

**Water Quality and Quantity Management Using
WSUD to Address Climate Change, Urbanisation and
Ageing Stormwater Infrastructure**

In Existing Developments

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The thesis submitted in fulfilment of the requirement for the degree of
Master of Applied Research

**Victoria University, Australia
Institute for Sustainable Industries and Livable Cities**

December 2025

Abstract

This research aims to advance the application of Water Sensitive Urban Design (WSUD) strategies to address the impacts of climate change and urbanization on existing urban stormwater drainage systems, creating more resilient and sustainable urban environments. Climate change and rapid urbanization pose significant challenges to water management worldwide. Integrating sustainable water management practices into urban planning offers a promising approach to mitigate these impacts. This thesis investigates the effectiveness of WSUD strategies in managing stormwater runoff, thereby improving water quality, and reducing flood risks in urban environments. Utilizing PCSWMM, a hydrologic and hydraulic modelling software, the performance of various WSUD features within a selected urban catchment area is simulated and analysed. The study evaluates these features to reduce peak flow rates, decrease pollutant loads, and defer stormwater system upgrades.

Furthermore, the research assesses the potential of these strategies to address climate change and urbanization impacts in existing developments. The study provides an integrated assessment of hydraulic behaviour, water quality outcomes, and life-cycle costs using a long-term continuous hydrologic and hydraulic modelling framework, enabling comparison of individual and hybrid WSUD strategies. Through comprehensive modelling and scenario analysis, this contributes to understanding WSUD's role in mitigating the adverse effects of climate change and urbanization on stormwater systems. The findings aim to inform urban planners, engineers, and policymakers on effective strategies for incorporating these methods into urban development plans, promoting sustainable stormwater management, and building resilient cities.

Declaration

“I, Fatemeh Khalaji, declare that the Master of Applied Research thesis entitled ‘Water Quality and Quantity Management Using WSUD to Address Climate Change, Urbanization and Ageing Stormwater Infrastructure in Existing Developments’ is no more than 50,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work”.

“I have conducted my research in alignment with the Australian Code for the Responsible Conduct of Research and Victoria University’s Higher Degree by Research Policy and Procedures.

This research was supported by an Australian Government Research Training Program (RTP)

Scholarship doi.org/10.82133/C42F-K220

This thesis has been edited for clarity of expression, punctuation and grammar using “Grammarly” tool. This use complies with VU guidelines on use of editors in HDR theses and overall VU policy on use of AI in research.”

Signature:

Date: 16/12/2025

Acknowledgement

I would like to express my sincere gratitude to both of my supervisors for their invaluable guidance and support throughout this study. I am especially thankful to A/Prof. Ashok Sharma for his exceptional scientific leadership, deep expertise, and the clarity he brought to this research. His insightful comments and advanced technical understanding greatly strengthened the analytical depth of this thesis. His steady support, encouragement, and genuine willingness to help at every stage made a remarkable difference in shaping the final outcomes, and I am truly grateful for his guidance throughout this journey.

My heartfelt and profound appreciation goes to A/Prof. Jianhua Zhang, whose constant support, thoughtful guidance, and genuine kindness deeply shaped my experience throughout this research. His calm presence, steady encouragement, and willingness to assist at every stage made a remarkable difference in both the progress of this project and my confidence along the way. His supportive mentorship created an environment where I always felt understood, motivated, and able to move forward with clarity.

I also extend my appreciation to Wyndham City Council (VIC, Australia) for supplying stormwater infrastructure network data, and I would like to acknowledge the Bureau of Meteorology (Australia) for providing the historical rainfall and climate datasets essential to this work. My sincere thanks also go to Cleannstormwater (Australia)—particularly Mircea Stancu and Gregory Chian—for their help in providing future climate data and valuable technical feedback. In addition, I am thankful to Dr Anthony Ladson (Moroka Pty Ltd) for providing the land-use datasets used in the modelling and spatial analysis.

Finally, I would like to express my heartfelt gratitude to my family, whose love, patience, and constant encouragement carried me through this journey. Their belief in me gave me the strength to keep moving forward, and I am truly grateful for their unwavering support.

List of Publications

1. Khalaji F, Zhang J, Sharma AK. Social and Economic Impacts of Water Sensitive Urban Design: A Review. *Water*. 2025; 17(1):16. <https://doi.org/10.3390/w17010016>
2. Building Future Resilience with Stormwater Management in Existing Developments Facing Climate Change and Urbanization Impacts: A Case Study in West Melbourne. (Under Review of Blue-Green Systems, IWA Publishing)

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List of Abbreviations

The following list of abbreviations is used throughout this thesis.

BoM Bureau of Meteorology

| | |
|--------|---|
| CPI | Consumer Price Index |
| EMC | Event Mean Concentrations |
| GIS | Geographic Information System |
| LCC | Life Cycle Cost |
| LID | Low Impact Development |
| NPV | Net Present Value |
| O & M | Operation & Maintenance |
| PCSWMM | Personal Computer Stormwater Management Model |
| RG | Rain Garden |
| RWT | Rainwater Tank |
| SWMM | Stormwater Management Model |
| TAC | Total Acquisition Cost |
| TAM | Total Annual Maintenance |
| WSUD | Water Sensitive Urban Design |

Chapter 1: Introduction

1.1 Background

Rapid population growth, expanding urbanization, the effects of climate change, and aging infrastructure have challenged the sustainability of current urban water management systems. Urban development leads to increased impervious surfaces, causing higher runoff volumes and pollutant loads, which in turn degrade receiving water bodies and strain drainage infrastructure (Walsh et al., 2005). Climate change exacerbates these issues by intensifying the frequency of extreme rainfall events, altering hydrologic regimes towards more intense storm events and floods. To address these escalating challenges, a paradigm shift in urban water management is underway – moving from traditional engineered solutions toward more sustainable, integrated approaches.

Water Sensitive Urban Design (WSUD) has emerged as a vital framework for integrating sustainable water management into urban planning, tackling the increasing challenges posed by urbanization and climate change (Khalaji et al., 2024, Leonard et al., 2019). WSUD is a holistic approach to urban water management that aligns water systems with natural ecosystems by minimizing runoff, improving water quality, and promoting biodiversity, while also providing co-benefits such as recreational and aesthetic value in cities, and has been shown to enhance urban water security through water conservation, flood mitigation and multi-functional landscape amenity (Sharma et al., 2016). This approach integrates ecological sustainability into planning, seeking to restore and enhance the natural water cycle within urban environments (Staff and Committee, 1999). Key WSUD principles include protecting natural water bodies, reducing potable water demand through water reuse and conservation, and employing decentralized green infrastructure like rainwater tanks, rain gardens, permeable pavements, green roofs, and other biofiltration systems. These green infrastructure measures help mitigate flooding risks and improve water quality (Brown et al., 2008, Leonard et al., 2019). Beyond environmental benefits, WSUD offers significant social and economic co-benefits by creating more attractive urban spaces, increasing property values, and reducing the long-term costs associated with large-scale stormwater infrastructure (Lloyd et al., 2002).

Urban water management practices have been evolving from centralized, infrastructure-heavy solutions toward decentralized, multi-functional systems exemplified by WSUD. In the early 20th century, urban water systems primarily focused on providing reliable potable water supply and rapid wastewater/stormwater removal, with little regard for environmental sustainability or the broader impacts of land development (Brown et al., 2008). As cities expanded and the environmental consequences became evident, it was clear that traditional drainage systems were inadequate – especially under extreme weather conditions like intense storms and prolonged droughts (De Haan et al., 2014). This realization has driven a shift towards integrated, eco-conscious water management approaches. WSUD and analogous concepts are implemented around the world (e.g. Best Management Practices, Sustainable Urban Drainage Systems, Low Impact Development, Green Infrastructure, and Nature-Based Solutions) represent this new paradigm (Fletcher et al., 2015). These approaches, despite differences in terminology and regional emphasis, collectively contribute to more sustainable and resilient cities by reconnecting urban water management with natural hydrological processes and by demonstrating the potential of decentralized WSUD systems to supplement conventional water services (Sharma et al., 2016). WSUD, in particular, was pioneered in Australia in the 1990s in response to growing concerns over stormwater pollution and urban stream degradation, uniquely integrating the entire urban water cycle (stormwater, wastewater, groundwater and potable supply) into city planning (Barton and Argue, 2007, Whelans et al., 1994). The approach aims to mimic pre-development hydrology to mitigate the impacts of urbanization on runoff and to improve resilience to climate change.

With WSUD gaining traction, many cities have begun to incorporate its principles into policy and practice. For example, urban runoff pollution and hydrologic disruption have been recognized as key causes of the "urban stream syndrome," a term coined to describe the flashier hydrographs, elevated nutrient and sediment concentrations, altered channel morphology, and reduced biodiversity observed in streams draining urban areas (Walsh et al., 2005). Regulatory frameworks in places like Australia have established stormwater targets requiring new developments to significantly reduce runoff and pollutant discharges. These requirements have driven the adoption of WSUD measures (such as rainwater harvesting, bioretention basins, constructed wetlands, and permeable surfaces) in new developments and are increasingly being applied to retrofit existing urban areas (O'Halloran et al., 2024).

1.2 Research Problem and Justification

Considering the background, the central research problem addressed in this thesis is:

How can Water Sensitive Urban Design strategies be effectively utilized to improve urban stormwater management (both quantity and quality) in existing developed areas, in the face of climate change and ongoing urbanization?

Urbanization in established communities has led to increased imperviousness, which in turn causes higher stormwater runoff peaks, larger runoff volumes, and greater pollutant loads entering waterways (Simpson et al., 2022). Climate change is expected to further intensify short-duration, high-intensity rainfall events, which will enhance urban flood vulnerabilities and water quality degradation. Stormwater infrastructure in many of the current developments was not designed for these future conditions – drainage systems in numerous locations are undersized or aging, which results in issues such as frequent street flooding, stream channel erosion, and pollutant loading in downstream waters. Enhancing conventional pipe-and-channel networks to handle increased flows is often extremely costly and disruptive in urbanized areas. Therefore, there is strong motivation to look at alternative sustainable options that can be retrofitted into existing urban areas to mitigate these problems.

Water Sensitive Urban Design offers a range of such measures. However, in the context of retrofitting – where space is limited, and one is constrained to designing within the bounds of an already established urban form – how effective such measures (like rainwater tanks and raingardens) are not yet known. The majority of WSUD performance investigations focus on new developed sites or undisturbed conditions; relatively few measurements have assessed how well these controls work in mature urban catchments and to what extent they can mitigate stress on legacy drainage infrastructure. Moreover, climate change predictions for the next several decades point not only to changes in rainfall intensity but also potentially to shifts in the total rainfall regime and greater dry spells. It is not yet clear how much of a transformation current WSUD policies can accommodate or adjust to such future advancements. It leaves one with severe practical questions:

- *Can WSUD features significantly reduce peak flows and pollutant loads under extreme future rainfall scenarios?*

- *To what degree can they delay or reduce the need for expensive infrastructure upgrades in existing urban areas?*

Answering these questions is important for urban water managers and planners as they seek cost-effective strategies to build climate resilience.

By systematically evaluating WSUD implementation in an existing urban catchment, under both present-day and projected future conditions, this study will provide scientific evidence on the magnitude of benefits achievable (in terms of flood mitigation, runoff volume reduction, and water quality improvement). This is directly useful for municipalities considering retrofitting green infrastructure – the results can inform guidelines on design and placement of WSUD measures for maximum benefit. Additionally, assessing performance under future climate and urban growth scenarios will help determine the robustness of WSUD solutions and whether they remain effective as conditions change. Importantly, an analysis of how much implementing rain water tanks and raingardens can extend the capacity of current drainage infrastructure can support infrastructure asset management decisions and potentially save costs by deferring upgrades (O’Halloran et al., 2024). Overall, the research is justified by the pressing need for adaptable, sustainable urban water management strategies in the face of mounting environmental change, and the outcomes will contribute both new knowledge and practical guidance for creating more resilient urban water systems.

1.3 Aim and Objectives

The overarching aim of this research is to investigate the effectiveness of Water Sensitive Urban Design strategies in managing urban stormwater quantity and quality under current and future climate/urbanization scenarios, to improve resilience in existing urban developments.

In essence, the thesis seeks to advance the application of WSUD for mitigating the adverse impacts of climate change and urban growth on urban water systems, thereby aiding in the creation of more sustainable and resilient cities.

To achieve this aim, the research is guided by the following specific objectives:

1. Assess the baseline stormwater collection system performance of the existing urban catchment in its current condition, in terms of runoff quantity (peak flows, runoff volumes, frequency of system overflows) and runoff quality (pollutant concentrations and loads).
2. Examine the impacts of future climate change and urbanization scenarios on stormwater quantity and quality and assess how WSUD strategies perform under these scenarios.
3. Evaluate the effectiveness of WSUD interventions (such as rainwater tanks and rain gardens) in the catchment under current and future condition.
4. Evaluate the economic feasibility and cost-effectiveness of WSUD solutions in the context of the case study.

Through these objectives, the study systematically addresses the aim: starting from diagnosing the current problem, implementing solutions, testing them against future changes, and deriving insights that will help in real-world adoption of WSUD for enhanced urban water sustainability.

1.4 Scope of the Study

The scope of this research is defined by several key parameters to ensure the objectives. The study focuses on a representative, established suburban catchment in west metropolitan Melbourne, Australia. WSUD measures considered in detail are household-scale rainwater tanks (RWTs) and bioretention rain gardens (RGs), with hybrid adoption tested. Performance is assessed via continuous simulation in Personal Computer Storm Water Management Model (PCSWMM) software using historic and projected rainfall, and via design storms for diagnostic peak analysis (Computational Hydraulics International (CHI)). Water-quality assessment centres on TSS (Total Suspended Solids), TN (Total Nitrogen) and TP (Total Phosphorus) loads. Economic appraisal is limited to qualitative life-cycle framing to contextualize potential upgrade deferral.

1.5 Methodological Overview

The research follows a quantitative modelling approach combined with scenario analysis. The **methodology** can be summarized in the following major steps:

- **Data Collection and Baseline Analysis:** Relevant data for the study catchment were collected, including stormwater network data (pipelines and nodes), rainfall records and climate data, flow monitoring data for calibration, and water quality data (e.g., stormwater pollutant concentrations) for baseline loading estimates. An initial analysis of this data established current land use characteristics (e.g., percentage imperviousness) and current system performance. This included identifying known issues in the catchment (locations of frequent flooding or observed pollutant problems) from council reports and stakeholder input.
- **Hydrologic-Hydraulic Modelling with PCSWMM:** A PCSWMM model of the catchment was constructed, integrating the collected data. Sub-catchments were delineated and parameterized (areas, impervious fractions, slopes, etc.), and the stormwater network was input with pipes, channels, and outlet details. The model was calibrated and validated using historical storm events by adjusting parameters to match observed flow peaks and volumes. Once validated, the model served as a baseline representation of the existing developed catchment as base scenario (no WSUD adoption).
- **WSUD Scenario Development:** WSUD measures were incorporated into the model for scenario analysis. RWTs were modelled by adding storage units to sub-catchments draining roof areas, with specified capacities and outflow usage patterns. RGs (bio-retention cells) were modelled, and its parameters were set based on design guidelines and literature values. Multiple WSUD implementation levels were tested. These were used to gauge performance sensitivity to the scale of WSUD uptake.
- **Scenario Simulations:** The model was run for a series of scenarios:
 1. **Baseline (No WSUD, current climate)** – to quantify current system performance
 2. **Current Climate + WSUD** – to assess possible improvements using WSUD under present conditions
 3. **Future Climate (2050, 2070) without WSUD** – to see potential deterioration in performance under current development situation
 4. **Future Climate + WSUD** – to evaluate how well WSUD can mitigate future impacts

5. **Future Urbanization without WSUD** – to examine effects of increasing imperviousness alone due to increase in development density
 6. **Future Urbanization + WSUD**
 7. **Future Urbanization and climate change without WSUD**
 8. **Future Urbanization and climate change + WSUD** – to test WSUD under combined future climate and growth. The climate change scenarios were implemented by adjusting rainfall input data and urbanization scenarios were implemented by increasing impervious surface fractions in sub-catchments.
- **Performance Metrics:** A set of quantitative performance metrics was computed from the model outputs for each scenario. Key quantity metrics included total annual runoff volume, peak discharge in the pipe at the catchment outlet (for various return-period storms), the number of instances of system overflow (surcharged manholes or surface flooding occurrences), and reduction in those metrics relative to the baseline. Quality metrics focused on total annual loads of TSS, TN, and TP leaving the catchment. Event mean concentration data were also used to estimate how WSUD affected pollutant concentrations in runoff.
 - **Life-Cycle Cost Estimation:** Alongside technical performance, a simplified economic evaluation was conducted. Cost estimates for implementing and maintaining the WSUD options in the catchment were developed over a typical project life (25-year life-cycle analysis). By comparing the costs, the study found the most cost-effective scenario. This step provides important context on whether WSUD is not only technically viable but also economically sensible for the studied scenario.
 - **Future recommendation:** Finally, the best scenario of implementing of WSUDs in hydraulic, water quality, cost effectiveness and adaptation capacity under future condition were defined. Key actions are updating city rules, offering incentives, planning for 2070's challenges, monitoring performance, and engaging the public through demos.

The overall methodological workflow is illustrated in Figure 3.1. The details of methodology are discussed in Chapter 3, using a calibrated stormwater model to test “what-if” scenarios on WSUD and environmental effects.

1.6 Thesis Structure

This thesis is organized into eight chapters, following a logical progression from context and theory, through methodology and results, to discussion and conclusions:

- **Chapter 1 – Introduction:** Presents the background of the research, outlines the problem statement and justification, defines the aim and objectives, clarifies the scope, and provides an overview of the methodology and thesis organization.
- **Chapter 2 – Literature Review:** Reviews relevant literature on urban stormwater challenges and the impacts of urbanization and climate change on water quantity and quality. It then surveys Water Sensitive Urban Design approaches and technologies, including specific measures like RWTs and RGs, and other structural/non-structural interventions. Key urban runoff pollutants and water quality standards (e.g., TN, TP, TSS and reuse guidelines) are discussed, followed by an overview of modelling tools used in stormwater quantity and quality management (such as SWMM/PCSWMM and others like MUSIC).
- **Chapter 3 – Methodology:** Describes in detail the research design and methods briefly introduced in Section 1.5. It specifies the study area characteristics, data collection procedures, model development in PCSWMM, calibration and validation process, scenario setups for WSUD implementation and future conditions, and the evaluation criteria for performance.
- **Chapter 4 – Baseline Conditions (Quantity & Quality 2020–2024):** Establishes the baseline hydrologic and water quality conditions of the case study catchment over a recent historical period. This chapter presents results such as rainfall/runoff analysis, current peak flow frequencies, locations of system overflows or flooding, and baseline pollutant load estimations. It identifies the key problem areas and times. The baseline findings motivate the need for interventions.
- **Chapter 5 – WSUD Performance under system hydraulics, water quality and future scenarios**
 - **Hydraulic Analysis of WSUD Scenarios (Quantity):** This part focuses on the quantity and flow rate (hydrologic and hydraulic) performance of various WSUD scenarios under current conditions. It compares hydrographs and flow statistics

between the no-WSUD scenario and WSUD-implemented scenarios. Results include reductions in surface runoff volume, decreases in peak discharge at critical points, and the extent of flood mitigation. System-wide metrics (total outflow volume, number of surcharge events) as well as local effects. Any trade-offs or unexpected outcomes are discussed.

- **Water Quality Analysis of WSUD Scenarios (Quality):** This evaluates the water quality improvements achieved by WSUD scenarios. Using the pollutant load modelling for TSS, TN, TP, this part quantifies the percentage reduction in these pollutant loads compared to the baseline.
- **Climate Change and Urbanization Impacts (Future Scenarios):** Finally, this section extends the analysis to future conditions. It presents the modelled impacts of climate change (for projected time horizons such as 2050 and 2070) on stormwater flows and discusses how **the intensification of projected storm events or changes in rainfall patterns** could worsen flooding and overload the system if no mitigation is applied. Similarly, it examines a scenario of further **urbanization** (increased imperviousness) and quantifies the additional runoff and pollutant loads expected. Then this evaluates how the previously designed WSUD solutions perform under these future scenarios. The synergistic effect of climate change and urban growth together is considered, illustrating the importance of proactive WSUD adoption in city planning. Uncertainty ranges (from climate models) are also discussed, to ensure conclusions are not over-specific to a single prediction.
- **Chapter 6 – Economic Analysis and Feasibility:** This chapter presents the 25-year life cycle costing analysis. It compiles the cost estimates for each WSUD scenario and analyses them in relation to the benefits documented in Chapter 5. The outcome of this chapter is an assessment of which WSUD options make economic sense for implementation in the case study area, providing practical guidance on feasible solutions.
- **Chapter 7 – Conclusion:** This selects the optimal WSUD scenario and outlines a practical implementation roadmap. It then translates results into policy and planning implications for urban water management, acknowledges limitations and assumptions, examines any unexpected outcomes, and situates the work within the literature, clarifying where it confirms or extends prior studies. The chapter closes by articulating the research's

academic and practical contributions, including a transferable framework for retrofit evaluation under combined climate–urbanization pressures.

- **Chapter 8 – Recommendations for Future Research:** The final chapter succinctly concludes the thesis by summarizing the key findings relative to each objective and the overall aim. The chapter provides clear recommendations for stakeholders (e.g., municipal engineers, urban planners, policymakers): this may include recommending specific WSUD measures or design standards for existing neighbourhoods, suggesting updates to stormwater regulations (like including climate resilience criteria), or outlining maintenance and monitoring programs to ensure WSUD longevity. It also identifies opportunities for future research that emerged during the study, such as the need for long-term field studies on WSUD performance under climate extremes, exploration of smart controlled WSUD systems to optimize performance, or research into community engagement strategies to support WSUD uptake. The conclusion reinforces the significance of the research by demonstrating that integrating green infrastructure into urban environments is both beneficial and essential for adapting cities to future climate and growth, it provides an evidence base to inspire action toward more water-sensitive and resilient urban design.

Chapter 2: Literature Review

2.1 Urban Stormwater Challenges

Urban areas face significant stormwater management challenges due to the human impact of development and lack of infrastructure. When a naturally vegetated area is developed, vegetation and pervious soils are replaced by impervious surfaces (roads, rooftops, parking areas), dramatically altering the hydrology of the area. Rainfall that once infiltrated into soils or was evapotranspired is instead converted largely to surface runoff. Consequently, urban catchments tend to produce runoff volumes many times greater than their pre-development counterparts. Studies have shown that runoff from fully impervious surfaces is 4–5 times higher than from pervious grassed surfaces for the same rain event (Walsh et al., 2012). This leads to increased peak flows (faster and higher flood peaks) in urban streams, because stormwater is channelled into drains and waterways with little efficient attenuation. The result is an increase in the likelihood of flash flooding in downtown areas, i.e., a short duration (high intensity) rainfall can exceed drainage capacity and flood streets or overflow sewers.

Another major challenge is the degradation of water quality in urban runoff. As stormwater washes over impervious surfaces, it contains built-up pollutants, such as construction site or eroded area sediment, nutrients from fertilizers or pet waste like nitrogen and phosphorus, heavy metals and hydrocarbons from vehicular movement and atmospheric deposition, pathogens from sewage spill or wildlife, and other pollutants (pesticides, debris, etc.) (Grande et al., 2019). These pollutants are delivered to receiving water bodies (streams, rivers, lakes, or estuaries) at concentrations exceeding natural background, contributing to eutrophication, turbidity, and toxicity for aquatic life (Masoner et al., 2019). The comprehensive reviews of urban stormwater pollutant data in Eastern Australia found that urban runoff typically contains elevated levels of TSS, TP, and TN that have necessitated regulatory load reduction targets to protect downstream ecosystems (Drapper et al., 2022). In addition, the initial runoff during rainfall usually has especially high concentrations of pollutants depositing on surfaces during dry periods and being readily washed off in returning rainfall events (Wei et al., 2013).

Together, hydrologic alteration and pollutant discharge create the “urban stream syndrome,” which is characterized by flashier flows, reduced water quality, channel erosion, and loss of biodiversity. These impacts can occur with only 5 - 10% of impervious cover which makes stormwater an important driving factor of urban watershed degradation (Walsh et al., 2005).

In conclusion, the urban stormwater challenge is multifaceted: cities must deal with flood control, water quality management, and infrastructure maintenance in an environment of limited space and resources. Traditional approaches that emphasize rapidly conveying runoff away have proven inadequate to fully address these issues, as they often simply pass problems downstream and do not mitigate pollution (Burns et al., 2012). This has led to the search for more sustainable, source-control oriented strategies that can complement or enhance conventional infrastructure – a central theme of modern Water Sensitive Urban Design.

2.2 Impacts of Urbanization on Water Quantity and Quality

Urbanization has a significant impact on both the quantity and quality of stormwater runoff. The increase in impervious surfaces related to urban development changes the water cycle processes or hydrologic processes in a direct way, which reduces infiltration and evapotranspiration but increasing surface runoff and leads to higher and quicker runoff volumes as well as lower stream water quality (Paul et al., 2001).

Urbanization often leads to the construction of engineered drainage systems, such as curbs, pipes, and channels, which rapidly collect and convey stormwater to streams. This efficient drainage network reduces opportunities for natural water infiltration and attenuation, resulting in higher volumes and increased frequency of flows that can destabilize stream channels and disrupt sediment transport (MacKenzie et al., 2022).

On the water quality side, urbanization introduces a variety of pollutant sources. Common pollutants and their urban sources include:

- **Sediments:** Sediment pollution in urban runoff largely originates from construction sites, exposed soils, and eroding streambanks, with fine suspended particles such as silt and clay being the primary contributors. These particles increase turbidity, act as carriers for

nutrients and heavy metals, and can smother benthic habitats, reducing ecological health (Novotny, 1994, Wang et al., 2017c).

- **Nutrients (Nitrogen and Phosphorus):** Nitrogen and phosphorus in urban runoff mainly come from fertilizers, pet waste, septic systems, and atmospheric deposition. These nutrients promote excessive algal growth and eutrophication in urban streams, especially in slow-moving waters, causing oxygen depletion and ecological harm (Krimsky et al., 2021).
- **Metals:** Vehicles are a major source (copper from brake pad wear, zinc from tire wear and galvanized structures, lead from old fuel additives or paint, cadmium, etc.) (Novotny, 1994). Metals are also derived from roofing materials, industrial sites and atmospheric fallout. At increased levels, these contaminants can be toxic to aquatic organisms, and they have a potential to build up in sediments (Soltaninia et al., 2022).
- **Hydrocarbons (oil, grease, PAHs):** Hydrocarbons in urban runoff originate from oil and fuel drips on roads and parking lots, vehicle emissions, and tire wear. These hydrocarbons, including toxic and persistent polycyclic aromatic hydrocarbons (PAHs) from vehicle exhaust and asphalt, are mostly bound to particulate matter in runoff and pose environmental risks (Liu et al., 2013, Peter et al., 2018).
- **Pathogens:** Bacteria (e.g., *E. coli*) and other pathogens in urban runoff come from pet waste, sewage leaks, and faulty sanitary systems. Storm events cause spikes in bacteria like *E. coli*, increasing health risks and often leading to beach closures (Ahmed et al., 2019).
- **Trash and Debris:** Urban runoff transports debris like plastic bags and bottles into waterways, harming wildlife and aesthetics. Cities use gross pollutant traps (GPTs and storm drain screens to capture pollutants over 5 mm, improving water quality and protecting ecosystems (Madhani and Brown, 2015, Allison et al., 1997).

Moreover, aging infrastructure presents a major challenge for managing stormwater. Designed decades ago for small storms, outdated drainage systems struggle with increased runoff from rapid urban growth, vegetation loss, and intensified rainfall (Rentachintala et al., 2022, Fengxiang et al., 2018). These systems require costly retrofits to handle large storms. Overflows cause urban flooding, and in cities with combined sewers, heavy rain triggers untreated sewage discharge (Petrie and Research, 2021).

In summary, urbanization significantly changes watershed hydrology by increasing runoff volumes and peak flows while reducing natural water retention. It also introduces a complex mix of pollutants into runoff, demanding comprehensive stormwater management. Traditional "end-of-pipe" approaches have had limited success, leading to adoption of WSUD strategies to minimize impervious surface connectivity, enhance infiltration, and treat runoff at its source by redesigning urban landscapes to mitigate hydrologic and water quality impacts. This integrated approach is critical for sustainable urban planning and watershed health (Shaikh et al., 2023).

2.3 Impacts of Climate Change on Stormwater Collection Systems

Climate change is expected to greatly affect urban stormwater collection systems. It will change precipitation patterns, sea levels, and how often extreme weather events occur. The most direct impact comes from changes in rainfall intensity and frequency (Wang et al., 2017b). Warming global temperatures are intensifying the hydrologic cycle, leading to more frequent and severe heavy rainfall events, even in regions where annual rainfall might decrease. The Intergovernmental Panel on Climate Change (IPCC) reports with high confidence that human-caused global warming is increasing the frequency and intensity of extreme precipitation events worldwide, with rare storms (e.g., 1-in-100 year) projected to become even more intense in the future (Bashmakov et al., 2022). Therefore, urban drainage systems designed using historical rainfall statistics are increasingly at risk of being overwhelmed, resulting in more frequent flooding unless adaptive strategies are implemented (Li et al., 2024b).

Studies in various cities have projected substantial increases in peak runoff due to climate change. Warming air holds about 7% more moisture per 1°C rise (Clausius-Clapeyron relation), resulting in more intense rainfall bursts. Observations confirm increasing frequency and intensity of short, convective storms in recent decades, leading to high urban flood risks even without land use changes. Drainage systems designed based on past rainfall records will face frequent overwhelming events, turning what was previously a 5-year flood into a 2-year or annual event. Modelling studies project urban flood volumes could increase by over 37% from the 2020s to the 2090s, with critical pressure levels surpassed at over 97% of flood-prone locations by the 2030s, especially in low-lying, highly urbanized areas (Li et al., 2024b, Nodine et al., 2024).

Climate change is altering total precipitation and seasonal patterns, with some regions experiencing wetter winters and drier summers or prolonged droughts interrupted by heavy rainfall than that of the past decades. Extended dry periods allow more pollutants to accumulate on surfaces through dry deposition of air pollutants, leading to more severe pollutant loading of first-flush runoff during subsequent intense rains, which can severely impact water quality (Trenberth, 2011). Conversely, more frequent heavy rains result in less pollutant build-up but cause chronic high flows that affect downstream waterways. These shifts pose significant challenges for urban drainage systems and water quality management, requiring adaptive responses to changing hydrologic regimes and pollutant dynamics (Yang et al., 2024).

Additionally, sea level rise driven by climate change complicates drainage in coastal cities by reducing outfall capacities due to tidal backup and raising tailwater levels in combined sewer systems, leading to more frequent combined sewer overflows. In flat coastal urban areas, impaired gravity drainage in low-lying zones necessitates pumping or other interventions to prevent flooding during high tides or storm surges (Bosselle et al., 2022). In many cities, these issues strain existing stormwater infrastructure and increase maintenance demands.

In short, climate change is forcing cities to rethink how to manage water systems. Without action, urban areas will face worsening floods and environmental decline. However, with proactive adaptation, especially by adoption of WSUD and other nature-based solutions, cities can build resilience and cope better with the uncertainties ahead.

2.4 Water Sensitive Urban Design (WSUD) Approaches

WSUD is an interdisciplinary approach that aims to reduce the negative impacts of urban development on the water cycle through the amalgamation of stormwater, wastewater, and water supply management into urban design (Staff and Committee, 1999). The goal of WSUD is to closely imitate natural water processes in the built environment. This approach helps reduce runoff volumes, lessen peak flows, improve water quality, and boost urban amenities and biodiversity (Leonard et al., 2019, Brown et al., 2008, Gurung et al., 2025). WSUD includes a variety of strategies and technologies, divided into structural measures (such as physical infrastructure and landscape features) and non-structural measures (including policies, practices, and behavioural changes).

WSUD and related approaches like Best Management Practices (BMPs), Sustainable Urban Drainage Systems (SUDS), Low-Impact Development, Green Infrastructure (GI), Nature-Based Solutions (NBS), and Stormwater Control Measures (SCM) promote integrated, eco-conscious stormwater management. WSUD, developed in Australia in the 1990s, uniquely integrates the entire urban water cycle into city planning to reduce stormwater pollution and enhance climate resilience. BMPs focus on water quality, while SUDS and LID (UK/North America) prioritize mitigating extreme rainfall and restoring natural water cycles (Whelans et al., 1994, Fletcher et al., 2015), and GI and NBS emphasize green spaces for environmental quality. Despite regional differences, these approaches collectively foster sustainable, resilient urban environments by reconnecting water management with natural systems (Rodríguez-Rojas et al., 2022).

WSUD strategies can be implemented at multiple scales, including the site-level (e.g., a property installing a RG), the neighbourhood-level (e.g., a subdivision served by a constructed wetland), and the city-level (e.g., integrating green corridors for stormwater conveyance and treatment) (Fletcher et al., 2015, Sharma et al., 2016). Common objectives of WSUD measures include reducing impervious connectivity to allow local infiltration, harvesting stormwater to both reduce runoff and potable water demand, biologically treating runoff through soil and plant processes to remove pollutants, and providing temporary storage to delay and desynchronize flows (Wong et al., 2009).

Key types of WSUD measures include rainwater tank, rain garden and other structural and non-Structural measures

2.4.1 Rainwater Tanks

RWTs are storage systems that capture runoff from roofs during precipitation events for future use. They are one of the more straightforward and popularly implemented WSUD strategies, especially at the household scale. By rooftop runoff capture, RWTs reduce stormwater that directly enters the drainage system and provide an alternative source of water for non-potability applications such as garden irrigation, flushing toilets, washing, or even potable supply with treatment. This double benefit of runoff mitigation and supply supplementation makes RWTs attractive in water-sensitive design (Gould, 1999).

Hydrologically, RWTs slow down primarily stormwater flows by storing and retaining a portion of rainfall and thus reducing the amount of runoff that enters the drainage system. The effectiveness of a RWT in mitigating peak flows is greatly dependent on its capacity in relation to the connected roof area and the drawdown between events. Small RWTs can capture runoff for light to moderate storms but can fill quickly in heavy storms and overflow, offering minimal benefit for peak flow mitigation in intense events. Large RWTs, or those that are actively controlled to maintain low water levels, possess great spare storage capacity to capture more runoff, including storing runoff partially during high storms, thereby reducing peak outflows (Berndtsson, 2010). Further, studies have shown that widespread adoption of rainwater harvesting across households can reduce overall runoff volume significantly. For example, Abi Aad et al. (2010) set that the use of rain barrels on residential house rooftops had a quantifiable decrease in combined sewer overflow frequency and volume. Similarly, Yazdanfar and Sharma (2015) observed that rainwater harvesting is a critical Low Impact Development (LID) (Shoemaker et al.) technique in offsetting the impacts of climate change on urban drainage infrastructure through minimizing effective imperviousness and providing a valuable water supply for dry seasons.

RWTs can be installed above or below ground, often with first-flush diverters to improve water quality. Their primary benefit lies in reducing runoff volumes, since roof runoff is generally less polluted than road runoff (Rahman et al., 2012).

In general, RWTs represent a viable, decentralized WSUD strategy providing storage to reduce runoff relief and an alternative source of water with low maintenance cost. RWTs are commonly required by planning laws in Australia and elsewhere as part of WSUD schemes. Research indicates that RWTs of several thousand liters of capacity have the potential to reduce household runoff by around 20–50% per year, depending on rainfall, connected roof area and household demand. Realizing this potential, however, depends heavily on appropriate tank sizing and design relative to local climatic conditions (Di Chiano et al., 2025).

2.4.2 Rain Gardens (Bio-retention Cells)

Rain gardens, bio-retention cells or biofiltration basins, are shallow landscaped depressions that use engineered soil media and vegetation to infiltrate and treat stormwater runoff. RGs are typically designed to receive runoff from impervious surfaces, which ponds on the surface

temporarily and then filters through a filter media where pollutants are removed by filtration, adsorption, and plant uptake (Wang et al., 2017a, Takaijudin et al., 2016). An under-drain is often included at the bottom of the media to collect the filtered water and convey it to the drainage system, although in some designs (when underlying soils are permeable) RGs are used for full infiltration to groundwater (Jiang et al., 2017).

RGs are among the most overt WSUD measures as they are among the only measures to address both flow and quality: reducing peak volumes and flows by holding water (some is evaporated or used by plants, some percolates, and the remainder is released more slowly through the underdrain), and improving water quality by filtering sediment, hydrocarbons, and nutrients in soil and mulch layers. Literature reports high pollutant removal efficiencies, typically >80% for TSS, 50–80% for TP, and 30–70% for TN, and the nitrogen removal augment can be achieved through the addition of an anoxic zone for denitrification (Wang et al., 2017a, Patrick et al., 2025).

A typical RG comprises a planting soil mix (sand, loam, and some organic matter) that is carefully chosen to have sufficient permeability (to drain within 24-48 hr) yet support plant growth. The vegetation is usually native or water-tolerant ornamental plants (grasses, shrubs, flowers) that can handle periodic inundation and long dry spells. These plants assist pollutant uptake (especially nutrients) and enhance soil structure with their roots. Beneath the media, a gravel layer with perforated pipe often ensures proper drainage. During storms, water pools in the RG (usually for a design ponding depth of 100–300 mm) and then infiltrates. Any overflow beyond the design storage is routed to conventional drains often via an overflow weir or stand-pipe at the surface (Dutta et al., 2021, Morash et al., 2019, Wang et al., 2024).

Bio-retention cells are easy retrofits within parking lots, streetscapes, and parklands to capture street runoff, to alleviate peak volumes and flows, slow down runoff, and improve downstream/CSO conditions for flash-flood mitigation (Lucas and Sample, 2015). Maintenance is critical. Routine weeding/pruning, inlet sediment clean-outs, and occasional media rejuvenation are required to prevent clogging. Well maintained RGs also yield co-benefits, such as more verdant streetscapes, urban cooling (via evapotranspiration), and habitat.

In summary, RGs (bioretention) are versatile, retrofit-friendly WSUD assets, which contribute to the creation of water sensitive places and resilient cities.

2.4.3 Other Structural and Non-Structural Measures

Beyond RWTs and RGs, WSUD incorporates a wide array of structural measures, each well-suited to particular contexts and scales. Some notable structural WSUD measures include:

- **Permeable Pavements:** Permeable pavements, including porous asphalt, pervious concrete, and permeable interlocking concrete pavers, are designed to be structural, load-bearing surfaces that allow rainfall to infiltrate through their voids to an underlying aggregate base layer. This base layer provides temporary storage, promotes infiltration into native soils, and filters sediments and nutrients at the source. Permeable pavements best manage small to medium frequency stormwater events and are used in car parks, driveways, pedestrian areas, and low-traffic streets. They are, however, at risk of losing permeability due to clogging from fine sediments and organic materials. Long-term hydraulic performance will require maintenance, including vacuum sweeping and surface cleaning (Selbig et al., 2019, Hoban, 2019, Sharma et al., 2018).
- **Green Roofs and Living Walls:** Green roofs and living walls can turn impermeable roofs and facades into vegetated systems. These developments can extend from shallow, retrofitting “extensive” roofs to deeper, amenity-focused “intensive” installations. Research shows that these systems retain rainfall roughly 50 to 100 percent during small storms, which reduce peak runoff rate significantly. However, for large storms, their performance is compromised. These systems provide insulation and mitigate urban heat islands by lowering roof level temperature up to 26 °C, with an average daytime reduction of 12.8°C (Beecham et al., 2019). Although the growing media, fertilizers, and irrigation affect potential improvements in water quality, improvements can be lost without careful structural design and maintenance, including weed management. For a building with limited surrounding space, green roofs could be essential measures (Wang et al., 2023, Beecham et al., 2019).
- **Infiltration Trenches and Soakaways:** These are subsurface, geotextile-lined, stone-filled pits that store and infiltrate runoff into permeable soils (wiki.sustainabletechnologies.ca); they attenuate flow peaks but need pretreatment and clear vertical separation from the groundwater table (watersensitivesa.com). Modelling found that soakaway retrofits connected to 65% of impervious areas cut combined-sewer overflow volumes by 68%, while even 8% coverage reduced them by 24%. These findings underscore the importance of

considering groundwater conditions and sewers coupling in design (Locatelli et al., 2015, Myers and Pezzaniti, 2019).

- **Vegetated Swales and Buffer Strips:** Shallow vegetated runoff conveyance and filter strips that slow flow, promote infiltration/settling, and pre-treat stormwater. Appropriate for small events and roadside locations; provide amenity but only for relatively small flows. They work best on moderate slopes (about 0.5–4 %), with underdrains needed on flatter grades and check dams or rock linings on steeper grades to help reduce bogginess or avoid scour (Ekka et al., 2021, Hoban, 2019).
- **Retention Ponds and Constructed Wetlands:** Permanent-water systems that remove TSS, TP, TN, and metals by settling and biological processes and reduce flows. Space-intensive but provide habitat/amenity, requiring mosquito-aware design and periodic dredging (≈10–20 years) (Mangangka et al., 2016).
- **Detention and Retention Basins:** They control flooding and peak flow through storage. Detention basins hold runoff temporarily and discharge it at managed rates to dampen peak flow, whereas retention systems store or reuse water for good, not discharging it to downstream drains. Both aid in quantity control and treatment, and are in combination with smaller LID measures for full management (Xu et al., 2020, Myers and Pezzaniti, 2019).

To facilitate comparison, Table 2.1 summarizes the core elements of these approaches.

Table 2.1. Summary of other Water Sensitive Urban Design (WSUD) Approaches and Their Characteristics

| Approach | Design Features | Benefits | Performance | Maintenance |
|----------------------------|---|---|--|---|
| Permeable Pavements | Porous asphalt, pervious concrete, or permeable pavers over an aggregate base layer for infiltration. | Minimizes runoff, filters sediments/nutrients; suitable for parking lots and low-traffic areas. | Effective for small storms (up to 90% runoff reduction in some cases); supports WSUD's pollution mitigation goals. | Vacuum sweeping 2-4 times/year to prevent clogging; inspect reservoir for sediment buildup (Hoban, 2019, Selbig et al., 2019, Sharma et al., 2018, Kuruppu and Rahman, 2023). |

| | | | | |
|---|---|---|--|--|
| Green Roofs and Living Walls | Layered vegetated systems with growing media, drainage, and waterproofing on rooftops/ facades. | Retains rainfall, reduces peak flows via evapotranspiration; provides insulation, UHI mitigation, and biodiversity. | 50–100% annual retention (climate-dependent); moderate water quality benefits, ideal for dense urban settings. | Irrigation during establishment, annual vegetation trimming, and drainage checks (Wang et al., 2023, Beecham et al., 2019, Alim et al., 2023). |
| Infiltration Trenches and Soakaways | Stone-filled trenches or pits with geotextile lining for subsurface storage and percolation. | Recharges groundwater, attenuates peaks; reduces downstream flooding. | High infiltration rates in permeable soils (up to 100% volume capture for small events); requires pre-treatment. | Sediment removal every 1-2 years, monitor for clogging; avoid in high groundwater areas (Locatelli et al., 2015, Myers and Pezzaniti, 2019). |
| Vegetated Swales and Buffer Strips | Shallow, grass-lined channels or vegetated strips along flow paths. | Slows flow, promotes settling/infiltration; enhances landscape amenity and pre-treats runoff. | Effective for small flows (30-60% pollutant removal); limited for large events, suitable for roadsides. | Mowing 2-3 times/year, sediment clearance, and replanting as needed (Ekka et al., 2021, Hoban, 2019). |
| Retention Ponds and Constructed Wetlands | Engineered basins with permanent water and aquatic vegetation for biological treatment. | Removes TSS, nutrients, metals via settling/uptake; creates habitat, recreation spaces. | 60-90% pollutant reduction; flow attenuation; space-intensive but multi-functional. | Dredging every 10–20 years, mosquito control, vegetation management (Mangangka et al., 2016, Sharma et al., 2023). |
| Detention and Retention Basins | Dry/wet basins for temporary/permanent storage with controlled outlets. | Shaves peaks, treats via settling; combinable with other LID for holistic control. | Peak reduction up to 70%; improved quality in wet variants; adaptable to site constraints. | Sediment removal annually, outlet inspections, vegetation control in wet basins (Xu et al., 2020, Myers and Pezzaniti, 2019). |

In addition to structural intervention, WSUD philosophy also involves non-structural measures that are just equally important. These are such steps as:

- **Land Use Planning Controls:** Requiring new development to preserve natural drainage characteristics (e.g., not building on floodplains, maintaining riparian buffers) and limit impervious surface cover (Mary-Lauy  et al., 2023). Zoning and planning regulations can encourage clustered development with room for greater infiltration or require a minimum portion of a lot as pervious (through green space or permeable pavement).
- **Building and Site Design Guidelines:** Inserting stormwater targets into building codes, such as requiring rainwater tanks or green roofs on new buildings, setting a portion of the parking lots permeable, or directing roof downpipes to gardens instead of through to drains (Ling et al., 2023).
- **Prevention of Pollution Practices:** Practices for reducing pollutants at their source, such as street sweeping initiatives to remove sediments and garbage before they enter drains, enforcing erosion and sediment control on construction sites, correct disposal of motor oil and chemicals to prevent illegal dumping, and public education on reducing use of fertilizer on lawns (Polukarova et al., 2020). These practices can result in an excellent reduction in the pollutant loads that need to be addressed.
- **Maintenance and Asset Management:** A regular maintenance regime for all stormwater infrastructure (traditional and WSUD) ensures they perform their function. Municipal programs must adapt to the inclusion of new WSUD infrastructure, educating crews to maintain RGs (weeding, replacing mulch), permeable pavement (vacuuming), etc. Proper maintenance extends the lifespan and functionality of WSUD measures, preventing issues like clogging or loss of vegetation (Sharma et al., 2015, Khalaji et al., 2024).
- **Incentives and Community Involvement:** Since WSUD might involve undertaking activities on private property (e.g., constructing a RG in one's front yard or a rain barrel), engaging the community and providing incentives (recognition, rewards) supports earlier take-up. Public education campaigns highlight the co-benefits of WSUD. Case studies reported by Leonard et al. (2019) and Khalaji et al. (2024) describe real examples where

cleaner neighbourhoods, cleaner neighbourhoods reduced urban heat, improved air quality, enhanced aesthetics, and increased community support were achieved. These studies also document initiatives such as stormwater fee credits or grants for property owners who adopt approved WSUD practices.

- 2.5 Modelling Tools for Urban Stormwater Management

Stormwater in urban environments, especially with WSUD and changing climate or urbanization conditions, is very reliant on computer models. The models simulate hydrologic and hydraulic processes, predict flood hazards, and estimate water quality under various conditions (Fletcher et al., 2015). There are diverse models from simple estimations to advanced dynamic simulations, and the following section covers important tools most relevant to WSUD.

2.5.1 Overview of PCSWMM (and EPA SWMM)

Storm Water Management Model (SWMM) of US EPA is one of the most widely utilized computer models for study of urban runoff amount, quality, and hydraulics at millions of points worldwide. The U.S. EPA designed SWMM simulates the influence of rainfall–runoff procedures, infiltration, pollutant load buildup and washoff, on hydraulic pipe network, channel, and storage system routing (Rossman and Huber, 2015). Since the release of SWMM 5, one of the major advancements has been the inclusion of the Low Impact Development (Shoemaker et al.) module to enable explicit modelling of WSUD practices such as RGs, permeable pavements, bioretention cells, green roofs, and rain barrels. These LID controls are parameterized based on physical surface, soil, and drainage layer characteristics and therefore the model is suitable for stormwater performance and water quality benefit assessment under different urban development scenarios (Abi Aad et al., 2010, Rossman, 2010). Different studies have demonstrated that it is useful for establishing the effectiveness of WSUD measures in managing combined sewer overflows as well as mitigating urban flooding (Lucas and Sample, 2015).

PCSWMM, developed by Computational Hydraulics International, has a commercial graphical user interface to the SWMM engine. With equal computational results, it supports usability with the integration of GIS, scenario management, optimization capabilities, and more advanced visualization features such as flood maps and statistical trend analysis (Rossman, 2010).

Practitioners and agencies who need to analyse many planning or regulatory scenarios at an efficient level find it particularly useful.

Due to its flexibility, global applicability, and calibration in various situations, SWMM (and PCSWMM) is typically recommended for WSUD and compliance assessment studies. However, precise input data and close calibration, particularly for water quality parameters, are required for the model, and some processes (e.g., infiltration system clogging, canopy interception) are estimated (Elliott et al., 2007).

2.5.2 Other Modelling Tools (e.g., MUSIC, MIKE URBAN, InfoWorks)

More than SWMM/PCSWMM, there are different urban stormwater modelling software tools. Each tool excels in a particular aspect of stormwater modelling:

- **MUSIC (Model for Urban Stormwater Improvement Conceptualisation):** The Model for Urban Stormwater Improvement Conceptualisation (MUSIC), developed by eWater in Australia, is frequently used to conceptual-scale WSUD planning (EWater, 2013b, Rashetnia et al., 2022). MUSIC facilitates the creation of treatment-train diagrams that include treatment train components such as wetlands, swales, and bioretention systems. Using stochastic rainfall generation and simplified algorithms, it simulates mean annual pollutant loads and treatment performance. Its applicability and use in Australian planning practice are making MUSIC very relevant for application by local governments, where there is usually a requirement to demonstrate compliance with stormwater quality outcomes (Lloyd et al., 2002). Nevertheless, since it is a water-quality-based model, MUSIC does not simulate detailed hydraulics, pipe networks, pipe backwatering, or dynamic flooding and is therefore only appropriate for conceptual WSUD design and performance assessment (Lloyd et al., 2002).
- **InfoWorks ICM (Integrated Catchment Model):** This offers interactive 1D/2D sewer, river system, and stormwater modelling. Water quality support, flood forecast, and real-time capability are offered. With advanced and comprehensive functionality, it is utilized mostly on large municipal projects but is costly (Wei et al., 2024).
- **HEC-HMS and HEC-RAS:** HEC-HMS models rainfall-runoff hydrology, and HEC-RAS calculates 2D flood hydraulics. Both programs are frequently used for flood determination

purposes but lack native WSUD/LID capability and cannot natively accommodate stormwater quality assessments (Brunner, 2021).

- **Mike Urban / Mike SHE:** MIKE URBAN models sewerage and drainage networks; It connects surface, ground and river hydrology for integrated catchment studies. They are advanced software tools that are used for advanced modelling activities but are generally employed by huge agencies (Lameche et al., 2023).

A new area of research is blending optimization and machine learning with current models to detect best practices for WSUD or to speed up prediction of outcomes. To counter computational issues, scientists use meta-models as substitutes for sophisticated models in order to assess quickly many different situations, such as calculating climate sensitivity. Elliott et al. (2007) noted that one model cannot meet all planning and design needs; instead, simple tools such as MUSIC are best suited for initial screening purposes and detailed design studies require sophisticated simulators such as SWMM. Yazdanfar and Sharma (2015) stated that dynamic modelling plays a crucial role in building adaptation measures through impacts from climate change and urbanization and highlighted capturing interactions between systems. The general trend in research indicates that integrated modelling is important, which links hydrological models and water quality models to better assess the ecological impacts from stormwater management interventions.

2.6 Summary and Identified Gaps

In this review, the challenges posed by urban stormwater and the approaches under the Water Sensitive Urban Design paradigm are explored to address them. Urban stormwater effects stem from increased impervious surfaces that escalate runoff volumes and flashiness, promote channel erosion and flooding, and mobilise sediments, nutrients, and metals which are the defined characteristics of the "urban stream syndrome." Superimposed climatic change is escalating rainfall extremes, invalidating designs set at historical conditions and increasing flood and water-quality risks. Accordingly, WSUD utilises decentralised interventions such as RWTs, bioretention, permeable pavements, green roofs, swales, and wetlands to partly reconnect natural hydrologic paths, dampen peaks, and lower pollutant loads. Several modelling studies (e.g., SWMM/PCSWMM, MUSIC) and evidence from site- to catchment-scale documented large TSS reductions (frequently ~80%), with consequential peak-flow moderation and additional co-benefits such as urban cooling and biodiversity enrichment.

In spite of such advances, material knowledge and practice gaps persist. Long-term, whole-of-catchment monitoring by empirical, rather than model-driven, measurement is lacking, hindering verification of modelled benefits and insights into durability, maintenance requirements, and leading to decades-long decay in performance. There is slender evidence on best WSUD retrofitting approaches in highly built-out, space-restricted catchments with legacy constraints, and on how designs sized to historical storms (e.g., requiring new design storms, larger storages, or WSUD–grey hybrids) fare under changing climates. Policy and governance gaps include uneven mandating, restricted integration of flow/ecological goals with pollutant targets, and difficulty in achieving community acceptability, which also hinder mainstreaming, highlighting interdisciplinary planning, asset-management procedures, and multi-criteria decision frameworks.

This thesis is structured to fill these holes by assessing WSUD retrofits in an existing urban catchment under existing and future climate conditions through the use of performance modelling to estimate hydrologic and water-quality results and linking these with comparative life-cycle economic assessment (including avoided costs of grey infrastructure). The research will yield decision-ready, catchment-scale evidence on retrofit effectiveness, climatically robust size and configuration, and maintenance consequences, and will provide practical advice for placing WSUD on policy and planning agendas. Through this process, it will promote the transition from theoretical promise to practical, resilient urban water management appropriate to both pressures from climate change and densification of cities.

Chapter 3: Methodology

3.1. Research Methodology Overview

This thesis employs an integrated hydrological-hydraulic modelling and life-cycle cost approach to investigate the effectiveness of WSUD adoption in an established urban catchment. The analysis utilizes PCSWMM modelling to simulate current conditions (from 2020 to 2024) as well as future scenarios (the years 2050 and 2070). The effectiveness of WSUD in this study is focused on assessing reductions measures of TN, TP, TSS, peak flow reduction in the stormwater drainage system and total runoff volume under climate change and urban development situations.

3.2. Research Framework

The research follows a structured, sequenced approach that includes eight key steps:

- I. Data collection and characterization: Collect surface water network geometry, land use configuration, soil parameters, and high-resolution rainfall data to set up baseline hydrological conditions.
- II. Model Setup and Parameterisation: Develop the PCSWMM (Personal Computer Stormwater Management Model), including sub-catchment delineation, infiltration parameters configuration, hydraulic routing adjustment, and continuous simulation option selection.
- III. Calibration and Validation: Parameter adjustment by using observed outflow data, and independent validation to ensure model reliability and predictability.
- IV. WSUD Scenario Formulation: Definition of five implementation scenarios representing different adoption levels and WSUD combinations, including RWTs, RGs, and combined systems.
- V. Baseline and Future Simulations: Application of the calibrated model for 2020–2024, using observed rainfall, and projected for years 2050 and 2070 to test WSUD performance under intensified climate conditions and high imperviousness based on the SSP2-4.5 long-term scenario.
- VI. Performance Evaluation: Quantification of hydraulic performance (runoff reduction, peak flow attenuation, overflow mitigation), water quality improvements (pollutant load reduction), in addition to cost metrics.

- VII. Life-Cycle Cost Analysis: Estimation of capital costs, maintenance costs, and equipment replacement over a 25-year analysis period to determine long-term cost-effectiveness.
- VIII. Comparative Evaluation and Selection: Integration of hydraulic, water-quality, and economic performance metrics to determine the most efficient and robust configuration of WSUD retrofits.

A consolidated overview of these steps is shown in the flow diagram in Figure 3.1, while detailed descriptions of the steps are provided in the subsequent sections.

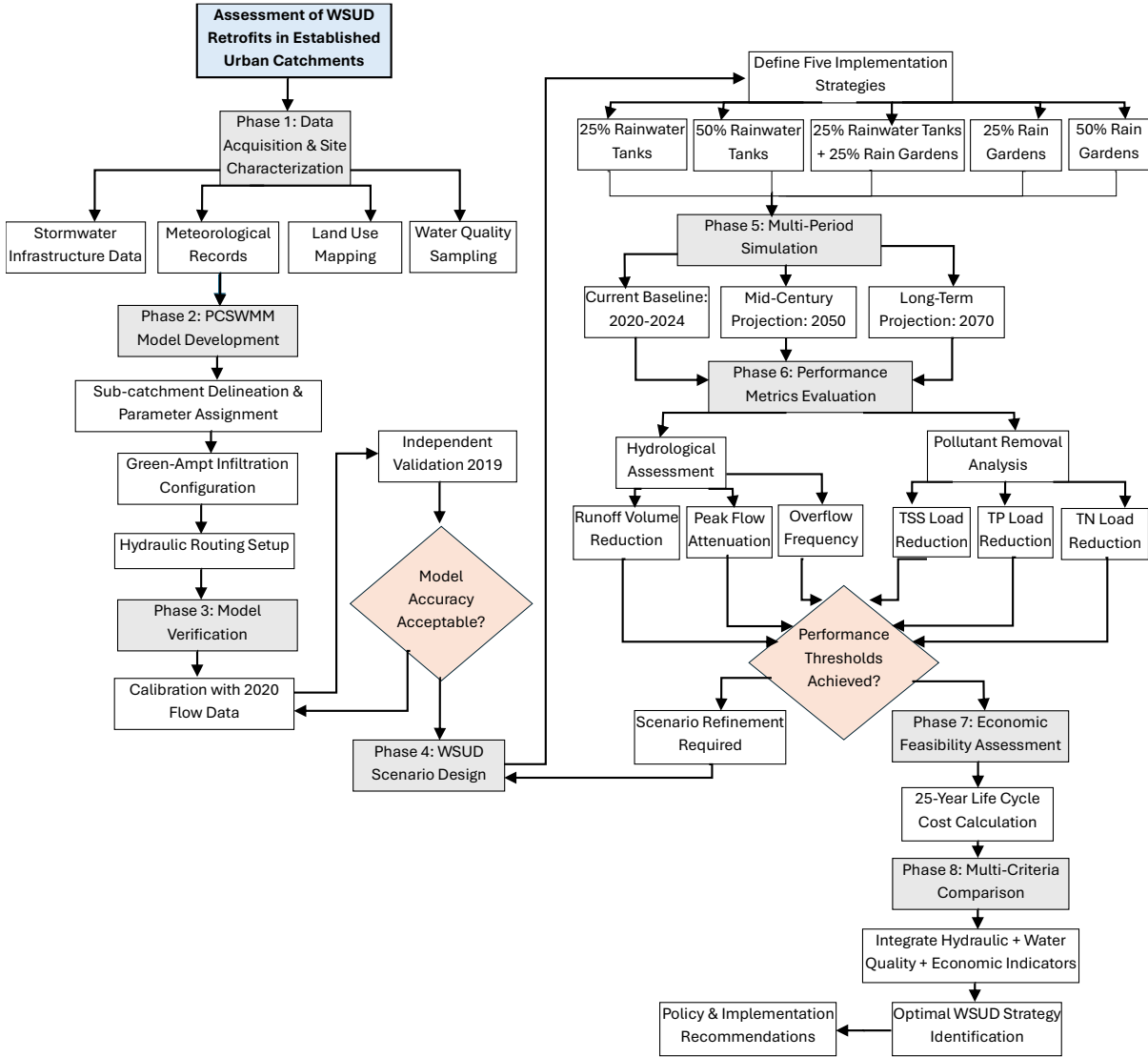


Figure 3.1 Flow diagram of the methodology

3.3. Study Area Description

The study is conducted in Dowling Avenue, Hoppers Crossing, a residential suburb in West Melbourne, Victoria, Australia. As shown in Figure 3.2, the catchment area spans approximately 170 hectares and includes about 3,000 residential houses, commercial zones, and green spaces. The area is serviced by a complex stormwater network with 29,619.8 meters of connected pipes, with maximum pipe widths of 1.8 meters (summary of some conduits are represented in Appendix 1).

This established suburban environment provides realistic constraints for assessing the effectiveness of WSUD retrofitting, including existing infrastructure, property boundaries and land use patterns that are common in many Australian suburban areas facing the combined pressures of aging drainage systems, intensifying rainfall and ongoing urban density.

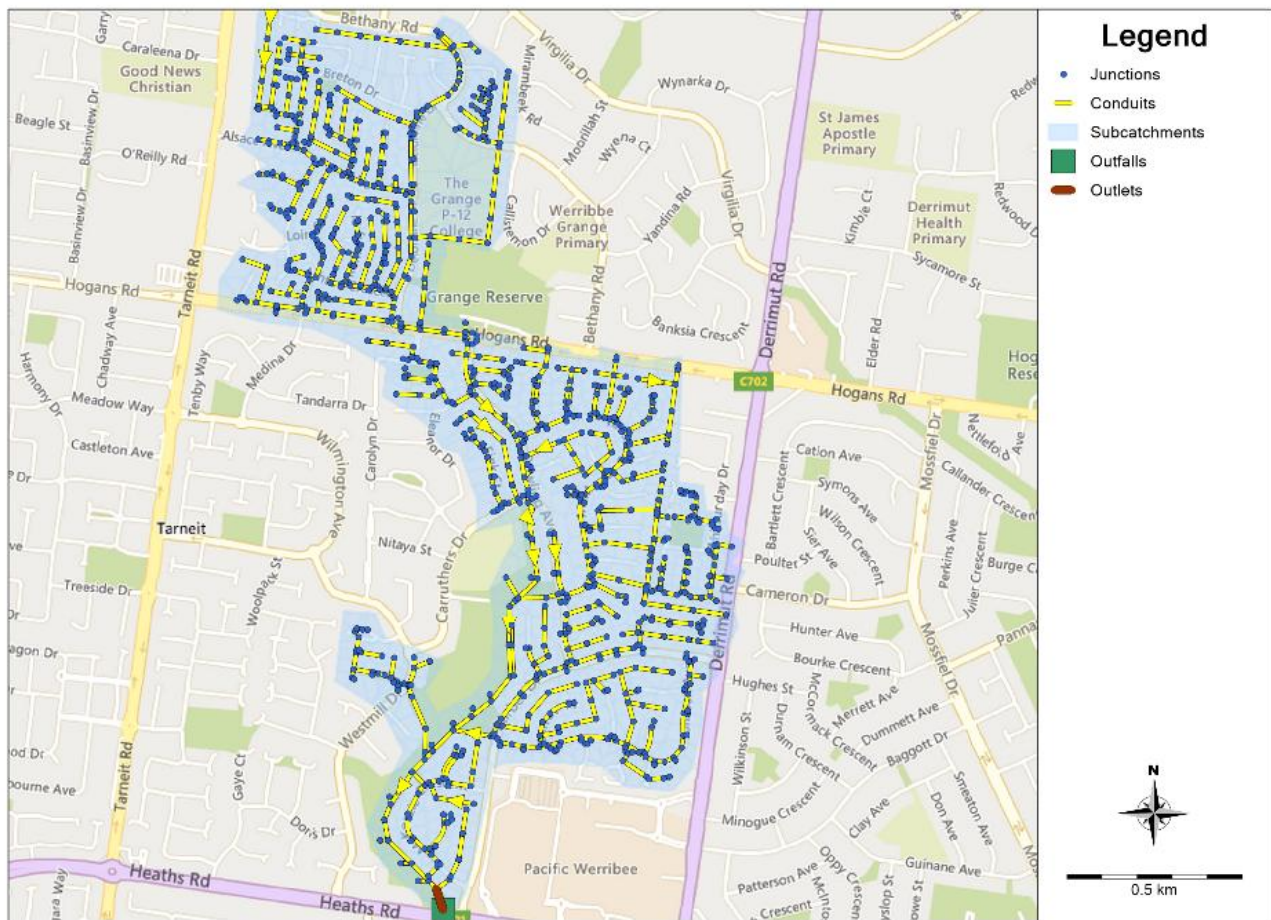


Figure 3.2. Case study area map

3.4 Data Collection and Sources

The success of the PCSWMM modelling process depends heavily on the accurate and thorough collection of relevant data, which are essential for model calibration. The following datasets were gathered from reliable sources to inform and support model development, calibration, and validation.

3.4.1. Stormwater Network Data

The foundational layer of the hydraulic model, the stormwater infrastructure network was obtained from Wyndham City Council, Victoria, Australia. This dataset included detailed information on all drainage pipes, such as their physical attributes (length, slope, diameter), connectivity nodes, and the overall layout of the drainage network within the catchment area. These data were provided in GIS shapefile format and had been subjected to quality assurance review through field visits to verify physical accuracy. In the current study, field inspections were undertaken to identify the discrepancies between the GIS database and actual site conditions (Figure 3.3). Discrepancies identified from the field inspection, including missing pipes and manholes, as well as connection errors, were corrected prior to model development to ensure spatial accuracy.



Figure 3.3. Examples of manholes inspected during field observations.

3.4.2. Rainfall and Evaporation Data

Rainfall and evaporation data from January 2020 to December 2024 for the same period, were collected from the Bureau of Meteorology (BOM), Australia. For rainfall, two datasets were obtained: 6-minute interval rainfall data and daily rainfall data. These high-resolution data are essential for the short-duration storm event simulation and for evaluating the system's response to peak intensities.

There were 710 days identified as precipitation over the 5 years period, when precipitation was higher than the 0.2 mm threshold corresponds to BOM's standard definition of a rainy day (BOM, 2007). During this time, 67 days had more than 10 mm of rainfall, thus indicating the potential for moderate to high runoff events. The annual total rainfall ranged from a minimum of 418.1 mm to a maximum of 704.6 mm, as illustrated in Figure 3.4. The temporal distribution of precipitation during the study period is presented in Figure 3.5 that shows the detailed time series from 2020 to 2024, thus unveiling seasonal patterns and individual storm events that influence the dynamics of this urban water system.

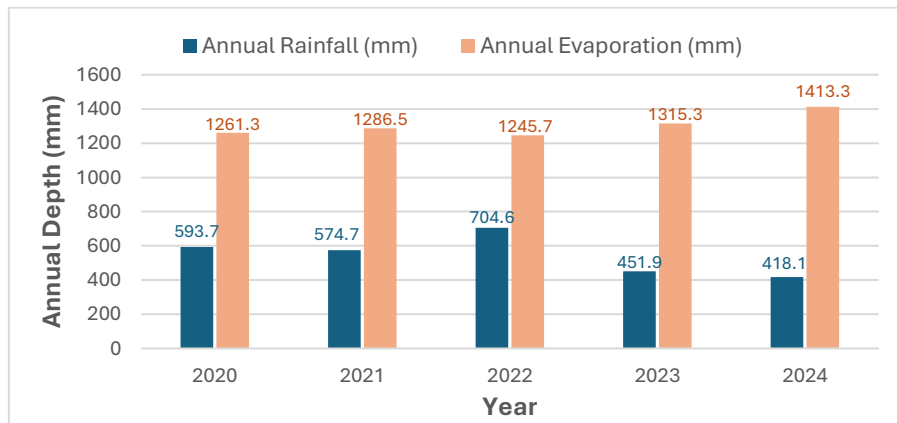


Figure 3.4. The annual total rainfall and evaporation across the 5-year period (2020–2024)

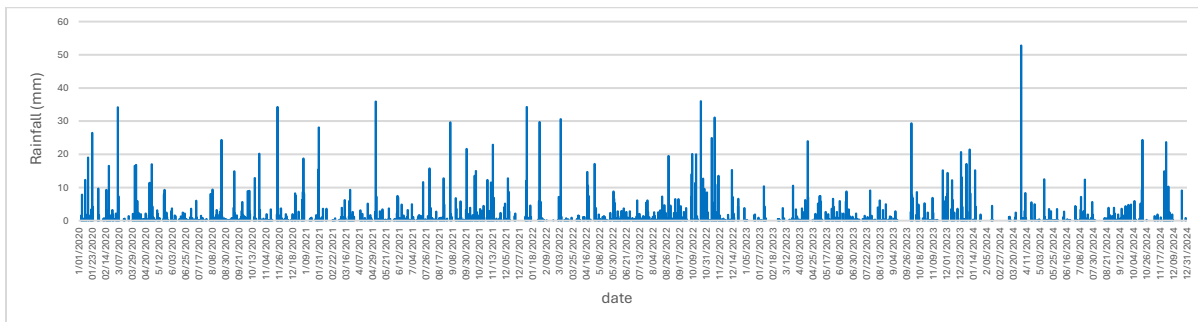


Figure 3.5. Detailed rainfall time series from 2020 to 2024.

The collected daily evaporation values were used to estimate potential evapotranspiration (PET) rates and incorporated into the PCSWMM model to account for atmospheric losses from pervious areas. The PET estimates were based solely on daily resolution data due to the unavailability of sub-daily evaporation records. These data inputs played a critical role in defining hydrologic losses, which influence both volume and timing of surface runoff. The mean annual evaporation over these five years is approximately 1300 mm, and its time series is shown in Figure 3.6.

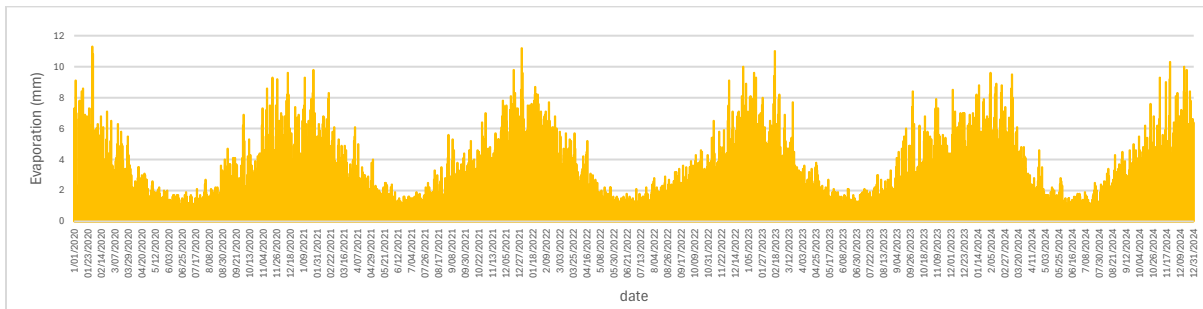


Figure 3.6. Detailed evaporation time series from 2020 to 2024.

As per stormwater modelling standards, rainfall intensity in both the 6-minute and daily graphs are expressed in millimetres per hour (mm/hr), though the values differ from how intensity is calculated. In the 6-minute data, each value reflects the rate that would occur if the rainfall during that short interval continued for a full hour, while the daily data averages total rainfall over 24 hours, resulting in much lower intensity values. Figure 3.7 illustrates this comparison clearly for year 2024. The 6-minute data (right panel) show distinct, high-intensity peaks that represent individual storm events, while the daily data (left panel) show smoothed patterns with significantly lower values. These sharp peaks accurately capture short-term rainfall events that are critical for this modelling, where peak flows are highly sensitive to sub-hourly intensity changes. Similar trends were observed in other years, so for clarity, only one year data are presented here.

Importantly, PCSWMM uses the actual rainfall depths from each time interval for its calculations, rather than scaled intensity values, which makes 6-minute data suitable and reliable for simulating short-term stormwater dynamics.

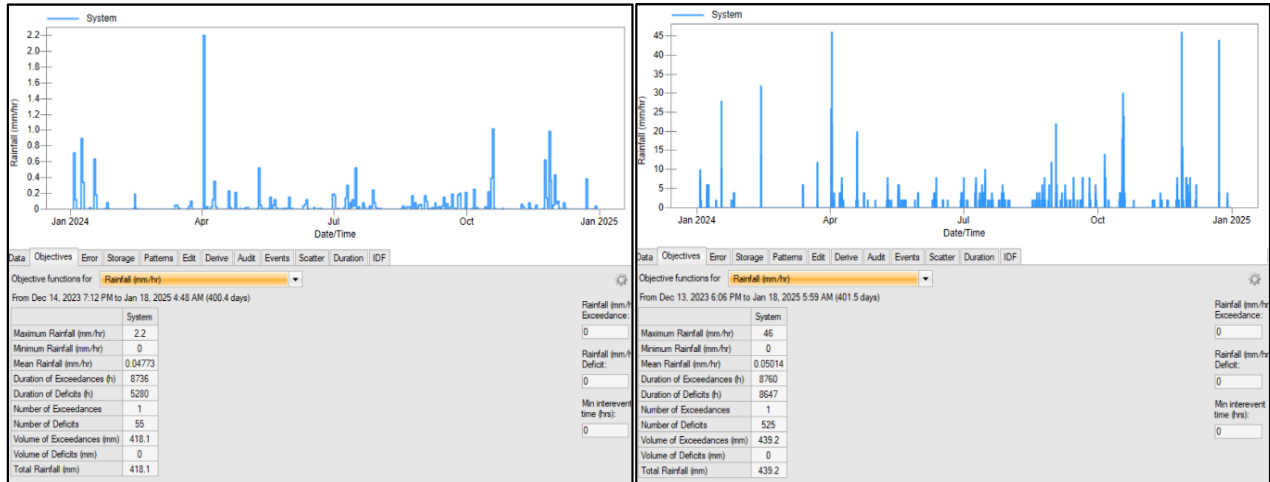


Figure 3.7. 2024 Rainfall Time Series: Daily (left) vs. 6-Minute Data

3.4.3. Land Use and Imperviousness

Land use and imperviousness across the study area were quantified using high-resolution Nearmap aerial imagery (a commercial cloud-based aerial mapping and geospatial intelligence platform; available at <https://www.nearmap.com>) for 2024, which provides parcel-scale mapping suitable for detailed urban hydrologic modelling. As shown in Figure 3.8, for a typical lot size of approximately 600 m², individual surface components, including roof area, driveways, footpaths, paved side pathways, and other hardstand elements, were digitised manually within each property boundary to obtain accurate estimates of impervious cover. This fine-grained, image-based digitisation approach offers substantially higher accuracy than zoning-based or coarse remote-sensing classifications, which often generalise residential parcels into uniform categories despite high variability in surface composition. This analysis of residential properties within the catchment revealed an average imperviousness of 64%, as illustrated in the figure.

To further improve the precision of land surface representation, a Digital Elevation Model (DEM) of the study area was integrated into the analysis. The DEM facilitated the delineation of slope, sub-catchment boundaries, and provided additional land use insight that complements the high-resolution imagery data. Based on this integration, consistent imperviousness values (predominantly 0.64, with lower values assigned to green area and higher for highly constructed zones) were systematically extracted. This dual approach ensures spatial consistency across the

model inputs. Additionally, hydraulic roughness values were assigned according to surface type, with the Manning’s n-value for impervious areas set at 0.01 and for pervious areas at 0.1, following standard hydrologic modelling practices (Rossman, 2022). This level of detail contributes to more reliable simulation of rainfall-runoff processes across the catchment.

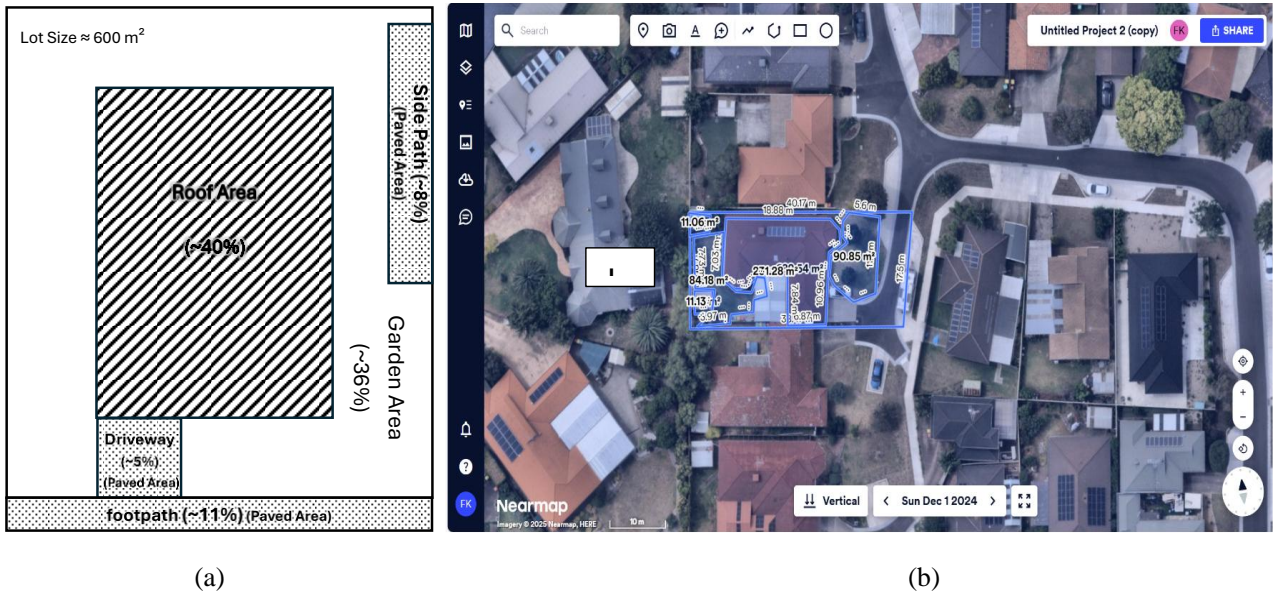


Figure 3.8. Typical residential surface layout (a) digitized from high-resolution Nearthmap imagery (b)

To support WSUD scenario development and population-based calculations, the number of residential properties within each sub-catchment was also estimated using Nearthmap imagery. Sub-catchment area was used as a practical proxy to indicate potential dwelling capacity, where larger sub-catchments typically accommodate more residential lots. Based on consistent patterns observed across the study area, sub-catchments smaller than approximately 1,500 m² generally corresponded to around two dwellings, those between 1,500 and 3,000 m² to roughly three dwellings, and sub-catchments between 3,000 and 5,000 m² also aligned with approximately three dwellings. Sub-catchments between 5,000 and 6,000 m² accommodated around four dwellings, those between 6,000 and 7,000 m² corresponded to about five dwellings, and areas between 7,000 and 10,000 m² typically associated with around seven dwellings. Very large sub-catchments exceeding 10,000 m² were observed to support up to ten dwellings.

These estimates were used to gauge the relative residential density of each sub-catchment and, more importantly, to indicate how many RWTs and raingardens could reasonably be allocated within each sub-catchment under the WSUD scenarios.

3.4.4. Soil Characteristics and Infiltration Parameters

Accurate representation of soil hydrological characteristics is essential for simulating surface runoff and infiltration processes in urban catchments. Soil parameters were selected based on Melbourne Water guidelines (Melbourne Water, 2022), reflecting the basaltic clays typical of western Melbourne, with a soil storage capacity of 120 mm and a field capacity of 50 mm applied in. The local soil conditions also support estimated values such as a suction head of 110 mm and a hydraulic conductivity of 10 mm/hr (Rossman, 2022).

3.4.5. Water Quality Data

Water quality monitoring data were collected at the catchment outlet using automatic samplers to establish baseline pollutant concentrations in a previous study. Event mean concentrations (EMCs) were determined as:

- **TN:** 2.63 mg/L
- **TP:** 0.36 mg/L
- **TSS:** 158 mg/L

These measured values are consistent with the characteristics of typical urban stormwater runoff reported in historical synthesis studies and recent reviews of urban stormwater in Eastern Australia (Drapper et al., 2022, Stormwater Center).

3.5. Model setup and parameterisation

The stormwater model used in this study was developed in PCSWMM (Version 5.2), which utilises the EPA-SWMM hydrologic–hydraulic engine to simulate rainfall–runoff processes, pipe network hydraulics, and pollutant transport. The model configuration consisted of two interconnected components: (1) hydrologic and hydraulic modelling for runoff generation and conveyance through the drainage network, and (2) water-quality modelling based on dynamics of pollutant buildup and wash-off. All hydrologic parameters, network geometry, climatic inputs, and pollutant

characteristics were incorporated following the data sources and procedures described in previous sections.

3.5.1. Hydrologic-Hydraulic Modelling Setup

Sub-catchment Delineation and Configuration

Sub-catchments were delineated based on the spatial arrangement of the stormwater pipe network and the information gained from the 5 m DEM. Each sub-catchment was assigned to drain to a specific inlet node in the stormwater network, and overland flow pathways were determined based on the surface slopes and drainage patterns. In the end, adjustments to the sub-catchment delineations were made to more realistically represent the convergence of stormwater at system network inlet locations.

Rainfall and Evaporation Input

The rainfall and evaporation time-series data, as described in Section 3.4.2, were imported into PCSWMM to drive the hydrologic simulations. The 6-minute rainfall data were uploaded as continuous annual time series of the five-year baseline period (2020–2024), enabling the model to simulate both individual storm events and cumulative hydrologic responses during wet and dry periods. Daily evaporation data were also imported separately for each year and were used to estimate potential evapotranspiration (PET) over pervious surfaces, with the model internally distributing daily values into sub-daily computational time steps to maintain continuous soil-moisture accounting. The rainfall and evaporation series were uniformly applied across all sub-catchments, and the model was run independently for each year.

Infiltration Modelling

Among the various infiltration methods available in PCSWMM, the Green-Ampt method was selected for this study. Although Green-Ampt is traditionally suited to event-based simulations, it can also be applied in continuous modelling, as it provides a physically based representation of suction head, soil conductivity, and initial soil moisture deficit to calculate infiltration rates (Rossman, 2022). This allows the method to capture long-term hydrological responses under varying rainfall and soil-moisture conditions. Compared to simpler empirical models such as the

Horton method, Green-Ampt provides a more robust and dynamic representation of infiltration, making it particularly suitable for multi-year simulations where soil moisture varies significantly between rainfall events.

The Green-Ampt parameters defined in Section 3.4.4 based on the properties of basaltic clay were entered into the model. Upon the given conditions, the initial moisture deficit was calculated using the following equation (3.1) from software user's manual (Rossman, 2022):

$$\text{Initial deficit} \equiv \frac{(\text{Soil Storage Capacity} - \text{Field Capacity})}{\text{Soil Storage Capacity}} \quad (3.1)$$

The initial moisture deficit calculated was 0.58, indicating that the soils start the simulation with 58% of their maximum infiltration capacity. During the continuous simulation, the model updates the soil moisture in real time, reducing infiltration capacity by saturating the soil during wet periods and restoring capacity through evapotranspiration during dry periods.

Surface Runoff Parameters

Additional hydrological parameters were specified for each sub-catchment to characterise surface runoff generation and routing. These parameters included sub-catchment width (representing the characteristic overland flow path length), area, percentage of impervious cover (averaging 64% based on the analysis), Manning's roughness coefficients for impervious ($n = 0.01$) and pervious ($n = 0.10$) surfaces, depression storage depth, and sub-catchments slopes derived from the DEM analysis. Together, these parameters govern both the timing and volume of runoff produced, as well as its transfer into the stormwater network.

Hydraulic Routing and Network Representation

Hydraulic routing through the pipe network was simulated using the dynamic wave method, which solves the full one-dimensional Saint-Venant equations for unsteady open channel flow. This approach was chosen because it explicitly considers the effects of backwash, backflow, overburden, and pressurized flow conditions, all of which become critical in high-intensity storms when pipes operate at or above their design capacity (Rossman, 2022). The dynamic wave method offers higher accuracy compared to simpler kinematic wave approaches, particularly for networks

with flat slopes and systems prone to overburden, both of which are features of the study catchment.

The detailed geometry of the pipe network obtained from Wyndham City Council, Victoria, Australia, including pipe lengths, diameters, inversion heights, slopes, and Manning roughness coefficients, was input into the model. The junction nodes were configured with edge elevations, ground elevations, and maximum depths to allow for accurate representation of surface flooding when system capacity is exceeded.

To evaluate hydraulic performance under different scenarios, several key performance indicators were determined. These metrics were selected to comprehensively assess the drainage system's ability to manage surface water under different conditions: total runoff volume (indicating the overall hydrological response), peak outflow rates at the watershed outlet (indicating maximum discharge to receiving waters), and frequency and duration of overflows at manholes (indicating system capacity exceedance and the likelihood of surface flooding).

When inflow rates exceed pipe capacity, the PCSWMM model tracks pressurized flow conditions in the network. Overflow events in this simulation are identified when manholes record a total flood volume greater than zero, indicating that the water level has exceeded the ground level and built up at ground level. The total flood volume, along with the duration of overflow and its frequency at each node, provide important indicators for assessing flood risk and identifying hydraulic bottlenecks where system upgrades or WSUD interventions may be most beneficial.

3.5.2. Water Quality Modelling Setup

The water quality section of the model is designed to simulate the behaviour of key stormwater pollutants under variable rainfall conditions. The three pollutants evaluated in this study—total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP)—were added to the PCSWMM in the Pollutants section. After defining the overall characteristics and event mean concentrations (EMCs), pollutant buildup and washoff were configured through the Land Use Editor of software, where separate functions were assigned to each pollutant based on the modelling approach chosen for this study.

Buildup Configuration

PCSWMM offers several options for modelling pollutant buildup, including Power (POW), Exponential (EXP), Saturation (SAT), and External time series (EXT). For this study, the Power (POW) function was chosen for all three pollutants because it provides a more realistic and adaptable way to represent how pollutants gradually accumulate on urban surfaces during dry-weather periods. Compared with exponential or saturation functions, the POW formulation better captures the inherently non-linear nature of buildup, allowing pollutant loads to increase over time while still approaching a natural saturation point (Rossman, 2022).

This makes the POW function especially suitable for continuous simulations, where the length and variability of antecedent dry conditions play a major role in shaping pollutant accumulation. Its ability to closely reflect real-world urban pollutant behaviour was the primary motivation for selecting this approach. The items entered the model for each pollutant in the Buildup tab were listed in Table 3.1.

Washoff Configuration

Among the washoff options available in PCSWMM—including the Exponential (EXP), Rating Curve (RC), and Event Mean Concentration (EMC) methods—the Exponential (EXP) function was selected for this study. This option was selected because EMC functions assume constant pollutant concentrations and therefore cannot represent the temporal variation that occurs during individual storm events (Yuan et al., 2023). The Rating Curve (RC) method, essentially a simplified form of the exponential function, also omits initial pollutant buildup, making it less suitable for continuous simulations where antecedent dry conditions play an important role.

In contrast, the EXP function links washoff to both runoff intensity and the remaining pollutant buildup, allowing more realistic modelling of concentration changes within and between storm events (Yuan et al., 2023, Rossman, 2022). It is widely used in urban stormwater quality studies and has demonstrated strong performance across varied rainfall and surface conditions. The parameters entered for each pollutant in the Washoff tab are summarised in Table 3.1.

Table 3.1. Buildup (POW) and Washoff (EXP) Parameters for TSS, TN, and TP in PCSWMM

| Pollutant | Buildup Function | Max. Buildup (mg/m ²) | Rate Constant (day ⁻¹) | Power Constant | Normalizer | Washoff Function | Washoff Coefficient | Washoff Exponent | Cleaning/BMP Effic. |
|-----------|------------------|-----------------------------------|------------------------------------|----------------|------------|------------------|---------------------|------------------|---------------------|
| TSS | POW | 250 | 0.30 | 1.5 | AREA | EXP | 0.10 | 2.00 | 0 |
| TN | POW | 100 | 0.25 | 1.20 | AREA | EXP | 0.05 | 1.5 | 0 |
| TP | POW | 15 | 0.20 | 1.00 | AREA | EXP | 0.08 | 1.8 | 0 |

3.6. Calibration and Validation

To secure the reliability and accuracy of the simulations, it is essential to include model calibration and validation as part of this research. Calibration involves changing model parameters to align with the observed data, and validation is a performance check with the independent data. Essentially, this step ensures that the model is a true representation of the system's behaviour and, therefore, it is safe to use it for prediction and scenario analysis.

3.6.1. Data Source and Monitoring Setup

The calibration and validation process relied on observed flow data that had already been collected by Victoria University (VU) as part of a stormwater monitoring project. For this study, these pre-existing data were supplied in the form of time-series files containing continuous flow measurements at the catchment outlet. At the main outlet pipe (monitoring point C1), discharge flow rates had been measured at 6-minute intervals and documented in the dataset.

The dataset included several rainfall events of varying magnitude, duration, and intensity suitable for parameter estimation and validation. It included multiple previously recorded rainfall events of varying magnitude, duration, and intensity across different seasons.

3.6.2. Calibration Process

The model was calibrated using flow data from 1 April 2020 to 1 May 2020, which was of excellent quality and deemed fully reliable. Because the stormwater network layout has been already established and its hydraulic parameters are relatively stable, the calibration process focused on

hydrologic parameters, following the recommendation of James (2003). These hydrologic parameters generally carry more uncertainty and exhibit greater spatial variability than the surveyed hydraulic system.

The parameters adjusted during calibration included:

- Sub-catchment width, which represents the characteristic overland flow path length;
- Percent imperviousness;
- Manning’s roughness coefficients for both impervious and pervious surfaces;
- Depression storage depths for each surface type;
- Sub-catchment slope; and
- Infiltration parameters, especially the initial moisture deficit.

Each of these parameters plays a distinct role in shaping the flow response. Sub-catchment width is particularly sensitive because it controls the time of concentration and affects the shape of the hydrograph entering the drainage network. Depression storage governs how much rainfall is temporarily held in surface depressions before runoff begins, influencing both runoff volume and the timing of the rising limb. The infiltration parameters, especially the initial moisture deficit, determine how rainfall is partitioned between infiltration and surface runoff, and significantly affect total runoff and peak discharge. These iterative refinements were essential for achieving a close match between modelled and observed conditions, reducing both structural and hydrologic uncertainty.

Parameters were adjusted through sensitivity analysis to ensure strong alignment between the model outputs and observed data. Model performance was assessed using the Nash–Sutcliffe Efficiency (NSE), Correlation Coefficient (R), and Root Mean Square Error (RMSE), as defined in Equations (3.2), (3.3), and (3.4).

$$NSE \equiv 1 - \frac{\sum_{i=1}^n (Q_{o,i} - Q_{s,i})^2}{\sum_{i=1}^n (Q_{o,i} - \bar{Q}_o)^2} \quad (3.2)$$

$$R \equiv \frac{\sum_{i=1}^n (Q_{o,i} - \bar{Q}_o) (Q_{s,i} - \bar{Q}_s)}{\sqrt{\sum_{i=1}^n (Q_{o,i} - \bar{Q}_o)^2 \sum_{i=1}^n (Q_{s,i} - \bar{Q}_s)^2}} \quad (3.3)$$

$$RMSE \equiv \sqrt{\frac{1}{n} \sum_{i=1}^n (Q_{o,i} - Q_{s,i})^2} \quad (3.4)$$

where $Q_{o,i}$ and $Q_{s,i}$ represent observed and simulated flows at time step i , $\overline{Q_o}$ and $\overline{Q_s}$ denote their respective means, and n is the number of observations.

The model calibration in this study was undertaken using approximately one month of observed data, representing a relatively short monitoring period. The use of a limited calibration dataset may introduce some uncertainty in model parameterisation, as it may not fully capture the full range of hydrological variability under different antecedent moisture and rainfall conditions. However, the selected calibration period included representative rainfall–runoff behaviour of the study catchment, and the model performance statistics indicated satisfactory agreement between observed and simulated flows. Given the data availability constraints typical of existing urban catchments, the adopted calibration approach is considered adequate for the comparative scenario-based analysis undertaken in this research.

3.6.3. Validation Process

After calibration, the model was validated using an independent dataset from 12 July 2019 to 9 August 2019. This period was deliberately chosen before the period used for calibration. Hence, it was completely independent and there was no risk of bias from the sequential climate conditions or hysteretic effects (where the response of the system depends on its previous conditions, not just current rainfall). The model was run with the same calibration parameters, without any changes, assessing its ability to predict flows on independent data.

Following the satisfactory calibration and independent validation results, it should be noted that the scenario simulations in this research were conducted as multi-year continuous runs rather than isolated rainfall–runoff events. Specifically, the model was driven using 6-minute rainfall and daily evaporation time series covering January 2020 to December 2024 (Section 3.4.2). This multi-year continuous simulation framework allows the system response to be evaluated under a wide range of rainfall conditions and wet–dry cycles, providing a robust basis for the comparative assessment of baseline and WSUD scenarios presented in Chapters 4 and 5.

3.7. Scenario Design and WSUD Implementation

This section outlines the development of the WSUD configuration, and the future-condition scenarios applied in this study. Scenario design establishes the modelling framework used to assess stormwater quantity and quality responses under both current and projected conditions. All scenarios were constructed using the calibrated PCSWMM model described in Section 3.6 and form the analytical foundation of Chapters 4 and 5.

3.7.1. WSUD Design Specifications

Two primary WSUD measure types were selected for evaluation, which are Rainwater Tanks (RWT) and Rain Gardens (RG). These measures were chosen based on several considerations including their proven effectiveness in residential catchments, feasibility of retrofit implementation within existing urban development, potential for distributed deployment across multiple properties, and complementary mechanisms for achieving both runoff volume reduction and water quality improvement.

Rainwater Tank Configuration

The RWT configurations in PCSWMM were set up to receive inflow directly from roof drainage areas, reflecting a typical residential system where gutters and downpipes channel rainwater into a storage tank (Figure 3.9).

Three tank sizes were assessed, 3.5 kL, 4.0 kL, and 4.5 kL, representing the range commonly installed in Australian homes and aligned with relevant plumbing standards and building regulations. The detailed specifications for each tank size are presented in Table 3.2.

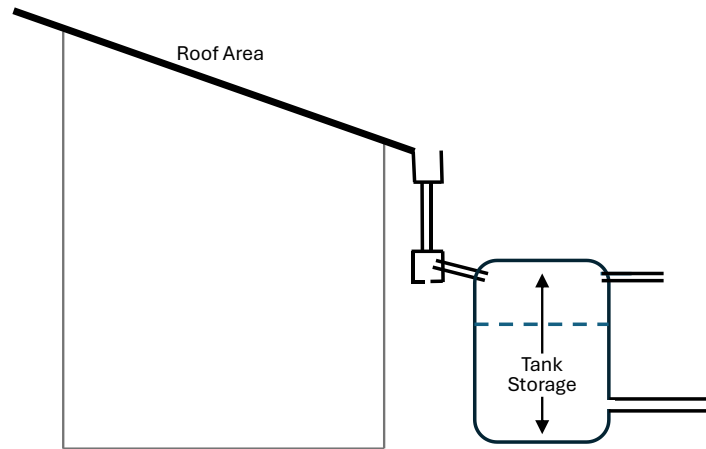


Figure 3.9. Typical configuration of a RWT system

The RWT design incorporates an orifice-controlled drainage mechanism that gradually empties stored water over a specified drain time, creating storage capacity for subsequent rainfall events while avoiding rapid discharge that would generate high peak outflows. The drain time parameter represents a critical design consideration balancing competing objectives: shorter drain times restore capacity more rapidly but produce higher discharge rates, while longer drain times provide greater peak flow attenuation but may leave tanks partially full when subsequent rainfall occurs (Abi Aad et al., 2010).

To determine the optimal drain time configuration, three drain period times evaluated were 6, 12, and 24 hrs. In all scenarios, no drain delay and no drain offset height were assumed to simplify the system design and ensure constant base conditions for comparison. The drain coefficient for each configuration was calculated using Equation (3.5):

$$C = \frac{2\sqrt{D}}{T} \quad (3.5)$$

where D is the height of stored water (in mm), and T is the drain time (in hr)

The calculated drain coefficients (Table 3.2) were applied in the model to represent the outflow characteristics of the RWTs under each scenario. The chosen configurations allow for an assessment of the influence of drain time on stormwater retention and discharge performance.

Rain Garden Configuration

RGs were modelled using PCSWMM's Low Impact Development (LID) bioretention module, which represents the layered system structure including surface ponding, engineered soil media, and storage/drainage layers (Rossman, 2022). The design specifications are illustrated in Figure 3.10, composing of a surface layer provides temporary ponding storage, an engineered soil media layer providing filtration and biological treatment, and a gravel storage layer facilitating drainage. This layered configuration reflects standard practice for Melbourne bioretention design and has been validated through extensive monitoring of constructed systems and detailed in Table 3.2, showing the three-layer configuration.

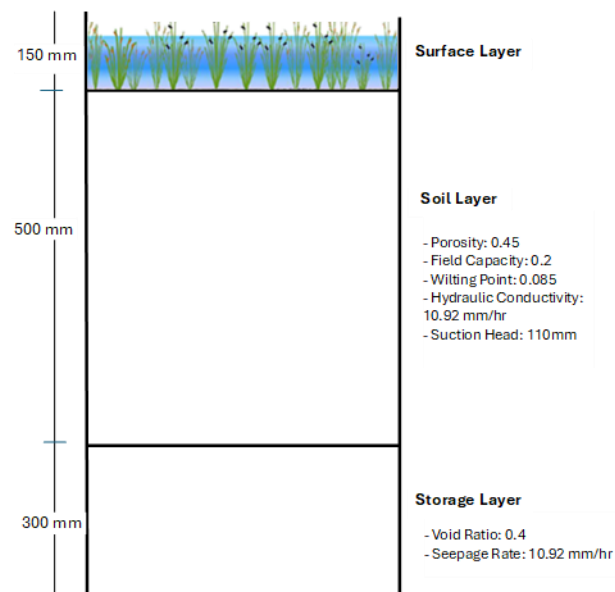


Figure 3.10. Schematic of the raingarden showing layer structure.

Two RG sizes evaluated were 10 m² and 15 m² per household. These sizes represent the practical range for residential implementation considering typical property dimensions, setback requirements, parking and access needs, and amenity considerations.

Pollutant Removal Mechanisms and Routing Options

Pollutant removal efficiencies applied for RGs and RWTs in this study selected were listed in Table 3.2 based on the typical performance ranges recommended in Melbourne Water (2022) guidelines and supported by experimental research such as Wang et al. (2017a) and Patrick et al. (2025). RGs commonly achieve high pollutant removal, with reported values frequently exceeding 80% for TSS, 50–80% for TP, and 30–70% for TN. RWTs provide moderate pollutant reductions through settling and volumetric reduction and their typical removals are in the ranges of 50–80% for TSS, 20–50% for TP, and 10–40% for TN, supporting the selected RWT removal values.

An additional critical configuration decision concerns the routing of RWT and RG discharge. Two routing options were evaluated for all scenarios:

- Return to pervious area: Overflow and controlled drainage are directed to adjacent pervious surfaces within the property (gardens, lawn areas), providing additional opportunities for infiltration and evapotranspiration.
- Without return to pervious area (direct to network): Overflow and drainage are connected directly to the stormwater drainage system. This configuration represents simpler installation but forgoes additional infiltration benefits.

The comparative testing of these routing options addresses the question of whether the additional complexity and cost of routing to pervious areas justifies the potential performance improvements, or whether direct network connection provides adequate benefits with simpler implementation.

All combinations of tank size (three options), drain time (three options), and routing configuration (two options), as well as every combination of RG size (two options) and routing configuration (two options), were systematically assessed, as shown in Table 3.2. The comparative analysis of these configurations helped identify the optimal setups for each scenario and informed design recommendations for effective RWT and RG implementation in residential retrofit settings.

Table 3.2. WSUD Technical Design Specifications (RWT & RG; adopted for this study)

| WSUD Type | Size / Capacity | Physical Dimensions | Hydraulic Parameters | | | TN Removal (%) | TP Removal (%) | TSS Removal (%) | Routing Options | |
|-----------|-------------------|---|---|-------------------|-------|----------------|-------------------------|-------------------|-------------------------|-------------------|
| | | | Drain Time | Drain Coefficient | | | | | | |
| RWT | 3.5 kL | Height: 1500 mm | 6 h | Drain Coefficient | 12.91 | 30% | 40% | 70% | Return to pervious area | Direct to network |
| | | | 12 h | | 6.46 | | | | | |
| | | | 24 h | | 3.22 | | | | | |
| | 4.0 kL | Height: 1800 mm | 6 h | | 14.14 | | | | | |
| | | | 12 h | | 7.07 | | | | | |
| | | | 24 h | | 3.53 | | | | | |
| | 4.5 kL | Height: 2000mm | 6 h | | 14.9 | | | | | |
| | | | 12 h | | 7.45 | | | | | |
| | | | 24 h | | 3.72 | | | | | |
| RG | 10 m ² | Surface area: 10 m ² Ponding depth: 150 mm Filter media: 500 mm Storage layer: 300 mm | Porosity: 0.45 Field capacity: 0.20 Wilting point: 0.085 Hydraulic conductivity: 10.92 mm/hr | 45% | 60% | 80% | Return to pervious area | Direct to network | | |
| | 15 m ² | Surface area: 15 m ² Ponding depth: 150 mm Filter media: 500 mm Storage layer: 300 mm | Suction head: 110 mm Void ratio: 0.40 Seepage: 10.92 mm/hr | | | | | | | |

3.7.2. Scenario Formulation and Implementation Scales

Five WSUD scenarios were developed representing different combinations of measure types and implementation scales across the catchment. The scenarios were designed to evaluate individual

measure performance, compare effectiveness between measure types, and assess potential synergies from hybrid configurations combining both RWTs and RGs.

- Scenario A (25% RWT): Installation of RWTs on 25% of residential properties, representing approximately 750 households out of the total 3,000 properties in the catchment.
- Scenario B (50% RWT): Installation of RWTs on 50% of residential properties (approximately 1,500 households).
- Scenario C (25% RWT + 25% RG): Hybrid configuration with RWTs on 25% of properties and RGs on a different 25% of properties.
- Scenario D (25% RG): Installation of RGs on 25% of residential properties (750 households).
- Scenario E (50% RG): Installation of RGs on 50% of residential properties (1,500 households).

The implementation scales (25% and 50%) were selected to represent realistic retrofit adoption rates achievable through combinations of mandatory requirements for new development or significant renovations, voluntary adoption supported by incentive programs, and direct public investment in streetside or common area installations.

3.7.3. Climate Change and Urban Growth Projections

Climate Change

In this research, assessing future climate impacts is critical for understanding the long-term resilience of WSUD interventions and determining whether systems designed for today's conditions will continue to perform under increasing climate pressures in the coming decades. The future 6-minute rainfall and daily evaporation datasets for 2050 and 2070 were generated from the regionalised projections for Melbourne, following the methodology system developed by Cleanstormwater, based on the SSP2-4.5 long-term scenario.

The SSP2-4.5 scenario (Shared Socioeconomic Pathway 2-4.5) from the IPCC Sixth Assessment Report is a moderate emissions pathway model and associated with approximately 2.5–3.0°C increase by 2100 (Lee et al., 2023). The regional climate projections for Melbourne under this

scenario reveal clearer intensification of extreme rainfall, including more frequent short-duration, high-intensity storms. They also point to higher evaporation rates driven by warmer temperatures and increased atmospheric moisture demand.

It should be noted that the future climate inputs used in this study were derived from a single set of regionalised projections. While this provides a consistent basis for scenario comparison, using multiple climate projections or ensemble datasets could better characterise the uncertainty associated with future rainfall and evaporation changes. Ensemble-based approaches typically capture a wider range of possible climate variability and may result in a broader spread in predicted runoff and pollutant responses. Future work could therefore benefit from incorporating multiple climate projections to further examine how robust WSUD performance is under climate uncertainty. Nevertheless, the selected projections are considered appropriate for achieving the comparative objectives of this study.

Urban Growth

Urban growth projections were developed to assess WSUD performance under increasing imperviousness driven by ongoing densification in outer western suburban Melbourne and the associated rise in directly connected imperviousness (DCI), which strongly influences stormwater runoff response.

Two future urbanization scenarios were created by applying increases to the baseline (2020–2024) catchment imperviousness of 64%, a value consistent with suburban catchment conditions documented in regional land-use and stormwater planning studies for outer-metropolitan Melbourne (Melbourne Water (2016), Department of Environment (2018)):

- 2050 Projection: A 20% increase in imperviousness was applied, raising average catchment imperviousness from 64% to 77%. This represents moderate ongoing densification over 25 years, consistent with observed densification rates in municipal growth projections.
- 2070 Projection: A 31% increase in imperviousness was applied, raising average catchment imperviousness from 64% to 84%.

The imperviousness increases were implemented in PCSWMM by proportionally adjusting the percent imperviousness parameter for all sub-catchments, maintaining the spatial pattern of

relative imperviousness while increasing absolute values. The additional impervious area was assumed to be directly connected to the stormwater system network following typical development practice. The existing composition of impervious surfaces (roof, driveway, road proportions established in baseline characterization) was maintained in the projections.

Scenario Decomposition Framework

To systematically evaluate how climate change and urbanization separately and both will affect the performance of the stormwater system in the future, three separate sets of scenarios for 2050 and 2070 were created:

- **Climate change-only scenarios:** These scenarios demonstrate the effects of climate change by using only future climate data to analyse system performance, independent of urbanization pressures.
- **Urbanization-Only Scenarios:** These scenarios isolate the impact of urban densification by increasing imperviousness while keeping the climate at baseline level (observed 2024 rainfall and evaporation).
- **Combined Scenarios:** These scenarios apply both climate change and urbanization projections simultaneously. The combined scenarios reflect the most realistic future conditions where both stressors operate concurrently and enable assessment of potential synergistic or antagonistic interactions between climate and urbanization impacts.

This three-scenario framework separates the effects of climate change and urbanisation, showing how much each contributes to future system performance, whether their impacts interact, and which stressor drives most performance decline.

3.8 Economic Evaluation

The economic feasibility of the proposed WSUD interventions was assessed using a life cycle costing (LCC) framework, with full assumptions, equations, and results presented in Chapter 6. Here, a brief methodological summary is provided to show how economic analysis was integrated into the scenario assessment.

A 25-year planning horizon was adopted to allow consistent comparison between RWTs (\approx 25-year design life) and RGs (\approx 50-year design life), following MUSIC v6 costing guidance and

standard engineering economics practice. All costs were converted to real 2025 AUD using a CPI factor of 1.7391, with a 7% real discount rate and a 1% annual escalation applied to pump replacement costs.

RWT LCC included total acquisition cost (TAC), the net present value (NPV) of annual O&M, and one pump replacement at year 12. RG LCC included TAC and annual O&M valued at 6.4% of TAC.

Per-unit LCCs were scaled according to the number of installations in each WSUD scenario, enabling comparison of economic performance between configurations. Detailed costing inputs and scenario-level results are provided in Chapter 6.

Chapter 4: Baseline Condition (Quantity & Quality, 2020–2024)

This chapter presents the baseline performance of the study catchment under current climate and land use conditions, establishing the reference case against which all WSUD intervention scenarios and future projections are evaluated. The baseline assessment characterizes the hydrologic, hydraulic, and water quality behaviour of the existing conventional stormwater drainage system without any WSUD measures, identifying current performance deficiencies and opportunities for improvement through nature-based retrofits. The baseline period spans five years (2020–2024), capturing substantial inter-annual climate variability including relatively dry years and wet years.

4.1. Climate and Hydrologic Context

4.1.1. Rainfall Characteristics

The study catchment over the five-year baseline period, as explained in Section 3.4.2, experienced strong year-to-year rainfall variability. The difference of 69% between the driest and wettest years is a clear indication of natural climate variability characteristic of Melbourne's temperate environment, which directly influences the frequency and scale of stormwater management problems.

For each year, the model was run twice, once with 6-minute rainfall data and the other with daily rainfall data. The 6-minute time step enabled a more precise evaluation of short-term flow fluctuations, whereas the daily time step offered a more general view of the system's long-term behaviour.

As an example, Figure 4.1 presents the results of the outflow from the outlet pipe (C1) in 2024, comparing the 6-minute and daily outputs. This shows how the system responds to different rainfall inputs and how the choice of time step affects the representation of flow dynamics.

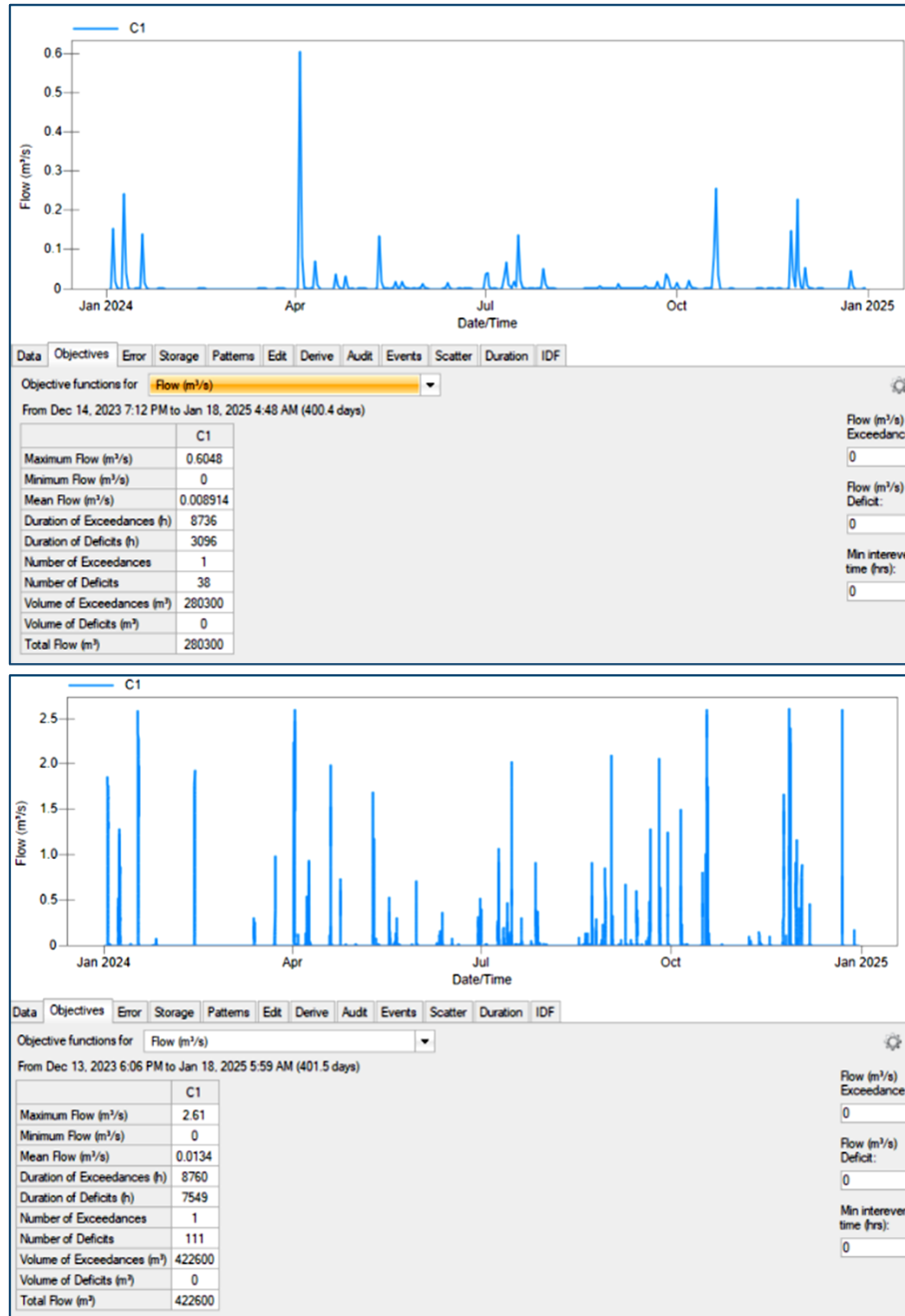


Figure 4.1. 2024 outflow results: Daily (top) vs. 6-Minute (bottom) Data

The figure clearly demonstrates that the 6-minute rainfall data produced much higher peak flows than the daily data. The daily time steps smooth out the hydrograph and eliminate the sharp peaks produced by short-duration, intense rainfall events. These peaks are critical for the design and evaluation of stormwater infrastructure because they represent the maximum hydraulic load on the

system. While the peak flows were significantly different, the average flows were similar at both resolutions, confirming that the main distinction is in capturing short-duration rainfall intensity rather than total rainfall volume.

Given these findings, the 6-minute rainfall data were chosen for all subsequent modelling. This decision was based on several factors:

- 6-minute data captured peak hydraulic loads much more reliably, which is essential for flood risk design and assessment.
- High-resolution data were essential to show rapid changes during short, intense storms.
- The drainage network responds rapidly to rainfall, often within minutes, making more precise time steps more appropriate.
- Higher resolution allows the model to better match the expected behaviour of the system during storm events.

While daily data were helpful in revealing long-term and seasonal patterns, they were incapable of capturing the detailed dynamics that are necessary for an accurate stormwater model in an urban watershed. Thus, all calibration, validation, and scenario analyses presented in the following sections use only 6-minute rainfall data.

4.1.2. Calibration Results

Before assessing the model performance, its predictive capability was verified through calibration and validation. The calibrated model showed excellent agreement with observed flow data at the catchment outlet. As illustrated in Figure 4.2, model achieved a Nash–Sutcliffe Efficiency (NSE) of 0.82, meaning it explained 82% of the variation in observed flows, which is well above the 0.50 benchmark for acceptable hydrologic models and close to the 0.80 “excellent” threshold. The Pearson correlation coefficient ($R = 0.915$) showed a strong match in the timing and magnitude of flow responses, consistent with the performance expectations noted by Rossman (2022).

Error statistics further supported the model’s reliability. The RMSE was $0.0704 \text{ m}^3/\text{s}$, indicating small prediction errors relative to observed flows. Additional measures, including low LSE and ISE values, confirmed model stability, and the overall ISE rating was classified as “Excellent.”

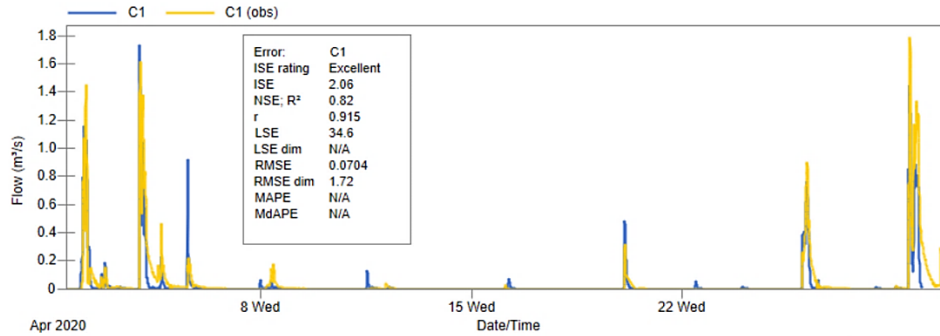


Figure 4.2. Observed vs. simulated flow at the outlet pipe (C1) showing excellent calibration accuracy.

4.1.3. Validation Results

As discussed in Section 3.6.2, the validation was conducted over a time period different from the calibration phase, allowing an independent assessment of model performance. The results demonstrated a strong and reliable system response. As shown in Figure 4.3, the model successfully reproduced the observed flow patterns throughout the validation period, confirming its capability to simulate the catchment’s hydrologic behaviour under different conditions.

The validation achieved an NSE of 0.762, indicating that the model maintained strong predictive accuracy on independent data, with only a slight decrease from the calibration value, and the correlation coefficient ($R = 0.918$) demonstrated excellent agreement in both flow timing and magnitude.

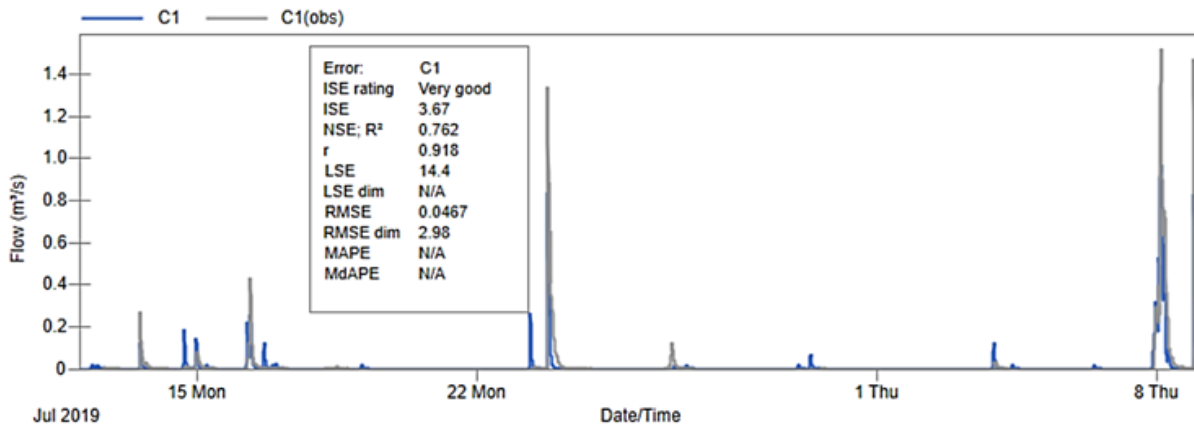


Figure 4.3. Observed vs. simulated flows at the outlet pipe (C1) during the validation period, confirming the model's predictive reliability.

The strong alignment between observed and simulated hydrographs confirm that the model is not over-fitted and provides reliable predictive performance. This consistency supports its suitability for evaluating WSUD strategies under varying urbanization and climate change scenarios.

4.2. Hydraulic Baseline Performance

4.2.1. Annual Runoff Volumes and System-Level Flow Characteristics

Surface runoff represents the volume of water that flows over the land surface toward the drainage network. Understanding total runoff generation is fundamental to assessing catchment water balance, quantifying hydrologic alteration, and establishing volume reduction targets for WSUD interventions.

PCSWMM’s annual surface runoff volumes from 2020 to the end of 2024, along with the corresponding annual rainfall totals, are presented in Table 4.2, allowing assessment of the rainfall–runoff relationship.

Total surface runoff closely followed annual rainfall trends, increasing from 45.54 ML in the driest year (2024) to 76.78 ML in the wettest year (2022). This confirms that runoff generation in this catchment is dominated by rainfall input, with minimal control from the existing conventional stormwater network.

Table 4.2. Annual Rainfall and Surface Runoff Generation (2020–2024)

| Year | Total Annual Rainfall (mm) | Total Runoff Volume (ML) |
|-------------|-----------------------------------|---------------------------------|
| 2020 | 593.7 | 62.19 |
| 2021 | 574.7 | 57.11 |
| 2022 | 704.6 | 76.78 |
| 2023 | 451.9 | 49.93 |
| 2024 | 418.1 | 45.54 |

From a WSUD design perspective, these baseline runoff volumes establish clear reduction targets. To restore more natural hydrologic conditions, runoff volumes should ideally be reduced to more than half, through distributed infiltration and harvesting measures. The following sections of this thesis will evaluate whether the proposed WSUD scenarios can achieve these necessary volume reduction targets.

4.2.2. Peak Outflow Dynamics

Another key design parameter is Peak outflow for evaluating flood risk. Peak outflow represents the maximum instantaneous discharge rate at the catchment outlet. Unlike runoff volumes (which accumulate over time), peak flows reflect the system's ability to convey concentrated flows during the most intense rainfall periods, typically lasting only minutes to hours.

Figures 4.4 illustrate the time-series of peak outflow at the outlet pipe (C1) for each year from 2020 to 2024 to enable identification of storm events and system response characteristics.

The most striking finding from this analysis is the remarkable consistency of peak outflows across all five years with the values varying only from 2.60 to 2.62 m³/s for five consecutive years in spite of the 69% change in rainfall totals for the same period. This means the system experienced similar peak-intensity storms each year, and the outlet pipe capacity ultimately limits how high peak flows can get. In contrast, total annual flow volumes changed noticeably between years since they are conditional on how often and how long it rains.

In 2022, the wettest year, runoff volume was highest (76.78 ML), yet the peak flow increased by less than 1%. This is the confirmation of the statement that the peak flows are associated to short, intense bursts of rainfall and pipe capacity, rather than total rainfall or soil moisture.

The catchment shows extremely high peak-to-mean flow ratios, meaning it is dry most of the time and then responds with sharp, fast runoff spikes during storms. This flashy pattern is the one typical of urbanised catchments that have little infiltration or detention and thus, are the main contributors to the pollution of receiving waterways. Moreover, it can cause erosion, habitat disruption, pollutant surges, and long periods without baseflow.

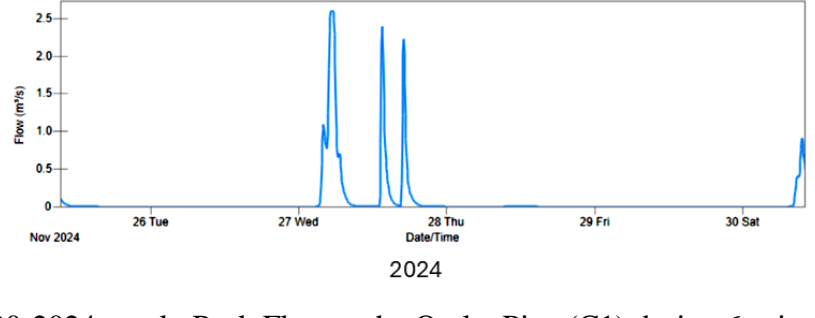
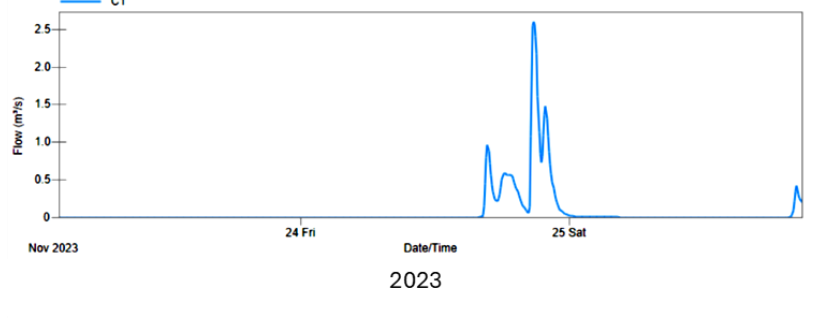
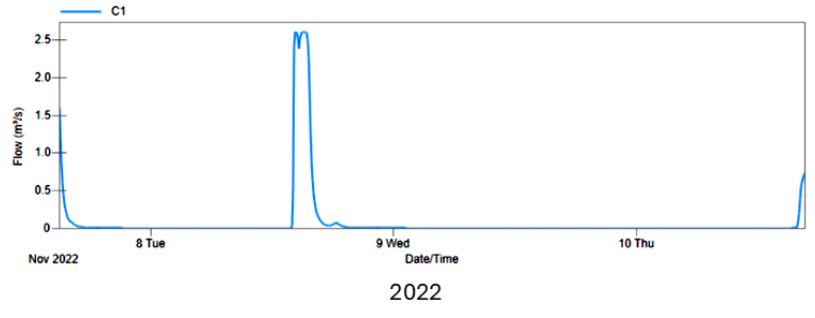
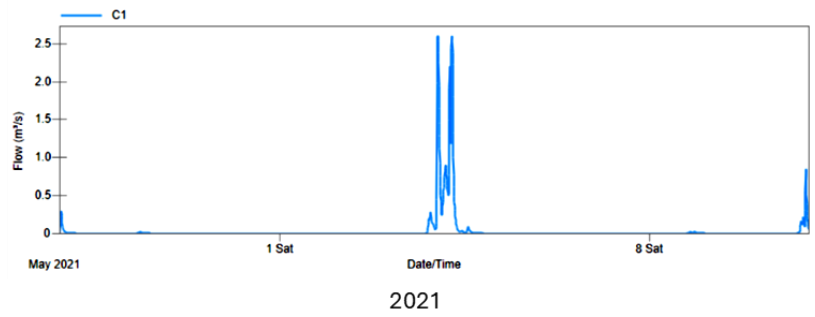
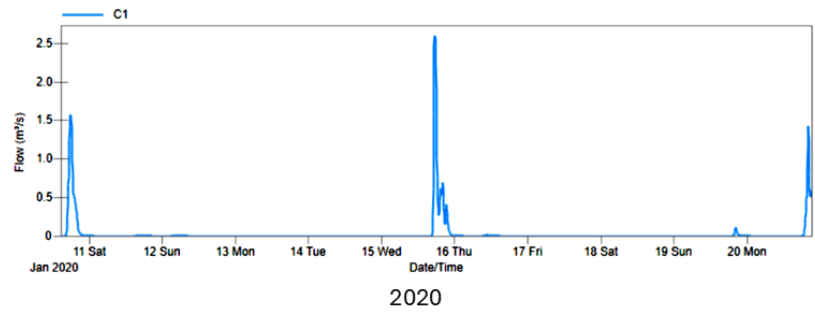


Figure 4.4. 2020-2024 yearly Peak Flow at the Outlet Pipe (C1) during 6-minute simulation.

These findings have clear implications for WSUD design. Since peaks are shaped by short, intense rainfall, WSUD systems must capture and detain water quickly. RWTs offer immediate storage, and RGs with adequate ponding depth can temporarily hold runoff before infiltration. Measures focused only on long-term volume reduction have limited impact on peak flows unless implemented at very large scale.

4.2.3. Overflow Frequency, Duration, and Spatial Patterns

In addition to peak flows, overflows were assessed using the 6-minute time resolution to identify manholes experiencing critical flooding. Overflow events were detected based on hydraulic outputs from manhole nodes within the model.

In this study, manholes with a flood volume greater than 0.001 ML and a maximum flood rate exceeding 0.01 m³/s were considered as overflowing nodes. These thresholds were selected to capture meaningful overflows while excluding negligible cases that represent minor surcharging without surface expression. It is important to note that a high flood rate alone may indicate surcharge conditions without actual overflow, as water can back up within the system without escaping it. Therefore, flood volume serves as a more reliable indicator of actual overflow, as it reflects the total water that leaves the system and appears at the surface. Conversely, prolonged flooding with very low flow rates may not generate significant volume and thus may not represent critical overflow conditions. By using both volume and rate alongside flood duration, this study accurately identifies manholes that require intervention and avoids overestimating the severity of minor or non-critical events (Rossman, 2022).

Overflow analysis revealed that the number of surcharged manholes varied dramatically across the five-year period from a minimum of 28 in 2021 to a maximum of 368 in 2022 out of 1009 manholes, which is driven primarily by short, intense storms rather than total annual rainfall. Table 4.3 summarizes the overflow characteristics by year.

Table 4.3. Annual Overflow Summary (2020- 2024)

| Year | Number of overflowed manholes out of 1009 manholes | Number of overflowed manholes in each duration of overflowing | |
|------------------------|--|---|-------|
| | | >1 hr | <1 hr |
| 2020 | 58 | >1 hr | 5 |
| | | <1 hr | 53 |
| 2021 | 28 | >1 hr | 11 |
| | | <1 hr | 17 |
| 2022 (wettest Year) | 368 | >1 hr | 45 |
| | | <1 hr | 323 |
| 2023 | 57 | >1 hr | 5 |
| | | <1 hr | 52 |
| 2024 | 54 | >1 hr | 13 |
| | | <1 hr | 41 |

Duration of overflow events can give a very important understanding of how deeply such events affect the operation and how serious they are, besides just frequency. As shown in Table 4.3, the majority of overflows in all years were brief events lasting less than 1 hr, suggesting temporary surcharging during peak storm intensity that recedes as rainfall abates. However, approximately 12% of overflows in 2022 exceeded 1 hr duration, indicating sustained hydraulic stress. Most concerning are the manholes that experienced exceptionally long overflow durations exceeding 5 hr in some cases.

Spatial Distribution of Overflows

Figures 4.5–4.9 show the spatial locations of overflowing manholes (indicated in red) for each year between 2020 and 2024, overlaid on the catchment network including pipes, nodes, sub-catchments, and the outlet location.

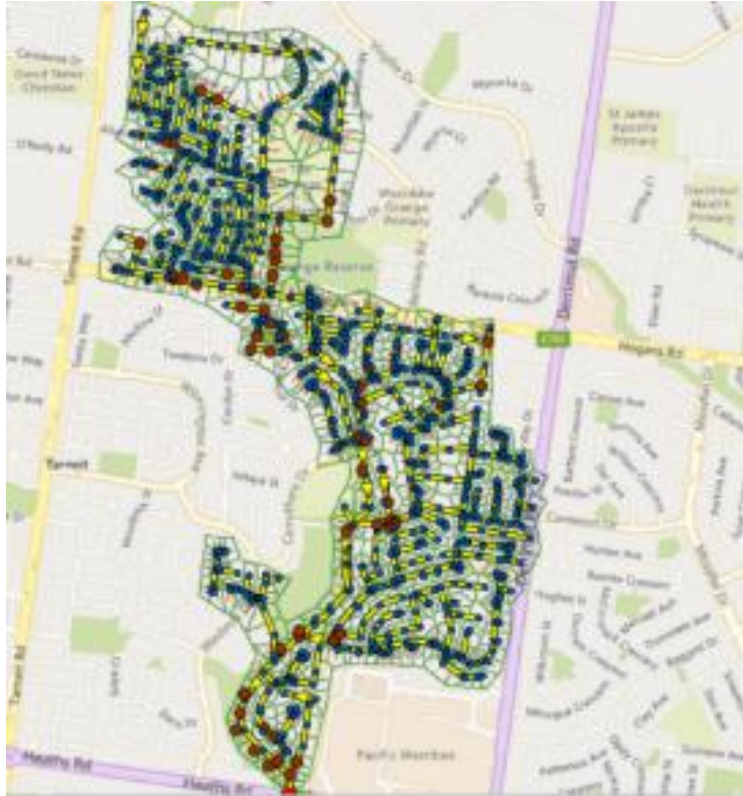


Figure 4.5. 2020 Overflowing Manholes Identified Based on Flood Volume and Flow Rate

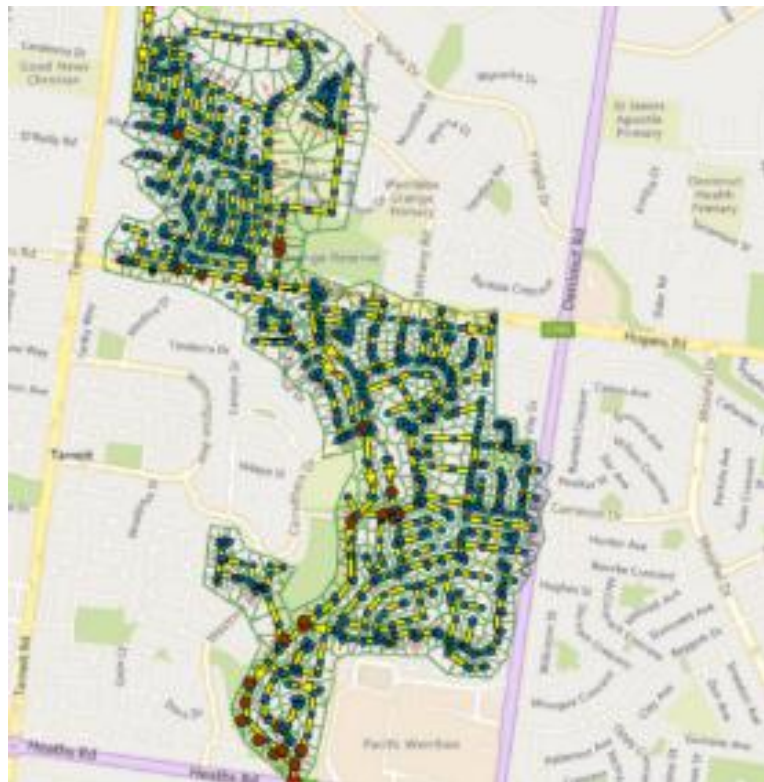


Figure 4.6. 2021 Overflowing Manholes Identified Based on Flood Volume and Flow Rate



Figure 4.7. 2022 Overflowing Manholes Identified Based on Flood Volume and Flow Rate

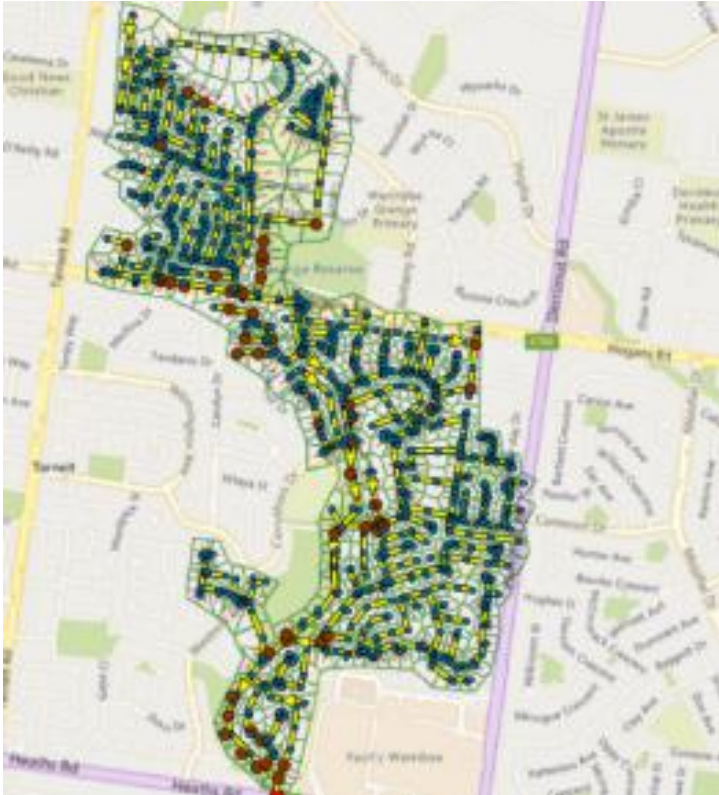


Figure 4.8. 2023 Overflowing Manholes Identified Based on Flood Volume and Flow Rate

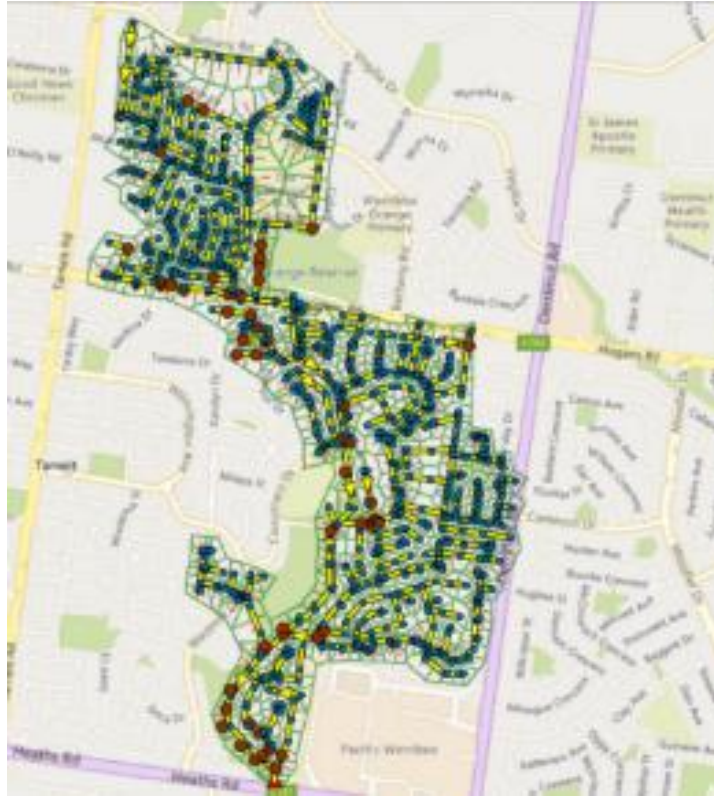


Figure 4.9. 2024 Overflowing Manholes Identified Based on Flood Volume and Flow Rate

This baseline overflow analysis over five years reveals a drainage system strained by capacity limits and vulnerable to short, intense rain bursts. Long-duration overflows often hit peripheral greenfield spots where pipes meet open channels, creating ponding in low-lying areas, mostly away from streets but poised to worsen with climate change or more development. Moderate overflows surged from one in 2020 to 21 manholes in 2022, driven by extreme intensities that spread surcharging wider and longer.

29 chronic nodes were identified as repeatedly overflowing (Appendix 2), highlighting persistent system weaknesses. Overflow behaviour closely followed rainfall intensity. In 2020, the driest year, only a few long-standing problem nodes overflowed. In 2021, slightly higher rainfall triggered minor increases at nodes such as 57001 and 12002. The system struggled most in 2022, when 1160 mm of rain and an extreme peak intensity of 124 mm/hr caused over 100 manholes to overflow, including many with no prior issues. Conditions improved in 2023 and 2024 as intensities dropped, confirming that short, intense bursts but not annual totals drive widespread surcharging.

Spatially, chronic overflows cluster at bottlenecks, depressions, flat slopes, and flow convergence points, needing upstream WSUD fixes or upgrades. Event-driven ones only kick in during extremes, highlighting future climate risks. Seasonally, summer convective storms dominate overflows, with clusters during saturated soil periods, but winter's steadier rain rarely causes issues. Though volumes aren't detailed here, a tiny fraction of manholes (about 1%) accounts for most overflow, posing the biggest flood threats due to their low spots and high inflows.

Overall, WSUD must prioritize cutting inflows from intense storms, targeting upstream of chronic nodes, while planning for emerging vulnerabilities. This sets the stage for evaluating WSUD scenarios ahead and boosting flood resilience in urban areas.

4.3 Quality Baseline Performance

Unlike sanitary wastewater systems where flows are treated at centralized facilities before discharge, stormwater drainage network provides zero treatment in this study. Pipes simply convey runoff and its pollutant load directly to receiving waters without any removal processes. Consequently, all pollutants mobilized from urban surfaces during rainfall are exported to downstream streams, creating the water quality degradation associated with the "urban stream syndrome." Table 4.4 presents the baseline annual pollutant loads discharged from the catchment outlet for each year from 2020 to 2024, calculated by multiplying the event mean concentrations (EMC) by the total annual runoff volume.

Table 4.4. Baseline Annual Pollutant Loads without WSUD Treatment (2020–2024)

| Year | Total Runoff Volume (ML) | TN Load (kg/year) | TP Load (kg/year) | TSS Load (kg/year) | TN EMC (mg/L) | TP EMC (mg/L) | TSS EMC (mg/L) |
|-------------|---------------------------------|--------------------------|--------------------------|---------------------------|----------------------|----------------------|-----------------------|
| 2020 | 62.19 | 163.6 | 22.4 | 9.33 | 2.63 | 0.36 | 150 |
| 2021 | 57.11 | 150.2 | 20.6 | 8.57 | 2.63 | 0.36 | 150 |
| 2022 | 76.78 | 201.9 | 27.6 | 11.52 | 2.63 | 0.36 | 150 |
| 2023 | 49.93 | 131.3 | 18.0 | 7.49 | 2.63 | 0.36 | 150 |
| 2024 | 45.54 | 119.8 | 16.4 | 6.83 | 2.63 | 0.36 | 150 |

In this area, the quality of stormwater depends on seasons and rain patterns. Pollutants accumulated on hard surfaces during dry summer times are removed very quickly by the first rains, thus creating a significant first-flush effect, whereas frequent winter rains keep the levels lower most of the time. Fine particles are washed off at the beginning of the storm events, thus carrying a large number of pollutants, and in general, runoff patterns are typical for a suburban residential area.

4.4 Baseline Summary and Key Problem Areas

The five-year baseline assessment indicates that the catchment's conventional drainage system is under significant stress, both hydraulically and environmentally, and will face worsening impacts from climate change and urban growth. Although the pipe network is able to cope with normal rainfall to a certain extent, chronic overflow occurs at some nodes, and extreme storms overwhelm much of the system. Since there is no treatment for pollutants, runoff carries contaminants directly to the receiving waters, resulting in poor ecological conditions. It would be expensive and hardly enough to solve these problems only by upgrading conventional pipes. Therefore, distributed WSUD measures, such as the use of RGs, RWTs, and hybrid systems, are the safest and most effective means to cut runoff, alleviate overflows, and enhance water quality, with the help of locally placed interventions at the most critical nodes and catchment-wide.

Chapter 5: WSUD Performance under system hydraulics, water quality and future scenarios

This section evaluates multiple WSUD retrofit configurations designed to address the identified hydraulic and water quality problems of stormwater drainage system. The analysis focuses on current climate conditions (2020–2024) to determine optimal WSUD strategies before extending to future scenarios.

5.1 WSUD Hydraulic Performance (2020–2024)

This section presents comprehensive hydraulic performance assessment for all WSUD scenarios across the five-year baseline period. The analysis begins by evaluating the critical design parameter of RWT drain time, followed by a comprehensive assessment of the impact of flow-routing configuration, before presenting detailed performance metrics for the optimal setup.

5.1.1 Impact of Flow Routing Configuration

Before evaluating different WSUD sizes, the influence of flow routing configuration was assessed for 2022 as the critical year with extreme overflow events, and for 2023 typical dry year. As outlined in Section 3, two routing options are available for managing the discharge from RWTs and raingardens. In the PCSWMM model, the selected routing setting applies to the portion of sub-catchment runoff allocated to these systems, meaning that all inflows routed through them follow the chosen configuration. Table 5.1 compares direct-outlet routing versus return-to-pervious routing for all five scenarios, using the largest system sizes, 4.5 kL rainwater to RWTs and 15 m² raingardens to capture the maximum effects.

Key Findings: Return-to-pervious routing consistently outperformed direct-outlet routing, improving overflow reduction by 11–27% during the 2022 extreme event and 20–51% in the more typical 2023, showing that allowing flows to infiltrate through pervious areas is substantially more effective than sending them directly back to the pipe network. In RWT scenarios, substantial roof-runoff volumes could drain slowly into lawns rather than re-entering the system, giving 18–27% improvement in 2022 and 31–37% in 2023. RG scenarios also benefited well through secondary surface infiltration. The hybrid scenario (25% RWT + 25% RG) performance demonstrated how

combining storage and infiltration becomes highly effective when flows are routed back to pervious areas.

Table 5.1. Impact of Flow Routing on Overflow Performance (2022 and 2023, 4.5 kL RWT, 15 m² RG)

| Scenario | LID Configuration | Number of Overflowed Manholes in 2022 (Wettest Year) | | | Number of Overflowed Manholes in 2023 (Typical Dry Year) | | |
|-----------------|-------------------|--|--------------------|-------------|--|--------------------|-------------|
| | | Direct Outlet | Return to Pervious | Improvement | Direct Outlet | Return to Pervious | Improvement |
| Baseline | None | 368 | 368 | — | 57 | 57 | — |
| A | 25% RWT | 360 | 291 | 18% | 31 | 13 | 31.4% |
| B | 50% RWT | 357 | 260 | 27.2% | 30 | 9 | 36.6% |
| C | 25% RWT + 25% RG | 358 | 274 | 23.5% | 30 | 5 | 43.6% |
| D | 25% RG | 362 | 319 | 11% | 35 | 28 | 20% |
| E | 50% RG | 360 | 271 | 24.7% | 34 | 5 | 50.6% |

Conclusion: All subsequent analyses use **return-to-pervious routing exclusively** as this represents best-practice WSUD implementation and achieves substantially superior performance.

5.1.2 Rainwater Tank Drain Time Optimization Analysis

Drain time is one of the most important design parameters for RWTs in stormwater drainage system management, as outlined in Section 3.7. Three drain-time configurations were assessed, and their corresponding drain coefficients (C) were previously presented in Table 3.2. After completing the modelling, the overflow performance for all three configurations over the full five-year period, using 4.5 kL RWTs with return-to-pervious routing, is summarised in Table 5.2.

Table 5.2. Impact of Tank Drain Time on Overflow Performance (2020–2024, 4.5 kL RWT, Return to Pervious)

| Scenario | Drain Time | Number of Overflowed Manholes | | | | | | | Overflow Duration | |
|-----------------|------------|-------------------------------|------|------|------|------|-------|----------------------------|---------------------------------------|---------------------------------------|
| | | 2020 | 2021 | 2022 | 2023 | 2024 | Mean | Mean Reduction vs Baseline | Mean >1hr Event Reduction vs Baseline | Mean <1hr Event Reduction vs Baseline |
| Baseline | None | 58 | 27 | 368 | 57 | 54 | 112.8 | — | — | — |
| 25% RWT | 6 hr | 9 | 11 | 278 | 12 | 31 | 69.8 | 38.1% | 77% | 61% |
| 25% RWT | 12 hr | 11 | 13 | 291 | 13 | 35 | 73.6 | 34.8% | 76% | 57% |
| 25% RWT | 24 hr | 15 | 15 | 308 | 16 | 39 | 78.6 | 30.3% | 69% | 42% |
| 50% RWT | 6 hr | 7 | 7 | 237 | 9 | 19 | 55.8 | 50.5% | 80% | 67% |
| 50% RWT | 12 hr | 9 | 11 | 263 | 9 | 23 | 63.4 | 43.8% | 78% | 61% |
| 50% RWT | 24 hr | 11 | 13 | 283 | 11 | 27 | 69.0 | 38.8% | 70% | 50% |

These combined results show that tank drain time has a clear and consistent influence on hydraulic behaviour across all years, with the same performance ranking in every scenario: 6-hr > 12-hr > 24-hr. Mainly, the 6-hr drain time led to the greatest total overflow reduction, particularly during the clustered storm sequence of 2022, where rapid emptying allowed tanks to recover storage between storm bursts and thus the occurrence of a large number of additional overflows that were the slow configurations. Despite this numerical advantage, the 12-hr drain time performed almost as well, providing substantial reductions in both total overflows and overflow durations while offering greater operational stability, more balanced detention behaviour, and full alignment with Melbourne Water guidelines. Duration metrics reinforce this pattern: both 6-hr and 12-hr configurations reduced long-duration (>1 hr) overflows by ~70–80%, while the 24-hr option consistently underperformed due to insufficient drainage between events, leading to higher counts of both long- and short-duration surcharges. Overall, while the 6-hr setting yields the highest

hydraulic benefit, the 12-hr drain time provides the most reliable and well-balanced performance, making it the preferred configuration for all subsequent WSUD modelling in this study.

5.1.3 Overflow Analysis

This section presents comprehensive overflow assessment across two critical dimensions: (1) optimization of WSUD component sizing (RWT capacity and RG area), and (2) comparative evaluation of implementation scenarios (coverage levels and measure combinations) to identify the configuration that delivers optimal flood risk reduction.

Three RWT sizes (3.5, 4, 4.5 kL) and two RG sizes (10, 15 m²) were evaluated to determine optimal configurations that balance performance, cost, and footprint requirements, as discussed in chapter 3. Table 5.3 presents overflow frequency for the wettest year (2022), a typical dry year (2023), and a moderate year (2020) to assess performance across the full range of observed conditions.

Table 5.3. Overflow Frequency by WSUD Size Configuration

| Scenario | Configuration | 2022 | | 2023 | | 2020 | |
|----------------------|--|-------------------------------|-------------------|-----------|-------------------|-----------|-------------------|
| | | Number of Manholes Overflowed | Reduction vs Base | Overflows | Reduction vs Base | Overflows | Reduction vs Base |
| Baseline | None | 368 | — | 57 | — | 58 | — |
| A₁ | 25% RWT 3.5 kL | 300 | 18.5% | 15 | 73.7% | 14 | 75.9% |
| A₂ | 25% RWT 4.0 kL | 293 | 20.4% | 14 | 75.4% | 13 | 77.6% |
| A₃ | 25% RWT 4.5 kL | 291 | 20.4% | 13 | 75.4% | 11 | 79.3% |
| B₁ | 50% RWT 3.5 kL | 268 | 27.2% | 10 | 82.5% | 10 | 82.8% |
| B₂ | 50% RWT 4.0 kL | 265 | 28.0% | 9 | 84.2% | 9 | 84.5% |
| B₃ | 50% RWT 4.5 kL | 263 | 29.2% | 9 | 84.2% | 8 | 86.2% |
| C₁ | 25% RWT 3.5 kL + 25% RG 10 m ² | 272 | 26.1% | 10 | 82.5% | 8 | 86.2% |
| C₂ | 25% RWT 4.0 kL + 25% RG 10 m ² | 276 | 25.0% | 6 | 89.5% | 7 | 87.9% |
| C₃ | 25% RWT 4.5 kL + 25% RG 15 m ² | 274 | 25.5% | 5 | 91.2% | 5 | 91.4% |
| D₁ | 25% RG 10 m ² | 320 | 13% | 29 | 49.1% | 31 | 46.5% |
| D₂ | 25% RG 15 m ² | 319 | 13.3% | 28 | 50% | 31 | 46.5% |
| E₁ | 50% RG 10 m ² | 277 | 24.7% | 6 | 89.5% | 7 | 87.9% |
| E₂ | 50% RG 15 m ² | 271 | 26.4% | 5 | 91.2% | 6 | 89.7% |

Component Sizing Effects on Overflow

The results show that increasing RWT size from 4.0 kL to 4.5 kL makes almost no difference in reducing overflows. In most storms, a 4.0 kL RWT already provides enough storage, and the extra half-kilolitre in a 4.5 kL RWT simply isn't used. In contrast, dropping the size to 3.5 kL does lead to a small but noticeable decline in performance around 5–10% each year. This suggests that while 3.5 kL RWT still performs better than having no RWT, it is slightly small to deliver reliable outcomes.

For RGs, the 15 m² design offers only minor improvements over the 10 m² option, despite needing much more space and costing more to build. Even in the extreme conditions of 2022, when extra capacity should matter most, the 15 m² system made almost no difference (<1–2.2%) from 10 m² option. It is because that when rainfall intensity becomes very high, infiltration limits performance regardless of surface area. Across normal years, the performance gap remains small because a 10 m² RG already handles residential runoff effectively. Making it larger mainly increases ponding area but will not significantly improve infiltration rate due to the limits of the native soil.

Given these results—and considering that the 4.0 kL RWT is the industry standard in Australia, with widespread availability, practical installation requirements, and consistency with Melbourne Water guidelines—the 4.0 kL RWTs + 10 m² RGs configuration was selected as the representative WSUD design for detailed hydraulic and water-quality assessment in this study.

Scenario Implementation Effects: Optimal Coverage and Measure Selection

On the other hand, Table 5.4 presents overflow duration performance just for 4 kL RWTs and 10 m² raingardens in the wettest year (2022), a typical dry year (2023), and a typical moderate year (2020), and mean overflow duration reduction for all years (2020-2024).

Assessment of the WSUD implementation scenarios shows that both coverage level and measure type strongly influence overflow behaviour, with high-coverage RWT and RG systems delivering the most substantial and stable benefits. As shown in Table 5.3, 50% RWT and 50% RG exhibit broadly comparable performance, each reducing overflow frequency by 24–91% across the range of wet, moderate, and dry years. The 50% RG scenario performs slightly better during typical years (2023 and 2020), reaching 89–91% reduction, while 50% rainwater RWT performs marginally better under extreme conditions (2022). Duration results in Table 5.4 further confirm this

similarity. Both scenarios achieve strong reductions of 78% for 50% RWT and 77% for 50% RG in long-duration (>1hr) events, and 60–63%, of reduction for short-duration (<1hr) events, demonstrating that infiltration-dominated and storage-dominated systems provide comparable resilience when deployed at sufficient coverage. The hybrid 25% RWT + 25% RG configuration also performs strongly, offering balanced improvements across both duration categories (73% and 61%) and achieving 25–91% frequency reduction, benefitting from the combined effect of RWT storage and distributed infiltration. In contrast, lower-coverage configurations such as 25% RWT or 25% RG show weaker reductions of typically below 55% for >1hr duration—and fail to provide reliable mitigation during the extreme 2022 event.

Table 5.4. Overflow Duration Performance by WSUD Implementation Scenarios (4.0 kL RWT, 10 m² RG)

| Scenario | 2020 | | 2022 | | 2023 | | Mean >1hr Event Reduction | Mean >1hr Event Reduction |
|------------------------------------|-------------------------------------|-----|-------------------------------------|-----|-------------------------------------|-----|---------------------------------|---------------------------------|
| | Number of Manholes Overflowed | | Number of Manholes Overflowed | | Number of Manholes Overflowed | | | |
| | >1h | <1h | >1h | <1h | >1h | <1h | | |
| Baseline | 5 | 53 | 39 | 329 | 5 | 52 | - | - |
| A: 25% RWT | 0 | 13 | 19 | 274 | 0 | 14 | 75% | 55% |
| B: 50% RWT | 0 | 9 | 16 | 249 | 0 | 9 | 78% | 60% |
| C: 25% RWT + 25% RG | 0 | 7 | 23 | 253 | 0 | 6 | 73% | 61% |
| D: 25% RG | 4 | 27 | 37 | 283 | 4 | 25 | 22% | 36% |
| E: 50% RG | 0 | 7 | 21 | 256 | 0 | 6 | 77% | 63% |

5.1.4 Surface Runoff Analysis

Having identified the optimal WSUD configuration (4.0 kL RWT+ 10 m² RG) based on overflow performance, this section now evaluates the broader volumetric benefits—specifically, the reduction in total surface runoff across the catchment. Reducing runoff volume is a core aim of WSUD because it directly addresses hydrologic change and plays a major role in lowering pollutant loads. Table 5.5 summarises the annual surface runoff (SR) for all scenarios from 2020–2024, along with percentage reductions compared to the no-WSUD baseline.

Table 5.5. Annual Surface Runoff (SR) Volume Performance (2020–2024, 4.0 kL RWT, 10 m² RG)

| Scenario | 2020 | | 2021 | | 2022 | | 2023 | | 2024 | |
|----------------------------|---------|--------------|---------|-------------|---------|-------------|---------|-------------|---------|-------------|
| | SR (ML) | ΔSR vs Base* | SR (ML) | ΔSR vs Base | SR (ML) | ΔSR vs Base | SR (ML) | ΔSR vs Base | SR (ML) | ΔSR vs Base |
| No WSUD (Baseline) | 62.19 | - | 57.11 | - | 76.78 | - | 49.93 | - | 45.54 | - |
| A: 25% RWT | 28.35 | -54.4% | 27.04 | -52.7% | 41.00 | -46.6% | 22.45 | -55.1% | 22.11 | -51.4% |
| B: 50% RWT | 23.84 | -61.7% | 23.21 | -59.4% | 34.91 | -54.5% | 19.02 | -61.9% | 18.77 | -61.9% |
| C: 25% RWT + 25% RG | 17.96 | -71.1% | 17.85 | -68.7% | 30.18 | -60.7% | 14.07 | -71.8% | 14.97 | -67.1% |
| D: 25% RG | 44.15 | -29.0% | 41.04 | -28.1% | 29.48 | -61.6% | 35.16 | -29.6% | 32.79 | -28.0% |
| E: 50% RG | 13.52 | -78.3% | 13.91 | -75.7% | 25.86 | -66.3% | 10.64 | -78.7% | 11.79 | -74.1% |

* % reduction in surface runoff in comparison to base case

Surface-runoff results in Table 5.5 shows clear performance differences between WSUD configurations, with effectiveness strongly shaped by both measure type and implementation coverage. The 50% RG scenario (E) could achieve the largest and most stable reductions of 74% on average, ranging from 66 to 79% over the five years. Therefore, it indicated the advantage of

widespread infiltration that was well-distributed throughout the catchment. The hybrid scenario (25% RWT + 25% RG) ranked second with a 67% mean reduction, delivering consistently strong performance due to the complementary interaction between tank-based roof runoff capture and distributed infiltration. The 50% RWT scenario (B) also performed reliably, achieving a 59% mean reduction with low climate sensitivity as tank storage and 12-hr drain time help in maintaining effectiveness at a relatively constant level between storm events.

At low implementation (25%), RWTs were more effective than RGs (mean 52% vs 37% reduction) because RWTs directly intercept roof runoff, which is the largest and most responsive source of impervious flow. Thus, they are able to provide immediate capture, detention, and reuse benefits. In contrast, 25% RG covers only a limited portion of contributing impervious areas, so its infiltration effect remains modest and roof runoff largely continues to discharge into the stormwater system. These findings demonstrate that small, spatially dispersed infiltration systems have inherently limited hydrologic impact at low coverage.

However, as coverage increases, the behaviour shifts. Infiltration-based WSUD becomes substantially more effective. At 50% coverage, RGs operate at a scale large enough to meaningfully reshape the catchment water balance, explaining why 50% RG surpasses 50% RWT, while the performance of the RWT remains relatively stable at different coverage levels. In general, only the scenarios with high coverage ($\geq 50\%$ RWT, $\geq 50\%$ RG, or the hybrid 25%+25%) consistently meet or exceed the $\geq 50\%$ runoff-reduction target, with the hybrid and 50% RG scenarios performing the strongest and most reliably across all years.

5.1.5 Outflow Analysis

In addition to counting overflowed junctions and runoff analysis, evaluating WSUD effectiveness also requires analysing outflow variations. Therefore, a detailed outflow assessment was performed based on hydraulic outputs from PCSWMM to compare the performance of different WSUD scenarios. Outflow data were extracted at the terminal pipe of the stormwater network for each scenario from 2020 to 2024.

Peak Outflow Analysis:

The comparative 5.1–5.5 graphs in below show the outflow rates for each scenario plotted against the recorded rainfall intensity during this peak event. It clearly illustrates the effectiveness of WSUD interventions in attenuating peak flows, with scenarios incorporating RWTs and raingardens.

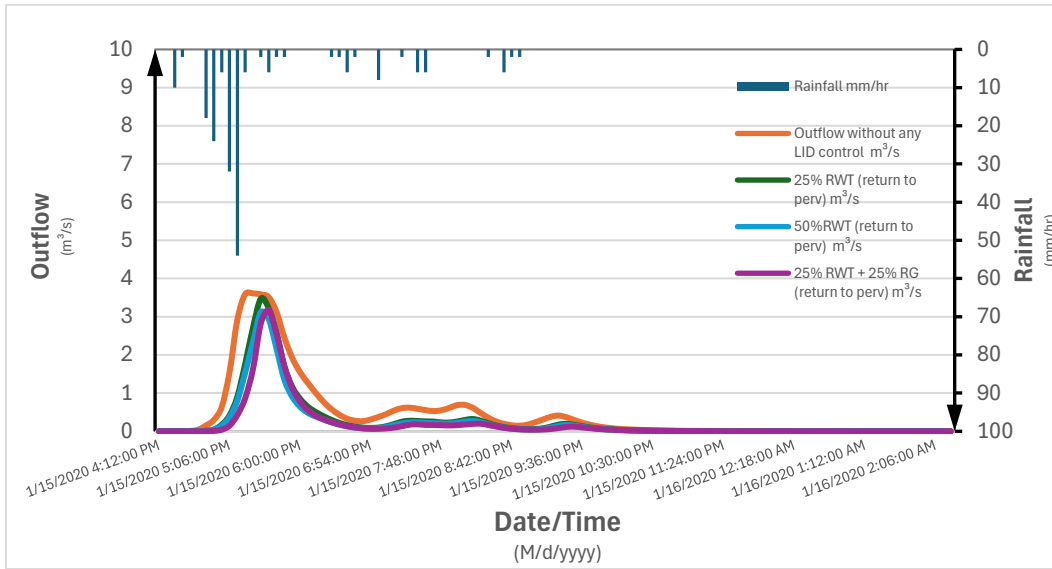


Figure 5.1. 2020 peak outflow comparison across four scenarios – relative to rainfall variations.

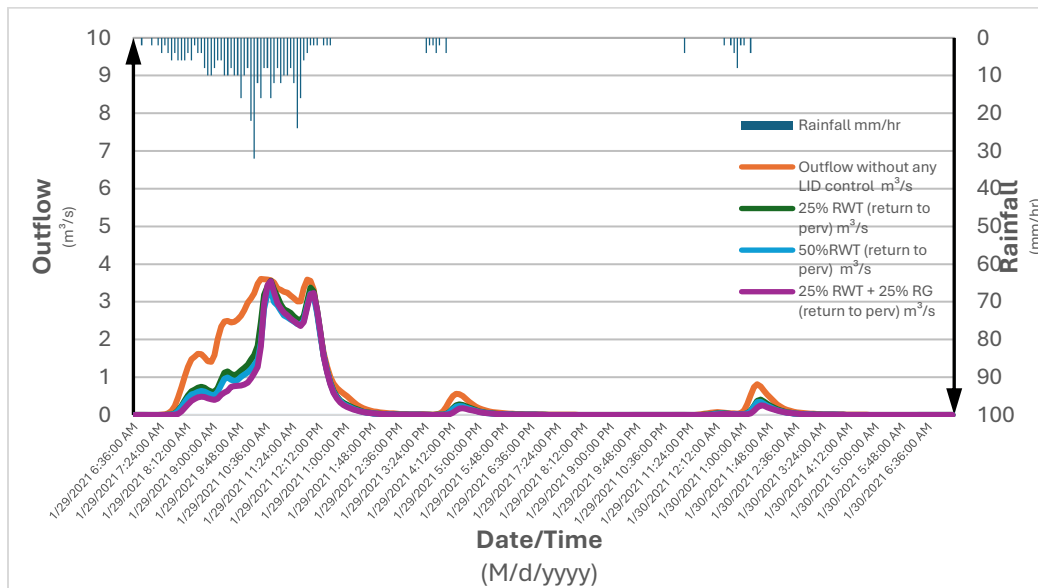


Figure 5.2. 2021 peak outflow comparison across four scenarios – relative to rainfall variations.

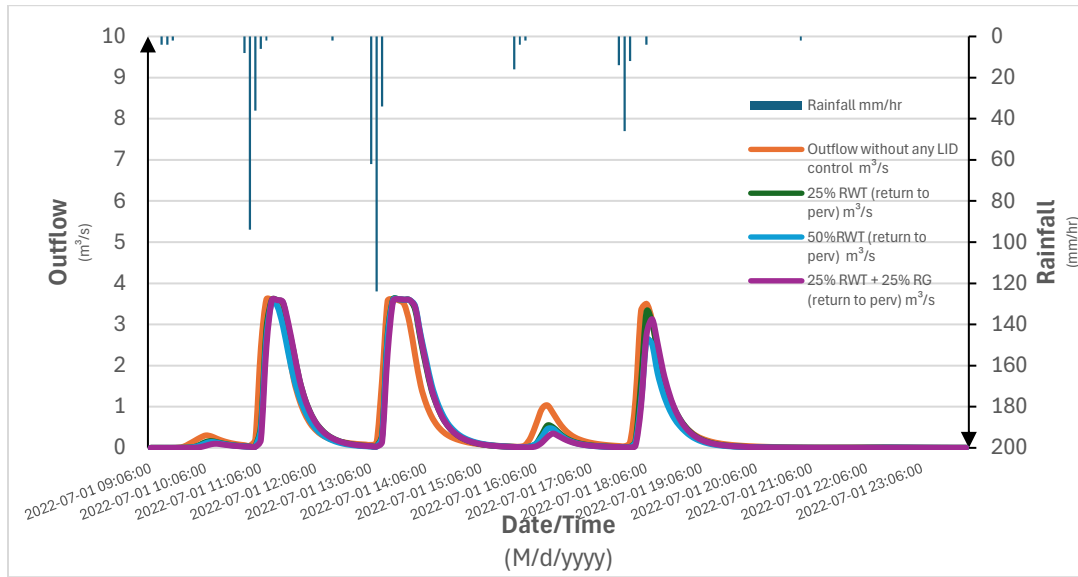


Figure 5.3. 2022 peak outflow comparison across four scenarios – relative to rainfall variations.

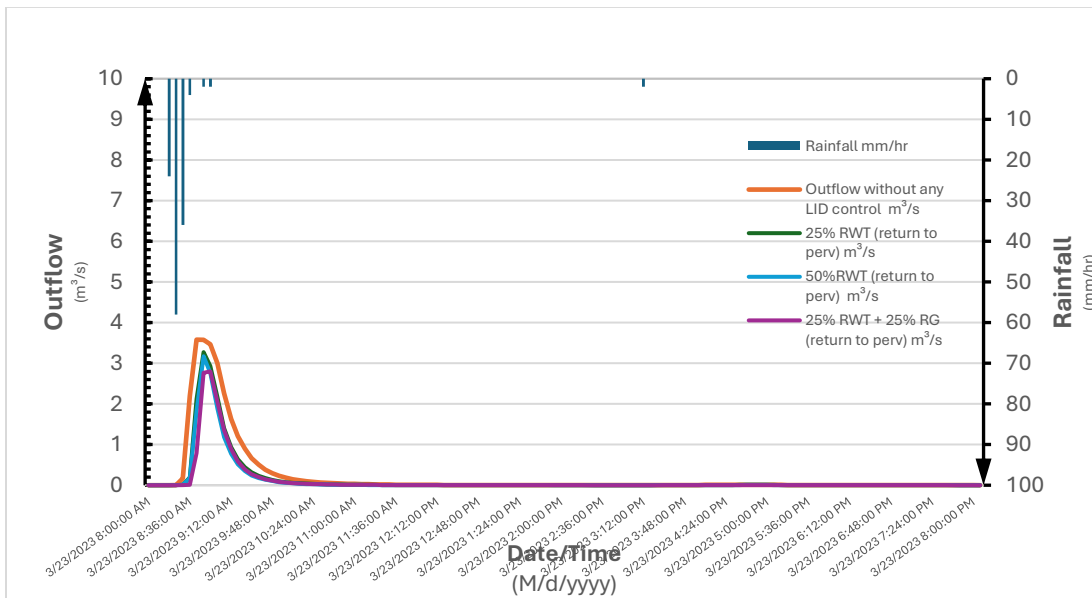


Figure 5.4. 2023 peak outflow comparison across four scenarios – relative to rainfall variations.

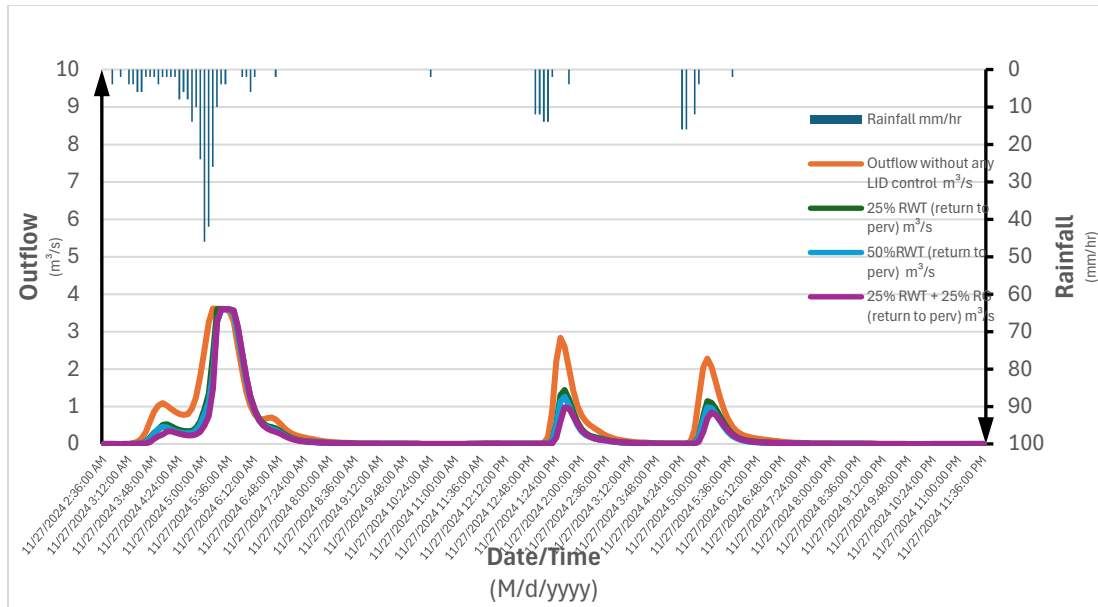


Figure 5.5. 2024 peak outflow comparison across four scenarios – relative to rainfall variations.

Peak-outflow analysis across the five-year period shows that WSUD delivers modest but hydraulically important peak-outflow reductions because the outlet is governed by a capacity-limited system where baseline peaks remained almost identical ($\sim 2.60 \text{ m}^3/\text{s}$) across all conditions. As shown in above Figures, the Hybrid (25% RWT + 25% RG) scenario consistently produced the greatest attenuation of $\sim 12\%$ on average and up to 16% during critical events in 2022 and 2023, due to combined early capture by RWTs and sustained infiltration from RGs. The 50% RWT configuration ranked second ($\sim 7\%$), especially effective in years with dry antecedent conditions (e.g., 2023). RG-only scenarios exhibited limited peak clipping ($< 5\%$) because infiltration processes require longer response times. Although the percentage reductions appear small, the absolute peak decreases ($0.15\text{--}0.42 \text{ m}^3/\text{s}$) significantly reduce pressure on downstream pipes that normally run at 95–105% capacity, bringing them back into safe operating ranges and extending recession limbs.

Mean Outflow Analysis:

Because peak-outflow attenuation alone cannot reveal how WSUD influences the overall hydraulic loading of the system, a complementary assessment of mean outflow was undertaken. Figures 5.6–

5.10 therefore present the multi-year mean-outflow trends for 2020–2024, demonstrating how different WSUD scenarios alter long-term discharge volumes and the sustained hydrologic behaviour of the catchment.

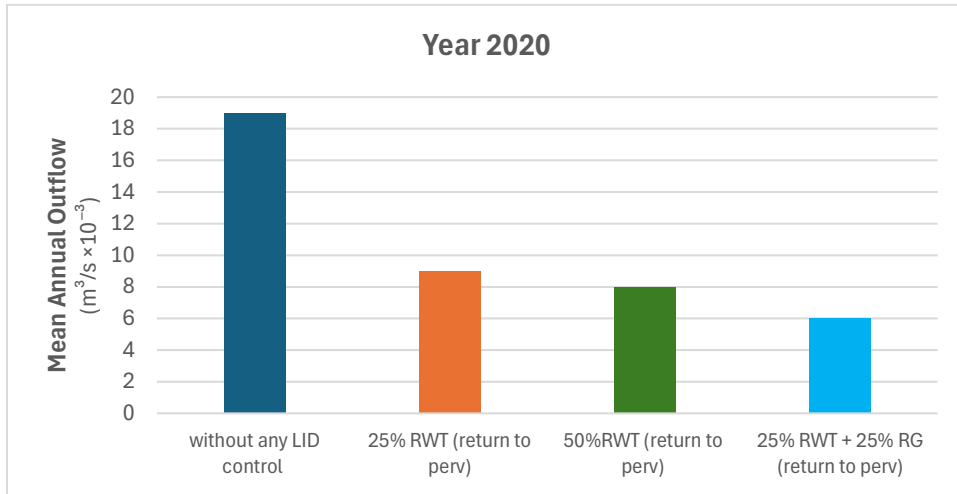


Figure 5.6. 2020 mean outflow comparison across four scenarios

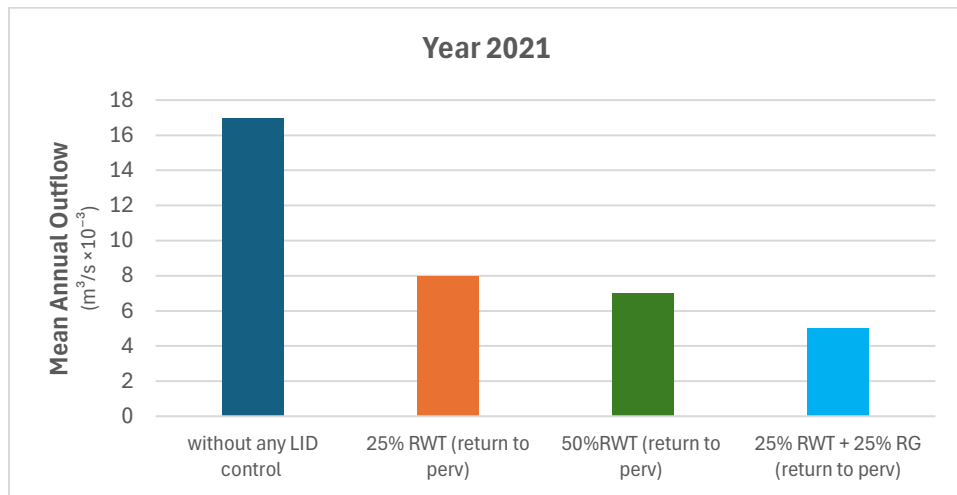


Figure 5.7. 2021 mean outflow comparison across four scenarios

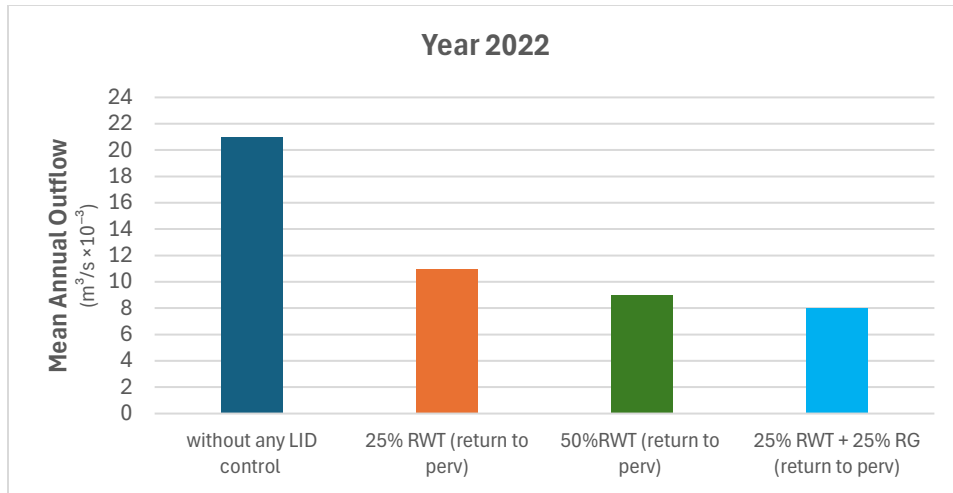


Figure 5.8. 2022 mean outflow comparison across four scenarios

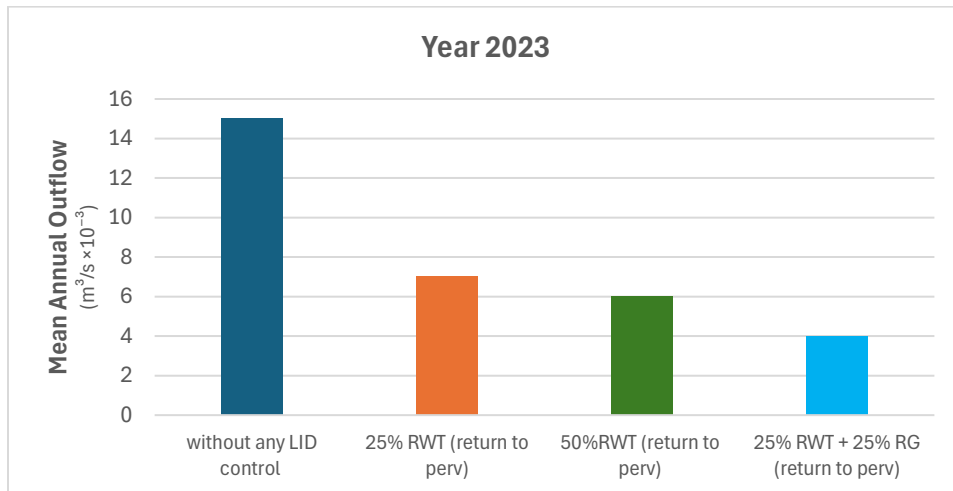


Figure 5.9. 2023 mean outflow comparison across four scenarios

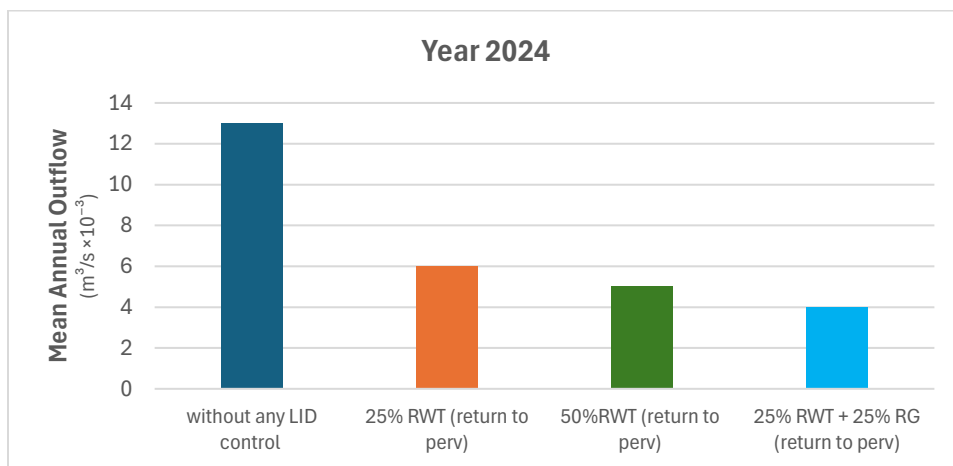


Figure 5.10. 2024 mean outflow comparison across four scenarios

In contrast to peak flows, mean outflows show substantial and highly consistent reductions, closely matching the surface-runoff volume reductions described earlier. As illustrated in figures, mean annual flows decreased by 62–70% under the Hybrid scenario and by 74–79% under the 50% RG scenario, with flows in 2020 dropping from 0.0195 to 0.0060 m³/s, and similar proportional reductions each year. The ranking of scenario performance in mean outflow matches the ranking for volume control is 50% RG > Hybrid > 50% RWT > 25% RWT > 25% RG, confirming that these benefits originate from source-control mechanisms (reuse, infiltration, evapotranspiration) rather than peak attenuation. Unlike overflow frequency or peak-flow metrics, mean-outflow reductions remained highly stable across wet and dry years, demonstrating strong long-term reliability.

5.2 WSUD Water Quality Performance (2020–2024)

As established in Section 4.3, the conventional drainage system provides no water quality treatment, conveying stormwater directly from impervious surfaces to receiving streams without filtration, retention, or biological processing. Table 5.6 presents the annual percentage reductions in TN, TP, and TSS loads achieved by each WSUD scenario relative to the no-WSUD baseline for the five-year analysis period. All results are based on the mid-range WSUD specifications: 4.0 kL RWTs with 12-hr drain time and 10 m² RGs with standard bioretention design.

Findings from Table 5.6 indicate that pollutant-load reductions follow a clear and consistent pattern across all five years. The 50% RG scenario is the best performer overall, achieving reductions of TN in rang of 15–21%, TP in rang of 21–28%, and TSS in rang of 30–40%. The main reason for its success is the combination of the greatest reduction in runoff volume ($\approx 76\%$) with multi-stage bioretention operations such as sedimentation, filtration, phosphorus adsorption, and denitrification.

The hybrid (25% RWT + 25% RG) scenario ranks second, providing reductions of TN in rang of 12–17%, TP in rang of 18–24%, and TSS in rang of 28–37.5%, which are equivalent to $\sim 70\text{--}95\%$ of the performance of the 50% RG option's performance, despite splitting the coverage between two measure types. RWTs primarily treat roof runoff via sedimentation, while RGs supply

filtration and biological treatment for ground-based runoff, thus creating a strong complementary effect.

Table 5.6. Annual Pollutant Load Reduction Percentage Achieved by WSUD Scenarios (mid-range 10 m² RG and 4 kL RWT)

| Year | Scenario | TN ↓ | TP ↓ | TSS ↓ |
|-----------------------|------------------|------|------|-------|
| 2020 | 25% RWT | 6% | 8% | 16% |
| | 50% RWT | 12% | 16% | 31% |
| | 25% RWT + 25% RG | 15% | 21% | 33% |
| | 25% RG | 9% | 12% | 18% |
| | 50% RG | 18% | 25% | 36% |
| 2021 | 25% RWT | 6% | 8% | 16% |
| | 50% RWT | 12% | 16% | 31% |
| | 25% RWT + 25% RG | 15% | 22% | 33% |
| | 25% RG | 9% | 13% | 18% |
| | 50% RG | 19% | 26% | 36% |
| 2022 (Wet) | 25% RWT | 5% | 6.5% | 13% |
| | 50% RWT | 10% | 14% | 26% |
| | 25% RWT + 25% RG | 12% | 18% | 28% |
| | 25% RG | 7% | 10% | 15% |
| | 50% RG | 15% | 21% | 30% |
| 2023 | 25% RWT | 7% | 9% | 17.5% |
| | 50% RWT | 14% | 19% | 35% |
| | 25% RWT + 25% RG | 17% | 24% | 37.5% |
| | 25% RG | 10% | 14% | 20% |
| | 50% RG | 21% | 28% | 40% |
| 2024 | 25% RWT | 7% | 9% | 17.5% |
| | 50% RWT | 14% | 19% | 35% |
| | 25% RWT + 25% RG | 17% | 24% | 37.5% |
| | 25% RG | 10% | 14% | 20% |
| | 50% RG | 21% | 28% | 40% |

The 50% RWT scenario shows intermediate results (reductions of 10–14% to TN, 14–19% to TP, and 26–35% to TSS) consistent with strong volume capture (reduction≈59%) but limited concentration treatment. Meanwhile, 25% RWT and 25% RG scenarios provide only modest benefits (reductions of 5–10% to TN, 6.5–14% to TP, and 13–20% to TSS), that emphasize low coverage cannot significantly improve catchment-scale water quality.

Pollutant Behaviour

- TSS shows the greatest reductions (up to 40%) due to effective sedimentation (in RWTs) and soil filtration (in RGs).
- TP reductions (up to 28%) occur mainly through particulate settling and phosphorus adsorption in RG soil media.
- TN shows the smallest reductions (up to 21%), since most nitrogen exists in dissolved forms requiring biological processing; RGs outperform RWTs due to their saturated zone that supports denitrification.

Climate Sensitivity

WSUD performance is consistently 2–6% higher in dry years than wet years. For example, in the 50% RG scenario:

- TN reduction: 21% (dry) vs 15% (wet)
- TP reduction: 28% (dry) vs 21% (wet)
- TSS reduction: 40% (dry) vs 30% (wet)

During dry years, infiltration capacity can be fully restored, and longer residence times are possible, whereas in wet years, treatment is limited due to soil saturation and RWT spill-and-bypass situations.

Mechanistic Insight

Across all scenarios, volume reduction contributes to 50–75% of the overall pollutant-load reduction, and treatment processes contributes 25–50% reduction. For TN, the reduction is mainly volume-driven. TP reduction is moderately split. TSS removal is strongly influenced by filtration + sedimentation.

5.3 WSUD Performance Summary (2020–2024)

The performance of WSUD in the urban catchment followed a very distinct pattern across all the analyses. Systems with high coverage (50% RWT, 50% RG, and the hybrid 25% RWT + 25% RG) showed the strongest and most stable hydraulic and water-quality benefits, while 25% scenarios only produced small and climate-sensitive improvements. The overflow and duration figures indicated that 50% RWTs and 50% RGs were quite close in performance overall, each resulting in a large reduction of the frequency of overflow and long-duration events, with the hybrid scenario performing almost as well due to the combined effect of storage and infiltration. Surface-runoff results confirmed this hierarchy. 50% RG provides the highest reductions, typically around the 70–80% range, followed by the hybrid with reduction of 65–70%, then 50% RWTs with reduction of 55–60%.

Peak-flow reductions were modest (generally 8–16%), but hydraulically meaningful in a capacity-limited network. Mean outflows closely followed the runoff-reduction pattern, showing large and stable annual reductions under high-coverage scenarios and confirming that WSUD benefits come mainly from source control rather than peak attenuation. Similarly, water-quality results showed the same ranking pattern. 50% RG was the best performer for removals of TN, TP, and TSS (approximately 15–40% reductions), the hybrid was following closely, and 50% RWT was providing moderate improvements, while low-coverage scenarios delivered only minor gains (removal < 20%). In general, RGs were more efficient in removing pollutants, while RWTs were more effective in capturing volume, and hybrid systems balanced both dimensions well.

Overall, the findings indicate that RWTs perform best in dry conditions, RGs in wet conditions, and the 25% RWT + 25% RG hybrid provides the most robust and climate-resilient performance.

5.4 Climate Change and Urbanization (Future Scenarios)

The previous sections have shown the performance of WSUD under the existing conditions (2020–2024), thus proving the significant gains for both hydraulic control and water quality improvement. However, the situation of urban water systems is worsening due to two combined factors: climate change, which is intensifying rainfall events and altering precipitation patterns, and urbanization,

which continues to increase impervious surface coverage and reduce natural infiltration capacity. It is critical to know how these future drivers affect both the performance of the baseline system and the effectiveness of WSUD, in order to be able to plan stormwater management that is still efficient over infrastructure design lifetimes going to mid-century (2050) and even further (2070).

This section evaluates system behaviour under three set of future scenarios:

- Climate-only scenarios: the effect of future rainfall changes under projected climate conditions, while imperviousness remains unchanged, allowing the isolated assessment of climate change impacts.
- Urbanization-only scenarios: Increased imperviousness under current climate conditions, isolating the effects of ongoing urban densification
- Combined scenarios: The effects of both climate change and urbanization are applied simultaneously to represent the most realistic future conditions.

5.4.1 Climate Change Only (2050 & 2070)

The climate-only scenarios isolate the effect of intensified rainfall on both baseline system behaviour and WSUD effectiveness by applying future climate projections while maintaining current urban form (64% imperviousness). This analysis addresses how vulnerable is the existing drainage infrastructure to climate change alone. In addition to annual rainfall totals, the temporal distribution of rainfall was examined using 6-minute rainfall time series for the future climate scenarios (2050 and 2070), including seasonal variability and changes in rainfall intensity, to ensure that projected runoff responses reflect shifts in rainfall characteristics rather than total volume alone.

Baseline Response to Climate Change (No WSUD)

Table 5.7 presents baseline system performance under climate-only conditions for both 2050 and 2070, with comparison to current 2024 baseline to quantify climate change impacts.

Table 5.7. Baseline System Performance Under Climate-Only Scenarios (No WSUD)

| Scenario | Annual Rainfall (mm) | Annual Rainfall vs 2024 Baseline | Total Runoff Volume (m ³) | Total Runoff Change vs 2024 Baseline |
|-------------------|----------------------|----------------------------------|---------------------------------------|--------------------------------------|
| 2024 (baseline) | 418.1 | — | 455,550 | — |
| 2050 Climate-only | 519.69 | +24.3% | 594,160 | +30.4% |
| 2070 Climate-only | 644.24 | +53.8 | 700,780 | +54% |

Climate-only projections show significant hydrological intensification despite maintaining a constant urban form. The intensities of short rainfall events in 2050 leading to about 520 mm rainfall cause runoff volume to increase by 30.4% compared to the base year 2024 as shown in Figure 5.7. This is mainly due to very short and intense rainfall events that the infiltration capacity cannot accommodate, although the total impervious area remains unchanged. The increase in the atmospheric moisture-holding capacity is evident from higher rainfall intensities during storm events thus, producing proportionally greater runoff generation.

By 2070, the climate impacts are even more significant, with runoff volumes increasing by 53.8% compared to current conditions. It should be noted that this increase takes place even though the 2070 climate scenario results in only 644 mm of total annual rainfall, which is about 9% less than the wettest historical year (2022, 704.6 mm). The apparent paradox is lower total rainfall producing higher runoff, which demonstrates that future hydrologic stress is driven by rainfall intensity rather than total volume. The 2070 climate produces more frequent high-intensity convective storms with peak rates exceeding infiltration and pipe conveyance capacity, thus, generating disproportionate runoff despite similar or lower annual totals.

A more detailed review of the event-scale rainfall series was undertaken to better understand the observed differences between rainfall and runoff responses. The analysis indicated that future rainfall increases are increasingly associated with shorter-duration, higher-intensity storm bursts rather than uniform increases over the whole year. Under the 2050 scenario, these intensified

events more frequently exceed the infiltration and minor storage capacity of the catchment, resulting in a disproportionate increase in direct surface runoff relative to total rainfall (+30.4% runoff versus +24.3% rainfall). By 2070, although storm intensities continue to increase, a larger portion of the catchment response is already runoff-dominated, meaning that additional rainfall produces a more proportionate increase in runoff (+54% versus +53.8%). This illustrates the combined impact of the concentration in time of rainfall and progressive system saturation on runoff generation in the future.

Furthermore, although high temperatures could increase potential evapotranspiration, intense storms produce fast runoff that bypasses soil-storage pathways, and longer dry periods limit actual evapotranspiration, meaning that the additional rainfall under climate change is not offset by atmospheric or soil-moisture processes.

5.4.2 urbanization Only (2050 & 2070)

The urbanization-only scenarios isolate the impact of increased imperviousness under current climate conditions, enabling assessment of how ongoing urban densification affects stormwater performance independent of climate change. This analysis is particularly relevant for existing urban areas undergoing infill development, subdivision, and redevelopment with higher-density housing forms. Table 5.8 presents baseline (no-WSUD) system performance under urbanization-only conditions for 2050 (77% DCIA) and 2070 (84% DCIA), with comparison to the current 2024 baseline.

Table 5.8. Baseline System Performance Under Urbanization-Only Scenarios (No WSUD)

| Scenario | Imperviousness | Imperviousness Change vs 2024 Baseline | Total Runoff Volume (m³) | Total Runoff Change vs 2024 Baseline |
|-----------------|-----------------------|---|--|---|
| 2024 (baseline) | 64% | — | 455,550 | — |
| 2050 Urban-only | 77% | +20% | 503,160 | +10.5% |
| 2070 Urban-only | 84% | +31% | 528,790 | +16.1% |

Urbanization-only scenarios show hydrologic responses that are fundamentally different in nature from those of climate-only scenarios. For instance, the 2050 urban-only scenario elevates imperviousness by 20% (from 64% to 77%), however, it results in a total runoff volume increase of only 10.5%. Similarly, the 2070 scenario increases imperviousness by 31% (from 64% to 84%) but the volume of runoff is raised by only 16.1%.

The reason for this sub-proportional response is that the catchment is already highly impervious (64%) under the baseline conditions. At such a level, a major part of the runoff generation has already taken place. Most rainfall on the existing 64% impervious area converts directly to runoff with minimal losses. The additional imperviousness comes from the conversion of the remaining pervious areas (gardens, lawns), which under the current conditions provide infiltration during moderate events but generate runoff during large events when the infiltration capacity is exceeded.

The link between imperviousness increases and runoff increases can be explained by the notion of "effective imperviousness", which is the proportion of imperviousness that produces runoff that is discharged into the drainage system. In catchments with low baseline imperviousness (20–40%), each extra percentage point of imperviousness brings about an almost equal increase in runoff because it converts surfaces that were infiltrating into surfaces that generate runoff. However, in catchments with high baseline imperviousness (>60%), the marginal effect becomes smaller. The mathematical relationship is closer to a logarithmic curve rather than a linear one and each additional percentage point of imperviousness leads to progressively smaller increases of runoff as the total imperviousness gets closer to saturation (100%) (Shuster et al., 2005).

The absolute runoff volumes in urbanization-only scenarios are lower than those of the wettest historical year. Thus, the urbanization alone under the condition of no climate intensification would still cause significant but manageable stress increases. Basically, urban densification makes runoff faster and peakier, even if total increases are only small. When pervious areas are turned into impervious surfaces, the remaining infiltration capacity is removed, leading to the occurrence of immediate runoff. While the changes at the catchment level look moderate, heavily developed areas experience much larger increases in runoff, highlighting the need for targeted WSUD measures and focused infrastructure upgrades.

5.4.3 Climate Change and Urbanization

The combined scenarios apply both future climate projections and increased imperviousness simultaneously, representing the most realistic future conditions where atmospheric changes and urban densification operate concurrently. This analysis reveals potential synergistic or antagonistic interactions between the two stressors and provides the most policy-relevant assessment of future system vulnerability.

Table 5.9 presents baseline (no-WSUD) system performance under combined climate-urbanization scenarios, with comparisons to current conditions.

Table 5.9. Baseline System Performance Under Combined Climate & Urbanization Scenarios (No WSUD)

| Scenario | Total Runoff Volume (m ³) | Change in Runoff vs 2024 |
|-------------------------------------|---------------------------------------|--------------------------|
| 2024 (baseline, current conditions) | 455,550 | — |
| 2050 Combined (77% DCIA + climate) | 671,980 | +47.5% |
| 2070 Combined (84% DCIA + climate) | 838,470 | +84.1% |

Combined climate change and urbanization scenarios show a distinct synergistic intensification of the hydrologic response, which exceeds the sum of individual stressor effects. While rainfall and imperviousness increase moderately on their own, their interaction leads to disproportionately large runoff volumes and a rapid loss of infiltration capacity throughout the catchment.

By 2050, annual rainfall increases from 418 mm to 520 mm, but total runoff will have gone up by almost 48%, which is a lot more than what would be expected from precipitation change alone. The reason for this huge amplification is that pervious area has been reduced to such an extent that most of the historical infiltration buffer has been lost because imperviousness has increased to 77%. As rainfall intensities increase, the remaining pervious surfaces also begin generating infiltration-excess runoff. As a result, a relatively modest rainfall increase produces almost double the proportional increase in runoff.

By 2070, the synergistic interaction is even more pronounced. Rainfall is increased to 644 mm, and imperviousness reaches 84%, leaving only 16% of the catchment capable of absorbing water.

Runoff increases by more than 84%, exceeding the runoff recorded in the wettest historical year (2022), even though 2070 receives less annual rainfall than 2022. This dramatic turnaround is an indication that in the future, stormwater will be more a function of rainfall intensity and reduced infiltration rather than total precipitation volume.

A numerical comparison of the non-linear combined effects confirms their reality. The observed runoff in 2050 is approximately 6% higher than the sum of climate-only and urbanization-only effects, whereas the non-linear excess in 2070 is about 14%. This change is reflective of the catchment's transition from being a partly buffered system today (with 36% pervious area) to almost impervious in 2070. As infiltration capacity collapses from roughly one-third of annual rainfall today to less than 10–12% by 2070. Hence, the system becomes highly sensitive to even small changes in rainfall intensity.

Overall, the combined scenarios demonstrate that climate change and urbanization do not act independently but interact to accelerate hydrologic impacts in a strongly non-linear manner. As urbanization approaches saturation and rainfall intensifies, the catchment moves to a state that is essentially unbuffered, thus creating the potential for chronic overloading of stormwater infrastructure and undermining the reliability of historical design assumptions.

5.4.4 Future Baseline vs WSUD Impacts

Having established the individual and combined effects of climate change and urbanization on baseline system performance, this section provides an integrated synthesis comparing WSUD effectiveness across all three scenario families. This comprehensive comparison enables assessment of whether WSUD effectiveness varies systematically by stressor type, and which WSUD configuration provides most robust performance across varying future conditions.

Table 5.10 presents a comprehensive comparison matrix showing baseline (no-WSUD) performance and the three high-coverage WSUD configurations (50% RG, Hybrid 25% RWT + 25% RG, and 50% RWT) across all scenario families for both 2050 and 2070.

Table 5.10. WSUD Performance Reductions Across All Future Scenarios (↓ - % reduction vs. no-WSUD baseline)

| Year | Scenario | WSUD Option | Total Runoff | Avg Outflow | TN ↓ | TP ↓ | TSS ↓ |
|------|--|------------------|----------------------------|---------------------------------|--------|--------|--------|
| | | | ↓ (from sub-catchments) | ↓ (discharge at the outfall) | | | |
| 2050 | Climate-only | 50% RG | 66.1% | 57% | 20.00% | 26.6% | 38.00% |
| | | 25% RWT + 25% RG | 63.80% | 57.20% | 16.20% | 22.8% | 35.60% |
| | | 50% RWT | 60.20% | 49.90% | 13.30% | 18.1% | 33.30% |
| | Urban-only | 50% RG | 64.3% | 55.7% | 20% | 26.60% | 38.00% |
| | | 25% RWT + 25% RG | 73.10% | 69.30% | 16.20% | 22.80% | 35.60% |
| | | 50% RWT | 52.80% | 45.40% | 13.30% | 18.10% | 33.30% |
| | Combined Climate + Urbanization | 50% RG | 57.40% | 42.50% | 20.00% | 26.60% | 38.00% |
| | | 25% RWT + 25% RG | 57.60% | 48.60% | 15.00% | 21.00% | 33.00% |
| | | 50% RWT | 57.20% | 42.70% | 12.30% | 16.50% | 31.00% |
| 2070 | Climate-only | 50% RG | 62.3% | 52.6% | 18.9% | 25.2% | 36.0% |
| | | 25% RWT + 25% RG | 58.5% | 51.1% | 15.3% | 21.1% | 33.8% |
| | | 50% RWT | 52.6% | 39.4% | 12.6% | 17.1% | 31.5% |
| | Urban-only | 50% RG | 63.3% | 54.8% | 20.6% | 27.4% | 39.2% |
| | | 25% RWT + 25% RG | 71.9% | 68.1% | 16.7% | 23.5% | 36.8% |
| | | 50% RWT | 53.1% | 44.0% | 13.7% | 18.6% | 34.3% |
| | Combined Climate + Urbanization | 50% RG | 51.4% | 37.6% | 18.9% | 25.2% | 36.0% |
| | | 25% RWT + 25% RG | 50.6% | 41.7% | 15.3% | 21.6% | 33.8% |
| | | 50% RWT | 48.2% | 31.9% | 12.6% | 17.1% | 31.5% |

Note: All percentage reductions (↓) are calculated relative to the no-WSUD baseline within each scenario family and time horizon. Absolute values are presented in metric units with reductions shown in parentheses.

A cross-scenario evaluation of WSUD performance reveals consistent hydraulic benefits and more moderate, but still meaningful water quality improvements across all configurations and future conditions. Performance varies by climate, urbanization, and combined stressors, yet several robust patterns emerge that clarify how WSUD systems behave under future catchment pressures.

- **Climate-Only Scenarios:**

Under intensified rainfall but stable imperviousness (64%), all three configurations perform within a narrow hydraulic range. By 2050, runoff reductions converge at 57–66% and outflow reductions at 50–57%, demonstrating that high WSUD coverage effectively manages increased rainfall regardless of design type.

However, water quality results differentiate the systems more clearly. RGs (50% RG) consistently provide the strongest pollutant removal, around 20% TN, 27% TP, and 38% TSS due to biological and media-based treatment processes. The Hybrid system follows with slightly lower reductions, while RWTs (50% RWT) achieve the lowest pollutant removal, as RWTs primarily rely on sedimentation.

By 2070, climate intensification causes modest declines in all metrics, mostly due to more frequent events exceeding system capacity.

- **Urbanization-Only Scenarios:**

When imperviousness increases to 77% (2050) and 84% (2070) while climate remains stable, performance patterns shift. The Hybrid system delivers the strongest hydraulic control across the entire study, achieving over 70% runoff reduction in both 2050 and 2070. Its strength derives from balanced treatment loads—RWTs managing roof runoff and RGs capturing ground-level flows—allowing efficient use of storage during more frequent, moderate events.

RGs maintain good performance but show some decline compared with climate-only conditions because each garden receives runoff from a larger contributing area. RWTs continue to provide moderate results.

Water quality outcomes remain consistent across climate and urbanization scenarios, confirming that treatment depends more on contact time within media than on event frequency or imperviousness.

- Combined Climate–Urbanization Scenarios:

Under the combined influence of climate change and urbanization—the most realistic future condition for the study area all WSUD configurations begin to operate in a capacity-limited regime. By 2050, they converge to similar hydraulic outcomes, reducing runoff by 57–58%, indicating that once rainfall intensities rise and imperviousness expands together, coverage level becomes more important than system type.

Despite this convergence, outflow behaviour shows clearer differentiation. The Hybrid system consistently maintains a 5–6 percentage point advantage, as its combined storage and infiltration allow it to moderate peaks more effectively under the sharper, faster hydrographs produced by densification and more intense storms.

Water quality performance remains within the typical 12–27% range, with RGs continuing to rank highest and RWTs lowest.

By 2070, combined-stressor performance declines more sharply runoff reduction falls by ~6% on average, and RWTs show the steepest losses due to early overflow during high-intensity events.

Configuration Robustness Rankings across all scenarios and time horizons:

- I. Hybrid (25% RWT + 25% RG) – Most robust overall; strongest under urbanization; narrowest performance spread; best peak-flow management.
- II. 50% RG – Strong hydraulic control under climate-only conditions and the highest water quality outcomes.
- III. 50% RWT – Adequate hydraulic management with the most variability across scenarios and the lowest pollutant treatment.

Generally, RGs suit climate-driven scenarios, hybrids are robust under urbanization, and RWTs offer moderate hydraulic gains at lower cost. Under combined climate–urbanization futures, all systems achieve similar hydraulic reductions (~50–58%), so site-specific factors should guide selection. Pollutant reductions remain modest, requiring complementary measures, while increasing WSUD coverage yields greater benefits than changing system type. A phased implementation ensures flexibility under uncertain future conditions.

5.4.5 Sensitivity and Uncertainty

Future scenario modelling inevitably involves multiple layers of uncertainty arising from climate projections, urbanisation trajectories, WSUD performance assumptions, and structural limitations within PCSWMM. Recognising these uncertainties is essential for interpreting the robustness of the results and supporting adaptive long-term planning.

Climate Projection Uncertainty

The central climate scenario applied in this research is SSP2-4.5, which represents a moderate warming pathway for the Melbourne region. However, regional climate models diverge substantially in their projections for rainfall totals and intensities. Ensemble climate models exhibit substantial variability in projected short-duration rainfall intensities and annual rainfall totals across different realisations. This variation directly influences future stormwater generation, bypass behaviour, and the potential performance of WSUD systems.

Under the central SSP2-4.5 projection, the combined climate-change and urbanisation scenario for 2050–2070 produces hydraulic reductions of approximately 50–57% when WSUD is implemented at 50% coverage. When rainfall intensities are assumed to be 20% lower (representing a mitigation-oriented scenario such as SSP1-2.6), hydraulic and pollutant load reductions improve modestly, reaching approximately 54–62%, as fewer extreme events exceed WSUD system capacities. Conversely, under a 30% higher intensity scenario (similar to SSP5-8.5), performance declines slightly, with hydraulic and load reductions in the order of 47–53% due to more frequent bypass during extreme rainfall.

Although proportional reductions in runoff and pollutant loads vary only modestly across climate futures, the absolute loads diverge substantially. Depending on the degree of rainfall intensification, 2070 pollutant loads may fall within a wide range. This indicates that while climate uncertainty does not lessen the relative effectiveness of WSUD, it strongly influences whether absolute water-quality objectives can be met through WSUD alone or require additional system-scale interventions.

Urbanization Projection Uncertainty

The future levels of imperviousness (77% by 2050 and 84% by 2070) have been estimated based on area densification trends over the years and local government planning forecasts. However, the real development paths will be determined by demographic, economic, and policy drivers and are, therefore, still unknown.

The sensitivity analysis shows that a change of $\pm 10\%$ in imperviousness brings about a change of runoff volumes by approximately $\pm 7\%$ and a change of hydraulic and pollutant-load reductions by WSUD by $\pm 5\%$. The limited sensitivity is due to the fact that in highly urbanised catchments where baseline imperviousness is already over 64%, the additional imperviousness has a diminishing marginal impact.

Although catchment-scale runoff changes little with varying imperviousness, local flooding can intensify where densification is concentrated. This underscores the need to prioritise WSUD in rapidly developing areas.

Uncertainty due to planning-policy changes also influences forecasts. Current schemes may set requirements for minimum ratios of pervious surfaces, but the actual imperviousness in new developments usually reaches 75–88%. If strengthened planning controls were to limit 2070 imperviousness closer to 75%, baseline runoff increases would moderate to around 72% (rather than ~84%), and WSUD pollutant-load reductions would improve slightly to ~54–59%. This demonstrates that urban-form management and WSUD implementation are jointly required for long-term stormwater resilience.

Overall, uncertainty does not undermine the role of WSUD, but strengthens the case for early, scalable, and adaptive implementation, supported by systematic monitoring and periodic reassessment.

5.4.6 Summary

The future scenario analysis confirms that climate change and urbanisation will substantially intensify stormwater pressures in the catchment. Climate-driven increases in rainfall intensity raise runoff by 30–54% by 2050–2070, while urbanisation contributes additional but more moderate increases. When combined, these drivers amplify each other, resulting in runoff growth of approximately 48–84% across the future horizons. These shifts highlight the growing importance of resilient and distributed stormwater management strategies.

Across all future conditions, WSUD demonstrates strong and reliable performance. The results show that hydraulic reductions remain typically within 48–73% depending on the scenario, and notable pollutant-load reductions are also achieved, particularly for sediments. Performance varies between configurations, but consistent patterns emerge. Under climate-only conditions, RGs provide the highest hydraulic and water-quality benefits, with reductions of up to 62–66% in runoff and strong improvements in TSS removal due to their infiltration-based treatment processes. Under urbanisation-driven futures, the Hybrid configuration (25% RWT + 25% RG) performs best, offering a balanced capability to treat both roof runoff and ground-surface contributions as imperviousness increases.

Under the most realistic combined scenarios for 2050 and 2070, all configurations maintain stable, meaningful performance, falling within a narrow band of approximately 48–58% hydraulic reduction and 31–36% TSS reduction. This convergence reflects the capacity of distributed WSUD systems to continue functioning effectively even as both hydrologic loading and imperviousness increase. The consistency of these results across the different future pathways demonstrates the robustness of WSUD as a long-term adaptation strategy.

Overall, the future scenario assessment clearly indicates that RGs and the Hybrid configuration are the strongest-performing WSUD options, with RGs providing the highest water-quality and

hydraulic benefits, and the Hybrid configuration delivering the most balanced performance under extensive urbanisation.

The outcomes of this study provide additional evidence on WSUD and LID performance in other scenarios and allow comparison with recent peer-reviewed studies. The strong coverage-dependency observed here — where high-coverage scenarios delivered substantial hydraulic and water quality benefits while low-coverage configurations produced only marginal improvements — can be compared with the findings of Li et al. (2024a), who reported runoff reductions of 26–42% from combined LID measures and similarly found that performance diminishes significantly for larger, less frequent events. This event-size sensitivity is one of the key findings of the present study and reflects the well-established understanding that source-control WSUD is primarily effective for frequent, moderate storms. The modest peak flow attenuation observed here is comparable to the range reported by Gurung et al. (2025), who reported peak flow reductions of 0–42% for high-impervious Australian urban catchments and noted that WSUD benefits in such settings are realised predominantly through volume reduction and overflow control rather than peak clipping. For water quality, the TSS > TP > TN reduction hierarchy across all scenarios is similar to trends observed in monitored Australian treatment systems (Drapper and Hornbuckle, 2018), reflecting the well-documented challenge of removing dissolved nitrogen at catchment scale. The somewhat lower pollutant load reductions compared to asset-level field studies — such as the mean reductions of ~80% TSS, ~62% TP, and ~55% TN reported by Sabbagh et al. (2025) across 50 monitored bioretention sites are expected, as catchment-scale modelling inherently incorporates bypass pathways and spatial coverage limitations that reduce apparent efficiencies relative to individual asset measurements.

A further consideration in interpreting these results is the long-term performance of WSUD elements under real-world conditions. In particular, bioretention systems such as rain gardens may experience gradual clogging and reductions in hydraulic conductivity over time due to sediment accumulation and organic matter build-up, which can increase bypass and reduce treatment effectiveness. Similarly, rainwater tanks may exhibit reduced operational efficiency if routine inspection and maintenance are not undertaken. While the present modelling assumes idealised, time-invariant performance consistent with adopted design guidelines, actual field performance may decline without appropriate maintenance regimes. This limitation is recognised in Melbourne

Water (2022), which recommends adopting conservative hydraulic conductivity assumptions in WSUD modelling to account for potential clogging effects. Nevertheless, long-term Australian monitoring reported by (Drapper and Hornbuckle, 2018) demonstrates that sustained pollutant reduction is achievable where WSUD assets are managed under structured maintenance programs. Accordingly, the results of this study represent expected performance under guideline-consistent maintenance conditions. Future research incorporating time-varying hydraulic conductivity or degradation functions could further improve the representation of long-term WSUD performance in modelling applications.

These findings form the foundation for the economic evaluation presented in Chapter 6, where life-cycle costs will be analysed to determine the most cost-effective and practical WSUD option for future implementation.

Chapter 6: Life Cycle Costing (LCC) and Economic Evaluation

6.1 Costing Framework and Assumptions

6.1.1 Purpose and Scope

The primary objective of this Life Cycle Cost (LCC) analysis is to evaluate and compare the long-term economic feasibility of RWT and RG as part of the proposed WSUD strategies in Hoppers Crossing, Victoria, Australia. This assessment supports evidence-based decision-making by quantifying both upfront and ongoing costs associated with each system, enabling prioritization of WSUD strategies that balance economic feasibility with environmental benefits.

At the commencement of this research, various sizing options were considered to find the best setting for both RWT and RG systems. Based on the appropriateness for residential and small-commercial applications in Victoria, three rainwater tanks capacities (i.e., 3.5 kL, 4.0 kL, and 4.5 kL) and two RG areas (i.e., 10 m² and 15 m²) were chosen for the preliminary assessment. After the hydraulic and water quality performance analyses, which are detailed in Chapters 4 and 5, respectively, the 4.0 kL RWT and 10 m² RG were identified as the best-performing configurations in terms of runoff reduction, pollutant removal efficiency, and overflow mitigation. Therefore, all other detailed analyses were based on these optimized sizes.

However, to be able to economically support the selection of the chosen sizes, a comprehensive LCC analysis was performed for all originally considered size variants. This method verifies whether the initial size selection based on hydrological performance and water quality is also the most cost-effective option. The performance metrics can be re-evaluated through the modelling framework if the economic analysis suggests that alternative sizes have better cost-effectiveness.

As explained in Chapter 3, the methodology follows the framework presented in the MUSIC v6 Costing Module eWater (2013a), as well as financial principles used in peer-reviewed studies,

including Newnan et al. (2004), Gurung et al. (2016) and Mahbub and Sharma (2019). The analysis encompasses:

- **Total Acquisition Cost (TAC):** All initial capital costs including purchase, transport, installation, and fittings — updated to 2025 market prices.
- **Pump replacement:** for each RWT (single event within 25 years)
- **Net Present Value (NPV) of Operation and Maintenance (O&M):** Ongoing costs discounted to present value using the Capital Recovery formula.
- **End-of-Life Costs:** Excluded as per the MUSIC methodology, focusing on design and operational stages.

Although RWTs and RGs are designed to last approximately 25 years and 50 years respectively, this study adopts a 25-year analysis period for both systems. This decision aligns with common infrastructure planning horizons and ensures a fair, consistent basis for comparing systems with different lifespans. Extending the analysis horizon to 50 years would introduce excessive uncertainty in cost projections and disproportionately favour the longer-lived RG system without reflecting realistic planning and budgeting cycles. This approach avoids overly skewed comparisons caused by extended timeframes and reflects practices in other studies such as the MUSIC guidelines and Newnan et al. (2004).

6.1.2 Economic Parameters

The economic parameters used in this analysis were derived from authoritative Australian sources to ensure accuracy and relevance to the local context. Table 6.1 summarizes the key parameters underpinning the LCC calculations.

The discount rate of 7% reflects a real (inflation-adjusted) rate appropriate for long-term public infrastructure investment in Australia. This rate combines the risk-free rate (approximated by long-term government bond yields of ~4.2%) with an infrastructure-specific risk premium (~2.8%) to account for uncertainties in construction, maintenance, and performance over the asset lifecycle (Australian Government, 2025).

Table 6.1. Economic parameters used in the LCC analysis.

| Parameter | Value | Explanation | Source |
|---|----------|--|------------------------------|
| CPI inflation factor | 1.7391 | Dec-2004 CPI \approx 80.1; Dec-2024 CPI \approx 139.4; $139.4/80.1 \approx 1.7391$ (used to restate TAM into 2025 AUD) | ((ABS), 2025) |
| Discount rate (real) | 7% | Risk-free \approx 4.2% + risk premium \approx 2.8% (infrastructure context) | (AustralianGovernment, 2025) |
| Pump/appliance real drift (sensitivity) | 1% / yr | Appliance-specific real escalation for sensitivity per Gurung et al. (2016) | (Gurung et al., 2016) |
| Analysis horizon | 25 years | Applied to both RWT and RG | |

The CPI inflation factor was calculated by comparing the Consumer Price Index from December 2004 (the reference year for MUSIC v6 default costs) to December 2024 ((ABS), 2025), yielding a factor of 1.7391. This factor is applied to all cost inputs originally stated in 2004 AUD to convert them to 2025 AUD, ensuring consistency and comparability with current market conditions.

For mechanical components such as pumps, a modest real drift of 1% per year is applied in sensitivity analysis to reflect the tendency of appliance costs to escalate slightly above general inflation due to technology improvements and supply chain factors (Gurung et al., 2016).

6.2 Costs by Option and Scale

6.2.1 RWT Costs

RWTs' capacities evaluated are 3.5 kL, 4.0 kL, and 4.5 kL—typical for residential/small-commercial use in Victoria.

Total Acquisition Cost (TAC)

The Total Acquisition Cost includes all upfront expenses required to bring a RWT system into operation. This comprises: Tank purchase, Delivery and transport to site, Installation, site preparation, plumbing/fittings and the initial pump (GST excluded per MUSIC convention).

In Table 6.2 costs were estimated based on 2025 market pricing obtained from local suppliers and installers in Victoria.

Table 6.2. Total Acquisition Cost for RWTs (2025 AUD).

| Capacity | TAC (AUD) |
|----------|-----------|
| 3.5 kL | 2,750.00 |
| 4.0 kL | 2,950.00 |
| 4.5 kL | 3,150.00 |

Annual Maintenance (TAM) and NPV of O&M

MUSIC v6 (eWater, 2013a) default TAM for a plumbed, pumped tank is 90 AUD (2004), which includes ≈ 10 AUD/yr pump operation. Restated in 2025 AUD using CPI factor 1.7391 gives TAM₂₀₂₅ = 156.52 AUD/yr. The 25-year present worth of a constant annual series at $i = 7\%$ is given by Equation (6.1).

$$NPV_{O\&M} = TAM \times \frac{(1+i)^n - 1}{i(1+i)^n} \quad (6.1)$$

Table 6.3 summarizes the annual TAM value adopted in this study and presents the resulting 25-year net present cost of operation and maintenance for the RWT configuration.

Table 6.3. O&M inputs and 25-year present worth for RWT (2025 AUD).

| Annual TAM (AUD/yr) | Discount rate i | Horizon N (years) | NPV(O&M) (AUD) |
|---------------------|-------------------|---------------------|----------------|
| 156.52 | 7% | 25 | 1,824.02 |

The NPV of O&M is **identical across all tank sizes** because maintenance requirements (cleaning, inspections, pump operation) do not vary significantly with storage capacity in this size range. Thus, O&M costs contribute equally to the LCC of each tank variant.

Pump Replacement (one event)

The initial pump is included in the TAC and is not counted again. However, to reflect the finite service life of mechanical components (typically 10–15 years for residential rainwater pumps),

one pump replacement is scheduled at year 12 of the analysis period. This timing represents a mid-range estimate within the expected pump lifespan and accounts for wear from regular cycling and environmental exposure.

The present value of the replacement pump cost is calculated using Equation (6.2), which accounts for both the real escalation in pump costs ($j = 1\%$ per year, reflecting appliance-specific price trends) and discounting back to present value:

$$PV_{pump\ replacement} = P_{pump} \times \frac{(1 + j)^n}{(1 + i)^n} \quad (6.2)$$

The adopted assumptions and the resulting present-worth value of pump replacement are summarized in Table 6.4.

Table 6.4. Pump replacement assumptions and present worth (2025 AUD).

| P_{pump}, 2025 AUD | j_{pump}, real | t (years) | PV_{pump} (AUD) |
|-----------------------------------|-------------------------------|------------------|--------------------------------|
| 550.00 | 1% / yr | 12 | 275.18 |

The discounted present value of the pump replacement is \$275.18, which is uniform across all tank sizes as pump specifications do not vary significantly for the capacity range under consideration.

Total LCC for Rainwater Tanks

The total Life Cycle Cost for each RWT variant is the sum of TAC, NPV(O&M), and PV of one pump replacement (Equation 6.3). The resulting per-unit LCC values for all tank capacities assessed in this study are presented in Table 6.5.

$$LCC_{RWT} = \underbrace{TAC}_{incl.\ initial\ pump} + NPV(O\&M, 25y) + PV_{pump\ replacement} \quad (6.3)$$

Table 6.5. Per-unit LCC for RWTs (25 years, 2025 AUD).

| Capacity | TAC (AUD) | NPV(O&M) (AUD) | PV(pump) (AUD) | LCC₂₅ (AUD) |
|-----------------|------------------|---------------------------|-----------------------|-------------------------------|
| 3.5 kL | 2,750.00 | 1,824.02 | 275.18 | 4,849.20 |
| 4.0 kL | 2,950.00 | 1,824.02 | 275.18 | 5,049.20 |
| 4.5 kL | 3,150.00 | 1,824.02 | 275.18 | 5,249.20 |

6.2.2 Rain Garden (RG) Costs

Two RG footprints are evaluated (10 m² and 15 m²). These sizes are appropriate for treating runoff from typical residential lots and small commercial sites in suburban developments.

Total Acquisition Cost (TAC)

The Total Acquisition Cost for RGs includes: excavation and earthworks, engineered filter media, planting and underdrain construction (Guam, 2012). These costs adjusted to Australian market conditions and 2025 pricing in Table 6.6.

Table 6.6. Total Acquisition Cost for raingardens (2025 AUD).

| RG Area | TAC (AUD) |
|-------------------|------------------|
| 10 m ² | 5,000.00 |
| 15 m ² | 6,000.00 |

The TAC for RGs is notably higher per unit than for RWTs, reflecting the labour-intensive nature of bioretention construction and the need for specialized engineered media.

Annual Maintenance Cost

RG maintenance costs are estimated using the MUSIC v6 convention, which expresses ongoing costs as percentages of TAC:

- **TAM** = 4.4% of TAC (eWater, 2013a): routine inspections, weeding, mulch replenishment, pruning, and vegetation health monitoring.
- **RC (Renewal Cost)** = 2.0% of TAC (eWater, 2013a): periodic renewal of organic matter, replanting of damaged vegetation, and minor structural repairs.

The sum of TAM and RC is taken as the total annual operation and maintenance requirement for each RG size, as summarized in Table 6.7.

Table 6.7. RG Total Annual O&M cost (2025 AUD).

| RG Area | TAM (4.4% TAC) | RC (2% TAC) | Total Annual O&M (AUD) |
|-------------------|-----------------------|--------------------|-----------------------------------|
| 10 m ² | 220.00 | 100.00 | 320.00 |
| 15 m ² | 264.00 | 120.00 | 384.00 |

NPV of O&M

The 25-year NPV of constant annual O&M expenditures for RGs is calculated using Equation 6.1 with using above calculated Total Annual O&M for each size.

Total LCC for Raingardens

The total Life Cycle Cost for RGs is calculated using Equation (6.4):

$$LCC_{RG} = TAC + NPV(O\&M, 25y) \quad (6.4)$$

Table 6.8 represents calculated NPV (O&M) and LCC for both raingarden sizes.

Table 6.8. RG NPV of O&M and per-unit LCC (25 years, 2025 AUD).

| RG Area | NPV(O&M) (AUD) | LCC₂₅ (AUD) |
|-------------------|---------------------------|-------------------------------|
| 10 m ² | 3,729.15 | 8,729.15 |
| 15 m ² | 4,474.98 | 10,474.98 |

6.2.3 Summary of Per-Unit Results

Comparison of the results in Table 6.5 and Table 6.9 consolidates the Per-Unit LCC outcomes for all evaluated WSUD options and provides a direct basis for comparison. The key findings are as follows:

- On a per-unit basis, RWTs are far more cost-effective than RGs, with the 3.5 kL tank costing approximately 56% of the 10 m² RG over the 25-year assessment period.
- Cost differences across tank sizes are relatively small (approximately 4–8%), indicating that size selection should be mainly determined by the performance rather than by the slight cost saving.
- RGs have significantly higher O&M requirements, with maintenance activities making up about 43% of their total LCC, compared with approximately 37% for RWTs. This reflects

the continual vegetation, media, and surface-treatment upkeep inherent to bioretention systems.

6.2.4 Scenario Roll-Up Costs

To evaluate the economic implications of different adoption strategies across the Hoppers Crossing development, per-unit LCC values were scaled to the five implementation scenarios defined in Chapter 2. Each scenario reflects a different combination of RWT and RG deployment across the 3,000-allotment development.

In Table 6.9 for each scenario, multiple sizing variants are presented to reflect the range of options evaluated.

Table 6.9. Scenario-level total LCC projections (25 years, 2025 AUD).

| Scenario | RWT Units | RG Units | Variant | Total LCC (Fletcher et al.) |
|------------------------|-----------|----------|----------------------------|--------------------------------|
| A: 25% RWT | 750 | 0 | 3.5 kL | 3,636,900 |
| | | | 4.0 kL | 3,786,900 |
| | | | 4.5 kL | 3,936,900 |
| B: 50% RWT | 1500 | 0 | 3.5 kL | 7,273,800 |
| | | | 4.0 kL | 7,573,800 |
| | | | 4.5 kL | 7,873,800 |
| C: 25% RWT + 25% RG | 750 | 750 | 3.5 kL & 10 m ² | 10,183,762 |
| | | | 4.0 kL & 10 m ² | 10,333,762 |
| | | | 4.5 kL & 15 m ² | 11,793,135 |
| D: 25% RG | 0 | 750 | 10 m ² | 6,546,862 |
| | | | 15 m ² | 7,856,235 |
| E: 50% RG | 0 | 1500 | 10 m ² | 13,093,725 |
| | | | 15 m ² | 15,712,470 |

The scenario-level life-cycle cost analysis reveals a clear and structured cost gradient driven jointly by WSUD technology type and implementation scale. The most economical configuration is

Scenario A, which applies RWTs at 25% coverage and uses the smaller end of the tank size range (3.5–4.0 kL), resulting in a total 25-year LCC of approximately \$3.8 million. This establishes the lower cost boundary for WSUD investment in the study area. At the opposite end of the spectrum, Scenario E, featuring 50% RG implementation, produces the highest cost at roughly \$13.1 million, creating a cost differential of about \$9 million between the cheapest and most expensive options, equivalent to more than a three-fold increase in expenditure. Between these two extremes, the intermediate scenarios follow an intuitive progression: Scenario B (50% RWT) nearly doubles the cost of Scenario A due to proportional scaling of tank deployment, while Scenario C (25% RWT + 25% RG) sits in the middle of the cost spectrum at \$10.33 million, reflecting the additional capital and recurrent costs associated with incorporating bioretention systems alongside tanks. This mid-range value is significantly lower than the RG-only scenario yet materially higher than the RWT-only cases, forming a central band of investment within which mixed-technology strategies reside.

These broader cost patterns are reinforced by the device-level cost comparisons. The selected 4.0 kL RWT is only about 4–5% more expensive than the minimum-cost 3.5 kL model, demonstrating that choosing the slightly larger storage volume has negligible impact on total expenditure at catchment scale. Similarly, the 10 m² RG is the lowest-cost bioretention configuration, whereas increasing to 15 m² raises unit costs by approximately 18–22%, clearly indicating that larger footprints generate disproportionately higher life-cycle costs. Deploying the optimal unit sizes (4.0 kL RWT and 10 m² RG) across the chosen hybrid scenario results in the \$10.33 million total cost noted above, which defines a balanced mid-point between the least expensive tank-only options (\$3.79–\$7.57 million) and the upper-cost RG-only case (\$13.09 million). Taken together, these values confirm that the selected tank and RG dimensions lie very close to the minimum achievable cost envelope while avoiding the steep cost premiums associated with larger bioretention footprints or high RG coverage. As a result, the \$10.33 million investment level can be interpreted as the central and most representative cost range for WSUD implementation in Hoppers Crossing, capturing the economic implications of combining both technologies without incurring the upper-tier costs that characterise RG–dominant strategies.

6.3 Cost-Effectiveness Analysis

To move beyond absolute LCC values and compare how efficiently each option delivers environmental benefits, cost-effectiveness was evaluated by normalising 25-year life-cycle costs against the cumulative performance of each device. For both technologies, cost-effectiveness was calculated as the ratio of LCC to the 25-year total runoff reduction or pollutant mass removed.

The results show a clear division of strengths. RWTs are markedly more cost-effective for runoff and volume management, with cost per megalitre of runoff reduced substantially lower than for RGs. This reflects their primary function as storage devices directly connected to roof catchments and downpipes, which allows a large proportion of stormwater to be intercepted at relatively low cost.

In contrast, RGs are more cost-effective for pollutant removal, particularly for TSS, TP and TN. Their engineered soil media and vegetation provide filtration, sorption and biological uptake, which strongly enhance water-quality performance per dollar spent. Comparisons between the 4.0 kL tank and 10 m² RG indicate that RGs remove nutrients and suspended solids at roughly 1.5–2.5 times lower cost per kilogram than tanks, whereas tanks remove runoff at several times lower cost per megalitre than RGs.

These findings support the conclusion that no single WSUD technology is universally superior. RWTs are the preferred option where volumetric control and flood mitigation are the main objectives, while RGs are better suited to situations where meeting nutrient and sediment reduction targets is critical. The hybrid Scenario C, which combines tanks and RGs at moderate coverage, therefore offers a balanced and cost-efficient response by exploiting the complementary strengths of both systems.

6.3.1 Non-Quantified Social and Environmental Benefits

The LCC figures presented in this chapter reflect only directly quantifiable costs and performance metrics. However, the true economic value of WSUD extends well beyond what cost-per-megalitre or cost-per-kilogram ratios can express, encompassing a range of social and environmental co-benefits that, while resistant to direct monetization, are integral to any comprehensive appraisal of WSUD investment.

Rain gardens and rainwater tanks contribute to urban heat island mitigation through evapotranspiration, reducing local temperatures and household cooling energy demand. Vegetated bioretention systems simultaneously support urban biodiversity by providing habitat for native flora and fauna and improving ecological conditions in downstream waterways — outcomes widely recognised in the literature as carrying measurable value even where no market price exists (Brown et al., 2008, Sharma et al., 2016). At the community level, greener streetscapes are consistently associated with improved resident wellbeing and neighbourhood amenity, while the 73–91% reduction in overflow frequency documented in Chapter 5 translates into lower flood-related disruption, reduced road wear, and decreased emergency response costs borne by councils rather than the WSUD operator. Infiltration through rain garden media also supports localised groundwater recharge, sustaining baseflow during the drier future conditions projected for 2050 and 2070, and the vegetation maintained across catchment-scale installations contributes incrementally to urban carbon sequestration.

Collectively, these co-benefits reinforce the economic rationale for WSUD investment beyond what direct cost metrics alone can capture. When evaluating scenarios against one another, the non-quantified social and environmental returns associated with bioretention systems should be considered alongside the LCC figures presented in this chapter, as they contribute meaningfully to the overall value delivered — particularly in hybrid configurations such as Scenario C, where the complementary strengths of both technologies are fully realised.

6.4 Sensitivity and Uncertainty Analysis

The LCC results inevitably depend on assumptions about economic parameters and asset performance. A targeted sensitivity analysis was therefore undertaken to test the robustness of the conclusions to plausible changes in discount rate, O&M cost escalation, and pump replacement timing.

Varying the discount rate between 5%, 7% (base case) and 9% showed that total LCCs change in the expected direction—lower discount rates increase the present value of future costs and higher rates reduce it. RGs, which have a higher share of O&M expenditure, exhibit larger percentage changes (around $\pm 20\%$) than RWTs (around $\pm 10\%$). However, the relative ranking of options does

not change. RWTs remain cheaper than RGs on a per-unit basis, and the 4.0 kL/10 m² sizes remain the most favourable within each technology family.

Assumptions about O&M cost escalation had a similarly asymmetric impact. When real O&M costs were increased by up to 2% per year above CPI, RG LCCs rose more rapidly than those of tanks, widening the cost gap between RG-dominant and RWT-dominant scenarios. This confirms that the long-term economic viability of large-scale bioretention depends heavily on the ability to manage maintenance efficiently, whereas tank-only strategies are less exposed to O&M escalation risk.

Finally, shifting the pump replacement year within a realistic range (early failure versus extended life) had only a minor effect on tank LCCs, changing totals by approximately $\pm 1\%$. Pump replacement therefore represents a relatively small component of total life-cycle cost, and uncertainty in pump lifespan does not materially influence the choice of tank size or deployment level.

Taken together, these sensitivity tests show that while absolute LCC values are uncertain, the key comparative findings are stable: RWTs consistently offer lower costs per unit of storage, RGs retain their advantage for pollutant removal, and the selected 4.0 kL and 10 m² sizes remain near-optimal under all tested conditions.

Chapter 7: Conclusion

This thesis evaluated the effectiveness of WSUD strategies in enhancing stormwater quantity and quality. The research, using PCSWMM modelling, scenario analysis, and economic evaluation, explored how distributed green infrastructure could increase urban water resilience not only at the current time but also under future climate and urbanization scenarios. This chapter brings together the main results of the study, determines the best WSUD configuration for the study area, discusses the broader policy and planning implications, recognizes the limitations and assumptions of the analysis, and outlines the academic and practical contributions of this work.

7.1 Final Selection of Optimal Scenario

The selection of an optimal WSUD scenario requires balancing multiple competing objectives: hydraulic performance (flood mitigation and runoff reduction), water quality improvement (pollutant load reduction), economic feasibility (life-cycle cost), and long-term resilience under future climate and urbanisation pressures. After the detailed investigation shown in Chapters 4 to 6, the Hybrid Scenario C (25% RWT + 25% RG) emerges as the most robust and balanced solution for implementation in the Hoppers Crossing catchment and similar established suburban developments.

7.1.1 Performance Summary

The Hybrid scenario, configured with 4.0 kL RWTs and 10 m² RGs deployed across 50% of residential properties (25% coverage each), demonstrated consistently strong performance across all evaluation criteria:

Hydraulic Performance (Current Conditions, 2020–2024):

- Surface runoff reduction: 67–72% annually, maintaining effectiveness across both wet and dry years
- Mean outflow reduction: 62–70%, closely matching runoff volume benefits
- Overflow frequency reduction: 73–91% depending on annual rainfall conditions, with particularly strong performance in typical dry years (91% in 2023)

- Long-duration overflow reduction: 73% reduction in events exceeding one hour, substantially mitigating chronic flooding at critical nodes
- Peak flow attenuation: 8–16%, modest but hydraulically meaningful in the capacity-limited outlet pipe

Water Quality Performance (Current Conditions, 2020–2024):

- Total Nitrogen reduction: 12–17% annually, primarily through volumetric control and biological processing in RGs
- Total Phosphorus reduction: 18–24%, achieved through particulate settling in tanks and adsorption in bioretention media
- Total Suspended Solids reduction: 28–37.5%, reflecting effective sedimentation and filtration across both measure types

Future Climate Resilience (2050 and 2070):

Under climate-only scenarios, the Hybrid configuration maintained 58–64% runoff reduction despite rainfall intensification of 24–54%. Under urbanisation-only scenarios with imperviousness increases to 77–84%, the Hybrid achieved the strongest hydraulic control of any configuration (71–73% runoff reduction), demonstrating superior performance when contributing areas expand. Most critically, under the combined climate-urbanisation scenarios representing realistic mid-century conditions, the Hybrid maintained 50–58% runoff reduction and 15–22% pollutant load reduction, outperforming RWT-only configurations and matching or slightly exceeding RG-only systems while requiring lower total coverage.

Economic Performance:

The Hybrid scenario presents a 25-year life-cycle cost of approximately \$10.33 million for the 3,000-property development, positioning it in the mid-range of the evaluated options. While this represents a substantial investment—approximately 3.8 times the cost of the lowest-cost 25% RWT scenario—it delivers disproportionately greater benefits through the synergistic interaction of storage-based and infiltration-based mechanisms. The cost-effectiveness analysis revealed that the Hybrid configuration achieves a favourable balance: tanks provide economical runoff volume control at lower cost per megalitre reduced, while RGs deliver superior pollutant removal at lower

cost per kilogram removed, allowing the combined system to address both quantity and quality objectives efficiently.

Rationale for Selection:

In addition to superior resilience to climate-urban change and economic effectiveness, several factors support the selection of the Hybrid scenario as optimal:

I. Balanced Multi-Objective Performance

Where single-measure scenarios typically perform well only in one aspect and poorly in others, the Hybrid setup achieves strong outcomes across all performance metrics. RWTs intercept roof runoff immediately at its source, providing rapid peak attenuation and volumetric control that remains effective even when tanks partially fill during sequential storms. RGs complement this by treating ground-level runoff from driveways, paths, and roads—pollutant sources that tanks cannot address—through infiltration, filtration, and biological uptake. This division of labour is such that different runoff routes are not only “captured” but also “treated” according to their specific characteristics.

II. Distributed Spatial Coverage

Deploying both measure types at 25% coverage creates a more spatially distributed network of source controls than concentrating 50% coverage in a single measure type. This distribution is particularly important in the study catchment, where overflow analysis identified 29 chronic problem nodes scattered throughout the network rather than concentrated in a single area. The Hybrid scenario's broader spatial footprint ensures that WSUD interventions occur in multiple sub-catchments, providing upstream mitigation that prevents flows from converging at downstream bottlenecks. Field observations and spatial analysis of overflow locations confirmed that many critical nodes receive inflows from 4–8 upstream sub-catchments; implementing tanks in some of these contributing areas and RGs in others creates a layered defence that reduces the probability of simultaneous capacity exceedance across all flow paths.

III. Implementation Feasibility and Community Acceptance

From a practical implementation perspective, the Hybrid scenario offers distinct advantages. Requiring only 25% coverage of each measure type—rather than 50% of a single type—

reduces the challenge of achieving high adoption rates for either technology individually. Property-level constraints that might prevent RG installation (limited yard space, poor soils, proximity to foundations) or tank installation (lack of suitable location, aesthetic concerns, plumbing complexity) do not preclude participating in the WSUD program, as property owners can select the measure most appropriate to their site conditions. This flexibility is expected to improve voluntary adoption rates and reduce implementation barriers compared to scenarios requiring 50% uptake of a single technology. Additionally, distributing implementation between two measures reduces supply chain pressure and installer capacity constraints that could emerge if 1,500 units of a single measure type were required within a short implementation timeframe.

7.1.2 Implementation Recommendations for the Optimal Scenario

To maximise the effectiveness of the Hybrid scenario in practice, spatial prioritisation is the primary determinant. WSUD implementation should first target the sub-catchments that contribute directly to the 29 chronic overflow nodes identified in the baseline assessment (Appendix 2). Hydraulic modelling demonstrated that even modest runoff reductions of 15–25% within the upstream contributing areas of nodes such as 3001, 14001, 230006, and 73002 can eliminate overflow occurrence in typical years and substantially decrease overflow duration and volume during extreme events. This clearly indicates that spatially strategic deployment yields far greater hydraulic benefit than uniform distribution across the catchment.

Following the identification of these high-priority areas, RGs should be installed first at the most hydraulically sensitive locations, as their performance is strongly dependent on precise placement relative to dominant flow paths. In addition to this locational dependency, RGs offer superior hydraulic and water-quality benefits through infiltration, filtration, and biogeochemical processing, making their early placement at the most sensitive sub-catchments essential for maximising system-wide performance. Once RGs have been deployed in the critical sub-catchments, RWTs should be added across the remaining suitable properties to complete the Hybrid configuration. This sequencing ensures that the infiltration-based benefits of RGs are maximised where they are most effective, while the broader volumetric and peak-attenuation

benefits of RWTs are distributed throughout the rest of the catchment to strengthen overall system performance.

7.2 Limitations and Assumptions

While this research provides robust evidence for WSUD implementation in established urban catchments, it is essential to acknowledge the key limitations, uncertainties, and assumptions that qualify the findings. This transparency ensures appropriate interpretation for policy and planning applications and highlights avenues for future refinement.

7.2.1 Modelling Framework Limitations

PCSWMM model is an industry-standard tool that has been validated through numerous applications. However, it still simplifies some complex processes. For example, the Green-Ampt infiltration method used in the model is based on the assumption that soil properties are uniform for each sub-catchment. It does not take into account that moisture, compaction, or conductivity might vary even in small-scale (e.g., an area close to a foundation that is compacted versus a garden bed that has been amended). This results in uncertainty of runoff, particularly when partial-area conditions are involved. Similarly, the LID module for RGs assumes consistent media, vegetation, and performance, but field studies show variability (40–95% pollutant removal) due to construction, maintenance, and antecedent conditions. At the catchment level, the effect of variations being random may cancel each other, but in the case of systematic degradation (e.g., due to maintenance being neglected), the performance may be even lower than the predictions.

Pipe network representation relies on council data verified through inspections, but uncertainties persist in roughness coefficients (affected by sediment or corrosion), invert elevations (due to settlement), and junction storage (potentially reduced by infill). Validation (NSE = 0.82 for calibration, 0.76 for validation) confirms reliable overall behaviour, but site-specific overflow predictions (e.g., the 29 identified chronic nodes) carry higher uncertainty and should guide priority investigations rather than definitive actions.

Water quality modelling uses buildup-washoff functions parameterized from literature and limited local data, lacking full calibration against continuous monitoring. EMC values (2.63 mg/L TN,

0.36 mg/L TP, 158 mg/L TSS) are averages that hide the variability of the events (e.g., TN varying from 0.5 to 6.0 mg/L). Therefore, load estimates and WSUD reductions (e.g., 15% TN in the Hybrid scenario) should be considered as signs of relative performance rather than accurate predictions. However, the main findings regarding the benefits of WSUD are still valid.

7.2.2 WSUD Performance Assumptions

Performance values for RGs (45% TN, 60% TP, 80% TSS reductions) and RWTs (30% TN, 40% TP, 70% TSS reductions) are taken from literature and Melbourne Water guidelines for well-designed and well-maintained systems. In practice, field results vary widely due to design quality, construction, vegetation health, and maintenance. RG nitrogen removal is highly sensitive to media design, carbon availability, anoxic conditions, and residence time. Poorly sized or overly sandy systems perform far below 45%, while optimised saturated designs can exceed 60%. The model uses mid-range values, but real installations can differ significantly.

Tank performance depends on how often tanks cycle between full and empty, household water use, and maintenance of first-flush devices. The model assumes ideal operation, but real households vary—especially during wet seasons when tanks remain full and overflow more often. Sensitivity testing (6, 12, 24-hr drain times) captures only part of this variability.

Maintenance is a major uncertainty. The analysis assumes regular inspections, cleaning, pump servicing, RG weeding, mulching, and media renewal. However, surveys show 30–50% of systems develop issues within five years, reducing performance. The thesis assumes education and council support maintain adequate performance, but if maintenance is poorer than expected, long-term outcomes will be lower.

As detailed in Section 5.4.5, climate projection uncertainty was addressed through scenario analysis (SSP2-4.5 representing moderate emissions) with sensitivity testing showing performance rankings remain stable under ± 20 –30% rainfall intensity variations. Urbanisation trajectory uncertainty (77% imperviousness by 2050, 84% by 2070) was addressed through separate climate-only, urbanisation-only, and combined scenarios.

7.2.3 Spatial and Temporal Scope

This study is based on a single 170-hectare suburban catchment with 64% imperviousness, residential land use, flat terrain, clay soils, and an older pipe network. Although typical of many outer-Melbourne areas, the results may not fully apply to catchments with different soils, slopes, land uses, or pollutant profiles. Industrial or commercial areas would also require different treatment approaches. The modelling method and evaluation framework remain transferable, but optimal hybrid configurations should be re-tested for each new catchment.

The climate assessment is based on a five-year period (2020–2024), which captures both wet and dry conditions but does not represent Melbourne’s full long-term variability. Ideally, a 20-year record spanning multiple climate phases would provide a more complete performance range. Data limitations restricted analysis to the available high-resolution monitoring period, but model validation (NSE = 0.76) and physically based processes support confidence in the broader relevance of the findings.

7.2.4 Economic Analysis Limitations

Costs use 2025 pricing and defaults, with sensitivity to escalation and discounts addressed earlier (Section 6.4). Bulk procurement could reduce costs 15–30%, but site variations may increase them. Excluded benefits (e.g., deferred upgrades, co-benefits like heat mitigation, flood damage avoidance) make the analysis conservative—full benefit-cost ratios would likely be more favourable.

7.2.5 Conclusion on Limitations

These limitations are inherent in modelling-based research addressing complex environmental systems and uncertain futures, and do not fundamentally undermine findings' validity. The research employed industry-standard methods, incorporated available data, explicitly tested key sensitivities, and transparently documented assumptions. Core conclusions, that distributed WSUD provides substantial cost-effective stormwater benefits, that Hybrid configurations offer most robust performance, and that WSUD maintains effectiveness under future scenarios, emerge consistently across sensitivity analyses.

The limitations identify clear priorities for future research:

- long-term empirical monitoring validating modelled performance
- expanded spatial analysis across diverse catchments; detailed economic analysis incorporating deferred costs and co-benefits
- refined climate-WSUD interaction analysis

Section 8 elaborates these priorities. This research provides rigorous evidence supporting WSUD implementation with clear configuration guidance, while recognising that adaptive management, ongoing monitoring, and periodic reassessment remain essential as long-term catchment-scale effectiveness becomes empirically observable.

7.3 Academic and Practical Contributions

This thesis makes contributions to both academic knowledge and practical application in the field of urban water management, specifically advancing understanding of how distributed Water Sensitive Urban Design systems perform in established urban contexts under present and projected future conditions. This final section articulates these contributions and their significance for research, policy, and practice communities.

7.3.1 Academic Contributions

While much research focuses on new developments, this study dives into retrofitting existing suburbs—where most cities need fixes. Using multi-year simulations in a typical Melbourne catchment (64% impervious), it shows WSUD can cut runoff by 50–72% and pollutants by 10–40%. The work also clarifies that performance does not increase linearly with coverage: modest implementation achieves only modest benefits, while approximately half-catchment coverage delivers the majority of improvements, and extremely high coverage adds little extra. This provides a realistic and evidence-based understanding of how far WSUD can go in retrofit environments.

Another academic contribution comes from separating climate and urbanisation impacts and examining their combined effect. The research shows that the combined 2050–2070 scenarios generate substantially higher stress than either factor on its own, confirming that single-driver planning underestimates future loads. Importantly, the thesis also quantifies how much WSUD

performance declines under severe future conditions: by 2070, effectiveness generally decreases by about 10–20% across hydraulic and pollutant removal metrics. Although reduced, WSUD still retains a meaningful role in moderating intensified runoff volumes and peak flows. This strengthens understanding of WSUD as an adaptation tool that remains functional—not failing—under future climate extremes.

A further academic contribution is the integrated hydraulic–quality–economic analysis framework developed in this study. Rather than treating hydraulic performance, pollutant removal, or cost as isolated components, the thesis evaluates them together, revealing their trade-offs and complementarities. This combined approach provides a clearer and more balanced representation of WSUD performance and creates a methodological template that can be applied to other catchments, including those considering broader green–blue infrastructure strategies.

By grounding the research in Melbourne’s temperate climate, basaltic clay soils, and established suburban form, the thesis adds regionally specific evidence to complement existing studies from other Australian cities. This local relevance supports ongoing policy development in Victoria and reduces uncertainty for councils seeking data that reflect their own environmental and social conditions.

Beyond its local applicability, the methodology and key findings of this work are transferable to other urban catchments facing the same stormwater issues. The integrated modelling framework, which combines continuous hydrologic, hydraulic simulation, water quality assessment, and life-cycle cost evaluation, does not depend on Melbourne's specific climate or infrastructure type but is rather made up of open, widely used tools (PCSWMM/EPA SWMM) and generalised design principles that are valid across temperate and subtropical regions.

Where no detailed local calibration data exists, the framework may be modified through the use of locally derived EMC values, soil infiltration parameters, and climate projections, whilst maintaining the same scenario structure and performance evaluation method. For instance, other Australian city practitioners, or those in similar international environments like the United Kingdom, parts of Europe, or urbanising areas of Southeast Asia, could use the same RWT, RG scenario logic on their catchments by re-parameterising the model with local rainfall, imperviousness, and design guideline inputs.

The coverage-dependency insight, that significant hydraulic and water quality benefits can only be achieved if the adoption rate reaches 50%, is probably applicable to a wide variety of urban catchment types, thus serving as a practical planning threshold which can be tested and fine-tuned in other contexts. Similarly, the insight that hybrid RWT + RG arrangements provide the most stable performance over changing climate and urbanization scenarios is in alignment with the broader LID literature and, therefore, should be predictive beyond this particular case study.

Thus, the work not only delivers site-specific findings but also a replicable methodological template that can facilitate evidence-based WSUD planning in various urban environments.

7.3.2 Practical Contributions

Alongside academic advances, the thesis generates practical guidance for councils and water managers. The modelling translates directly into implementable design considerations—such as appropriate system scales, operational settings, and routing choices—that can be adopted. The spatial prioritisation approach used in this study focuses on areas contributing to recurring overflow nodes and provides a clear method for sequencing WSUD rollout in established suburbs.

The economic evaluation, although deliberately conservative, demonstrates that distributed WSUD can achieve major hydraulic benefits at costs that compare favourably with grey infrastructure upgrades. This equips councils with credible evidence that WSUD is financially realistic rather than aspirational.

The research also supports climate adaptation planning by showing that WSUD retains substantial effectiveness despite the harsher rainfall intensification expected by 2070. Although performance drops by roughly 10–20%, the systems still prevent a large fraction of the projected increase in runoff and remain a viable long-term adaptation pathway for practical projects.

Finally, the established methodological flow covers everything from model setup and scenario design to cost evaluation and decision-making integration, which could serve as a portable plan. Different local governments may adopt this approach to generate catchment-specific WSUD plans, thereby facilitating the dissemination of the research findings to areas outside the study region.

Chapter 8: Recommendations for Future Research

8.1 Recommendations for Policy, Planning and Implementation

The findings of this research highlight the need for a more structured, proactive, and long-term approach to stormwater management in established suburbs. The following recommendations outline how city councils with similar study area conditions can translate the modelling insights into practical, resilient planning and infrastructure strategies.

I. Establish Realistic Stormwater Targets for Established Suburbs

Stormwater regulations in many jurisdictions are still anchored in assumptions developed for greenfield development or historical climate conditions. In contrast, retrofit environments face spatial, infrastructure, and imperviousness constraints that limit the level of improvement achievable through WSUD. Targets for established suburbs therefore need recalibration to reflect realistic retrofit performance and to place equal emphasis on volumetric control, hydrologic restoration, and waterway protection.

Existing design standards should also be updated to reflect mid-century climate projections rather than historical rainfall patterns. Councils should plan drainage performance, WSUD sizing, and assessment thresholds in alignment with 2050–2070 design conditions to ensure resilience under intensified rainfall and increasing urban density.

Overall, targets for established areas must be grounded in achievable retrofit outcomes rather than idealised greenfield benchmarks. Volume-reduction targets, in particular, should be embedded as a core policy objective given their strong influence on both flood mitigation and waterway health. These revised targets should guide assessment of development applications, catchment-scale planning, and regional stormwater strategies.

II. Strengthen Development Planning Controls

Given the steady increase in imperviousness from redevelopment and subdivision, planning schemes must ensure that new development does not further degrade system performance.

Councils should require WSUD for all development types to introduce additional hardstand areas for new dwellings, extensions, garage additions, subdivisions, and commercial works.

Minimum installation requirements such as 4 kL RWTs or RGs of at least 10 m² should be mandated as part of statutory planning and building codes. Councils should also adopt minimum runoff reduction expectations (e.g., a baseline target of around 50% volume reduction for compliant sites) to maintain consistency across infill development.

For sites where installation is not feasible, alternative compliance through financial contribution to shared public WSUD installations should be clearly defined.

3. Deliver Long-Term Incentive and Support Programs

It is particularly important to have a long-term, adequately funded incentive plan to thoroughly refurbish the suburbs that have already been established. While mandatory controls address new development, most of the catchment's impervious area lies within existing properties. Encouraging voluntary uptake requires financial and non-financial support.

Rebates, stormwater fee reductions, and stormwater credit programs can be the major factors in adoption growth.

Such initiatives may be supported by the effects of previous large-scale projects, thus giving a clear demonstration that a sustained investment in rebates can gradually achieve a widespread uptake.

Importantly, incentives should be paired with accessible technical support: pre-approved designs, installer panels, free site assessments, and simplified approvals for compliant systems.

4. Apply Strategic Spatial Prioritisation

Rather than distributing WSUD uniformly across a catchment, local governments should focus on sub-catchments that are putting the most pressure on the most vulnerable parts of the drainage network. Areas that are the source of recurring overflow locations, districts with flood complaints, and localities with sensitive land uses or vulnerable residents should form the early focus of implementation.

Staged expansion can follow, moving from the highest-risk areas to secondary locations and eventually full catchment coverage. This approach ensures that limited resources yield maximum system-wide improvement.

5. Integrate WSUD Into Core Infrastructure Planning

Councils should embed WSUD directly into their infrastructure planning and capital works evaluations. Traditional stormwater management has relied on increasing the size of the pipes or building detention facilities after the occurrence of problems. Nevertheless, the models indicate that widely spread WSUD can turn down the system's pressure and thus, in some instances, can postpone or even cancel the need for conventional upgrades.

Comparative assessment frameworks should therefore be standard practice, evaluating grey, green, and hybrid alternatives based on life-cycle cost, resilience to future conditions, environmental performance, and adaptability.

As part of this transition, governance arrangements should progressively shift toward 2070-design performance levels, including smarter operational practices such as real-time monitoring of WSUD assets. IoT-enabled sensors integrated into RG underdrains and tank overflows can support adaptive system management, for example by enabling dynamic drain adjustments during extended dry periods.

6. Invest in Community Engagement and Social Participation

WSUD uptake depends heavily on public understanding and participation. Councils should invest in visible demonstration sites, co-design workshops, and public education initiatives. These activities contribute to the normalization of WSUD technologies and highlight co-benefits such as cooling, amenity, biodiversity, and increased property value.

Community participation is pivotal for long-term retrofit success. Engagement programs should have culturally inclusive communication materials, co-design processes for public WSUD projects, and open-house demonstration events to create familiarity and lower the level of perceived complexity. Maintenance support, such as household guidance, shared maintenance programs, or council-assisted stewardship, should be integrated into engagement initiatives to help residents sustain system performance over time.

8.2 Future Research Opportunities

This thesis demonstrates that distributed WSUD can substantially improve stormwater performance in an established, highly impervious suburban catchment, but it also highlights several important gaps that future research should address:

A first priority is long-term empirical monitoring of actual WSUD installations over at least 5–10 years. Continuous flow and water quality monitoring at representative properties, combined with periodic audits of vegetation, media condition, and maintenance, would test how well modelled performance holds over time as systems age, clog, and experience wet and dry climate cycles. These data would refine design guidelines and modelling parameters and improve confidence in long-term projections.

The second major area of investigation involves expanding analysis beyond the single Hoppers Crossing catchment used in this thesis. The current results were developed for a relatively flat, clay-soil, predominantly residential catchment in a temperate rainfall regime. Applying the same framework to steeper catchments, sandy-soil areas, highly built-out inner suburbs, mixed commercial–residential areas, and regional cities with different rainfall seasonality would clarify how soil type, topography, land use and climate shape WSUD effectiveness. Such comparative work could support practical decision tools that guide practitioners toward different WSUD mixes in different catchment types.

Future research should also systematically explore mixed WSUD configurations beyond the limited set tested here. This thesis evaluated discrete scenarios (such as 25% RWT, 50% RWT, 25% RG, 50% RG, and a 25%–25% Hybrid), but did not map the full design space. Optimization studies should look at a wider matrix of RWT–RG combinations, such as 25–75%, 50–50%, and 75–25% mixes, and compare their performance in terms of hydraulics, water quality, and costs. Since the current results were obtained for the Hoppers Crossing rainfall regime, it is likely that different climates will favour different balances, i.e., more RG-heavy configurations in wetter climates and more tank-heavy configurations where rainfall is lower or more seasonal. Future optimization studies should therefore test these mixed configurations under different climatic conditions and rainfall patterns to determine how rainfall amount and distribution affect the most efficient RWT–RG ratio.

Finally, future studies should investigate equity and integration questions:

- how the benefits and burdens of WSUD are distributed across:
 - renters and owners
 - high- and low-income areas
 - different cultural communities

- how WSUD can be more tightly integrated with alternative water supply systems, such as:
 - greywater reuse
 - precinct-scale stormwater harvesting

Together, these research directions would extend the applicability of this thesis, strengthen the evidence base for large-scale WSUD implementation, and support the development of water-sensitive, climate-resilient urban environments across a wider range of contexts than the single case study examined here.

References

- (ABS) 2025. Australian Bureau of Statistics, <https://www.abs.gov.au/>.
- ABI AAD, M. P., SUIDAN, M. T. & SHUSTER, W. D. J. J. O. H. E. 2010. Modeling techniques of best management practices: Rain barrels and rain gardens using EPA SWMM-5. 15, 434-443
- AHMED, W., HAMILTON, K., TOZE, S., COOK, S. & PAGE, D. J. S. O. T. T. E. 2019. A review on microbial contaminants in stormwater runoff and outfalls: Potential health risks and mitigation strategies. 692, 1304-1321
- ALIM, M. A., JAHAN, S., RAHMAN, A., RAHMAN, M. A., LIEBMAN, M., GARNER, B., GRIFFITH, R., GRIFFITH, M. & TAO, Z. 2023. Experimental investigation of a multilayer detention roof for stormwater management. *Journal of Cleaner Production*, 395, 136413
- ALLISON, R. A., MCMAHON, T. A. & CHIEW, F. H. 1997. *Stormwater gross pollutants*, CRC for Catchment Hydrology.
- AUSTRALIANGOVERNMENT 2025. , Department of Finance. Cost-Benefit Analysis Guidance Note. <https://www.finance.gov.au/publications>.
- BARTON, A. B. & ARGUE, J. R. J. A. J. O. W. R. 2007. A review of the application of water sensitive urban design (WSUD) to residential development in Australia. 11, 31-40
- BASHMAKOV, I. A., NILSSON, L. J., ACQUAYE, A., BATAILLE, C., CULLEN, J. M., FISCHEDICK, M., GENG, Y. & TANAKA, K. 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Chapter 11.
- BEECHAM, S., RAZZAGHMANESH, M., BUSTAMI, R. & WARD, J. 2019. The role of green roofs and living walls as WSUD approaches in a dry climate. *In: SHARMA, A., GARDNER, T. & BEGBIE, D. (eds.) Approaches to water sensitive urban design*. Elsevier.
- BERNDTSSON, J. C. J. E. E. 2010. Green roof performance towards management of runoff water quantity and quality: A review. 36, 351-360
- BOM. 2007. *Climate statistics for Australian locations - definitions for rainfall*. Retrieved Feb 14, 2025, from <https://www.bom.gov.au/climate/cdo/about/definitionsrain.shtml> [Online]. Australian Bureau of Meteorology,. [Accessed].
- BOSSERELLE, A. L., MORGAN, L. K. & HUGHES, M. W. J. E. S. F. 2022. Groundwater rise and associated flooding in coastal settlements due to sea-level rise: a review of processes and methods. 10, e2021EF002580
- BROWN, R., KEATH, N. & WONG, T. Transitioning to water sensitive cities: historical, current and future transition states. 11th international conference on urban drainage, 2008. IWA Publishing, Edinburgh, Scotland.
- BRUNNER, G. J. U. A. C. O. E. H. E. C. H. 2021. HEC-RAS River Analysis System: HEC-RAS 2D User's Manual.
- BURNS, M. J., FLETCHER, T. D., WALSH, C. J., LADSON, A. R., HATT, B. E. J. L. & PLANNING, U. 2012. Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform. 105, 230-240
- COMPUTATIONAL HYDRAULICS INTERNATIONAL (CHI), PCSWMM 2023 (Version 7.6.3695). 7.6.3695 ed. Guelph, Ontario, Canada.

- DE HAAN, F. J., FERGUSON, B. C., ADAMOWICZ, R. C., JOHNSTONE, P., BROWN, R. R., WONG, T. H. J. T. F. & CHANGE, S. 2014. The needs of society: A new understanding of transitions, sustainability and liveability. 85, 121-132
- DEPARTMENT OF ENVIRONMENT, L., WATER AND PLANNING. 2018. *Stormwater Issues Paper*. Melbourne, Australia. https://www.water.vic.gov.au/__data/assets/pdf_file/0027/672426/Stormwater-Issues-Paper.pdf?utm_source=chatgpt.com.
- DI CHIANO, M. G., MARCHIONI, M. & BECCIU, G. 2025. Probabilistic models for optimal rainwater harvesting tank sizing: a comparison with traditional approaches. *Water Resources Management*, 39, 5211-5225
- DRAPPER, D. & HORNBUCKLE, A. 2018. Removal of nutrients, sediment, and heavy metals by a stormwater treatment train; a medium-density residential case study in Southeast Queensland. *Water*, 10, 1307
- DRAPPER, D., OLIVE, K., MCALISTER, T., COLEMAN, R. & LAMPARD, J.-L. J. F. I. E. C. 2022. A review of pollutant concentrations in urban stormwater across eastern australia, after 20 years. 3, 853764
- DUTTA, A., TORRES, A. S. & VOJINOVIC, Z. J. W. 2021. Evaluation of pollutant removal efficiency by small-scale nature-based solutions focusing on bio-retention cells, vegetative swale and porous pavement. 13, 2361
- EKKA, S. A., RUJNER, H., LEONHARDT, G., BLECKEN, G.-T., VIKLANDER, M. & HUNT, W. F. J. J. O. E. M. 2021. Next generation swale design for stormwater runoff treatment: A comprehensive approach. 279, 111756
- ELLIOTT, A., TROWSDALE, S. A. J. E. M. & SOFTWARE 2007. A review of models for low impact urban stormwater drainage. 22, 394-405
- EWATER 2013a. <https://ewater.atlassian.net/wiki/spaces/MD6/pages/56470236/Life+Cycle+Costing+of+T+reatment+Measures>.
- EWATER 2013b. MUSIC by Ewater: User Manual. EWater Melbourne, Australia.
- FENGXIANG, Q., WANYAN, Y. & LI, Q. J. C. E. R. J. 2018. Influencing Factors and Strategies for Sustainable Urban Drainage System. 3, 1-3
- FLETCHER, T. D., SHUSTER, W., HUNT, W. F., ASHLEY, R., BUTLER, D., ARTHUR, S., TROWSDALE, S., BARRAUD, S., SEMADENI-DAVIES, A. & BERTRAND-KRAJEWSKI, J.-L. J. U. W. J. 2015. SUDS, LID, BMPs, WSUD and more—The evolution and application of terminology surrounding urban drainage. 12, 525-542
- GOULD, J. J. 1999. Rainwater catchment systems for domestic supply.
- GRANDE, E., VISSER, A., BEITZ, P. & MORAN, J. J. W. 2019. Examination of nutrient sources and transport in a catchment with an Audubon certified golf course. 11, 1923
- GUAM, E. 2012. Guam Environmental Protection Agency. Rain Garden Installation Training Guide. Santos Memorial Park, Piti, Guam. https://www.ncei.noaa.gov/data/oceans/coris/library/NOAA/CRCP/project/694/120827_Guam_Rain_Garden_Installation_Guide.pdf.
- GURUNG, S. B., WASSON, R. J., BIRD, M. & JARIHANI, B. 2025. Water-Sensitive Urban Design (WSUD) Performance in Mitigating Urban Flooding in a Wet Tropical North Queensland Sub-Catchment.

- GURUNG, T. R., STEWART, R. A., BEAL, C. D. & SHARMA, A. K. J. W. R. M. 2016. Investigating the financial implications and viability of diversified water supply systems in an urban water supply zone. 30, 4037-4051
- HOBAN, A. 2019. Water sensitive urban design approaches and their description. *In: SHARMA, A., GARDNER, T. & BEGBIE, D. (eds.) Approaches to water sensitive urban design.* Elsevier.
- JAMES, W. Rules for responsible modeling. 2003. CHI Guelph, Ontario.
- JIANG, C., LI, J., LI, H., LI, Y., CHEN, L. J. W., AIR, & POLLUTION, S. 2017. Field performance of bioretention systems for runoff quantity regulation and pollutant removal. 228, 468
- KHALAJI, F., ZHANG, J. & SHARMA, A. K. J. W. 2024. Social and Economic Impacts of Water Sensitive Urban Design: A Review. 17, 16
- KRIMSKY, L. S., LUSK, M. G., ABEELS, H. & SEALS, L. J. S. O. T. T. E. 2021. Sources and concentrations of nutrients in surface runoff from waterfront homes with different landscape practices. 750, 142320
- KURUPPU, U. & RAHMAN, A. 2023. Effects of subbase materials on phosphorous attenuation in permeable pavement system and correlation between pollution attenuation and subbase materials. *Water and Environment Journal*, 37, 166-177
- LAMECHE, E. K., BOUTAGHANE, H., SABER, M., ABDRABO, K. I., BERMAD, A. M., DJEDDOU, M., BOULMAIZ, T., KANTOUSH, S. A., SUMI, T. J. W. S. & TECHNOLOGY 2023. Urban flood numerical modeling and hydraulic performance of a drainage network: A case study in Algiers, Algeria. 88, 1635-1656
- LEE, H., CALVIN, K., DASGUPTA, D., KRINNER, G., MUKHERJI, A., THORNE, P., TRISOS, C., ROMERO, J., ALDUNCE, P. & BARRETT, K. 2023. *Climate change 2023: synthesis report. Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change.*
- LEONARD, R., IFTEKHAR, S., GREEN, M. & WALTON, A. 2019. Community perceptions of the implementation and adoption of WSUD approaches for stormwater management. *Approaches to water sensitive urban design.* Elsevier.
- LI, J., ZENG, J., HUANG, G. & CHEN, W. 2024a. Urban flood mitigation strategies with coupled gray-green measures: a case study in Guangzhou City, China. *International Journal of Disaster Risk Science*, 15, 467-479
- LI, Y., WANG, P., LOU, Y., CHEN, C., SHEN, C. & HU, T. J. J. O. H. R. S. 2024b. Assessing urban drainage pressure and impacts of future climate change based on shared socioeconomic pathways. 53, 101760
- LING, Z., PENG, L. & WEN, H. J. Y. Y. S. T. X. B. T. J. O. A. E. 2023. Comparison on the stormwater runoff effects of roof greening in different urban functional areas. 34, 491-498
- LIU, A., EGODAWATTA, P., GUAN, Y. & GOONETILLEKE, A. J. S. O. T. T. E. 2013. Influence of rainfall and catchment characteristics on urban stormwater quality. 444, 255-262
- LLOYD, S. D., WONG, T. H. & CHESTERFIELD, C. J. 2002. Water sensitive urban design: a stormwater management perspective.
- LOCATELLI, L., MARK, O., MIKKELSEN, P. S., ARNBJERG-NIELSEN, K., WONG, T. & BINNING, P. J. J. O. H. 2015. Determining the extent of groundwater interference on the performance of infiltration trenches. 529, 1360-1372

- LUCAS, W. C. & SAMPLE, D. J. J. J. O. H. 2015. Reducing combined sewer overflows by using outlet controls for Green Stormwater Infrastructure: Case study in Richmond, Virginia. 520, 473-488
- MACKENZIE, K., SINGH, K., BINNS, A., WHITELEY, H. & GHARABAGHI, B. J. J. O. H. 2022. Effects of urbanization on stream flow, sediment, and phosphorous regime. 612, 128283
- MADHANI, J. T. & BROWN, R. J. J. E. E. 2015. The capture and retention evaluation of a stormwater gross pollutant trap design. 74, 56-59
- MAHBUB, P. & SHARMA, A. J. J. O. H. 2019. Investigation of alternative water sources for fish farming using life cycle costing approach: a case study in North West Tasmania. 579, 124215
- MANGANGKA, I. R., LIU, A. & GOONETILLEKE, A. 2016. *Enhancing the storm water treatment performance of constructed wetlands and bioretention basins*, Springer.
- MARY-LAUYÉ, A. L., GONZÁLEZ-BERGONZONI, I., GOBEL, N., SOMMA, A., SILVA, I., LUCAS, C. M. J. E. M. & ASSESSMENT 2023. Baseline assessment of the hydrological network and land use in riparian buffers of Pampean streams of Uruguay. 195, 80
- MASONER, J. R., KOLPIN, D. W., COZZARELLI, I. M., BARBER, L. B., BURDEN, D. S., FOREMAN, W. T., FORSHAY, K. J., FURLONG, E. T., GROVES, J. F., HLADIK, M. L. J. E. S. & TECHNOLOGY 2019. Urban stormwater: An overlooked pathway of extensive mixed contaminants to surface and groundwaters in the United States. 53, 10070-10081
- MELBOURNE WATER. 2016. *Management of the ecological impacts of urban land and activities on waterways: Issues Paper – Understanding the Science*. Melbourne, Australia. https://www.clearwatervic.com.au/resource-library/publications-and-reports/management-of-the-ecological-impacts-of-urban-land-and-activities-on-waterways-issues-paper-understanding-the-science.php?utm_source=chatgpt.com.
- MELBOURNE WATER. 2022. *MUSIC (Model for Urban Stormwater Improvement Conceptualisation) Guideline*. Available online: https://clearwatervic.com.au/user-data/resource-files/am-gui-music-guideline_2022_release-a.pdf (accessed on April 2025). https://clearwatervic.com.au/user-data/resource-files/am-gui-music-guideline_2022_release-a.pdf.
- MORASH, J., WRIGHT, A., LEBLEU, C., MEDER, A., KESSLER, R., BRANTLEY, E. & HOWE, J. J. S. 2019. Increasing sustainability of residential areas using rain gardens to improve pollutant capture, biodiversity and ecosystem resilience. 11, 3269
- MYERS, B. R. & PEZZANITI, D. 2019. Flood and peak flow management using WSUD systems. In: SHARMA, A., GARDNER, T. & BEGBIE, D. (eds.) *Approaches to water sensitive urban design*. Elsevier.
- NEWNAN, D. G., ESCHENBACH, T. G. & LAVELLE, J. P. 2004. *Engineering economic analysis*, Oxford University Press.
- NODINE, T. G., CONLEY, G., RIIHIMAKI, C. A., HOLLAND, C. & BECK, N. G. J. S. R. 2024. Modeling the impact of future rainfall changes on the effectiveness of urban stormwater control measures. 14, 4082
- NOVOTNY, V. 1994. *Water quality: prevention, identification and management of diffuse pollution*, Van Nostrand-Reinhold Publishers.

- O'HALLORAN, D., MCLEAN, J., MORISON, P., SIMS, A., WEBER, T., MARKWELL, K., WALKER, B., LIGHT, O. & HART, B. 2024. Targets for Urban Stormwater Management in Australia. 16, 3686
- PATRICK, A. N., BERNARD, K., TIRPAK, R. A., SIMPSON, I. M., SMITH, J. S., WINSTON, R. J. J. W. S. & TECHNOLOGY 2025. Hydrologic and water quality performance of an 8-year old bioretention cell treating residential runoff. 92, 752-769
- PAUL, M. J., MEYER, J. L. J. A. R. O. E. & SYSTEMATICS 2001. Streams in the urban landscape. 32, 333-365
- PETER, K. T., TIAN, Z., WU, C., LIN, P., WHITE, S., DU, B., MCINTYRE, J. K., SCHOLZ, N. L., KOLODZIEJ, E. P. J. E. S. & TECHNOLOGY 2018. Using high-resolution mass spectrometry to identify organic contaminants linked to urban stormwater mortality syndrome in coho salmon. 52, 10317-10327
- PETRIE, B. J. E. S. & RESEARCH, P. 2021. A review of combined sewer overflows as a source of wastewater-derived emerging contaminants in the environment and their management. 28, 32095-32110
- POLUKAROVA, M., MARKIEWICZ, A., BJÖRKLUND, K., STRÖMVALL, A.-M., GALFI, H., SKÖLD, Y. A., GUSTAFSSON, M., JÄRLSKOG, I. & ARONSSON, M. J. E. I. 2020. Organic pollutants, nano-and microparticles in street sweeping road dust and washwater. 135, 105337
- RAHMAN, A., KEANE, J., IMTEAZ, M. A. J. R., CONSERVATION & RECYCLING 2012. Rainwater harvesting in Greater Sydney: Water savings, reliability and economic benefits. 61, 16-21
- RASHETNIA, S., SHARMA, A. K., LADSON, A. R., BROWNE, D. & YAGHOUBI, E. J. U. W. J. 2022. A scoping review on Water Sensitive Urban Design aims and achievements. 19, 453-467
- RENTACHINTALA, L. R. N. P., REDDY, M. M., MOHAPATRA, P. K. J. W. S. & TECHNOLOGY 2022. Urban stormwater management for sustainable and resilient measures and practices: a review. 85, 1120-1140
- RODRÍGUEZ-ROJAS, M. I., GRINDLAY MORENO, A. L. J. I. J. O. E. R. & HEALTH, P. 2022. A discussion on the application of terminology for urban soil sealing mitigation practices. 19, 8713
- ROSSMAN, L. & HUBER, W. 2015. *Storm water management model reference manual volume I, hydrology. US EPA Office of Research and Development, Washington, DC.*
- ROSSMAN, L. A. 2010. *Storm water management model user's manual, version 5.0*, National Risk Management Research Laboratory, Office of Research and ...
- ROSSMAN, L. A. 2022. *Storm Water Management Model User's Manual Version 5.2*. Cincinnati, OH, USA. <https://www.epa.gov/system/files/documents/2022-04/swmm-users-manual-version-5.2.pdf>.
- SABBAGH, M., BROWNE, D., PICKERING, L., LINTERN, A. & WINFREY, B. 2025. Urban stormwater bioretention reduces runoff and improves water quality: A global meta-analysis of field studies. *Journal of Hydrology*, 134163
- SELBIG, W. R., BUER, N. & DANZ, M. E. J. J. O. E. M. 2019. Stormwater-quality performance of lined permeable pavement systems. 251, 109510

- SHAIKH, T. A., ADJOVU, G. E., STEPHEN, H. & AHMAD, S. Impacts of urbanization on watershed hydrology and runoff water quality of a watershed: a review. *World Environmental and Water Resources Congress 2023*, 2023. 1271-1283.
- SHARMA, A., BEGBIE, D. & GARDNER, T. 2015. *Rainwater tank systems for urban water supply: design, yield, energy, health risks, economics and social perceptions*, Iwa Publishing.
- SHARMA, A., GARDNER, T. & BEGBIE, D. 2018. *Approaches to water sensitive urban design: potential, design, ecological health, urban greening, economics, policies, and community perceptions*, Woodhead Publishing.
- SHARMA, A. K., PEZZANITI, D., MYERS, B., COOK, S., TJANDRAATMADJA, G., CHACKO, P., CHAVOSHI, S., KEMP, D., LEONARD, R. & KOTH, B. J. W. 2016. Water sensitive urban design: An investigation of current systems, implementation drivers, community perceptions and potential to supplement urban water services. 8, 272
- SHARMA, A. K., SANCILOLO, P., BEHROOZI, A., NAVARATNA, D. & MUTHUKUMARAN, S. 2023. Stormwater harvesting potential for local reuse in an urban growth area: a case study of Melton growth area in the west of Melbourne. *Water*, 15, 2093
- SHOEMAKER, L., RIVERSON, J., ALVI, K., ZHEN, J. X., PAUL, S. & RAFI, T. 2009. *SUSTAIN: a framework for placement of best management practices in urban watersheds to protect water quality*, National Risk Management Research Laboratory, Office of Research and
- SHUSTER, W. D., BONTA, J., THURSTON, H., WARNEMUENDE, E. & SMITH, D. R. 2005. Impacts of impervious surface on watershed hydrology: A review. *Urban Water Journal*, 2, 263-275
- SIMPSON, I. M., WINSTON, R. J. & BROOKER, M. R. J. S. O. T. T. E. 2022. Effects of land use, climate, and imperviousness on urban stormwater quality: A meta-analysis. 809, 152206
- SOLTANINIA, S., TAGHAVI, L., HOSSEINI, S. A., MOTAMEDVAZIRI, B. & ESLAMIAN, S. J. W. R. 2022. The effect of land-use type and climatic conditions on heavy metal pollutants in urban runoff in a semi-arid region. 12, 384-402
- STAFF, C. P. & COMMITTEE, V. S. 1999. *Urban Stormwater: Best-Practice Environmental Guidelines*, CSIRO Pub.
- STORMWATER CENTER. *The simple method to calculate urban stormwater loads*. [Online]. Center for Watershed Protection. Available: <https://www.stormwatercenter.net/monitoring%20and%20assessment/simple%20meth/simple.htm> [Accessed]. [Online]. [Accessed].
- TAKAIJUDIN, H., GHANI, A. & ZAKARIA, N. A. 2016. Challenges and developments of bioretention facilities in treating urban stormwater runoff; A review.
- TRENBERTH, K. E. J. C. R. 2011. Changes in precipitation with climate change. 47, 123-138
- WALSH, C. J., FLETCHER, T. D. & BURNS, M. J. 2012. Urban stormwater runoff: a new class of environmental flow problem.
- WALSH, C. J., ROY, A. H., FEMINELLA, J. W., COTTINGHAM, P. D., GROFFMAN, P. M. & MORGAN, R. P. J. J. O. T. N. A. B. S. 2005. The urban stream syndrome: current knowledge and the search for a cure. 24, 706-723
- WANG, J., CHUA, L. H., SHANAHAN, P. J. E. S. W. R. & TECHNOLOGY 2017a. Evaluation of pollutant removal efficiency of a bioretention basin and implications for stormwater management in tropical cities. 3, 78-91

- WANG, J., MEI, G., GARG, A., CHEN, D. & LIU, N. J. J. O. E. M. 2023. A simplified model for analyzing rainwater retention performance and irrigation management of green roofs with an inclusion of water storage layer. 326, 116740
- WANG, M., ZHANG, D. Q., SU, J., TRZCINSKI, A. P., DONG, J. W. & TAN, S. K. J. C. S., AIR, WATER 2017b. Future scenarios modeling of urban stormwater management response to impacts of climate change and urbanization. 45, 1700111
- WANG, M., ZHUANG, J. A., SUN, C., WANG, L., ZHANG, M., FAN, C. & LI, J. J. L. 2024. The application of rain gardens in urban environments: a bibliometric review. 13, 1702
- WANG, Q., ZHANG, Q., WU, Y. & WANG, X. C. J. C. 2017c. Physicochemical conditions and properties of particles in urban runoff and rivers: Implications for runoff pollution. 173, 318-325
- WEI, H., WU, H., ZHANG, L., LIU, J. J. W. S. & TECHNOLOGY 2024. Urban flooding simulation and flood risk assessment based on the InfoWorks ICM model: A case study of the urban inland rivers in Zhengzhou, China. 90, 1338-1358
- WEI, Z., SIMIN, L. & FENGBING, T. J. T. S. W. J. 2013. Characterization of urban runoff pollution between dissolved and particulate phases. 2013, 964737
- WHELANS, C., MAUNSELL, H. G., THOMPSON, P. J. D. O. P. & URBAN DEVELOPMENT OF WESTERN AUSTRALIA, P., AUSTRALIA 1994. Planning and management guidelines for water sensitive urban (residential) design.
- WONG, T. H., BROWN, R. R. J. W. S. & TECHNOLOGY 2009. The water sensitive city: principles for practice. 60, 673-682
- XU, Z., HUA, W., XIONG, L., HE, Z. J. E. S. & RESEARCH, P. 2020. Novel design of volume of detention tanks assisted by a multi-source pollution overflow model towards pollution control in urban drainage basins. 27, 12781-12791
- YANG, Y., ZHU, D. Z., LOEWEN, M. R., ZHANG, W., VAN DUIN, B. & MAHMOOD, K. J. S. O. T. T. E. 2024. Impacts of climate change on urban stormwater runoff quantity and quality in a cold region. 954, 176439
- YAZDANFAR, Z. & SHARMA, A. 2015. Urban drainage system planning and design—challenges with climate change and urbanization: a review. 72, 165-179
- YUAN, L., MIKELONIS, A. M. & YAN, E. 2023. Using SWMM for emergency response planning: A case study evaluating biological agent transport under various rainfall scenarios and urban surfaces. *Journal of Hazardous Materials*, 458, 131747

Appendices

Appendix 1. Summary of some stormwater network conduits

| Conduit Name | Inlet Node | Outlet Node | Length (m) | Roughness | Geom1 (m) | Slope (m/m) | Max. Flow (m ³ /s) | Max. Velocity (m/s) | Max/Full Flow |
|--------------|------------|-------------|------------|-----------|-----------|-------------|---------------------------------|----------------------|---------------|
| 1004 | 1004 | 1003 | 56.72 | 0.01 | 1.35 | 0.001 | 0.555 | 1.45 | 0.25 |
| 1005 | 1005 | 1004 | 29.98 | 0.01 | 0.3 | 0.001 | 0.001 | 0.09 | 0.03 |
| 2001 | 2001 | 1003 | 8.122 | 0.01 | 0.38 | 0.001 | 0.008 | 0.28 | 0.1 |
| 2002 | 2002 | 2001 | 38.93 | 0.01 | 0.38 | 0.001 | 0.007 | 0.27 | 0.09 |
| 2003 | 2003 | 2002 | 10.23 | 0.01 | 0.3 | 0.001 | 0.006 | 0.32 | 0.15 |
| 2004 | 2004 | 2003 | 53.31 | 0.01 | 0.3 | 0.0108 | 0.005 | 0.39 | 0.04 |
| 2005 | 2005 | 2004 | 74.16 | 0.01 | 0.3 | 0.0048 | 0.003 | 0.58 | 0.04 |
| 2006 | 2006 | 2005 | 69.51 | 0.01 | 0.22 | 0.0072 | 0.001 | 0.35 | 0.03 |
| 3001 | 3001 | 1004 | 13.61 | 0.01 | 0.68 | 0.001 | 0.026 | 0.39 | 0.07 |
| 3002 | 3002 | 3001 | 36.68 | 0.01 | 0.68 | 0.001 | 0.025 | 0.36 | 0.07 |
| 3003 | 3003 | 3002 | 13.2 | 0.01 | 0.6 | 0.0011 | 0.025 | 0.38 | 0.1 |
| 3004 | 3004 | 3003 | 27.47 | 0.01 | 0.6 | 0.001 | 0.025 | 0.38 | 0.1 |
| 3005 | 3005 | 3004 | 25.68 | 0.01 | 0.52 | 0.001 | 0.02 | 0.23 | 0.12 |
| 3006 | 3006 | 3005 | 44.76 | 0.01 | 0.52 | 0.0036 | 0.019 | 0.33 | 0.06 |
| 3007 | 3007 | 3006 | 63.41 | 0.01 | 0.52 | 0.0056 | 0.017 | 0.74 | 0.04 |
| 3008 | 3008 | 3007 | 12.82 | 0.01 | 0.52 | 0.0933 | 0.016 | 1.37 | 0.01 |
| 3009 | 3008 | 3009 | 63.92 | 0.01 | 0.52 | 0.001 | 0.015 | 0.46 | 0.09 |

Appendix 2. Recurring Overflowed Manholes (2020_ 2024)

| Manhole ID | Notes |
|--------------|--|
| 3001 | Likely critical node, appears every year. |
| 57001 | Overflowed 2021–2024. Possibly impacted by downstream backup. |
| 12002 | Overflowed 2020, 2022–2024. High sensitivity to rainfall bursts. |
| 14001 | Overflowed every year. Known bottleneck. |
| 14003 | Persistent surcharge, every year. |

| | |
|---------------|---|
| 4002 | Present 2020–2024, vulnerable to mid-size events. |
| 22002 | Every year; poor drainage or elevation issue. |
| 14144 | Likely critical node, appears every year. |
| 14164 | Likely critical node, appears every year. |
| 22001 | 2020–2024; likely impacted by upstream flows. |
| 230006 | Every year. Major overflow node. |
| 1005 | Overflowing even in light rainfall years like 2020 & 2024. |
| 80001 | Common to 2022–2024. May overflow due to cumulative stress. |
| 14160 | 2020, 2023–2024. Triggered under heavy events. |
| 68001 | Notable in 2020, 2023–2024. Likely downstream issues. |
| 80002 | 2020, 2022–2024. Possibly undersized pipe or blocked. |
| 73002 | Likely critical node, appears every year. |
| 3005 | All five years. Persistent capacity issue. |
| 189004 | 2020, 2022–2024. Overflowed during intense bursts. |
| 19002 | Likely critical node, appears every year. |
| 29001 | 2020–2024. Likely at topographical low point. |
| 14162 | Every year. Repeat overflows suggest pipe/gradient issue. |
| 14181 | Appears all years. May need capacity upgrade. |
| 2001 | Present every year; problematic node. |
| 166006 | 2020, 2022–2024. Heavy rainfall triggers it. |
| 2003 | Overflowed from 2020–2024. Chronic bottleneck. |
| 166007 | All years except 2020. May have recent capacity issues. |
| 3006 | 2020–2024. Overflows persist despite variations. |
| 68003 | 2020, 2022–2024. Downstream capacity limits |