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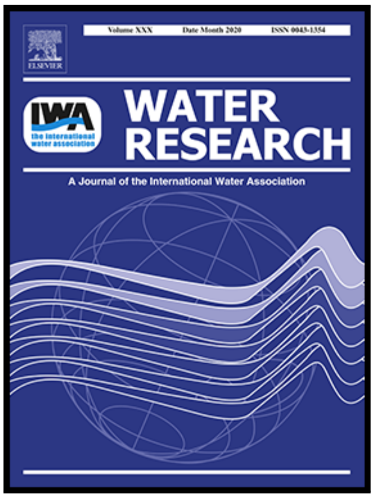

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Highlights

- A new method was developed to quantify the water performance of urban developments
- SUWMBA can inform better urban development and integrated urban water management
- Conflicting objectives need integrated solutions to be simultaneously met
- No one design-technology configuration fits all environmental contexts
- Restoring evapotranspiration to the natural case is easier than other hydrological flows

Site-scale Urban Water Mass Balance Assessment (SUWMBA) to quantify water performance of urban design-technology-environment configurations

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Abstract

Historically, little consideration has been given to water performance of urban developments, such as “hydrological naturalness” or “local water self-sufficiency”. This has led to problems such as increased stormwater runoff, flooding, and lack of local contributions to urban water security. Architectural design, water servicing technologies and environmental conditions are each known to influence water performance. However, most existing models have overlooked the integration of these factors. In this work, we asked ‘*how the water performance of urban developments at site-scale can be quantified, with joint consideration of architectural design, water servicing technologies, and environmental context (i.e.*

climate and soil)'. Answering this question led to the development of a new method and tool called Site-scale Urban Water Mass Balance Assessment (SUWMBA). It uses a daily urban water mass balance to simulate design-technology-environment configurations. Key features include: (i) a three-dimensional boundary focussed on the "entity" of development (ii) a comprehensive water balance accounting all urban water flows, (iii) methods that include key variables capturing the interactions of natural, built-environment and socio-technological systems on water performance. SUWMBA's capabilities were demonstrated through an evaluation of a residential infill development case study with alternative design-technology-environment configurations, combining three dwelling designs, seven water technologies and three environmental contexts. The evaluation showed how a configuration can be identified that strikes a balance between the conflicting objectives of achieving the desired dwelling densities whilst simultaneously improving water performance. For two climate zones, the optimal configuration increases the total number of residents by 300% while reducing the imported water per capita and stormwater discharge by 45% and 15%, respectively. We infer that SUWMBA could have strong potential to contribute to performance-based urban design and planning by enabling the water performance of dwelling designs to be quantified, and by facilitating the setting of locally-specific water performance objectives and targets.

Keywords: water sensitive urban design (WSUD), performance-based urban planning, urban infill, integrated urban water system modelling, urban water metabolism, recycling

1. Introduction

Urban development, especially infill, provides a great opportunity to reshape cities and address the water-related challenges (Newton et al., 2012) such as flooding, drought, reduced water security, and urban heat, among others. However, this opportunity is not being embraced, and business-as-usual development is recognised to have significant negative water-related impacts (Murray et al., 2011; Renouf et al., 2019). It is generally well established that water extraction from and waste discharge to the environment to support urban areas needs to be reduced, and urban hydrology needs to mimic the pre-urbanised/natural hydrological flows. This is being promoted in a variety of programs: Water Sensitive Urban Design (Australia), Sponge City (China), Nature-Based Solutions (EU), and Low Impact Development (USA) (Fletcher et al., 2015). However, evidence for how best to do this at the local scale is missing due to a lack of suitable methods.

This work aims to improve the quantification of the water performance of residential dwelling design to provide evidence that can support better urban development. “Water sensitive performance” or “water-wise performance” includes biophysical, societal, and ecological attributes outlined by Rogers et al. (2020) and International Water Association (2016). In this study, "water performance" refers to the biophysical attributes which represents a set of objectives related to the protection and functionality of water in the urban landscape, including the maintenance of pre-urbanised hydrological flows (i.e. hydrological naturalness) and water resource management (Renouf et al., 2020a). The societal and ecological attributes are beyond the scope of the current study.

Architectural design and technology solutions are main Opportunities for improving water performance. Architectural design solutions aim to accommodate greater dwelling density whilst retaining green space and permeability to restore pre-urbanised hydrology and improve liveability. Examples include sustainable urban greening strategies (Jim, 2013), water sensitive planning (Carmon and Shamir, 2010), and improved infill housing design (London et al., 2020; Murray et al., 2011). Technological solutions aim to generate supplementary water supplies to reduce reliance on imported water and to mitigate the effects of changed hydrology. Examples include water harvesting and recycling, water-efficient appliances/fixtures and runoff retention, detention and infiltration measures. An excessive number of solutions emerge when architectural design and technologies are jointly considered (hereafter design-technology configurations). How to systematically quantify, evaluate, and compare these configurations is not clear.

In conventional urban design and planning, 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. Collaborative urban design and planning is suggested to foster better integration (McEvoy et al., 2018; Serrao-Neumann et al., 2017; van de Ven et al., 2016). However, it needs to be supported by quantitative evidence of the water performance of design-technology configurations. Furthermore, urban designers and architects typically follow planning and construction policy and regulations. Influencing and changing these policies also requires scientific evidence of the benefits.

A review of current methods that evaluate aspects of water performance is provided in Table 1. The review showed that current methods have three main limitations in terms of our objectives: (i) inappropriate system boundary (i.e. inappropriate assessed entity and spatial scale); (ii) inadequate consideration of urban water flows leading to incomplete water performance evaluation (with some exceptions discussed later); (iii) lack of appropriate architectural design and technology variables or their integration. The assessed entity for most methods is the urban water infrastructure, which is useful for engineering design purposes, but less useful for informing urban design and planning. Methods with a landscape perspective, which assess the urban entity (indicated by UE in the table), are generally at large urban scale (i.e. city-scale) and do not have the required detail to observe the design-technology interactions. Current methods often do not consider both natural and anthropogenic flows, leading to an incomplete water performance evaluation of the solutions and their impacts on the urban water cycle. Methods using urban water mass balance (i.e. with black ticks for both 'natural and 'anthropogenic' flows) can be useful for our purposes as they consider all urban water flows, but have been used for large urban scale. Some methods focusing on urban drainage (e.g. SWMM, MUSIC, MIKE URBAN, etc.) are too complex for users outside the engineering community (Elliott and Trowsdale, 2007). Our review did not cover sustainability rating systems (e.g. BREEAM, LEED) due of limitations that have been previously described, including lack of hydrological performance, local condition consideration, and strong scientific basis (Berardi, 2012; Komeily and Srinivasan, 2015; Sharifi and Murayama, 2013; Siew et al., 2013).

To fill the gap in methods that suit our purposes, we sought to find out "*how the water performance of urban developments at site-scale can be quantified, with joint consideration of architectural design, water servicing technologies, and environmental context (i.e. climate and soil)"*? The result was the Site-scale Urban Water Mass Balance Assessment (SUWMBA) tool. A key novelty of SUWMBA is that it enables systematic quantification and evaluation of architectural design and water servicing technologies, using quantitative water performance indicators. Three key innovations to answer the research question were the underpinning urban water mass balance, explicit definition of the physical system boundary of urban developments (i.e. landscape perspective), and integration of key variables representing the interactions of natural, built-environment and socio-technological systems, which are elaborated in the discussion section. This novel development helps overcome current limitations of methods including inappropriate system boundary, partial consideration of urban water flows, lack architectural design variables, and limited range of technologies (refer to Table 1).

This paper describes SUWMBA's development and its underlying methods (section 2). SUWMBA's capabilities are demonstrates through a case study in sections 3 and 4. We answer the research question in Section 5 by highlighting the attributes of the SUWMBA tool that were found to be needed to achieve our objective. Limitations and future research needs are discussed in detail in Section 5.1. Our overall conclusions are provided in section 6.

Table 1.

2. Description of SUWMBA method

2.1. Development

SUWMBA is an integrated urban water system model. It integrates (i) all urban water flows (natural and anthropogenic), (ii) decentralised and centralised urban water systems, and (iii) architectural design and water servicing technologies, framed by the environmental context. SUWMBA is based on urban water mass balance originally developed by Kenway et al. (2011) and further developed by Renouf et al. (2018) and Farooqui et al. (2016) for city and precinct scale applications. SUWMBA advances this approach for applications at the site-scale. Figure 1 details how the urban water mass balance is modelled in SUWMBA. Arrows depict the movement of water between various surfaces and storages. The transformation of water inflows into outflows are due to interactions between the hydrological and socio-technological systems. Sections 2.2-2.7 describe how these are modelled in SUWMBA. The urban water mass balance is derived from the estimated urban water flows as per equation (1). Water performance indicators are derived from this data, as described in section 2.8. All parameters, flows, and acronyms used in SUWMBA are explained in Table 2.

SUWMBA was developed in Microsoft Excel's Visual Basic for Applications (Excel-VBA) and MATLAB. Both versions have the same objective, which is to quantify water performance of urban design-technology-configurations. The Excel version is a more rapid tool with in-built libraries, and suited for use in collaborative urban design and planning context. It is developed as part of 'Water sensitive outcomes for infill developments' project (IRP4) of the Cooperative Research Centres for Water Sensitive Cities (CRCWSC) (https://watersensitivecities.org.au/content/project-irp4/). The MATLAB version is more suited for performing high-resolution urban water mass balance and automating scenario analysis, hence more useful for research purposes. Details about their differences and screenshots of SUWMBA's user interface are presented in the Supplementary Material. The MATLAB version was used in this work to automate calculations. Further details of the Excel version can be found in the tool's user manual (Moravej et al., 2020). For accessing SUWMBA contact the corresponding author.

SUWMBA's development was informed by input from stakeholders with expertise in building and landscape design, urban water, policy, research, teaching, community engagement, and environmental management. Details of tool testing by the stakeholders, and the synthesis of their feedback that informed the tool's iterative development can be found in the Supplementary Material. The role of tools such as SUWMBA in real-world knowledge generation, decision making, and collaborative planning, is an interesting extension of this work. However, it is not explored significantly in this paper, instead, we focus on its primary function of quantifying water performance.

Figure 1.

Table 2.

2.2. Urban water mass balance

The urban water mass balance is a key output from SUWMA. Equation (1) shows the water mass balance developed for the defined urban system boundary (Figure 1), the terms and units of which are defined in Table 2. It is based on the principle of mass conservation such that "the sum of inflows = the sum of outflows + change in storage". This equation holds for any given time period and urban system boundary. Following Farooqui et al. (2016) approach, recycling and reuse (W_{ReGW} and W_{ReWW}) were accounted for by considering them as both a flow out of the urban system boundary and then a flow back into the system boundary as an input.

$$\begin{aligned} &P + W + \left(W_{Rain} + W_{SW} + W_{ReGW} + W_{ReWW} + W_{ReAqu}\right) = \\ &ET + \left(SW + SW_{RC}\right) + \left(WW + WW_{RC} + W_{ReGW} + W_{ReWW}\right) + GW + I + \Delta S \end{aligned} \tag{1}$$

2.3. Urban system boundary and temporal resolution

The three-dimensional urban system boundary (Figure 1) is defined horizontally by the spatial scope of the urban area being assessed (defined by user), and vertically from rooftop/treetops to the root zone (i.e. 1 m below surface), consistent with the three-dimensional definition used by Renouf et al. (2018) and Kenway et al. (2011).

SUWMBA simulates all water flows on a daily time-step but the output can be reported at any larger time scales. Some flows happen in shorter time frames, such as seconds for toilet flushing and minutes for rainfall-runoff, and multiple times per day. However, sub-daily time-step was not considered because it increases the complexity and input data requirements, which would limit SUWMBA's appeal for informing collaborative design and planning processes. Complexity is recognised as one of the main barriers to the adoption of integrated urban water models (Bach et al., 2014). More detail on the temporal resolution is provided in the Supplementary Material.

2.4. Hydrological model

Hydrological flows (infiltration, evapotranspiration and runoff) are estimated using a widely-used algorithm adapted from Chiew and McMahon (1999), and used in the MUSIC model (eWater, 2011). The algorithm was modified so that SUWMBA can also account for anthropogenic flows and technologies that influence hydrological flows, such as irrigation, harvest and use of rainwater and stormwater runoff, permeable paving, and green roofs. The model treats some of the water technologies (green roof and permeable pavement) as land cover types, and simulates their water flows based on their specifications (e.g. infiltration rate, thickness, storage capacity, etc.). Hydrological flows are estimated for each land cover depending on its impervious fraction, storage capacity, and soil type. This estimation approach enables modelling of hydrological connectivity between different surfaces, which is an important urban design aspect. The hydrological model can be calibrated for a specific context, however, general calibrations exist for Australian capital cities (eWater, 2011) and for specific soil types (Myers et al., 2015).

The hydrological model used in SUWMBA is presented in Figure 2 and equations (2)-(17) (see Table 2 for the definitions of the term). First, the units for hydrological parameters were converted from mm to m^3 based on the land cover areas (equations (2)-(5)). Precipitation on impervious surfaces generates impervious runoff once a small initial loss is exceeded (equation (6)). The initial loss storage is assumed to fully evaporate at the end of each day. Irrigation demand is calculated using soil moisture deficiency defined by the irrigation trigger factor (equation (7)), which enables exploring the potential impacts of different level of water restrictions and irrigation habits of residents on water performance. Irrigation is set to zero for impervious and non-irrigated pervious surfaces. Infiltration is calculated using an infiltration rate defined by soil moisture storage as an exponential function (equation (8)). Maximum infiltration occurs when the soil moisture is empty and gradually decreases to a minimum when soil moisture is full. Infiltration excess forms one part of the stormwater runoff from pervious surfaces (equation (9)). The other part is generated if the infiltrated water exceeds soil moisture store capacity (equation (10)), called the saturation excess. Evapotranspiration is subtracted from soil moisture (equation (11)). Water further percolates and recharges the storage aquifer as a constant percentage of soil moisture above field capacity (equation (12)). The soil moisture is calculated (equation (13)) considering all inflows and outflows to/from the soil. Stormwater runoff is generated as a summation of impervious runoff, infiltration excess and saturation excess (equation (14)). Stormwater runoff can flow to other land cover surfaces or leave the urban system boundary, depending on the urban design configuration. Stormwater discharge (*SW*, see Table 2 and Figure 1) is a summation of the stormwater of land covers directed to the outlet of the urban system boundary (equation (17)). Finally, evapotranspiration and infiltration are summed up for all land covers (equations (15) and (16)).

$$IMPSC^i = impsc^i \times A^i \times IMPF^i \div 1000 \tag{2}$$

$$FC^i = fc^i \times A^i \times \left(1 - IMPF^i\right) \div 1000 \tag{3}$$

$$COEFF^i = coeff^i \times A^i \times \left(1 - IMPF^i\right) \div 1000 \tag{4}$$

$$SMSC^{i} = smsc^{i} \times A^{i} \times \left(1 - IMPF^{i}\right) \div 1000 \quad (5)$$

$$IMP_{t}^{i} = \max\left\{\left(P_{t}^{i} - IMPSC^{i}\right), 0\right\} \quad (6)$$

$$IRR_{t}^{i} = \begin{cases} \left(IRRT_{t}^{i} \times FC^{i}\right) - S_{t-1}^{i} + P_{t}^{i} + SW_{t}^{i-1} & S_{t-1}^{i} + P_{t}^{i} + SW_{t}^{i-1} > IRRT^{i} \times FC^{i} \\ 0 & else \end{cases} \quad (7)$$

$$INF_{t}^{i} = \min\left\{\left(COEFF^{i} \times e^{\left(-SQ^{i} \times \frac{S_{t-1}^{i}}{SMSC^{i}}\right)}\right), P_{t}^{i} + IRR_{t}^{i} + SW_{t}^{i-1}\right\} \quad (8)$$

$$INFEX_{t}^{i} = P_{t}^{i} + IRR_{t}^{i} + SW_{t}^{i-1} - INF_{t}^{i} \quad (9)$$

$$SATEX_{t}^{i} = \max\left\{\left(S_{t-1}^{i} - SMSC^{i}\right), 0\right\} \quad (10)$$

$$ET_{t}^{i} = \min\left\{\left(10 \times \frac{S_{t-1}^{i}}{SMSC^{i}}\right), \left(K_{c}^{i} \times ET_{0t}^{i}\right)\right\} + \min\left\{P_{t}^{i}, IMPSC^{i}\right\} \quad (11)$$

$$I_{t}^{i} = \max\left\{\left(RFAC^{i} \times \left(S_{t-1}^{i} - FC^{i}\right)\right), 0\right\} \quad (12)$$

$$S_{t}^{i} = S_{t-1}^{i} + INF_{t}^{i} - SATEX_{t}^{i} - I_{t}^{i} - ET_{t}^{i} \quad (13)$$

$$SW_{t}^{i} = IMP_{t}^{i} + INFEX_{t}^{i} + SATEX_{t}^{i} \quad (14)$$

$$ET_{t} = \sum_{i} ET_{t}^{i} \quad (15)$$

$$I_{t} = \sum_{i} I_{t}^{i} \quad (16)$$

$$SW_{t} = \sum_{i} SW_{t}^{i} \quad (17)$$

Figure 2.

2.5. Water demand model

Indoor water demand is estimated using algorithms developed by Makki et al. (2015) for six indoor water end-uses (toilet flushing, washing machine, dishwasher, shower, tap, and bath). The algorithms were derived from a linear regression of a large, high-resolution water use dataset for South East Queensland in Australia, and have been found to be predictive of indoor water use in Australia generally. It enables consideration of consumer water use behaviours (frequency, duration, etc.), appliances and water fixtures (efficiency level, type, capacity, etc.), demographics (gender, age profiles), and household socio-demographics (income). Outdoor water is estimated using equation (7), summed up for all land covers to give total outdoor water demand. Previous studies have shown that built-environment variables such as lot size, land cover, housing value (as a proxy of income), density, and housing age (as a proxy of efficiency of appliances, maturity of garden, and leakage) are influential (Stoker et al., 2019). The combination of indoor and outdoor water demand models in SUWMBA allows for quantifying the impacts of these variables on water performance and exploring the influence of behaviours and the built environment on water use.

2.6. Water harvesting and storage model

A storage behaviour model is used to model the supply-demand behaviour of each storage in the assessed urban system. It is a daily water mass balance for each storage that models how the storage meets the demand set by the water demand model and the demand-supply connection matrices (see section 2.7), for given tank size and inflow calculated from the hydrological model. The storage behaviour model uses a 'yield-before-spill' operating rule (Fewkes and Butler, 2000; Makropoulos et al., 2009) (see equations (18) to (21) and terms defined in Table 2).

$$V_t^q = V_{t-1}^q + Q_t^q - D_t^q \tag{18}$$

Subject to

$$0 \le V_t^q \le V_{max}^q$$

$$Y_t^q = \min \begin{cases} D_t^q \\ V_{t-1}^q + Q_t^q \end{cases} \tag{19}$$

$$V_t^q = \min \begin{cases} V_{t-1}^q + Q_t^q - Y_t^q \\ V_{max}^q \end{cases} \tag{20}$$

$$Spill_t^q = \max \begin{cases} V_{t+1}^q + Q_t^q - D_t^q - V_{max}^q \\ 0 \end{cases} \tag{21}$$

2.7. Linking water supply and demand

Supplementary water supplies (i.e. harvested rainwater and stormwater runoff, and reused/recycled greywater/wastewater) are linked to their corresponding demand. SUWMBA can explicitly define (i) the connection between different water sources and end-uses (matrix *SD*), (ii) the contribution of end-uses as an input to the treatment system for reuse/recycling (matrix *ReM*), and (iii) the priority of usages when multiple sources are available for the same end-use. Matrix *SD* is a matrix array of water sources and end-uses, which can represent the priority usages when multiple sources are available for the same end-use. Arrays in *ReM* are binary indicating inputs to the treatment system or the storage from specified end-use component. See the Supplementary Material for an example.

The structure of *SD* and *ReM* matrices allows for flexible consideration of any treatment systems and associated water quality implications. This novel feature enables SUWMBA's users to explore the impacts of treatment systems to meet a range of end-uses on water performance. For example, they can explore what would be the water performance implication of treating harvested rainwater (i.e. a water source) to drinking quality compared to a less sophisticated treatment system that is only suitable for irrigation purposes. Moreover, current local policies levy limitations on suitable end-uses depending on water quality and the type of dwellings (e.g. indoor greywater reuse is not allowed for multi-dwellings).

SUWMBA can be used to test these local policies and the potential (dis)benefits if the policies were to change.

2.8. Water performance indicators

Water performance indicators, derived from the urban water mass balance data, are another key output from SUWMBA. They were based on indicators proposed by Renouf et al. (2020a), the full list of which can be found in the Supplementary Material. A sub-set of three indicators were used to demonstrate SUWMBA in this paper: hydrological naturalness, imported water use per capita, and water self-sufficiency.

Hydrological naturalness shows the extent to which hydrological flows of the urban system have changed relative to a pre-urbanised case, for evapotranspiration (*ET*), stormwater discharge (*SW*), and infiltration (*I*). It is a ratio of the annual volume of the hydrological flow in the assessed case to that of the pre-urbanised case, expressed as a percentage. It helps gauge progress toward mimicking natural flows.

Imported water per capita and water self-sufficiency represent the reliance of the assessed urban system on water mains. These water performance indicators can be improved through a combination of i) reducing water demand, ii) utilizing supplementary water sourced from within the urban system (i.e. internalization of supply), and iii) reuse/recycling and cascading (Agudelo-Vera et al., 2013). Self-sufficiency is defined as the fraction of demand that is met by water sourced from within the urban system boundary.

3. Case study testing of design-technology-environment configurations

The purpose of the case study was to demonstrate the capabilities of SUWMBA for understanding interactions between design, water technologies and the environmental context. Water performance was quantified for twenty-one design-technology configurations (see Figure 3), combining three dwelling architectural designs (Table 3) and seven technologies (Table 4). The identifiers for the configurations are denoted by the dwelling design typologies (A = single-storey detached houses, B = sub-divided single-storey houses, and C = two-storey semi-detached units) and the technology (Table 4). For example, B_GWR represents sub-divided single-storey houses with greywater reuse (see Figure 3). The configurations were modelled in the context of three Australian cities (Brisbane, Melbourne, and Adelaide), representing sub-tropical, temperate, and semi-arid climates with different soil types.

The architectural designs were sourced from London et al. (2020), and represent typical dwelling typologies associated with suburban densification occurring in Australian capital cities (Murray et al., 2011). They are fundamentally different in terms of the architectural design principles (London et al., 2020). This study focuses on the water performance of these designs with different technologies and under different environmental conditions. Other (dis)benefits such as (green) space quality, thermal comfort, land consumption, density, and liveability; are also important and can be found elsewhere (Renouf et al., 2020b; Renouf et al., 2020c).

Design A is the reference case representing 71% of current dwelling types in Australia (ABS, 2016). It is characterised by generous indoor and outdoor private space providing green space enabling infiltration, evapotranspiration and associated benefits (London et al., 2020). Being a low-density typology, it has a high land consumption, leading to extensive horizontal growth and low efficiency in utilizing land.

Design B represents the business-as-usual infill development occurring in Australia, which is sub-division of single lots to achieve a higher density than design A. It typically characterised by large impervious areas (i.e. building footprints, driveways, parking spaces, etc.) that leave little or no quality outdoor space for permeable surfaces, greening, and mature trees (London et al., 2020). Potential negative water-related impacts of design B have been mentioned in the literature (Murray et al., 2011; Renouf et al., 2019), but quantifications of these impacts are rare.

Design C has been proposed as an alternative infill development typology, that aims for similar or higher dwelling density to design B, but maintaining outdoor spaces on the site (London et al., 2020; Murray et al., 2011). It provides more capacity to plan and incorporate water sensitive design solutions by consolidating lots rather than sub-dividing.

The occupancies (residents per dwelling) were assumed based on the statistics for the relevant city, 2.5 for Brisbane and Adelaide and 2.3 for Melbourne (ABS, 2016). So, the total number of residents provided by designs A, B, and C are respectively 5, 10, and 15 in Brisbane and Adelaide; and 4.6, 9.2, and 13.8 in Melbourne.

A pre-urbanised case (PRE) for each city was also evaluated as a reference case for the hydrological flows. The PRE was assumed to be 90% short vegetation and 10% bare soil.

Daily flows were simulated for each configuration over a 14-year period from 01/01/2005 to 31/12/2018, using daily rainfall and potential evapotranspiration data (BOM, 2019). This period includes wet and dry years so the design-technology configurations could be considered for a range of climatic conditions.

Figure 3.

The efficiency of appliances and fixtures were characterised using Water Efficiency Labelling Standards (WELS) (www.waterrating.gov.au). WELS is a water rating scheme that labels appliances and fixtures from 1 to 6 stars depending on the water consumption: the more stars the more water efficient. We assumed 3-star appliances and fixtures in most cases. In the 'efficient appliances and fixtures' (EA) technology case, 5-star appliances and fixtures was assumed (see Table 4). Water rating label of 5- and 6-starts are considered 'efficient' according to WELS. SUWMBA was ran for an average Australian water use behaviour, which consists of 7.1 minutes shower duration and average tap usages of 1 minute per instance. Other indoor water demand parameters are defined in the Supplementary Material. In terms of outdoor water demand, the base case assumes all vegetated areas are irrigated. The crop factors and irrigation trigger factors defined in Figure 3. The parameters of technologies are detailed in Table 4.

Table 3.

Table 4.

4. Results

The urban water mass balance and water performance indicators generated for the case study configurations demonstrate the function of SUWMBA for jointly considering architectural design, water technologies, and environmental context. The urban water mass balance results (Table 5-7) allowed us to observe how the key influencing variables of the design-technology-environment configurations influence all urban water flows. The results of selected performance indicators (Table 8, Figure 4 and Figure 5) allowed us to draw out the interactions between design, technology and environment.

4.1. Influence of design-technology-environment variables on hydrology

Comparing the water mass balance data of different cities (Table 5-7) shows that environmental context has the most influence on the hydrological flows. The flows are greater for Brisbane than Melbourne and Adelaide, due to higher precipitation and potential evapotranspiration in Brisbane's sub-tropical climate (see $\overline{P}$ and $\overline{ET_0}$ values in Figure 3). Soil characteristics, particularly soil moisture store capacity, are also influential. Therefore, climate and soil variables are key variables in SUWMBA.

The degree in which architectural design influences water performance can be observed in the hydrological naturalness ratios (Table 8) by comparing A_BC, B_BC, and C_BC, excluding the impacts of technologies. In general, architectural designs negatively impact the hydrology by increasing *SW* (>100%) and decreasing *ET* and *I* (<100%) to varying degrees (exceptions discussed later), corresponding well with imperviousness. The highest impact was seen for B_BC followed by C_BC and A_BC designs. For example, in Adelaide B_BC was found to increase

SW to 301%, reduce *I* and *ET* to 24% and 80%, due to it having the highest impervious fraction, with 79% of the site is covered with ‘hard’ surfaces such as roof and pavement (see Table 3). Therefore, land cover characteristics, influenced strongly by architectural design, are key variables in SUWMBA.

ET naturalness ratios for A_BC in Melbourne and Adelaide, and for C_BC in Adelaide were estimated to be more than 100%, which is due to irrigating vegetated areas by imported water (*W*). Irrigation water subsequently evapotranspires, adding to natural evapotranspiration. The irrigated areas in A_BC and C_BC designs are 59% and 38% of the total site (see Table 3). The irrigation of these areas is enough to offset the loss of evapotranspiration due to lost vegetation and more to restore it to pre-urbanised levels. Therefore the extent of vegetated area (whether irrigated or not) is an important land cover variable in SUWMBA. When those areas are irrigated, the conflicting issue of water demand for irrigation needs to be considered (discussed in section 4.2).

Water technologies can mitigate the negative impacts of architectural designs to a degree that depends on interactions with the environmental context, and the architectural design. Table 8 shows that none of the configurations were able to restore pre-urbanised *SW* and *I* to pre-urbanised levels (i.e. *SW* naturalness is always >100% and *I* naturalness is always <100%). However, pre-urbanised *ET* could be restored with certain configurations (e.g. A_GR). Some technologies are more effective in this regard in certain environmental context. For example, GR is the most effective technology to reduce stormwater discharge for design B (due to large roof areas) in Brisbane and Melbourne, but not as effective as SWH in Adelaide.

Configurations with the best water performance in terms of (lowest) *SW*, were found to be those with the largest total storage (S_{max}), in terms of combined built-storage (e.g. tanks) and natural storage (e.g. soil moisture capacity). For example, *SW* naturalness of design A in Melbourne range from 113% to 174%, with A_SWH having the largest storage (36 m^3) being the best, and A_BC having the smallest storage (26 m^3) being the worst. Although the importance of total storage seems obvious, the degree to which it impacts water performance is not well-understood and utilised in urban design. Total storage is a key variable that is determined by both architectural design (e.g. permeable area for facilitating soil moisture storage) and technology specifications (e.g. tank size).

The other important technology variable that influences hydrology is how the tank storages are managed. For example, although S_{max} of B_GR (26 m^3) is larger than of B_SWH (23 m^3) in Adelaide, the latter has a better (lower) *SW* naturalness (216% compared to 222%) because the stormwater store is actively managed to meet the demand. This variable also influences water demand and supply, which is discussed in section 4.2 and 4.3.

Table 5.

Table 6.

Table 7.

Table 8.

4.2. Influence of design-technology-environment variables on water supply and demand

Urbanisation results in more water passing through the urban system compared to the pre-urbanised case due to the import of water into the urban system to meet water demand. The amount of imported water (*W*) depends on the environmental context, the architectural design and the water technologies in place. Architectural design determines the number of occupants and the irrigated areas, which influence indoor and outdoor water demand respectively. The degree to which water demand has been influenced by the architectural design can be observed by comparing *W* of A_BC, B_BC, and C_BC configurations. For example, in Brisbane the values were 376, 515, and 790 m^3/yr for A_BC, B_BC, and C_BC, respectively. Higher water demand observed for C_BC configurations is due to more residents (15 in C compared to 5 in A) and relatively large irrigated areas (see green areas in Table 3).

The environmental context also influences irrigation demand via the amount of precipitation, potential evapotranspiration and soil moisture store capacity (*SMSC*).

For example, Adelaide has a higher water demand than the other locations due to the need for higher and more frequent irrigation because the soil moisture capacity is small, it is not frequently restored by precipitation, and it rapidly depletes due to high evapotranspiration. Water technologies have the greatest potential to reduce demand for *W*, and also wastewater discharge (*WW*). For example, greywater reuse can potentially reduce *W* by 24% (B_GWR in Brisbane) to 32% (C_GWR in Adelaide). The important variables are the water demand (both indoor and outdoor), piping configurations and the supply-demand matrices (i.e. *SD* and *ReM*) and storage volume. Water demand, in turn, depends on the number of dwellings, occupants per dwelling, technology specifications (e.g. appliances efficiency, types, capacity, etc.), and irrigated areas.

Piping configurations, which determine how the water source(s) supply end-uses, is particularly important. For example, B_RWH configuration includes 4 rainwater tanks (one for each dwelling) of $2m^3$ to give a total of $8m^3$, compared to the B_SWH configuration, which consists of 1 stormwater tank of 10 m^3. While the S_{max} of B_SWH is larger than that of B_RWH, the demand for the latter is lower. Higher demand, in this case, strikes a better balance between inflow to and outflow of the rainwater tanks. The balance is a combination of architectural design variables (e.g. roof areas) and associated demand (i.e. pipe configurations). This result indicates how SUWMBA can be used to analyse the implication of different treatment systems on water performance.

The case study assessment has highlighted the need for joint consideration of design-technology-environment variables, because the configurations not only impact water supply and demand but also impact hydrology. Failing to consider the impact of all relevant variables might lead to solutions that improve one aspect of water performance but worsen others, which is explored in the next section.

4.3. Interactions between design, technology and environment

Figure 4 allows us to observe trade-offs between the two objectives of reducing reliance on *W* and reducing *SW*. These indicators are shown together, ranked from highest to lowest in terms of *W* per capita. The *W* per capita for A_BC in Brisbane, Melbourne, and Adelaide is 206, 231, 270 L/person/day, respectively. The highest reduction in *W* per capita in each of the cities ranged from 50% to 61%. The highest reduction in Brisbane and Melbourne was achieved by B_RWH, whereas in Adelaide it was B_GWR. This suggests that no one design/technology configuration performs best in all circumstances.

The reason for the substantial reduction in *W* per capita for the B configurations is two-fold. Firstly, the limited garden area for design B minimises outdoor water demand per capita. Secondly, the presence of supplementary water supplies (i.e. greywater reuse, rainwater harvesting) meet a fraction of the total demand leading to further reduction of *W*. The concept of water-sensitivity promotes water's functionality for greening, cooling, amenity etc., which is lost in design B. So, the lowest *W* per capita, although desirable in terms of water performance, should be considered along with the lost benefits of other functionalities of water.

Design B generally performs best in terms of *W* per capita (50-61% reduction), but ranks among the worst in terms of *SW* (increased by 39-72%), compared to A_BC. These trade-offs show that achieving one water performance objective in isolation (e.g. *W* reduction) without considering other aspects (e.g. *SW*) does not necessarily lead to an overall water performance improvement. Therefore, a comprehensive water performance evaluation across a range of indicators is required to prevent unintended impacts, which was enabled in SUWMBA.

The case study analysis found middle-ground configurations, where multiple water performance objectives are simultaneously met. For example, Figure 4 shows that in C_SWH, *W* per capita is reduced relative to A_BC by roughly 45%, and *SW* is only increased by 14% in Brisbane, and reduced by around 15% in Melbourne and Adelaide. Noting that design C accommodate 300% more residents compared to A, this result shows how architectural design and technologies with certain specifications can work together to achieve multiple objectives in a given environmental context.

This example has shown the potential for joint evaluation of design and water technologies in order to optimise for both water efficiency and stormwater management. A similar process could be performed for other performance indicators that are important in other contexts. For example, increasing evapotranspiration for heat mitigation versus water self-sufficiency.

a) Brisbane	b) Melbourne	c) Adelaide

Figure 4.

Water performance varies under different climatic conditions (eg. wet versus dry years). The indicator of water self-sufficiency was used to show SUWMBA's ability to explore the influence of such variations (Figure 5). Understanding the variability of water performance is important because a configuration that provides a medium level of water self-sufficiency but with low variability might be favourable over the one that has high self-sufficiency in normal or wet years but fails in times of droughts when water self-sufficiency is most needed, as evidenced by the A_SWH case in Melbourne (see Figure 5).

Figure 5 shows that self-sufficiency can vary significantly depending on the configuration. It can be as low as 10% for A_RWH in Adelaide or as high as 36% for A_SWH in Melbourne. The highest degree of water self-sufficiency was found to be achieved by GWR, except for design B in Brisbane and Melbourne. GWR also shows lower variability, meaning that it provides relatively constant water self-sufficiency in both wet and dry years, so it is more reliable than other technologies. The reason is the steady inflow to the GWR system compared to other technologies, which rely on precipitation.

a) Brisbane	b) Melbourne	c) Adelaide
Figure 5.		

5. Discussion

We identified that the SUWMBA needed to have the following innovative features in order to jointly examine the influence of architectural design, water technologies and environmental context:

- A framework based on urban water mass balance;
- A landscape perspective;
- A site-scale system boundary; and
- Methods that are parameterised for key variables to model design-technology interactions.

Urban water mass balance is a fundamental feature of SUWMBA. It enabled an explicit definition of the urban system, which led to a unique landscape perspective.

Satisfying the urban water mass balance required consideration of all water flows into and out the defined system, as well as changes in storage. Therefore, it ensured a holistic quantification of water performance, which could not be achieved by other methods that focus on urban water infrastructure or that capture a partial picture of water flows (see Table 1). The need for a holistic picture of water performance was evidenced by the results showing potentially conflicting water performance objectives, requiring integrated design and technology solutions. The need to account for all urban water flows (both natural and anthropogenic) to prevent unintended problem-shifting has been recognised previously (Renouf et al., 2018). However, this is the first time it has been possible to provide detailed evidence to support the need for integrated solutions, by virtue of higher resolution possible at the site scale.

A novel aspect of SUWMBA is the landscape perspective, which is different from the urban water infrastructure or urban catchment perspectives taken in other methods. Collaborative discussions between urban designers/planners, water managers/engineers, stakeholders, decision-makers, as well as other disciplines (urban heat, liveability, etc.), revolve around land parcels. Therefore, SUWMBA's landscape perspective allows it to be used in collaborative urban design and planning processes. The case study results demonstrated how SUWMBA can be used to identify a 'best' case for a given landscape configuration, which balances multiple and sometimes conflicting objectives. In this case, storage was shown to be an important variable, which can feed into discussions between architects and water engineers about how best to accommodate the required storage into the assessed landscape, and how this would, in turn, affect water performance and urban water infrastructure.

The site-scale system boundary opted for in SUWMBA was motivated by the fact that decisions about architectural design and water technologies are mostly made at this scale. Previous work using this holistic approach has focused on larger urban scales, for example, city- or precinct- scale (e.g. Farooqui et al. (2016); Last (2011); Renouf et al. (2018)), which is useful for strategic planning, but less useful for decision-making at operational level. We found that site-scale provided the higher resolution needed to observe the interactions between design and water technologies.

The case study evaluation enabled the key variables that influence performance to be identified. Key design variables were found to be number of dwellings, land cover characteristics, irrigated area, and occupants per dwelling. Key water technology variables are the total storage capacity, the demand-supply matrix, and the type of supplementary water harnessed. The methods used in SUWMBA needed to be parameterised so that these variables can be modified to explore what-if scenarios. The importance of environmental variables was also highlighted, showing that no one design-technology combination fits all environmental contexts. The inclusion of architectural design and environmental variables is important for developers and planners because it helps them to analyse if choices made in one setting are applicable to another. SUWMBA is an important advancement over other models that generally lack architectural design variables (refer to Table 1). The ability to jointly explore both architectural design variables and water technologies, with consideration of the environmental context, is a feature that differentiates SUWMBA from existing methods.

Preliminary use of SUWMBA to explore most common design-technology configurations seen in Australia showed the impacts of densification is substantially different for alternative configurations (i.e. compare the performance of design B with C). Therefore, decisions about boosting or limiting densification are influenced by the interactions between design, technology and environmental context. This result suggests policies that solely consider densification indicators (e.g. people/ha) might limit creativity for creating integrated solutions in architectural and technology space.

5.1. Limitation and future research needs

SUWMBA does not account for the nutrients and energy implications of water servicing options. There may be synergies and trade-offs between water, nutrients and water-related energy which should also be explored. This is an opportunity for future iterations of the tool.

SUWMBA's conceptualization of water flows may be limited for some regional contexts. For example, it does not account for snow accumulation, which is important for colder climates, or water supply by tankers, which is important for some cities in developing countries. Nor does it provide a good representation of areas with complex groundwater systems. Such aspects would need to be added for use in regions other than Australia.

Future research could consider linking site-scale evaluation using the SUWMBA tool to larger scale frameworks. While SUWMBA focuses on site-scale assessment, it is recognised there is interest in extrapolating an understanding water performance up to larger urban scales (precinct or city scale), as evidenced by other tools and models that operate at this scale (Table 1). We suggest that future research can link SUWMBA to urban water systems transition models (e.g. CRC Scenario Tool (Rauch et al., 2017)) to scale up the (dis)benefits from site-scale design-technology interventions to meet water performance objectives set at the larger-scales (e.g. city-scale) as outlined by Hoffmann et al. (2020) as a research priority. Another interesting extension could be the identification of water performance pathways due to the uptake of alternative site-scale architectural design and new water technologies as a response to societal transitions and climate change. Since current transition models do not capture design-technology interactions (as shown in Table 1), they cannot perform such analysis without use of SUWMBA, or developing similar site-scale models.

Future work should focus on the application of SUWMBA in a variety of locations and contexts to further elicit its capacities. Future applications could use SUWMBA to simultaneously optimise architectural design and technologies to achieve some pre-defined targets. This would be a multi-objective 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 multiple technologies together. We analysed technologies in isolation for simplicity to demonstrate SUWMBA's capabilities. However, multiple interactions exist when technologies are considered together which are also captured in SUWMBA.

An interesting direction for future research could be exploring the role of SUWMBA in real-world knowledge generation, decision making and collaborative planning. The interactions between models/tools and people using them in a collaborative urban design and planning context are not well-understood (McEvoy et al., 2018). Recent studies showed that the context including style of use (e.g. interactive nature of the tool, style of facilitation, etc.), phase of planning that a tool is used, and societal context (e.g. culture, capacity of local stakeholders, etc.) could have an impact on the use and the added value of the tools in real-world participatory workshops (McEvoy et al., 2019). Different tools seem to deliver different types of participation and outcomes (e.g. learning vs. final product) (McEvoy et al., 2018). Our limited observation in SUMWBA's testing and development process (see the Supplementary Material) in Australian context inferred that SUWMBA improved both learning and the quality the design as the results of collaborative activities. However, these societal aspects need further research that was beyond our scope.

Finally, it is acknowledged that decisions about urban design at the site-scale are not made solely based on water performance. Other environmental performance aspects such as urban heat, liveability, and green space quality are needed prior to cost-benefit analysis and in turn for guiding multi-criteria decision-making processes. SUWMBA could be used alongside other performance evaluation processes, an example of which is provided by (Renouf et al., 2020a), and to feed into cost-benefit analysis and multi-criteria decision support systems. The 'Investment Framework For Economics of Water Sensitive Cities' (Pannell, 2020) is a recent example that could benefit from the quantifications provided by SUWMBA. Current multi-criteria decision support systems for site-scale design process (inter alia Jalilzadehazhari and Johansson (2019) and Hu (2019)) do not have water performance elements. Therefore a priority for future research could be the use of SUWMBA in a multi-criteria decision support systems that include cost-benefit analysis alongside other environmental performance.

6. Conclusions

This paper introduced a new approach (i.e. SUWMBA) for quantifying the water performance of site-scale urban developments and their holistic impacts on the urban water cycle. In answering the research question we found that the water performance of design-technology-environment configurations can be quantified by (i) defining a three-dimensional urban entity, (ii) accounting all water flows, both natural and anthropogenic, and (iii) capturing the interactions of natural, built-environment and socio-technological systems by incorporating key influential variables related to hydrology, architectural design, technologies, and end-use water demand. SUWMBA is an important advancement over other site-scale models because it specifically (i) accounts for architectural design variables such as number of dwellings, land cover characteristics, irrigated area, and occupancy (ii) holistically quantifies water performance such as hydrological naturalness and self-sufficiency, among others, and (iii) focuses on assessed "entity" of development. This focus gives greater clarity regarding the impacts of design, compared to other models which typically have a wider focus, for example urban catchment or urban water infrastructure (refer to Table 1).

SUWMBA's successful application for evaluating representative site-scale design-technology-environment configurations in Australia showed substantial variation in water performance. For example, certain architectural design (i.e. sub-divided single-storey houses) can have 301% more stormwater discharge compared to pre-urbanised levels, while others (i.e. single-storey detached houses with stormwater harvesting) only mildly escalate it up to 113%. SUWMBA helped to identify trade-offs indicating that although some configurations perform best by having low imported water per capita, they show a poor performance in other water performance aspects (e.g. high stormwater discharge). This demonstrated that comprehensive water performance evaluation across a range of indicators is required to prevent unintended impacts. SUWMBA could also identify configurations that simultaneously met conflicting objectives such as densification, improve hydrology, and reduce reliance on imported water. The result showed design C (i.e. two-storey semi-detached units) with 10 m^3 stormwater harvesting system can not only increase the total number of residents by 300% but also can reduce the imported water per capita and stormwater discharge by 45% and 15%, respectively. This result shows the importance of joint consideration of architectural design and technologies to achieve multiple objectives in a given environmental context.

From the case study application of SUWMBA, we have inferred future uses including its potential to:

i. jointly evaluate the influence of both design and technology interventions given local environmental conditions on the water performance of an urban development;

ii. understand trade-offs and conflicting objectives of different performance objectives;
iii. screen water performance improvements for a particular environmental context;
iv. identify the required architectural design and technology specifications needed to reach water performance targets for a particular environmental context;
v. compare, benchmark and monitor the performance of developments types and their associated water servicing technologies, and
vi. inform investment strategies by providing data for cost-benefit analyses.

This knowledge can be used to inform better urban design and land use development and integrated urban water management.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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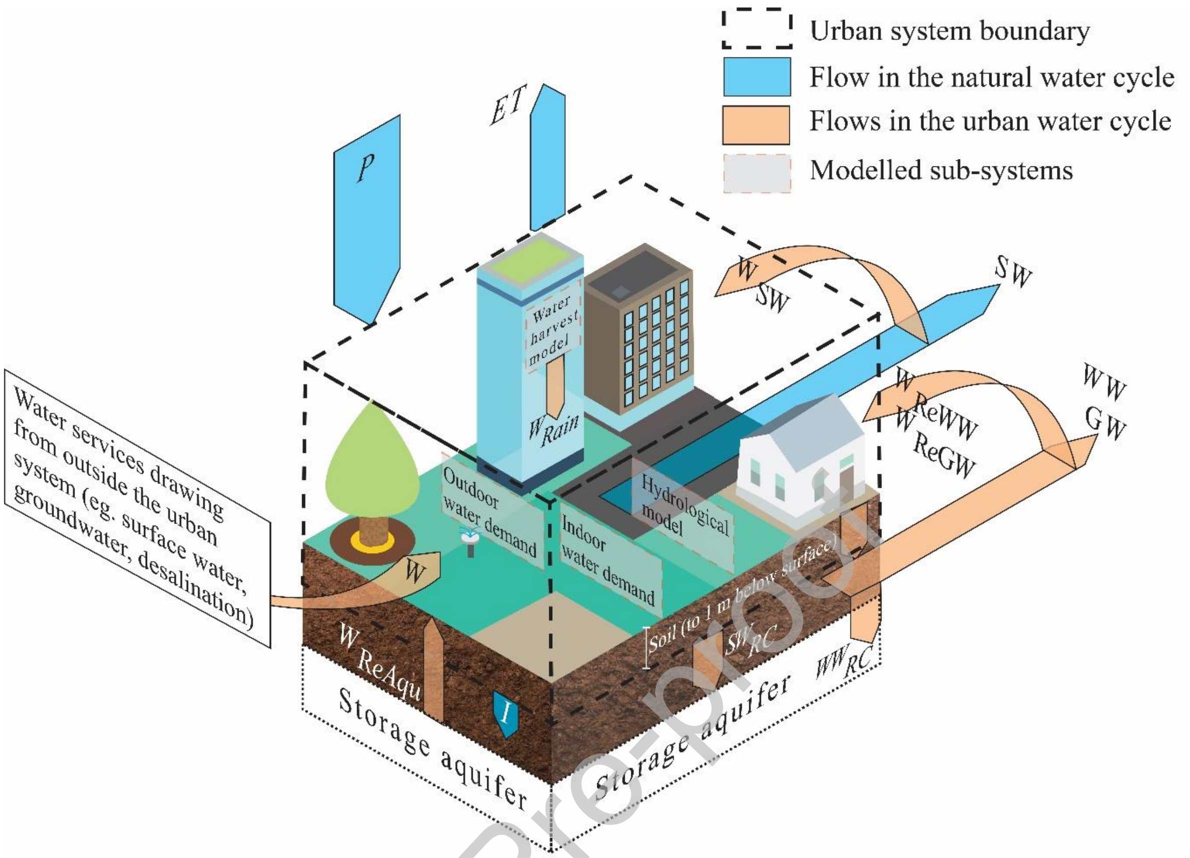


Figure 6. Conceptualization of the urban system components, boundary, and urban water flows represented in SUWMBA urban water balance framework. Adapted from Kenway et al. (2011) and Renouf et al. (2018).

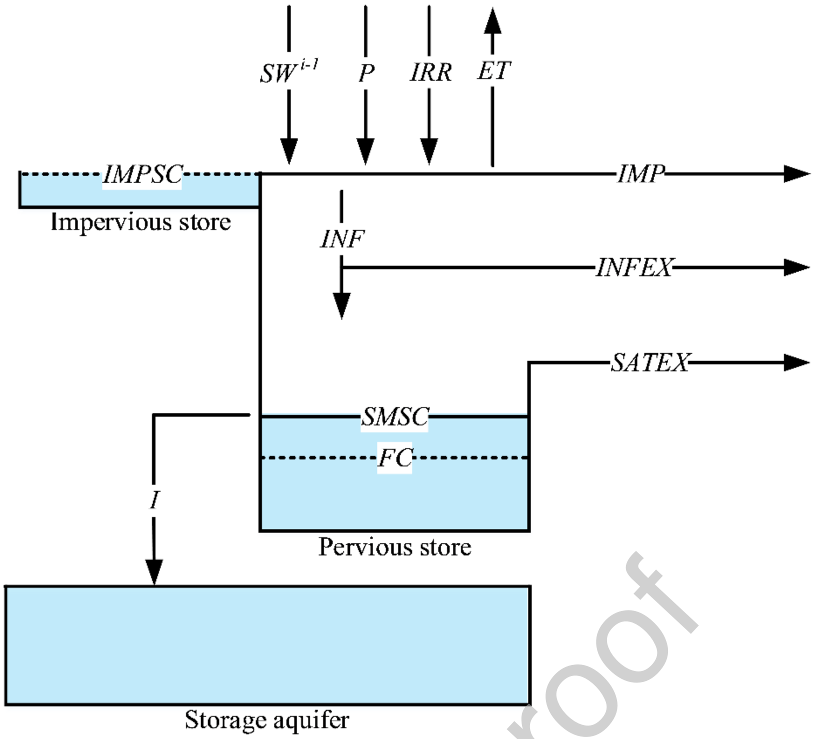


Figure 7. Representation of SUWMBA's hydrological model adapted from eWater (2011).

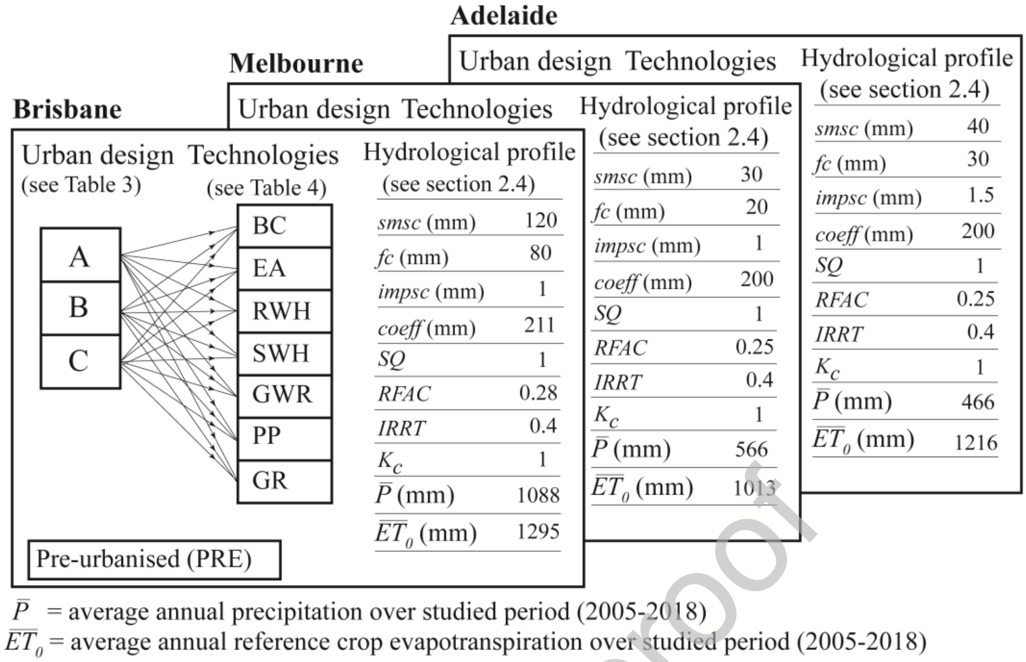
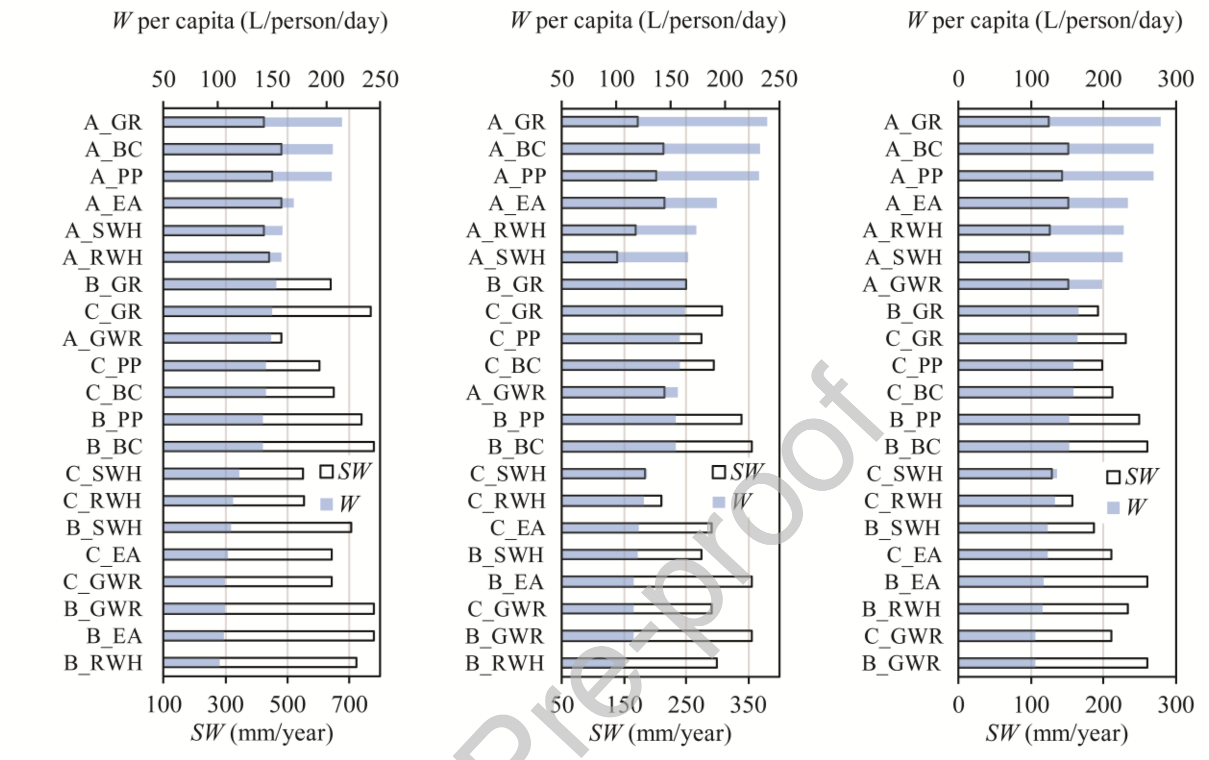


Figure 8. Design-technology configurations (see Table 2 for the acronyms). Hydrological profile were obtained from guidelines relevant to the three cities (Healthy Land and Water, 2018; Melbourne Water, 2018; Myers et al., 2015).



d) Brisbane e) Melbourne f) Adelaide

Figure 9. Imported water (*W*) per capita against stormwater discharge (*SW*) of design-technology-environment configurations. See Case study section for the definitions of configurations. Note that the overlapping bars are not stacked.

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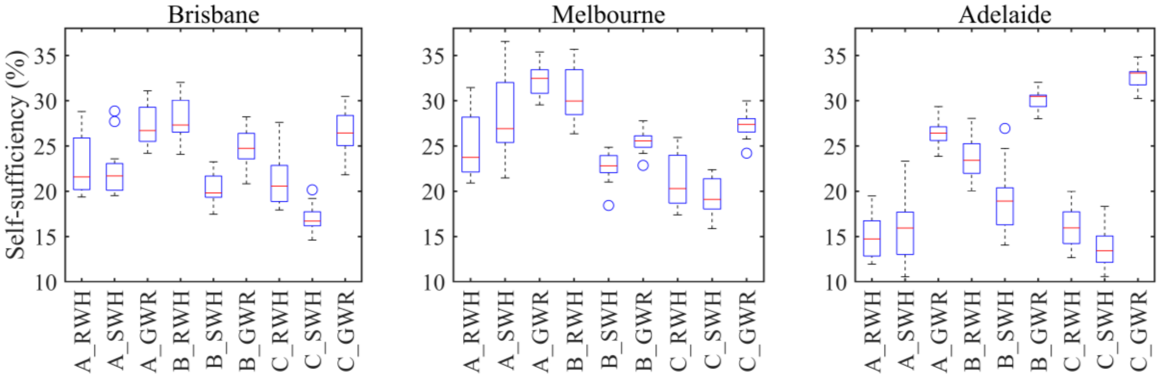

Figure 10. Self-sufficiency of design-technology-environment configurations. Note the self-sufficiency of other technologies is zero and not presented here. The boxplots show the range of annual self-sufficiency for each year from 2005-2018. Wider boxplots indicate higher variability in self-sufficiency.

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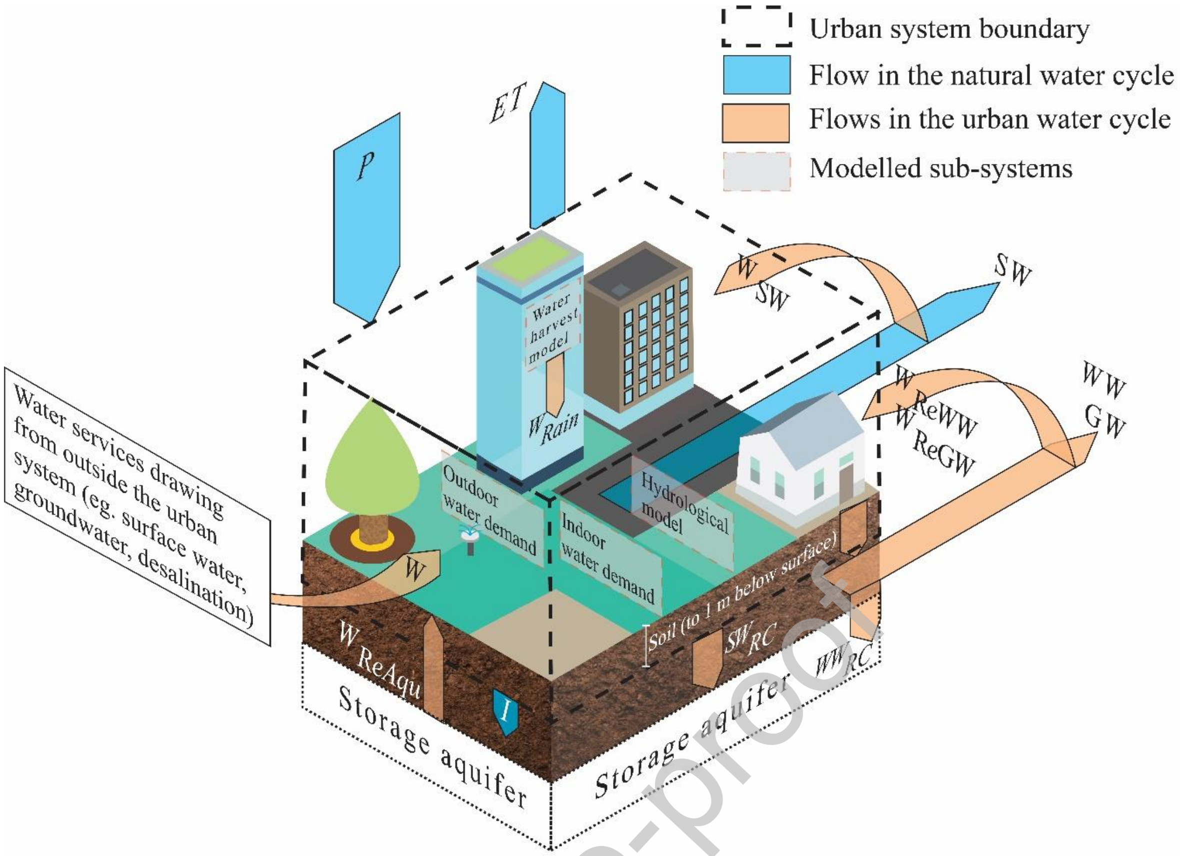

Urban system boundary
Flow in the natural water cycle
Flows in the urban water cycle
Modelled sub-systems
P
ET
SW
W_{SW}
Water harvest model
W_{Rain}
W_{ReWW}
W_{ReGW}
WW
GW
Hydrological model
Outdoor water demand
Indoor water demand
Water services drawing from outside the urban system (eg. surface water, groundwater, desalination)
W
W_{ReAqu}
I
Storage aquifer
Soil (to 1 m below surface)
SW_{RC}
WW_{RC}
Storage aquifer

Table 9. A summary of available methods and their utility to quantify water performance of urban development at site-scale (✓ and ✓ represent complete and partial consideration, respectively).

Method	Year	Ref	Water flows		Adaptation solutions							Performance									Spatial scale				
			Natural flows	Anthropogenic flows	Rainwater harvesting	Stormwater harvesting	Reuse and recycling	Efficient appliances	Green roofs	Permeable pavements	Urban design	Volume of water	Contaminants	Technical performance of technologies	Energy	Cost	Societal factors	Urban form	Water performance	Site	Precinct	City	Other	
MIKE URBAN	2009	a	✓						✓	✓		✓								✓	✓			U
SWMM	2010	b	✓		✓	✓			✓	✓		✓								✓	✓	✓		U
MUSIC	2014	c	✓		✓	✓				✓		✓	✓							✓	✓	✓		U
CityDrain3	2016	d	✓	✓	✓	✓	✓					✓									✓	✓		U
Sobek-Urban	2018	e	✓			✓						✓		✓							✓	✓		U
Urban Developer	2011	f	✓	✓	✓	✓	✓			✓	✓	✓								✓	✓	✓		U
Aquacycle	2001	g	✓	✓	✓	✓	✓					✓								✓	✓	✓		U
UVQ	2005	h	✓	✓	✓	✓	✓					✓	✓							✓	✓	✓		U
UWOT	2008	i	✓	✓	✓		✓	✓				✓		✓						✓	✓			U
City Water Balance	2010	j	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓						✓		U
WaterCress	2011	k	✓	✓	✓	✓	✓					✓											rb	U
WaterMet^2	2015	l	✓	✓	✓	✓	✓					✓	✓	✓	✓	✓			✓			✓		U
WABILA	2016	m	✓		✓				✓	✓		✓							✓				g1	U
CWBM	2018	n	✓	✓	✓	✓	✓	✓				✓										✓	g1	U
UMEF4Water	2018	o, u	✓	✓	✓	✓	✓					✓			✓				✓		✓	✓		U
CRC Scenario Tool	2017	p	✓		✓	✓						✓		✓			✓						g2	U
DUWSiM	2013	q	✓	✓	✓		✓					✓			✓			✓					g3	U
UrbanBEATS	2013	r	✓		✓									✓				✓					g2	U
Envision Scenario Planner	2016	s	✓	✓	✓		✓				✓	✓	✓		✓					✓	✓			U
Adaptation Planning Support Tool	2016	t	✓	✓	✓	✓	✓		✓	✓									✓		✓			U
SUWMBA			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓					✓	✓				U

a = (DHI, 2017), b = (Rossman, 2010), c = (eWater, 2011), d = (Burger et al., 2016), e = (Deltares, 2018), f = (Snowdon et al., 2011), g = (Mitchell et al., 2001), h = (Mitchell and Diaper, 2005), i = (Makropoulos et al., 2008), j = (Last, 2011), k = (Cresswell et al., 2011), l = (Behzadian and Kapelan, 2015), m = (Henrichs et al., 2016), n = (Zeisl et al., 2018), o = (Renouf et al., 2018), u = (Farooqui et al., 2016), p = (Rauch et al., 2017), q = (Willuweit and O'Sullivan, 2013), r = (Bach et al., 2013), s = (Trubka and Glackin, 2016), t = (van de Ven et al., 2016). rb = river basin, g1 = grid (1 km), g2 = grid (200 × 200 m), g3 = grid (4 ha), UWI = urban water infrastructure, UC = urban catchment, UE = urban entity.

Table 10. List of acronyms used in SUWMBA development and testing

Flows in urban water mass balance (see section 2.1.)	
P	Precipitation minus harvested rainwater and stormwater (m^3)
W	Imported water (m^3)
W_{Rain}	Water sourced from rainwater harvesting (m^3)
W_{SW}	Water sourced from stormwater harvesting (m^3)
W_{ReGW}	Water sourced from greywater reuse or recycling (m^3)
W_{ReWW}	Water sourced from wastewater recycling (m^3)
W_{ReAqu}	Water sourced from storage aquifer (m^3)
ET	Evapotranspiration (m^3)
SW	Stormwater discharge (m^3)
SW_{RC}	Stormwater recharged to storage aquifer (m^3)
WW	Wastewater discharge (m^3)
WW_{RC}	Wastewater recharged to storage aquifer (m^3)
GW	Greywater discharge (m^3)
I	Infiltration (m^3)
ΔS	Change in total storage (m^3)
Subscripts/superscripts (see section 2.3. and 2.5.)	
t	Time step of calculation (day)
i	Number of land cover. i is sequenced from upstream to downstream depending on the urban design configuration. For land cover i, the upstream and downstream notation is i-1 and i+1, respectively
q	Number of storage

Hydrological flows within the urban system boundary (see section 2.3.)	
P_t^i	Precipitation on the land cover *i* at the time step of *t* (m^3)
SW_t^i	Stormwater runoff from the land cover *i* at the time step of *t* (m^3)
IMP	Impervious runoff (m^3)
IRR	Irrigation demand (m^3)
S	Soil moisture (m^3)
INF	infiltration to soil (m^3)
INFEX	Infiltration excess (m^3)
SATEX	Saturation excess (m^3)
ET_0	reference crop evapotranspiration (potential evapotranspiration) (m^3)
Hydrological model parameters (see section 2.3.)	
IMPSC, *impsc*	Impervious store capacity in m^3 and mm, respectively
A^i	Area of land cover *i* (m^2)
$IMPF^i$	Impervious fraction of land cover *i*
FC, *fc*	Field capacity in m^3 and mm, respectively
COEFF, *coeff*	Maximum infiltration loss in m^3 and mm, respectively
SMSC, *smsc*	Soil moisture store capacity in m^3 and mm, respectively
IRRT	Irrigation trigger factor
SQ	Infiltration loss exponent
RFAC	Groundwater recharge factor
K_c	Crop factor
Water harvest and storage model (see section 2.5.-2.6.)	
V_t^q	Volume of water in storage *q* at the end of time interval *t* (m^3)
Q_t^q	Inflow to storage *q* during the time interval *t* (m^3)

D_t	Demand during the time interval t (m^3)
V_{max}	Storage capacity (tank size) (m^3)
Y_t	Yield from the storage during the time interval t (m^3)
$Spill_t$	Spill from the storage during the time interval t (m^3)
SD	Supply-demand matrix
ReM	Reuse and recycling matrix
S_{max}	Total storage
Case study (see section 3)	
PRE	Pre-urbanised case
A	Single-storey detached houses
B	Sub-divided single-storey houses
C	Two-storey semi-detached units
BC, EA, RWH, SWH, GWR, PP, GR	Indicator of technologies. BC = base case (no implemented technologies), EA = efficient appliances and fixtures, RWH = rainwater harvesting and use, SWH = stormwater harvesting and use, GWR = greywater reuse, PP = permeable pavements, GR = green roofs

Table 11. Architectural designs and their parameters (London et al., 2020)

	 Single-storey detached houses (A)	 Sub-divided single-storey houses (B)	 Two-storey semi-detached units (C)
Site area	1,422 m^2	1,422 m^2	1,422 m^2
Number of dwelling per site	2	4	6
Annual household income	\$A70,000	\$A70,000	\$A70,000
Roof area of each dwelling (imperviousness = 1)	152 m^2 (304 m^2 in total) sloping tiles	189 m^2 (756 m^2 in total) sloping tiles	85 m^2 (510 m^2 in total) flat concrete
Pavement area per each dwelling (including car park) (imperviousness = 0.95)	140 m^2 (280 m^2 in total)	93 m^2 (372 m^2 in total)	62 m^2 (372 m^2 in total)
Green fence area per dwelling (short vegetation) (imperviousness = 0)	67 m^2 (134 m^2 in total)	10 m^2 (40 m^2 in total)	0 m^2

Green space per each dwelling (¾ short vegetation and ¼ tall vegetation) (imperviousness = 0)	352 m^2 (704 m^2 in total)	63.25 m^2 (254 m^2 in total)	90 m^2 (540 m^2 in total)

Table 12. Technology cases and their parameters

Technology	Parameters
Base case (BC)	No technologies implemented.
Efficient appliances and fixtures (EA)	5 star water efficient fixtures Front loader washing machine Half-flush toilet is usually used Eco dishwasher
Rainwater harvesting and use (RWH)	Number of rainwater tanks: A = 2, B = 4, C = 6 Size = 2 m^3, half-full at $t = 0$. Roof coefficient = 0.9 Roof connection = 100%. Rainwater usage = washing machine, toilet flushing, irrigation. No first flush diverter
Stormwater harvesting and use (SWH)	Number of stormwater tanks = 1 Size = 10 m^3, half-full at $t = 0$. Land cover connection to stormwater tank = 100%. Stormwater usage = toilet flushing, irrigation.
Greywater reuse (GWR)	Production = shower, washing machine, tap, bath Usage = toilet flushing, irrigation Size = 5 m^3

Permeable pavement (PP)	impervious fraction = 60% was assumed No underneath storage
Green roof (GR)	*IRRT* = 0.1 *smsc* = 120 mm, *fc*= 80 mm Thickness = 150 mm

Table 13. Urban water mass balance results (average annual flows in m^3/yr) for design-technology configurations in Brisbane. Positive values for inflows and negative values for outflows.

Design	Tech-nology	Inflows				Outflows				W_{ReGW}	Urban Water Mass balance			S_{max}
		P	W	W_{Rain}	W_{SW}	ET	SW	I	WW		inflow	outflow	ΔS	
Pre-urbanised		1,547	0	0	0	-926	-421	-200	0	0	1,547	-1,547	1	170
A	BC	1,547	376	0	0	-881	-689	-121	-233	0	1,924	-1,924	-1	102
	EA	1,547	310	0	0	-877	-690	-121	-168	0	1,857	-1,856	1	102
	RWH	1,461	290	86	0	-870	-613	-123	-233	0	1,838	-1,837	0	106
	SWH	1,462	291	0	85	-877	-606	-123	-233	0	1,838	-1,838	0	112
	GWR	1,547	272	0	0	-877	-689	-123	-125	108	1,819	-1,813	6	107
	PP	1,547	376	0	0	-866	-649	-175	-233	0	1,924	-1,922	2	114
	GR	1,547	392	0	0	-973	-611	-123	-233	0	1,940	-1,940	0	108
B	BC	1,545	515	0	0	-420	-1,123	-53	-465	0	2,060	-2,061	-1	38
	EA	1,545	386	0	0	-420	-1,123	-53	-336	0	1,931	-1,932	-1	38
	RWH	1,402	372	143	0	-379	-1,020	-53	-465	0	1,917	-1,917	0	46
	SWH	1,440	410	0	105	-420	-1,018	-53	-465	0	1,955	-1,956	-1	48
	GWR	1,545	388	0	0	-420	-1,123	-53	-337	128	1,933	-1,933	0	43
	PP	1,545	515	0	0	-409	-1,065	-122	-465	0	2,060	-2,061	-1	53
	GR	1,545	560	0	0	-667	-921	-53	-465	0	2,105	-2,107	-1	51
C	BC	1,545	790	0	0	-632	-935	-72	-698	0	2,336	-2,337	-2	87
	EA	1,545	597	0	0	-629	-935	-72	-506	0	2,142	-2,142	0	87
	RWH	1,379	625	166	0	-587	-799	-86	-698	0	2,170	-2,169	0	99
	SWH	1,411	656	0	134	-630	-787	-86	-698	0	2,202	-2,200	1	97
	GWR	1,545	582	0	0	-630	-935	-86	-477	222	2,127	-2,127	0	92
	PP	1,545	790	0	0	-618	-867	-154	-698	0	2,336	-2,337	-1	83
	GR	1,545	821	0	0	-795	-789	-86	-698	0	2,366	-2,367	-1	96

Table 14. Urban water mass balance results (average annual flows in m^3/yr) for design-technology configurations in Melbourne. Positive values for inflows and negative values for outflows.

Design	Tech-nology	Inflows				Outflows				W_{ReGW}	Urban Water Mass balance			S_{max}
		P	W	W_{Rain}	W_{SW}	ET	SW	I	WW		inflow	outflow	ΔS	
Pre-urbanised		805	0	0	0	-521	-176	-109	0	0	805	-806	-1	43
A	BC	805	389	0	0	-594	-308	-61	-233	0	1,194	-1,195	-1	26
	EA	805	323	0	0	-590	-308	-62	-168	0	1,128	-1,129	-1	26
	RWH	706	291	98	0	-578	-222	-62	-233	0	1,096	-1,096	0	30
	SWH	694	278	0	111	-590	-199	-62	-233	0	1,083	-1,084	-1	36
	GWR	805	263	0	0	-590	-308	-62	-107	126	1,067	-1,067	0	31
	PP	805	389	0	0	-581	-290	-89	-233	0	1,193	-1,193	0	29
	GR	805	401	0	0	-664	-247	-62	-233	0	1,205	-1,206	-1	26
B	BC	805	520	0	0	-318	-513	-27	-465	0	1,324	-1,324	1	9
	EA	805	391	0	0	-318	-513	-27	-337	0	1,195	-1,195	0	9
	RWH	656	371	149	0	-274	-410	-27	-465	0	1,176	-1,176	0	17
	SWH	687	402	0	118	-318	-395	-27	-465	0	1,206	-1,206	1	19
	GWR	805	388	0	0	-318	-513	-27	-335	131	1,192	-1,193	0	14
	PP	805	520	0	0	-307	-489	-62	-465	0	1,324	-1,324	1	13
	GR	805	552	0	0	-504	-360	-27	-465	0	1,356	-1,356	1	23
C	BC	805	805	0	0	-445	-423	-43	-698	0	1,610	-1,610	0	22
	EA	805	609	0	0	-443	-423	-43	-504	0	1,414	-1,414	0	22
	RWH	631	631	174	0	-413	-281	-43	-698	0	1,436	-1,436	0	34
	SWH	644	644	0	161	-443	-264	-43	-698	0	1,449	-1,448	1	32
	GWR	805	582	0	0	-443	-423	-43	-477	221	1,386	-1,387	0	27
	PP	805	805	0	0	-439	-395	-78	-698	0	1,610	-1,610	0	21
	GR	805	821	0	0	-568	-315	-43	-698	0	1,625	-1,625	0	31

Table 15. Urban water mass balance results (average annual flows in m^3/yr) for design-technology configurations in Adelaide. Positive values for inflows and negative values for outflows.

Design	Tech-nology	Inflows				Outflows				W_{ReGW}	Urban Water Mass balance			S_{max}
		P	W	W_{Rain}	W_{SW}	ET	SW	I	WW		inflow	outflow	ΔS	
Pre-urbanised		663	0	0	0	-442	-125	-96	0	0	663	-662	0	57
A	BC	663	492	0	0	-652	-218	-53	-233	0	1,155	-1,156	-1	34
A	EA	663	426	0	0	-648	-219	-54	-168	0	1,089	-1,089	-1	34
A	RWH	587	417	75	0	-625	-167	-54	-233	0	1,079	-1,079	0	38
A	SWH	583	412	0	80	-648	-141	-54	-233	0	1,075	-1,076	-1	44
A	GWR	663	361	0	0	-648	-218	-54	-104	129	1,024	-1,024	0	39
A	PP	663	492	0	0	-638	-206	-77	-233	0	1,154	-1,154	0	38
A	GR	663	510	0	0	-707	-179	-54	-233	0	1,173	-1,174	-1	34
B	BC	662	556	0	0	-354	-375	-23	-465	0	1,218	-1,218	0	13
B	EA	662	427	0	0	-354	-375	-23	-336	0	1,088	-1,089	0	13
B	RWH	531	425	131	0	-312	-286	-23	-465	0	1,087	-1,087	0	21
B	SWH	556	450	0	106	-354	-269	-23	-465	0	1,111	-1,112	-1	23
B	GWR	662	388	0	0	-354	-375	-23	-297	169	1,050	-1,049	0	18
B	PP	662	556	0	0	-341	-358	-53	-465	0	1,218	-1,218	0	18
B	GR	662	604	0	0	-501	-277	-23	-465	0	1,266	-1,267	-1	26
C	BC	662	866	0	0	-492	-306	-32	-698	0	1,527	-1,528	-1	29
C	EA	662	672	0	0	-489	-303	-38	-504	0	1,333	-1,334	-1	29
C	RWH	534	738	128	0	-447	-216	-38	-698	0	1,399	-1,399	0	41
C	SWH	543	747	0	119	-489	-184	-38	-698	0	1,408	-1,409	-1	39
C	GWR	662	582	0	0	-489	-306	-38	-411	287	1,243	-1,244	0	34
C	PP	662	866	0	0	-476	-286	-67	-698	0	1,527	-1,528	-1	28
C	GR	662	898	0	0	-588	-237	-38	-698	0	1,560	-1,561	-1	38

Table 16. Hydrological naturalness ratio (%) for design-technology-environment configurations

Design	Technology	Brisbane			Melbourne			Adelaide		
		ET	SW	I	ET	SW	I	ET	SW	I
Pre-urbanised		100	100	100	100	100	100	100	100	100
A	BC	95	164	60	114	174	56	148	175	55
	EA	95	164	60	113	174	57	147	175	57
	RWH	94	146	61	111	126	57	141	134	57
	SWH	95	144	61	113	113	57	147	113	57
	GWR	95	164	61	113	174	57	147	174	57
	PP	94	154	87	112	165	82	144	165	80
	GR	105	145	61	128	140	57	160	144	57
B	BC	45	267	27	61	291	25	80	301	24
	EA	45	267	27	61	291	25	80	301	24
	RWH	41	243	27	53	232	25	71	229	24
	SWH	45	242	27	61	224	25	80	216	24
	GWR	45	267	27	61	291	25	80	301	24
	PP	44	253	61	59	277	57	77	287	55
	GR	72	219	27	97	204	25	113	222	24
C	BC	68	222	36	86	240	40	111	245	33
	EA	68	222	36	85	240	40	111	243	39
	RWH	63	190	43	79	159	40	101	173	39
	SWH	68	187	43	85	149	40	111	148	39
	GWR	68	222	43	85	240	40	111	245	39
	PP	67	206	77	84	224	72	108	229	70
	GR	86	187	43	109	179	40	133	190	39

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