their own source node, to separate the area for WSUD strategies such as permeable pavements. Much like the roads, the parameters used for these nodes are in accordance with MUSIC guidelines and recommendations, refer to Figure 3.12 below, for the source node setup and parameters used in MUSIC.

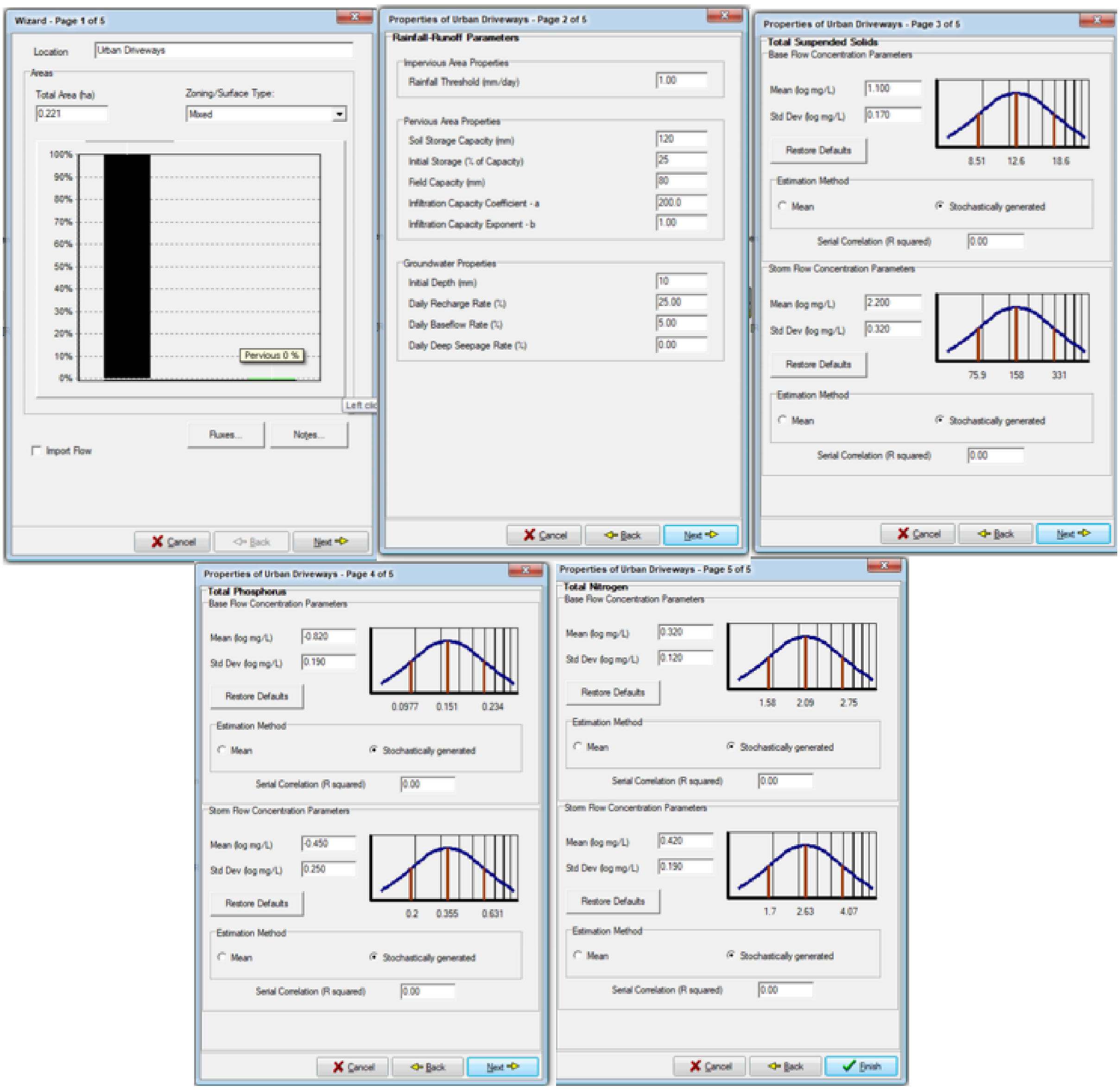

Figure 3.12 – Urban Driveway area source node (MUSIC)

3.7.6. Free Drainage Source Nodes

The final source node created in MUSIC is for free draining areas. This includes all areas of the catchment that are not covered by a typical house layout, driveway or road. This area has can change significantly with the homeowners' building sheds, house extensions, addition of council footpaths or other impervious surfaces. This area tends to be the most variable in MUSIC models and a conservative 30% impervious value has been applied. The total area calculated is 1.640ha for the catchment. The parameters used for this source node are in accordance with MUSIC guidelines and recommendations and align with the general precedence set by the neighbouring stormwater management plans created, refer to Figure 3.13 below, for the source node setup and parameters used in MUSIC.

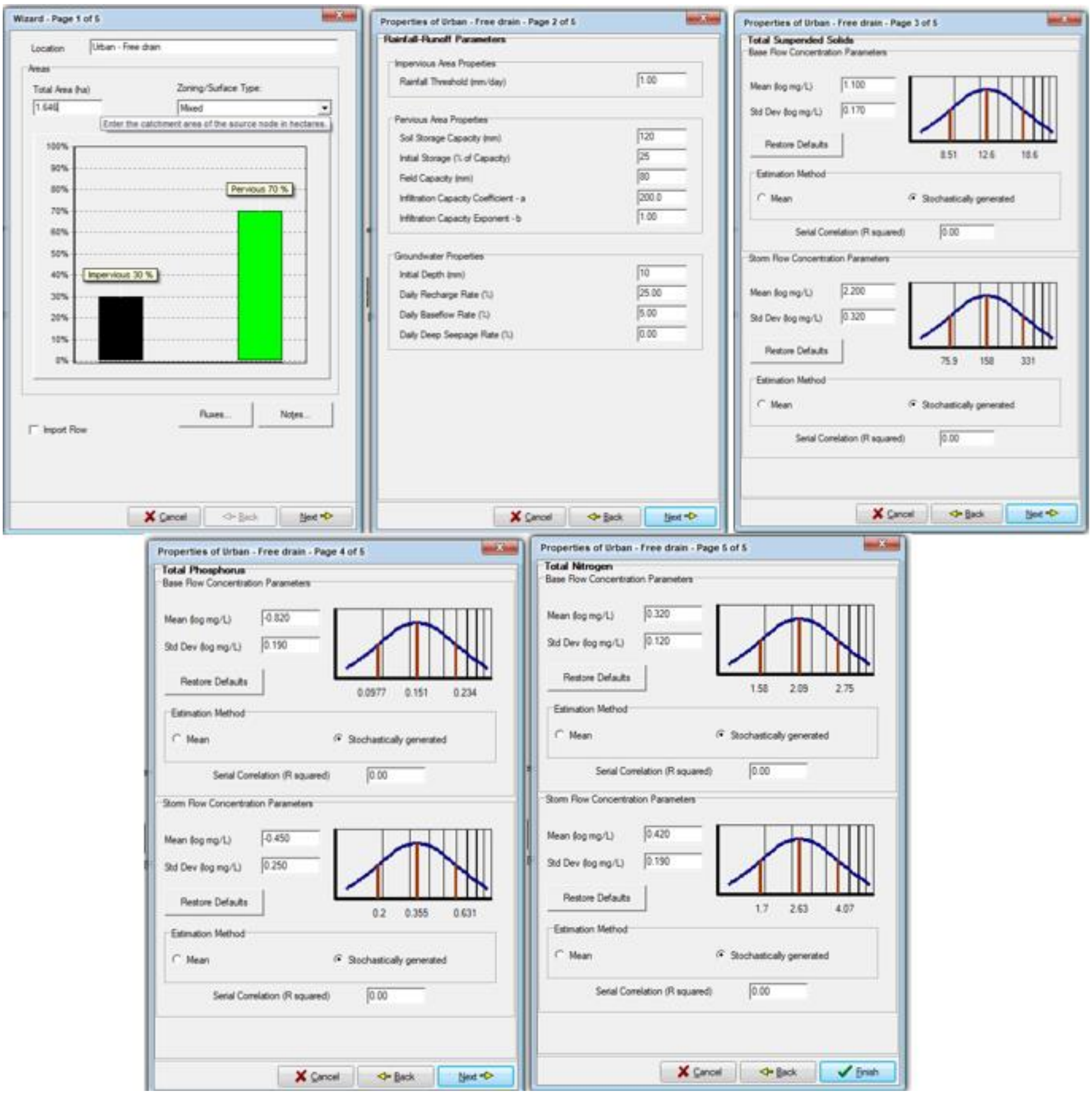

Figure 3.13 – Urban Free Draining source node (MUSIC)

3.7.7. WSUD MUSIC Simulation

Now post development nodes are created, WSUD can be modelled. The process for designing WSUD in MUSIC can be demonstrated in the below flow chart in Figure 3.14, for this study it is not necessary for any detailed design of WSUD.

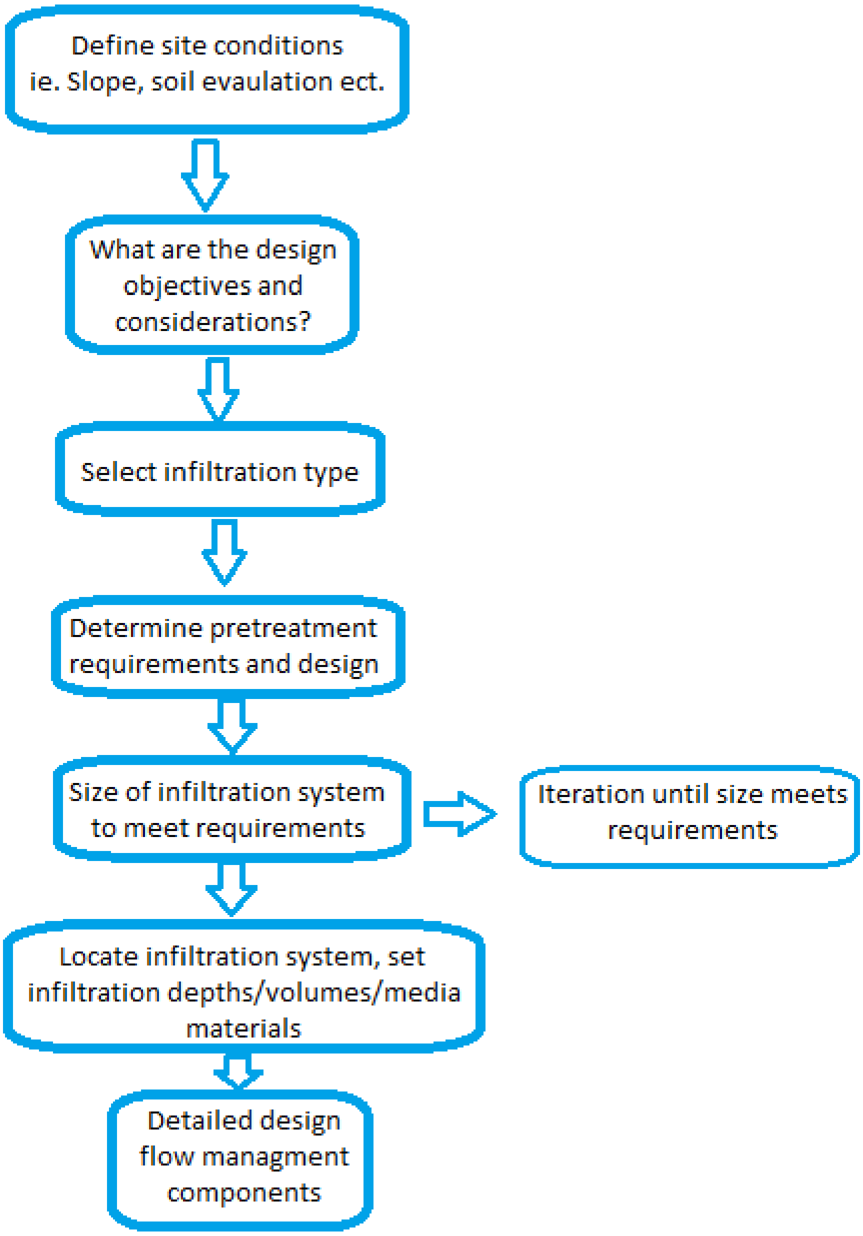

Figure 3.14 – WSUD MUSIC design flow chart

3.7.8. Bioretention Basin

Bioretention basins are generally the last form of treatment before stormwater is released, this node has been created to determine the bioretention basin as a stand-alone system and in a combined system. There are many adjustable properties in MUSIC that alter the effectiveness of Bioretention basins or provide cost effective solutions. These include, inlet, storage, filter and media, lining, vegetation and infiltration and outlet properties. For this case study, I have added the recommended parameters as outlined by Water by Design – MUSIC Modelling Guidelines Version 10, 2010. These guidelines have been created based on many years of research and development around the development of bioretention basins.

For this case study, inlet and outlet flow will not be restricted by pipe size or outflow weirs, as the basin is also downstream the low flow properties can be set to 0. The size of the bioretention has been re-iterated until using values $50m^2$, $75m^2$ and finally $100m^2$. It was found by running the model, the bioretention passed by achieving appropriate pollutant reduction levels when the size was $100m^2$.

Figure 3.15 below, displays all parameters used for the bioretention basin and how to nodes were set out to achieve total reduction in flow.

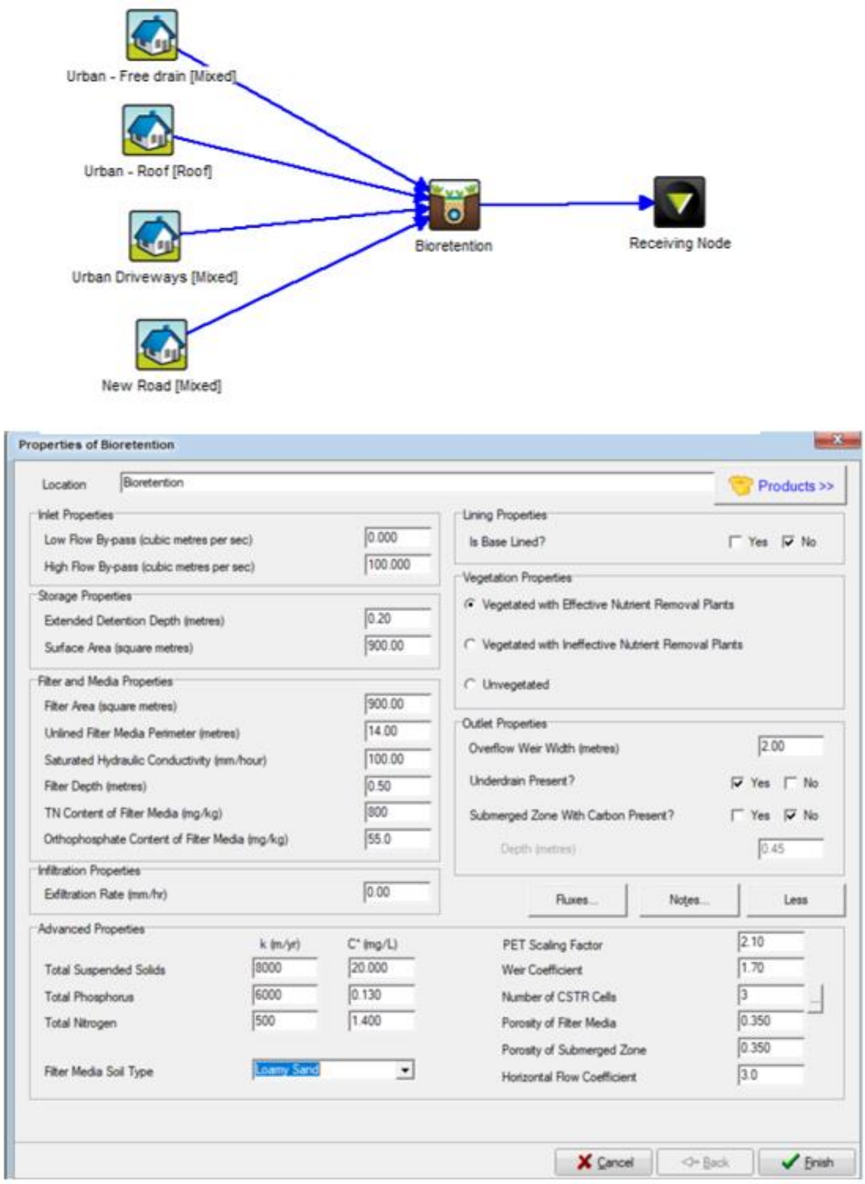

Figure 3.15 – MUSIC design parameters and model set out – Bioretention Basin (MUSIC)

3.7.9. Bioretention Swale

The bioretention swale exhibits many of the same design parameters as the bioretention basin, although is placed in the road verge. The low flow bypass can be 0 for this case as well, although the length of the swale and depth is to be 'user defined'. In this case scenario the swale will be positioned beside the existing road, it will be assumed there is a one-way crossfall. The length of the swale, not entering in neighbouring properties, will be 100m and the depth is to be 0.500m. The other important parameters, such as the bed slope will be default and the extra filtration rate for swales is set to 0 as there are no under drains. According to Water by Design – MUSIC Modelling Guidelines Version 1.0 – 2010, there are three options when modelling swales. Option A – Receives distributed lateral inflow along the entire length of the swale and discharges to a single point, in this case the whole length of the swale is modelled, with one single node. This is the option that will be used for this case study.

Option B – Swale accepts a point source at each end, the swale is then modelled at each segment where the swale has its own discharge point in the case, in each segment with separate nodes.

Option C – Swale accepts a point source at multiple locations, although each segment of the swale flows into the other. The swale is modelled with a single outlet point at the downstream and a series of swale nodes is used. Figure 3.16 below, displays all parameters used for the bioretention basin and how to nodes were set out to achieve total reduction in flow.

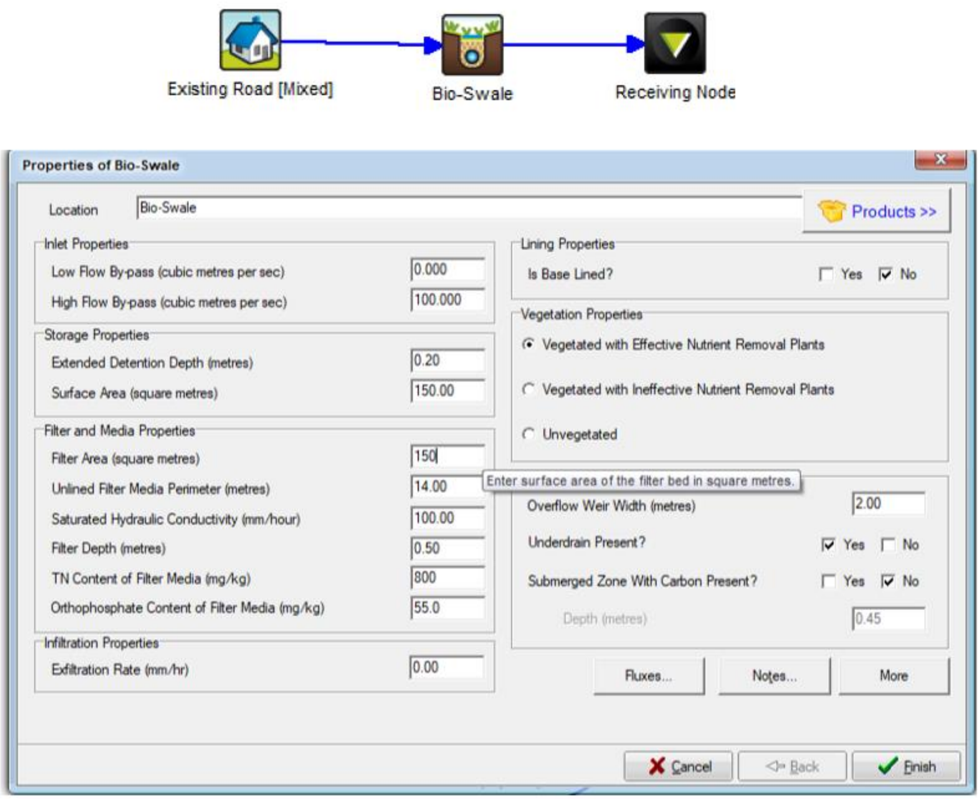

Figure 3.16 – MUSIC design parameters and model set out – Bioretention Swale (MUSIC)

3.7.10. Tree Pits

Bioretention tree pits or street trees act as small pods that drain into larger areas such as bioretention basins or wetlands. They contain a tree with filter media and a subsoil drain and are seen as a far more visually pleasing method to treat runoff and possibly store to a small scale. Thirty-one tree pits are proposed in this case study, which equates to one tree pit places between ever two lots.

Figure 3.17 below, displays all parameters used for the bioretention tree pits and how to nodes were set out to achieve total reduction in flow.

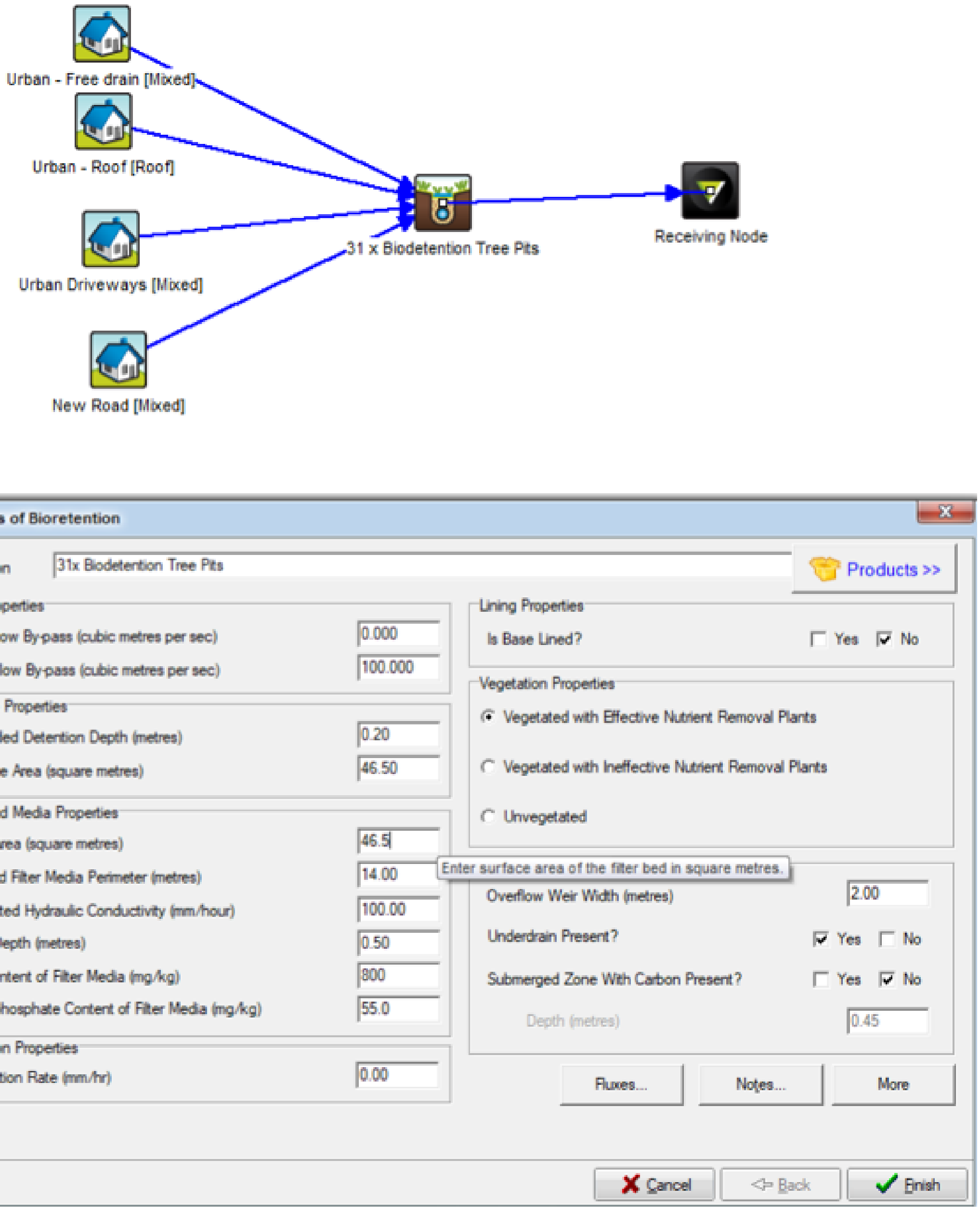

Figure 3.17 –MUSIC design parameters and model setout – Bioretention Tree pits (MUSIC)

3.7.11. Permeable Pavements

Permeable pavements, also known as porous pavements, allow runoff to drain in between paving or through paving to underlying media. The underlying media is free draining and doesn't typically hold storage capacity. It is recommended two source nodes are setup when modelling permeable pavements, one node for the surface flow to the porous area and another node for the direct rainfall on the impervious or hard surface of the paving. This type of treatment generally is not used in areas with large external catchments, that often have wetlands. The surface area was calculated using the total area of driveways, with a filter depth of 0.300m. The remaining parameters are recommended values.

Figure 3.18 below, displays all parameters used for the bioretention tree pits and how to nodes were set out to achieve total reduction in flow.

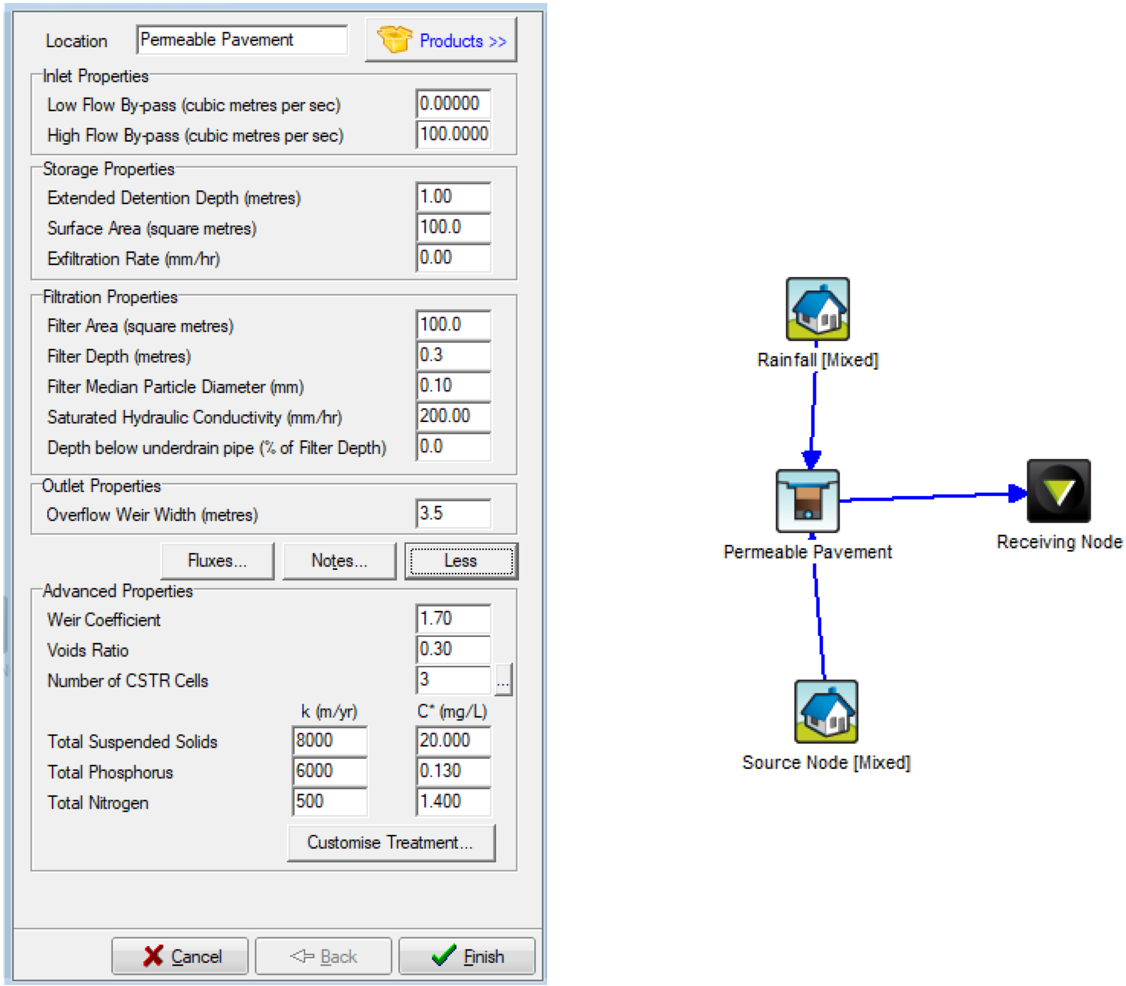

Figure 3.18 – MUSIC design parameters and model set out – Permeable pavements (MUSIC)

3.7.12. Rainwater Tanks

Rainwater tanks are often designed to cater for the demand needs of the house using per capita internal water demands. Therefore, the size of the tanks would differ from house to house in reality. It is assumed each house will have a 10kL water tank for the purpose of the case study and 50% of the roof area for each house will be directed to the rainwater tank. MUSIC may not be an appropriate model for rainwater tanks as MUSIC uses a continuous simulation method for runoff, instead of an event flow method, there peak average flows may not be as accurately represented. Although it's been decided to keep rainwater tanks in the model as they do play a significant part in reducing peak flows and runoff.

Figure 3.19 below, displays all parameters used for the bioretention tree pits and how to nodes were set out to achieve total reduction in flow.

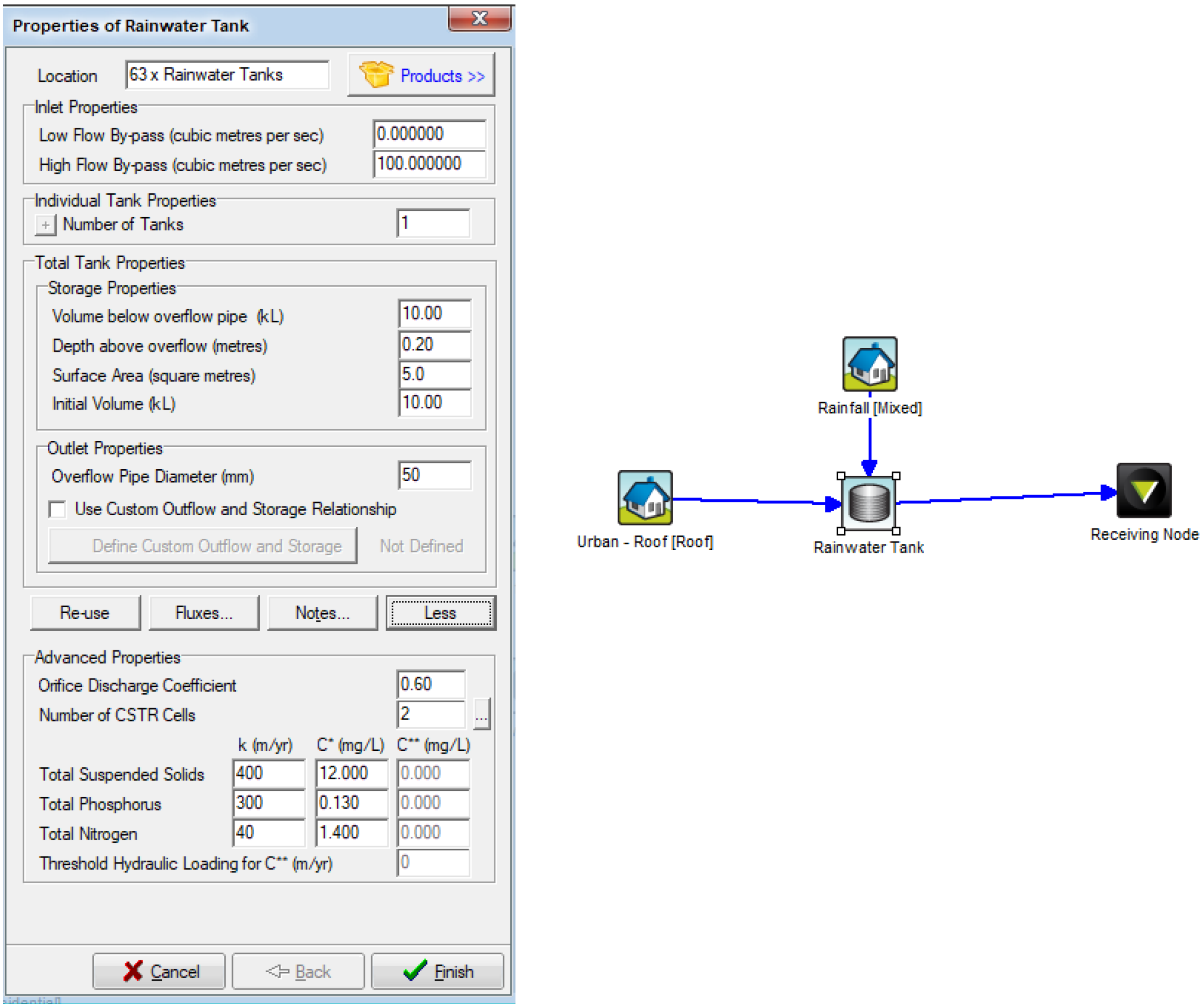

Figure 3.19 – MUSIC design parameters and model set out – Rainwater tanks (MUSIC)

3.7.13. Post-development Summary

The results attained from the music modelling for each WSUD strategy will be converted into hydrographs to display a clear representation of how the implementation of WSUD can be compared to the pre-developed case and post-developed case without WSUD over the storm event.

This will provide details on the WSUD performance, and the below data can also be extracted:

- Peak rainfall during the storm event
- The peak flow or discharge rate during the storm event
- The change in the rising and fall limb during the storm event
- Overall time of concentration in the catchment and,
- Total volume of runoff

For this study we are particularly interested in the reduction of the total runoff volume with the addition of WSUD, this data can then be utilised to estimate reduction in RDII on the existing sewer network.

3.8. Estimate RDII for Catchment

RDII, as found in the literature review, can be difficult to measure when there has been no monitoring of the upstream and downstream of the sewer section under analysis. Common methods determined for quantifying RDII included flow gauging in pipes, manholes and pumps and an analysis of ADWF vs PWWF at chosen points along in the network, from the results we can predict the expected RDII and/or derive a ratio in which RDII occurs. Refer to Figure 3.20, for an example of an analysis conducted on a catchment in Victoria, Australia by Nasrin et. al. 2018.

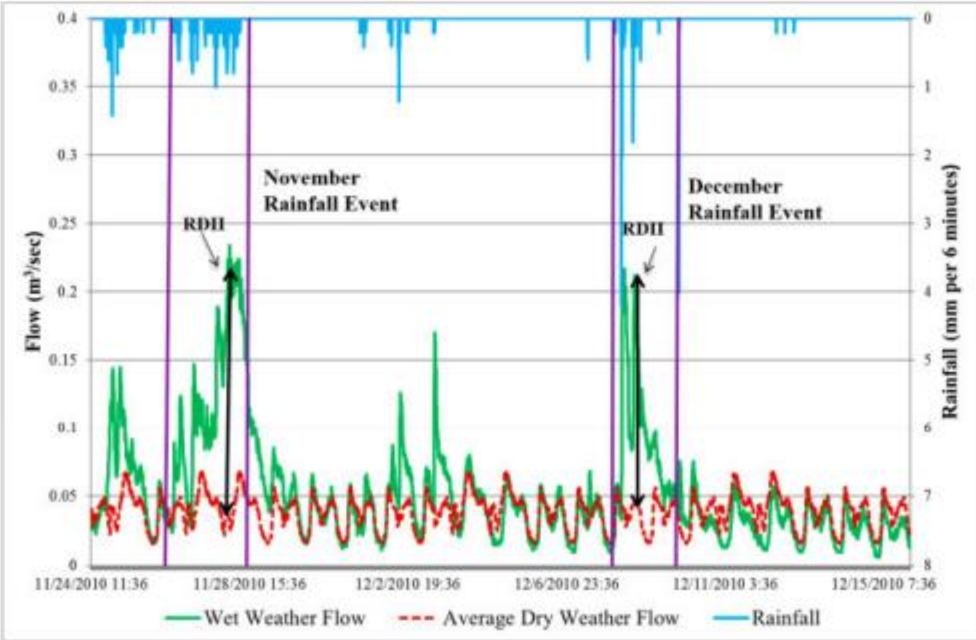

Figure 3.20 – RDII Hydrograph, sewerage performance (Nasrin et al. 2018)

RDII is also, inherently difficult to quantify as there are many variables that can persuade infiltration such as, type of weather events, age and capacity of network, soil type and structure, population, ground water table, ground cover a climate. Existing reports reviewed in the literature review found the strongest influence and contributor of RDII is the sewer networks age and material type, one such report by Keily, 2019 – Sewer inflow and infiltration for catchments with high rainfall and aging infrastructure. Keily, was able to determine an estimated contributing percentage of RDII that affected different sewer materials, refer to Table 3.8 below.

Infiltration derived flow for sewers from peak rainfall					
Sewer material	*PVC*	*VC*	*AC*	*Conc.*	*EW*
Infiltration rate % for each material	*0.048*	*0.125*	*0.172*	*0.151*	*0.242*

Table 3.8 – Infiltration rate for different materials (Keily 2019)

This data was basin on a hydraulic model in an area with very limited data available. The hydraulic model was used based on monitored sewer pump flow data over a four-year period, therefore other many other variables that effect infiltration as previously discussed were not accounted for.

WSAA guidelines have adopted a RDII ratio of 0.2%, this is the percentage of peak flow that is estimated to enter the sewer network in high rainfall events. This ratio was determined through a I/I best management practices study by WSAA in conjunction with GHD and Urban Water Solutions, in 2011 and furthered continued in 2012. This adopted ratio, along with the pipe material infiltration rate shown in Table 3.8 Will be used for this case study.

The methodology for estimating the reduced RDII from the implementation of WSUD will be as follows.

- Estimated RDII will be calculated using the hydraulic capacity procedure outlined in the literature review (Gravity Sewerage Code of Australia, 2021). We can determine the maximum RDII in L/s expected for the catchment, with the assumption of no major network defects.

- The I/I ratio determine through the different pipe materials (Keily) and the 0.2% contributing factor by WSAA guidelines can be adopted to the determine maximum RDII value to be anticipated through rainfall.

- Utilising the determined peak reduction factors found through the MUSIC model analysis for each WSUD strategy, we can determine the relationship and estimate a total RDII mitigated.

4. Evaluation of Results

4.1. Introduction

As discussed though-out the chapter 3 – Methodology, the results for this case study have been obtained using MUSIC modelling. Standard data, nodes or links can be exported by right clicking to show properties of the selected item and selecting the 'Export' command, this gives the user the option to select a particular time-step, inflow parameter and outflow parameter. In this case study, the TSS, TP, TN loads are not necessarily required as we are more concerned with the stormwater quantity and flows. The outflows can be selected in the above menu, and exported to 'Flux files', from where they can be saved as .csv files and brought into Microsoft Excel. The output data can the be utilised in the generation of stormwater hydrographs – a plot of the flow property against a time-step.

Using hydrographs to display data, was found to be an effective method to display how the storm is affecting post-development conditions and an efficient representation of WSUD effectiveness. Data that can be extracted from the hydrographs are as following:

- **Volume of total runoff**
  - This can be found by the area under the plotting graph and is in m^3.
- **Peak discharge**
  - The maximum discharge, found by drawing a line to the y-axis from the peak storm position, displayed in m^3/s.
- **Peak rainfall**
  - largest portion of rainfall shown on the graph, displayed in mm.
- **Rising/Falling limb**
  - Shown on the graph as the rate of incline/decline. The steeper the rising/falling limb, the higher the velocity (m3/s).
- **Lag time**
  - Distance in time between peak rainfall and peak flow in minutes.
- **Time of Concentration (tc)**
  - The time from the end of excess rainfall to the point of inflection where recession in the curve begins (falling limb), t_c is a dimensionless unit

Typically, a best-case scenario for WSUD in a developed catchment, is to return runoff conditions back to pre-developed conditions. We can then be assured that stormwater from the catchment will not result in flooding because of the development.

4.2. Existing Catchment Runoff

The existing catchment peak discharge was calculated using the rational method and compared using XP-Rafts. Refer to Table 4.1 for the values used for the Major Q50 and Minor Q2 storm events, these storm events are the recommended minimum design storms for a residential development of this size.

Catchment Calculations (Major and Minor Storm ARI's)							
Number	Area	C2	I2	Q2	C50	I50	Q50
	ha		mm/hr	m^3/s		mm/hr	m^3/s
1	4.050	0.63	97	0.686	0.85	194	1.857
Total Runoff		Minor	0.686	m^3/s			
		Major	1.857	m^3/s			
Total Area			4.050	ha			

Subcatchment Summary Table				
Number	Catchment Name	Catchment Description	C_{10}	tc
1	E1	Rural areas (2-5 dwelling units/ha)	0.74	15

Table 4.1 – Rational Method Calculations - Major and Minor Storm Event

Storm events from Q1 – Q100 were then calculated and modelled in XP-Rafts for comparative purposes. The peak discharges were used to compare with MUSIC to determine the error percentage expected with the software.

$$\text{Percentage Error} = \frac{Rational\ Method\ or\ XPRafts\ -\ MUSIC\ Model}{Rational\ Method\ or\ XPRafts} * 100$$

Refer to Table 4.2 below. These calculations are used to compare accuracy of the MUSIC model peak flows.

Storm Event	Rational Method Peak Runoff	XPRAFTS Model Peak Runoff	MUSIC Model Peak Runoff	Music Error Rational Method	Music Error XP - RAFTS
(ARI)	(m^3/s)	(m^3/s)	(m^3/s)	%	%
1	0.500	0.491	0.462	7.6	5.9
2	0.686	0.664	0.642	6.5	3.3
5	0.989	0.950	0.920	6.9	3.2
10	1.182	1.140	1.086	8.13	4.7
20	1.434	1.380	1.280	10.7	7.2
50	1.857	1.785	1.655	10.9	7.3
100	2.168	2.082	1.922	11.3	7.7

Table 4.2 – Peak runoff error calculation

It is determined, the smaller the storm event the greater the accuracy between the methods, MUSIC can produce data that maybe considered reasonably accurate for this case study.

4.3. Music Rainfall Data

To best display the design storm used for creating hydrographs, a hyetograph can be created. The rainfall data inputted into MUSIC was from the year 1990, attained from the close's rainfall gauge to the catchment. Refer to the time series MUSIC plot in figure 4.1 below, for rainfall and evapo-transpiration for 1990.

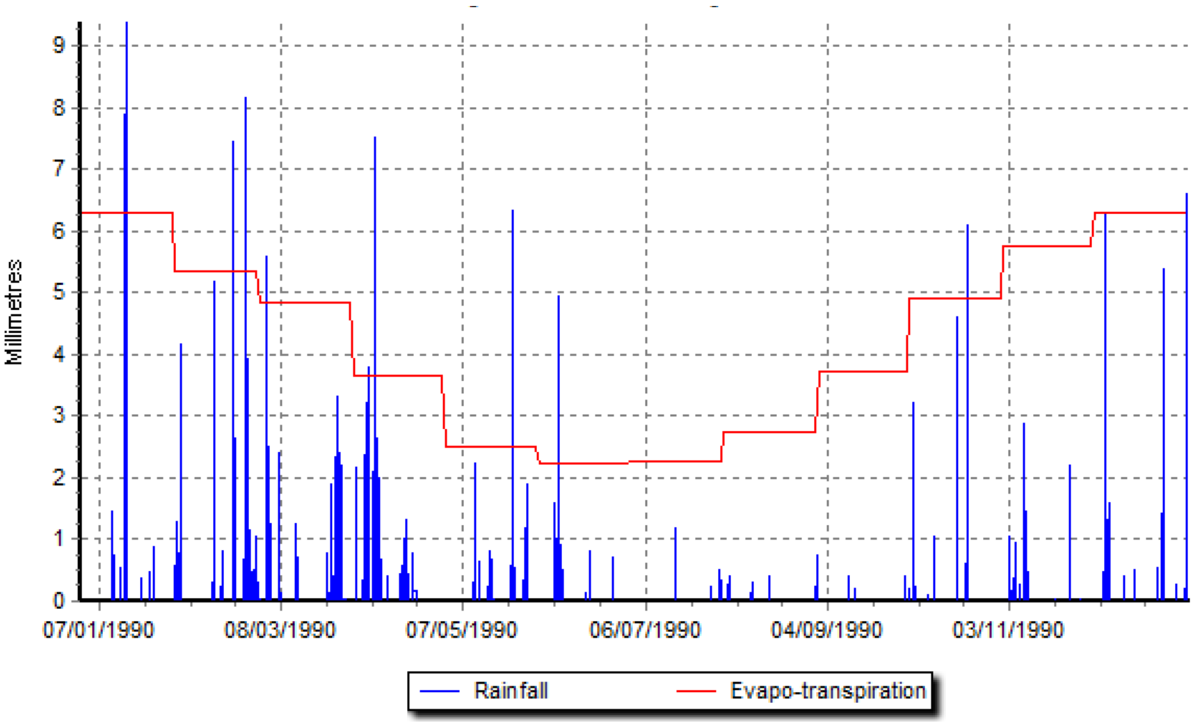

Figure 4.1 – Time Series graph (MUSIC)

In the year, the 24th of February had the largest amount of rainfall, this rain period was broken into 6-minute time steps to create the hyetograph of the storm event, see figure 4.2 and table 4.3 below. The hyetograph displays two peaks in the storm event, first peak at 16.51mm around the 30-minute mark and the second smaller peak at 4.84mm around the 108-minute mark.

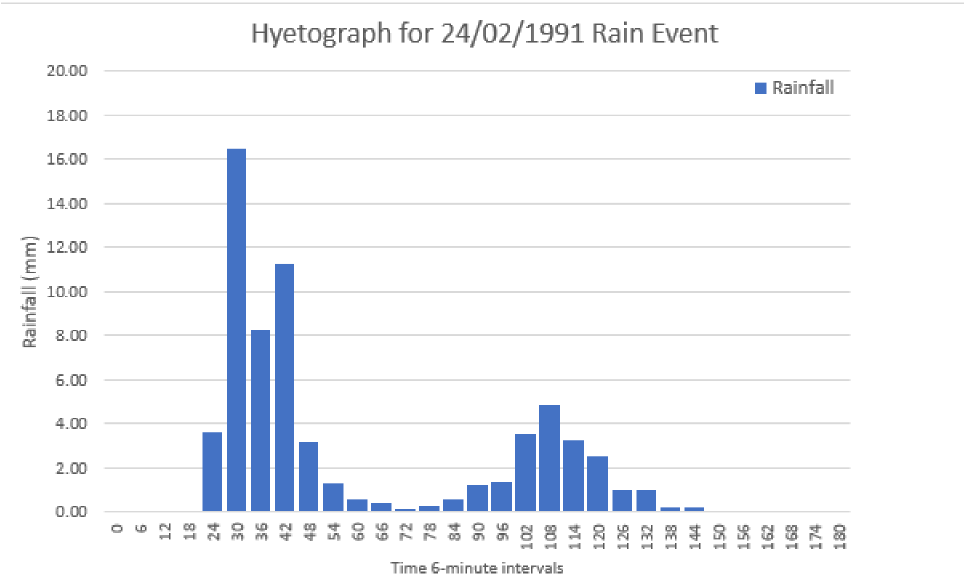

Figure 4.2 – Hyetograph from largest rainfall event

Time (6-minute steps)	
0	0.00
6	0.00
12	0.00
18	0.00
24	3.65
30	16.51
36	8.26
42	11.25
48	3.15
54	1.27
60	0.55
66	0.45
72	0.15
78	0.24
84	0.54
90	1.20

Time (6-minute steps)	
90	1.20
96	1.35
102	3.56
108	4.84
114	3.25
120	2.51
126	1.00
132	1.00
138	0.21
144	0.19
150	0.05
156	0.05
162	0.04
168	0.04
174	0.03
180	0.04

Time (6-minute steps)	
180	0.04
186	0.03
192	0.02
198	0.01
204	0.01
210	0.01
216	0.00
222	0.00
228	0.00
234	0.00
240	0.00
246	0.00
252	0.00
258	0.00
264	0.00
270	0.00

Time (6-minute steps)	
270	0.00
276	0.00
282	0.00
288	0.00
294	0.00
300	0.00
306	0.00
312	0.00
318	0.00
324	0.00
330	0.00
336	0.00
342	0.00
348	0.00
354	0.00
360	0.00

Table 4.3 – Hyetograph, rainfall data

4.4. WSUD Hydrographs

Hydrographs have been created for the bioretention basin, bioretention swale, tree pits, permeable pavements, rainwater tanks and finally a combination of all WSUD.

4.4.1. Bioretention Basin Hydrograph

The bioretention hydrograph can be seen below in *Figure 4.3*. The bioretention was modelled with a filter area of 900m^2 with a filter media depth of 0.5m. The post developed case, without a bio-retention basin, discharge peaked at 0.81242mm^3/s. The implementation of the bioretention basin reduced this peak flow to 0.23012mm^3/s, this is a total reduction in peak flow of 71.7% with a lag time of approximately 22 minutes. The hydrograph shows as water enters the basin, it is slowly released gradually over time and that the basin is working efficiently. The second peak as shown in the post developed case, appears to be removed by the basin, this could mean the basin does not reach peak capacity. The reduction from the second peak to the same time-step with the basin, shows a reduction of approximately 40%. Both rising and falling limb have reduced significantly from the post developed case.

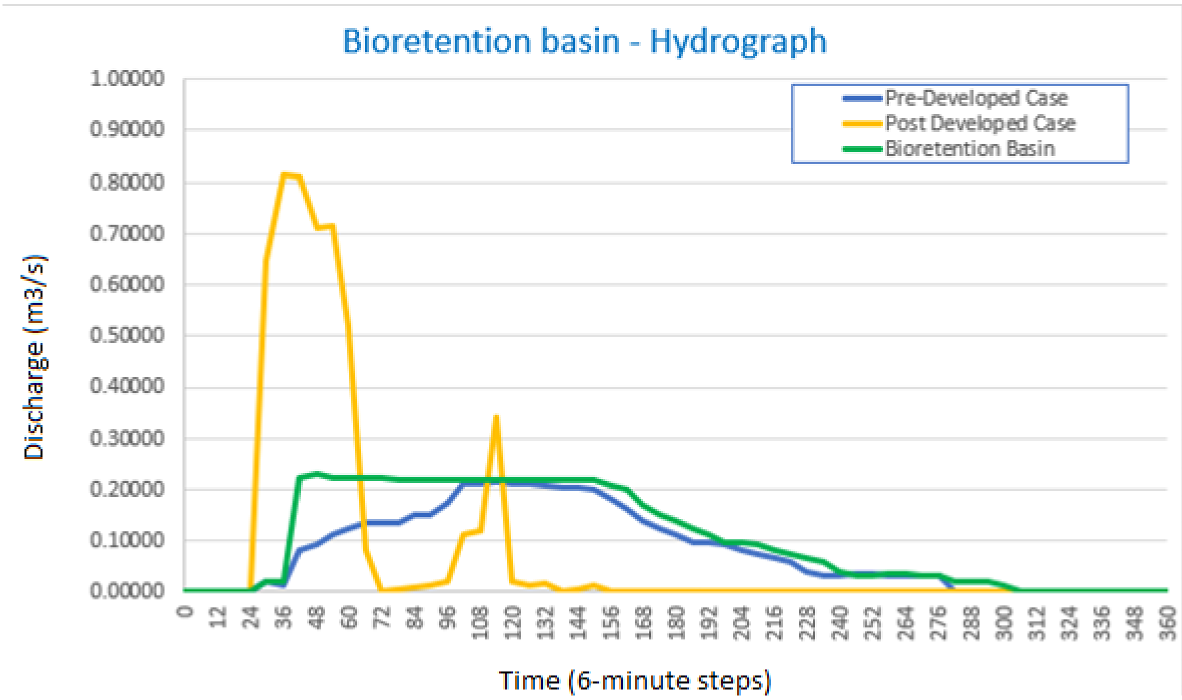

Figure 4.3 – Bioretention basin, Hydrograph

4.4.2. Bioretention Swale Hydrograph

The bioretention swale hydrograph can be seen below in *Figure 4.4*. The bioretention swale was modelled with a filter area of 150m^2 with a filter media depth of 0.5m, the swale is 100m long and 1.5m wide. The post developed case, without a bioretention swale, discharge peaked at 0.81242mm^3/s. The implementation of the bioretention swale reduced this peak flow to 0.61115mm^3/s, this is a total reduction in peak flow of 32.9% with no lag time shown. As the rainfall directly runs straight into the swale, this could explain why there was no lag to the storm event, yet a reduction in peak flow. A new peak at approximately 100 minutes is shown with a total reduction in the second peak by 44%. The water then gradually flows from the swale to the outlet.

The rising and falling limb from the first peak appears to remain unchanged, although the rising and falling limb are reduced for the second peak. Therefore, velocity is reducing through the swale.

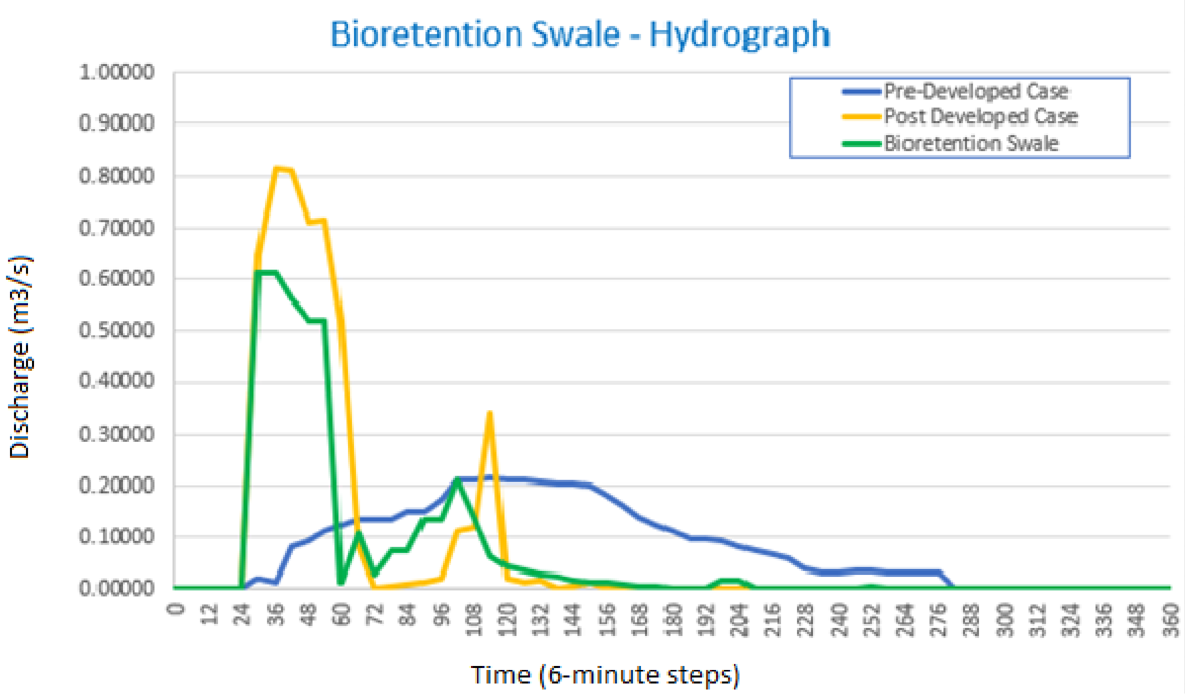

Figure 4.4 – Bioretention swale, Hydrograph

4.4.3. Tree Pits Hydrograph

The hydrograph for the tree pits can be seen below in *Figure 4.5*. The tree pits were modelled with a filter area of 46.5m^2 with a filter media depth of 0.5m and there was a total of 30 tree pits modelled equating to 1 tree pit per two lots. The post developed case, without the tree pits, discharge peaked at 0.81242mm^3/s. The implementation of the tree pits reduced this peak flow to 0.71242mm^3/s, this is a total reduction in peak flow of 12.3% with no lag time shown. As the rainfall directly runs straight into the tree pits, this could explain why there was no lag to the storm event, yet a reduction in peak flow. The second peak appears to be in the same position of the post developed case, although has a total reduction in flow by 31.4%. The rising and falling limb from the first peak appears to remain unchanged, although the rising and falling limb are reduced for the second peak. Therefore, velocity is reducing through the tree pits as expected.

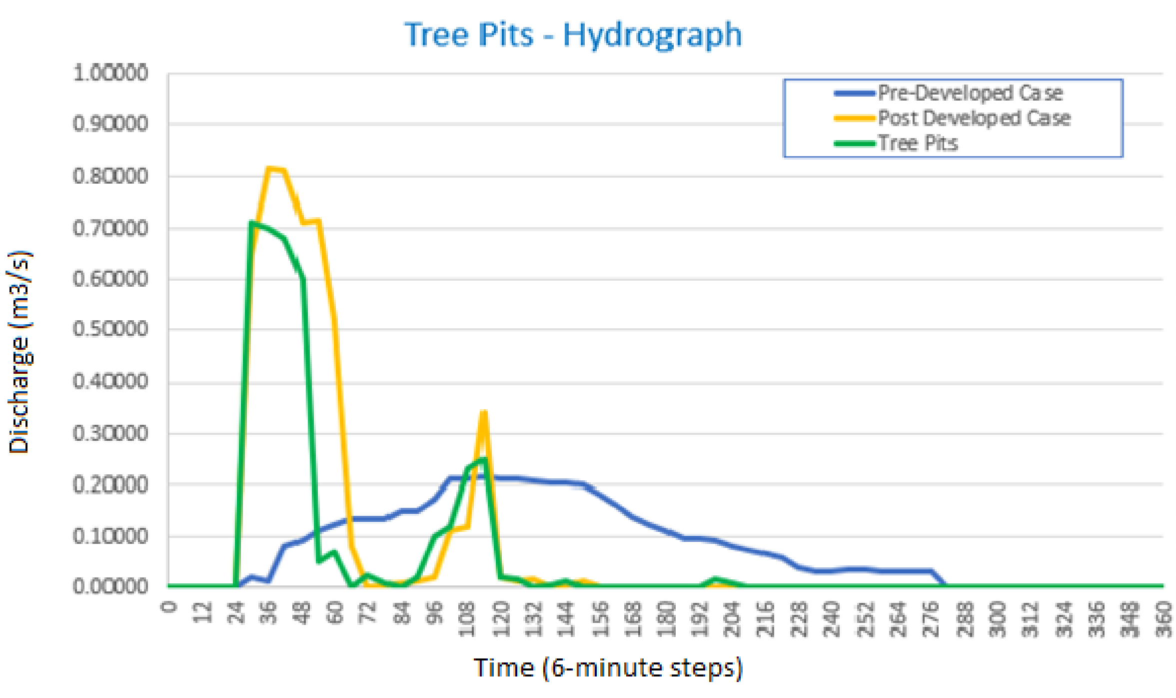

Figure 4.5 – Tree pits, Hydrograph

4.4.4. Permeable Pavements Hydrograph

The hydrograph for the permeable pavement can be seen below in F*igure 4.6*. The permeable pavement was modelled with a filter area of 100m^2 with a filter media depth of 0.3m. The permeable pavement was proposed on all access driveways for each lot, and a 0.3m depth was chosen to reduce excavation. The post developed case, without the permeable pavements, discharge peaked at 0.81242mm^3/s. The implementation of the permeable pavements reduced this peak flow to 0.62112mm^3/s, this is a total reduction in peak flow of 23.5% with a lag time of approximately 6 minutes. As the rainfall infiltrates into the pavements, this process could explain why there is a lag. The second peak appears to be brought forward with a time indifference of approximately 12 seconds and has a total reduction in flow by 11.4%. The rising from the first peak appears to remain unchanged and the fall limb has a slight reduction in velocity. The rising and falling limb for the second peak shows a significant reduction in velocity, this could be because of the infiltration rate and water storage in the pavements during the event.

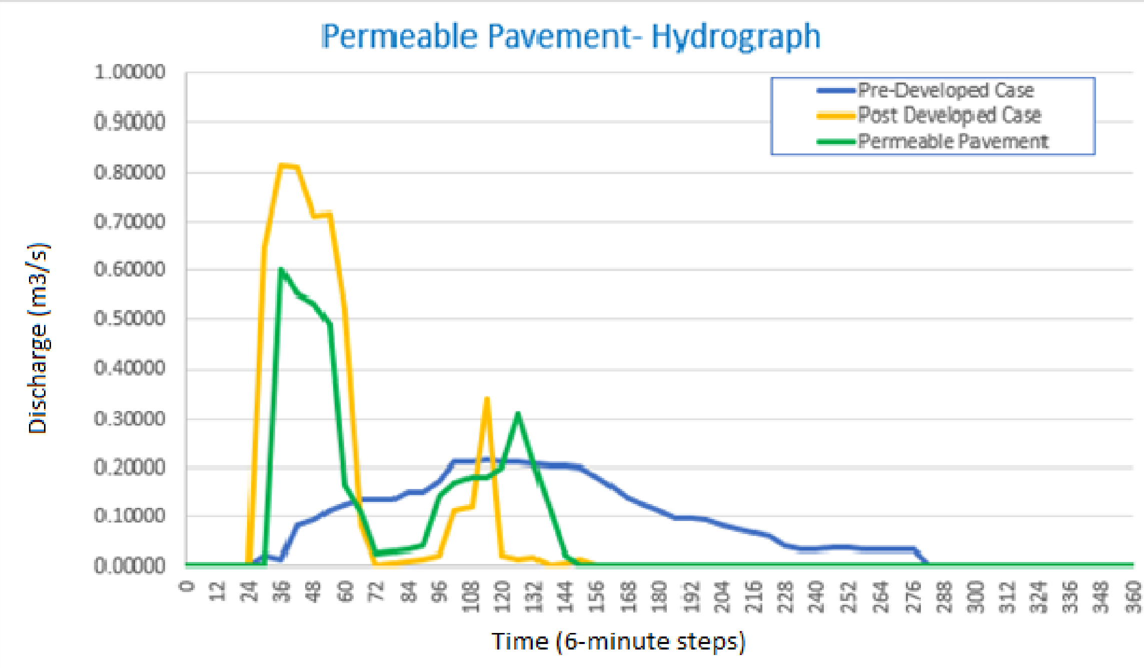

Figure 4.6 – Tree pits, Hydrograph

4.4.5. Rainwater Tanks Hydrograph

The hydrograph for the rainwater tanks can be seen below in *Figure 4.7*. The rainwater tanks were modelled to a size of 10kL each and there was a total of 63 modelled, which is one tank per lot. The post developed case, without the rainwater tanks discharge peaked at 0.81242mm3/s. The implementation of the rainwater tanks reduced this peak flow 0.55233mm3/s, this is a total reduction in peak flow of 32.0% with a lag time of approximately 26 minutes. As the rainfall runs from the roof of the houses into the tanks, this process could explain why there is a larger lag. The second peak appears to be removed, as the velocity has reduced significantly, this is evident by the rising and falling limbs. The reduction in flow from the second peak is 36.5%.

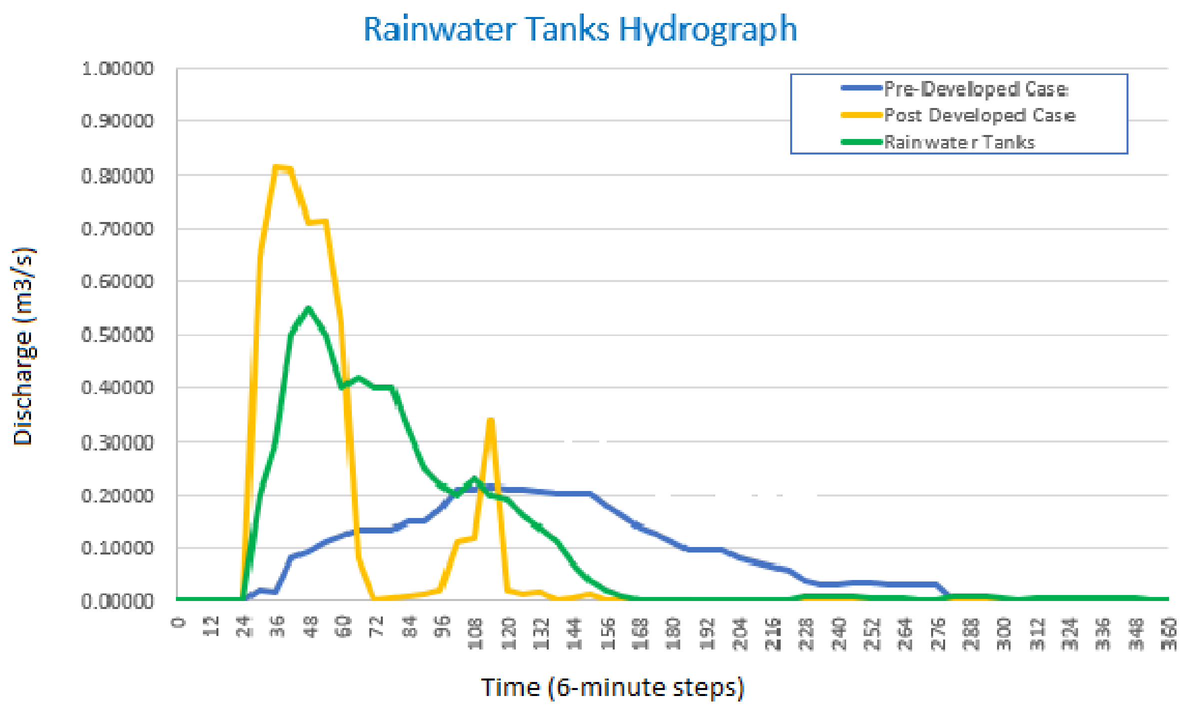

Figure 4.7 – Rainwater Tanks, Hydrograph

4.4.6. Combined WSUD Hydrograph

The hydrograph for the combined WSUD can be seen below in *Figure 4.8*. The combined data was modelled by adding all the WSUD strategies into the same model. The all-designs flow into the bioretention basin. The post developed case, without the WSUD, discharge peaked at 0.81242mm^3/s. The implementation of all WSUD reduced this peak flow to 0.15155mm^3/s, this is a total reduction in peak flow of 81.3%. The new peak flow has a lag time of approximately 6 minutes. The second peak has been removed as the bioretention basin does not reach capacity. The total reduction from the post development second peak to the new flow is 60.2%. The rising and falling limbs have reduced indicating a reduction in velocity. The combination of all the WSUD does not return the stormwater runoff to pre-development, although it does average the discharge over the time more smoothy.

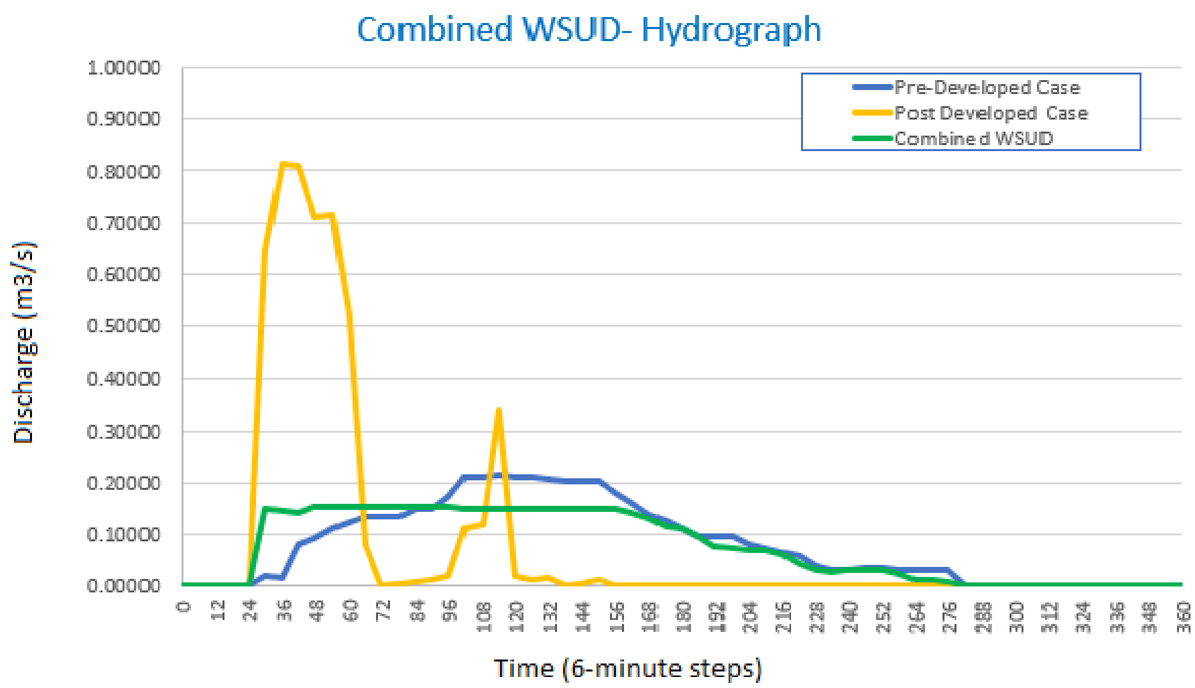

Figure 4.8 – Combined WSUD, Hydrograph

4.5. MUSIC Results Summary

The bioretention basin was the most effective strategy and was able to return the peak flow closely to the pre-developed scenario. The combination of all WSUD was the most effective as expected, although did not perform far better than the bioretention basin on its own. The lag time is also not if expected for the combined WSUD, this could possibly be due to an error in the MUSIC model. The rainwater tanks have produced the greatest lag time in the storm event, this was expected, as roof water is diverted to the storage reservoir, whereas other WSUD strategies are filtering the stormwater and discharging to an outlet.

The final MUSIC Modelling results are displayed in Table 4.4 below, these results will be used in conjunction with sewerage calculations to determine an estimated reduction in RDII from the post-developed case.

WSUD Strategy	1st Peak Flow Reduction	2nd Peak Flow Reduction	1st Peak Lag Time	Rising Limb	Falling Limb
Bioretenion Basin	71.7%	40.0%	22 Minutes	Reduced	Reduced Significantly
Bioretention Swale	32.9%	44.0%	0 Minutes	Unchanged	Reduced
Tree Pits	12.3%	31.4%	0 Minutes	Unchanged	Reduced
Permeable Pavement	23.5%	11.4%	12 Minutes	Unchanged	Reduced
Rainwater Tanks	32.0%	36.5%	26 minutes	Reduced Significantly	Reduced Significantly
Combined WSUD	81.3%	60.2%	6 Minutes	Reduced Significantly	Reduced Significantly

Table 4.4 – MUSIC Modelling Results

4.6. Estimated RDII Reduction

As outlined in the Literature Review, maximum expected RDII can be found using the WSAA SEQ - Code hydraulic design capacity calculations. Although many other RDII contribution factors are considered to form this set of calculations, this will provide a base value of RDII that can be used for this case study. The procedure is outlined below.

RDII = 0.028 * A_{Eff} * C * I

Determining C (IFF leakage severity coefficient):

Surrounding soil data found from neighbouring SMPs and geotechnical reports have found the local soils to be 'sandy loam soils', this soil has good drainage and low soil movement properties. Using *Table 4.5* below, we can adopt a value of 0.6, S_{aspect} = 0.2 and N_{aspect} = 0.4.

Influencing aspect	Low impact	High impact
Soil aspect, S_{aspect}	0.2	0.8
Network defects and inflow aspect, N_{aspect}	0.2	0.8
$C = S_{aspect} + N_{aspect}$	Minimum = 0.4	Maximum = 1.6

Table 4.5 – leakage Severity Coefficient (C) (SEQ – Gravity Sewerage Code 2021)

Determining I (Rainfall intensity of catchments location in Carseldine):

The rainfall intensity needs to be determined at the location for a 1-hour duration, to then determine an AEP of 39.35% - this value is a containment standard by the Regional environmental regulations for sewerage spill frequency. The design rainfall intensity data for Carseldine can be found at the Australian Government – Bureau of Meteorology website (http://www.bom.gov.au/water/designRainfalls/revised-ifd/), using 2016 IFDs (intensity Frequency Duration).

To determine the AEP of 39.35% we need to interpolate two values from the IFD data, from which we have determined:

50% AEP = 40.4mm/hr

20% AEP = 55.0mm/hr

Through linear interpolation we find:

39.35% AEP = 45.6mm/hr.

We then can determine the factor size

Factor Size: $= (40/A(ha))^{0.12}$

$= (40/4.05)^{0.12}$

= 1.32

Factor Containment: Using Table 4.6 below we determine a Factor Containment value of **1.0.**

AEP	100%	98.17%	86.47%	63.21%	39.35%	18.13%	9.52%
$Factor_{Containment}$	0.2	0.4	0.6	0.8	1.0	1.3	1.5

Table 4.6 – Factor Containment vs AEP (SEQ – Gravity Sewerage Code 2021)

Determine I:

Intensity: $= I_{39.35}$ x Factor size X Factor Containment

= 45.6 x 1.32 x 1.0 = 60.2mm/hr

To determine A_{FF} :

A_{FF} = A x (Density / 150)$^{0.5}$ – For Density <150 EP/Ha

A_{FF} = A – For Density >150 EP/Ha

For EP – Assume 5 EP/house hold in accordance with BCC guidelines.

EP = 5 x 63 = 315 in 4.05ha

Therefore, EP = 76EP/ha

A_{FF} $= 4.05 \times (76 / 150)^{0.5}$

= 2.88 Ha

Therefore:

RDII = 0.028 * A_{Eff} * C * I

RDII = 0.028 * 2.88 * 1 * 60.2

= 4.85 L/s

As pervious discussed, the above RDII value of 4.85L/s is the maximum expected amount of RDII from the catchment. Using the I/I ratio from WSAA guidelines of 0.2% we conclude an expected 0.0097L/s or flow into the sewer system from the catchment without the implementation of WSUD strategies. Refer to Table 4.7 below for the estimated RDII in the catchment in accordance with WSAA guidelines.

WSUD Strategy	Peak Flow Reduction	Estimated Reduction in RDII L/s
Bioretenion Basin	71.7%	0.0068
Bioretention Swale	32.9%	0.0032
Tree Pits	12.3%	0.0012
Permeable Pavement	23.5%	0.0023
Rainwater Tanks	32.0%	0.0031
Combined WSUD	81.3%	0.0079

Table 4.7 – Mitigated RDII estimation WSAA guidelines

Now, taking into considering pipe material in accordance with case study completed by Keily 2019. Refer to table 4.8 below for expected RDII flow into each pipe material.

RDII (L/s)	Expected RDII for PVC (L/s)	Expected RDII for VC (L/s)	Expected RDII for AC (L/s)	Expected RDII for Conc. (L/s)	Expected RDII for EW (L/s)
4.85	0.02328	0.0606	0.08342	0.07322	0.11737

Table 4.8 – Expected RDII for different pipe materials

We can now calculate the total expected RDII mitigated for each WSUD strategy for different pipe materials. Refer to Table 4.9 Below.

WSUD Strategy	Peak Flow Reduction	Estimated Reduction in RDII (L/s) for PVC	Estimated Reduction in RDII (L/s) for VC	Estimated Reduction in RDII (L/s) for AC	Estimated Reduction in RDII (L/s) for Conc.	Estimated Reduction in RDII (L/s) for EW
Bioretenion Basin	71.7%	0.0017208	0.0043737	0.0060228	0.0052341	0.008415429
Bioretention Swale	32.9%	0.0007896	0.0020069	0.0027636	0.0024017	0.003861473
Tree Pits	12.3%	0.0002952	0.0007503	0.0010332	0.0008979	0.001443651
Permeable Pavement	23.5%	0.000564	0.0014335	0.001974	0.0017155	0.002758195
Rainwater Tanks	32.0%	0.000768	0.001952	0.002688	0.002336	0.00375584
Combined WSUD	81.3%	0.0019512	0.0049593	0.0068292	0.0059349	0.009542181

Table 4.9 – Expected RDII for different pipe materials

4.7. Results Conculsion

The results above show that the implementation of WSUD in the proposed development contribute to a reduction in RDII. The combined scenario featuring all the WSUD strategies used, produced the best results. To achieve these results, assumption had to be made due to a lack of site data.

Firstly, there are assumptions built into the peak discharge calculations, as determined by the error differences in each method. The rational method assumes uniform steady rainfall and tends to neglect storage effects. The XPRafts model was also based on assumptions, although takes storage into consideration in accordance with AR&R 2019.

There are assumptions built into MUSIC model around the different WSUD design parameters and rainfall event, although for a preliminary design, these assumptions can be deemed acceptable and in accordance with Water by Design 2010. There are also inbuilt assumptions in the RDII estimation method by WSAA, the hydraulic design capacity calculations generally provide us with the maximum expected RDII, and peak discharge losses were compared to this value, due to lack of real time sewer monitoring data.

The approach to determine total reduced RDII, as a direct consequence of implementing the proposed WSUD strategies could be considered broad in this case, although the results shown above provide clear indication of reduction in peak discharge and change to the storm event in the residential development.

5. Discussion and Conclusions

5.1. Introduction

Urban drainage systems are becoming more susceptible to failure and overloading. As increasing amounts of land is converted into urban residential areas on a yearly basis, this rapid urbanisation is in turn resulting in urban systems to be less efficient causing flood, sewerage overflows and network failure.

WSUD has been a very popular aspect in modern times to counteract and reduce the negative impacts of urbanisation, such as increase in impervious areas and pollutant runoff. A large amount of research is available from councils and governments around the quality effects of WSUD and treatment of stormwater runoff, although there is a significant knowledge gap in utilising WSUD for mitigating RDII in existing sewerage systems. Flooding in urban areas has been a major problem for many years and a major public health and environmental concern around flooding is the presence of effluent in the flood waters as a result from SSO, network and WWTP overload and sewerage network failure.

5.2. Discussions

The aim of this study was to determine and quantify the mitigating effects of WSUD in relating to RDII. It was found that there are many assumptions and parameters involved in not only determining WSUD quantity, but also in RDII on existing sewerage systems. When determining a relationship between WSUD and RDII, it was seemingly difficult to return accurate results.

There are many variances and conflicts found in the literature around quantifying RDII, each council and government agency has differing methods, that would produce different results. Contacting local councils found the main solution to reduce RDII was post corrective action, instead of initial mitigation methods.

It was found in this analysis, MUSIC model contained a percentage of error when compared with other methods, especially when determining discharge runoff and therefore MUSIC model may not be the best approach for frequent flow and hydrology analysis. There were many assumptions made with the WSUD design, these assumptions were made based on 'best practices' using MUSIC modelling guides, accuracy could have been increased by investigating a developed scenario with WSUD existing and a site investigation and monitoring to quantify performance. All strategies did comply with quality requirements in accordance with BCC planning scheme, although it could be noted there was a small difference in the pollutant results each time the model was run, which could present an oversight in the sizing/quantity of the strategies. Further investigation is required to determining the capability of MUSIC and if alternative software could produce increased accuracy.

Many of the cases did not show much lag time in the storm event and the combined strategies did not perform as well as expected, displaying slightly better reduction in peak flows then the bioretention basin on its own. This catchment size for this case study was relatively small, results between different catchments sizes could vary significantly as the error difference from the assumptions made would change. The most effective solution in reducing runoff and mitigating RDII would be installing a bioretention basin, although basins take up allot of room in a residential development and therefore reduce the developer's profits. Bioretention basins also require on-going maintenance to be effective.

The study of RDII found there were many parameters involved in determining accurate results via a desktop study and flow monitoring data over extended periods of time would increase results greatly. It was found the BCC standards heavily relied on estimation values. RDIII was considered in BCC guidelines, although they do not extinguish between sewage flows and I/I to achieve accurate results. Other parameters such as water table, soil permeability, river levels and potable water consumption also were not considered to a large extent.

This study has shown that WSUD does play a part in mitigating RDII and benefits local councils and water authorities to continue research in this area. Furthermore, this study has identified that MUSIC modelling can be used for WSUD performance modelling and can assist in the design process and is an appropriate tool to determine what WSUD should be installed in your development.

The study identified a knowledge gap in the framework around using WSUD strategies to help reduce RDII and provided a potential method to encourage further research around closing this gap in knowledge.

5.3. Further Research

This study has demonstrated the importance of further research in this area and can be used as a good starting point to promote different methods and or applications alike or differing to this case study, to further the knowledge around mitigating RDII. Further research that could help fill the knowledge gap identified include:

- Comparing the effectiveness of WSUD vs conventional mitigation methods around performance, cost and restoring natural hydrological storm characteristics to urban developments.
- Evaluating the effectiveness of WSUD for different historical rainfall events, catchment size, shape, slopes and parameters. Determine how the implementation of WSUD in the past could have changed to outcome around large flood events.
- This study has the potential and flexibility to be replicated using different stormwater hydraulic and hydrological modelling techniques or analysing the difference in methods, outlining which method is the most accurate.
- Refinement and eradicate, where possible, areas where assumptions have been used. Gather accurate site information around the above case study and conduct a feasibility/economic analysis for the proposed mitigation methods used.
- Using alternative WSUD strategies such as wetlands with large catchments, green roofs and infiltration trenches. Analysing different construction techniques and vegetation used in bioretention systems.

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Appendix A – Project Specification

ENG4111/4112 Research Project

Project Specification

For: Belal Yousif

Title: A Water Sensitive Urban Design approach to mitigate the effects of infiltration and inflow on existing sanitary sewer networks during peak wet weather flows.

Major: Civil Engineering

Supervisors: Justine Baillie

Enrollment: ENG4111 – EXT S1, 2022

ENG4112 – EXT S2, 2022

Project Aim:

Develop and evaluate an urban water sensitive strategy for mitigating infiltration and inflow on an existing sanitary sewer network in a problematic catchment. Conduct hydraulic modelling of commonly used WSUD strategies and develop a framework for reducing stormwater infiltration and inflow into existing sanitary sewer systems.

Programme: Version 1, 16h March 2022

1. Create a project timeline including date of completion for project millstones and conduct a risk assessment for the project.

2. Undertake an in-depth literature review of the project, discover common and uncommon WSUD strategies and identify other research undertaken that may be of interest to this area of study.

3. Explore problematic catchments that have been affected by heavy rainfall around the Brisbane area and have resulted in sewer contamination in flood waters and/or where sewer overflows have occurred.

4. Scope and research the suitably chosen catchment and identify applicable parameters required for this research project within the catchment area.

5. Assess periods and impacts of intense rainfall events on the sanitary sewer network in the chosen problematic catchment. Identify other potential causes i.e., Pipe material, change in land use.

6. Identify and prepare a strategy to mitigate sewer infiltration and inflow in the chosen catchment. Undertake hydraulic modelling, determined in the literature review, to access potential mitigation strategies.

If time and resources permit:

- A feasibility/economic analysis can be proposed for the identified mitigation methods for the selected catchment.
- A comparison between a different catchment that has vastly different parameters (slopes, impervious area, shapes) can be explored.
- Identify and eradicate, if possible, areas of assumption in the study.

Appendix B – Project Milestones and Task Plan

Legend
Progress report due
Presentation during ENG4903 due
Submit draft thesis
Completion of thesis
Working weeks for specific task

Project: A Water Sensitive Urban Design approach to mitigate the effects of RDII on existing sewer systems

Project Supervisor : Justine Baillie

Task name	Stard date	End date	WEEK 1	WEEK 2	WEEK 3	WEEK 4	WEEK 5	WEEK 6	WEEK 7	WEEK 8	WEEK 9	WEEK 10	WEEK 11	WEEK 12	WEEK 13
			March					April				May			
Project Specification	**21/02/2022**	**23/03/2022**													**Progress Report due: 25th May**
Review Topics/area of interest															
Preliminary literature review															
Submit Topic															
Literature Review	**21/02/2022**	**17/04/2022**													
Current guidelines in AUS and Internationally															
Previous student dissertations															
Previous journals															
Knowledge gaps															
Write up															
Methodolgy	**18/04/2022**	**22/05/2022**													
Data collection															
Catchment study															
Data analysis and evaluation															
Write up															

Semester 2 starts

Task name	Stard date	End date	WEEK 13	WEEK 14	WEEK 15	WEEK 16	WEEK 17	WEEK 18	WEEK 19	WEEK 20	WEEK 21	WEEK 22	WEEK 23	WEEK 24	WEEK 25	WEEK 26	WEEK 27	WEEK 28	WEEK 29	WEEK 30	WEEK 31	WEEK 32	WEEK 33
			May		June				July				August					September				October	
Semester 2 starts																							
Evaluation of Results	**30/05/2022**	**24/07/2022**																**Draft due: 7th September**		**ENG4903: 19th September**			**Final Due Date: 13th October**
Model completion																							
Input and output data																							
Estimation and finding																							
Conclusions and Discussions	**25/07/2022**	**21/07/2022**																					
Summary of findings																							
Further investigations																							
Introduction and background	**22/07/2022**	**18/09/2022**																					
Finalise thesis chapters	**22/07/2022**	**18/09/2022**																					
Absract, limitations, list of figures/tables																							
References/Appdendix																							
Draft feedback and additional input	**26/09/2022**	**13/10/2022**																					