Blue-Green Systems

 Blue-Green Systems Vol 4 No 1, 45 doi: 10.2166/bgs.2022.026

Understanding the effects of site-scale water-sensitive urban design (WSUD) in the urban water cycle: a review

Xuli Meng[a,b]

[a] Centre for Technology in Water and Wastewater, School of Civil and Environmental Engineering, University of Technology Sydney, Ultimo, NSW 2007, Australia
[b] Moreton Bay Regional Council, Strathpine, QLD 4500, Australia
E-mail: xuli.meng@student.uts.edut.au

XM, 0000-0001-5108-2454

ABSTRACT

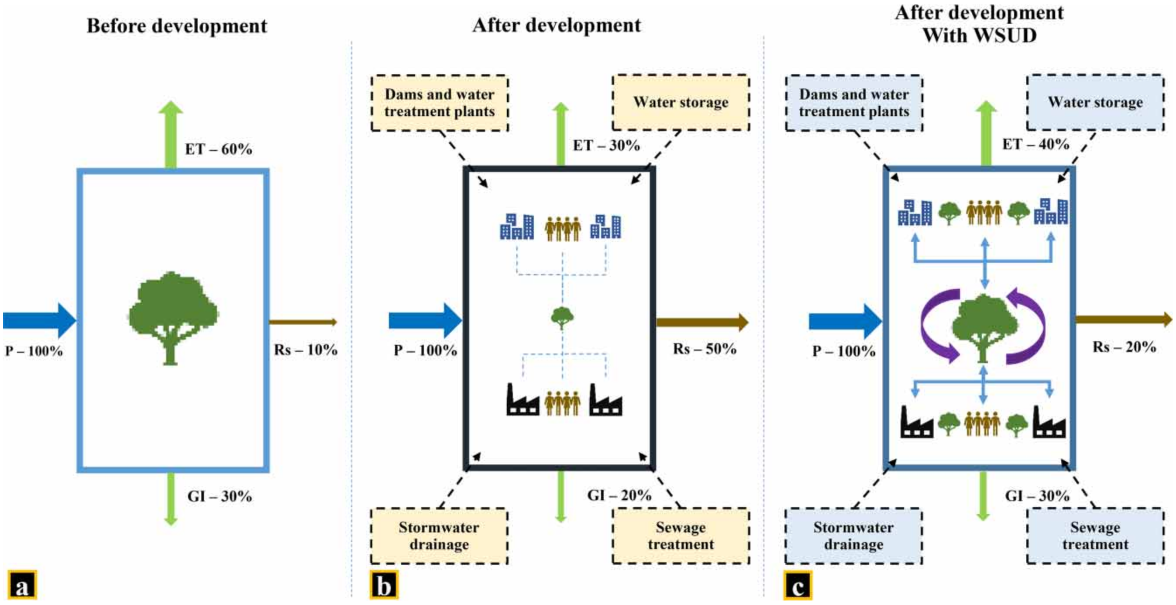
With city growth, the development of vacant or under-used land parcels is becoming more common compared to the past. The current 'water-sensitive urban design (WSUD)' approach to such development will improve resource efficiency, liveability, and the amenity of cities, especially natural water systems. However, there is a need to quantify the water performance of site-scale WSUD options, especially about how these options impact the 'natural' and 'anthropogenic' flows in the urban water cycle. This study reviewed research about site-scale applications, summarizing the urban water cycle studies from before development to after development. Key findings (i) include very big margin was quantified by (a) water retention (30–100%) and (b) portable water demand reduction (18–100%) for selected site-scale WSUD options through six research studies; (ii) still unclear about the selected site-scale WSUD options' interaction performance in the urban water cycle between each water accounts, and (iii) need to clarify the site-scale WSUD option's contribution under specific rainfall scenarios. In summary, this study aims to review the literature on the urban water cycle; review the effects of site-scale WSUD options in the urban water cycle; review the water mass balance and relevant evaluation application, and highlight the opportunities for the future urban water cycle studies.

Key words: hydrological cycle, urban water cycle, water mass balance, water performance evaluation framework, water-sensitive urban design (WSUD)

HIGHLIGHTS

- Reviews the literature on the urban water cycle, including before development, after development, and after development with WSUD.
- Reviews the effects of site-scale WSUD options in the urban water cycle.
- Reviews the water mass balance and relevant evaluation application.
- Highlights the opportunities for future urban water cycle studies.

GRAPHICAL ABSTRACT



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. 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) and 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, water-sensitive urban design (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; and connecting distributed WSUD designs to natural waterways (Chesterfield *et al.* 2016; Ball *et al.* 2019). To date, several studies have examined the response of stormwater runoff and potable water demand to city-region scale (Meng *et al.* 2022) and street-scale (Meng & Kenway 2018) through WSUD, but it is still unclear for the understanding of site-scale landscaped features through WSUD implementations, like rainwater tanks, detention tanks, and green roofs (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. 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 1 presents three water mass balance concept models to compare the water account changes under different scenarios: they are before the development model (natural water cycle), after the development model (business as usual), and after development with the WSUD model (the sustainable model with site-scale WSUD options).

Figure 1(a) shows people to observe the before development phase of the urban water cycle and shows the natural movement of water without human intervention. This first phase consists of three main processes, including evaporation and transpiration – liquid changing to vapour, in the example, evaporation occurs when water in oceans, lakes, and rivers warms and turns into a gas, rising to the air; the second process consists of plants releasing water into the air in a process called transpiration; then there is precipitation – when liquid or solid water falls to earth, which is when the clouds eventually become too heavy and the water falls back to the earth as rain, hail, sleet, or snow; and finally, infiltration, percolation, and runoff – liquid water absorbed into the earth, which is the water that falls to the earth and then flows into waterways (runoff), absorbed into the ground (infiltration) or aquifers and underground water pockets (percolation) (Wong *et al.* 2013).

The second phase is about after development in the urban area with anthropogenic flows, 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), and at the same time, stormwater runoff increases (Figure 1(b)). 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 (Figure 1(b) and 1(c)). These streams are **dams and water treatment plants**, dams are used to capture rain, and the water is cleaned at a water treatment plant before being pumped into underground

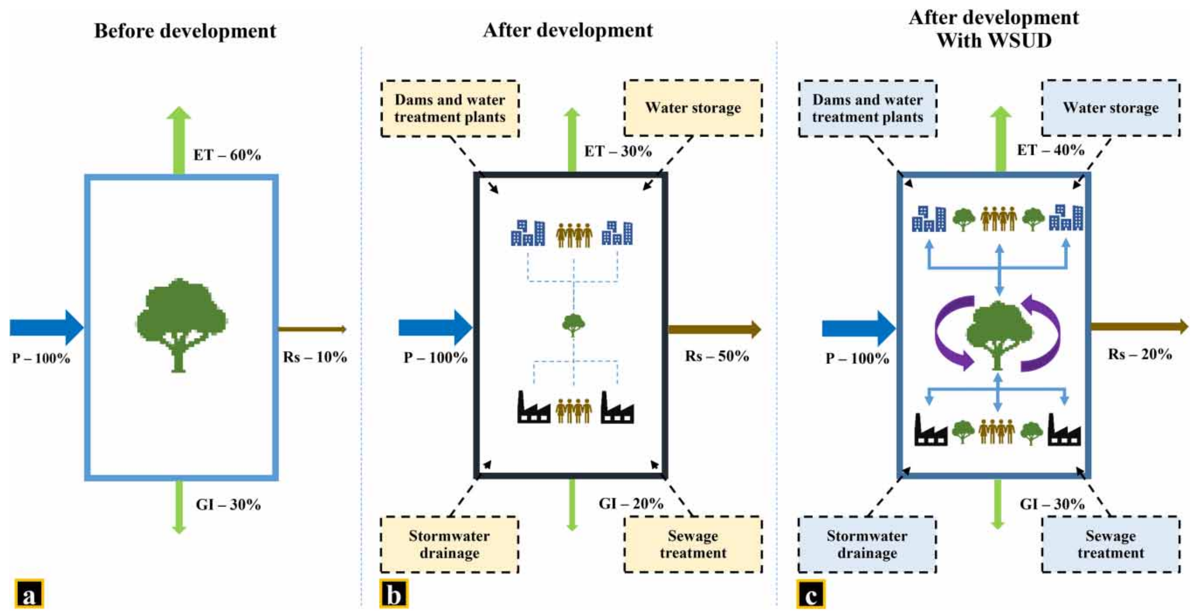


Figure 1 | Concept model to present water mass balance in (a) before development, (b) after development, and (c) after development with WSUD models. P: precipitation; ET: evapotranspiration; GI: groundwater; Rs: stormwater runoff.

pipes; **water storage**, which is the clean water, is stored in water reservoirs and towers until it is needed; **stormwater drainage**, water runoff from buildings and streets is collected in stormwater drains, where it flows to the ocean; and the last stream, **sewage treatment**, which is water after you use it, water 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 after development with WSUD applications, 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 are assisted to reduce runoff and 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 amenities, 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).

In the after development phase and after development with the WSUD phase (Figure 1(b) and 1(c)), the urban water cycle improves urban water resource management and combined the water-related component systems, such as water supply, treatment, demand, distribution, wastewater collection, surface water and groundwater quality, and quantity control (Figure 1(b) and 1(c)). There are three main aspects in this cycle; the first aspect is the water supply infrastructure to influence 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 the urban water cycle (Mcpherson 1973).

In the past, most urban water cycle 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 urban water cycle 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 flow between water-related component systems. The accurate data outcome can develop a fully labelled flowsheet. After the quantification of each flow, a balance of a conserved quantity can be generated (Equation (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.

$$Accumulation = Input - Output + Generation - Consumption \quad (1)$$

The current water management model is focused on local hydrological flow movement in a catchment-scale study. This means that 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, treating the catchment as a whole (Cisakowski *et al.* 2011). For water movement outside 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?

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 (Fletcher *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.* 2016). 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, and 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 that 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).

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 at the site-scale level. On the site-scale level, 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. Consequently, overland flow makes more severe damage to the properties if they are located far away from the catchment scale of WSUD sites.

As a 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; however, most of the site-scale WSUD technologies will not connect with creeks or rivers directly because the linear connection is difficult (Meng & Kenway 2018).

This paper 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 site-scale WSUD options for the urban water cycle, this paper reviewed water retention and potable water demand reduction in the urban water cycle in a quantitative manner (Table 1). Table 1 lists 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 (Figure 2). 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 34–92%. 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.

Table 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

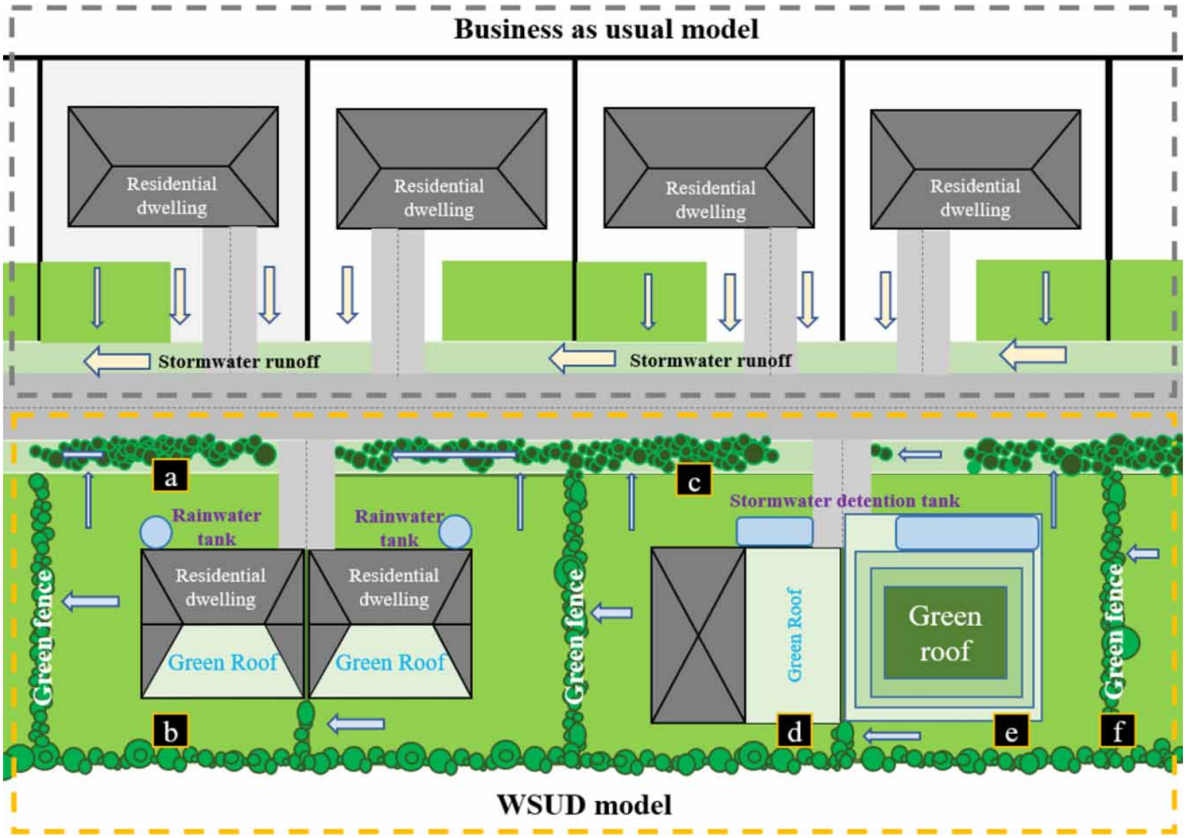


Figure 2 | (a) New residential dwelling with rainwater tanks, (b) linear park/garden with WSUD functions, (c) new building with stormwater detention tank, (d) horticulture garden, (e) green roof, and (f) green fence. The figure is adapted from Meng & Kenway's research in 2018 (Meng & Kenway 2018).

The stormwater detention tank has also 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). In newer areas, the stormwater drains have been engineered to allow for rainwater runoff 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 selection for future urban planning is the green roof option (Imteaz *et al.* 2011) (Figure 2). 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 studies have 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) summarized 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 excellent option for water detention that can be used in urban development (Figure 2). 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 paper, and it is a green alternative to concrete outdoor surfaces, such as an amenity area in the residential dwelling backyard (Figure 2). 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 parks 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% Annual Exceedance Probability (AEP)) (Ngo *et al.* 2016).

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. Indeed, Figures 1 and 2 demonstrate an overview of site-scale WSUD options in the urban water cycle and how these options shift the water flows between each water account, but researchers still need a quantitative tool to calculate the water account changes in and out of the urban water cycle.

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). 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' (Equation (4) and Table 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.* (2011) and Renouf *et al.* (2018) 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 & 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 was 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 Equation (2) to describe the water that flows into and out of the system. From a hydrological perspective, it represents the sum of water inflow equalling water outflow and the change in this urban hydrological cycle.

In recent studies, the shift of water mass balance was influenced by an 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 (Equation (2)). Equation (3) was established based on Equation (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). Further, scholars brought the estimates of anthropogenic and natural flows together into the urban water mass balance (Equation (4)) (Renouf *et al.* 2018) using the method described in the original framework of Farooqui *et al.* (2016) (Table 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 (Equation (4)). Changes in storage were assumed to be zero (Equation (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

Table 2 | Urban water cycle analysis through the water mass balance tool

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

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 include 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).

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, and 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.

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 lists some main water performance evaluation methods in the urban water cycle, and 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 1) and water performance evaluation methods listed (Table 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.

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. Future research could clarify these effects in the real-world environment, especially the interactions between each account and people using them in a collaborative urban design and the planning context are not well understood 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 optimize architectural design and technologies to achieve some pre-defined targets through site-scale WSUD options. This would be a multi-objective optimization, maximizing 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 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 analyze 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.

Table 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 scale (Moravej *et al.* 2020)[a]	Hydrological naturalness	Hydrological flows of the urban system have changed.
	Imported water use per capita	Reliance of the assessed urban system on water mains.
	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, and inlet and outlet levels 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.

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

7. CONCLUSION

This paper reviewed the development of the urban water cycle and how the site-scale WSUD option interacted with the water cycle. In answer to 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 a 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 the 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.

ACKNOWLEDGEMENTS

The author acknowledges Qilin Wang and Long D. Nghiem from the Centre for Technology in Water and Wastewater (CTWW), the University of Technology Sydney for their great support in this project; acknowledges Brooklyn Meng for his proofreading, editing, and great contribution in the project; acknowledges Eric Ruiz from The Hills Shire Council for data collection; and acknowledges Chloe Meng and Chi Zheng's support during the project period.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST STATEMENT

The authors declare there is no conflict.

REFERENCES

ADB 2016 *Asian Water Development Outlook 2016: Strengthening Water Security in Asia and the Pacific*. Asian Development Bank, Mandaluyong City.

Alamdari, N., Sample, D. J., Liu, J. & Ross, A. 2018 Assessing climate change impacts on the reliability of rainwater harvesting systems. *Resources, Conservation and Recycling* **132**, 178–189.

Astaraie-Imani, M., Kapelan, Z., Fu, G. & Butler, D. 2012 Assessing the combined effects of urbanisation and climate change on the river water quality in an integrated urban wastewater system in the UK. *Journal of Environmental Management* **112**, 1–9.

Bach, P., Rauch, W., Mikkelsen, P., Mccarthy, D. & Deletic, A. 2014 A critical review of integrated urban water modelling - Urban drainage and beyond. *Environmental Modelling and Software* **54**, 88–107.

Ball, J., Babister, M., Nathan, R., Weeks, B., Weinmann, E., Retallick, M. & Testoni, I. 2019 *Australian Rainfall and Runoff: A Guide to Flood Estimation*. Commonwealth of Australia, Barton.

Booth, D. & Jackson, C. 2007 Urbanization of aquatic systems: degradation thresholds, stormwater detection, and the limits of mitigation. *Journal of the American Water Resources Association* **33** (5), 1077–1090.

Chesterfield, C., Rogers, B., Beck, L., Brown, R., Dunn, G., de Haan, F., Lloyd, S., Urich, C. & Wong, T. 2016 *A Water Sensitive Cities Index to Support Transitions to More Liveable, Sustainable, Resilient and Productive Cities*. Singapore International Water Week, Singapore.

Cisakowski, A., Clauson, S., Parker, L., Rocklin, D., Stilwell, C. & Trudeau, D. 2011 *Fall. Water metabolism in Eugene-Springfield: A mass balance case study*. University of Oregon.

Commonwealth of Australia 2015 *Stormwater Management in Australia*. Commonwealth of Australia, Canberra.

Coombes, P. 2015 Transitioning drainage into urban water cycle management. In *s.l., 9th International Water Sensitive Urban Design*.

EIU 2011 *Asian Green City Index. Assessing the Environmental Performance of Asian's Major Cities*. Siemens AG, Munich.

Elliott, A. & Trowsdale, S. 2007 A review of models for low impact urban stormwater drainage. *Environmental Modelling and Software* **22** (3), 394–405.

eWater 2016 *MUSIC Guidelines – Recommended Input Parameters and Modelling Approaches for MUSIC Users*. Melbourne Water, Melbourne.

Farooqui, T., Renouf, M. & Kenway, S. 2016 A metabolism perspective on alternative urban water servicing options using water mass balance. *Water Research* **106**, 415–428.

Feng, Y., Burian, S. & Pomeroy, C. 2016 Potential of green infrastructure to restore predevelopment water budget of a semi-arid urban catchment. *Journal of Hydrology* **542**, 744–755.

Fletcher, T., Andrieu, H. & Hamel, P. 2013 Understanding, management and modeling of urban hydrology and ITS consequences for receiving waters: a state of the art. *Advances in Water Resources* **51**, 261–279.

Fletcher, T., Shuster, W., Hunt, W., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J., Mikkelsen, P., Rivard, G., Uhl, M., Dagenais, D. & Viklander, M. 2015 SUDS, LID, BMPs, WSUD and more - The evolution and application of terminology surrounding urban drainag. *Urban Water Journal* **12** (7), 525–542.

Grunewald, U. & Schoenheinz, D. 2014 Acidification of water bodies due to mining activities in the Lower Lusatia region – causes, severity and remedial conceptions. *Hydrologie Und Wasserbewirtschaftung/Hydrology and Water Resources Management* **58** (5), 274–285.

Haase, D. 2009 Effects of urbanisation on the water balance – a long-term trajectory. *Environmental Impact Assessment Review* **29**, 211–219.

Huang, C., Vause, J., Ma, H. & Yu, C. 2013 Urban water metabolism efficiency assessment: integrated analysis of available and virtual water. *Science of the Total Environment* **452–453**, 19–27.

Hunter, P., Colford, J., LeChevallier, M., Binder, S. & Berger, P. 2001 Waterborne diseases. *Emerging Infectious Diseases* **7** (3), 544.

Imteaz, M., Abdallah, S., Ataur, R. & Amimul, A. 2011 Optimisation of rainwater tank design from large roofs: a case study in Melbourne, Australia. *Resources, Conservation & Recycling* **55** (11), 1022–1029.

Jain, S. K. & Singh, V. P. 2019 *Engineering Hydrology: an Introduction to Processes, Analysis, and Modeling*. McGraw-Hill Education, New York

Kenway, S., Gregory, A. & McMahon, J. 2011 Urban water mass balance analysis. *Journal of Industrial Ecology* **15** (5), 693–706.

Kuller, M., Bach, P. M., Ramirez-Lovering, D. & Deletic, A. 2017 Framing water sensitive urban design as part of the urban form: a critical review of tools for best planning practice. *Environmental Modelling & Software* **96**, 265–282.

Leeuwen, C., Frijns, J. & Wezel, A. 2012 City blueprints: 24 indicators to assess the sustainability of the urban water cycle. *Water Resources Management* **26** (8), 2177–2197.

Lenny, W., Pham, T., Vi, L., Caroline, S., Manouchehr, A., Nguyen, H., Pham, H. & Michael, B. 2011 Arsenic pollution of groundwater in Vietnam exacerbated by deep aquifer exploitation for more than a century. *Proceedings of the National Academy of Sciences* **108** (4), 1246.

Li, C., Peng, C., Chiang, P.-C., Cai, Y., Wang, X. & Yang, Z. 2019 Mechanisms and applications of green infrastructure practices for stormwater control: A review. *Journal of Hydrology* **568**, 626–637.

Lloyd, S. D., Wong, T. H. F. & Chesterfield, C. J. 2002 *Water Sensitive Urban Design: A Stormwater Management Perspective*. CRC for Catchment Hydrology, Clayton

Maksimović, Č., Prodanović, D., Boonya-Aroonnet, S., Leitão, J. P. & Djordjević, S. 2010 Overland flow and pathway analysis for modelling of urban pluvial flooding. *Journal of Hydraulic Research* **47** (4), 512–523.

Martinez, S. E., Escolero, O. & Wolf, L. 2010 Total urban water cycle models in semiarid environments – quantitative scenario analysis at the area of San Luis Potosi, Mexico. *Water Resources Management* **25**, 239–263.

Mcpherson, M. 1973 Need for metropolitan water balance inventories. *Journal of the Hydraulics Division* **99** (1), 1837–1848.

Memon, F. A. & Ward, S. 2015 *Alternative Water Supply Systems*. IWA Publishing, London.

Meng, X. & Kenway, S. 2018 Analysing water sensitive urban design options – using water mass balance to analyse hydrological performance of water sensitive urban design options in infill development. *Water* **3** (4), 1–18.

Meng, X., Li, X., Nghiem, L. D., Ruiz, E., Johir, M. A., Gao, L. & Wang, Q. 2022 Improved stormwater management through the combination of the conventional water sensitive urban design and stormwater pipeline network. *Process Safety and Environmental Protection* **159**, 1164–1173.

Mentens, J., Raes, D. & Hermy, M. 2006 Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landscape and Urban Planning* **77** (3), 217–226.

Meyer, W. & Turner, B. 1992 Human population growth and global land-use/cover change. *Annual Review of Ecology and Systematics* **23** (1), 39–61.

Moravej, M., Renouf, M., Lam, K., Kenway, S. & Urich, C. 2020 Site-scale Urban Water Mass Balance Assessment (SUWMBA) to quantify water performance of urban design-technology-environment configurations. *Water Research* **188**, 116477–116477.

Moravej, M., Renouf, M. A., Kenway, S. & Urich, C. 2022 What roles do architectural design and on-site water servicing technologies play in the water performance of residential infill? *Water Research* **213**, 118109–118109.

Ngo, T. T., Yazdi, J., Mousavi, J. S. & Kim, J. H. 2016 Linear system theory-based optimization of detention basin's location and size at watershed scale. *Journal of Hydrologic Engineering* **21**, 6016013.

Nichols, P., Lucke, T. & Drapper, D. 2015 Field and evaluation methods used to test the performance of a Stormceptor® class 1 stormwater treatment device in Australia. *Sustainability* **7** (12), 16311–16323.

Nie, W., Yuan, Y., Kepner, W., Nash, M., Jackson, M. & Erickson, C. 2011 Assessing impacts of Landuse and Landcover changes on hydrology for the upper San Pedro watershed. *Journal of Hydrology* **407** (1), 105–114.

Novotny, V., Ahern, J. & Brown, P. 2010 *Water Centric Sustainable Communities: Planning, Retrofitting, and Building the Next Urban Environment*. Wiley, Hoboken.

Nunes, R. T. S., Prodanoff, J. H. A., Nunes, B. & Freitas, M. A. V. 2011 Incorporating water sensitive urban design (WSUD) practices into the planning context: the conceptual case for lot-scale developments. *WIT Transactions on Ecology and the Environment* **167**, 341.

Ozgun, K., Moulis, A. & Leardini, P. 2017 *Water-Potential-Mapping for Urban Flood/Drought Resilience: A Holistic Approach to Sustainable Spatial Planning and Design by Augmenting Use, Reuse and Storage Capacity of Storm Water in South East Queensland*. Syros-Delos-Mykonos Islands, University of Thessaly, Volos.

Payne, E., Hatt, B., Deletic, A., Dobbie, M., McCarthy, D. & Chandrasena, G. 2015 *Adoption Guidelines for Stormwater Biofiltration Systems, 2* edn. CRCWSC, Melbourne.

Peña-Guzmán, C., Melgarejo, J., Prats, D., Torres, A. & Martínez, S. 2017 Urban water cycle simulation/management models: a review. *Water* **9** (285), 1–29.

Quattro, J., Greig, T., Coykendall, D., Bowen, B. & Baldwin, J. 2002 Genetic issues in aquatic species management: The shortnose sturgeon (Acipenser brevirostrum) in the southeastern United States. *Conservation Genetics* **3** (2), 155–166.

Raadgever, T. & Hegger, D. 2018 *Flood Risk Management Strategies and Governance*. Springer International Publishing, Cham.

Renouf, M. A., Kenway, S. J., Lam, K. L., Weber, T., Roux, E., Serrao-Neumann, S., Choy, D. & Morgan, E. A. 2018 Understanding urban water performance at the city-region scale using an urban water metabolism evaluation framework. *Water Research* **137**, 395–406.

Shafique, M. 2018 Green roof benefits, opportunities and challenges – a review. *Renewable & Sustainable Energy Reviews* **90**, 757–773.

Shahzad, H., Myers, B., Boland, J., Hewa, G. & Johnson, T. 2022 Stormwater runoff reduction benefits of distributed curbside infiltration devices in an urban catchment. *Water Research* **215**, 118273–118273.

Sharma, A. K., Begbie, D., Gardner, T., Begbie, D. & Sharma, A. 2015 *Rainwater Tank Systems for Urban Water Supply : Design, Yield, Energy, Health Risks, Economics and Social Perceptions*. IWA Publishing, London.

Thom, J., Szota, C., Coutts, A., Fletcher, T. & Livesleya, S. 2020 Transpiration by established trees could increase the efficiency of stormwater control measures. *Water Research* **173**, 115597–115597.

Vanwoert, N., Rowe, B., Andresen, J., Rugh, C., Fernandez, T. & Xiao, L. 2005 Green roof stormwater retention: effects of roof surface, slope, and media depth. *Journal of Environmental Quality* **34** (3), 1036–1044.

Verbeeck, K., Van Rompuy, R., Hermy, M. & Van Orshoven, J. 2014 Infiltrating into the paved garden – a functional evaluation of parcel imperviousness in terms of water retention efficiency. *Journal of Environmental Planning and Management* **57**, 1552–1571.

Victorian Government 2014 *Growing Green Guide: A Guide to Green Roofs, Walls and Facades in Melbourne and Victoria, Australia*. State Government of Victoria, Melbourne.

Wahl, T. & Plant, N. 2015 Changes in erosion and flooding risk due to long-term and cyclic oceanographic trends. *Geophysical Research Letters* **42** (8), 2943–2950.

Whittinghill, L. J., Rowe, B. D., Andresen, J. A. & Cregg, B. M. 2014 Comparison of stormwater runoff from sedum, native prairie, and vegetable producing green roofs. *Urban Ecosystems* **18**, 13–29.

Wong, T. H. 2015 Water sensitive urban design – the journey thus far. *Australasian Journal of Water Resources* **10** (3), 213–222.

Wong, T. & Brown, R. 2009 The water sensitive city: principles for practice. *Water Science & Technology* **60**, 673–681.

Wong, T. H., Allen, R., Brown, R. R., Deletic, A., Gangadharan, L., Gernjak, W., Jakob, C., Johnstone, P., Reeder, M.., Tapper, N., Vietz, G. & Walsh, C. J. 2013 *blueprint2013–Stormwater Management in a Water Sensitive City*. Cooperative Research Centre for Water Sensitive Cities, Melbourne.

Zhang, K., Manuelpillai, D., Raut, B., Deletic, A. & Bach, P. M. 2019 Evaluating the reliability of stormwater treatment systems under various future climate conditions. *Journal of Hydrology 568*, 57–66.

First received 4 December 2021; accepted in revised form 7 June 2022. Available online 17 June 2022