Enhancing Site-Scale Stormwater Management Through Real-Time Adapter Control System

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Certificate of Original Authorship

I, Xuli Meng, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution. This research is supported by the Australian Government Research Training Program.

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List of Publications

1. **Xuli Meng**, 2022. Understanding the Effects of site-scale Water Sensitive Urban Design (WSUD) in urban water cycles – a review. *Blue-Green Systems,* 4(1), pp. 45-57.
2. **Xuli Meng**, 2024. Revolutionizing control systems: unleashing the power of Real-time Adaptive Control (RTAC) in stormwater management. *IWA World Water Congress & Exhibition 2024*
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List of Acronyms

AEP	Annual Exceedance Probability
ARI	Average Recurrence Interval
ARR	Australian Rainfall and Runoff
APP	Area-Pipeline-Policy
BAU	Business-As-Usual
C^*	Equilibrium Value
COD	Chemical Oxygen Demand
EPA	Environmental Protection Agency (Australia)
ET	Evapotranspiration
EY	Exceedance Year
GI	Groundwater Infiltration
GP	Gross Pollutant
I	Inflow
k	Exponential Rate Constant
LID	Low Impact Development
M	Named by the author's family name MENG, represents the recovery capacity in the stormwater harvesting tank systems between two continuous rain at the same point
O	Outflow
P	Precipitation
PMP	Probable Maximum Precipitation
Q	Discharge (typically in cubic meters per second or liters per second)
q	Hydraulic loading of the treatment measure
Rs	Stormwater Runoff
TSS	Total Suspended Solids
TP	Total Phosphorus
TN	Total Nitrogen
V	Volume
v	Velocity
WSUD	Water Sensitive Urban Design

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Abstract

Urbanization, driven by population growth and rural-to-urban migration, has dramatically altered land use patterns, transforming natural landscapes into impervious surfaces such as roofs, roads, and parking lots. This shift has led to increased stormwater runoff, causing flooding, water quality degradation, and disturbances to aquatic ecosystems. A critical challenge in urban water management is overland flow flooding, where stormwater moves across surfaces before entering natural watercourses or underground systems. This localized flooding presents risks that traditional flood management strategies cannot adequately address. Additionally, the rising demand for potable water further stresses existing resources, underscoring the need for innovative solutions in stormwater management and water conservation.

This PhD thesis explores the application of Real-Time Adaptive Control (RTAC) systems for site-scale stormwater management, incorporating advanced technologies such as cloud computing, Wi-Fi connectivity, and control units. The enhanced RTAC model allows real-time stormwater runoff analysis, optimizing storage and release mechanisms in stormwater harvesting facilities. This approach reduces the load on urban drainage networks, mitigates flooding, and protects infrastructure.

The effectiveness of the RTAC system is demonstrated through its use in stormwater harvesting tanks within urban catchments, where it enhances storage efficiency during rainfall and ensures controlled release to urban waterways, reducing flooding risks. Prior to implementing the RTAC system in water-sensitive frameworks, this thesis compares a combined Water Sensitive Urban Design (WSUD) model with conventional WSUD models to evaluate their runoff management performance. Projections for 2000–2030 show an increase in impervious surfaces from 74.34% to 83.84%, leading to an

additional 1,340 ML/yr of stormwater runoff. Both WSUD models reduce runoff and improve infiltration, with the combined WSUD model showing 20-30% better performance across various rainfall scenarios.

The thesis also introduces the Site-Scale Real-Time Adaptive Control (SRAC) model for managing overland flow flooding. The SRAC model dynamically manages runoff by preemptively discharging water before storms, creating storage capacity, and releasing water post-storm. A case study demonstrates that the SRAC model reduced flooding volumes by over 98% during severe storms and decreased drainage system demand by 43%, potentially saving AU$7.87 million in infrastructure costs.

The SRAC-WSUD method also outperforms conventional WSUD in pollutant removal, significantly reducing Total Suspended Solids, Total Phosphorus, and Total Nitrogen across different rainfall scenarios. While there was no significant difference in Gross Pollutant removal, the SRAC-WSUD method improved pollutant management and flow control. Future research should focus on optimizing water storage and addressing water quality concerns in stormwater harvesting systems.

Chapter 1 Introduction

1.1 Background

Urbanization, driven by rapid population growth and the migration from rural to urban areas, has led to significant changes in land use patterns. The conversion of natural landscapes into impervious surfaces—such as roofs, roads, and parking lots—has profoundly affected hydrological systems at various scales. These changes have resulted in increased stormwater runoff, which contributes to a range of environmental and infrastructural challenges, including flooding, water quality degradation, and disruptions to aquatic ecosystems.

As urban areas expand, the traditional hydrological cycle is disrupted. The natural processes of infiltration and absorption are hindered by the proliferation of impervious surfaces, leading to higher volumes and faster flows of stormwater. This intensified runoff can overwhelm existing drainage infrastructure, exacerbating flooding, especially in areas with inadequate drainage systems. Moreover, the growing demand for potable water in urban settings places additional stress on water resources, further complicating stormwater management efforts and highlighting the need for innovative solutions.

Overland flow flooding, a significant issue in urban water management, occurs when stormwater flows across land surfaces before entering natural watercourses or emerging from underground sources. Unlike traditional flooding, which typically affects specific low-lying areas or riverbanks, overland flow flooding can impact a wide range of locations. This form of flooding presents unique challenges that conventional flood management strategies often fail to address effectively. The proliferation of impervious surfaces and the inadequacies of outdated drainage systems make urban areas particularly vulnerable to these flooding events.

Addressing these challenges requires advanced approaches to stormwater management. Traditional methods frequently fall short in dealing with the complexities introduced by urbanization. As a result, there is a pressing need for modern technologies and strategies that enhance the efficiency and effectiveness of urban water management systems.

1.2 Objectives

The primary objective of this PhD thesis is to advance the development of Real-Time Adaptive Control (RTAC) systems tailored for site-scale stormwater management. This research aims to integrate cutting-edge control technologies, such as cloud computing, Wi-Fi-based connections, and advanced control unit systems, into stormwater management strategies. The enhanced RTAC method is designed to enable real-time data analysis and control of stormwater runoff storage and release. By optimizing storage volume requirements through the recovery capacity factor (M), this method seeks to reduce the demand on urban drainage networks and mitigate flooding risks, ultimately safeguarding urban infrastructure.

Additionally, this thesis evaluates the performance of a combined WSUD model compared to conventional WSUD approaches. The research assesses how these models handle future urban development and manage increased stormwater runoff resulting from the expansion of impervious surfaces. The goal is to demonstrate the superior performance of the combined WSUD model in reducing runoff and enhancing infiltration and evapotranspiration.

Furthermore, the thesis introduces the Site-Scale Real-Time Adaptive Control (SRAC) model as an innovative solution to address overland flow flooding. This model aims to manage runoff dynamically by creating storage capacity before storms, minimizing discharge during storms, and controlling water release after storms. A case study in the Upper Caddies Creek Catchment in Sydney, Australia, is used to validate the effectiveness of the SRAC model. The objective is to showcase how the SRAC model can significantly reduce flooding volumes, decrease infrastructure demands, and offer a cost-effective solution for urban stormwater management.

1.3 Thesis outline

This thesis is organized to provide a comprehensive examination of advanced stormwater management technologies and their applications (Figure 1-1). The initial chapters offer a thorough background on the impact of urbanization on hydrological systems. They explore the challenges posed by increased stormwater runoff and overland flow flooding, emphasizing the need for innovative management solutions.

Subsequent chapters focus on the development and application of the enhanced RTAC method. This includes an in-depth analysis of modern control technologies and their integration into site-scale stormwater management systems. The effectiveness of the RTAC method is evaluated through practical applications and case studies, demonstrating its improvements in stormwater runoff management and infrastructure protection.

The thesis then shifts to a detailed examination of the combined WSUD model, comparing its performance with conventional WSUD approaches. This section presents findings on how the combined WSUD model addresses future urban development scenarios and enhances runoff reduction, infiltration, and evapotranspiration across various rainfall conditions.

Following this, the thesis introduces the SRAC model, detailing its design and functionality in managing overland flow flooding. The effectiveness of the SRAC model is assessed through a case study in the Upper Caddies Creek Catchment, highlighting its impact on flood control and infrastructure cost savings.

Finally, the thesis discusses the limitations of the RTAC and SRAC methods. It addresses challenges related to water quality control and identifies areas for further research. Recommendations for future studies are provided, focusing on integrating effective water quality control measures into the RTAC system and evaluating the long-term effectiveness and cost-efficiency of the SRAC-WSUD approach, particularly in reducing pollutant loads in receiving water bodies.

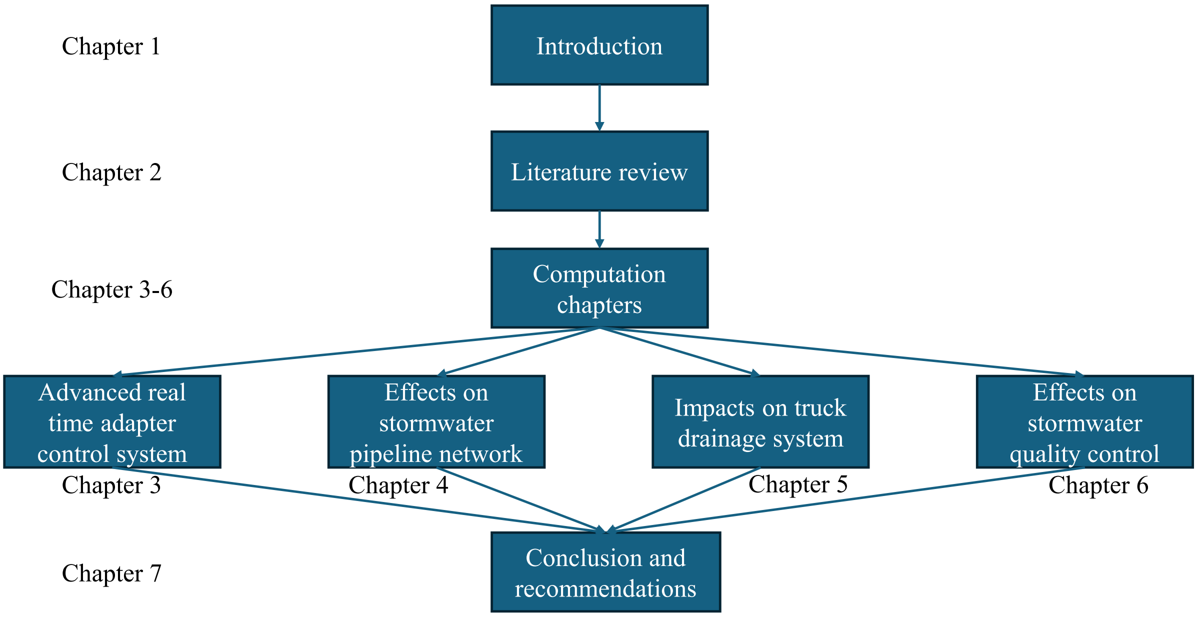

Figure 1-1 The structure of the thesis

Chapter 2 Understanding the Effects of site-scale Water Sensitive Urban Design (WSUD) in the urban water cycle – a review

Related publication:

Xuli Meng, 2022. Understanding the Effects of site-scale Water Sensitive Urban Design (WSUD) in urban water cycles – a review. *Blue-Green Systems,* 4(1), pp. 45-57.

2.1 Introduction

The population growth and the movement of people from rural to urban areas cause land-use changes in the form of urbanization (Fletcher, et al., 2015). The urbanization process replaced large areas of natural ground with impervious surfaces, such as roofs, roads, parking lots, and footpaths in the urbanized landscape (Miller et al., 2014). These activities lead to a massive and comprehensive change to the hydrological system across a range of spatial scales in the urban water cycle, including catchment-scale (city, street and cross-street levels) and site-scale (householder level). For example, stormwater runoff and sedimentation have had a rapid increase with urbanization (Meyer & Turner, 1992; Booth & Jackson, 2007; Novotny, et al., 2010). Increased stormwater runoff has directly affected a wide range of pressures, such as a crisis of water quality (Astaraie-Imani, et al., 2012), sedimentation and erosion issues (Nie, et al., 2011), risk of flooding (Wahl & Plant, 2015; Raadgever & Hegger, 2018), waterborne diseases (Hunter, et al., 2001), pollution of underground water (Lenny, et al., 2011), aquatic species issues

(Quattro, et al., 2002) and acidification of water bodies (Grunewald & Schoenheinz, 2014).

In the natural water system, increased impervious surfaces reduce the infiltration and evapotranspiration (Ball, et al., 2019), thereby increasing the stormwater runoff (Thom, et al., 2020), changing urban hydrology characteristics greatly. The increased stormwater runoff leads to many flooding issues such as overland flow flooding in the urban area (Maksimović, et al., 2010). Overland flow flooding mitigation is a big challenge for all urban planners, which is water that runs across the land after rain, either before it enters a creek or stream, or after rising to the surface naturally from underground (Jain & Singh, 2019). Unlike river flooding, overland flow flooding significantly impacted sub-catchments rather than the whole city, which poses a greater hazard to localized areas but on-site flood mitigation solutions and their functions are unclear (Maksimović, et al., 2010). Additionally, in the anthropogenic flow system, the amount of potable water keeps increasing, and many cities are facing high pressure because of the rapid increase in water supply (Commonwealth of Australia, 2015). Are there any water management solutions that can mitigate overland flow flooding and reduce the potable water demand within the urban water cycle?

As a broader urban stormwater management framework, WSUD is an approach to the planning and design of urban environments that support healthy ecosystems through smart management of water, it manages all water streams as a resource (Fletcher, et al., 2013), promotes recycling and mitigates the impact of urban stormwater through the shift of the landscaped features to solve both water quality (Wong, 2015) and water quantity issues (Ball, et al., 2019). WSUD has been recognized as an innovative way to restore the natural hydrological cycle, including stormwater runoff and groundwater restoration (Ozgun, et al., 2017). The implementations of WSUD involve removing sections of the deteriorated concrete riverbank and undertaking environmental rehabilitation of the riparian zone; introducing more distributed biorientation tanks; connecting distributed WSUD designs to natural waterways (Chesterfield, et al., 2016a; Chesterfield, et al., 2016b; Ball, et al., 2019). To date, several studies have examined the response of stormwater runoff and potable water demand to city-region scale, like an artificial wetland, naturalized waterway and channel (Meng, et al., 2022); street-scale such as bio-retention, bio-detention and bio-swale (Meng & Kenway, 2018); but it is still unclear for the understanding about site-scale landscaped features through WSUD implementation, like rainwater tank, detention tank and green roof (Li, et al., 2019). Furthermore, how do site-scale WSUD options restore the water cycle in the urban catchment and what is an urban water cycle?

2.2 Urban water cycle

The urban water cycle is the water movement between water accounts in the urban area. In the pre-development phase, the urban water cycle presented the 'natural' water flows, in the after-development phase, the urban water cycle combined the 'anthropogenic' flows with 'natural' water flows in the urban water cycle.

Figure 2-1a allows people to observe the before-development phase of the urban water cycle, it shows the natural movement of water, without human intervention. This phase consists of three main processes, including evaporation and transpiration - liquid changing to vapour, which evaporation occurs when water in oceans, lakes and rivers warms and turns into a gas, rising to the air; plants release water into the air in a process called transpiration; precipitation - liquid or solid water falling to earth, which is eventually the clouds become too heavy and the waterfalls back to the earth as rain, hail, sleet or snow; and Infiltration, percolation and run-off - liquid water absorbing into the earth, which is the water that falls to the earth flows into waterways (run-off), or it can absorb into the ground (infiltration) or aquifers and underground water pockets (percolation) (Wong, et al., 2013).

The second phase is after development, it is the urban water cycle when people when humans use water, including four components (Figure 2-1b). To have a better understanding of the urban water cycle in the city development, Wong, et al, (2013) highlighted four main human water streams in the urban water cycle (Figures 2-1b and 2-1c). They are dams and water treatment plants, which are waterfalls from the sky as rain and are captured in dams and the water is cleaned at a water treatment plant before being pumped to you in underground pipes; water storage, which is the clean water is stored in water reservoirs and towers until it's needed; stormwater drainage, which is water run-off from buildings and streets is collected in stormwater drains, where it flows to the ocean; and sewage treatment, which is after you use water, it is piped to a sewage treatment plant to be cleaned and treated and the clean water or effluent, is then returned to waterways at the outfall (Wong, et al., 2013).

The third phase is the WSUD stage, which is a contemporary approach to the planning and design of urban environments that are 'sensitive' to the issues of water sustainability, resilience and environmental protection (Wong, et al., 2013). In this phase, WSUD applications assisted to reduce runoff, increase evapotranspiration and infiltration to soil profiles (Coombes, 2015). Integrated WSUD solutions often meet multiple objectives (such as water supply, stormwater drainage, management of stormwater quality, provision of amenity and protection of waterways) and are dependent on linked interactions with surrounding infrastructure. Importantly, the limitations of design processes are not always apparent and diligence is required to ensure that substantial problems are avoided (Coombes, 2015).

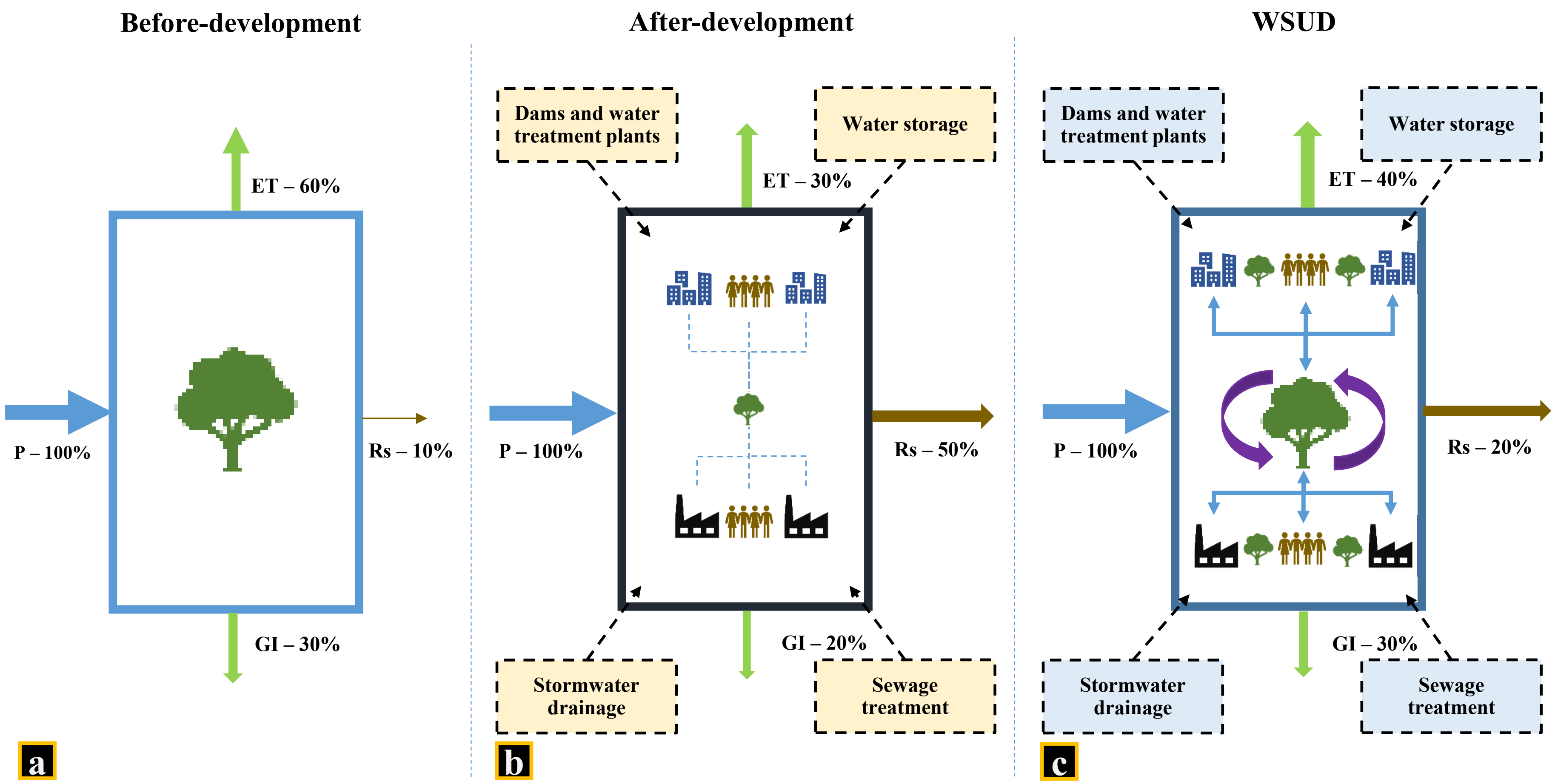

Figure 2-1 concept model to present water mass balance in (a) before development (b) after development and (c) WSUD model. P: precipitation; ET: Evapotranspiration; GI: groundwater infiltration; Rs: stormwater runoff

In the after-development phase and WSUD phase, the urban water cycle (UWC) is an integrated system to improve urban water resource management and to develop together with the water-related component systems, such as water supply, treatment, demand, distribution, wastewater collection, surface water and groundwater quality and quantity control (Figure 2-1b & 2-1c). There are three main aspects in this cycle; the first aspect is the water supply infrastructure to inform the design so that the supply matches the demand (Bach, et al., 2014); the second aspect is understanding the influence of urbanization on natural hydrological flow (Haase, 2009); and thirdly, water mass balance is recommended as an important tool to assess water performance in UWC (Mcpherson, 1973).

In the past, most UWC models only focused on the quantitative simulation of either anthropogenic water flows or natural water flows for catchment-scale which is a big area, such as city, cross-street, and street levels. For example, Aquacycle and Single-source Urban Evaporatranspiration-interception Scheme (SUES), two of the most common UWC models, only focus on the water cycle for natural flows at a catchment scale. Some other researches only focus on catchment-scale anthropogenic water flows (Peña-Guzmán, et al., 2017). Currently, some scholars who started the research concentrate on the input and output of both 'natural' and 'anthropogenic' flows at the catchment level, but very limited studies focus on water flows at a site level.

When the boundary of the water system and all relevant subsystems have been defined, then the challenge is to quantify water flows into and out of the urban water cycles and also the flows between water-related component systems. The accurate data outcome can develop a fully labelled flowsheet. After quantification of each flow, a balance of a conserved quantity can be generated (Eq. 2-1). In this equation, accumulation means the change in storage and this element is the act of building up in the system. Input and output represent the flows entering or leaving the system. Generation and consumption represent the flows produced or consumed within the system.

$$Accumulation = Input - Output + Generation – Consumption \qquad (Eq.\ 2\text{-}1)$$

The current water management model is focused on local hydrological flow movement in a catchment-scale study. This means local precipitation, stream and groundwater are treated as inputs; and the outputs are stormwater runoff, groundwater infiltration, and evapotranspiration. When the water research area is the whole catchment, this system focuses on water movement without considering influences outside of the system, which is treating the whole catchment as a whole (Cisakowski, et al., 2011). For water movement out of the system, there is a high probability that it will be impacted by population increases, urbanization, and climate change. For example, an urban area with continued population growth requires more water supplies. However, in most cases, water sources are outside the urban catchment boundary and are not included in the urban water system. Further, urbanization and climate change could introduce extra water flows to the local water cycle, such as flooding and irrigation across the boundary (Cisakowski, et al., 2011). So, what is the site-scale WSUD option's function in flood mitigation and water demand reduction?

2.3 Site-scale WSUD options

The term WSUD is commonly used to reflect a new paradigm in the planning and design of urban environments that is 'sensitive' to the issues of water sustainability and environmental protection (Nunes, et al., 2011). Since the 1990s, WSUD began to be used in Australia, with the first known reference to it in 1992 and then shortly after in a report prepared for the Western Australian Government in 1994 (Fletchera, et al., 2015). In the years that immediately followed, the concepts of WSUD were fleshed out through a series of position papers by Wong and others (Lloyd, et al., 2002; Wong & Brown, 2009). Lloyd et al. (2002) described WSUD as a philosophical approach to urban planning and design that aimed to minimize the hydrological impacts of urban development on the surrounding environment. Stormwater management is a subset of WSUD directed at providing flood control, flow management, water quality improvements and opportunities to harvest stormwater to supplement mains water for non-potable uses (Lloyd, et al., 2002).

WSUD is an integrated method through the better setting and aligning of water issues in urban planning, which includes both site-scale WSUD and catchment-scale WSUD applications. It is not merely to address water issues, but also involves water-related economic, social and governance problems (Wong & Brown, 2009; Chesterfield, et al., 2016a). In this process, retention, infiltration, evapotranspiration, treatment and harvesting are the main philosophy behind WSUD - minimizing the impact of development on the natural hydrological system in terms of water flow. Generally, catchment-scale WSUD applications are designed to reduce the harm it causes to the rivers and creeks directly, two common catchment-scale WSUD applications are biofilter systems and constructed wetlands (Zhang, et al., 2019). Through the catchment-scale WSUD applications, scholars found that both water quality and the hydrological regime of the urban waterway system have improved, bringing the water cycle closer to its near natural state (Shahzad, et al., 2022). Further, researchers highlighted those larger systems are recommended to ensure reliable performance in pollution reduction, flow frequency mitigation and reliability as an alternative water supply within the implications of climate change on future rainfall (Zhang, et al., 2019).

Although WSUD options were introduced to the urban water cycle studies as solutions to restore the urban water cycle at a high level, such as artificial wetlands, basins and swales. However, these catchment-scale WSUD options are not designed to capture minor flows, such as overland flows in the site-scale level. On the site-scale site, there is a high demand to find appropriate WSUD options to capture overland flows because the overland flow excesses rainfall runoff from homes, driveways and other surfaces that can lead to flooding. Indeed, Overland flow flooding can be unpredictable runs across the land after rain, either before it enters a creek or stream, or after rising to the surface naturally from underground. As the consequence, overland flow makes more severe damage to the properties if they are located far away from the catchment scale WSUD sites.

As the solution, site-scale WSUD applications could catch minor flows as they treat and return stormwater into the ground, helping to recharge natural groundwater and stream baseflows in a small area (Moravej, et al., 2022; Shahzad, et al., 2022). The application of site-scale WSUD would take the local climate into account and restore the natural hydrological cycle, and most of the time site-scale WSUD technologies will not connect with creeks or rivers directly.

This chapter reviews the site-scale WSUD options in the urban water cycle studies, however, there is only limited research to demonstrate and list the impacts on groundwater infiltration and evapotranspiration. To have a more balanced review of the contribution of the site-scale WSUD options to the urban water cycle, this chapter reviewed water retention and potable water demand reduction in the urban water cycle through a quantitative manner (Table 2-1). Table 2-1 listed the existing research on main site-scale WSUD options' performance in water retention and potable water demand reduction. These site-scale WSUD options include rainwater reuse and detention, green roof, horticulture garden, grasscrete and linear park (Kuller, et al., 2017; Meng & Kenway, 2018).

The first option analyzed in site-scale WSUD is rainwater reuse. Rainwater tank systems have been used as local harvesting and water supply source in many areas (Memon & Ward, 2015; eWater, 2016). In recent times, rainwater harvesting systems have become an important water supply source in urban areas where water supply systems are not sustainable. Harvested rainwater can also provide an 'improved' drinking water source in urban and peri-urban areas of developing countries where surface water can be contaminated by faecal pathogens, and/or good quality groundwater is not readily available (Sharma, et al., 2015). An analysis of 62 cities in Southern Brazil indicated that rainwater harvesting could potentially reduce potable water demand by 34% to 92%. However, this analysis did not consider the seasonality of demand, or the dynamics of roof runoff volume, available storage volume and demand (Sharma, et al., 2015). Unharvested rainwater has led to much overland flow flooding in the past. More rainwater tanks provide high stormwater harvesting capacity and reduce more potable water demand.

The stormwater detention tank has been proposed as an alternative stormwater management option, that aims to slow down the rain off from high imperviousness areas to the pipeline system under the streets (Figure 2-1). In newer areas, the stormwater drains have been engineered to allow for the rainwater run-off from the whole street. In some older areas, with the number of dwellings per street rising, the urban development places extra pressure on infrastructure, and water authorities often require detention systems to alleviate this. However, it is unclear of the performance of detention tanks in overland flow flooding and the urban water cycle.

The third and a popular selection for future urban planning is the green roof option (Imteaz, et al., 2011). Researchers from Europe and Australia have identified that green roofs can reduce rainwater runoff in the urbanized area (Mentens, et al., 2006; Victorian Government, 2014). In fact, the green roof not only affects stormwater runoff, maximum thermal insulation and supplies more biodiversity space, but also has social and economic benefits, i.e., some green roofs can be planted with edible food (Vanwoert, et al., 2005; Feng, et al., 2016). In most green roof projects, the grass roof can be chosen to replace more traditional roofs due to lower requirements for building structures.

Two water retention research has shown that water retention from the green roof option is 53%-99% in Verbeeck's research and 58%-98% in Whittinghill's research (Verbeeck, et al., 2014; Whittinghill, et al., 2014). In Whittinghill's research, stormwater retention (%) of extensive green roofs vegetated with a mix of Sedum species, a native prairie mix, and a fertilized vegetable and herb garden for light, medium, and heavy precipitation events from the growing seasons of 2009–2011 and the number of observations for each green roof treatment and rain event size combination from total 12 plots (Whittinghill, et al., 2014). Further, Shafique (2018) summarised that the water retention (%) from the green roofs ranges from 55% to 88% to verify the previous research in 2014, which is based on seven studies about the green roof's hydrological performance in different regions all around the world, including Sweden, Germany, USA, Italy, China and the UK. As for potable water demand reduction about the green roof, Alamdari et al. (2018) found that in some places, the runoff capture might decrease to as low as 12% while the water supply reliability would fall to 18%. However, it was also estimated that parts of the regions would experience a lift in reliability as high as 22% in terms of water supply.

The fourth site-scale WSUD option is the horticulture garden, which is another good option for water detention that can be used in urban development. Researchers have emphasized that urban development, such as large-area car parks and driveways leads to stormwater runoff and pollution loads for natural water systems (Nichols, et al., 2015).

The WSUD grasscrete option is the fifth site-scale WSUD option to be reviewed in this chapter and it is a green alternative to concrete outdoor surfaces, such as an amenity area in the residential dwelling backyard. Researchers found that permeable material can help increase infiltration performance at an affordable price (Huang, et al., 2013). Indeed, grasscrete can be selected to replace traditional solid surfaces in the amenity area in the selected urban development area.

Linear park, which can be implemented to connect the previous site-scale WSUD options. It includes subtropical boulevards and neighbourhood shadeways in the urban area (Meng & Kenway, 2018). This option transmitted parts of traffic lanes to the 'natural' level linear park to connect with drainage systems and waterways in the urban area. A Korean case study showed that with the presence of a list of the linear park in an upstream river, the flood peak downstream decreases by 30%-83%, corresponding to two scenarios of rainfall duration with a return period of 1 in 100 years (1% AEP) (Ngo, et al., 2016).

Table 2-1 Overview of WSUD options and their functions (based on (Kuller, et al., 2017; Meng & Kenway, 2018)) in a quantitative manner to compare how much change in water retention and potable water demand reduction caused by site-scale WSUD options

	Detention	GI	ET	Water retention	Treatment	Harvesting	Potable water demand reduction
Rainwater tank	N/A	N/A	N/A	N/A	N/A	✓	34%-92% (Sharma, et al., 2015)
Detention tank	✓	N/A	N/A	N/A	N/A	N/A	N/A
Green roof	✓	N/A	✓	53%-99% (Verbeeck, et al., 2014) 58%-98% (Whittinghill, et al., 2014) 55%-88% (Shafique, 2018);	✓	✓	18%-22% (Alamdari, et al., 2018)
Horticulture garden	✓	N/A	✓	100% (Verbeeck, et al., 2014)	✓	N/A	N/A
Grasscrete	✓	N/A	✓	50% (Verbeeck, et al., 2014)	✓	N/A	N/A
Linear park	✓	✓	✓	30%-83% (Ngo, et al., 2016)	✓	N/A	N/A

Overall, these site-scale WSUD applications can: reduce the volume and peak flow; increase evapotranspiration and infiltration; decrease imperviousness ratio; improve stormwater runoff quality; convert some pollutants into inert substances; add to neighbourhood aesthetics; improve land value; recover biodiversity; and supply an alternative and local water source (Payne, et al., 2015; Meng & Kenway, 2018). Among these six site-scale WSUD options, there is no single option that can reduce both stormwater runoff and potable water demand at the same time. It requires applying more than one site-scale WSUD option to achieve a multifunction design target in the stormwater management project. Figure 2-2 presented three water mass balance concept models to compare the water account changes under different scenarios, they are before-development model (natural water cycle), after-development model (business as usual) and the WSUD model (sustainable model with site-scale WSUD options). Figure 2-2b presented that urbanization disturbs groundwater and evapotranspiration flows through the sealing of native soils with impervious surfaces and through modifications to the subsoil by constructed drainage and other infrastructure (trenches and excavations, e.g. water supply), at the same time stormwater runoff increases. Figure 2-2c presented how the site-scale WSUD applications manage natural and anthropogenic flows in the urban water cycle. Figure 2-1 and Figure 2-2 could assist scholars to have an overview of site-scale WSUD options in the urban water cycle, but researchers still need a quantitative tool to calculate the water account changes in and out of the urban water cycle.

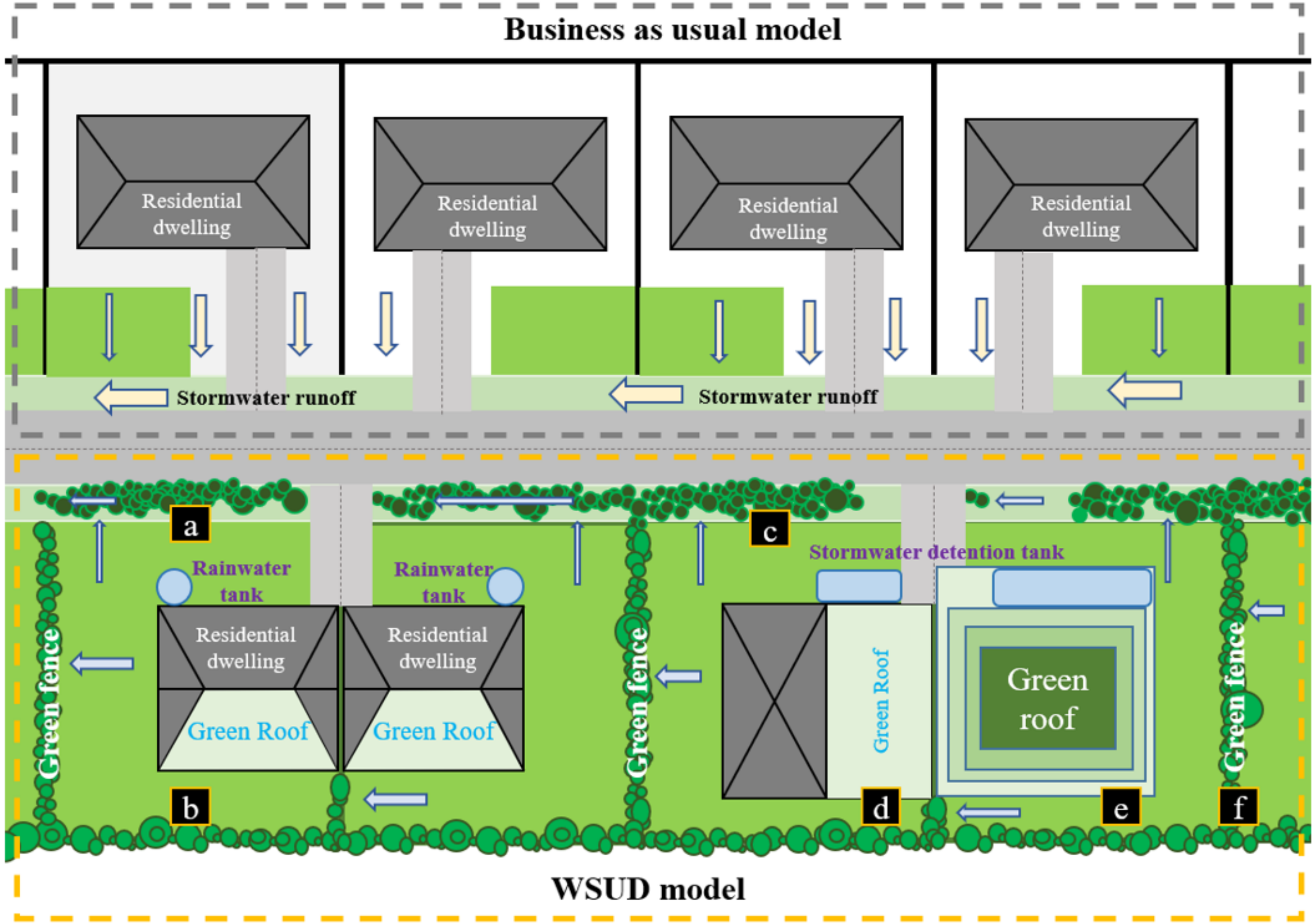

Figure 2-2 (a) new residential dwelling with rainwater tanks, (b) linear park/garden with WSUD functions, (c) new building with stormwater detention tank, (d) horticulture garden, (e) green roof, (f) green fence. The figure is adapted from Meng & Kenway's research in 2018 (Meng & Kenway, 2018)

2.4 Water mass balance

Water mass balance is an equation to describe the water flows into and out of the urban water cycle (Figure 2-2). During the early-stage studies of the urban water cycle, the equation represents the sum that the water inflows equal to water outflows (the change in storage). In fact, there are two different opinions on water mass balance establishment. The first approach can be applied to the water supply infrastructure to inform the designers so that the supply matches the demand (Bach, et al., 2014). The second approach concentrates on hydrological catchments to understand the influence of urbanization on natural hydrological flow (Haase, 2009). Based on these two opinions, Kenway, et al. (2011) developed the urban water system to study 'anthropogenic' and 'natural' flows at the same time and highlighted that water resource management needs to treat 'cities as catchments' (Eq. 2-4 Table 2-2).

This new water mass balance framework aims to: 1) aid resource managers to have a better understanding of the hydrological performance for all water account movements in urban water systems; 2) provide a conceptual model to quantify water storage in each account in order to determine water resource reallocation; 3) identify and quantify the new water flows from within the urban water system, such as wastewater recycling, rainwater, and stormwater reuse; 4) assist water cycle managers and urban planners to simulate hydrological performance under different scenarios in the urban water environment (Kenway, et al., 2011).

Furthermore, Kenway, et al. (2013) and Renouf, et al. (2016) have developed an urban water system evaluation framework, which is founded on a water mass balance, to assist urban planners and water managers to have improved systematic analysis. Through this evaluation framework, Meng and Kenway (2018) proved that site-scale WSUD options

can decrease stormwater runoff and assist to bring the hydrological flows back to a 'natural' level. Recently, a catchment in Sydney, Australia with over 1,000 ha was used for demonstration purposes of WSUD in restoring the natural hydrological cycle (Meng, et al., 2022). The performance of site-scale WSUD in stormwater management, evapotranspiration and infiltration was evaluated through water mass balance models on a long timeline and further assessed under three rainfall scenarios. The results obtained provided a comprehensive evaluation and understanding of site-scale WSUD in a catchment-level application for future development (Meng, et al., 2022).
As a model based on the processed description, water mass balance models represent the physical processes observed in the real world (Elliott & Trowsdale, 2007). Typically, water mass balance models contain parameters such as stormwater runoff, subsurface flow, evapotranspiration, and channel flow (Elliott & Trowsdale, 2007). Water mass balance follows Eq.2 to describe the water flows into and out of the system. From a hydrological perspective, it represents the sum of water inflow equaling water outflow and the change in this urban hydrological cycle.

In recent studies, the shift of water mass balance was influenced by impervious fraction change in related WSUD projects (Meng & Kenway, 2018). Thus, a modified water balance model was established to link simplified representations of the hydrological processes relative to the catchment (Eq. 2-2). Eq. 2-3 was established based on Eq.2 without any change in stored water (ΔS), including both impervious and pervious lands, rainfall coming into the system and evapotranspiration, runoff, and infiltration going out of the stormwater system. This modified water balance model simply treated a catchment without any extra water input or water stored in that area (Table 2-2). Further, scholars brought the estimates of anthropogenic and natural flows together into the urban water mass balance (Eq. 2-4) (Renouf, et al., 2018), using the method described in the original framework of Farooqui et al. (2016) (Table 2-2). The aim was to achieve a mass balance, such that total inflows equal total outflows, plus any changes in storage, thereby ensuring a comprehensive and accurate account (Eq. 2-4). Changes in storage were assumed to be zero (Eq. 2-3). In this context, storage refers to soil moisture and water stored in reservoirs within the urban system. This means no changes in storage (assuming there are stable climatic conditions) and no influence on this stored water. Previous research has shown that WSUD can reduce stormwater runoff in the urban water cycle and help to recover the hydrological cycle (Meng & Kenway, 2018; Meng, et al., 2022). However, it is unclear about the site-scale WSUD options in the overland flow flooding control in the urban water cycle.

After analysis, within appropriate site-scale WSUD options, scholars highlighted that WSUD technologies can restore natural hydrological flow and reduce potable water demand (Meng & Kenway, 2018; Moravej, et al., 2022). For example, distributed infiltration systems can benefit downstream water bodies by reducing the runoff flow rate and volume discharges from the catchment (Shahzad, et al., 2022). Furthermore, the infiltration decreased by 34% (Moravej, et al., 2022) and 62% (Meng & Kenway, 2018) in variable cases, the infiltration deduction decreased by 17% in Moravej's study (Moravej, et al., 2022) and decreased by 49% in Meng's research (Meng & Kenway, 2018). Next, scholars developed relevant assessment frameworks to evaluate water accounts' performance in the urban water cycle.

Table 2-2 Urban water cycle analysis through water mass balance tool

Equations	Definitions	Natural hydrological flows	Anthropogenic flows	WSUD effects
Eq. 2-2	$P = Rs + ET + GI + \Delta S$ (Meng, et al., 2022)	✓	✕	✓
Eq. 2-3	$P = Rs + ET + GI$ (Meng, et al., 2022)	✓	✕	✓
Eq. 2-4	$(P + C + D + Re) = (ET + Rs + WW + GI + Re) + \Delta S$ (Renouf, et al., 2018)	✓	✓	✓

Where *P* is unharvested precipitation falling in the urban boundary, i.e. total precipitation less any rainwater or stormwater harvested within the urban system area. *C* is total centralized (external) water supplies, which includes surface waters (*Cs*), groundwater (*Cg*), and desalinated water (*Cd*). *D* is total decentralized (internal) water supplies harvested from within the urban system area, which includes harvested precipitation (rainwater) (*Dp*) and harvested surface water runoff (*Ds*), and bore water (*Dg*). *ET* is evapotranspiration, which includes transpiration from plants and evaporation from surfaces. *Rs* is the runoff of surface water/stormwater discharged from the urban system areas (not including that which is harvested). *WW* is wastewater discharged from the urban system areas (total wastewater generated less than which is recycled). *GI* is infiltration into groundwater. *Re* is reuse/recycling of wastewater and *ΔS* is the change in the stored water within the defined urban system (Renouf, et al., 2018; Meng, et al., 2022).

2.5 Evaluation framework in the urban water cycle

Water performance indicators are the key part to assess water mass balance data through an evaluation framework. In the conventional urban water evaluation framework, water technologies are commonly considered after the urban form has been designed. This overlooks the interactions between urban design and urban water systems and the potential that can be unlocked by better integrating the two. However, it needs to be supported by quantitative evidence of the water performance of design-technology configurations (Moravej, et al., 2022).

Table 3 listed some main water performance evaluation methods in the urban water cycle, they can be used to assess the potable water demand, water consumption, natural water accounts movement, and relationships between natural and anthropogenic flows, such as stormwater reuse and greywater recycling (Martinez, et al., 2010; Meng & Kenway, 2018; Moravej, et al., 2022). The current site-scale urban water cycle studies did not fit the gap between the current water mass balance frameworks (Figure 2-1) and water performance evaluation methods listed (Table 2-3), as most of the research is aimed at the catchment scale. Nevertheless, there are no relevant studies that can examine the water movements in each site-scale WSUD option through the water mass balance analysis and evaluation framework.

Table 2-3 Examples of indicators used to describe the site-scale WSUD performance of urban water cycles

Source	Indicators	Definitions

Green City Index (EIU, 2011)	Water use per capita	Domestic water consumption per capita (liters/person/day).
	Water system leakages	The proportion of water lost in the water distribution system.
	Water quality policy	Measurements about cities' policy towards improving the quality of water (surface and centralized water supply).
	Water sustainability policy	Measurements about cities' efforts to manage water management more efficiently.
City Blueprint (Leeuwen, et al., 2012)	Total water footprint	The total volume of freshwater that is used to produce the goods consumed by the society.
	Water scarcity	The ratio of total water footprint to total renewable water resources.
	Water self-sufficiency	The ratio of the internal use to the total water footprint. A higher percentage indicates more water demand is sourced locally.
	Water system leakages	The proportion of water lost in the distribution system.

	Water efficiency	Assessment of the comprehensiveness of measures to improve the efficiency of water usage.
	Consumption	Domestic water consumption per capita (litres/person/day).
	Attractiveness (amenity)	Water used for landscape maintenance as measured by community sentiment in an urban area.
Asian Water Development Outlook (ADB, 2016)	Household water security	The sanitation needs at the household level.
	Urban water security	Status of urban water-related services in cities, towns and other urban areas.
	Economic water security	Water to be used in economic sectors for sustainable development.
Urban water metabolism evaluation framework - city scale (Renouf, et al., 2018)	Urban water efficiency per person	Domestic water consumption per person.
	Urban water efficiency per unit of functionality	Domestic water consumption per unit of urban function.
	Water-related energy efficiency per person	Total energy use for the water system per person.

	Water-related energy efficiency per unit of functionality	Total energy use for the water system per unit of functionality.
	Nutrient recovery from urban water	The proportion of the nutrient load in wastewater that is beneficially used.
	Water supply internalization	The proportion of internally harvested/recycled water in total water demand.
	Water use within a safe operating space	The rate of centralized water relative to the sustainable urban water allocation.
	Water pollutant load within safe operating space	Point-source and diffuse nutrient loads are discharged to surface and ground waters relative to sustainable discharge rates.
	Supporting diverse functions	Water is needed to maintain desired functions relative to the water budget for the functions.
Urban Water Mass Balance Assessment – site	Hydrological naturalness	Hydrological flows of the urban system have changed
	Imported water use per capita	Reliance of the assessed urban system on water mains

scale (Moravej, et al., 2020) *	Water self-sufficiency	Reliance of the assessed urban system on water mains
Area-Pipeline-Policy method (natural) (Meng, et al., 2022)	WSUD treatment area	The landowner type; topography background; and soil type.
	Suitable to connect with the existing stormwater pipeline network	Stormwater pipeline type; stormwater pipeline capacity; inlet and outlet level of the connecting point in the pipeline network.
	Support from the local community and government	Community engagement; local councils have a policy and financial support.

* Rest of water performance indicators were based on indicators proposed by Renouf et al. (2018).

2.6 Future research needs

The current site-scale WSUD option studies do not account for the effect of these different options on urban water balance accounts, such as the change of stormwater runoff, groundwater infiltration and evaporation, without a doubt, this is an opportunity for future iterations of the urban water cycle study. The future research could clarify these effects in real-world environment, especially, the interactions between each account and people using them in a collaborative urban design and planning context are not well-understand about how the interaction impacts the overland flow flooding in the different rainfall scenarios.

Future work should focus on the application of site-scale WSUD options in a variety of rainfall scenarios and contexts to further elicit its capacities. Future applications could apply very frequent rainfall events to simultaneously optimise architectural design and technologies to achieve some pre-defined targets through site-scale WSUD options. This would be a multi-objective optimisation, maximising different water performance objectives to check if- and how-, for example, the natural water balance can be achieved. Another research need is the consideration of appropriate season rainfalls in the urban water cycle. For instance, future research may evaluate the performance of the site-scale WSUD options in the urban flood mitigation with certain Annual Exceedance Probability (AEP) targets, such as 10% AEP, 1% AEP and 0.1% AEP. The detention tank is developed from the rainwater tank but with detention purposes. It is recognized to collect, store and reuse the stormwater but also to mitigate overland flow flooding issues in certain rainfall events (Meng, et al., 2022). How will urban planners assess the detention tank's flood mitigation performance with certain rainfall events? To answer the question, the first step is to predicate seasonal rainfalls. These are known to extend hydrological predictions spanning several weeks to months, which can enable proactive planning and adaptive responses. Next, the model can be evaluated in three annual rainfall scenarios (high, average, and low rainfall) to assess the changes in the urban water cycle through the water mass balance model. After that, the research can analyse the flooding information with certain rainfall events. It is necessary to introduce the very wet, average and very dry scenarios with predicated seasonal rainfall to evaluate flood mitigation performance.

2.7 Conclusion

This chapter reviewed the development of the urban water cycle and how the site-scale WSUD option interacted with the water cycle. In answering the research question, this review found that the water performance of design-technology-environment configurations can be partially quantified by (i) water retention, and (ii) portable water demand reduction. The site-scale WSUD options have undergone significant change over the last several decades, moving from a wide range of environmental, sanitary, social and economic considerations taken into account to an approach focused on both natural hydrological and anthropogenic flows. The profession has thus developed and adopted new models to describe these site-scale WSUD options and is likely to continue to do so, as the transition to a more sustainable and integrated approach occurs. This review has demonstrated that modern tools have evolved in response to restoring water accounts in the urban water cycle.

However, site-scale WSUD, as an integrated water management approach, includes the positive effects on water quality control and water quantity management. Complexities of climate change together with urbanization impacts, which vary spatially and temporally, necessitate scrutiny of possible adaptation measures in each location, such as overland flow flooding. In such a complex system, future urban planners should focus on identifying factors of site-scale WSUD options impacting on urban water cycle as well as developing location-based adaptation options and practically implementing site-scale WSUD options to minimize the impacts on the urban water cycle.

Chapter 3 Revolutionizing control systems: unleashing the power of Real-time Adaptive Control (RTAC) in stormwater management

Related publication:

Xuli Meng, 2024. Revolutionizing control systems: unleashing the power of Real-time Adaptive Control (RTAC) in stormwater management. *IWA World Water Congress & Exhibition 2024*

3.1 Introduction

Urbanization presents significant challenges for water management, including water scarcity and urban flooding risks (Feng, et al., 2022; Biswas & Tortajada, 2022). The growing population and dwindling freshwater resources exacerbate the scarcity issue, posing social and economic challenges in many cities (Tansar, et al., 2022). Additionally, the extensive impervious areas in conventional stormwater drainage networks result in excessive surface runoff and intensified peak flow, further increasing the risk of urban flooding (Tansar, et al., 2023). This combination of urbanization and global climate change has led to more frequent and severe flooding events worldwide, threatening infrastructure and public safety (Biswas & Tortajada, 2022).

In response to these challenges, WSUD has emerged as an effective approach to mitigate urban flooding in urban catchments. While previous research has primarily focused on assessing the static effects of water-sensitive designs, there is a pressing need to explore the potential of real-time control systems (Xu, et al., 2022). Specifically, the integration of dynamic control logic into conventional WSUD options, such as stormwater storage tanks, can significantly enhance their performance. By leveraging real-time data and adaptive decision-making, these systems can optimize the management of stormwater storage tanks (Shishegar, et al., 2021).

Stormwater harvesting tanks are a classic storage facility that is designed to store rainwater from rooftops, as the part of WSUD stormwater systems, it is currently implemented based on the underlying assumption of statistical stationarity of rainfall, which threatens to become outdated under climatic uncertainty (Zhang, et al., 2019; Zhang, et al., 2020). However, traditional stormwater harvesting tanks have limitations because they cannot capture new rainfall once they are full from previous rain events (Kuller, et al., 2021). This design flaw can result in a quick filling of the harvesting tank between two storms, which can take a couple of days to consume (Nguyen, et al., 2022). For the detention purpose, the conventional stormwater harvesting tanks are designed to slow down how fast the rain runs off the dwelling roof into the stormwater harvesting facilities during the low rainfall event (Watt, et al., 2003; Wong, et al., 2013; Shishegar, et al., 2021).

In contrast, the 'smart' stormwater runoff management model, known as the Real-Tine Adaptive Control (RTAC) model, is based on real-time precipitation forecasts (Valizadeh, et al., 2019). This innovative approach allows urban planners to leverage real-time data to manage stormwater infrastructure more effectively. By using the model to forecast precipitation patterns and analyze the data from onsite sensors, urban planners can better predict the optimal timing and volume of stormwater runoff storage to mitigate the risk of flooding (Valizadeh, et al., 2019).

The RTAC model's adaptability and scalability make it suitable for deployment in a wide range of contexts. This adaptability allows urban planners to manage stormwater runoff across entire catchments, providing a more comprehensive and integrated approach to stormwater management. The model's ability to analyze and utilize data in real-time can also provide insights into the long-term trends and patterns of stormwater runoff, allowing urban planners to make informed decisions about future infrastructure investments (Meng, et al., 2023; Meng, et al., 2023). The RTAC model comprises a control unit computing system and individual RTAC systems. The RTAC method enables storage facilities to release less runoff water to the urban waterway in a short time as more runoff water can be stored during the storm. This helps to reduce the demand on the urban drainage network, which reduces the risk of flooding and prevents damage to urban infrastructure (Meng, et al., 2023; Meng, et al., 2023).

To implement the RTAC method, a set of the RTAC for the individual system includes a computer-controlled valve to control the storage volume release from the stormwater harvesting facility, a pressure transducer installed in the stormwater storage facility to measure the storage water volume, and a control panel for bidirectional communication to receive rainfall forecast data from the Bureau of Meteorology (BOM) and to send commands to the individual RTAC systems to release water from each system.

The RTAC model's potential benefits are not limited to real-time stormwater management. The model's ability to analyze and utilize data in real-time can provide insights into the long-term trends and patterns of stormwater runoff. This information can be critical for developing sustainable and effective stormwater management systems that can adapt to the changing climate and urban environment.

In conclusion, the RTAC model represents a significant advance in stormwater management, leveraging cutting-edge technology to provide more efficient and effective storage and management of stormwater runoff. Its adaptability and scalability make it a valuable tool for urban planners seeking to implement sustainable and effective stormwater management systems. By using the RTAC model, urban planners can make informed decisions about future infrastructure investments and manage stormwater runoff across entire catchments, providing a more comprehensive and integrated approach to stormwater management.

3.2 Methods

Stormwater harvesting facilities have become increasingly prevalent in developed areas as a means of managing water resources (Jacobson, 2011). These facilities allow for the collection and storage of rainwater, which can then be used for non-potable purposes such as irrigation or toilet flushing (Schmitt, et al., 2020). With advancements in technology, particularly in the areas of WIFI and cloud computing, a new platform for managing these stormwater harvesting facilities has become practical. This platform is known as the RTAC method (Meng, et al., 2023).

The RTAC system consists of several key components, including a computer-controlled valve, pressure transducer, and a control panel for bidirectional communication. Additionally, a cloud computing platform is a critical component of the RTAC system, allowing for real-time evaluation of site data such as water level and local precipitation forecasts. This information is used by the software to make decisions about flow control through the actuated valve, as shown in the control logic of the RTAC model (Figure 3-1).

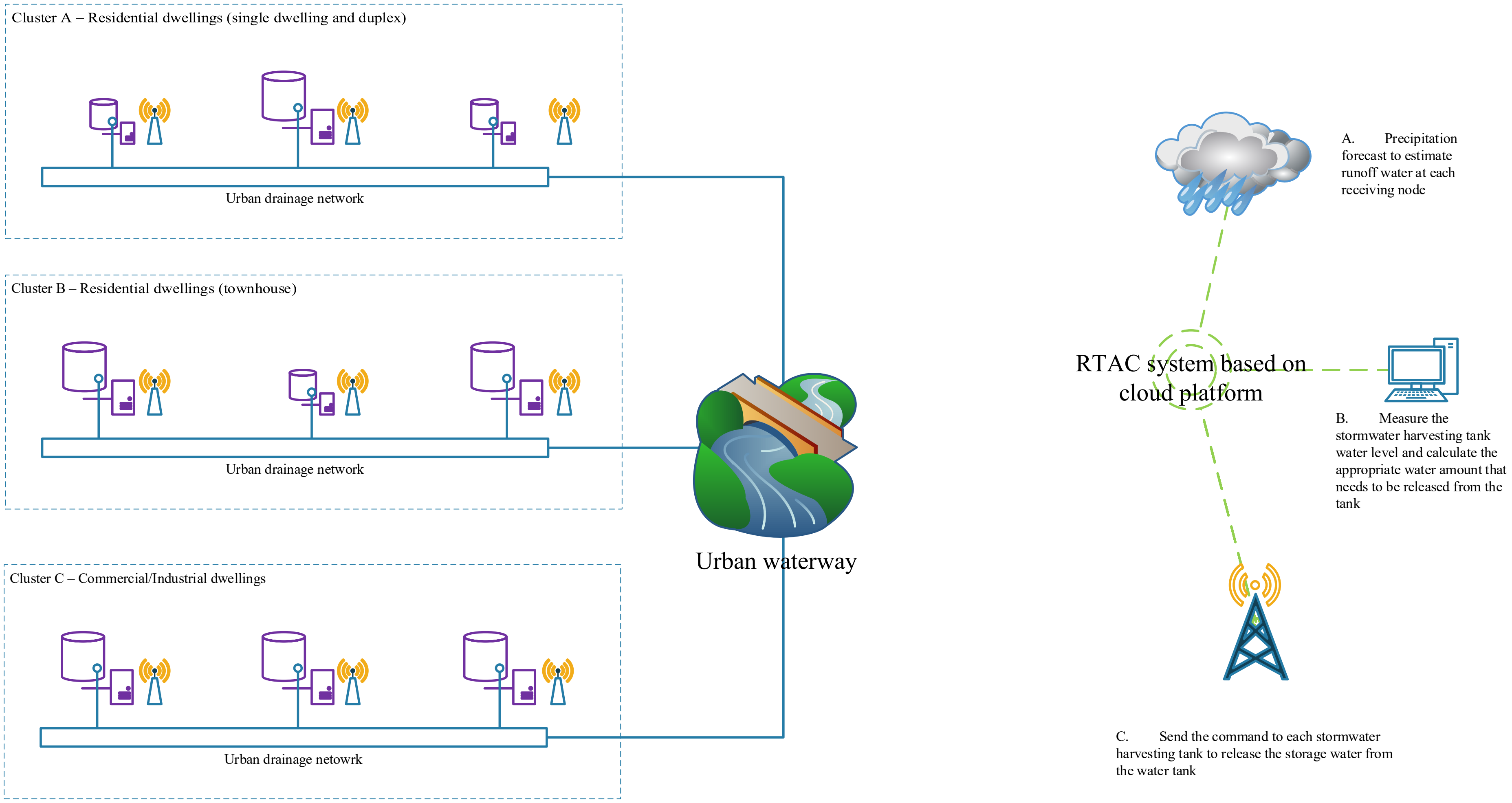

Figure 3-1 The control logic of the RTAC model

One of the main benefits of the RTAC system is its ability to manage stormwater harvesting facilities in a coordinated manner. This means that isolated stormwater harvesting facilities can be linked together, and their storage can be managed to control the amount of water released from each tank based on system demand (Li & Burian, 2023). This helps to reduce the demand on the urban drainage network, which can become overloaded during heavy rainfall events.

The RTAC method can be applied to various types of building clusters within an urban catchment area, including single-dwelling buildings, townhouses, and commercial, industrial, and high-rise building (Figure 3-1). The size of the stormwater harvesting facilities varies depending on the building type, ranging from 2,000L to 5,000L for single-dwelling buildings, 5,000L to 20,000L for townhouses, and 200,000L or greater for commercial, industrial, and high-rise buildings (Meng & Kenway, 2018).

In addition to managing stormwater storage, the RTAC system also allows for real-time evaluation of site data, including water level and the distance from the stormwater harvesting system to the trunk drainage system. This information can be used to optimize the system and ensure that it is operating at maximum efficiency. The RTAC system is particularly effective at reducing the amount of runoff water released to the urban waterway during heavy rainfall events. By storing more runoff water during the storm, the system can release less runoff water to the urban waterway in a shorter amount of time, reducing the burden on the urban drainage network. Overall, the RTAC method offers a practical and efficient means of managing stormwater harvesting facilities in developed areas. With its real-time evaluation of site data and coordinated management of stormwater storage, the RTAC system can help reduce the demand on urban drainage networks and improve the efficiency of water resource management.

3.2.1 Methods for calculating the stormwater storage in conventional option

The calculation of the stormwater storage in the conventional option is based on the water mass formula (Meng & Kenway, 2018):

Inflow = Outflow + Change in the stored water volume within the defined boundary (Eq. 3-1)

The water mass formula, as described by Meng and Kenway in 2018, provides a basis for calculating stormwater storage by considering the inflow, outflow, and change in stored water volume within a defined boundary (Meng, 2022). This study focuses on the storage of stormwater in rainwater tanks between two very frequent level rainfall events (Meng, et al., 2023). This approach has been proven as a practical method for capturing roof water before it generates excess flows (Meng, et al., 2023; Li & Burian, 2023).

Inflow refers to the amount of water entering the stormwater harvesting facility, which is determined by the catchment area connected to the facility (Li & Burian, 2023). The size of the catchment area can vary depending on the building cluster, ranging from single-dwelling buildings to commercial, industrial, and high-rise buildings. The amount of water captured by the catchment area is influenced by factors such as rainfall intensity, duration, and frequency. The inflow rate can be estimated by various methods, such as using rainfall data and hydrological models to predict runoff. The inflow rate can also be measured directly using flow meters or water level sensors. Accurate measurement of inflow is crucial for estimating the available water storage and optimizing the system's performance. Outflow refers to the amount of water leaving the stormwater harvesting facility during a particular time period, such as during a storm event. The outflow can be affected by various factors such as the size of the storage facility, the water demand within the system, and the condition of the infrastructure used to control the flow (Meng, 2022).

For example, during a rain event, the inflow of water to the stormwater harvesting facility increases, and the outflow rate may be adjusted by control infrastructure such as valves or pumps to manage the amount of water released from the facility. In addition, during periods of low demand, the outflow can be reduced to allow more water to be stored in the facility. The amount of outflow is a crucial factor in the calculation of the stormwater storage as it influences the amount of water available for use within the system and the amount of water released into the environment.

Change in the stored water volume within the defined boundary refers to the difference between the volume of water stored in the stormwater harvesting facility at the end of a time period compared to the beginning of that period. The change in stored water volume can be positive or negative, depending on the inflow and outflow rates during the period (Meng, 2022).

The storage volume of a stormwater harvesting facility is dependent on various factors such as the size and shape of the facility, the catchment area, and the hydraulic characteristics of the system. The storage capacity of the facility is a critical factor in determining the amount of water that can be harvested and stored for later use. The water level in the stormwater harvesting facility is a function of the size, the amount of water captured by the connected catchment areas, and the outflow of the harvesting system. The water level can be measured using water level sensors and is an important parameter in the control of the system.

The conventional model for calculating stormwater storage uses a mass balance equation to account for the inflow, outflow, and change in stored water volume. This equation allows for the estimation of the available water storage and the optimization of the system's performance. The calculation of stormwater storage in the conventional option is a critical aspect of managing stormwater harvesting systems. Inflow, outflow, and change in stored water volume are the key parameters in the water mass formula, which provides a basis for calculating stormwater storage. Accurate measurement and estimation of these parameters are crucial for the optimal design and operation of stormwater harvesting systems (Valizadeh, et al., 2019)..

The water level in stormwater harvesting facilities in this chapter is a function of size, the amount of water captured by connected catchment areas, and the amount of outflow of the harvesting system. This is reflected in the following mass balance equation between the previous and current storms. In the conventional model (Eq. 3-2):

$$Volume_{current} = Volume_{previous} + Inflow_{current} - Outflow_{current} - Excess_{current} \quad (Eq.\ 3\text{-}2)$$

By using this equation, the current volume of stormwater storage can be calculated based on the previous volume, the inflow, outflow, and excess. The inflow represents the amount of stormwater that enters the system, while the outflow represents the amount of water that is released from the system. The excess represents the amount of stormwater that exceeds the system's storage capacity and is not able to be stored (Jamali, et al., 2020)..

In summary, the conventional method for calculating stormwater storage is based on the water mass formula and the mass balance equation between previous and current storms. These equations take into account factors such as the size of the facility, the amount of water captured by connected catchment areas, and the amount of outflow from the harvesting system. By using these equations, the current volume of stormwater storage can be calculated based on the inflow, outflow, excess, and previous volume, providing a useful tool for conventional stormwater management.

3.2.2 How to calculate stormwater storage in the RTAC model

In the RTAC model, this chapter introduced a new factor, M_{curent} (named by the author's family name, MENG), to present the recovery capacity in the stormwater harvesting systems between two continuous rain at the same point (Eq. 3-3).

$$Volume_{current} = Volume_{previous} + Inflow_{current} - Outflow_{current} - M_{current} - Excess_{current} \quad (Eq.\ 3\text{-}3)$$

Where $Volume_{current}$ and $Volume_{previous}$ represent the storage volume at the end of the current and previous time steps, respectively. This chapter is specifically focused on water level and water flow analysis during very frequent rainfall events. It assumes the utilization of existing detention tank systems in the study area, with an average size of 500 L, rather than introducing new harvesting systems. The research also assumes that all rainwater from the 5.28 m^2 roof will be collected and stored in the detention tank systems using the Rainwater Tank Attenuation Concept (RTAC) model.

In the case of a 34.1 mm rainfall event in Brisbane, assuming that the first 4 mm accounts for initial losses, the detention tank can effectively capture approximately 1-hour of the specific year rainfall event (1h1EY), which is equivalent to 34.1 mm in the Brisbane area. This means that 5.28 m^2 of connected roof space, receiving 30.1 mm of rainfall, will fill the 500 L detention tank. When the 1h1EY level rainfall starts, the tank will reach capacity. In anticipation of further precipitation, the RTAC model will trigger the release of water from the tank, utilizing system-connected valves. As a result, the detention tank system will be either fully or partially emptied and ready to capture precipitation from the next rainfall event.

$Inflow_{current}$ is the current volume of captured water from connected areas (roof areas are connected to facilities, while other surface areas are connected to a basin or lake). $Outflow_{current}$ represents the outflow from the stormwater harvesting system for recycling use or other demand. Please note that the project scope does not include supply-demand matrix or reuse & recycling matrix studies. The methodology used to calculate $M_{current}$ in this study assumes that all runoff water will be collected and discharged to the trunk drainage network between each very frequent rainfall event. The volume of water between the total outfall volume (in m^3) represents the recovery capacity from the stormwater harvesting tank systems.

Recovery factor *M,* is a novel factor introduced in the RTAC model to represent the recovery capacity in stormwater harvesting systems between two consecutive rain events at the same point. The RTAC model employs a mass balance formula to describe the change in storage volume over time, which incorporates inflows and outflows from the control volume. The new formula considers two continuous rainfall events at the same location and is used to calculate $M_{current}$.

$M_{current}$ is calculated by assuming that all runoff water will be collected and discharged to the trunk drainage network. The recovery capacity from the stormwater harvesting tank systems is the difference between the total outfall volume and the amount of water that flows into the network. The amount of water released to the stormwater drainage system (SWDS) depends on the precipitation forecast. If more rainfall is forecast, the RTAC model will release more stored water to prepare a bigger capacity in the stormwater harvesting systems, and vice versa.

During the after-storm period, the valve would release harvested stormwater when the cloud computing platform controlled by the central computer system sends a command to the real-time control release valve. If the predicted rainfall is higher than the available storage capacity, the valve will release all stored water from the harvesting system. Conversely, if the predicted storage water is less than the available storage capacity, the volume of the released water should be close to that rainfall. The RTAC model is the first to incorporate a cloud computing platform and WIFI-based connection system to control individual stormwater harvesting facilities, and $M_{current}$ plays a crucial role in determining the required storage volume for stormwater runoff in these facilities.

The general mass balance describes the change over time and includes inflows and outflows from the control volume (Meng, et al., 2022); formula four describes a mass balance in the RTAC model, which considers two continuous rainfall at the same location. $E_{current}$ is the current excess water that flows into the urban drainage network when the tank storage capacity is exceeded (Figure 3-1).

The amount of water released to the SWDS depends on the precipitation forecast; if more rainfall is forecast, the SWDS model will release more stored water ($R_{current}$ and $R_{previous}$) to prepare a bigger capacity in the stormwater harvesting systems, and vice versa. $R_{current}$ is based on the Bureau of Meteorology's (BOM) rainfall forecast (less than one day) and $R_{previous}$ is based on the BOM's rainfall forecast data (above one day). Storage for use is the storage amount for demand use during the rainfall event. To clarify the influence of M in the RTAC model, the author developed a new formula to calculate M_{crrent}.

$$M_{current} = Volume_{previous} - Rain\ forecast_{previous} - Rain\ forecast_{current} - Storage\ for\ use \quad (4)$$

Figure 3-2b presented three time periods in the RTAC model: before, during, and after the storm. During the after-storm period, the valve would release harvested stormwater when the cloud computing platform (controlled by the central computer system) sent a command to the real-time control release valve. For instance, if the predicted rainfall is higher than the available storage capacity, the valve will release all stored water from the harvesting system. If the predicted storage water is less than the available storage capacity, the volume of the released water should be close to that rainfall.

3.2.3 The control logic of RTAC

Figure 3-2 presented the difference between the conventional and RTAC model in the stormwater storage management. The RTAC system is designed to optimize the management of stormwater harvesting facilities in developed areas. The key component of the system is the control logic, which uses real-time data to make decisions about how to manage the flow of water through the system.

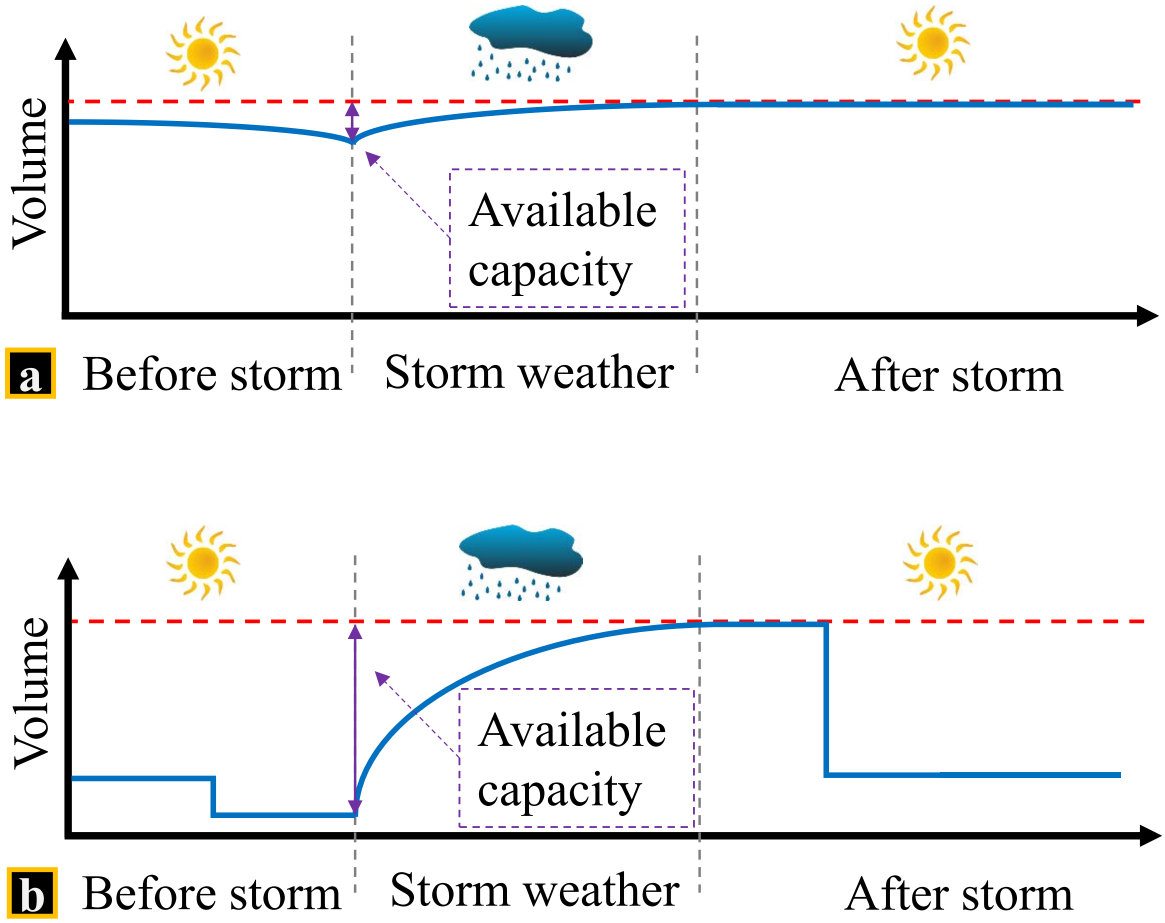

Figure 3-2 Water storage performance of individual stormwater storage facilities in the (a) conventional model and (b) RTAC model during very frequency rainfall events

The control logic is configured to perform several functions that are critical to the efficient management of stormwater harvesting facilities. One of the key functions is to discharge water in advance of storm events if necessary to create storage capacity. This helps to ensure that the system is prepared to capture and store as much runoff as possible during a storm event. Another key function of the control logic is to minimize discharge during storm events. This helps to reduce the amount of runoff that enters the urban drainage network, which can help to alleviate the pressure on the network during heavy rain events. By minimizing the amount of discharge during a storm event, the system can also retain more water for future use, such as for irrigation or other non-potable uses.

Water reuse from stormwater storage tanks provides numerous advantages that contribute to sustainable water management and address pressing water-related challenges (Tansar, et al., 2022). By harnessing the potential of captured stormwater for non-potable uses, there are unlock a range of benefits.

One of the primary advantages of water reuse is the reduction in demand for freshwater resources (O'Donnell, et al., 2020). By utilizing stored stormwater for non-potable purposes such as irrigation, industrial processes, or toilet flushing, lessen the reliance on traditional freshwater sources (Zhang, et al., 2020). This reduction in freshwater demand helps to conserve valuable water supplies, especially in regions where water scarcity is a significant concern. It also reduces the strain on existing water infrastructure, including water treatment plants and distribution networks.

Moreover, water reuse from stormwater storage tanks promotes water sustainability by alleviating the burden on water treatment and supply infrastructure (Nguyen, et al., 2022). Traditional water treatment processes require significant energy and resources, and they often involve complex treatment methods to ensure water quality and safety. By utilizing captured stormwater for non-potable purposes, the system can reduce the amount of water that needs to undergo extensive treatment, thus reducing energy consumption and the associated environmental impact (Tansar, et al., 2022). This, in turn, contributes to the overall sustainability of the water supply system.

In areas facing water scarcity or experiencing drought conditions, water reuse from stormwater storage tanks becomes particularly valuable (Zhang, et al., 2019). These regions often struggle with limited water availability, increased competition for water resources, and the need to implement strict water conservation measures. By reusing captured stormwater, communities can alleviate the strain on local water sources and mitigate the impact of drought (Xu, et al., 2022). This helps to ensure a more reliable water supply for essential non-potable uses, such as landscaping, industrial processes, or firefighting. The subsequent study will aim to provide clarification on the effective utilization of stored water from these storage systems.

In addition to minimizing discharge during storm events, the control logic is also designed to withhold water directly after storm events to allow the downstream stormwater trunk drainage system to regain capacity. This is important because the downstream drainage system can become overwhelmed with runoff during a heavy rain event, which can lead to flooding and other problems. By withholding water from the stormwater harvesting system after a rain event, the downstream drainage system has time to recover, which helps to prevent flooding and other issues. Once the downstream drainage system has regained capacity, the control logic can then release water from the stormwater harvesting system. This ensures that the system is prepared for the next rain event, and that it has sufficient capacity to capture and store runoff.

Overall, the control logic of the RTAC system is designed to optimize the management of stormwater harvesting facilities in developed areas. By using real-time data to make decisions about how to manage the flow of water through the system, the RTAC system can help to reduce the impact of stormwater runoff on the urban drainage network, while also maximizing the use of captured runoff for non-potable uses (Heaney, et al., 2002; Sydney Water, 2019).

3.3 Case study

In 2019, a pilot study was conducted in Brisbane to test the effectiveness of the Real Time Adaptive Control (RTAC) system in a practical environment. The aim of the pilot project was to assess the performance of the RTAC model in real-world conditions and identify potential limitations that may impact its effectiveness. The RTAC system comprised a 500L detention tank, a water tank level sensor, a Wifi control water valve, and an innovative adaptive control system designed to manage precipitation forecast information and evaluate the storage capacity in the RTAC model.

The selection of Brisbane as the testing location was a carefully considered decision. The city is situated in a region that experiences more rainfall, especially during the months of January to March, which was the period selected for this project's study. Additionally, Brisbane is known for having overland flow flooding issues and more flooding damages compared to other cities, making it an ideal location for testing the water tank level sensor and control valve.

Figure 3-3 presented the logic of the connection of the project. The water tank utilized in this project had a capacity of 500L and was fitted with an ultrasonic water tank level meter sensor. The installation of the sensor was done at the top of the retention tank to enable it to measure the water level accurately. The water tank level meter sensor employed an ultrasonic transmitter unit to measure the water level, ensuring high accuracy and reliability. The system had a user-friendly interface that displayed the measured water level on a bar graph, allowing individuals to monitor the water level in real-time. Additionally, the system allowed users to set alarms for specific water levels, such as high and low levels or when the tank was empty, ensuring that the water storage requirements were met.

To manage stormwater runoff in real-time, this pilot project utilized a WiFi control water valve, which allowed them to control the release amount of water from the detention tank remotely. The valve was connected to the computer system through an Android application program, which enabled remote control of the valve from anywhere using a smartphone. The WiFi control water valve was designed to be easy to install and safe to use, as it did not require any plumbing work and could be easily fitted over the existing levered ball valve. The valve adopted WiFi international technology, ensuring that it was compatible with most devices. Additionally, the valve had a high reliability rate and was designed with an automatic feature that turned off the water valve and sent a notification to the smartphone app when it detected water level reached to 400L level, ensuring the available capacity in the system (Figure 3-3).

This project utilized an Android control system to manage rainfall data and control the water valve's release from the tank. The software was designed to provide a user-friendly interface that allowed individuals to monitor rainfall data and control the valve remotely through the application program. The software was easy to use and efficient, making it an ideal solution for managing the stormwater runoff in real-time.

The water tank level sensor and control valve system utilized in this project were designed to provide an efficient solution for managing stormwater runoff in real-time. The system was easy to install, safe to use, and highly reliable, making it an ideal solution for urban planners looking to manage the stormwater runoff in their cities. Additionally, the system had a smart control system, allowing individuals to monitor the water level in real-time and set alarms for specific water levels, ensuring that varying water storage requirements were met.

This pilot project is the first time to test the RTAC control system in the RTAC model to control Runoff Water Dynamically Through a Wifi based System, which enabled the model to adapt to changing weather conditions and adjust the system in real-time. The RTAC model can accurately calculate the reduced amount of runoff, which is critical in managing stormwater runoff effectively, especially in areas with high runoff volumes and limited drainage capacity.

The three-month test for the RTAC model started on 1st January 2019, during which the project used a 12-hour rainfall forecast to analyze the release water amount from the retention tank. As the rainfall in the first and second months was very limited, the real test started from the middle of March 2019. On 16th, 17th, and 18th of March, the RTAC system released three times 300L water from the tank (the release amount is set as 300L per time as the default), resulting in the balance in the tank being 385L, 474L, and 303L after each release, respectively.

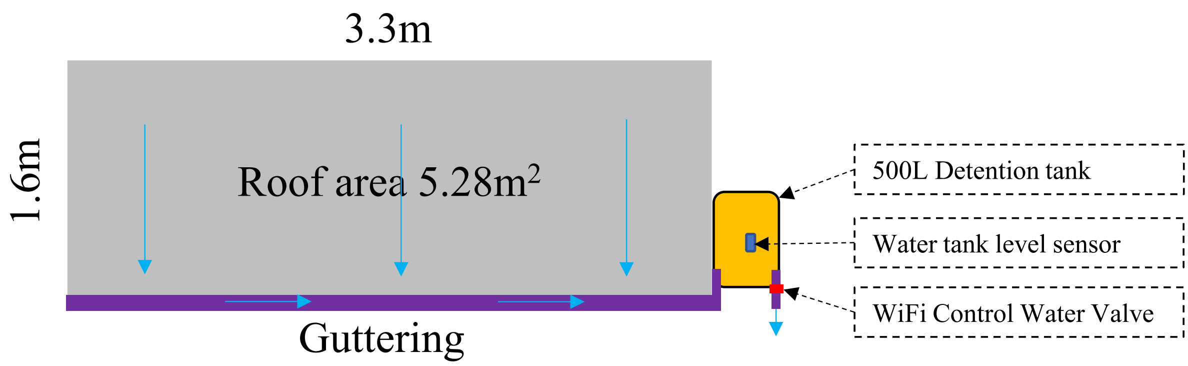

Figure 3-3 Conceptual model for the experimental design conducted in 2019

In this study, the model can calculate the reduced amount of runoff in different scenarios, including 12EY (exceedances per year), 6EY, 4EY, 2EY, and 1EY, enabling urban planners to design effective stormwater management systems and reduce the risk of flooding. The RTAC model can also analyze precipitation forecast information to calculate the accurate release amount from the detention tank based on the forecast, enabling urban planners to predict the amount of runoff and adjust the system accordingly. By analyzing precipitation forecasts, the model can optimize the release amount from the detention tank, reducing the risk of flooding.

A recent case study conducted in 2023 in Sydney demonstrated the effectiveness of the RTAC model in mitigating overland flow flooding and reducing more runoff water. By implementing the model in a larger area, urban planners can manage stormwater runoff more effectively and reduce the risk of flooding. The RTAC model's adaptability and ability to calculate the reduced amount of runoff make it a valuable tool for urban planners looking to implement effective stormwater management systems (Meng, et al., 2023).

3.4 Results

3.4.1 Methods for Calculating Stormwater Storage in the Conventional Model

The conventional model for calculating stormwater storage utilizes a mass balance approach, as described by Meng and Kenway (2018). The formula is expressed as:

Inflow = Outflow + Δ Stored Water Volume

This model accounts for the inflow, outflow, and changes in stored water volume within a defined boundary. Inflow is determined by the catchment area connected to the facility, which varies based on building type and other factors such as rainfall intensity and duration. Outflow is managed by control infrastructure like valves or pumps, which adjust the release of water based on system demand and storage capacity.

The change in stored water volume reflects the difference between water levels at the beginning and end of a specific period. Accurate measurement of these parameters is critical for optimizing the system's performance and ensuring adequate water storage for non-potable uses. The mass balance equation for stormwater storage in the conventional model is:

$$Volume_{current} = Volume_{previous} + Inflow_{current} - Outflow_{current} - Excess_{current}$$

This equation allows for the calculation of current stormwater storage volumes, considering previous storage levels, current inflows and outflows, and any excess water that exceeds system capacity.

3.4.2 Calculating Stormwater Storage in the RTAC Model

The RTAC model introduces a new factor, $M_{current}$, which represents the recovery capacity in stormwater harvesting systems between consecutive rainfall events. The modified mass balance equation is:

$$Volume_{current} = Volume_{previous} + Inflow_{current} - Outflow_{current} - M_{current} - Excess_{current}$$

This study focuses on using existing detention tank systems with an average size of 500 liters. For example, during a 34.1 mm rainfall event in Brisbane, the system is designed to capture runoff from a 5.28 m^2 roof area. The RTAC model manages the release of stored water based on forecasted precipitation, ensuring the tank is ready for subsequent rainfall events.

The recovery factor, $M_{current}$, is calculated by considering the total outfall volume and the amount of water released to the trunk drainage network between rainfall events. This factor allows the RTAC system to dynamically adjust storage capacities in anticipation of future precipitation, optimizing the management of stormwater harvesting facilities.

3.5 Discussion

The RTAC system represents a significant advancement in stormwater management, offering real-time, adaptive control of water storage and release in urban environments. By integrating cloud computing and WIFI-based communication, the RTAC system provides a highly responsive solution to the challenges posed by variable and intense rainfall events. This coordinated management approach not only reduces the burden on urban drainage networks but also enhances the efficiency of water resource utilization.

The pilot study conducted in Brisbane in 2019 demonstrated the practical application and benefits of the RTAC system. With a setup including a 500-liter detention tank, water level sensors, and WIFI-controlled valves, the system effectively managed stormwater runoff in real-time. The ability to remotely control water release based on precipitation forecasts proved crucial in optimizing storage capacity and minimizing overflow during heavy rains.

Moreover, the RTAC system's ability to calculate and adjust for recovery capacity ($M_{current}$) between rainfall events ensures that stormwater harvesting facilities are consistently prepared for subsequent precipitation. This dynamic management capability reduces the risk of flooding and maximizes the use of captured stormwater for non-potable applications, contributing to sustainable water management practices.

The RTAC system offers a robust and efficient solution for urban stormwater management. Its real-time adaptive control mechanism, supported by advanced technological integration, positions it as a critical tool for urban planners and water resource managers in mitigating the impacts of stormwater runoff and enhancing water sustainability. Future studies and larger-scale implementations will further validate and refine the system's effectiveness, potentially leading to widespread adoption in urban areas facing similar challenges.

3.6 Conclusion

This study introduces an innovative approach to stormwater management through the utilization of advanced control technologies. The RTAC method, based on cutting-edge technologies such as cloud computing, Wi-Fi-based connections, and control unit computing systems, enables real-time data analysis and control of stormwater runoff storage and release in stormwater harvesting facilities.

The RTAC method represents a significant advancement in stormwater management as it allows urban planners and stormwater specialists to effectively manage the storage capacity of existing stormwater harvesting facilities, such as tanks. This is achieved by utilizing a recovery capacity factor, *M,* which determines the necessary storage volume for stormwater runoff in these facilities. Through optimizing the storage and release of runoff water, the RTAC method alleviates the demand on the urban drainage network, thereby reducing the risk of flooding and safeguarding urban infrastructure.

The results of applying the RTAC method demonstrate its effectiveness in managing stormwater harvesting tanks within urban catchments. The method enables more efficient and effective storage of runoff water during storms and facilitates the controlled release of a reduced volume of runoff water into the urban waterway within a shorter timeframe. This capability is crucial for minimizing the risk of flooding and mitigating damage to urban infrastructure.

In conclusion, the RTAC method represents a significant advancement in stormwater management, harnessing state-of-the-art technologies to optimize the storage and release of runoff water in stormwater harvesting facilities. By enabling real-time data analysis and control, this method enhances the efficiency and effectiveness of stormwater management, contributing to the reduction of flood risk and the protection of urban infrastructure. The scalability and adaptability of the RTAC method make it suitable for implementation in diverse stormwater infrastructure, offering a comprehensive and integrated approach to stormwater management. Overall, the RTAC method has the potential to revolutionize stormwater management practices and deliver substantial benefits in this field.

However, it is important to acknowledge certain limitations of the RTAC method. Further research studies are necessary to gain a more comprehensive understanding of the effective utilization of stored water from these storage systems. Conducting large-scale catchment studies under different settings and varied conditions would provide valuable insights into the performance and effectiveness of the RTAC method. Additionally, the issue of water quality control in stormwater harvesting facilities remains uncertain. Therefore, it is crucial to direct research and development efforts towards integrating effective water quality control measures into the RTAC system. These entails addressing concerns related to potential contaminants and pollutants in collected stormwater and implementing appropriate treatment processes to ensure its suitability for various non-potable uses.

By addressing these limitations and conducting extensive studies, the refinement and validation of the RTAC method can be achieved, enhancing its reliability and effectiveness in stormwater management. This, in turn, would provide more robust and comprehensive solutions for sustainable stormwater management in urban environments.

Chapter 4 Improved stormwater management through the combination of the conventional water sensitive urban design and stormwater pipeline network

Related publication:

Xuli Meng, Xuan Li, Long D. Nghiem, Eric Ruiz, Mohammed A. Johir, Li Gao, Qilin Wang, 2022. Improved stormwater management through the combination of the conventional water sensitive urban design and stormwater pipeline network. *Process Safety and Environmental Protection,* Volume 159, pp. 1164-1173.

4.1 Introduction

As mentioned in Chapters 2 and 3, it is challenging to reduce the stormwater runoff and restore the natural hydrological cycle globally, especially for the areas with rapid population growth (Commonwealth of Australia, 2015). It is estimated that 3,000 GL of stormwater runoff are produced in Australian urban areas each year (Ball, et al., 2019), such as the Moreton Bay area from South East Queensland (SEQ) (Queensland Government, 2017) and metropolitan Sydney (Sydney Water, 2013). In Sydney, the most populous city in Australia, flooding due to stormwater become a part of daily life during the summer months (Ball, et al., 2019). The subtropical climate in Sydney makes it prone to weather that can cause flooding from rivers, creeks, storm tides and especially overland flows (Ahmed, 2018). A huge demand (200 GL/yr) for stormwater runoff reduction is required for Sydney (Commonwealth of Australia, 2015).

As a broader urban stormwater management framework, WSUD manages all water streams as resources (Robin, et al., 1997; Fletcher, et al., 2013; Renouf, et al., 2016), promotes recycling, mitigates the impact of urban stormwater through the shift of the landscaped features to solve both water quality and water quantity issues (Wong, 2015; Peña-Guzmán, et al., 2017; Ball, et al., 2019), in both street catchment scale (Meng & Kenway, 2018) and site scale (Moravej, et al., 2021). WSUD has been recognized as an innovative way to restore the natural hydrological cycle, including stormwater management, and groundwater restoration (Ozgun, et al., 2017; Thomson & Newman, 2018). The implementations of WSUD involve removing sections of the deteriorated concrete riverbank and undertaking environmental rehabilitation of parts of the riparian zone; introducing more distributed bioretention tanks; connecting distributed WSUD designs to natural waterways (Jacobson, 2011; Chesterfield, et al., 2016a; Commonwealth of Australia, 2019; Xiong, et al., 2020). To date, several studies have examined the response of stormwater runoff to street-scale landscaped features through WSUD implementation (Li, et al., 2019). However, the application and efficiency of WSUD at catchment scales, especially for a catchment with a big catchment area (>1,000 ha) have not been investigated (Cheah, 2006; Meng & Kenway, 2018). The performance and mechanism of the WSUD model in mitigating the stormwater runoff in a big urban catchment remains unclear.

Currently, most of the WSUD projects were isolated and located in the catchment without connections with the stormwater pipeline network (Meng & Kenway, 2018). A recent study reported that the stormwater runoff was reduced by connecting the conventional WSUD projects linearly through street parks or linear raingardens on the road (Meng & Kenway, 2018). However, a minimum of 10% road surface is required for changing the land use which might be an obstruction for some highly developed urban areas (Meng &

Kenway, 2018). Thus, in this chapter, we hypothesized that connecting conventional WSUD implementations with the existing stormwater pipelines could mitigate the stormwater runoff without further surface change requirements.

This chapter investigated the performance of conventional WSUD and combined WSUD (linearly connected conventional WSUD with existing stormwater pipelines) in stormwater management and accommodating future urban development. A catchment in Sydney, Australia with over 1,000 ha was used for demonstration purposes. The performance of combined and conventional WSUD in stormwater management, evapotranspiration and infiltration was evaluated through 5 different water mass balance models on a long timeline, from pre-development (1770) and development (2000) to future (2030), and further assessed under three rainfall scenarios (i.e. high, average and low) using the data from past 70 years. The results obtained provided a comprehensive evaluation and understanding of combined WSUD in a catchment-level application for future development.

4.2 Methodology

4.2.1 Study area and catchment boundary

4.2.1.1 Study area

Upper Caddies Creek catchment, Sydney was selected to investigate the performance of conventional WSUD and combined WSUD with stormwater pipelines for stormwater runoff management. Due to the rapid urbanization, the Upper Caddies Creek catchment is facing a critical issue in stormwater runoff management from the 20^{th} to 21^{st} century, especially for the fast increase of runoffs and unexpected flows (Critchley, et al., 1991;

Brown, 2005; Farooqui, et al., 2016). The Upper Caddies Creek catchment is around 1,238 ha, located 35 km west of Sydney's central business district (CBD) with a humid subtropical climate (Figure 4-1). This catchment includes highway, road and intersection (254.32 ha); hydroarea (6.6 ha); hydroline (56.19 ha); developed area (799.77 ha); and open space (121.43 ha). The imperviousness rate for each cluster are highway, road and intersection (90%); hydroarea and hydroline (5%); developed are (90%); and open space (40%).

In the past, local authorities have introduced many WSUD models to an area and most of them are lined. However, with further development and urbanization, the impervious fraction of many lands has increased resulting in the poor performance of the current stormwater management system in buffering and storing runoffs. Consequently, flooding, especially overland flow flooding, has occurred more frequently (Meng & Kenway, 2018). Furthermore, the Upper Caddies Creek catchment is a rapidly developing area, expecting more than 30,000 new residents in the next 30 years (Sydney Water, 2019). The high-density buildings introduced in recent years led to more stormwater runoff and more overland flow flooding (Brown, 2005). This further increases the burden of storm management in this area.

Aside from urban development, climate change is another important factor impacting the stormwater runoff (Kenway, et al., 2011). An increasingly irregular rainfall pattern has been observed over the catchment in recent years. From 1950 to 2020, rainfall is extremely uneven between summer and winter (averagely 97 mm in summer and 57 mm in winter) in this area (BOM). Heavy rainfalls and storms are more common in the summer with over 50% rainfall of the whole year, which bring a large amount of runoff to the catchment in a very short period after the storm. Moreover, the Upper Caddies Creek catchment has an overall slope of over 0.93%, which leads to a large runoff flow and low infiltration. It requests the new stormwater management system to collect runoff swiftly and effectively.

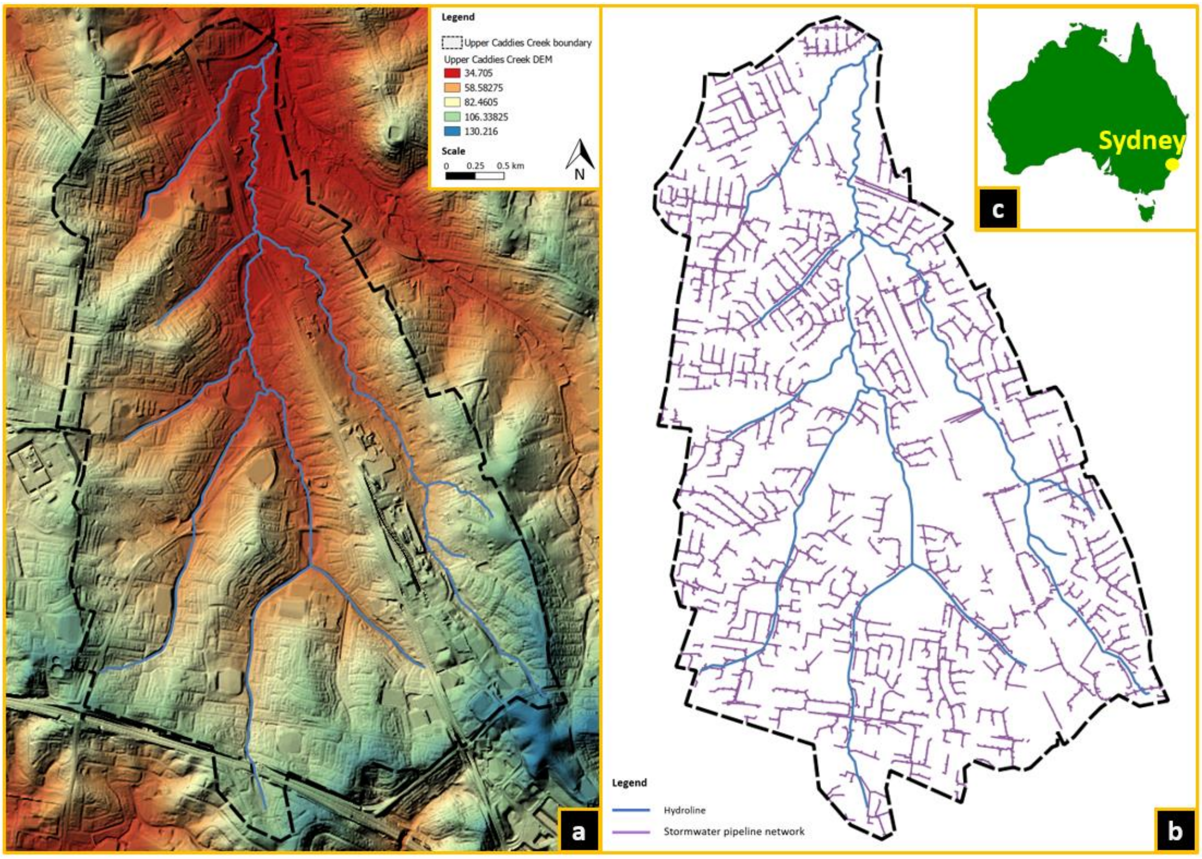

Figure 4-1 (a) Upper Caddies Creek catchment in the Digital Elevation Model (DEM) model (Geoscience Australia), (b) hydroline (blue) and stormwater pipeline network (purple) in the Upper Caddies Creek catchment, (c) the Upper Caddies Creek catchment in Sydney, Australia

4.2.1.1 Determination of catchment boundary

The Upper Caddies Creek catchment includes developed and undeveloped areas. Based on the cadastral information provided from Blacktown City Council and The Hills Shire Council, the developed area involves high-rise apartments and townhouses, standalone residential houses, commercial and industrial buildings. The undeveloped area includes open space areas, parks, natural waterways, gardens, and natural land. Conventionally, the determination of catchment boundary is based on natural features, such as hills and mountains. The surrounding waterways of the natural features form what is known as the watershed. However, rapid urban construction changed the catchment boundary significantly (Bach, et al., 2014). In the study area, large residential and commercial zones have reshaped the natural watershed since pre-development. To accurately determine the catchment boundary, we collected land use data from the local governments and analyzed these data to create catchment zones. The process combined both natural geographic information and developed area to generate new watershed boundaries with the consideration of urban development through ArcGIS 10.6.1. In particular, the streets that discharge stormwater to the catchment area were also included in the catchment boundary creation. Also, the building roofs, concrete driveways, and gardens were separated from the developed area to determine the imperviousness of the catchment. In the past, these streets may be separated by different catchments based on the contour line information and residential zones, leading to inaccurate imperviousness rate for the whole area (Meng & Kenway, 2018).

4.2.2.2 Selection and establishment of conventional and combined WSUD projects

In this chapter, we have developed an innovative APP (Area-Pipeline-Policy) method to select appropriated WSUD sites based on the following criteria (Table 4-4), including three stages: 1) treatment area; 2) whether it is suitable to be connected with existing stormwater pipeline networks; and 3) support availability from the local community.

Table 4-4 Selection criteria for fourteen WSUD projects

Criteria stages	Indicators	Criteria
WSUD treatment area	1) the landowner type; 2) topography background; and 3) soil type.	Excellent; Good; Medium; Pass; and Fail
Suitable to connect with the existing stormwater pipeline network	1) stormwater pipeline type; 2) stormwater pipeline capacity; 3) inlet and 4) outlet level of the connecting point in the pipeline network.	
Support from the local community	Local councils have relevant policy supports.	

The assessment for treatment areas includes the area's topography, drainage patterns, soils, geology, ground cover, and sensitive regions. For example, we selected the possible treatment areas such as 1) bioretention and sediment basins that were utilized in public open spaces; 2) natural treatment of large stormwater channels through planted vegetation and imitating natural stream form; 3) grassed and vegetated swales that were utilized in the appropriate location where adequate maintenance agreements can be achieved; 4) swales and bioretention systems included in center medians of main streets; 5) bioretention systems that were utilized in verges at low points of the street where adequate maintenance agreements can be achieved; 6) dense planting of natural stream banks which prevent erosion and the integrity of the waterway; 7) significant vegetation preserved where appropriate. Due to the limited soil type information, only half clay and clay were included as options in the assessment. The groundwater condition was set as ‘no difference’ due to the lack of such information.

The second stage assessed the suitability of possible treatment areas to be connected with the existing stormwater pipeline networks. This process identified whether sites were suitable with stormwater pipeline's type, capacity, inlet and outlet types, and layouts. This procedure was assessed based on the latest water-sensitive technical design guidelines through two stages. The first stage is to assess the potential extent and locations available for WSUD, including topographic information; underground services; geotechnical characteristics; environmental and cultural heritage features; planning constraints and climatic conditions. The second stage is to assess upstream catchments; catchment hydrology; integration of WSUD with existing or proposed drainage systems; ecological conditions of vulnerable or threatened to receive waterways (Melbourne Water, 2005; Sharma, et al., 2018).

The third stage is to assess whether support from local communities and local government authorities, such as WSUD guideline support is provided (personal communication with local council). After these three stages of assessment, fourteen possible locations were selected from the Upper Caddies Creek catchment for the establishment of fourteen isolated WSUD projects. The location of these fourteen new WSUD projects is shown in Figure 4-2c, including six WSUD projects from the south subcatchment; two from the west subcatchment; two from the north subcatchment; and four from the east subcatchment.

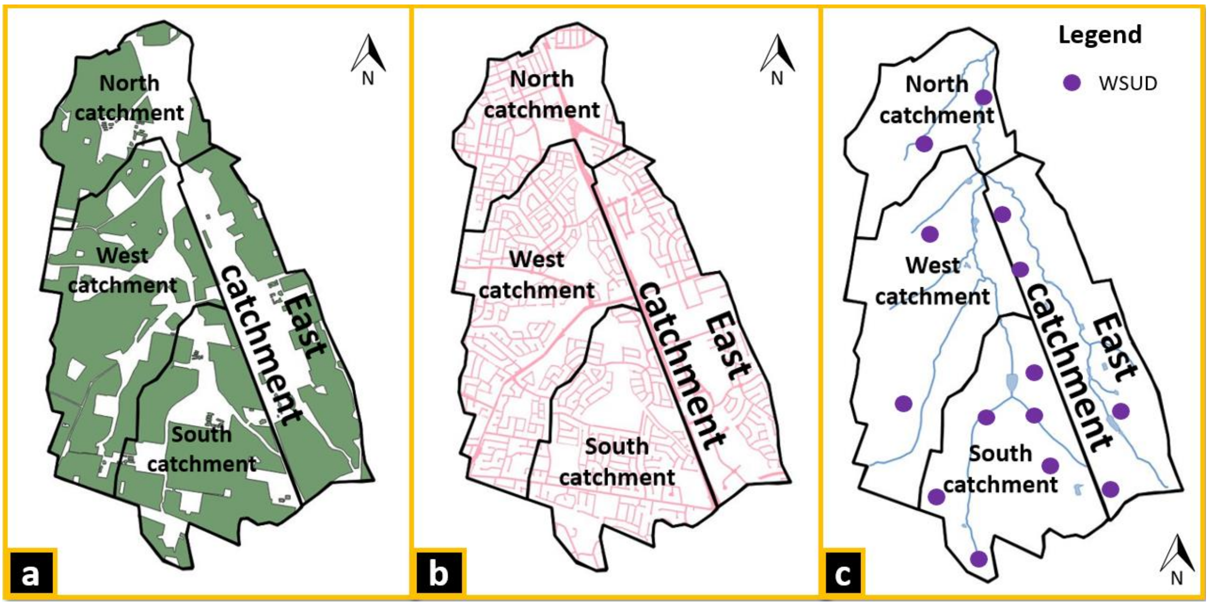

Figure 4-2 Land use information about Upper Caddies Creek catchment: (a) developed area 64.59% (green colour), (b) road and intersection area 20.54% (pink lines), (c) area of hydroarea and hydroline 5.07% (blue colour). Fourteen conventional WSUD projects are labelled as purple dots

While these fourteen new WSUD projects are introduced to work with the existing WSUD model, some parts of the existing stormwater pipeline network will be upgraded to meet the minimum slope requirement as described in the supplementary information (SI). The combined WSUD model was further applied to connect these fourteen isolated WSUD projects with the existing stormwater pipeline network linearly to evaluate their hydrology performance (SI).

4.2.2 Water mass balance models

As a model based on process description, water mass balance models represent the physical processes observed in the real world (Elliott & Trowsdale, 2007). Typically, water mass balance models contain parameters such as stormwater runoff, subsurface flow, evapotranspiration, and channel flow (Elliott & Trowsdale, 2007). Conventional mass balance follows Eq.4-1 to describe the water flows into and out of the system. From a hydrological perspective, it represents the sum of water inflows equaling water outflows and the change in this urban hydrological cycle.

$$P = Rs + ET + GI + \Delta S \quad (Eq.\ 4\text{-}1)$$

where P is direct precipitation on all surfaces in the catchment (GL/yr). Rs is runoff from the catchment area (GL/yr). ET is evapotranspiration (GL/yr), which includes transpiration from plants and evapotranspiration from surfaces. GI is infiltration (GL/yr), and ΔS is the change in stored water (GL/yr).

In this chapter, the shift of water mass balance was influenced by impervious fraction change in the related fourteen conventional WSUD projects. Thus, a modified water balance model was established to link simplified representations of the hydrological processes relative to the Upper Caddies Creek catchment (Eq. 4-2).

$$P = Rs + ET + GI \quad (Eq.\ 4\text{-}2)$$

Eq. 4-2 was established based on Eq. 4-1 without any change in stored water (ΔS), including both impervious and pervious lands, the rainfall coming into the Upper Caddies Creek system (GL/yr), evapotranspiration (GL/yr) and infiltration (GL/yr) out of the stormwater system. This modified water balance model simply treated the Upper Caddies Creek catchment without any extra water input or water stored in the study area. This chapter assumed zero values for the change in storage to compare all five water mass balance models on one platform. Further, the volume of hydrological flows in the Upper Caddies Creek was calculated from the water mass balance tool, the core algorithm is based on the rainfall-runoff modelling algorithm of MUSIC (Model for Urban Stormwater Improvement Conceptualisation) (Water by Design, 2010; CRCWSC, 2018), which is a model commonly used for stormwater infrastructure design (Elliott & Trowsdale, 2007). The water balance model was used to assess the stormwater management performance of conventional and combined WSUD due to urban development (section 4.2.3) and different rainfall conditions (section 4.2.4).

4.2.3 Stormwater management performance of conventional and combined WSUD due to urban development

To assess the stormwater management performance of conventional and combined WSUD with different urban development conditions, five daily time-step hydrological models were applied including pre-development model (1770), development model (2000), Business-As-Usual model (BAU model (2030)), conventional WSUD model (2030), and combined WSUD model (2030). The water mass balance in the pre-development model (1770) represents the hydrological cycle before the development. In 2000, due to the city development pressure, large amounts of land in the study area were changed from low-density residential zones to high-density development zones (State Planning Authority of New South Wales, 1968). At the same time, local water authorities lodged relevant stormwater management plans to accommodate the increase of stormwater runoff volume. The development model (2000) presents the water mass balance based on the year 2000's land use information. The year 2030 was set as a benchmark year to check the performance of conventional and combined WSUD. Thus, BAU model (2030) was used to present water mass balance in 2030 with a *hypothesis* that there is no additional WSUD implementation since 2000. Hypothetical scenarios with fourteen conventional WSUD projects and combined WSUD projects using stormwater pipeline network in 2030 were proposed as conventional WSUD model (2030), and combined WSUD model (2030), respectively. Different to the conventional WSUD model, in the combined WSUD model, isolated WSUD sites will be connected with natural waterways through the new stormwater pipeline network.

The land use information was provided by the local government. The soil characteristic parameters in this study were applied based on the default values from MUSIC. The imperviousness rates in the catchment areas were set at 90% for highway-road-intersection, 5% for hydroarea, 50% for hydroline, 90% for the developed area, and 40% for open space (CRCWSC, 2018). Further, the imperviousness rate of the fourteen selected WSUD was set as 5%. The water mass balance model (as described in section 2.2) was used to compare 5 water mass balance scenarios. The precipitation data in this study was generated from the Seven Hills (Collins Street) station (station number 67026, Bureau of Meteorology (BOM), Australian Government), which is 3 km south of the study area. The recent 5-year-average rainfall (1,494 mm/yr) data was applied to all water mass balance models. The evapotranspiration of the study area was obtained from the average point potential evapotranspiration metadata (BOM, Australia Government), which is based on a standard 30-years climatology (1961 – 1990). The evapotranspiration was set as 'same' in all 5 water balance models in this chapter.

4.2.4 Stormwater management performance of conventional and combined WSUD under different rainfall scenarios

Due to the dynamic rainfall conditions, it is also critical to assess the performance of conventional and combined WSUD under different rainfall conditions. This chapter obtained the daily precipitation (mm/day) data from 1950 to 2020 from the Seven Hills (Collins Street) station and further classified the daily precipitation data into three categories (i.e. high, average and low rainfall). A list of rainfall intensity from 1950 to 2020 including high average annual rainfall (highest 5 years), average annual rainfall (median 5 years) and low average annual rainfall (lowest 5 years) were applied to evaluate the performance of BAU, conventional WSUD and combined WSUD models in 2030 (as described in section 4.2.3).

4.3 Results

4.3.1 Land-use change due to urban development

The urban development was determined based on the land-use information. With the DEM and GIS analysis and recent land-use information collected from the water authorities, five different clusters in the Upper Caddies Creek catchment were listed, including highways-roads-intersections, hydroareas, hydrolines, developed area, and open space. Before 1770, the Upper Caddies Creek was a large wetland. Europeans started to drain the area and form defined creeks and change the area since 1770 (Sydney Water, 2019). Thus, the value for the developed area was 0 in 1770, which presents a natural stormwater system. With urban development, highway-road-intersection and developed areas increased to 254.32 ha and 799.77 ha individually. With future development, in 2030, the developed area is estimated to further increase to 824.59 ha.

Table 4-5 Land use change for the Upper Caddies Creek catchment

	Highway & road	Hydroarea[1]	Hydroline[2]	Developed area	Open space	Fourteen new WSUD	Imperviousness rate
Pre-development model (1770)	-	0.53%	4.54%	-	94.93%	-	8.5%[3]
Development model (2000)	16.43%	0.53%	4.54%	51.67%	26.83%	-	74.32%
BAU model (2030)	20.54%	0.53%	4.54%	66.59%	7.81%	-	83.84%
Conventional WSUD model (2030)	20.54%	0.53%	4.54%	64.59%	9.81%	-	82.84%
Combined WSUD model (2030)	20.54%	0.53%	4.54%	64.59%	2.71%	7.10%	80.35%

[1] Natural water bodies, such as lakes and ponds.

[2] Waterways, including rivers and creeks.

[3] Based on the year 1770 land use information.

Land use conditions would further change the imperviousness in the catchment area. It is evident that the imperviousness rate increased from 8.5% to 74.32% due to the initial development from 1770 to 2000. With no urban implementation since 2000, the imperviousness rate was estimated to further increase to 83.84% in 2030 (BAU models). This is commonly observed with the urbanization process, where more open areas with high imperviousness rates changed into urban catchments with low imperviousness rates, leading to more stormwater runoff (Bach, et al., 2014). To mitigate the increase of stormwater runoff due to the high imperviousness rate in the study site, fourteen WSUD projects (87 ha) were proposed for the WSUD study for future development. Using conventional WSUD, the imperviousness rate of the whole catchment in the study area decreased from 83.84% in BAU 2030 to 82.84%. With the combined WSUD model, after the connection between the existing stormwater pipeline network and fourteen WSUD sites (7.10% of the whole catchment), the imperviousness rate was estimated as 80.35% (Table 4-5), which is 3.49% lower than the BAU model. The reduced imperviousness rates in both conventional and combined WSUD in comparison to BAU 2030 suggest the potential of reducing stormwater runoff in the catchment area.

In addition, this study found that many natural-lined hydrolines were replaced by concrete-lined hydrolines due to maintenance requirements. It implies that the conventional catchment boundary determined by geographic information may not present the actual hydroline conditions due to the urban development (NSW Government, 1990). Thus, the application of the new geotechnical tools is highly recommended for future research to assist the identification of the boundary and the impervious fraction for each catchment.

4.3.2 Stormwater runoff changes due to urban development and implementation of conventional and combined WSUD projects

A strong link between increased stormwater runoff and urban development was observed (Figure 4-3). Within urban development, there was more land change from the natural vegetation cover (pre-development model) to less impervious covers (development, BAU, conventional WSUD, and combined WSUD models). The imperviousness rate thereby increased from a low level (8.5%) in the pre-development stage to high levels (70%-85%) in developed stages. The increase of imperviousness rate due to the urban development greatly affected the stormwater runoff in the catchment area (Figure 4-3). From the pre-development stage to the development model 2000, the stormwater runoff increased by 7,512 ML/yr. With future development to accommodate more population, the stormwater runoff was estimated to increase by 1,340 ML/yr from 2000 to 2030, if no further WSUDs are implemented.

This low stormwater runoff in the pre-development stage is related to the low impervious fraction of the open areas as discussed in section 4.3.1. In the pre-development model, at the beginning of a storm, a large amount of precipitation is caught by trees and vegetation as an interception. The water stored on vegetation is usually well exposed to wind and offers large areas of evapotranspiration, so that storms of light intensity and short duration may entirely be depleted by interceptions. When the available interception and depression storage is completely exhausted and when rainfall intensity at the soil surface exceeds the soil's infiltration capacity, stormwater runoff begins. In contrast, in developed stages, more lands were changed from the natural vegetation cover to less impervious covers, which greatly reduced the foliage, interception, and depression storage volume of the catchment area, leading to the occurrence and increase of overland flow and stormwater runoffs.

To mitigate the increased stormwater runoff due to urban development, fourteen WSUDs were proposed in the catchment area, as described in section 4.3.1. Compared to the BAU 2030 model, both conventional and combined WSUDs reduced the impervious fraction in the catchment and combined WSUDs showed a better reduction in the impervious fraction of the catchment area (decreased 1% for the conventional WSUD model and 3.49% for the combined WSUD model compared to BAU model). With the conventional WSUD, the stormwater runoff was reduced by 1.06% (124 ML/yr) in comparison to the BAU model, while combined WSUD reduced the stormwater runoff by 4% (514 ML/yr). This observation is consistent with a previous study, where the rise of imperviousness rate resulted in more stormwater runoff in the hydrological cycle (Linsley, et al., 1958; Meng & Kenway, 2018).

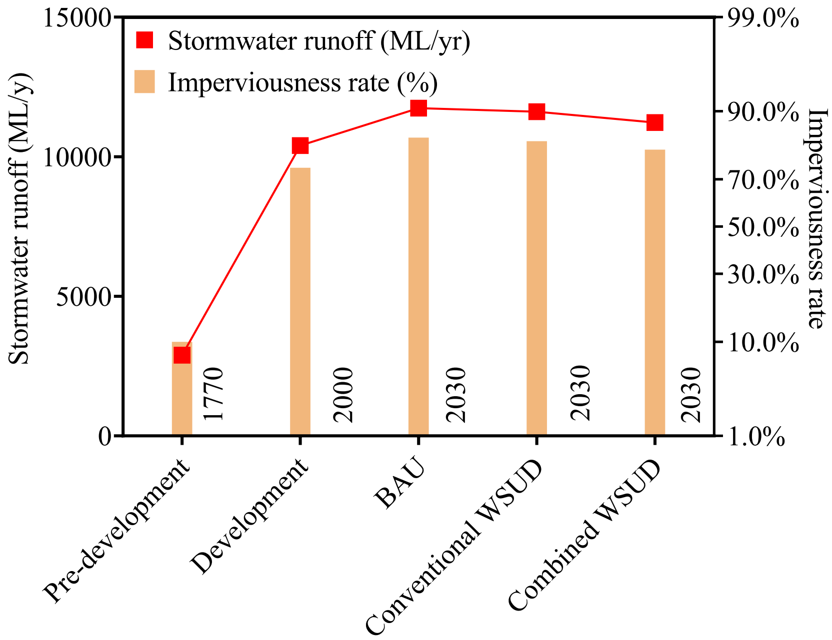

Figure 4-3: Stormwater runoff, evapotranspiration, and infiltration within imperviousness fraction in pre-development, development, BAU, conventional WSUD and combined WSUD models

To assess the performance of conventional and combined WSUD, full hydrological cycle for pre-development (1770), development (2000), BAU (2030), conventional WSUD (2030), and combined WSUD (2030) models was established (Figure 4-4). It is evident that the change of land use due to the urbanization process greatly increased the stormwater runoff, but reduced the evapotranspiration and infiltration in the catchment area in developed stages.

In the pre-development model of the study area, evapotranspiration counted 71% of the hydrological cycle's outputs (Figure 4-4a). Furthermore, 11% of water infiltrated through the soil surface and fill puddles and surface depressions (Figure 4-4a). From 1770 to 2000, the evapotranspiration and infiltration in the catchment area reduced by 5,696 ML/yr and 1,814 ML/yr individually (Figure 4-4a and 4-4b). Due to the urban development, compared with the pre-development model (1770), stormwater runoff increased by over

258% in the development model (2000), which became the major output (over 63%) of hydrological cycle output of the Upper Caddies Creek catchment (Figure 4-4b). Considering an average of 10-15% of runoff would be held by natural vegetation cover environments (Chesterfield, et al., 2016b), high stormwater runoff volume in the development model (2000) suggests more overland flow flooding due to the development (Linsley, et al., 1958; Ma, et al., 2019; Natarajan & Radhakrishnan, 2019).

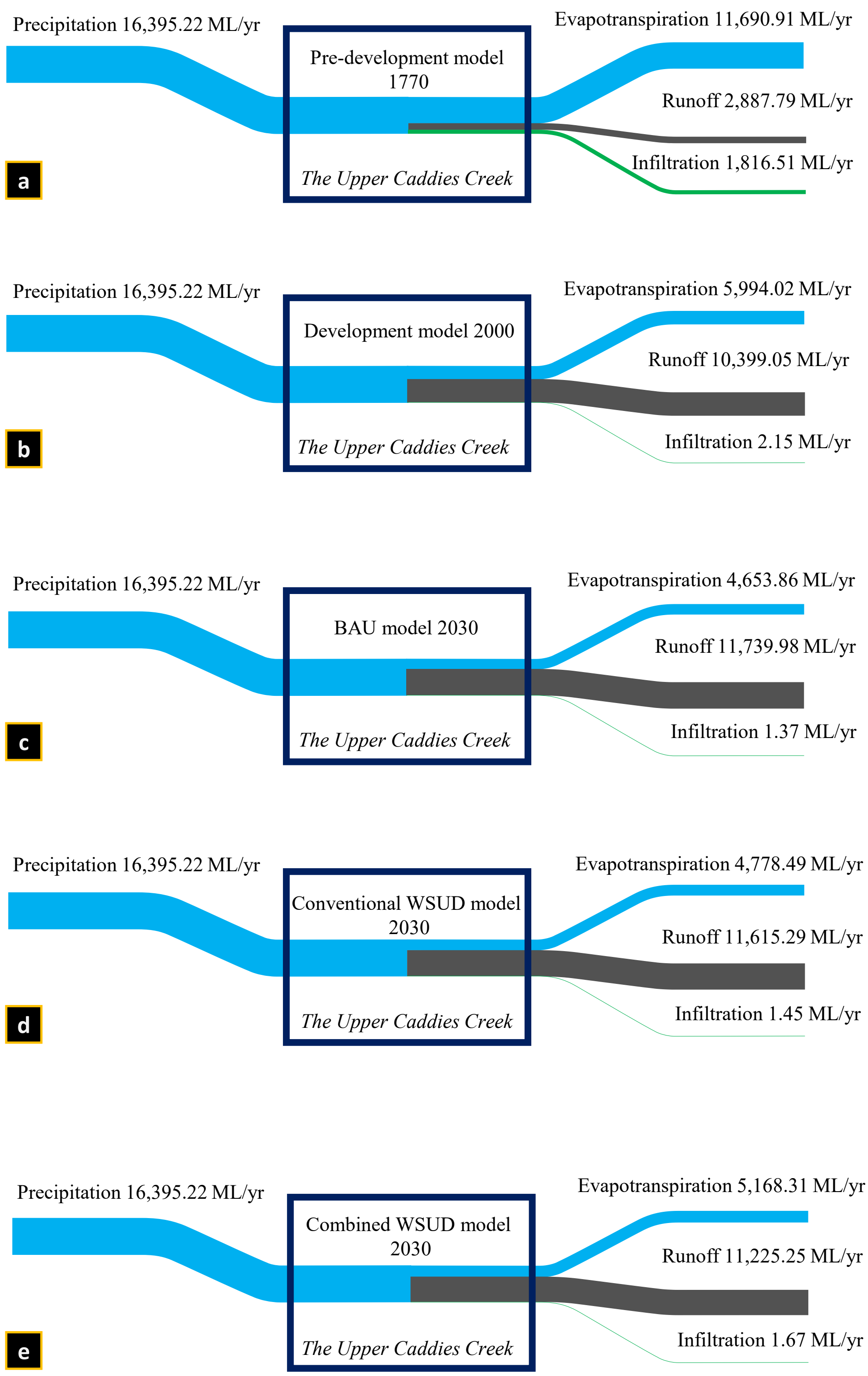

Figure 4-4 The Upper Caddies Creek's water mass balance in (a) pre-development model in 1770, (b) development model in 2000, (c) BAU model in 2030, (d) conventional WSUD model in 2030, and (e) combined WSUD model in 2030

Similar to other new residential development areas in Sydney, the Upper Caddies Creek catchment is expected to house more than 30,000 new residents by 2030 (Sydney Water, 2019). This would lead to a continued increase of impervious covers in the catchment area, leading to more stormwater runoff and affecting the hydrological cycle. With future development, it was estimated that the evapotranspiration and infiltration would further reduce by 1,341 ML/yr and 1 ML/yr from 2000 to 2030. In the BAU model, the stormwater runoff was estimated to increase by 12.89% from 2000 to 2030, which accounts for over 70% of the output in the hydrological cycle. This implies that with the current stormwater system, more stormwater runoff is expected in 2030. Moreover, groundwater management is a big challenge in the world because of groundwater's 'invisibility' (Mcpherson, 1973; Sugg, et al., 2015; Renouf & Kenway, 2017). Through the water mass balance models, the decrease of groundwater infiltration due to urban development would further reduce the groundwater level.

The implementation of conventional and combined WSUD projects both reduced the stormwater runoff and helped to restore natural water cycles. In the conventional WSUD projects, the stormwater runoff was over 124ML/yr less than the BAU model in 2030 (Figure 4-4d). The conventional WSUD also increased the groundwater and evapotranspiration by 0.08 ML/yr and 125 ML/yr respectively.

With a linear connection to stormwater pipelines, the combined WSUD (2030) (Figure 4-4e) presented a better performance in reducing stormwater runoff than the conventional WSUD. Compared with the conventional WSUD, the combined WSUD model further reduced 390 ML/yr of stormwater runoff. Furthermore, the evapotranspiration and infiltration increased by about 400 ML/yr in combined WSUD projects in comparison to the conventional WSUD projects. The increase of evapotranspiration, especially in the combined WSUD model would release more moisture into the atmosphere to reduce urban heat island effects (Thom, et al., 2020). Thus, the combined WSUD is a promising approach in stormwater mitigation, especially for future development. Implementation of combined WSUD projects also assists in recovering groundwater and evapotranspiration systems in the Upper Caddies Creek catchment. The change in groundwater infiltration would help to mitigate the salinity issue in this catchment and recover the groundwater system back to an affordable level (Thom, et al., 2020).

4.3.3 Performance of conventional and combined WSUD under dynamic rainfall conditions

The rainfall conditions are generally decreasing over the years in Upper Caddies Creek, an annual decrease in rainfall of 33 mm per decade was identified from 1950 to 2020. However, there was a generally positive trend (8 mm/year) in mean annual rainfall since 2000. The observed rainfall trends over shorter periods include wetter periods in the 1950s and 1970s, and a drying trend over the Millennium Drought (Sydney Water, 2013). Then, three rainfall scenarios were established to evaluate water accounts in the hydrological cycle, which are high rainfall scenrio (the average rainfall of highest 5 years), low rainfall scenrio (the average rainfall of lowestest 5 years), and average rainfall scenario (the average rainfall of 5 years most close to the mean of 70 years data) were further summarized. The average rainfall of high, low and average rainal scenarios was 1,453.44 mm/yr, 511.36 mm/yr, and 912.36 mm/yr, respectively.

Figure 4-5(a) identified that the mean rainfall at high rainfall years was over 1,400 mm/yr, which is 59% higher than the average rainfall years, and nearly 2 times higher than that of the low rainfall years (Figure 4-5a). Moreover, the rainfall was uneven monthly, the average rainfall in summer (292.76 mm) doubles the average rainfall in winter (122.12 mm) from 1950 to 2020 (Figure 4-5a). These rainfall data were further applied as high rainfall, low rainfall, and average rainfall conditions into the models to evaluate the performance of conventional and combined WSUD under dynamic rainfall conditions.

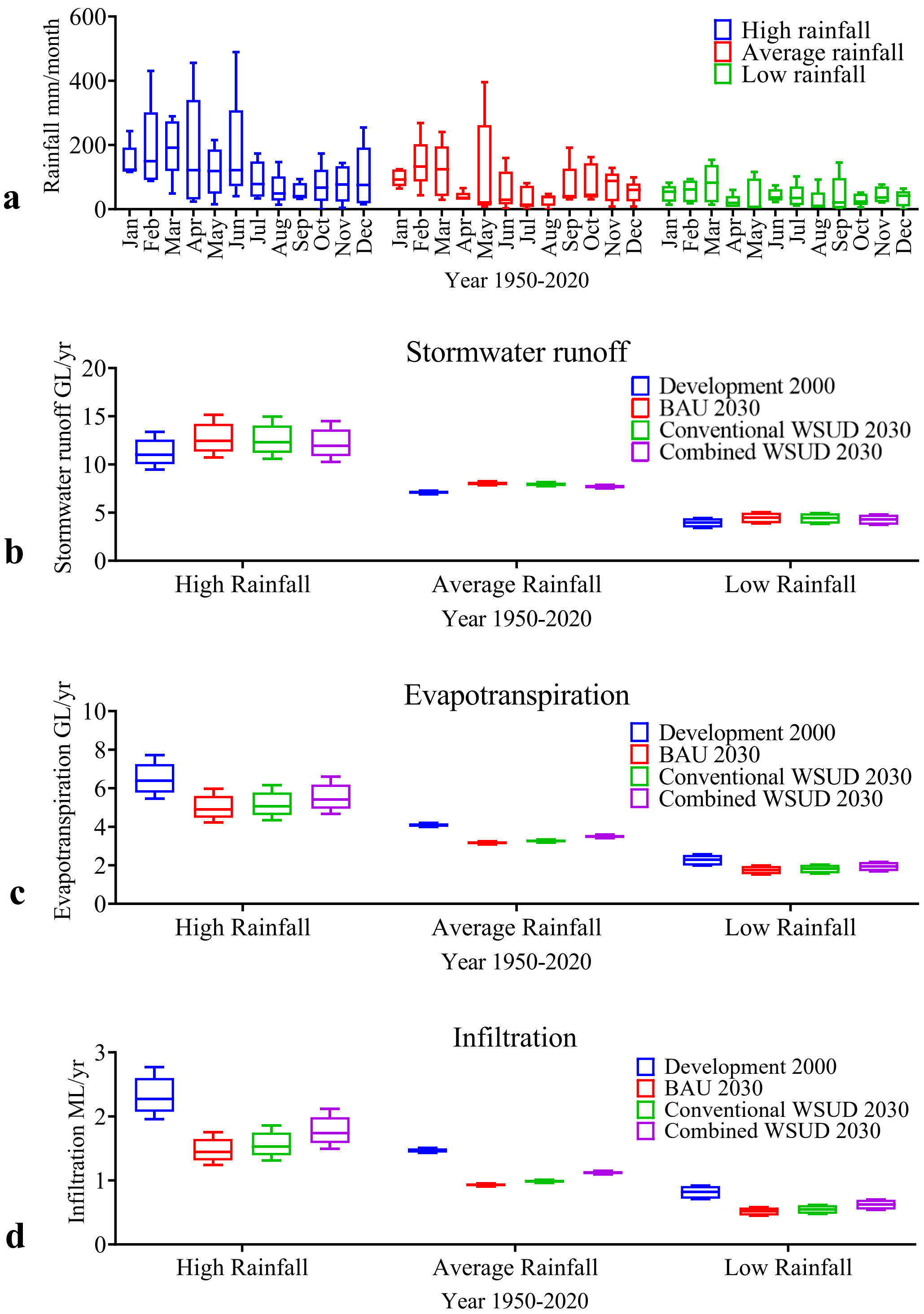

Figure 4-5 (a) Rainfall data from 1950 to 2020 for high, average and low scenarios, (b) stormwater runoff, (c) evapotranspiration and (d) infiltration within the development model 2000, BAU model 2030, conventional WSUD model 2030 and combined WSUD model 2030 in high, average and low rainfall scenarios

The impact of urban development in increasing the stormwater runoff and reducing the evapotranspiration and infiltration was observed in all the models in 2030 compared to the development model 2000 under all three rainfall conditions (Figure 4-5). In particular, under high rainfall conditions, the stormwater runoff increased by about 3 GL/yr and the infiltration and evapotranspiration reduced by about 1 GL/yr and 0.5 ML/ yr, respectively in all the models of 2030 than that of the development model 2000. The finding was similar to the previous researches (Heaney, et al., 2002; Haase, 2009; Miller, et al., 2014).

Regardless of the rainfall conditions, the combined WSUD model showed the best performance in managing stormwater to accommodate future development among all three models (i.e. BAU 2030, conventional and combined WSUD 2030) (Figure 4-5). In the comparation to BAU 2030 model, under average rainfall conditions, combined WSUD 2030 reduced by 0.33 GL/yr of stormwater and increased the infiltration and evapotranspiration by 0.19 ML/yr and 0.33 GL/yr, respectively. More importantly, combined WSUD 2030 exhibited better stormwater management capacity under high rainfall conditions in comparison to BAU 2030. With high rainfall conditions, combined WSUD 2030 reduced by over 0.51 GL/yr of stormwater runoff and increased the infiltration and evapotranspiration by 0.30 ML/yr and 0.51 GL/yr, respectively. The conventional WSUD model also reduced the stormwater runoff and increased the infiltration and evapotranspiration compared to the BAU 2030 model. However, the reduction of stormwater runoff and increase of infiltration and evapotranspiration of the conventional WSUD was about 20-30% lower than that of the combined WSUD. This implies the combined WSUD projects have the capability to host more water in the soil, mitigate stormwater runoff and increase the evapotranspiration through the combined WSUD model.

4.4 Discussion

The urban development dramatically changed the land use in the Upper Caddies Creek catchment with over 68% - 87% of ground land being developed from 2000 to 2030. This land change greatly increased the imperviousness rate, thereby impacting the hydrological cycle of the catchment. From 2000 to 2030, the stormwater runoff is excepted to increase by around 1,340.93 ML/yr if no action is taken. The increased stormwater runoff is more likely to turn into overland flow flooding, causing serious damage to the catchment area. Moreover, the infiltration and evaporation of stormwater are also reduced due to the urban development from 2000-2030, which would further impact the groundwater level and the water cycle. Generally, the frequency and duration of stormwater runoff are usually affected by the rainfall and the land cover, rather than antecedent conditions (Syed, et al., 2003; Gallo, et al., 2013). Thus, the changes in the water cycle in the catchment is likely caused by:

1. Higher road and intersection percentage would form part of the overland flow system, which was around 20.54% (254 ha) of surface land in the study site used for transportation. The concrete and asphalt surface are impervious and results in a large amount of runoff.
2. Commonly, in the urban catchment, the existing stormwater pipe network is designed to collect stormwater runoff to meet old conveyance and flood immunity targets in accordance with the city planning scheme. However, the growth of cities

changed the imperviousness fraction significantly, and the higher density of impervious land will cause more stormwater discharge to the stormwater pipeline network (Gallo, et al., 2013). Without any implications of the water-sensitive designs, more stormwater runoff will lead to more frequent overland flow flooding issues.

3. The high density of impervious channels would decrease the stream channel storage and at the same time, groundwater infiltration will decrease (Gallo, et al., 2013). This study assumed that there would be more stormwater runoff generated in the hydroline system due to most of the stormwater renewal program, which will be changed to lined drains (concrete or rock bottom).

To mitigate the stormwater issues, two approaches were proposed in this study, namely conventional WSUD projects and combined WSUD projects. Although both conventional and combined WSUD projects reduced the stormwater runoff and increased the infiltration and evaporation in comparison to BAU 2030 models, combined WSUD projects showed better performance. The reduction of stormwater runoff and increase of infiltration and evaporation in combined WSUD was about 20-30% higher than that of the conventional WSUD. Furthermore, combined WSUD projects were much more efficient per unit in stormwater runoff reduction. For example, while 7.1% (87.92 ha) of catchment shifted to the combined WSUD area in this study, stormwater runoff reduction level was equivalent to 35.5% (439.60 ha) of the catchment changed to conventional WSUD area. Therefore, the combined WSUD model could be much more efficient than an equivalent conventional WSUD model, even if they had the same WSUD treatment areas. This is due to the linear connection with stormwater pipes in the combined WSUD projects, which provide the pathway to link separated WSUD projects with the existing waterway or stormwater pipeline network, thereby greatly reducing the imperviousness level of the catchment.

Generally, a lower imperviousness level corresponds with less stormwater runoff and higher storage capacity in an area (Gori, et al., 2019). For instance, in soil science, storage capacity is the amount of water held in well-drained soil (low imperviousness) by capillarity after access water has drained away by gravity and the rate of downward movement has materially decreased (Ball, et al., 2019). At the same time, if the amount of rainfall exceeds the storage capacity of the soil, it will lead to more stormwater runoff and then overland flooding (Gori, et al., 2019). In this case, the linear connection of these conventional WSUD implementations with the stormwater pipeline network in the combined WSUD projects could reduce the stormwater runoff by over 514 ML/yr more than stormwater runoff reduction of 390 ML/yr in the conventional WSUD model (compared to the BAU model).

4.5 Conclusion

This study for the first time proposed the combined WSUD model and evaluated the performance of combined and conventional WSUD models in accomodating the future development in a medium to large urban catchment through the modern geotechnical tools and water mass balance tool. This leads to the following conclusions:

- The urban development from 2000-2030 in the catchment increased the impervious fraction from 74.34% in 2000 to 83.84% in 2030 if additional WSUD is not implemented. This leads to about 1,340 ML/yr more stormwater runoff, which could cause serious flooding within the catchment.

- Conventional and combined WSUD both reduced the stormwater runoff and increased the infiltration and evaporation. However, the performance of combined WSUD was about 20-30% higher than that of conventional WSUD.
- The combined WSUD model presented the best performance in the stormwater management system under all rainfall scenarios, including high rainfall, average rainfall and low rainfall scenarios. It demonstrated a great potential to be applied while planning projects to improve hydrological performance through the shift of the impervious fraction.

Chapter 5 Impacts of site real-time adaptive control of water-sensitive urban designs on the stormwater trunk drainage system

Related publication:

Xuli Meng, Xuan Li, Allan Charteris, Zhenyao Wang, Mu. Naushad, Long D. Nghiem, Huan Liu, Qilin Wang, 2023. Impacts of site real-time adaptive control of water-sensitive urban designs on the stormwater trunk drainage system. *Journal of Water Process Engineering*, Volume 53, p. 103656.

5.1 Introduction

Currently, WSUD implementations are widely adopted (Fogarty, et al., 2021) in both regional scale treatments (natural and artificial wetlands, lakes, and basins) (Meng & Kenway, 2018) and site scale treatments (water tanks, green roofs, and green fences) (Moravej, et al., 2021). At the regional scale, bio-systems are one of the most commonly used WSUD technologies in Australia (Peña-Guzmán, et al., 2017; Zhang, et al., 2021). Stormwater from a regional scale catchment (between 1ha to 50ha) is conveyed to a bio-basin system for the water quantity and water quality control, such as artificial wetland, bio-retention basin, bio-detention basin, and bio-swale. These bio-basin systems could collect and treat a large amount of stormwater runoff at the same time. However, when more clean runoff water (roof water) flows to the bio-systems, there is a high possibility for the runoff water overflowing directly from the bio-systems into the natural waterways without treatment. As a result, developing a new way to reduce clean runoff water (roof water) is in high demand.

5.1.1 Conventional Water Sensitive Urban Design (WSUD)

Increasing climate variability and population levels mean that many areas of the world are facing serious water shortages. In response, researchers have highlighted that WSUD would be not only a solution to urban stormwater management (Cheah, 2006; Meng & Kenway, 2018), but also an alternative source of water in cities, a dual purpose that is becoming more important as water restrictions become more widespread (Thomson & Newman, 2018). Stormwater as an alternative water source is relatively simple to reuse through WSUD and to treat to potable standards (Wong & Brown, 2009). WSUD is a set of principles that can be applied to manage water, providing opportunities for developers sustainably, water authorities, and local communities to minimize the negative impacts of developments by integrating them with the area's natural features (Wong & Brown, 2009; Lottering, et al., 2015; Nasir, et al., 2022; Lin, et al., 2023). This chapter will focus on stormwater runoff management, especially for clean runoff water (roof water) management on the site scale.

In WSUD site scale options, a stormwater harvesting tank is a common solution to hold more stormwater runoff. Stormwater harvesting tanks delay the rain that runs off roofs from entering stormwater drains under the streets (Duan, et al., 2016; Meng & Kenway, 2018). In newer areas, stormwater drains have been engineered to receive stormwater runoff from the whole street. In some older areas, as the number of dwellings per street rises, the extra pressure placed on stormwater infrastructure often means that local government authorities require further stormwater detention systems to cope with the increased inputs (Moravej, et al., 2021). Usually, rainwater from roofs rushes into the stormwater system within a couple of minutes; if the drains are already at full capacity, this runoff will flow directly to the waterway as an overland flow. When a stormwater harvesting tank is installed, the roof water drains into the tank and is stored for future use, or may be permitted to drain out slowly (via an orifice outlet) into the stormwater drains. In this manner, the water may take hours to get into the drains (Duan, et al., 2016). Generally, onsite rainwater harvesting and stormwater soil infiltration (where soil type permits), evapotranspiration, and recycling work together to limit the undesirable changes caused by urbanization to the hydrologic regime of natural waterways (Rogers, et al., 2020). Thus, WSUD leads to a reduced need for water extraction and stormwater to natural waters (Castonguay, et al., 2018).

Current research shows that WSUD options could reduce stormwater runoff in most rainfall events (Fletcher, et al., 2013). However, the reduction of runoff by WSUD treatment options is currently limited (Jamali, et al., 2020), because during very frequent rainfall events, WSUD facilities fill quickly and lose their stormwater storage and delay capability. Developing a new stormwater control system is a challenge for water management due to the rapid increase in storage demand and limited space to install more stormwater harvesting systems. This chatpter selected a developed area from Sydney, Australia, to model a newly developed real-time adaptive control system (RACS) without installing more stormwater harvesting infrastructure (Meng, 2019)+. Installation and real-world testing of this system would require only minor modifications to the existing WSUD infrastructure.

5.1.2 Continuous monitoring and adaptive control (CMAC) method

A real-time control technology, continuous monitoring and adaptive control (CMAC) system was installed and tested in the City of Philadelphia (USA) in a 2017 CMAC system installation for the Philadelphia Water Department (Wright & Marchese, 2018). This was further demonstrated in Brooklyn, New York (Marchese, et al., 2019), using data from the local weather forecast and field-deployed sensors (e.g., water level sensors) to automatically control stormwater release rates in real-time to better prepare for and respond to precipitation events.

Regional scale stormwater harvesting with CMAC is a combined software and hardware solution for weather forecast-integrated real-time control of stormwater storage assets at a district level (Xu, et al., 2021). CMAC studies have focused on regional runoff management to the stormwater trunk drainage system, such as a basin, lake, or wetland. There is an opportunity to develop a new control system and clarify the effects of continuous monitoring and adaptive control on site-scale runoff water management.

5.1.3 ILSAX2 method

This chapter chose the ILSAX2 method to examine excess flow and storage capacity changes in the local trunk drainage system. ILSAX is a dynamic method that runs hydraulic grade lines on a surface (above-grate) level and a subsurface (below-grate) level system, which Geoffrey O'Loughlin developed in 1983 (O'Loughlin, 1986).

As an advanced dynamic stormwater model, ISLAX2 (developed from ISLAX with more specific infiltration-runoff factors) calculates catchment hydrographs and performs unsteady flow hydraulic computations on drainage networks (Ball, et al., 2019). The rainfall runoff and loss methods supported include the time area unit hydrograph with Horton infiltration (from runoff) (Natarajan & Radhakrishnan, 2019). Horton infiltration defines four soil types: (1) low runoff potential, high infiltration rates (consisting of sand and gravel); (2) moderate infiltration rates and moderately well-drained soils; (3) slow infiltration rates (may have layers that impede downward movement of water); (4) high runoff potential, very slow infiltration rates (consists of clays with a permanent high-water table and a high swelling potential) (QUDM, 2018).

For the impervious area,

$$\textit{Excess rainfall} = \textit{total rainfall} - \textit{evapotranspiration} \quad (Eq.\ 5\text{-}1)$$

For the pervious area,

$$\textit{Excess rainfall} = \textit{total rainfall} - \textit{evapotranspiration} - \textit{infiltration} \quad (Eq.\ 5\text{-}2)$$

In the hydrology part: runoff starts when the excess rainfall depth exceeds the storage capacity; further, runoff starts from impervious areas first (no infiltration, small storage and short time of concentration) and then from pervious areas (Engineers Australia, 2006; Commonwealth of Australia, 2019). Reliable estimation of the hydraulic performance of drainage systems is one of the most important aspects of stormwater drainage design (Mcpherson, 1973; Larock, et al., 2000). To achieve accurate hydraulic analysis, it is imperative that the designer has the correct design information and makes appropriate assumptions regarding the behaviour of the drainage system over its operating lifetime through a dynamic hydrology and hydraulic method, ILSAX2 (Larock, et al., 2000; 12d Solutions, 2021).

5.2 Methods

5.2.1 Data collection

This project selected the Upper Caddies Creek catchment (Figure 5-1) as the study area to test Meng's real-time adaptive control systems on site scale because it is a developed urban catchment with high stormwater storage demand (Meng, 2019). The current project area is highly modified due to urban development with many fluvial erosion and deposition areas. Subsoils are saline, and this is evident in surface scalds where water tables are close to the surface (Office of Environment and Heritage, 2018). Like other new residential development areas in Sydney, the Upper Caddies Creek catchment is a very important area in which to manage stormwater well, as the city plans to settle more than 10,000 new residents there in the next 20 years (Sydney Water, 2019).

As land use has changed from pre-development bushland with variable perviousness to urban properties with high imperviousness rates, the developed areas have poor performance in buffering and storing runoff. Consequently, flooding - especially overland flow flooding - has occurred more and more frequently. The other stormwater-related issue in the Upper Caddies Creek catchment is uneven rainfall, where the existing stormwater harvesting system cannot provide enough capacity. As a result, large amounts of stormwater runoff flow directly to the natural waterway (Upper Caddies Creek) in this highly developed area.

This chapter identifies the catchment boundary and calculates the land's pervious/impervious rate using the latest version geographic information system (GIS) and Digital Elevation Model (DEM) tools (ArcGIS 10.6.1) (Figure 5-1). The new catchment boundary combined the natural topography condition and human development information to identify the catchment boundary.

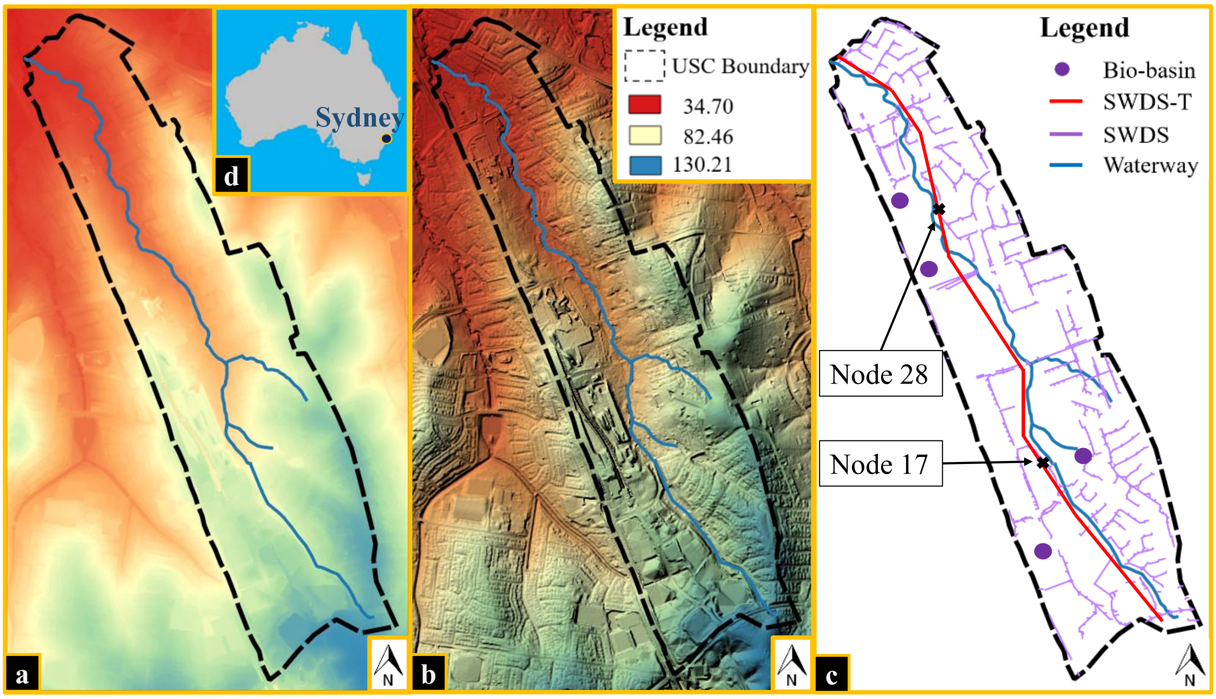

Figure 5-1 Upper Caddies Creek catchment (soil type: high runoff potential, very slow infiltration rates) in (a) Digital Elevation Model (DEM) (Geoscience Australia); (b) DEM with contour shading; and (c) the stormwater drainage network with WSUD implementation. Note: SWDS-T = stormwater trunk drainage system

The study area includes developed and undeveloped lands: the developed area comprises high-rise apartments, townhouses, standalone residential houses, and commercial and industrial buildings; the undeveloped area includes open space areas, parks, natural waterways, gardens and natural land. To generate an accurate imperviousness rate for different land areas, this project separates building roofs and concrete driveways from gardens within the developed area to establish an imperviousness rate for the identified clusters. This method can increase the accuracy of performance in hydraulic and hydrology calculations, compared to assigning an imperviousness rate to a whole catchment. Figure 5-2a presents a mixture of two main existing stormwater harvesting methods in the catchment area: regional-scale stormwater harvesting through basins or lakes; and site-scale stormwater harvesting through water tanks. Both basins/lakes and tanks connect with the stormwater trunk drainage system through the local drainage system.

The study area is around 319 ha, including a very high imperviousness rate area (65.5 ha), a high imperviousness rate area (206.1 ha), and a low imperviousness rate area (47.5 ha). The high imperviousness rate area includes a 5,300m major road - Old Windsor Road (the A2) from Norwest Boulevard crossing to Windsor Road crossing - and two train stations (Kellyville and Bella Vista). The whole catchment has a big demand for stormwater storage because the existing natural waterway can no longer provide enough water storage capacity after the rapid development in this area.

Table 5-6 Land use in Upper Caddies Creek catchment

Cluster	Land use	Area (ha)	Area (%)
1	Highway, road and intersections	65.5	20.54
2	Developed area	206.1	64.58
3	Hydroarea, hydroline and open space	47.5	14.88
Total		319	100%

1 ha = 10,000 m^2

5.2.2 SRAC method

This chapter has refined an innovative SRAC (Site Real-Time Adaptive Control) method based on site control technologies to manage two clusters of stormwater storage facilities in the catchment: one is regional scale basins and lakes; the other is site scale water tanks (Meng, 2019). Like CMAC, SRAC is a system solution based on a cloud computing platform that incorporates input from onsite sensors, weather information, data analytics, and artificial intelligence (AI) to give new life to isolated stormwater infrastructure, especially to manage storage capacity more efficiently and dynamically (Meng, 2019).
A conventional stormwater harvesting tank is developed from the rainwater tank, from the detention purpose, it is designed to slow down how fast the rain runs off the dwelling roof into the SWDS during the low rainfall event (Kändler, et al., 2020). Unlike conventional stormwater harvesting applications that cannot catch new rainfall if they are full after the previous rain, the SRAC model's 'smart' stormwater runoff management is based on real-time precipitation forecasts. So the SRAC model could provide more stormwater runoff storage capacity between two continuous rainfall events. As an example, based on a government rainwater tank field study in Sydney, new houses complying with building standards had, on average, a 210 m^2 roof area connected to a 4,200 L rainwater tank in the study area as the primary design feature (State of New South Wales, 2011).

This chapter is only focusing on the water level and water flows studies under very frequent rainfall events because the study assumed to use the existing stormwater harvesting tanks (average size 4,200 L) in the study area rather than introduce new harvesting systems, also the current research assumed all roof water will be collected and stored in the stormwater harvesting systems under the SRAC model. In a 24 mm rainfall event, assuming the first 4 mm is the initial loss, the capture of stormwater harvesting tank roughly equals 1h1EY of rain (the single rainfall event of 1h1EY is 24.5 mm in the Upper Caddies Creek area), that is, 210 m^2 of connected roof space x 20 mm of rainfall = 4,200 L. When the 1h1EY level rainfall starts, the water tank will fill. If more precipitation is forecast, the SRAC model will send the command to release the water from the tanks (using system-connected valves), then the stormwater harvesting tank system will be fully or partially empty and ready to catch the precipitation from the next rainfall. Without a doubt, if the SWDS considers the site rainwater tanks as part of the stormwater harvesting and storage system, the SRAC model could assist in providing greater stormwater storage capacity for future rainfall events.

In some areas (developed over 30 years), the rising number of dwellings per street places extra storage pressure on stormwater infrastructure (Sydney Water, 2019). At the same time, 82% of local residents have installed rainwater tanks (Meng, et al., 2022), which provides an opportunity to upgrade the rainwater tanks to stormwater harvesting tanks controlled by the SRAC method. Such a site-scale stormwater harvesting SRAC system would include the computer-controlled valve, pressure transducer and control panel for bidirectional communication (Figure 5-2).

The control logic of the SRAC model is presented in Figure 5-2. The cloud computing platform developed by Meng plays an essential role in the SRAC model (Meng, 2019). The software evaluates individual site data (e.g., water level, the distance from the stormwater harvesting system to the trunk drainage system) and the local precipitation forecast to make real-time decisions about flow control through the actuated valve. When stormwater harvesting tank needs to store more runoff water from the future storm, the system will send the command to valve to release stored water before more rain from the stormwater harvesting tank.

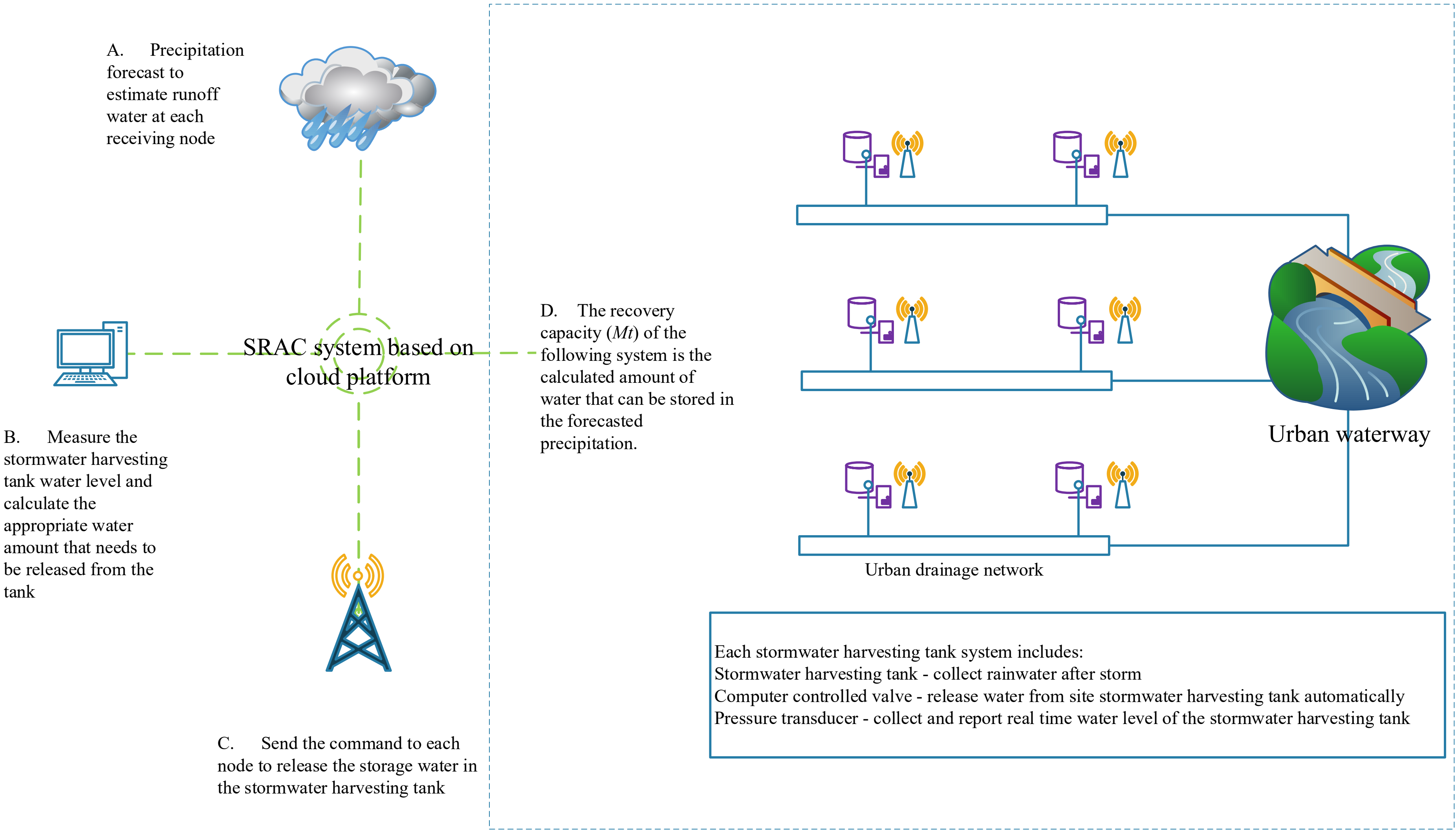

Figure 5-2 The control logic of the SRAC model developed from Meng's real-time adaptive control system (Meng, 2019)

5.2.3 Conventional WSUD and the SRAC-WSUD model

The water level in stormwater harvesting is a function of size, the amount of water captured by connected catchment areas, and the amount of outflow of the harvesting system. This is reflected in the following mass balance equations. In the conventional WSUD model (Figure 5-3a & 5-3c):

$$Volume_{time} = Volume_{time-1} + Inflow_{time} - Outflow_{time} - Excess_{time}$$

$$V_t = V_{t-1} + I_t - O_t - E_t \quad (Eq.\ 5\text{-}3)$$

In the SRAC-WSUD model (Figure 5-3b & 5-3d):

$$Volume_{time} = Volume_{time-1} + Inflow_{time} - Outflow_{time} - M_{time} - Excess_{time}$$

$$V_t = V_{t-1} + I_t - O_t - M_t - E_t \quad (Eq.\ 5\text{-}4)$$

where V_t and V_{t-1} are the storage volume at the end of the current and previous time-steps, respectively. I_t is the current volume of captured water from connected areas (roof areas are connected to tanks; other surface areas are connected to a basin or lake), O_t is the outflow from the stormwater harvesting system for recycling use or other demand (the project scope excluded supply-demand matrix or reuse & recycling matrix studies). M_t which was named by the first author's family name MENG, represents the recovery capacity in the stormwater harvesting tank systems between two continuous rain at the same point (Figure 5-3) (Meng, 2019). The methodology to calculate the M_{time} (M_t) in this chapter is to assume all runoff water will be collected and discharged to the trunk drainage network. The water amount between the total outfall volume (m^3) is the recovery capacity from the stormwater harvesting tank systems.

The general mass balance describes the change over time and includes inflows and outflows from the control volume; formula 4 describes a mass balance in the SRAC-WSUD model, which considered two continuous rainfall at the same location. *R* is the release water in the SWSUD model which occurs before and after rain, and E_t is the current excess water that flows into the SWDS when the tank storage capacity is exceeded.

The amount of water released to the SWDS depends on the precipitation forecast; if more rainfall is forecast, the SWSUD model will release more stored water (R_t and R_{t-1}) to prepare a bigger capacity in the stormwater harvesting systems, and vice versa. R_t is based on the Bureau of Meteorology (BOM), Australian Government rainfall forecast (less than one day) and R_{t-1} is based on the BOM's rainfall forecast data (above one day). S is the storage amount for demand use during the rainfall event. To clarify the influence of M in the SRAC model, the authors refine the formula to calculate M (Meng, 2019).

$$M_{time} = Volume_{time-1} - Rain\ forecast_{time-1} - Rain\ forecast_{time} - Storage\ for\ use$$

$$M_t = V_{t-1} - R_{t-1} - R_t - S \quad (Eq.\ 5\text{-}5)$$

Figure 5-3d presents three time periods in the SRAC model, before rain, during rain, and after rain. During the after-rain period, the valve would release harvested stormwater when the cloud platform sent a command to the real-time control release valve. If the predicted rainfall is higher than 1EY rainfall event, the SRAC will release all stored water from the harvesting system. If the predicted rainfall event is less than 1EY rainfall event, the volume of the release water should be close to that rainfall. Generally, the control logic is configured to discharge water in advance of storm events if necessary to create storage capacity, minimize discharge during storm events, withhold water directly after storm events to allow the downstream stormwater trunk drainage system to regain the capacity, then release water after rain.

5.2.4 Parameters in the study design

To simulate the SRAC-WSUD method, this study introduced a 2,526 m stormwater trunk drainage system (SWDS-T) along the natural waterway (Upper Caddies Creek) to study the influence of drainage system conveyance capacity through hydrology and hydraulic indicator factors (Figure 5-1c). This SWDS-T included a total of 36 nodes and 1 outlet. Five impact factors - excess flow, local flow, all inflow, all outflow and net flow - were selected to analyze at two points on the stormwater trunk drainage system: node 17 (upstream) and node 28 (downstream). The outflow was represented by the flow from the outlet, which is downstream of node 36 Local flow was represented by the flow for each of the 36 nodes in the stormwater trunk drainage system.

The study applied ArcGIS 10.6.1 to analyze spatial data and geomatic information. It used ILSAX2 method to simulate the Hydrological-Hydraulic performance of the SWDS in both conventional WSUD and SRAC-WSUD models through the software 12d Model (Version 14 C2k), as 12d Model provides comprehensive tools for the design, analysis and optimization of stormwater projects using dynamic (hydrograph) and 2d drainage methods (12d Solutions, 2021).

The study obtained precipitation data from the Seven Hills (Collins Street) station (BOM). This chapter selected 1EY as the highest single rainfall event to test the SRAC model, because the average rainwater tank in the study area is 4,200 L. Therefore, the maximum rainfall that can be captured in 1EY rainfall (based on the average roof size of 210 m^2 is 24.5 mm).

To identify the effect of the SRAC-WSUD in a dynamic model, this chapter used the ILSAX2 method to analyze relevant hydrology and hydraulic impacts. The rainfall events in the study are 12EY, 4EY (98.17% AEP), 2EY (86.47% AEP) and 1EY (63.21% AEP)

(Engineers Australia, 2006; Commonwealth of Australia, 2019). The Intensity–Frequency–Duration (IFD) depth data at the study area are generated from BOM, they are eight rainfall event scenarios including 1h12EY (9.48 mm), 1h4EY (13.80 mm), 1h2EY (18.90 mm), 1h1EY (24.5 mm), 2h12EY (12.10 mm), 2h4EY (17.50 mm), 2h2EY (23.90 mm), 2h1EY (30.70 mm).

For the boundary conditions, the soil type in this chapter was set as high runoff potential with very slow infiltration rates based on the previous research in 2022 (Meng, et al., 2022). In the hydrology part, runoff starts from impervious areas first (no infiltration, small storage and short time of concentration) and then from pervious areas. At the same time, inlet capacity determines the flow from the surface SWDS to the subsurface systems. The inlet capacity calculations are performed on the pipe, or bypass route flows that arrive at or above the grate level. The invert level of the bypass or pipe inverts adjacent to the node determines whether the conduit belongs to the above- or below-grate system (Tran, et al., 2006).

This project selected very frequent rainfall event as the design target because the stormwater trunk drainage system in this chapter is designed to manage overland flow. Further, the current and previous rainfall events in a single simulation were set as same. For example, in the 1h12EY scenario, the current and previous rainfall events are both 12EY. To give an overview of the SRAC method, the authors introduced the SRAC-WSUD model to compare it with the conventional WSUD model. In the SRAC-WSUD model, the study assumed that stormwater harvesting technologies could release storage water in all rainfall scenarios in this chapter (from 12EY to 1EY) and provide enough capacity to capture forecasted rainfall; and stormwater harvesting facilities can collect and store all stormwater runoff from the site under all very frequent rainfall events, which rainfall targets were proved achievable in a recent rooftop rainwater harvesting research from Hu’s research team in 2019 (Hu, et al., 2019).

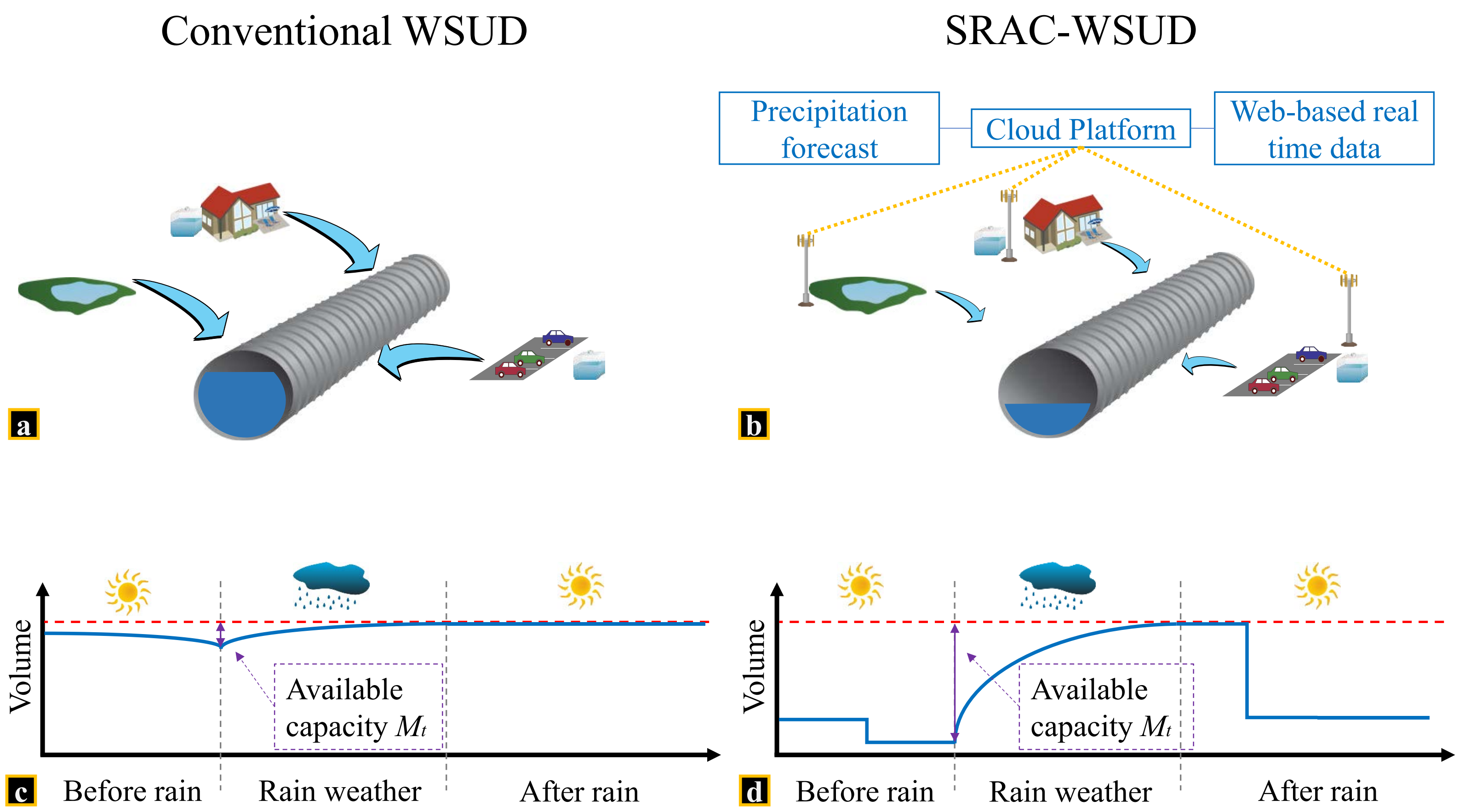

Figure 5-3 Concept of conventional WSUD and SRAC-WSUD models (a) SWDS catch and store more runoff water in the conventional WSUD model than the model with SRAC-WSUD; (b) with the SRAC-WSUD method, the SWDS receives less runoff water at any given time from the catchment; (c) water storage performance of individual rainwater tanks in the (c) conventional WSUD model and (d) SRAC-WSUD model

5.3 Results

Fig 3c & 3d show that the controlled method (SRAC-WSUD method) is better than the uncontrolled method (conventional WSUD) to improve urban stormwater management by reducing excess flow volume. Furthermore, the results from this chapter show that the SRAC-WSUD model would capture most of the stormwater runoff in all 12EY, 4EY, 2EY and 1EY rainfall events during both 1h and 2h stormwater periods. This concords with previous research showing that there will be less water flow to the SWDS if stormwater harvesting systems can always be emptied before storm events (Jamali, et al., 2020).

5.3.1 Influence of SRAC on excess flow

Comparing the conventional WSUD and SRAC-WSUD model results of different rainfall events (Table 2–3) shows that the SRAC method has a significant influence on the excess flow. Reducing excess flow reduces problematic overland flow and water ponding in the study area. SRAC reduced the excess flow (node flooding) issues under all very frequent rainfall events. In two minor flooding scenarios, 4EY and 2EY, the SRAC model completely eliminated excess flows. In the 1EY rainfall event, without the SRAC model, 15 (1h duration) and 14 (2h duration) nodes had excess flow issues; with the SRAC model, only 1 node experienced excess flow in each rainfall event. In tables 5-7 & 5-8, the reduced excess flow volume has a significant rise, from nil to 14,650 m^3 (1h1EY) and 11,272 m^3 (2h1EY) when the stormwater rainfall starts increasing, which means the SRAC model could mitigate the excess flow issue and hold more runoff water in the stormwater harvesting system between two continuous rainfall events. At the same time, in the SRAC-WSUD model, the total flooding volume also decreased by over 98% in these two events, with the greatest reduction in total excess flow in 1h1EY (14,650 m^3), compared with than 2h1EY (11,272 m^3).

Figure 5-4 to 5-7 shows that SRAC could assist the existing stormwater trunk drainage system to be restored back to pre-rainfall event functionality levels. SRAC modelling reveals that, depending on the initial conditions, the presence of the SRAC design may postpone the peak flow rate of outflow by approximately 10 min in 1h rainfall duration scenarios (for 1h2EY and 1h1EY) and 8 min in the 2h rainfall duration scenarios (for 2h2EY and 2h1EY). The excess flow was reduced 33% - 42% in these 16 scenarios (Figure 5-6 & 5-7). The outcomes would not only mitigate the overland flow flooding in the study area but also contribute to the flood resilience downstream, far beyond the outflow point. This will also provide valuable insights for future research on overland flow flooding.

5.3.2 Influence of SRAC on the storage volume and outfall volume

Comparison of the two model's average storage performance through the ILSAX2 method (Table 5-7 and 5-8) shows that the average storage volume was reduced by 27 - 59% in the 1h stormwater period and 40 -58% in the 2h stormwater period. At the same time, the average outfall flows and total outfall volume in the SRAC-WSUD model are lower than in the conventional WSUD model. The study found that the SRAC could reduce average outfall flow 36-50% and total outfall volume 42 - 50% in the 1h storm duration. In 2h storm duration, there was a 41 - 54% decrease in average outfall flow and

42 - 50% decrease in total outfall volume. These findings are similar to the flood mitigation performance of a WSUD study in Nanjing (Hu, et al., 2019).

5.3.3 Influence of SRAC for stormwater trunk drainage system

The project located in a high runoff potential area with very slow infiltration rates (Office of Environment and Heritage, 2018) and this chapter shows that the SRAC method could mitigate the overland flow issue in an urban catchment. Infiltration-excess overland flow develops when the rate of water input on the land surface is higher than the infiltration rate. Accordingly, storms can bring a large amount of rainfall to the study area in a very short period. Identifying the SRAC influence upstream and downstream of the stormwater trunk drainage system can help designers to manage stormwater runoff and reduce overland flow issues in this area. Two nodes were chosen to examine inflow and outflow discharge rates as well as net flow volume (Figure 5-4 to 5-7): node 17, upstream of the trunk drainage system; and node 28, which was selected from downstream (Figure 5-1c). In the same rainfall duration, the reduction ratios of local flow, all inflow and outflow, and net flow all decreased with the increase in precipitation.

Figure 5-4 to 5-7 show that the SRAC method could assist in restoring the existing stormwater trunk drainage system's capacity back to pre-rainfall-event functionality levels faster. SRAC modelling reveals that, depending on the initial conditions, the presence of the SRAC design postponed the peak flow rate of outflow by approximately 10 mins in 1h rainfall duration scenarios (for 1h2EY and 1h1EY) and 8 mins in the 2h rainfall duration scenarios (for 2h2EY and 2h1EY). The net volume was reduced between 33% and 42% in 16 scenarios. These outcomes would not only mitigate overland flow flooding in the study area but also contribute to flood resilience downstream, far beyond the outflow point.

Further, Figure 5-4 to 5-7 allowed comparison between flow information between conventional WSUD and SRAC-WSUD models. Generally, for the same rainfall duration, the reduction ratio of total inflow and outflow increased with increasing rainfall amounts. For nodes 17 and 28, the highest reductions in total inflow, outflow and net flow were achieved by the 2EY scenario during the 1h rainfall period, and by the 1EY scenario during the 2h rainfall period. This suggests that the SRAC method is performing stably in a shorter rainfall period.

Table 5-7 Hydraulic analysis results of stormwater trunk drainage system in 1h stormwater duration

Rainfall Scenarios (IFD depth)	Model	Nodes with excess flow	Total excess flow volume (m^3)	Reduced excess flow volume (m^3)	Average storage volume (m^3)	Average storage percentage full	Average outfall flow (m^3/s)	Total outfall volume (m^3)	M_t (m^3)
1h12EY (9.48 mm)	CWSUD	0	0	-	49.71	19.88%	3.88	23,820	-
	SWSUD	0	0	0	22.08	8.80%	1.73	11,830	11,990
1h4EY (13.80 mm)	CWSUD	3	600	-	85.88	33.88%	6.34	36,180	-
	SWSUD	0	0	600	35.06	14.13%	2.80	18,310	17,870
1h2EY (18.90 mm)	CWSUD	13	5,860	-	103.33	41.08%	7.98	46,550	-
	SWSUD	0	0	5,860	55.34	22.13%	4.26	26,110	20,440
1h1EY (24.5 mm)	CWSUD	15	14,830	-	114.66	45.88%	9.23	54,830	-
	SWSUD	1	180	14,650	82.63	32.50%	6.05	34,550	20,280

Table 5-8 Hydraulic analysis results of stormwater trunk drainage system in 2h stormwater duration

Rainfall Scenarios (IFD depth)	Model	Nodes with excess flow	Total excess flow volume (m^3)	Reduced excess flow volume (m^3)	Average storage volume (m^3)	Average storage percentage full	Average outfall flow (m^3/s)	Total outfall volume (m^3)	M_t (m^3)
2h12EY (12.10 mm)	CWSUD	0	0	-	30.48	12.22%	3.14	29,270	-
	SWSUD	0	0	0	14.15	5.72%	1.48	14,520	14,750
2h4EY (17.50 mm)	CWSUD	1	396	-	52.83	20.91%	5.15	44,390	-
	SWSUD	0	0	396	22.13	8.80%	2.35	22,260	22,130
2h2EY (23.90 mm)	CWSUD	14	4,537	-	67.80	26.91%	6.71	59,290	-
	SWSUD	0	0	4,537	33.87	13.58%	3.46	31,770	27,520
2h1EY (30.70 mm)	CWSUD	14	11,408	-	83.31	33.13%	8.23	73,030	-
	SWSUD	1	136	11,272	49.54	19.61%	4.84	41,930	31,100

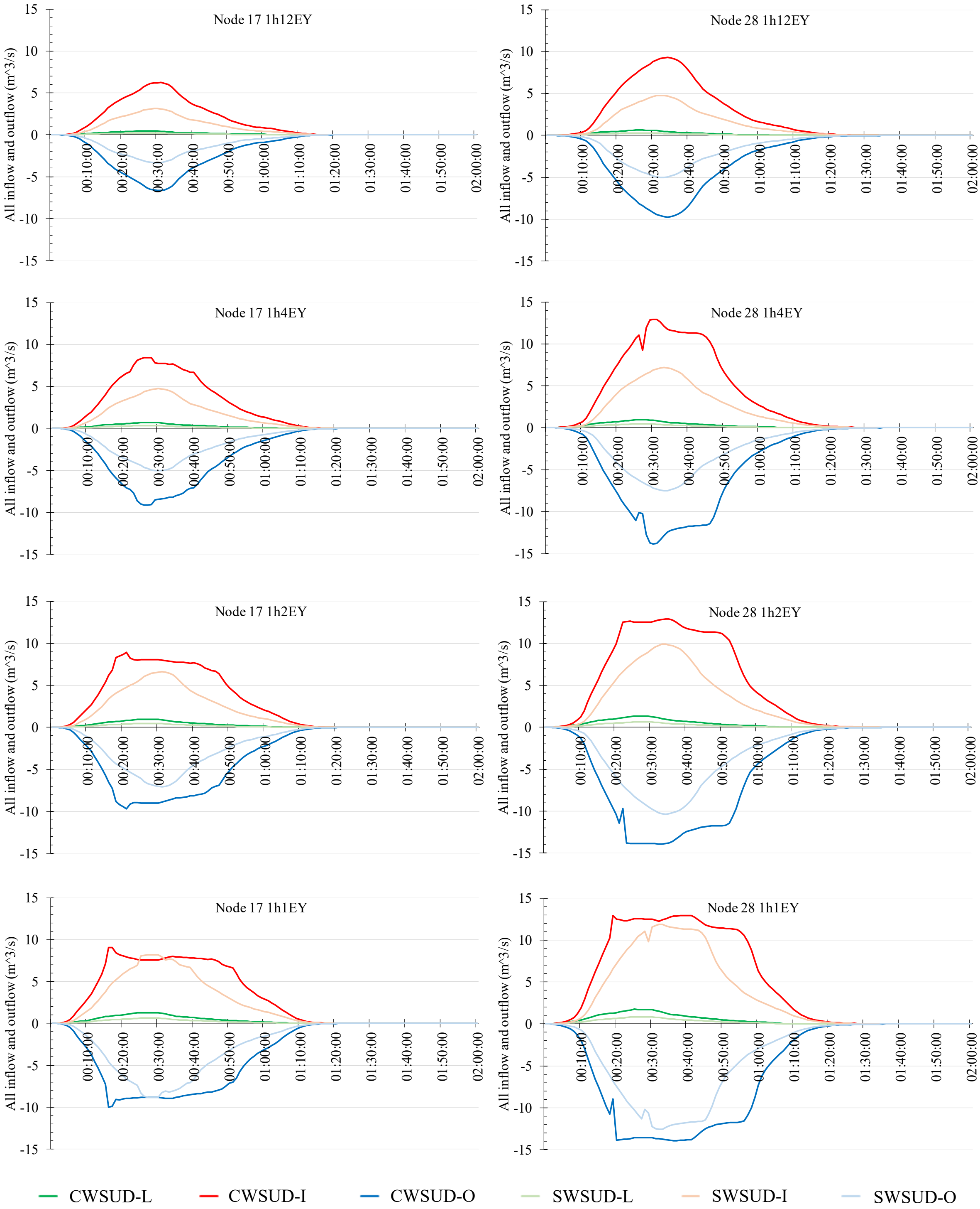

Figure 5-4 Local (L), inflow (I) and outflow (O) for node 17 (upstream) and node 28 (downstream) in CWSUD model (conventional WSUD) and SWSUD model (SRAC-WSUD) under 12EY, 4EY, 2EY and 1EY rainfall event (1h duration)

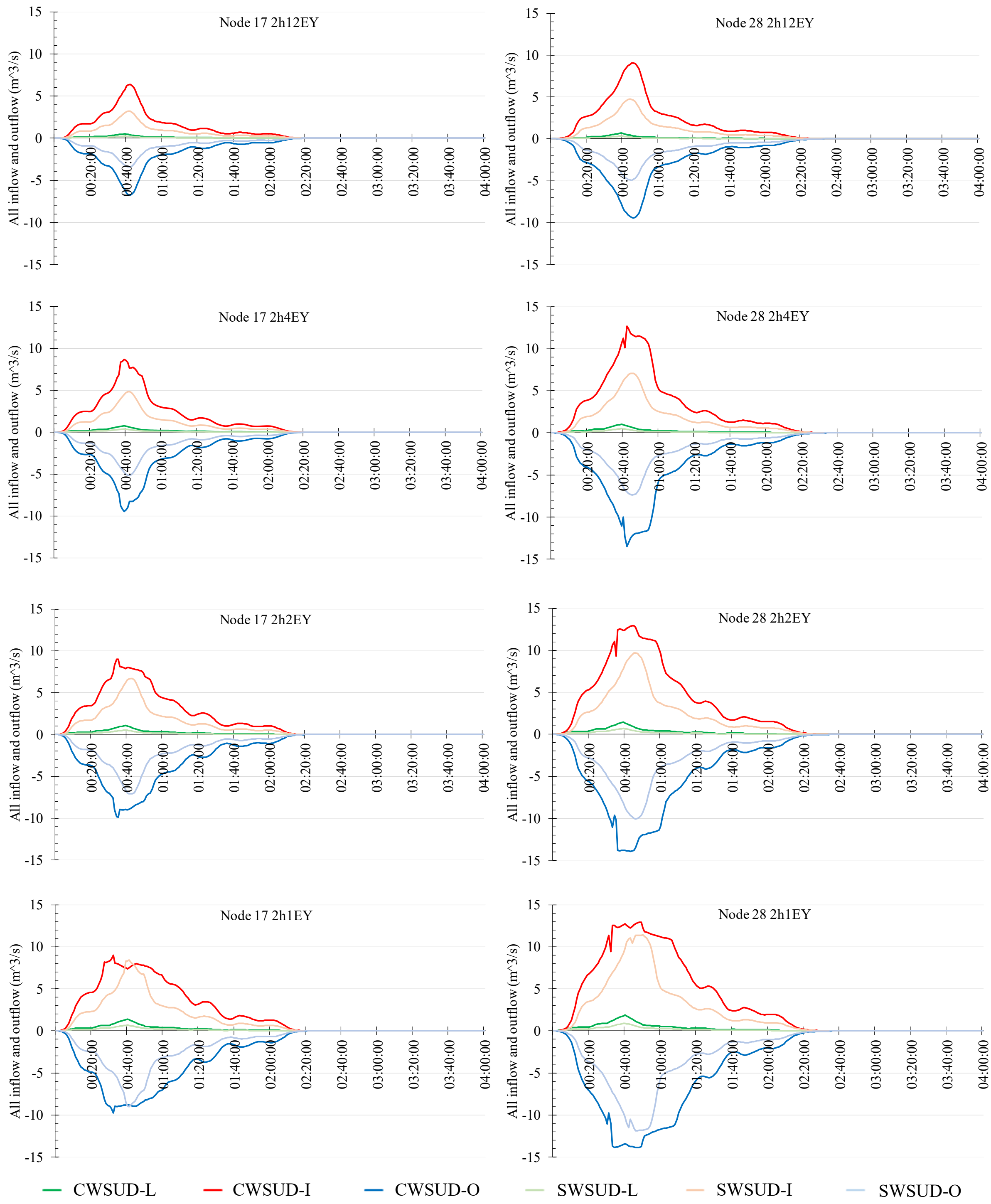

Figure 5-5 Local (L), inflow (I) and outflow (O) for node 17 (upstream) and node 28 (downstream) in CWSUD model (conventional WSUD) and SWSUD model (SRAC-WSUD) under 12EY, 4EY, 2EY and 1EY rainfall event (2h duration)

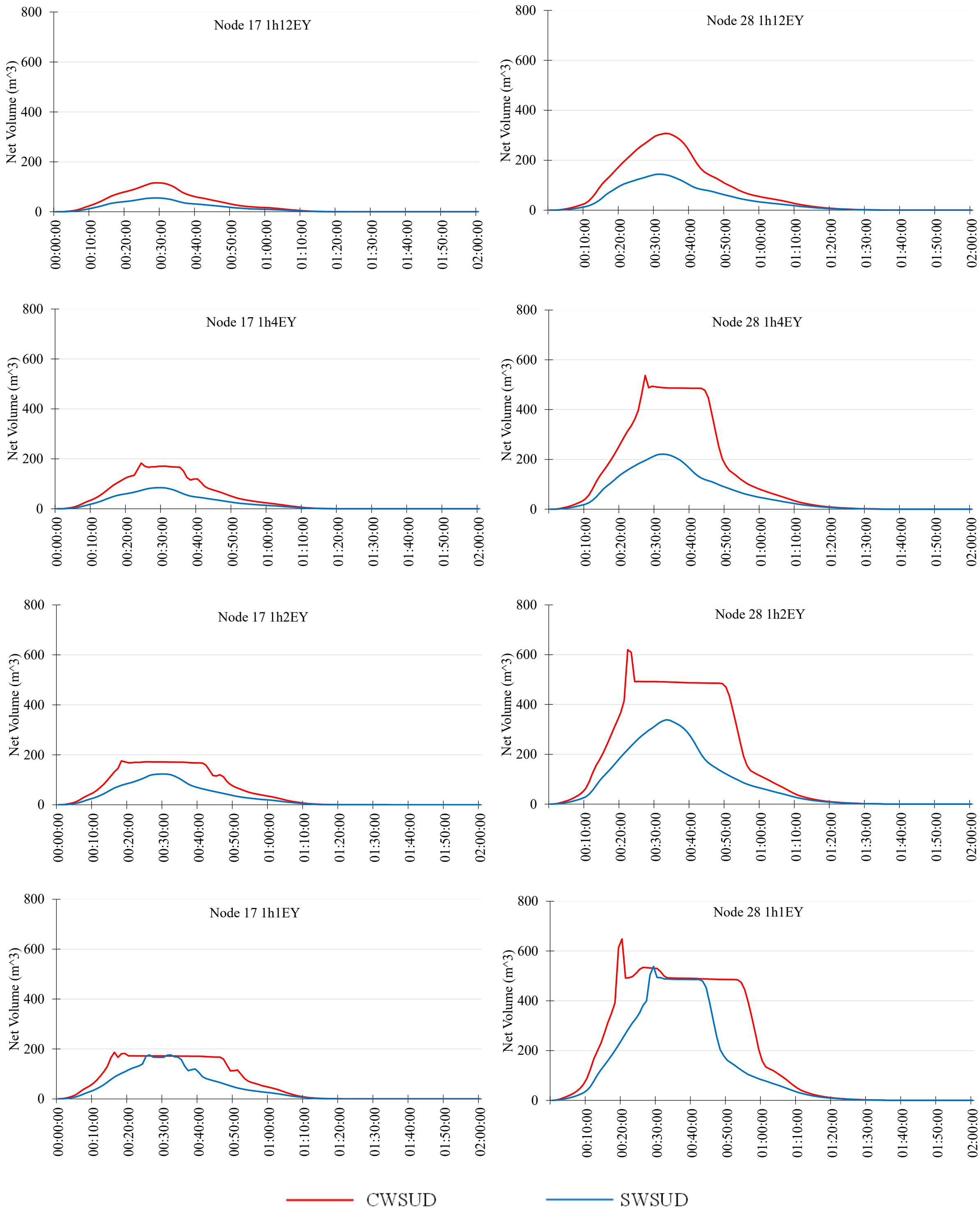

Figure 5-6 Net flow for node 17 (upstream) and node 28 (downstream) in CWSUD model (conventional WSUD) and SWSUD model (SRAC-WSUD) under 12EY, 4EY, 2EY and 1EY rainfall event (1h duration)

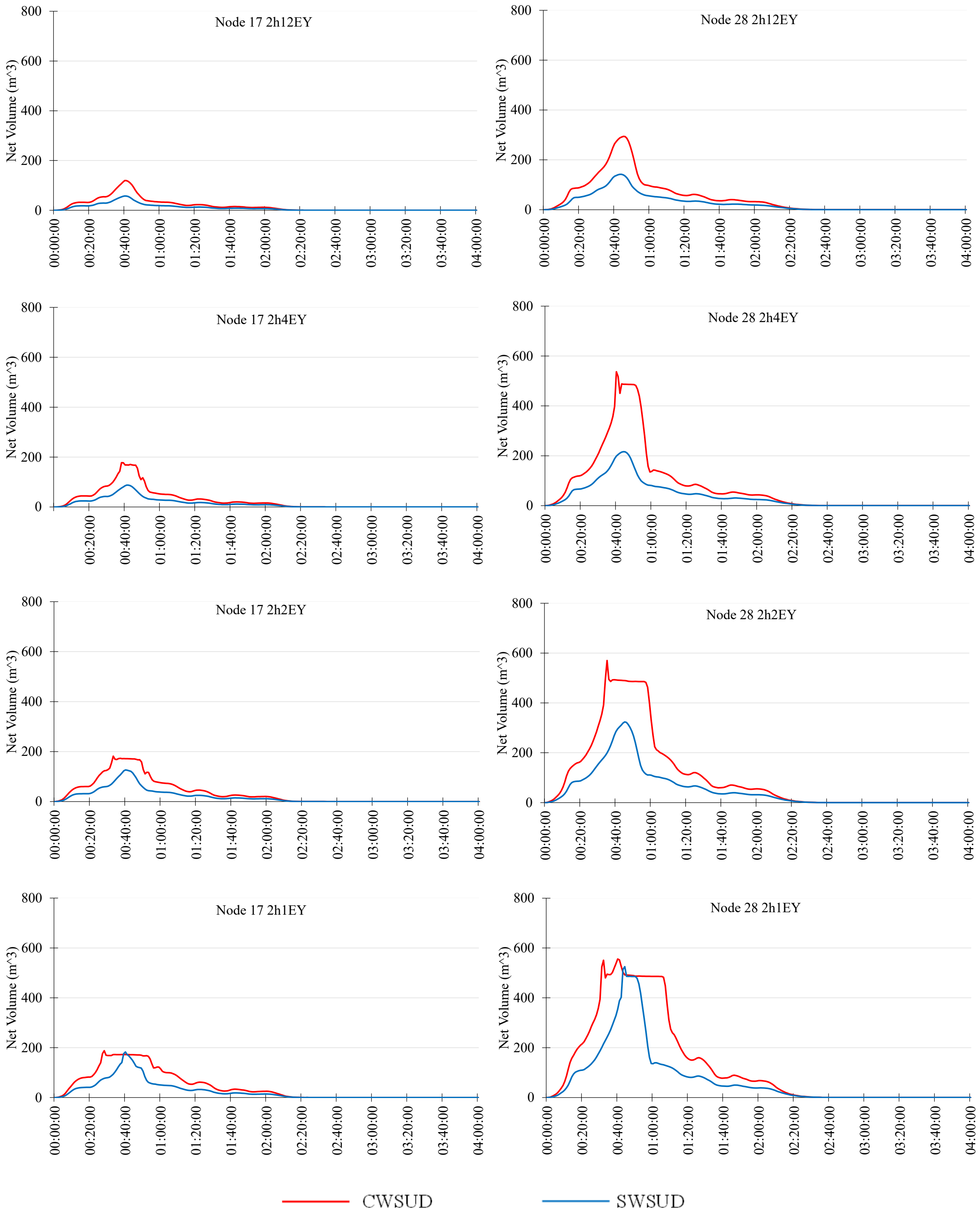

Figure 5-7 Net flow for node 17 (upstream) and node 28 (downstream) in CWSUD model (conventional WSUD) and SWSUD model (SRAC-WSUD) under 12EY, 4EY, 2EY and 1EY rainfall event (2h duration)

5.4 Discussion

5.4.1 SRAC in stormwater runoff management

Most overland flow flooding occurs whenever the surface water at a node exceeds the maximum defined inlet capacity. The capacity of the trunk drainage system is one of the variables that should determine the potential of runoff transport in an urban drainage system. As a result, when a node's inflow exceeds the outflow, the excess flow will occur, which is a flood. In general, junction flow (excess flow from the pipeline's node) and pressured pipeline flow (such as net flow-storage capacity at each node, and total outfall volume) in the drainage system are two indexes for urban flood forecasting. At the node level, overflow will cause inundation around the junction area. When the pipeline is close to full of water, the local node will overflow; thus, the pipeline may need to be enlarged. On a regional scale, traditional quantitative studies on stormwater management systems' resilience to flooding used a drainage-based approach (Meng, et al., 2022). They focused on the hydraulic reliability of large water storage systems in the urban drainage network, such as basins and lakes. Therefore, site-scale designs (primarily rainwater tanks) have not been taken into account under an overarching method, as the recovery capacity under the conventional WSUD model is negligible. SRAC is an innovative method for quantifying the resilience of stormwater management systems and minimizing the disturbance of the system during floods (Valizadeh, et al., 2019). Importantly, this chapter is the first time to prove that the SRAC method redistributes flows toward functional parts of the system, and minimizes the time required for the stormwater trunk drainage system to recover to its normal capacity to absorb the surface runoff produced in rainfall events. As a consequence, the SRAC modelling shows the reduction of surface runoff is particularly prominent for the simulations carried out with saturated conditions, while under the initial unsaturated conditions, the peak discharges are delayed, and their magnitudes are smaller. A recent review (Meng, 2022) has noted the importance of the initial conditions for simulations of hydrology and flood resilience and pointed out that aspects of their relationships remain understudied. The findings presented in this chapter help to address this important research gap. The chapter also used a new indicator factor - the recovery capacity (M_t) - to identify the extra storage capacity in the trunk drainage system created through the comparison of total outfall volume between conventional WSUD and SRAC-WSUD models (Table 2 - 3). The results show that urban development in the study area has caused higher peak flow rates and higher occupation volumes in the stormwater trunk drainage system. These results would normally trigger enlargement of the stormwater trunk drainage system, but do we have available land to build this infrastructure? In the new SRAC model, because both the inflow-outflow rate and net volume decreased at the same time, less overland flow flooding would occur.

According to the results, peak flow increased with an increasing return period, but because of only the low level of rainfall (very frequent rainfall event) was studied in this chapter, no overflow was forecasted in all of the nodes in the trunk drainage system. The next stage of research should introduce more rainfall events to study the overflow and mitigation effects.

Furthermore, in this model, the amount of M_t depends on the tank's storage capacity, and the length of time to release the storage water between two continuous very frequent rainfall events. The detailed performance of M_t for the individual stormwater harvesting system needs to be clarified in future analysis.

5.4.2 Reduce river flood risk with SRAC implementation

Within a broader stormwater management system for a river catchment level, this chapter demonstrates that SRAC-WSUD would increase the accuracy of forecast river levels and flood extents. As shown in Figure 5-2, the runoff water would finally flow to the urban waterway, which is part of a creek or river.

Currently, it is difficult to forecast the water level (river height) in a flood because the rain that has fallen on a catchment takes time to travel to the outlet of the catchment, and river flow downstream of the catchment within a certain period will largely be influenced by rain that has already fallen on the catchment and been observed. This means that the river flow forecast between the very frequent rainfall event period will be reasonably accurate. River flow forecasts beyond this period will be less accurate, as it is necessary to use rainfall forecasts. This chapter demonstrated that the SRAC model can be used to mitigate overland flow floods despite very frequent rainfall events; it further shows that the reduced runoff would decrease downstream river flood risks.

5.4.3 Stormwater drainage demand with SRAC implementation

The SRAC method also impacts stormwater drainage demand in this chapter. Through the comparation of pipeline demand between conventional WSUD and SRAC-WSUD models (within the same parameters, including pipe size, type, diameter, grade etc.), the results show that the SRAC-WSUD model required less pipeline to deliver the same runoff water.

The average storage percentage of the full drainage system is the main indicator to present the possible capacity rate in the pipe, at the point where the flow would become pressurized. Calculation of two different models in ILSAX2 showed that the conventional

WSUD model would maintain the study site as a ‘typical’ stormwater drainage management system, with large stormwater pipes and large capacity demand. However, SRAC-WSUD can help alleviate the negative impacts of typical development. There is a negative linear correlation when stormwater harvesting sites (applied SRAC method) increase as the drainage capacity decreases.

With a SRAC-WSUD model, designers can replace typical stormwater drainage capacity designs with an optimized design (using fewer barrels or smaller pipe sizes). In the study area, during the 4EY rainfall event, the conventional WSUD model required a 549m DN1800 drainage system to achieve the same capacity performance as the SRAC-WSUD model, which used only a 311m DN1800 system. Meanwhile, the SRAC-WSUD model achieved a similar drainage capacity to the conventional WSUD model with less stormwater drainage demand. The reduced demand for barrels saves implementation and other relevant costs. These costs include installation, materials, and relevant maintenance. For instance, in the 4EY rainfall event, the SRAC-WSUD model slowed down the stormwater drainage demand and decreased the required drainage capacity by nearly 43%, allowing a possible SWDS-T designed capacity reduction of 57m DN1200, 69m DN1500 and 111m DN1800 in a single trunk drainage system; that is, the SRACWSUD model decreases the required stormwater drainage capacity by over $500m^3$. For a new build, it would save roughly AU$2.84m for excavating, bed, lay, joint and backfill with imported material by depth; and AU$1.03m for supply and delivery of drainage pipes. This means that the SRAC-WSUD model could save around AU$4m in direct costs and AU$3.87m in indirect savings for better environmental outcome opportunities (fewer concrete constructions) (Heaney, et al., 2002; Sydney Water, 2019). Around AU$7.87m could be saved, according to the cost estimates for stormwater systems developed by Heaney, et al. (2002).

5.5 Conclusion

The chapter focuses on the effectiveness of overland flow flooding control through existing site-scale WSUD facilities, such as rainwater tanks. To address this, the authors developed a SRAC model that can dynamically manage runoff water from frequent rainfall events by discharging water in advance of impending storm events to create storage capacity, minimizing discharge during the storm, and releasing water after the rain.

The results offer a method to quantify the resilience of urban stormwater trunk drainage systems in terms of the hydraulic dimension using the analytical concept of a new site scale stormwater management system. Further, in this system, the SRAC method provides a refined indicator factor (M_t) to measure additional stormwater storage capacity between two continuous very frequent rainfall events. SRAC's cloud-based management of existing stormwater harvesting capacities in relation to precipitation forecasts and real-time database) limits time-consuming hydraulic simulations for stormwater trunk drainage systems under very frequent rainfall events. The SRAC method presented in this chapter offers a useful way for water planners and water managers to manage stormwater systems more dynamically, increasing the capacity to capture and store more stormwater runoff within the same drainage system. The main conclusions from the SRAC case study application in the Upper Caddies Creek Catchment (Sydney, Australia) are:

- The SRAC software performs well in controlling the local flow, inflow, outflow, and net flow in a 2,500 m stormwater trunk drainage system of a catchment area greater than 300 ha under very frequent rainfall events in 1h and 2h rainfall durations, including 12EY, 4EY, 2EY and 1EY.

- The SRAC-WSUD model, if implemented successfully, could reduce over 98% of total flooding volume in the two worst flooding events modelled (1h1EY and 2h1EY) and the SRAC-WSUD model reduces more total flooding water in 1h1EY (14,650 m^3) than in 2h1EY (11,272 m^3).
- For the same rainfall durations (1h or 2h), analysis of nodes 17 (upstream of the SWDS-T) and note 28 (downstream of the SWDS-T) showed the reduction ratio of flow amount in total inflow & outflow increased with the increase of rainfall amount.
- The SRAC-WSUD model would also enable treatment of more stormwater runoff in the downstream Rouse Hill Recycling Plant, as the SRAC method can control the valve to release 'appropriate' water at 'appropriate' times, rather than offering only 'one-off' runoff to the natural waterway.
- The SRAC-WSUD model, if implemented successfully, could reduce drainage system demand on the SWDW-T by 43%, and a new construction for a similar catchment incorporating SRAC-WSUD at planning stages could save the equivalent of AU$7.87m in infrastructure investment.

The results of this chapter show that SRAC can aid in flood control, thereby helping cities become more resilient to natural calamities. To do this, it requires a constant feed of rainfall monitoring data with weather forecasts. However, due to a lack of observed data, no effort was made to calibrate the SRAC model in this high-level study in a bigger catchment area (> 300 ha). Model parameter values were obtained from the published literature and the conclusion is drawn from multiple scenarios. Future SRAC research could further identify the impacts of the SRAC method on stormwater biofilters and optimize the process of nutrient removal (Zhang, et al., 2021).

Chapter 6 Assessing the effectiveness of site real-time adaptive control for stormwater quality control

Related publications:

Xuli Meng, Xuan Li, Long D. Nghiem, Mohammad Rafe Hatshan, Ka Leung Lam, Qilin Wang, 2023. Assessing the effectiveness of site real-time adaptive control for stormwater quality control. *Journal of Water Process Engineering*, p. 104324.

6.1 Introduction

Urbanisation has significantly altered natural water resources, negatively impacting water quantity and quality adversely affecting aquatic ecosystems (Zhang, et al., 2019; Zhang, et al., 2020; Xu, et al., 2021). Urban sprawl contributes significantly to water pollution, including the presence of suspended solids, phosphorus, and nitrogen, which pose a threat to water quality and the aquatic environment (EIU, 2011; Sydney Water, 2019; Meng, 2022).

Stormwater management is a pressing challenge for urban areas, particularly in light of climate change and rapid urbanization (Cheah, 2006; Clark & Siu, 2011; Meng, 2019). Traditional stormwater infrastructure, including pipes, channels, and storage systems, may not withstand increasingly frequent and intense rainfall events, resulting in urban flooding and water quality degradation (Neumann & Sharma, 2010; Xiaolu, et al., 2013; Meng, 2022). Additionally, land availability and cost constraints may limit the construction of new stormwater infrastructure. As a result, there is a need for innovative and sustainable solutions to optimize the performance of existing stormwater systems and improve their resilience (U.S. EPA, 2021; Meng, et al., 2022; Meng, et al., 2023).

WSUD (water-sensitive urban designs) is an approach to integrating the urban water cycle into urban planning and design to mitigate the impacts on waterways and to make the best use of stormwater by developing natural water cycle processes (Grant & ProQuest, 2016; Jamali, et al., 2020; Fogarty, et al., 2021). They can mitigate risks associated with a changing climate, support water quality management for a growing population, generate social and environmental benefits, and reduce human costs associated with everyday maintenance (CRC WSC, 2016; BCC, 2017; Fogarty, et al., 2021). Introducing new stormwater harvesting tanks (SHT) system to highly developed areas pose a challenge in stormwater management due to limited available land. As part of WSUD, SHTs are extensively utilized for controlling both stormwater quantity and quality (Robin, et al., 1997; Duan, et al., 2016; Gori, et al., 2019; Jamali, et al., 2020; Meng, et al., 2022). The latest studies have revealed that using site real-time adaptive control (SRAC) can effectively enhance the stormwater storage capacity and mitigate the runoff water volume in managing stormwater quantity (Meng, 2019; Meng, et al., 2023). However, there remains limited empirical or scholarly comprehension on how to facilitate the integration of this technology for improved removal of water pollutants from the perspective of stormwater quality.

Our hypothesis was that stormwater harvesting systems utilizing the SRAC-WSUD method could reduce the main stormwater pollutant factors in all rainfall weather conditions while simultaneously providing a reliable SRAC-WSUD control mechanism (Meng, 2019). The SRAC-WSUD method utilizes sensors, weather data forecasting and analysis, and artificial intelligence to effectively optimize storage capacity management (Jamali, et al., 2020; U.S. EPA, 2021; Lin, et al., 2023) by regulating the release of water from rainwater tanks to natural waterways.

In the early-stage SRAC-WSUD study, the newly developed impact factor *M* could help designers to measure the recovery capacity between two continuous rainfall events (Meng, 2019; Meng, et al., 2023). The implementation of a cloud-based management system within the SRAC seamlessly integrates its existing stormwater harvesting capabilities with real-time databases and precipitation forecasts, as outlined in the study by Meng et al. in 2023. These studies primarily focus on stormwater quantity control. However, the current study takes a distinct approach, aiming to simulate and assess the impacts on stormwater quality control within the SRAC-WSUD method. This chapter assumes that the '*M*' factor plays a potential role in influencing water quality control within the SRAC-WSUD method. This chapter represents a high-level preliminary research effort aimed at simulating the potential outcomes of quality control within the context of the SRAC-WSUD method. The '*M*' factor, denoting recovery capacity, is a critical component in this simulation. It is assumed that all runoff water will be collected and discharged to the designated receiving point, and the '*M*' factor is calculated as the difference between the total outfall volume (measured in cubic meters) and the amount of water collected in the stormwater harvesting tank systems (Meng, et al., 2023). This unique study seeks to shed light on the implications of the '*M*' factor and its potential impact on pollutant reduction, differentiating it from the 2019 and 2023 studies, which primarily concentrate on stormwater quantity control within the SRAC-WSUD method (Meng, 2019; Meng, et al., 2023).

Based on that, this chapter presents a method to assess SRAC-WSUD in controlling stormwater quality, which is a critical issue for urban areas facing climate change and rapid urbanization. Our study indicates that the SRAC-WSUD method can effectively reduce stormwater pollutants in all rainfall weather conditions while offering a reliable control mechanism (Meng, 2019). By introducing the SRAC-WSUD system, we can optimize the performance of existing SHT and enhance their resilience, while avoiding costly upgrades with new stormwater infrastructure. Our research findings provide valuable insights for future innovative stormwater management applications utilizing the SRAC-WSUD method, which can mitigate the challenges of urbanization and climate change.

6.2 Method

The research employed a single case study approach, involving the collection and analysis of modelling data to gain insights into the removal of water pollutants through SRAC-WSUD. To achieve the research objectives, this chapter assessed the effects of the SRAC-WSUD system on the removal of stormwater pollutants by examining the changes in impact factors (total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN) and gross pollutants (GP)). TSS are very fine particles that remain suspended in stormwater. These particles are smaller than the MUSIC standard's 'medium particulate' category. GP, on the other hand, are larger materials that are clearly visible to the naked eye and can be physically removed from stormwater. These items are larger than the 'medium particulate' category in the MUSIC standards. They can include items like plastic bottles, leaves, and debris. They were used to (i) monitor water pollutant removal, (ii) evaluate the performance of SRAC-WSUD systems in controlling stormwater quality, and (iii) model their impact on a stormwater network over a 12-month simulation period, using different rainfall scenarios (high and low rainfall) and varying system settings. A Model for Urban Stormwater Improvement Conceptualisation (MUSIC) was setup for each scenario to compare modelling results. MUSIC is a popular water quality model in

Australia to assist water planners and managers in simulating water pollutant removal performance.

6.2.1 Case selection

According to recent estimates, over 4 billion people now reside in urban areas, posing significant environmental challenges, particularly for water resources (Meng, et al., 2022). The demand for land in these areas has a direct negative impact on water-sensitive designs. With continued population growth and urbanization, an additional 2.5 billion people are projected to the urban population by 2050 (Meng, et al., 2022). As a result, sustainable development challenges will become more concentrated in cities, particularly in countries with the fastest predicted rates of urbanization.

This project selected a 5.98 ha area from the Upper Caddies Creek catchment (Figure 6-1a) as the study area to test real-time adaptive control systems on a site scale because it is a developed urban catchment with high stormwater pollutants removal demand. The Upper Caddies Creek catchment is characterized by rapid development and holds substantial requirements for WSUD, encompassing numerous developed suburbs (OEH, 2018; Meng, et al., 2022). It stands as a highly urbanized region with a need for SHT, given the extensive modifications resulting from urbanization (Figure 6-1). Notably, the subsoils in the catchment are saline, as evidenced by surface scalds that occur when the water table is close to the surface. Natural water cycle restoration is critical to the area, given the anticipated increase in residents, similar to other new residential areas in Sydney (OEH, 2018).

The conversion of land use from pre-development bushland with varying degrees of permeability to urban properties with high imperviousness has led to a decrease in the ability of developed areas to buffer and store runoff, resulting in increased stormwater runoff and decreased infiltration, leading to higher peak flows and faster rates of runoff (Ahmed, 2018). Urban stormwater runoff can contain a variety of pollutants such as sediment, nutrients, heavy metals, and organic compounds from sources such as vehicular traffic, industrial activities, and urban agriculture, posing risks to both human health and the environment (Fletcher, et al., 2015).

Changes in land use can also affect the natural hydrologic cycle, leading to changes in the quantity and quality of stormwater runoff (Sydney Water, 2019). For instance, removing natural vegetation can reduce the landscape's ability to intercept, store, and evaporate stormwater, whereas introducing new vegetation can improve stormwater quality by promoting infiltration and pollutant uptake. This chapter incorporated land use information, SHT, and receiving bioretention system from The Hills Shire Council, Australia (Figure 6-1). The existing receiving bioretention system in the study area is designed for existing development, can not afford the new stormwater treatment requirement. At the same time, most new buildings installed SHT as required by the local planning scheme, providing an opportunity to rethink how to utilize the existing WSUDs to remove water pollutants.

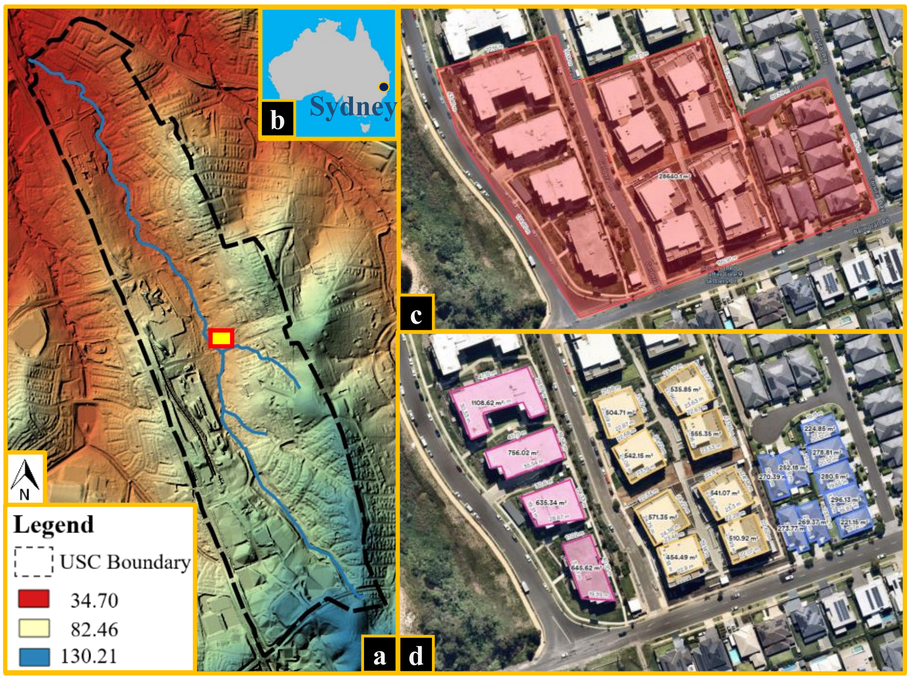

Figure 6-1 (a) Study area in the local catchment (unit: m AHD); (b) study area in Sydney, Australia; (c) study area includes house, townhouse and apartment; (d) roof areas of house, townhouse and apartment

6.2.2 SRAC-WSUD method

A typical SRAC-WSUD system consists of a water level sensor, an actuated valve, and an internet connection (Marchese, et al., 2019; Meng, 2019; U.S. EPA, 2021). The sensor monitors the water level in the facility and sends the data to a cloud-based platform, where an algorithm determines the optimal valve position based on the current and forecasted rainfall conditions, as well as the downstream capacity and constraints (Meng, 2019; Meng, et al., 2023). The valve then adjusts the outflow rate from the facility accordingly, creating more storage space when needed and releasing water when possible (Meng, 2019; Meng, et al., 2023). This way, SRAC-WSUD systems can dynamically manage stormwater runoff at site scale, reducing peak flows, mitigating floods and improving water quality potential.

SRAC-WSUD systems were first time implemented and studied in Australia by Xuli Meng in 2019 (Meng, 2019) and developed initially from real-time adaptive control (RTAC) (Marchese, et al., 2019). Based on the initial model, Meng identified that the SRAC-WSUD method could manage stormwater runoff for water quantity and quality control purposes (Meng, 2019). Currently, RTAC systems can be used to control regional-scale facilities, such as wetlands or basins, to enhance their ecological functions by maintaining optimal water levels for vegetation and wildlife habitats, as well as reducing nutrient loads and pollutants by increasing retention time and treatment efficiency (Marchese, et al., 2019; Meng, 2019). In this study, the research applied the SRAC model to all construction types.

The control logic of the SRAC model is depicted in Figure 6-2. The cloud computing platform developed by Meng (2019) plays a crucial role in the SRAC model. This software assesses specific site data, such as water level and the distance between the stormwater harvesting system and the waterway, along with local precipitation forecasts. It then uses this information to make real-time decisions regarding flow control through the actuated valve. The stormwater harvesting system is designed to collect roof water. When the stormwater harvesting tank anticipates the need to store more roof water from an upcoming storm, the system sends a command to the valve, prompting the release of stored water before the incoming rainfall from the stormwater harvesting tank. This chapter is a preliminary investigation aimed at examining the implementation of the SRAC model in urban catchments that already have rainwater tanks in place. In the subsequent phase, the research will undertake a larger catchment study (above 300 ha).

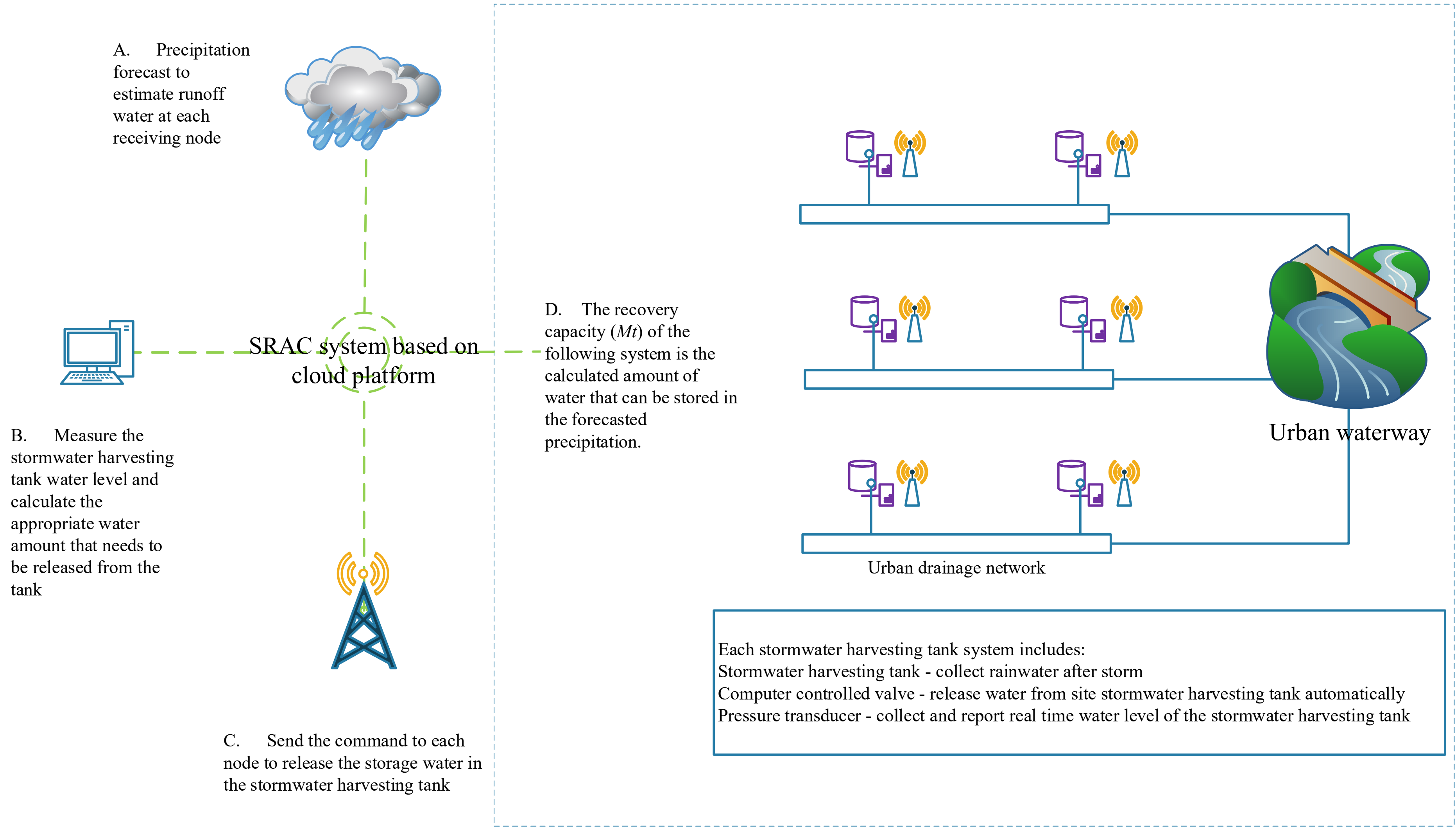

Figure 6-2 The control logic of the SRAC model developed from Meng's real-time adaptive control system (Meng, 2019)

In a recent case study in Sydney, SRAC-WSUD systems have been proven to effectively mitigate overland flow flooding at both site and regional scales by creating more storage space in stormwater facilities during very frequent rainfall events (Meng, et al., 2023). Based on that study, Eq. 6-1 presented the conventional WSUD method uses the mass balance equation:

$$Volume_{time} = Volume_{time-1} + Inflow_{time} - Outflow_{time} - Excess_{time}$$

$$V_t = V_{t-1} + I_t - O_t - E_t \quad (Eq.\ 6\text{-}1)$$

Users can calculate the storage volume at the end of the current time-step, where I_t is the current volume of captured water, O_t is the outflow, and E_t is the excess water that flows into the system when the storage capacity is exceeded.

Different to the conventional WSUD method, the SRAC-WSUD method considers the recovery capacity in the stormwater harvesting tank systems between two continuous rainfall events. The following is the mass balance equation (Eq. 6-2):

$$Volume_{time} = Volume_{time-1} + Inflow_{time} - Outflow_{time} - M_{time} - Excess_{time}$$

$$V_t = V_{t-1} + I_t - O_t - M_t - E_t \quad (Eq.\ 6\text{-}2)$$

Where M_t represents the recovery capacity, *M,* which was named by the first author's family name MENG, represents the recovery capacity in the stormwater harvesting tank systems between two continuous rains at the same point (Meng, 2019; Meng, et al., 2023). The methodology to calculate the M_{time} (M_t) in these studies assume all runoff water will be collected and discharged to the receiving point in the system (Meng, 2019).

The amount of water released into the receiving waterway is determined by the precipitation forecast, as illustrated in Figure 6-2b. The SRAC-WSUD method utilizes the rainfall forecast data to release stored water (R_t and R_{t-1}). The data used in this chapter were sourced from the Bureau of Meteorology (BOM) in Australia. The storage amount reserved for demand during the rainfall event is represented by *S.* To calculate the recovery capacity (*M*), the SRAC-WSUD method uses the formula (Eq. 6-3) as outlined by Meng at the beginning in 2019 (Meng, 2019) and redeveloped by Meng et al. in 2023 (Meng, et al., 2023):

$$M_{time} = Volume_{time-1} - Rain\ forecast_{time-1} - Rain\ forecast_{time} - Storage\ for\ use$$

$$M_t = V_{t-1} - R_{t-1} - R_t - S \quad (Eq.\ 6\text{-}3)$$

Figure 6-2d illustrates that the SRAC-WSUD method has three periods: before, during, and after rain. During the after-rain period, the valve releases harvested stormwater when the cloud platform sends a command to the real-time control release valve (Figure 6-2). The cloud computing platform developed by Meng plays an essential role in the SRAC method (Meng, 2019).

If the predicted rainfall is higher than a certain threshold, the SRAC-WSUD releases all stored water from the harvesting system to create more storage capacity; if the predicted rainfall event is less than the threshold, the volume of the released water should be close to that rainfall (Meng, 2019). The control logic is configured to discharge water in advance of storm events if necessary to create storage capacity, minimize discharge during storm events, and withhold water directly after storm events to allow the downstream stormwater quality control system to treat this water rather than discharge them to the downstream as high flow (Meng, 2019). The SRAC-WSUD method is an improved method that considers the recovery capacity of the harvesting system and optimizes the stormwater treatment based on the precipitation forecast (Meng, et al., 2023).

6.2.3 Concept model

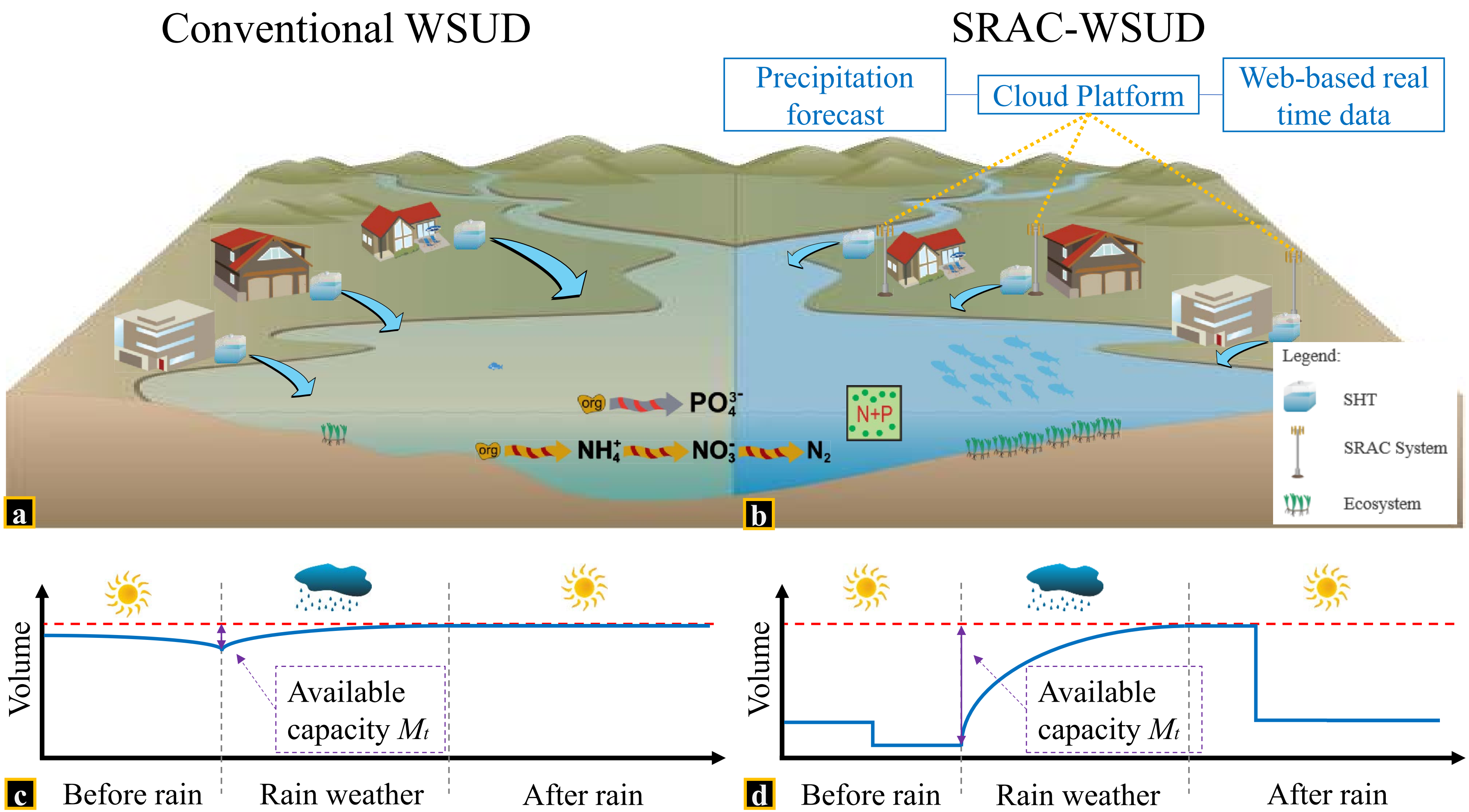

Figure 6-3 Concept model to compare conventional WSUD and SRAC-WSUD, (a) conventional WSUD method; (b) SRAC-WSUD method; (c) M_t performance in the conventional method; (d) M_t performance in the SRAC-WSUD method

The chapter aims to compare two methods: conventional WSUD and SRAC-WSUD (Figure 6-3). Figure 6-3b & 6-3d depict the SRAC-WSUD method's three periods: pre-rain, during rain, and post-rain. In the post-rain period, the cloud platform commands the real-time control release valve, releasing harvested stormwater. The cloud computing platform is vital for SRAC's functionality in controlling runoff discharge. Consequently, TP and TN levels decreased in the receiving water body. TSS refers to solids in stormwater, TP refers to organic and inorganic phosphorus compounds (PO_4^{3-}), TN refers to nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_3^-) and organic nitrogen, and GP includes any items in the water system such as sediments, plastic bottles, domestic wastes, metals, and paper (Figure 6-3).

In this chapter, the assessment of water quality utilized MUSIC 6, as shown in Figure 6-4. The stormwater treatment process involves the collection of all roof water through stormwater harvesting tanks. Subsequently, this collected water is directed to a swale-bioretention system. In cases where the water flow capacity exceeds the design of the bioretention system, the excess water follows an overland flow path towards the waterway, which serves as the designated receiving point. The chapter adopts the following method parameters for assessment purposes: 6 minutes rainfall data from 01/01/1959 to 31/12/1959 (1 calendar year) for rainfall data and monthly Potential Evapo-Transpiration (PET). This chapter presents an innovative way to compare the treatment performance of the two modern water treatment methods, as illustrated in Figure 6-3c & 6-3d, which show how the available capacity, *M*, generated from the concept models can significantly impact the stormwater treatment performance.

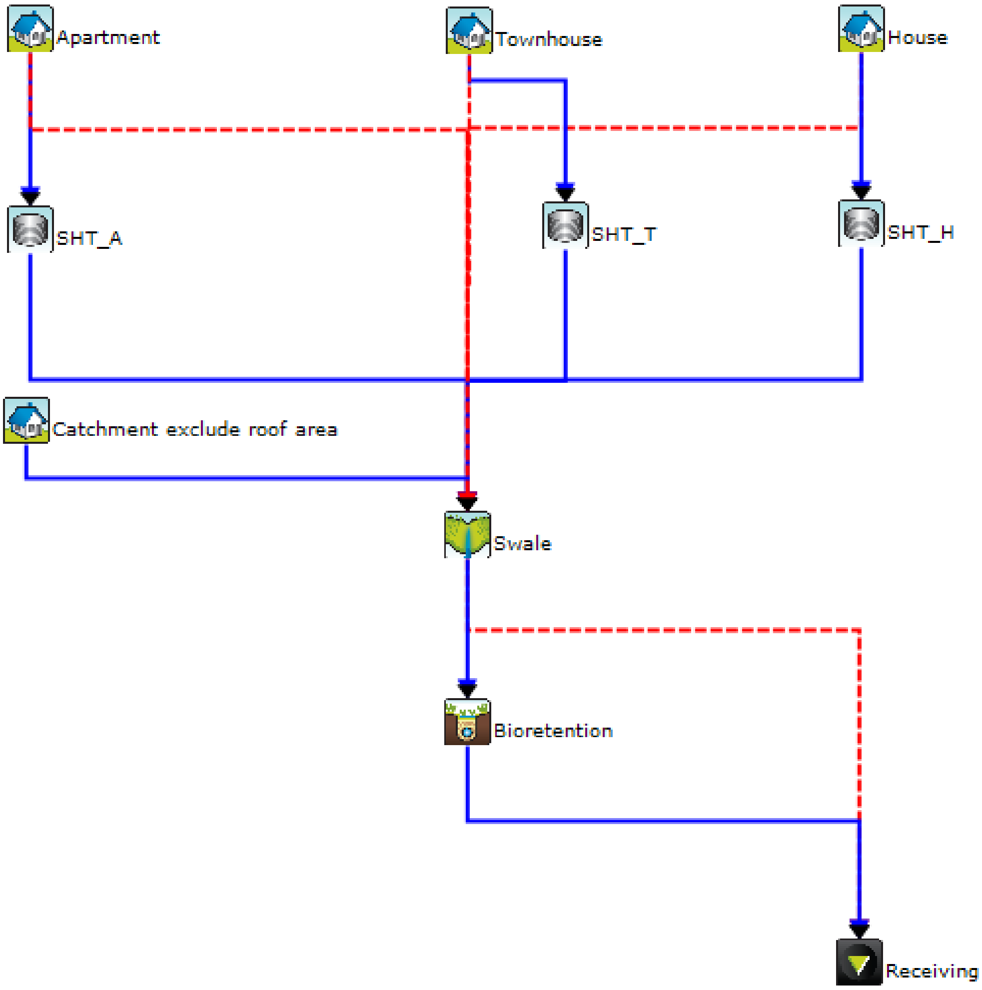

Figure 6-4 Concept model in MUSIC 6 tool (blue lines represented main water flow path and red lines represented overflow water path)

6.3 Results

The results data were collected from the project site during the average rainfall (whole year), high rainfall (wet weather from January to March) and low rainfall (dry weather from July to September) periods, including the residual loads of TSS, TP, TN, and GP in the stormwater runoff during these rainfall scenarios. The SRAC-WSUD method was found to be more effective than the conventional WSUD method in reducing the total amount of pollutants, including TSS, TP, and TN, while decreasing the flow rate (Figure 6-5).

For the average rainfall scenario, the SRAC-WSUD method resulted in a reduction in the total amount of pollutants, including a 196.72 kg/year decrease in TSS, a 0.07 kg/year decrease in TP, and a 0.78 kg/year decrease in TN, while increasing flow by 0.06 ML/year. There was no significant difference between the two methods in GP removal.

In the high rainfall scenario (based on 3-month wet weather data), the SRAC-WSUD method resulted in a more significant increase in flow rate compared to the whole-year scenario, with a 0.23 ML/year increase. At the same time, it resulted in a significant decrease in pollutants, including a 38.24 kg/year decrease in TSS, a 0.38 kg/year decrease in TP, and a 3.09 kg/year decrease in TN.

Similarly, the low rainfall scenario (based on 3-month dry weather data) showed an enormous increase in flow rate with a 0.65 ML/year and a decrease in the total amount of pollutants, including an 11.31 kg/year decrease in TSS, a 0.06 kg/year decrease in TP, and a 0.61 kg/year decrease in TN.

The comparison of GP between the conventional WSUD and SRAC-WSUD methods did not reveal any significant difference for all scenarios.

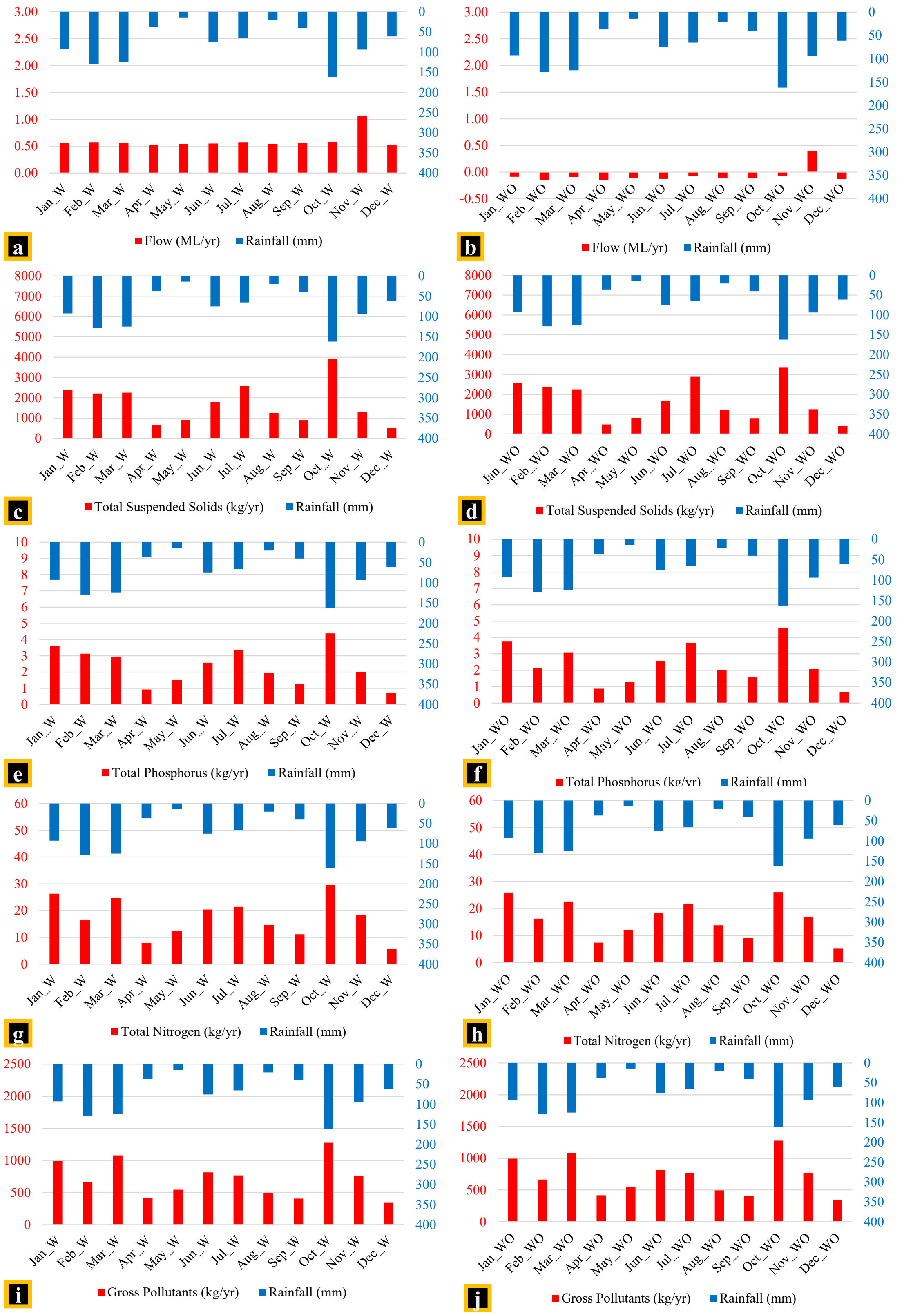

Figure 6-5 Presents the modelling results used to compare the flow and pollutant removal efficiency of the SRAC-WSUD and conventional WSUD methods, (a) and (b)

illustrate the flow changes in the SRAC-WSUD and conventional WSUD methods, respectively; (c) and (d) show the TSS changes in the SRAC-WSUD and conventional WSUD methods, respectively; (e) and (f) display the TP changes in the SRAC-WSUD and conventional WSUD methods, respectively; (g) and (h) present TN changes in the SRAC-WSUD and conventional WSUD methods, respectively; Finally, (i) and (j) demonstrate GP changes in the SRAC-WSUD and conventional WSUD methods, respectively, during different rainfall periods throughout the year

Table 6-1 compares the treatment results of two stormwater management systems - conventional WSUD and SRAC-WSUD systems. The effectiveness of the SRAC-WSUD in reducing pollutants in the stormwater runoff for the entire calendar year scenario was compared to that of the conventional WSUD. The table presents data on the flow rate of stormwater runoff and the amounts of TSS, TP, TN, and GP for SRAC-WSUD, conventional WSUD, and the difference.

Table 6-1 Pollutants removal results to compare whole calendar year's performance.

	Flow (ML/yr)	TSS (kg/yr)	TP (kg/yr)	TN (kg/yr)	GP (kg/yr)
SRAC-WSUD	30.29	2886.22	6.76	64.24	0.00
Conventional WSUD	30.35	3125.98	6.87	63.00	0.00
Difference	0.06	196.72	0.07	-0.78	0.00

Therefore, we can conclude that the conventional WSUD system may effectively reduce TSS. However, both systems have limited capacity to reduce TP and TN in stormwater runoff. The SRAC-WSUD system is effective in reducing pollutants in stormwater runoff, has a comparable performance in reducing TSS compared to the conventional WSUD system. Nonetheless, further studies are needed to assess the systems' capacity to reduce TP and TN in stormwater runoff. It is important to note that while the SRAC-WSUD system may have limitations in reducing TP and TN, it is a step towards improving the effectiveness of stormwater management systems.

6.4 Analysis

The findings in Section 3 demonstrate that the real-time controlled approach (SRAC-WSUD method) is superior to the conventional WSUD in enhancing urban stormwater quality by reducing TSS, TP and TN. As a result, stormwater harvesting systems that utilize the SRAC-WSUD method could reduce the main stormwater pollutant factors in both high, low and average rainfall weather conditions while also providing a reliable control mechanism through SRAC-WSUD.

6.4.1 How the *M* impacts pollutant removal

Urban areas generate stormwater runoff that can have detrimental effects on water quality. Due to the rapid development in the area, water planners face numerous water management issues, including runoff contamination, nutrient loading, trash and debris, bacterial contamination, and thermal pollution. These problems arise due to the accumulation of pollutants from impervious surfaces. They can negatively impact water bodies, ecosystems, and human health. Effective management strategies and public awareness are vital for mitigating urban stormwater pollution and preserving water quality. Various techniques have been developed to mitigate this impact, but the SRAC system is one of the new methods without any new treatment infrastructure input. Compared to conventional WSUD, SRAC-WSUD systems have gained considerable attention in influencing water quality due to their ability to reduce peak flows from stormwater storage facilities.

This chapter employs the First Order Kinetic (k - C^*) Model to determine water quality changes through the MUSIC tool as pollutants enter a treatment measure like a pond or wetland (Reed, et al., 1995; Zhang, et al., 2023). This model explains how contaminant concentrations tend to reach an equilibrium value at a particular location and time via an exponential decay process, where k represents the exponential rate constant and C^* is the equilibrium value or background concentration (Eq. 6-4). The k-C^* model is expressed algebraically as

$$(C_{out} - C^*) / (C_{in} - C^*) = e^{-k/q} \quad (Eq.\ 6\text{-}4)$$

where C_{out} is the output concentration, C_{in} is the input concentration, and q is the hydraulic loading of the treatment measure. Higher k values mean faster attainment of equilibrium and greater treatment capacity, provided that C^* is less than C_{in}. The rate constant k can be thought of as the hydraulic loading that yields an output concentration above C^* (which is approximately 0.37 times the inflow concentration) for a given situation. The background concentration C^* may vary depending on the type of flow (stormflow or baseflow) and the presence of a permanent pool in the treatment measure (Reed, et al., 1995).

Delaying the peak flow rate in the SHT system through available capacity *M* can improve runoff water treatment by WSUD applications, including reducing hydraulic loading of treatment measure *q* and increasing C_{in} / C_{out}. The top four indicators for monitoring water quality changes before urbanization and development with WSUD are TSS, TP, TN, and GP. Treating more runoff water can remove more water pollutants, and MUSIC evaluates stormwater quality performance based on these four factors to establish a comprehensive system for reviewing the removal of pollutants by WSUD (Zhang, et al., 2023). However, further research is needed to clarify the complex relationship between available capacity, *M*, *q*, and $C_{in} / C_{out.}$

6.4.2 Restore natural water cycle through SRAC-WSUD

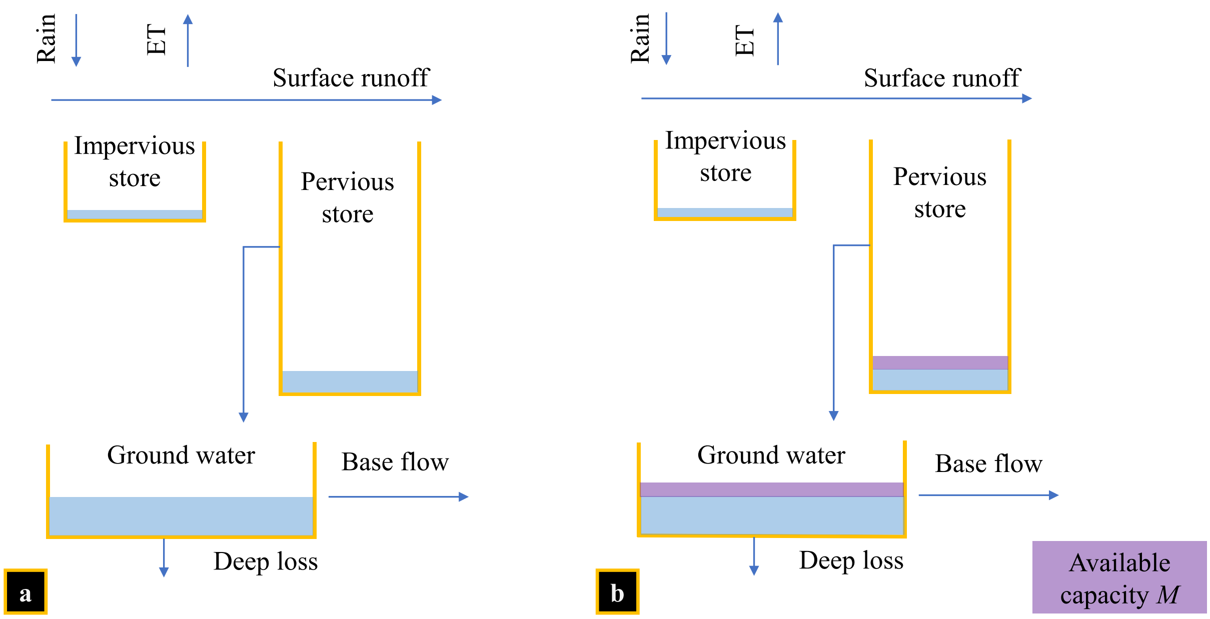

Figure 6-6 Available capacity M in the natural water cycle

Restoring the water cycle is a complex process that requires a multi-faceted approach (Wong & Brown, 2009; Wong, et al., 2013; Zhang, et al., 2020). The SRAC-WSUD method plays a vital role in this process, with its available capacity, *M*, helping to regulate the flow of water and ensure a consistent water infiltration (Figure 6-6).

The SRAC-WSUD method is an innovative approach to stormwater management that assists in restoring the water cycle by deferring the peak flow rate by 8-10 minutes. By deferring the peak flow rate, more runoff water can be treated by existing WSUD designs, allowing for more infiltration to the pervious store and more water to flow into the groundwater system (Figure 6-6b). This approach can significantly improve the health of ecosystems that are impacted by the water cycle, such as wetlands, which play a crucial role in filtering and purifying water. Restoration of wetlands and other natural areas is essential to improving the health of the water cycle and ensuring its proper functioning (Wong, 2015; Zhang, et al., 2021).

The SRAC-WSUD method is an adaptive control technology that focuses on SHT. This approach maximizes available resources, promotes ecological health and resilience, and supports the fauna and flora system. One of the key advantages of the SRAC-WSUD method in water cycle restoration is that it can utilize existing waterways and various WSUD applications, such as bioretention, bio-swale, and bio-basin, without requiring new land to construct WSUD designs. This design provides more surface land for urban development, such as recreation areas for the local community, reducing the land demand from fauna and flora systems.

Moreover, the SRAC-WSUD method has been shown to effectively manage stormwater quality and reduce the demand for water-sensitive design by 21%. Implementing a new system for a similar catchment incorporating SRAC-WSUD at the planning stage could save the equivalent of AU$157k in infrastructure investment (Meng, et al., 2023). The innovative approach of SRAC-WSUD in managing stormwater can assist in restoring the water cycle by deferring peak flow rates and utilizing existing WSUD designs, thereby improving the health of ecosystems impacted by the water cycle and ensuring a sustainable and healthy water cycle for generations to come (Heaney, et al., 2002).

In conclusion, SRAC-WSUD is a valuable tool in restoring the water cycle and supporting the fauna and flora system. Its innovative approach to stormwater management can significantly improve the health of ecosystems impacted by the water cycle, without requiring new land for construction. The use of SRAC-WSUD in managing stormwater quality can reduce the demand for water-sensitive design and save costs, making it an efficient and effective approach for restoring the water cycle.

6.4.3 Contributions of SRAC in the stormwater quality management

The implementation of SRAC systems in stormwater management has effectively mitigated the impact of frequent rainfall events by delaying peak flows in the drainage system. Recent research by Meng et al. (2023) found that implementing SRAC systems can delay peak flows by 8-10 minutes, which improves TSS removal in the SRAC-WSUD method as runoff water can continuously flow to downstream WSUD applications, such as bioretention basins and bioswales.

The SRAC-WSUD method, which considers the recovery capacity of the harvesting system and optimizes the stormwater treatment based on precipitation forecasts, can increase retention time and treatment efficiency in stormwater facilities, resulting in improved water quality. Increased retention time allows for better sedimentation, filtration, and biological uptake of pollutants (Peña-Guzmán, et al., 2017; Rogers, et al., 2020).

During the whole year period, the SRAC-WSUD method demonstrated superior performance in TSS removal, with a reduction of 38.24 ML/yr compared to the conventional WSUD method (Figure 6-7a). Furthermore, during the same period, the SRAC-WSUD method exhibited an additional pollutant removal of 7.50% in TP and 6.70% in TN loads compared to the conventional WSUD method (Figure 6-7b).

Despite requiring regular maintenance for the cloud platform, sensor, valve, and associated parts, which leads to increased maintenance costs, the SRAC-WSUD method provides a cost-effective and efficient approach to managing stormwater runoff and improving water quality in urban areas. However, further research is necessary to understand the long-term performance and maintenance requirements of SRAC systems to ensure their sustainable implementation.

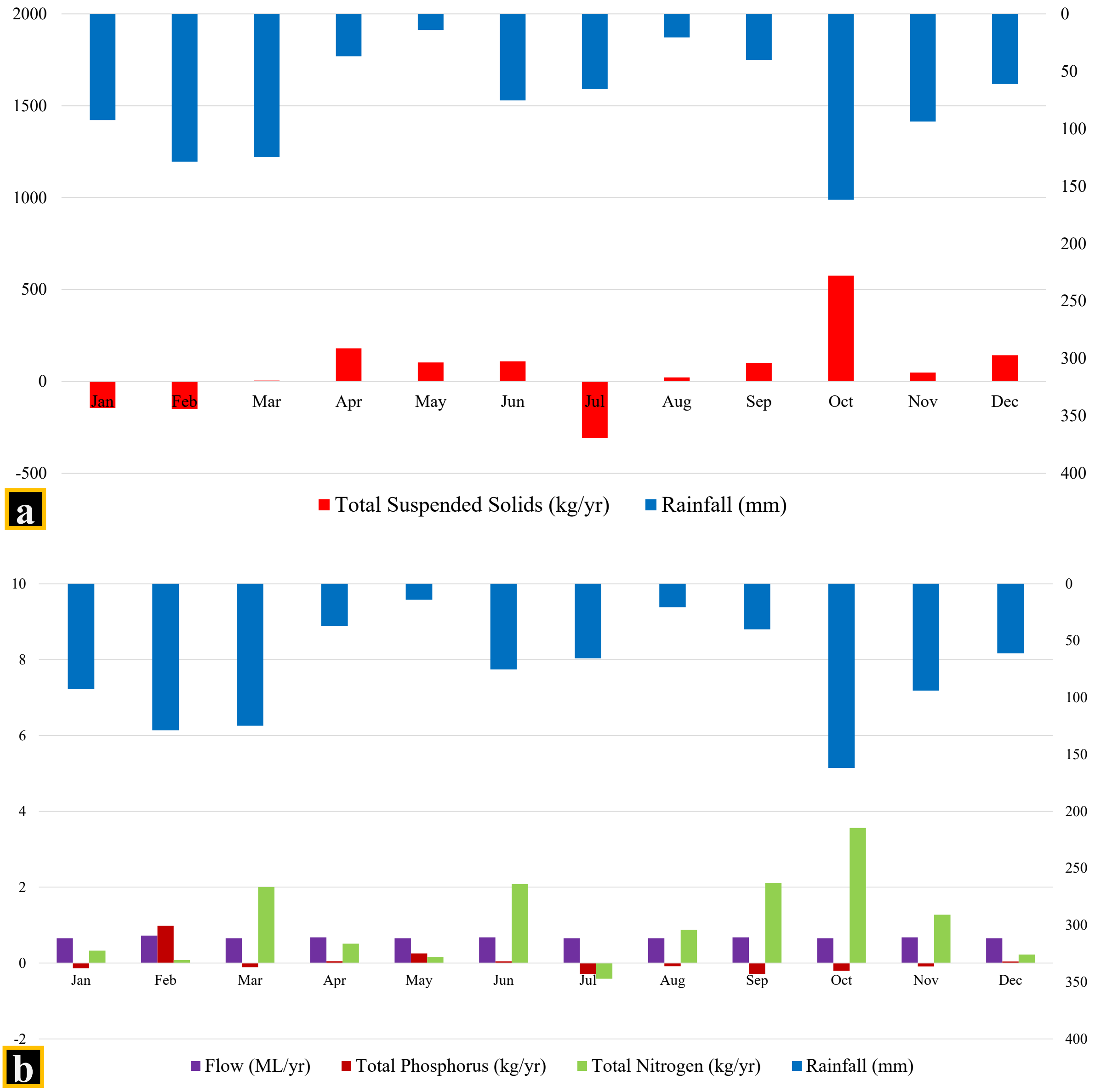

Figure 6-7 Illustrates the difference between the conventional WSUD and SRAC-WSUD methods in terms of TSS change and flow, TSS, and TN change over one calendar year, (a) shows the TSS change in the conventional and SRAC-WSUD methods; (b) displays the flow, TSS, and TN change in both methods during the same period

6.5 Conclusion

The use of SRAC-WSUD has significantly improved in reducing the pollutants load in the receiving water body. The TSS, TP, and TN showed a reduction using SRAC-WSUD, whereas GP showed a 100% reduction in both scenarios. The difference in reduction between conventional WSUD and SRAC-WSUD shows the effectiveness of the SRAC-WSUD in reducing pollutants' load during both wet and dry weather scenarios. Based on the results of this chapter, it is recommended that SRAC-WSUD be considered in the design of stormwater management systems to improve the reduction of pollutants in the receiving water body. However, further studies are required to determine the long-term effectiveness of SRAC-WSUD in reducing the pollutants' load. Moreover, the cost-effectiveness of using SRAC-WSUD in the design of stormwater management systems should also be considered to make informed decisions.

Chapter 7 Conclusions and Recommendations for Future Works

7.1 Conclusions

This PhD thesis significantly advances the field of stormwater management through the development and application of Real-Time Adaptive Control (RTAC) and Site-Scale Real-Time Adaptive Control (SRAC) systems. Urbanization, driven by population growth and the transformation of natural landscapes into impervious surfaces, has exacerbated issues related to stormwater runoff, flooding, and water quality degradation. The RTAC method, utilizing cutting-edge technologies such as cloud computing and Wi-Fi-based control systems, provides a robust solution for managing stormwater runoff in real-time. By optimizing the storage and release of stormwater in harvesting facilities, RTAC alleviates the burden on urban drainage networks, thereby mitigating flooding risks and protecting urban infrastructure.

The effectiveness of the RTAC method has been demonstrated through its application to stormwater harvesting tanks within urban catchments. This system enables more efficient storage during storms and controlled release of runoff water, significantly reducing flooding risk and potential damage to infrastructure. Additionally, the evaluation of the combined WSUD model alongside conventional WSUD approaches has revealed its superior performance in managing future urban development scenarios. The combined WSUD model effectively reduces stormwater runoff and enhances infiltration and evapotranspiration, offering a more sustainable approach to stormwater management.

The introduction of the SRAC model further refines stormwater management strategies by addressing overland flow flooding. The SRAC method dynamically manages runoff by creating additional storage capacity before storms and controlling post-storm water release. This model has proven effective in reducing flooding volumes and infrastructure demands, with potential cost savings in infrastructure investments. The case study conducted in the Upper Caddies Creek Catchment demonstrated the SRAC model's capability to handle frequent rainfall events and significantly reduce flood volumes.

Despite these advancements, the PhD thesis highlights several areas for improvement. The effectiveness of stored water utilization and water quality control within stormwater harvesting facilities remains a challenge. Both RTAC and SRAC methods require further refinement to integrate effective water quality control measures and ensure the long-term effectiveness and cost-efficiency of stormwater management systems.

7.2 Recommendations for Future Works

Future research should focus on several key areas to enhance the effectiveness and applicability of RTAC and SRAC methods in stormwater management. First, comprehensive studies are needed to better understand the utilization of stored water from stormwater harvesting systems. Maximizing the benefits of stored water while ensuring its quality is crucial for optimizing stormwater management.

Second, further research should explore the integration of advanced water quality control measures within the RTAC system. Addressing concerns related to potential contaminants and pollutants in collected stormwater will ensure the water is suitable for various non-potable uses and improve overall system performance.

Third, large-scale catchment studies under diverse conditions are essential to validate the findings of this PhD thesis and refine the RTAC and SRAC models. These studies should investigate different urban settings and varying climatic conditions to assess the models' adaptability and performance in real-world scenarios.

Additionally, future research should evaluate the long-term effectiveness and cost-efficiency of the SRAC-WSUD approach. Understanding the long-term benefits and potential savings in infrastructure costs will provide valuable insights for urban planners and policymakers.

Finally, future work should explore the potential for integrating the RTAC and SRAC methods with other stormwater management strategies and technologies. Combining these methods with green infrastructure solutions, such as green roofs and permeable pavements, could offer a more comprehensive approach to managing stormwater in urban environments.

Addressing these areas of research will contribute to the refinement and validation of advanced stormwater management systems, ultimately leading to more resilient and sustainable urban environments.

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