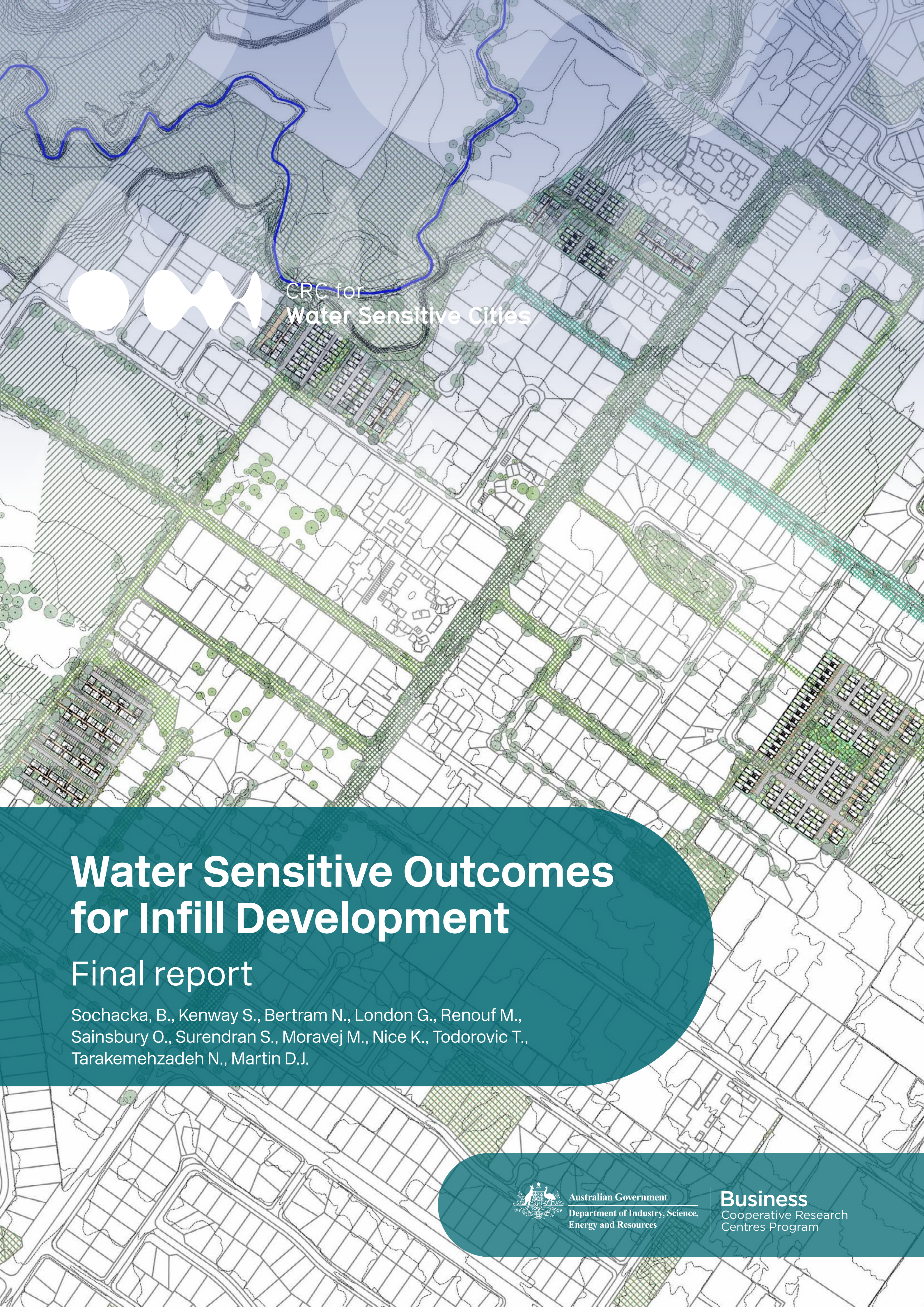

CRC for
Water Sensitive Cities

Water Sensitive Outcomes for Infill Development

Final report

Sochacka, B., Kenway S., Bertram N., London G., Renouf M., Sainsbury O., Surendran S., Moravej M., Nice K., Todorovic T., Tarakemehzadeh N., Martin D.J.

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Water Sensitive Outcomes for Infill Development. Final Report
Water Sensitive Outcomes for Infill Development (Project IRP4)
IRP4-1-2021

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Contents

Figures and tables

Glossary

amenity A desirable or useful feature or facility of a building or place.

architectural urban space quality Relates to the extent to which indoor and outdoor spaces are efficiently designed and organised for improved amenity, usability and flexibility.

aquifer In this report, aquifer refers to a shallow groundwater resource, as distinct from a deep groundwater resource.

aquifer storage and recovery (ASR) Aquifer storage and recovery is a technique of managed aquifer recharge (MAR). Aquifer storage and recovery is the process of withdrawing the stored water from the aquifer for use. This term has been adopted from the Aquacycle tool of Mitchell et al. (2001, p.33), citing (Digney and Gillies 1995).

BAU Business as usual. Also referred to as standard industry practice.

Aquacycle Aquacycle is a daily urban water balance model for simulating the total urban water cycle and especially suited to investigating supplementary water sources (rain and stormwater harvesting and grey and wastewater recycling) in urban catchments. Refer to Mitchell et al. (2001) and Mitchell (2005) for more information.

BOM Bureau of Meteorology

brownfield land Previously developed land. Commonly, it is land previously used for industrial or commercial purposes, which is currently vacant, and which may also have some impediment such as contamination (compare with ‘greenfield’ and ‘greyfield’ land).

built form The human-made surroundings that provide the setting for human activity, ranging in scale from buildings to parks.

catchment This work uses the hydrological meaning of catchment, which is an area of land where surface water converges to a single point (drainage basin).

CRCWSC Cooperative Research Centre for Water Sensitive Cities

efficiency Efficiency is considered in terms of resource efficiency, which is the amount of resource input per unit of service, function, product. In this work it refers to water efficiency, and more specifically to the water efficiency of the urban area being evaluated. Also see ‘urban water efficiency’.

evaluation framework A structure and analysis process used to collate, organise and link evaluation questions, outcomes or outputs, indicators, data sources, and data collection methods. In this instance the evaluation framework refers to evaluation of an ‘urban entity’ – i.e. the components within a 3dimensional physical boundary. See also ‘urban entity’).

evapotranspiration The process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces, and by the transpiration of plants.

Existing/EX scenario EX refers to the current prevailing state of the precinct as in 2019. This essentially means the state before infill with/without intervention. This is also known as pre-urban (pre-European) development. This is an acceptable reference case for a highly urbanised infill development.

Framework In the context of this report, the Framework refers to the Infill Performance Evaluation Framework.

greenfield land	Land that has previously been undeveloped (compare with 'brownfield' and 'greyfield' land).
greyfield land	Undeveloped or underutilised land, e.g. land that is economically obsolescent, outdated, failing, or not utilised to its full potential (compare with 'greenfield' and 'brownfield' land).
hydrology	The study of the movement, distribution, and management of water.
infiltration	For this report, infiltration is water that enters the soil, percolates through the soil, and passes out of the urban area boundary, 1m below the surface. This can also represent groundwater recharge if it is assumed that the infiltrated water continues to make its way to sub-surface aquifers.
impermeable	See 'permeable'. Impermeable is the opposite of permeable.
impervious	See 'pervious'. Impervious is the opposite of pervious.
impervious area	This work is interested in the total impervious area (TIA), including both 'effective' and 'non-effective' impervious areas. The 'effective' impervious area is the portion of an area for which runoff does not infiltrate and that drains via a constructed drainage system (Melbourne Water 2018). 'Non-effective' impervious areas are those where the runoff flows to another surface. Directly connected impervious area is that impervious area which has a direct hydraulic or overland flow connection to waterways (McIntosh et al. 2013, Walsh and Kunapo 2009, Walsh et al. 2005). To avoid confusion with others' interpretations of impervious area, we use the term 'built area' fraction to collectively describe all surfaces through which water does not infiltrate (i.e. roof surfaces of houses and sheds, concrete or bitumen driveways and, concrete or paved patios, paths).
impervious fraction	Percentage of a site that is effectively impervious. See 'impervious area'.
imported water	Water sourced from outside the urban system, such as centralised supplies from dams, groundwater reserves, seawater, etc., as distinct from water sourced from within the urban system, such as harvested rainwater and stormwater, recycled wastewaters, etc.
infill / infill development	An urban planning term for the process of redevelopment within established urban areas, typically using previously undeveloped or underutilised parcels of land (greyfield), or redeploying previously developed land (brownfield). Infill generally has an emphasis on residential dwellings, but it does not exclude other building types.
internally-sourced water	Water harvested / generated within the 'entity' – urban system (rainwater, stormwater, recycled wastewater which is used). Often referred to as 'decentralised' water (but can be centrally managed).
managed aquifer rechargemass balance	Managed aquifer recharge (MAR) is the process of transferring surface water to the groundwater system to (i) increase the yield of an aquifer that is already exploited, or (ii) take advantage of its natural storage capacity instead of relying on surface storage. A type of material flow analysis that generates a comprehensive account of the flows of a resource into and out of an entity/system (sum of the inflow equals sum of the outflows and the change in storage), with the change in storage acting as a check for the conservation of mass. See also 'water mass balance'.
MUSIC	MUSIC (Model for Urban Stormwater Improvement Conceptualisation) is designed to help urban stormwater professionals visualise possible strategies to tackle urban stormwater hydrology and pollution impacts.
natural water cycle	The continuous movement of water around the world through the processes of evaporation, transpiration, condensation, precipitation, runoff, infiltration and percolation.
natural water flows	Water flows in the natural water cycle, i.e. precipitation, stormwater runoff, infiltration to aquifers and groundwater and evapotranspiration, as distinct from anthropogenic (human-made) water flows.

permeable Relating to materials that allow the passage of water. See distinction to 'pervious'. In this work, we use it to refer to permeable paving.

pervious Admitting passage, i.e. capable of being penetrated by water. Pervious surfaces allow water to penetrate through the surface. See distinction to 'permeable'. In this work, we refer to the pervious/impervious fraction of a surface in relation to hydrological modelling.

pervious fraction See 'impervious fraction' (opposite).

precinct The scale at which infill is planned and managed by the local authority, e.g. as a development zone or through a planning scheme. It may be as small as a suburban block or as large as a small suburb.Hundreds of parcels of land each with at least one building. A large number of 'lots' and multi-building complexes combined. Several neighbourhoods, e.g. a small suburb covering an area of 100 hectares (Coombes and Roso 2019, Table 9.6.3).

precipitation rainfall

pre-urbanisation/PRE This refers to the catchment/area before any development; it is also known as 'natural condition'. For the Australian context, it is the pre-European settlement (1825) covered with native vegetation. The typical features of PRE are increased evapotranspiration (ET), infiltration (I) and a smaller proportion of stormwater discharge (SW). It is an acceptable reference for hydrological performance of a less urbanised area or greenfield development.

pre-urban development See 'Existing' (EX)

recharge Water that infiltrates through the soil beyond the urban area boundary (i.e. 1m below the surface) into a shallow aquifer. Referred to as deep percolation in MUSIC and BOM.

resource efficiency Resource input per unit of service or functionality (e.g. litres of water used per person).

site An individual infill development site, e.g. single or multiple residential dwellings on a piece of private land. A large parcel of land with multiple buildings. Sometimes a small number of 'lots' combined.

stormwater discharge Stormwater runoff that is discharged from the study area, which may be a fraction of the original amount of runoff, considering that some may drain to pervious surfaces and infiltrate. See also 'stormwater runoff'.

stormwater runoff Rainfall that flows over the ground surface. It is created when rain falls on roads, driveways, parking lots, rooftops and other paved surfaces that do not allow water to soak into the soil (infiltrate).

SUWMBA The Site-scale Urban Water Mass Balance Assessment (SUWMBA) Tool is a daily urban water balance model that simulates the urban water cycle specifically for urban developments at the site scale, to concurrently examine the influence of both the built form design and water servicing features. (Moravej et al. 2020)

supply internalisation The sourcing of water from within the urban system, to reduce reliance on water sourced from the supporting environment.

typology See 'urban design typology'.

UMEF4Water Urban Metabolism Evaluation Framework for Water. This is a wider water analysis framework focused more at city-scale and solely on water. (Renouf et al. 2016)

UMEP model Urban Multi-scale Environmental Predictor (UMEP) model used to evaluate urban heat.

urban A location characterised as population clusters of 1,000 or more people, with a density of at least 200 people/km^2 (ABS 2017).

urban area The 2-dimensional (area-based) boundary of the 'urban entity (3-dimensional boundary)'. The area being evaluated (such as a precinct or suburb), or the broader area in which a site being evaluated is located.

urban design The shape of the physical features of cities, towns and villages, and their associated municipal services (or the process/practice of shaping urban spaces).

urban design typology The taxonomic classification of (usually physical) characteristics commonly found in buildings and urban places.

urban entity The 3-dimensional 'system' being evaluated for performance. This includes the buildings (and water consuming appliances), water, infrastructure (piped and natural flows and related treatment systems), landscape (to 1m depth of soil) and associated land surfaces and vegetation, and related water storages This term is used interchangeably with 'urban area' in this report and framework.

urban metabolism The process of resources flowing through and being transformed and consumed in an urban entity to sustain all the technical and socio-economic processes that occur within it.

urban space quality See 'architectural urban space quality'.

urban system The combination of physical areas and technical systems associated with the urban area being assessed or evaluated. It includes built forms and landscapes within the physical urban area (see 'urban area boundary') and also the water services that draw from urban catchments, which may be outside the urban area being assessed. See Figure 5 for an illustration of the urban system.

urban system boundary The limits of the physical 3-dimensional envelope surrounding the urban area being evaluated, to the height above the tree line and to a depth of 1m below the ground surface (see also 'urban entity' and 'urban system'.

urban thermal comfort In this work, urban thermal comfort refers to climate sensitive urban design involving creating thermally comfortable, attractive and sustainable urban environments by enhancing positive natural and human-made features through architecture, planning and landscape design. This report focuses on the 'thermal comfort' component of urban design, and the role of water sensitive urban design (WSUD) in achieving climate sensitive streets, neighbourhoods and cities.

urban water cycle The movement and use of water within an urban area, which is managed by urban water infrastructure, including (water supply and use, wastewater collection, treatment, recycling and disposal), as distinct from the natural water cycle.

urban water efficiency In this work, water efficiency is considered in terms of the urban area being evaluated, and how efficient is the freshwater consumption of the urban area. Hence, it is the volume of fresh water (sourced from outside the urban system) consumed in the urban area, per capita of population living in the urban area. To distinguish it from other uses of the term water efficiency, such as end user water efficiency or appliance water efficiency, it is referred to here as 'urban water efficiency'.

urban water mass balance A water comprehensive assessment of all water flowing into, out of, and stored within an 'urban system' or 3-dimensional areas. See 'water mass balance'.

urban water metabolism evaluation The quantification of the water metabolism characteristics of an urban area, based on analysis of direct water exchanges between the urban area and the environment.

UTCI Universal Thermal Climate Index or the ‘feels like’ temperature

water efficiency In this work, water efficiency is considered in terms of an urban area, and how efficient is the freshwater consumption of the urban area. Hence, it is the volume of fresh water (sourced from outside the urban system) consumed in the urban area per capita of population living in the urban area. To distinguish it from other uses of the term water efficiency, it is referred to here as ‘urban water efficiency’.

water mass balance An equation that describes the flow of water in and out of an entity/system (sum of the inflow equals sum of the outflows and the change in storage), with the change in storage acting as a check for the conservation of mass.

water performance In this work, water performance describes a set of performance objectives related to the protection and functionality of water in the urban landscape. It includes the maintenance of natural water flows, water resource management, and water-related amenity. It captures the biophysical qualities of a water sensitive city.

water sensitive Having the attributes of a water sensitive city.

water sensitive cities A vision for urban water management that requires the transformation of urban water systems from a focus on water supply and wastewater disposal to more complex, flexible systems that integrate various sources of water; operates through both centralised and decentralised systems, delivers a wider range of services to communities, and integrates into urban design (Wong and Brown 2009b).

water sensitive interventions Water sensitive interventions are water resource management interventions such as improved water use efficiency, diversification of water supplies (harvesting of rainwater and stormwater runoff, wastewater recycling), or urban planning interventions such as water sensitive urban designs (WSUD), management of dwelling densities, green space, etc.

water servicing The supply of water for urban uses (potable water and fit-for-purpose water), and the collection, treatment and disposal (or reuse) of the resulting wastewaters.

WS-Con Water Sensitive Conservative

WS-Max Water Sensitive Maximised

WSUD Water sensitive urban design

Executive summary

Australian cities have experienced significant growth recently and this trend is expected to continue. State governments have promoted development within the city boundary on land that has been underutilised (e.g. vacant), or where uses have changed (e.g. former industrial land), but significant development also occurs by densification of existing lower value areas (knock-down rebuild, extensions and subdivision). This type of development is 'infill development' and allows increasing urban density. The current business-as-usual (BAU) practice is characterised by subdivision of land to maximise dwelling yield at the expense of useable greenspace. Current BAU has significant adverse impacts on urban hydrology, resource use efficiency, and the amenity and liveability of urban areas. It thus misses an important opportunity that infill development presents – to incrementally redevelop our cities in a way that improves their liveability and sustainability at the same time.

There is a need to understand the impacts of BAU infill development and create design alternatives that deliver superior outcomes in terms of liveability, hydrological performance and resource efficiency of suburban precincts. The CRC for Water Sensitive Cities' *Water sensitive outcomes for infill development research project* (IRP4) responded to this need by developing the Infill Development Performance Evaluation Framework, which is used to demonstrate the range of benefits delivered by water sensitive medium density designs in different case study applications across Australia.

More specifically the project sought to answer the following questions:

1. How can the water sensitive performance of urban development (and associated water servicing) be defined?
2. Which urban design and water servicing variables influence performance?
3. How can the performance of urban densification (infill) be measured and represented?
4. What are the water-related impacts of urban densification (infill), and how do they vary in different contexts (e.g. climate, land, infrastructure, demographic and design) in Australia?
5. What are the urban heat impacts of urban densification (infill) in Australia and what role can water play in heat mitigation?
6. How do water servicing alternatives influence performance in different contexts?
7. Which design and water servicing variables should guide design solutions?
8. What water performance objectives or targets might be appropriate for infill development?
9. What design typologies give good performance in different Australian contexts?
10. How might performance evaluation influence governance and planning mechanisms (policy, planning processes, design codes, etc) across a range of contexts?

This is the final report of the project, bringing together the key insights from the multiple research components that were undertaken to address the above questions. The main findings of the project are:

- **Current infill development practice (BAU) has significant adverse effects on urban water performance and thermal comfort. The assessment of BAU in terms of infill housing design has confirmed its adverse impact on almost all aspects of urban water performance, however those on local hydrology, particularly stormwater runoff, and water demand seem most significant.**

  The impact of housing design was evident in the site-scale analysis. This found that standard industry infill development practice (BAU) would almost triple the volume of stormwater discharge generated compared with pre-developed state (ranging from 267% in Brisbane to 291% and 301% in Melbourne and Adelaide) and almost double it when compared with the low density, single detached houses development. Industry standard subdivision would almost triple the number of residents, but because it almost eliminates green spaces (and in turn outdoor water demand), the water demand increases by only 36% in Brisbane, 31% in Melbourne and 13% in Adelaide.

  Precinct-scale analysis of infill in Salisbury, SA, and Knutsford, WA, assessed the extent of densification impact on precinct performance and the ways in which it could be mitigated by interventions in the public realm. The analysis demonstrated an almost 2.5 fold increase in stormwater runoff compared with low density residential areas with single detached house in Knutsford. In Salisbury the increase of stormwater runoff in BAU infill development was by only 19% (or 8% of annual rainfall volume) when compared with current low density development. The water demand rose by 80% when compared with current use in Salisbury and 60% in Knutsford when compared with low density residential development, which was mostly driven by population increase. In terms of per capita use of water, standard infill development actually reduced. In Knutsford, per person use of imported water for the low density development was estimated to be 325L/person/day and infill redevelopment scenario was able to reduce it to 110L/person/day. In Salisbury that reduction was from 251 L/person/day in current low density development to 159 L/person/day.

BAU infill development had also a significant effect on the urban heat island effect. We found that currently on very hot days, 77% of the Salisbury case study area exhibits temperatures above 42°C Universal Thermal Climate Index ('feels like' temperature), which indicates a very strong heat stress for humans. The analysis found that with the infill development, the outdoor areas that experience very strong heat stress will increase to 83% of the precinct.

- **Water sensitive design can simultaneously enable densification (accommodate more residents), retain or improve natural hydrology, and create more liveable built forms.**

  A set of water sensitive (WS) housing typologies has been developed, characterised by more compact built form and with priority given to green space area and useability. These typologies were found to provide benefits in terms of water performance – particularly minimising effect on local hydrology – when compared with standard industry practice across a number of locations in Australia. In both Knutsford (Perth) and Salisbury (Adelaide), WS design retained more stormwater than both BAU and existing, low density development (EX). Analysis of the Knutsford precinct design showed that 24% in EX, 60% in BAU and 13% in WS of the rainfall volume was converted to runoff, while in Salisbury these differences were smaller but still significant with values of respectively 42% (EX), 50% (BAU) and 31–39% (WS). While water demand was shown to be higher in WS compared with EX or BAU (in Salisbury WS scenario was 2.3 in Knutsford 2.4 higher than EX), WS designs achieved higher water use efficiency – a higher number of people whose demand is met with 1kL of imported (mains) water. In Knutsford, 1 kL of imported water satisfies demand of 3 people in EX, 6 in BAU and 11 in WS.

  WS designs significantly improved the outlook to gardens, vegetation and trees and solar access and cross-ventilation of the outdoor private space. Designing at precinct scale allows for improved public open space: its availability and diversity, size and proportion, access and connectivity, multi-functionality and outlook to vegetation. These benefits are more significant in Knutsford than Salisbury because Knutsford does not currently have public open space within its boundary. Additionally, WS designs improve thermal comfort of the precinct by ameliorating effects of urban heat island effect. In EX, 77% of the study area exhibited temperatures above 42°C UTCI on a high heat day while water sensitive designs can reduce this to 68% for WS-Con or 59% for WS-Max.

- **Much of the influence of cities on stormwater and cooling can be addressed with good building design, and related land use and vegetation management**.

  We found that density, dwelling occupancy, building compactness and built cover, surface materials and vegetation area played a significant role in water sensitive performance of the precinct.

- **Water servicing options and hybrid infrastructure can provide additional water supplies, and help service growing populations, improve water security and manage wastewater flows.**

  We evaluated the impact of water servicing alternatives at site (single household) and precinct scale. In both cases it was evident than no single alternative servicing option could meet 100% of demand and that different servicing options perform differently in terms of their impact on water demand and hydrology depending on the context. The analysis showed that self-sufficiency, that is the volume of water use which alternative water supply (from 'within' the system) can meet on annual basis, can vary significantly depending on the context and technology used, ranging from 10% in the case of rainwater tanks in Adelaide for a dry year to 36% for stormwater harvesting in Melbourne for a wet year.

  Precinct analysis showed incorporating alternative water servicing options can improve water use efficiency despite the fact that all gardens would be irrigated – from 251 L/person/day to 116**L**/person/day in Salisbury and from 325 L/person/day to 110 L/person/day in Knutsford. In the case of Knutsford, wastewater recycling met 90–100% of the irrigation demand in the analysed scenarios while rainwater tanks alone could meet only 30–40% of this demand. In Salisbury, rainwater tanks in a dry year could only meet 20% of irrigation demand while the recycled stormwater supplied through purple pipe varied between 40% and 100%, depending on the area of irrigated greenspace assumed.

  An additional benefit of rainfall-independent water servicing options (e.g. wastewater recycling) which was not quantified through indicators but identified in water mass balance was reduced wastewater discharge from the site (assuming the sewer is accessed on site). This was an important bonus to the land developer who would otherwise pay to upgrade the existing sewer network. The impact of water servicing options on urban water performance depended on their storage capacity, rainfall-dependency, and the efficiency of household appliances.

- **The recommended water sensitive typologies, and associated water infrastructure, perform differently in different environments. Site and precinct context (climate, soil, etc.) proves to be very important.**

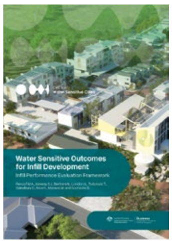
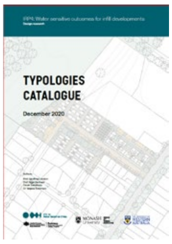
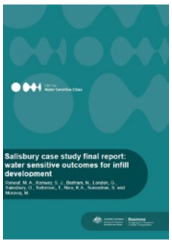
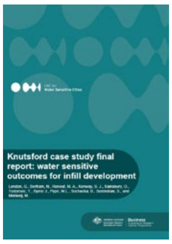
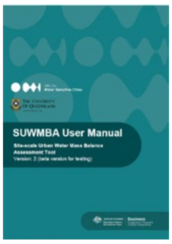
  The 'self-sufficiency' of different water servicing options, for example, was influenced by the rainfall patterns, area of irrigated vegetated space and extent of infill development, which impacts on both the demand and supply of alternative sources. Similarly, the effect of pervious surfaces on stormwater retention is smaller with clay soils and long heavy rainfall events.

Recommendations to implement water sensitive infill development include:

- Pay stronger attention to quantified performance (e.g. in water, liveability and heat management) supported by analysis. This is needed to reduce, or slow the acceleration of negative impacts of conventional infill development and guide improved design. It is also needed to create opportunities for densification that do not compromise water performance outcomes
- Establish city-scale, and related precinct-scale, targets informed by a management goal. This is needed to shape future designs of housing and streetscape typologies uptake. Clear precinct or regional targets can be designed. Without targets, it is harder for designers to know when solutions have reached required levels of performance. More specifically, the performance framework should be used to guide regulation both in setting targets and in checking they have been achieved.
- Use standardised designs, assessment tools, methods and indicators. This would help embed water sensitive infill development principles in current redevelopment practice and inspire further development of water sensitive design alternatives.
- Foster multidisciplinary cooperation in planning, design, engineering, architecture, hydrology and urban climate to achieve superior outcomes for urban environments in terms of sustainability and liveability.
- Recognise and address barriers in the current governance arrangements and planning mechanisms as well as market and community reservations regarding novel design options to enable uptake of more innovative housing options.

The following publications provide more details about project's outputs:

Table 1. List of IRP4 key publications

	Publication title and link	Description
	Water sensitive outcomes for infill development: Infill performance evaluation framework	Outlines how to evaluate development options
	Infill typologies catalogue	Evidence-based design guidelines, describing a range of housing typologies, at densities and configurations relevant to Australian cities
	Salisbury case study final report: Water sensitive outcomes for infill development	Results of application of the Framework and typologies catalogue in Salisbury, South Australia
	Water Sensitive Outcomes for Infill Development: Knutsford Case Study Final Report	Results of application of the Framework and typologies in Perth, Western Australia
	User Manual for Site-scale Urban Water Mass Balance Assessment (SUWMBA) Tool	Describes the freely downloadable SUWMBA tool and how to use it to assess site water performance

1. The challenge and opportunity of infill development

Australian cities have experienced rapid urban growth over the past decades and this trend is projected to continue. To limit the adverse effects of the unchecked expansion of cities associated with urban sprawl, including longer commute times and higher resource use, urban planners have advocated for accommodating some of the future population within already developed areas as opposed to greenfield development on the city fringe. This has been done through restricting urban growth to the current urban footprint and encouraging densification of existing precincts, many of which are characterised by suburban landscape with single detached houses on large lots, resulting in one of the lowest densities in urban areas worldwide. These changes imply a need for moving from currently dominant low density housing design to medium and high density residential development on the one hand, and redeveloping underutilised or vacant land referred to as 'infill development', on the other. To foster these changes, major Australian cities have adopted higher target densities and goals regarding the percentage of new dwellings that should be built through infill development, envisioning that approximately half of the projected urban growth, totalling 9.5 million people between 2020–2050 (Coleman 2016), will be accommodated within established urban areas.

1.1. Challenge: impact of infill development on hydrology, resource use and liveability

In practice, infill development has generated a number of problems related to its environmental performance and urban amenity. For example, standard (business as usual – BAU) industry practice is characterised by a higher fraction of land occupied by built form and a larger driveway which habilitates access to garages (Murray et al. 2011). This increases imperviousness of the urban area which, as demonstrated by Renouf et al. (2018), is likely to further alter the pre-developed hydrology by reducing groundwater infiltration and evapotranspiration and elevating stormwater runoff, thus exacerbating any potential issues with drainage (Figure 1).

Current typical (BAU) infill development is characterised by single-storey detached or semi-detached units with limited useful greenspace and extensive paved areas (Murray et al. 2011). Most major cities in Australia can expect significant infill development over the coming decades, and the issues

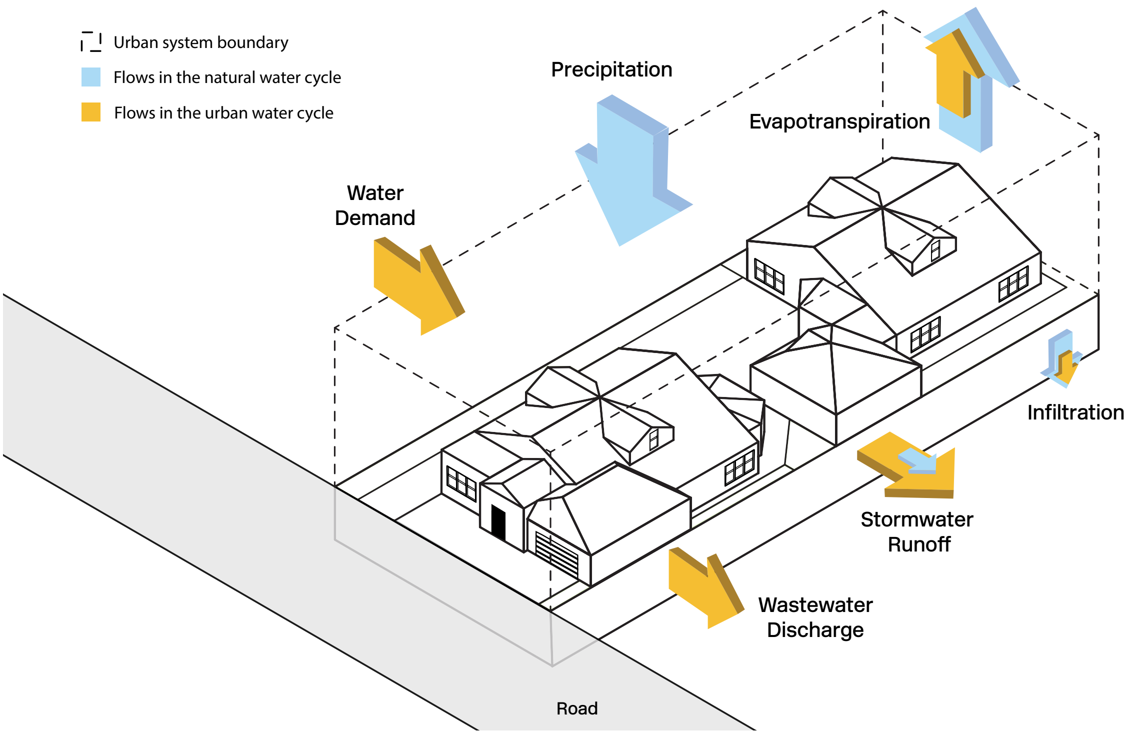


Figure 1. Infill development – two dwellings on a single lot, BAU (business as usual) standard industry practice. The figure shows the urban water mass balance of infill development site and water flows. This includes altered flows (orange arrows) and natural (pre-urbanisation) conditions (blue arrows). The dotted lines mark the 'system boundary' which is assessed for performance.

stemming from the current standard industry practice are likely to continue to have a significant impact on (i) hydrological performance, (ii) resources efficiency, and (iii) amenity and liveability of urban areas.

BAU infill design solutions often decrease liveability for residents and their neighbours. One example of this is the useability of space, both internal and external. The internal design is driven by easily marketable 'number of rooms' and often results in smaller bedroom sizes which restrict flexible use or multiple occupancy (Murray et al. 2011). Useable external spaces (e.g. gardens) are sacrificed to deliver priority features for real estate value – large internal floor area and garages integrated with the building structure. Where green space is provided, privacy considerations are often overlooked, resulting in limited use of these spaces (Murray et al. 2011). Extensive paved areas for driveways and smaller gardens can impact the broader precinct, for example, by exacerbating the urban heat island effect resulting in higher ambient temperatures.

1.2. Opportunity: water sensitive infill development

Infill development, if well designed, is an opportunity to redevelop our cities in a way that improves liveability, hydrological performance and resource efficiency, *as well as* higher population. This report shows that water sensitive infill housing design which maximises pervious and vegetated space can deliver superior outcomes in terms of reducing stormwater runoff compared with existing low density development, particularly if it also includes alternative water servicing technologies (e.g. rainwater tanks). Accommodating more people on the same lot will inevitably lead to higher total water demand (Figure 2). However, incorporating alternative sources for supply at household scale (e.g. greywater recycling) can help to meet part of this demand and thus improve the overall water efficiency of the precinct. Applying the principles of architectural best practice to housing design may help to avoid the mistakes that proliferate current infill practices and issues with the BAU approach related to privacy and useability of space.

Applying water sensitive design at the precinct scale can also deliver wider benefits, including improved thermal comfort and more natural local hydrology. This project demonstrates whole-of-precinct sustainable design is both possible and desirable. The methods developed in this research could support urban regeneration (Thomson and Newman 2018) or green urbanism (Newton and Glackin 2018, Newton et al. 2011)Newton et al. 2011, which are both premised on tapping redevelopment as an opportunity. Building on the foundation of water sensitive cities (which looks holistically at the value of water in urban environments), water seems particularly well positioned to be a vehicle for urban regeneration.

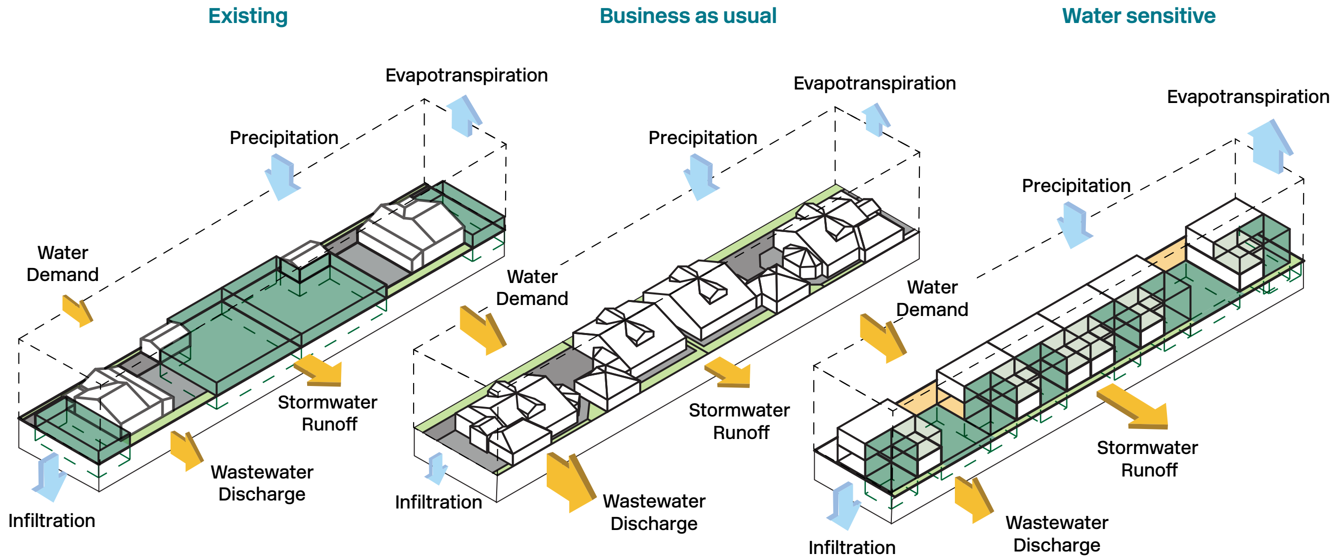


Figure 2. Urban water mass balance of current low density development (EX) and two infill development scenarios: standard infill industry practice (BAU) and water sensitive infill alternative (WS)

1.3. What is missing: knowledge gaps related to water sensitive performance and design

Creating water sensitive precincts requires a change in current urban planning practice regarding infill: a transition from mitigation of incremental, detrimental changes to performance-driven decision making. While there are some barriers related to current institutional and market arrangements, it seems that there are also knowledge gaps. In particular, we need to understand:

(1) *How water sensitive precincts perform and what sets them apart from 'business as usual'*. Prior to this project there were few published examples of water-centred urban regeneration at precinct scale that quantified the benefits and impacts so they may guide best practice.[1] A contributing problem is the lack of quantitative evaluation of (a) different housing designs, both the BAU and conceptual designs of water sensitive alternatives, (b) combinations of these designs with different alternative water servicing options, (c)combination of these designs with precinct-scale water sensitive interventions through design (e.g. water sensitive streetscape) and large storage water servicing options (recycling and harvesting at precinct scale) in terms of their impacts on the urban water cycle. Part of the problem with quantifying water performance relates to difficulty in consistently defining the 'system boundary' and identifying which built environment (house elements), water system (piping and draining and storage), and natural environment (e.g. soils and vegetation) are considered within or outside that boundary.

(2) *How water sensitive considerations could change the design of infill housing.* The second gap relates to the lack of water sensitive designs tailored to infill conditions. While some preliminary designs for better infill development have been proposed (Murray et al. 2011), they have not been assessed for their water impacts.

1 Notable exceptions include the large-scale work of Turenscape in China and many water-focused urban redevelopment projects in the Netherlands and Denmark. But these projects involve vastly different environments to Australian urban conditions.

1.4. Water sensitive outcomes for infill development (IRP4)

This report presents key insights from the CRC for Water Sensitive Cities project, *Water sensitive outcomes for infill development* (IRP4), which was developed to respond to these two major knowledge gaps. Specifically, the project sought to (Figure 3):

- create designs for water sensitive infill development based on an understanding of current industry practice and water servicing options that could be integrated at different scales
- develop a new Infill Performance Evaluation Framework, and use it (with accompanying tools designed specifically for infill contexts) to assess different designs at site and precinct scales
- showcase well-performing water sensitive designs at the precinct scale through real-life case studies
- explore opportunities, especially in terms of governance arrangements, for promoting water sensitive infill stemming from the learnings from the case studies.

The research focused on real-life case studies – precincts in Salisbury (South Australia) and Knutsford (Western Australia) – that are already beginning to experience infill development to meet high population density targets. The research engaged local stakeholders (water and urban planners from case study contexts), as well as representatives of government and utilities from other states. It included several activities in which broader audiences were involved in ideation and experimentation (e.g. design charrettes, field trips, consultation meetings and tool testing). The multidisciplinary project team, which included architects and engineers, developed designs, tools and frameworks in an iterative process where these products were tested, evaluated by stakeholders and improved accordingly. Details about the project team and process can be found in the appendix.

The theory of change which informed this research is summarised in Figure 3. It outlines the issues the project addressed, strategies it employed, outputs it developed and outcomes it sought to achieve. Use the 🔗 icon next to each box in Figure 3 to be redirected to specific outputs via a hyperlink to the relevant publication. Click on links in Figure 3 to be redirected to relevant content in this report. The project builds on previous CRCWSC research: Urban metabolism framework (B1.2); Urban design and infrastructure (D5.1); Urban heat island (B3.2 and 3.1); CRCWSC toolkit (TAP); and the Water Sensitive Cities Index (D6.2).

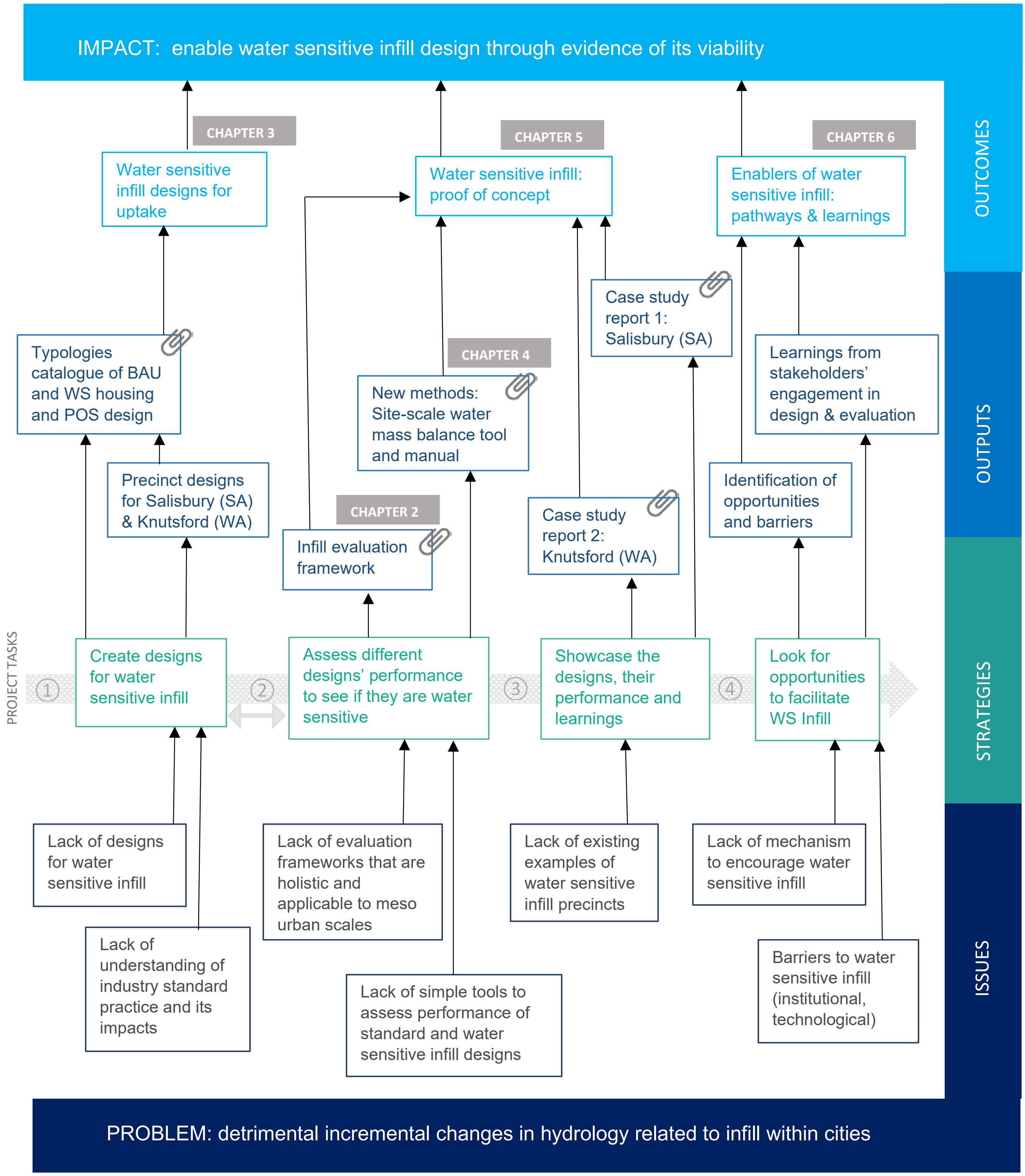


Figure 3. How to improve business as usual infill development? Theory of Change of the project. Click on the chapter box to get redirected to the content within this report. Click on clip icon to get redirected to other IRP4 publications.

2. Defining 'water sensitive infill': principles and evaluation criteria

Water sensitive infill development is defined as housing and public open space designs that deliver aggregate superior outcomes at a precinct scale in terms of urban water performance, mitigation of urban heat impacts, and architectural and urban spaces quality. Specifically, it restores natural hydrology; improves water storage and soil moisture; enables use of supplementary water supplies; facilitates irrigation of vegetated areas, and passive mitigation of outdoor urban heat; provides spaces and deep root zones for vegetation; and has well designed quality dwellings and urban spaces for improved amenity, usability and flexibility. This definition has been translated into a set of specific criteria and indicators which form the basis of the Infill Performance Evaluation Framework (Figure 4).

The idea of water sensitive infill is underpinned by the concept of water sensitive cities, understood as a place that:

- serves as a potential water supply catchment, providing a range of different water sources at a range of different scales, and for a range of different uses
- provides ecosystem services and a healthy natural environment, thereby offering a range of social, ecological and economic benefits
- consists of water sensitive communities where citizens have the knowledge and desire to make wise choices about water, are actively engaged in decision making, and demonstrate positive behaviours.

The idea of water sensitive infill also resonates with the principles that underpin concepts such as Sponge Cities or Water Wise Cities, particularly with goals related to retaining stormwater runoff to ameliorate pluvial flooding in highly urbanised areas and reducing dependency on centralised water supply. While water for greening and urban heat mitigation are specific to arid and hot climates, urbanisation and climate change are relevant to many cities worldwide. With the emergence of heatwaves in places that did not experience them before, and water stress for example due to lower availability of snow-fed water replenishment, many parts of the world are likely to face similar challenges in the future.

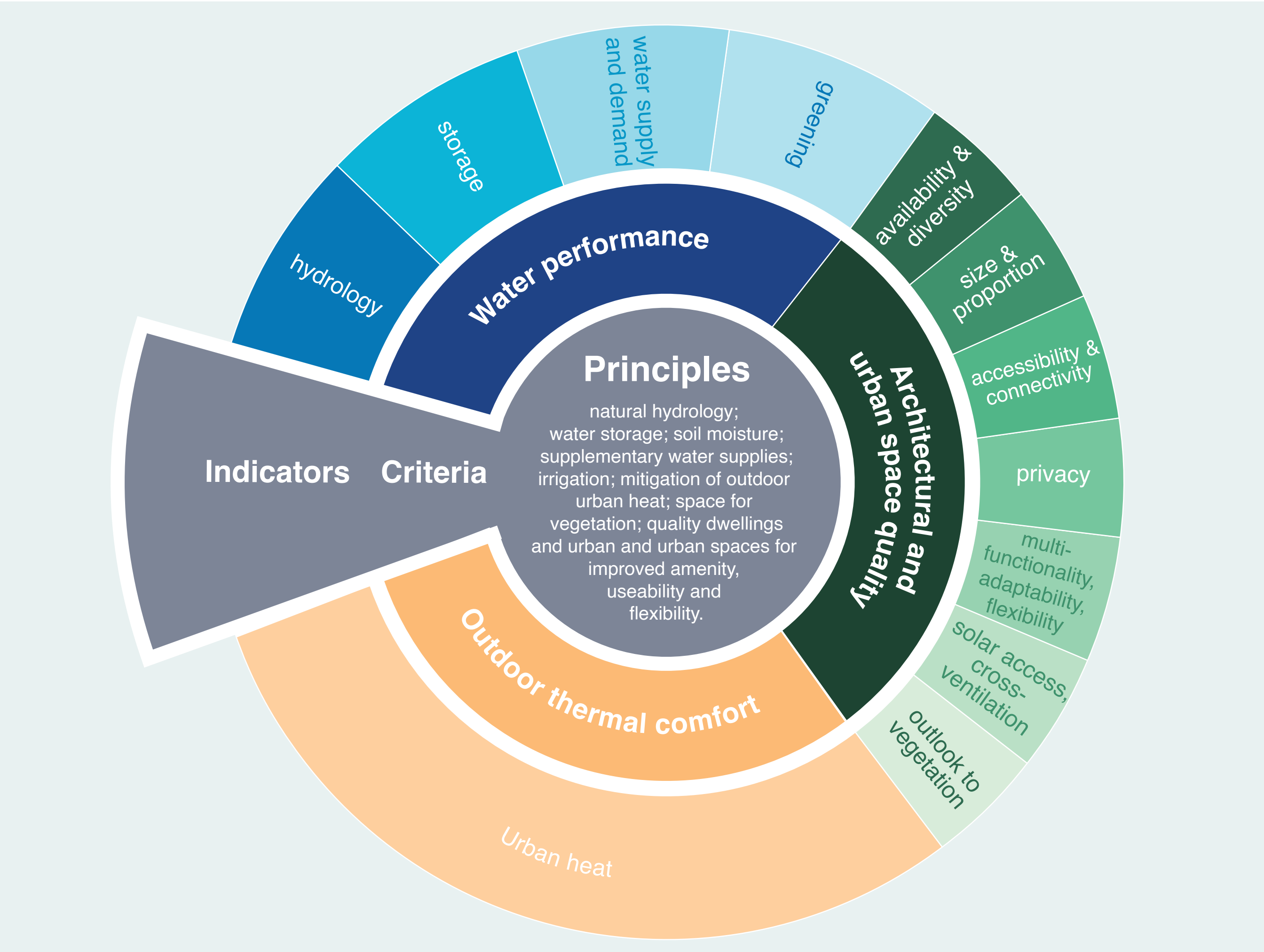


Figure 4. Infill Performance Evaluation Framework: principles, criteria and indicators (simplified)

2.1. Principles of water sensitive infill design

1. Good water sensitive infill design does not further adversely alter the natural hydrology (infiltration, evapotranspiration and stormwater discharge) of the development area, and ideally mimics the hydrological water balance of a reference state
   a. Maintenance/restoration of annual stormwater discharge volumes towards a reference state can contribute to protecting the ecological condition of waterways and water quality.
   b. Maintenance/restoration of annual stormwater discharge volumes towards a reference state, coupled with a capacity for water storage (see principle 2), can contribute to reduced flood risk.

2. Infill designs incorporate water storages to facilitate the availability of supplementary water supply, and slow/retain/detain runoff for reducing flooding.

3. Infill designs facilitate soil moisture storage (where beneficial) through permeable surfaces that promote infiltration (see principle 1).

4. Infill designs reduce reliance on imported water, facilitating the use of supplementary water supplies (harvested rainwater and stormwater, recycled greywaters and wastewaters), by making space for water storage and/or connections to supplementary supplies.

5. Infill designs enable irrigation of vegetated areas with supplementary water supplies, to support greening for cooling (see principle 7) and amenity (see principle 8).

6. Infill designs include space and deep root zones for vegetation and large trees, to provide greening for cooling and amenity.

7. Infill designs enable passive mitigation of outdoor urban heat through building orientation and tree canopy shading.

8. Dwellings and urban spaces are efficiently designed and equipped to enable improved amenity, usability and flexibility.

2.2. Criteria and indicators of water sensitive infill design

The principles are operationalised into criteria and indicators as outlined in Table 2.

The Infill Performance Evaluation Framework can be applied at different urban scales (single sites, precincts, suburbs, towns, hydrological catchments and sub-catchments, cities), however for infill development scenarios the focus will tend to be on site- and precinct-scales evaluation, where:

- ‘site’ refers to an individual parcel of private land being developed for single or multiple residential dwellings, or an area of public land whose development is associated with urban densification or renewal such as a road or street corridor or park

- ‘precinct’ refers to the scale at which infill is planned and managed by the local authority, for example, structure plans, development zones, planning schemes. It may be as small as a suburban block or as large as a small suburb. Precinct-scale evaluation allows examination of how performance is influenced by the extent and distribution of densification, WSUD in the public realm, and precinct-scale water servicing options.

Table 2. Performance principles, criteria and indicators

Aspect	Principle number	Performance criteria	Examples of performance indicators	
Hydrology	1	Restored natural water flows	Infiltration (groundwater recharge) volume is restored towards a reference state, by the presence of pervious surfaces	Annual volume of infiltration (ML/yr or mm/yr) in an average rainfall year Fraction of rainfall that infiltrates (%) in average rainfall year Naturalness of infiltration – annual volume infiltration relative to reference state
			Evapotranspiration volume is restored towards a reference state, by the presence of vegetated surfaces, vegetation selection, and irrigation of vegetation	Annual volume that evapotranspires (ML/yr or mm/yr) in an average rainfall year Fraction of rainfall that evapotranspires (%) in average rainfall year Naturalness of evapotranspiration – annual volume that evapotranspires relative to reference state
			Stormwater discharge volume and peak flow rate is restored towards a reference state, by the harvesting, storage and use of rainwater and stormwater (see also principles 2, 4, 5)	Annual volume of stormwater discharged (ML/yr or mm/yr) in an average rainfall year Fraction of rainfall that converts to stormwater discharge (%) in average rainfall year Naturalness of stormwater discharge – annual volume of stormwater discharged relative to reference state
	1a	Waterway and wetland ecology, water quality	Peak daily stormwater discharge is restored towards a reference state	Number of stormwater discharge events relative to reference state in a wet year. Peak daily stormwater discharge volume in average rainfall year, relative to reference state in a wet year
	1b	Flood resilience (overland flow)		
Water storage capacity	2		Water storage capacity (in tanks, basins, etc.) within the infill development is optimised	Volume of onsite constructed water storage, relative to optimal storage volume
	3		Soil moisture storage capacity is maximised through permeability	Volume of soil moisture storage capacity, relative to reference state

Table 2. Performance principles, criteria and indicators (*Continued*)

Aspect	Principle number	Performance criteria	Examples of performance indicators	
Water demand and supply	4	Water security and drought resilience	Water demand is minimised by water-efficient appliances, water-efficient behaviours and higher dwelling occupancy (where possible) Water supply self-sufficiency is maximised by harvesting, storing, using supplementary water sourced from the urban system	Per capita use of imported water Self-sufficiency (% of water demand met by water sourced from within the urban system)
Greening	5	Space and water for vegetation	Reliability of supplementary water supply is sufficient to enable irrigation, even in dry periods, to maintain soil moisture and dense tree canopies	Volumetric reliability of supplementary water supplies in a dry year (or alternatively dry season)
	6		The amount of space for vegetation is optimised	Fraction of area that can support vegetation Fraction of area with deep root zone
Urban heat	7	Outdoor thermal comfort	Outdoor thermal comfort can be maintained within a tolerable range (relevant to the climate)	Fraction of locations less than a threshold 'feels like' (UTCI) temperature on a hot day
Architectural and urban space qualities	8	Amenity and useability (private and public)	The following qualitative performance criteria are met for dwelling interiors, and outdoor private, communal and public spaces: A. Availability and diversity B. Size and proportion C. Accessibility and connectivity D. Privacy and noise management though balanced transition between spaces E. Multifunctionality, adaptability, flexibility F. Solar access, cross-ventilation G. Outlook to gardens, vegetation, canopy trees	Qualitative appraisal of the criteria A-G by an expert. More details detailing how these are assessed available here

How to assess if infill redevelopment is water sensitive?

To evaluate whether a given development is water sensitive, we have taken a **systematic and quantitative** approach in a structured process described by the Infill Performance Evaluation Framework. The proposed framework is underpinned by a **whole-of-water-cycle approach** to urban water management, considering different water flows, both natural (e.g. precipitation) and anthropogenic (e.g. wastewater discharge). It includes a clear **spatial definition of a 3-dimensional system boundary**, which allows evaluation of the impacts of specific urban designs on the water cycle at different urban scales. The methods for evaluating water sensitive infill performance build on the Urban Metabolism Evaluation Framework for Water (UMEF4Water) which was developed as part of the CRCWSC's project B1.2. Its conceptual underpinnings and methods are discussed in more detail in the following reports:

- Urban metabolism for planning water sensitive city-regions: Proof of concept for an urban water metabolism evaluation framework
- Urban metabolism for planning water sensitive cities.

To adapt the framework to an infill development context, aspects of architectural, urban space and heat analysis were added to the evaluation. The Infill Performance Evaluation Framework also caters for a wider range of scenario parameters to account for differences between different infill developments, and proposes dedicated tools for analysis at fine urban scales (e.g. site scale suitable for individual lots and dwellings).

1. Definition of the infill area and the infill scenarios

Existing (EX) development state:
Represents the typical state of development before re-development, on a defined area of land, with a starting population.

Business as usual (BAU) infill state:
Represents the type of higher-density development that might be built in the current development market, on the defined area of land, with a target population increase

Alternative infill state:
Represents a alternative scenario of higher-density development, on the defined area of land, with the same / similar target population as the BAU scenario

2. Definition of the parameters for each scenario

Environmental parameters:
Rainfall
Potential evapotranspiration
Soil type

Built form parameters of dwelling typologies (site-scale):
Building and surface dimensions
Surface types, vegetation types
Imperviousness of hard surfaces
Water storage / retention on site

Urban design parameters (precinct-scale):
Density of the built forms
Areas of roads, road reserves
Area of green space, vegetation types
Water storage / retention in landscape

Water servicing parameters:
Indoor / outdoor water demand
Rainwater / stormwater harvesting
Water storage
Wastewater recycling
Groundwater recharge / reuse

3. Urban water performance analysis

Quantifying the urban water mass balance for the assessed area (using the *SUWMBA or* Aquacycle tools):

Natural water flows:
Precipitation
Evapotranspiration
Infiltration
Stormwater runoff

Urban water flows:
Indoor/ outdoor water demand
Mains water supply
Harvested water supplies
Recycled water supplies
Wastewater discharge to environment

4. Architectural and urban space analysis

Rating the characteristices and quality of the architechural and urabn spaces in the assessed area (using the *Architectural and Urban Space Quality Rating Scheme*):
Dwelling amenity and function
Outdoor private space
Outdoor communal space
Outdoor public space

5. Urban heat analysis

Predicting the 'feels like' (UTCI) temperature
(using the *UMEP model*)
Fraction of locations that are greaterthan a reference temperature (UTCI) on a hot summer day

6. Reporting performance

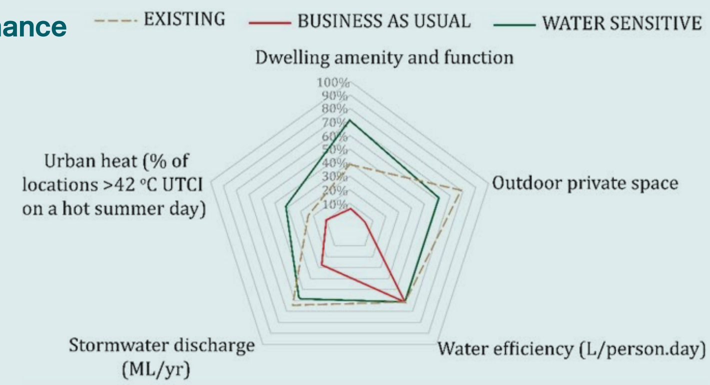


Figure 5. Components of the Infill Performance Evaluation Framework (Renouf et al. 2020b, p. 15.)

3. Methods for evaluation

Infill performance evaluation consists of four steps:

1. Definition of the infill area and the infill scenarios: the area that will be redeveloped and the projected population to be accommodated in the infill development
2. Definition of parameters of each scenario: establishing values for different design variables and climatic variables, which are then inputs to the models that are used for indicator generation
3. Analysis of the (i) water performance, (ii) architectural and urban space quality, and (iii) urban heat performance using tools appropriate for the scale of assessment
4. Graphic representation of the water sensitive performance through indicators. This could be a radar chart as used in this project, but could also be other data visualisation means that allow comparison of different options against several indicators.

While the analysis can be performed using different tools and techniques, the framework proposes a set of tools for the three main dimensions of the water sensitive infill performance: water performance, urban heat performance and architectural and urban space quality.

3.1. Water performance

Water performance is assessed using urban water mass balance, consistent with the methodology described in the final report from project B.1.2. It is premised on the concept of urban metabolism, which considers urban areas as systems and focuses on quantifying flows of resources and materials through them. It thus focuses on water volumes, both natural (e.g. precipitation) and anthropogenic (e.g. imported, mains water supply) and is underpinned by the assumption that within a pre-defined 3-dimensional system boundary, the sum of all inflows equals the sum of all outflows accounting for change of water stored within this boundary (Figure 6). The main benefit of urban water mass balance is that is enables: (i) an explicit definition of the urban system, and (ii)comprehensive water performance evaluation by dictating the consideration of all urban water flows and their interactions within the defined urban system. Being based on the principle of mass conservation, it provides a strong theoretical background for a systematic quantification method that is applicable for analysis in any spatial and temporal scale. Therefore, it is well-suited for infill context.

Due to scope and time, we have not specifically analysed water quality impacts. However, water quantity is a strong proxy of water quality and our strong view is that moving catchment hydrology much closer to pre-development (pre-urbanised) conditions is highly likely to also improve water quality.

The analysis of the water flows was conducted using two different tools at precinct and site scale. Precinct-scale analysis is more complex than site-scale analysis and involves a range of potential building typologies as well as more interactions of different technologies and infrastructure components. The input parameters for the analysis conducted through tools for precinct- and site-scale evaluations included:

- environmental conditions (rainfall, potential evapotranspiration, soil type)
- characteristics of the housing typologies (areas of different land cover surfaces (e.g. roof, garden, pavement, etc.), surface types, imperviousness, water storage)
- parameters of urban design at precinct scale (density, area of roads, road verges, area of greenspace and vegetation types, water storage in landscape)
- water serving parameters (indoor/outdoor water demand, storage capacity (e.g. rainwater tank, stormwater harvesting), groundwater recharge and reuse, water supply system representing the connection between different water sources and end uses).

The review of existing models (Moravej et al. 2021)revealed a need for a site-scale tool for water mass balance analysis that goes beyond assessing the effectiveness of specific WSUD assets and evaluates the impact of architectural design of built form at high resolution. The Site-scale Urban Water Mass Balance Analysis (SUWMBA) model was thus developed especially for the IRP4 project (Moravej et al. 2021) and used to assess performance of various housing typologies. The rainfall/runoff model used in MUSIC was modified to enable analysis of infill designs. SUWMBA's inputs include specific site surface analyses derived from architectural drawings, vegetation type, number of dwellings, occupancy rate, details of household demographics, appliance efficiency, and environmental parameters (daily time series of precipitation, potential evapotranspiration, and soil characteristics) (Figure 7). The outputs are urban water mass balance and water performance indicators outlined in Table 2 (principles 1 to 4). Detailed description of SUWMBA's methods can be found in (Moravej et al. 2021), its user manual in Moravej et al. (2020), and an example use in Renouf et al. (2019).

At the precinct scale, Aquacycle software was used (Mitchell et al. 2005), which is a daily urban water balance model, particularly suited to modelling decentralised water sources such as stormwater and recycled water. SUWMBA is not suitable for precinct-scale analysis, because it does not model runoff flows within the precinct and the operations of water servicing technologies beyond site scale. The rainfall/runoff model uses parameters that were derived from the average typology fractions of a roof, garden and pavement surfaces. Compared with SUWMBA, indoor and outdoor water demand is modelled with less precision – the household water demand model used fixed water demand factors, while the outdoor water demand is customised by the modeller and the potential evapotranspiration values. Aquacycle analysis includes detailed modelling of water servicing options (rainwater and stormwater harvesting, greywater reuse, wastewater recycling, ASR) at different scales. The calibration factors used in Aquacycle assume no base flow, so 'base flow recession constant (ratio)' is set to zero.

The water flows modelled in SUWMBA and Aquacycle inform urban water performance indicators (Table 2). Some of the indicators need to be evaluated at site scale, while others only make sense at precinct scale (e.g. drought resilience). In practice, precinct-scale analysis is underpinned by site-scale analysis, because conducting site-scale analysis enables definition of typology-average design parameters. Conducting precinct-scale analysis which then informs specific indicators demonstrates how improved performance at the site scale might translate to the performance of the large urban area. The indicators also allow specification of the reference state to which hydrological indicators are compared. This can be a target state, the pre-urbanised state, or an altered pre-urbanised state (where receiving water bodies adapted to 'urbanised' water balance and reached an equilibrium).

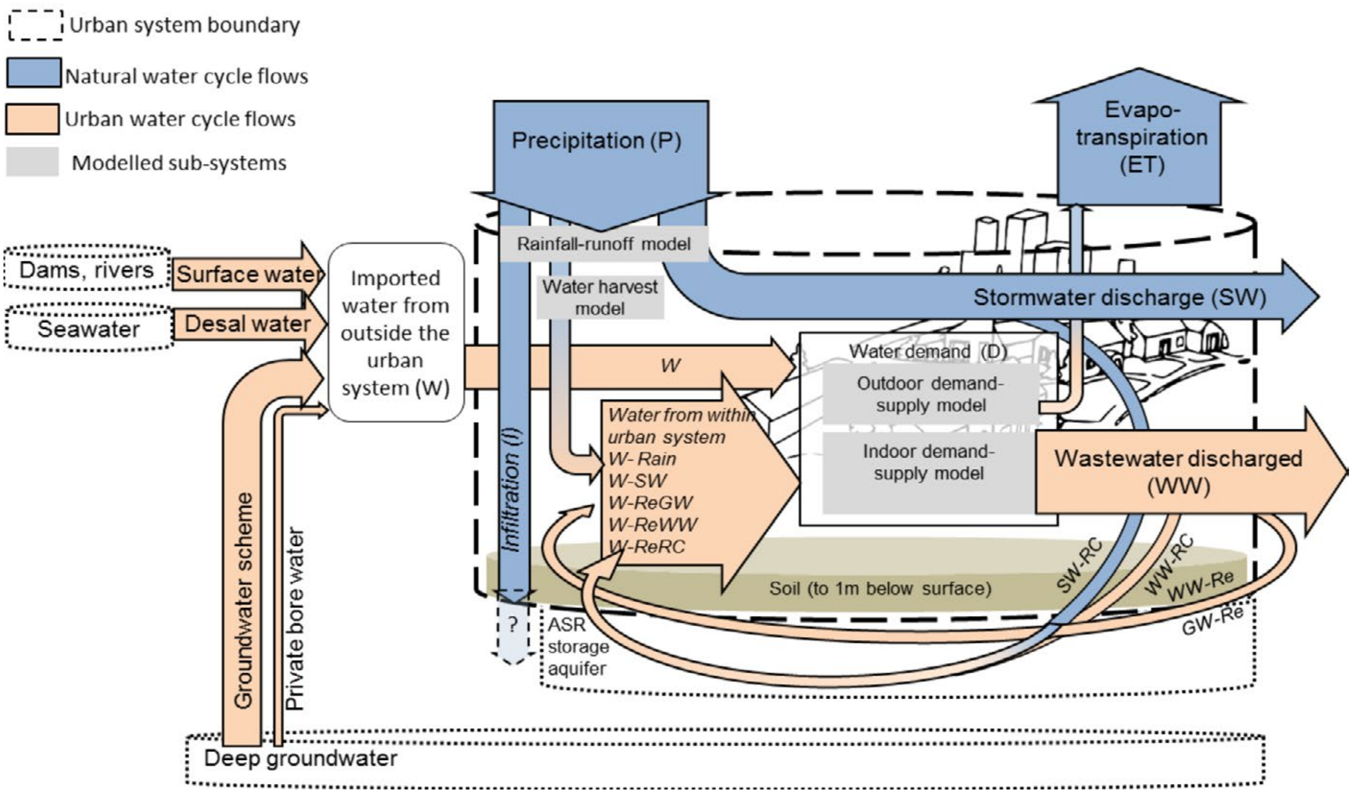


Figure 6. Water mass balance – conceptual model (Renouf et al. 2020b, p. 42.)

3.2. Urban heat performance

Urban heat analysis used the Universal Thermal Climate Index (UTCI) which represents the subjective experience and thermal stress of heat on a person in an outdoor area. urban heat performance was assessed using the SOLWEIG module from the Urban Multi-scale Environmental Predictor (Lindberg et al. 2018) model. This model calculates the mean radiant temperature experienced by a human body at each modelled point in site-scale dwelling typologies and was used to calculate UTCI for each modelled point. The performance indicator for urban heat is the fraction of areas in the precinct that have a 'feels like' (UTCI equivalent) temperature on a very hot summer day that is less than a certain threshold (e.g. 42°C UTCI), a level of very strong heat stress.

3.3. Architectural and urban space quality

The IRP4 architectural team assessed the performance of private, communal and public spaces and house interiors against seven qualitative performance criteria using a detailed scoring system. For example, privacy and noise are scored based on the degree (0 – absent, 1 – low, 2 – medium, 3 – high) to which a dwelling interior provides privacy and noise proofing through positioning of windows, screens and fences (e.g. bedrooms not directly facing private open space used by all occupants or communal/ public space). The maximum score for public, private and communal spaces, assessed separately is 21 (sum of maximum score of 3 obtained against all seven criteria). Details of this qualitative appraisal are outlined in the [Infill Performance Evaluation Framework].

How to assess water impacts of specific housing designs?

Site-scale Urban Water Mass Balance Analysis (SUWMBA) is a daily urban water mass balance tool that provides a comprehensive account of all urban water flows (natural and anthropogenic) in, within, and out of a defined urban system. It can quantify the water performance of site-scale design-technology-environment configurations. SUWMBA is developed in Microsoft Excel's Visual Basic for Applications (Excel-VBA) and MATLAB. The latter is developed as an easy-to-use rapid tool with in-built libraries for Australian cities, suited for collaborative urban design and planning contexts. The former was developed for research purposes suited for high-resolution analysis with the capability to automate scenario analysis. The Excel-VBA version can be only used for urban entities up to 4 ha. If no rainwater harvesting system exists, it can be used up to 50 ha. The water flows are estimated as annual volumes, by default, but different time periods can also be evaluated.

The main steps performed by SUWMBA are represented in Figure 7.

Inputs. The in-built libraries include daily time series for precipitation and potential evapotranspiration as well as soil characteristics parameters calibrated for Australian cities derived from the literature. Other inputs include definition of zones within the analysed site which involves entering the area of different land cover surface categories (e.g. roof, garden etc.). The impervious fractions can be selected from data libraries depending on the surface categories entered. To model water demand, user input requires number of people, their age and income for a given site as well as water-using appliances types and efficiency ratings. Rainwater harvesting is calculated based on input data on sizing of the rainwater tanks.

Outputs. The first section of the results is the water mass balance for the urban entity being assessed. Inflows and outflows are separated and presented in ML/year and mm/yr. A schematic representation of urban entity and inflows and outflows is provided on the right-hand side of the urban water mass balance flows. The second section of the results are 25 water performance indicators, which are based on estimated flows.

The SUWMBA Tool is freely available on CRCWSC website.

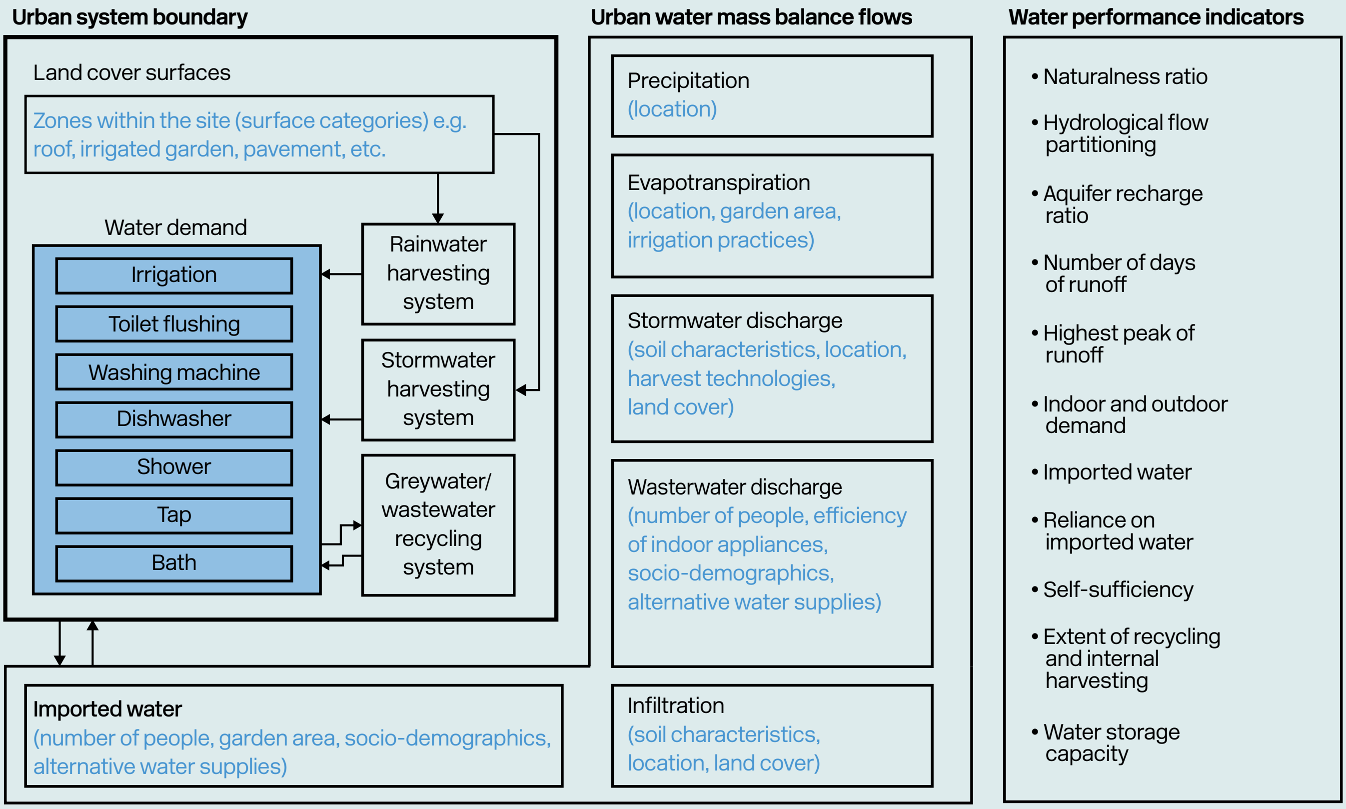


Figure 7. Main elements of SUWMBA tool analysis: urban system boundary, urban water mass balance flows, water performance indicators. Inputs in purple

4. Water sensitive design: housing typologies and precinct design

The Infill Typologies Catalogue (London et al. 2020b) provides evidence-based design guidance for infill development through a comparative review of current industry practice, together with best practice examples and new designs for specific sites in Australian cities. The catalogue illustrates typical infill development housing typologies, documents typical low density dwellings they usually replace and proposes several options for water sensitive housing and public realm design. The standard industry practice ('business as usual' or BAU) infill typologies are derived from existing infill housing examples and thus represent what is currently found on the market. The water sensitive typologies were developed in an iterative process, which was informed by the Infill Performance Evaluation Framework and analysis of water and urban heat impacts, as well as architectural quality criteria. The catalogue of water sensitive designs presents housing typologies at a range of densities (from 42 to 100 dwellings per hectare) which provide alternatives to current BAU practices. The designs in the catalogue propose built form and open space configurations relevant to Australian cities and applicable to different contemporary infill development scenarios.

The catalogue presents typologies (Figure 8) in a way that facilitates comparison between existing (EX), industry standard practice (BAU) and water sensitive (WS) designs. Each housing typology includes context (lot and street), floor (interior) plans, tabulated data on occupancy and density, and also 3-dimensional diagrams which detail parameters important for water flows analysis: vegetated areas of gardens, permeable and non-permeable surfaces, spaces for deep-root trees and water storage. The housing typologies are grouped into three categories representing scales of infill development opportunity:

- Small scale infill developments with groups of two to six dwellings and some communal outdoor space, which provides sufficient space for a courtyard, terrace, or townhouse housing typologies.
- Medium scale infill developments, from six to 20 units, with significant communal outdoor space, which allows for the construction of stacked or cluster houses, 'walk up' apartments, mid-rise apartment buildings.
- Large scale infill developments, more than 20 dwellings, significant communal and public outdoor space, which allows for redevelopment of urban spaces, and whole precinct design.

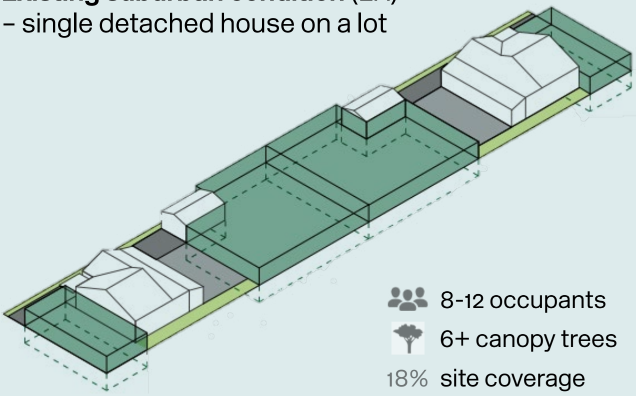
4.1. Small and medium scale infill housing typologies

The comparative review found that BAU is usually one to three buildings on a single sub-divided lot, or a group of four to eight buildings on two adjoining lots. Dwellings are usually detached or semi-detached 1- and 2-storey houses, duplex houses, dual occupancy or terrace houses, or low rise apartment blocks. Typically, BAU infill has large building footprints and driveways, leaving little space for gardens and large canopy trees. This limited outdoor space in turn affects the dwelling's amenity, as it results in poor solar access and cross-ventilation.

In comparison, water sensitive typologies have been designed to increase compactness and thus available outdoor spaces on site. The proposed housing typologies have increased height, with 2- to 3-storey houses and 3- to 5-storey apartment blocks. When possible, for example in medium scale infill developments, buildings have been clustered to optimise the available outdoor space. Notably, water sensitive housing designs tend to increase density compared with BAU (in the examples shown from 28–78 to 42–100 dwellings per hectare). In addition to increased density, the WS typologies have been designed with a higher level of adaptability for different household types and accommodating change during the life of a household. This in turn can lead to higher household occupancy rates.

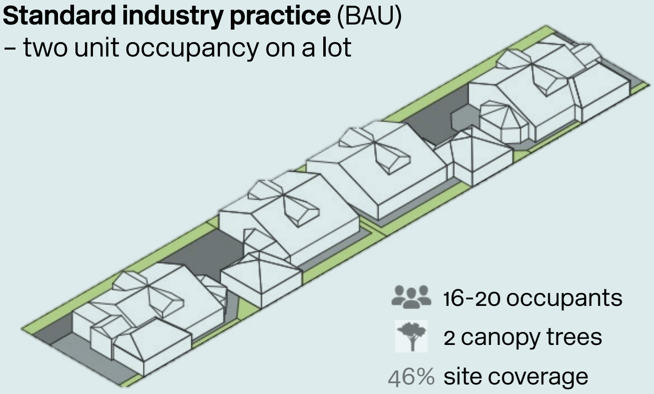
How are water sensitive housing designs different from business as usual?

Existing suburban condition (EX)
– single detached house on a lot



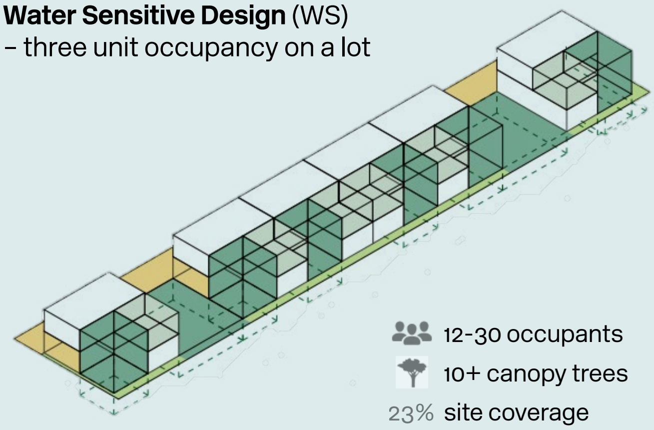
8-12 occupants
6+ canopy trees
18% site coverage

Standard industry practice (BAU)
– two unit occupancy on a lot



16-20 occupants
2 canopy trees
46% site coverage

Water Sensitive Design (WS)
– three unit occupancy on a lot



12-30 occupants
10+ canopy trees
23% site coverage

Figure 8. Existing (EX), Business as Usual (BAU) and Water Sensitive (WS) typologies: courtyard, terrace, townhouse category (London et al. 2020b, pp. 10–12.)

- permeable surface - people
- permeable surface - car
- non-permeable surface
- non-permeable surface - usable
- deck / terrace
- garden
- garden - usable
- tree
- deep root zone

Principle 1: *WS infill prioritises* ***consolidating open space into useable 'outdoor rooms'*** *for trees, people and sun.*

In contrast BAU tends to build in a way that the open space is 'left over' and frequently unusable.

Principle 2: *WS prioritises limiting the amount of site available to vehicles and enabling* ***permeable multi-use surfaces****.*

In contrast, BAU tends to prioritise cars and vehicle movement within the site, resulting in substantial impervious surface areas and poor streetscapes.

Principle 3: *WS prioritises the* ***retention of all existing mature trees*** *and addition of new large canopy tree spaces within each site, together with associated water harvesting.*

BAU tends not to enable large-scale tree canopy through deep soil areas.

Principle 4:
WS creates adaptable and therefore sustainable ***spaces for a range of uses:*** *ageing-in-place, multi-household, multi-generation.*

BAU tends to have a fixed assumption of household type and its space needs, leading to inflexible limited-life housing.

Water performance of infill housing typologies

The typologies were evaluated for their water performance using the SUWMBA Tool, which aggregates daily water mass balances based on real rainfall data from BOM. Three geographical contexts (Brisbane, Melbourne and Adelaide) and three housing typologies: single storey detached house (EX), 2 sub-divided single-storey houses on a single site (BAU) and 2-storey semi-detached units (WS) were used for initial testing (Moravej et al. 2021). The housing designs differed in the number of accommodated residents and areas of greenspace and paved surfaces as described in Table 3. The analysis was performed at site scale, treating a single site as a confined system, and thus ignoring any impact of roads or overflow from neighbouring lots.

Urban water mass balance analysis of the EX, BAU and WS typologies showed that WS designs provided better outcomes than BAU in terms of stormwater runoff, groundwater infiltration and evapotranspiration, thus altering local hydrology to a lesser degree than BAU but higher than EX. (Table 4).

Comparing stormwater discharge naturalness, WS designs (with no alternative water servicing options) would reduce the volume of stormwater runoff from 267% of the volumes for natural (pre-developed) flows in BAU in Brisbane and 291% in Melbourne to 222% and 240% respectively. Incorporating stormwater harvesting and use could reduce the stormwater discharge naturalness to as low as 190% in Brisbane and 159% in Melbourne. This is a better outcome than EX design without any alternative water servicing options, which altered natural (pre-developed) stormwater runoff by 164% in Brisbane and 174% in Melbourne. It is also much lower than BAU which, even with rainwater tanks, achieved reductions to only 243% and 232% for Brisbane and Melbourne. In Adelaide, WS designs elevated stormwater runoff and reduced infiltration more than EX, with patterns similar to those in Melbourne. However, unlike Melbourne and Brisbane, WS designs brought evapotranspiration closer to its level in pre-developed conditions due to Adelaide's dry climate.

At the same time, due to increased population, WS designs almost doubled the demand for imported water. Even with efficient appliances or rainwater harvesting, the yearly demand for WS was significantly higher than EX or BAU. Thus, implementing WS designs should be considered alongside water supply augmentation with local, decentralised options (at household but also precinct scale) (Table 5).

Table 3. Architectural designs and their parameters (London et al. 2020b.)

		EX	BAU	WS
Design parameters	Description	Single-storey detached houses on a large lot	Sub-divided single-storey houses with large area of driveways	Two-storey compact semi-detached units with green backyards and internal linear driveway
	Page in the *Infill Catalogue*	11–12	13–14	15–16
Density	Number of dwelling per site	2	4	6
	Total residents	4.6–5*	9.2–10*	13.8–15*
Impervious area	Roof	21%	53%	36%
	Pavement (inc. driveway)	20%	26%	26%
Pervious area	Green space	50%	18%	38%
	Green fence	9%	3%	0%

* Depending on the city analysed

Table 4. Hydrological naturalness ratio (%) for different scenarios

Scenarios/ options		Brisbane			Melbourne			Adelaide		
		ET	SW	I	ET	SW	I	ET	SW	I
No alternative water servicing options	Pre-urbanised	100	100	100	100	100	100	100	100	100
	EX	95	164	60	114	174	56	148	175	55
	BAU	45	267	27	61	291	25	80	301	24
	WS	68	222	36	86	240	40	111	245	33
Rainwater harvesting	EX	94	146	61	111	126	57	141	134	57
	BAU	41	243	27	53	232	25	71	229	24
	WS	63	190	43	79	159	40	101	173	39
Permeable pavement (60% area)	EX	94	154	87	112	165	82	144	165	80
	BAU	44	253	61	59	277	57	77	287	55
	WS	67	206	77	84	224	72	108	229	70

Notes: Annual flows for ET – evapotranspiration, SW – stormwater runoff, I – infiltration compared with reference case – pre-urbanised hydrology. Colour scale represents departure from natural pre-urbanised hydrology (green = least altered, red = most altered). (Moravej et al. 2021.)

Table 5. Imported water demand for different scenarios in m3/yr (Moravej et al. 2021)

Scenario		Water demand in m³/yr (imported water)		
		Brisbane	Melbourne	Adelaide
No technologies	EX	376	389	492
	BAU	515	520	556
	WS	790	805	866
Efficient appliances	EX	310	323	426
	BAU	386	391	427
	WS	597	609	672
Rainwater harvesting	EX	290	291	417
	BAU	372	371	425
	WS	625	631	738

4.2. Large scale infill developments: water sensitive precincts

Large scale infill developments allow for whole-of-precinct design. This permits incorporation of other elements that improve water sensitive performance, beyond WS housing typologies. This could include redesigning the public realm by:

- creating green laneways by extending vegetated street verges and planting more street trees
- allowing for permeable surfaces (pavements)
- creating new greenspaces (parks and squares) or improving public access to some existing ones (Figure 9).

A range of alternative water servicing technologies could also be economically viable (e.g. wastewater recycling) or provide a higher yield (e.g. rainwater harvesting) at scales larger than single household.

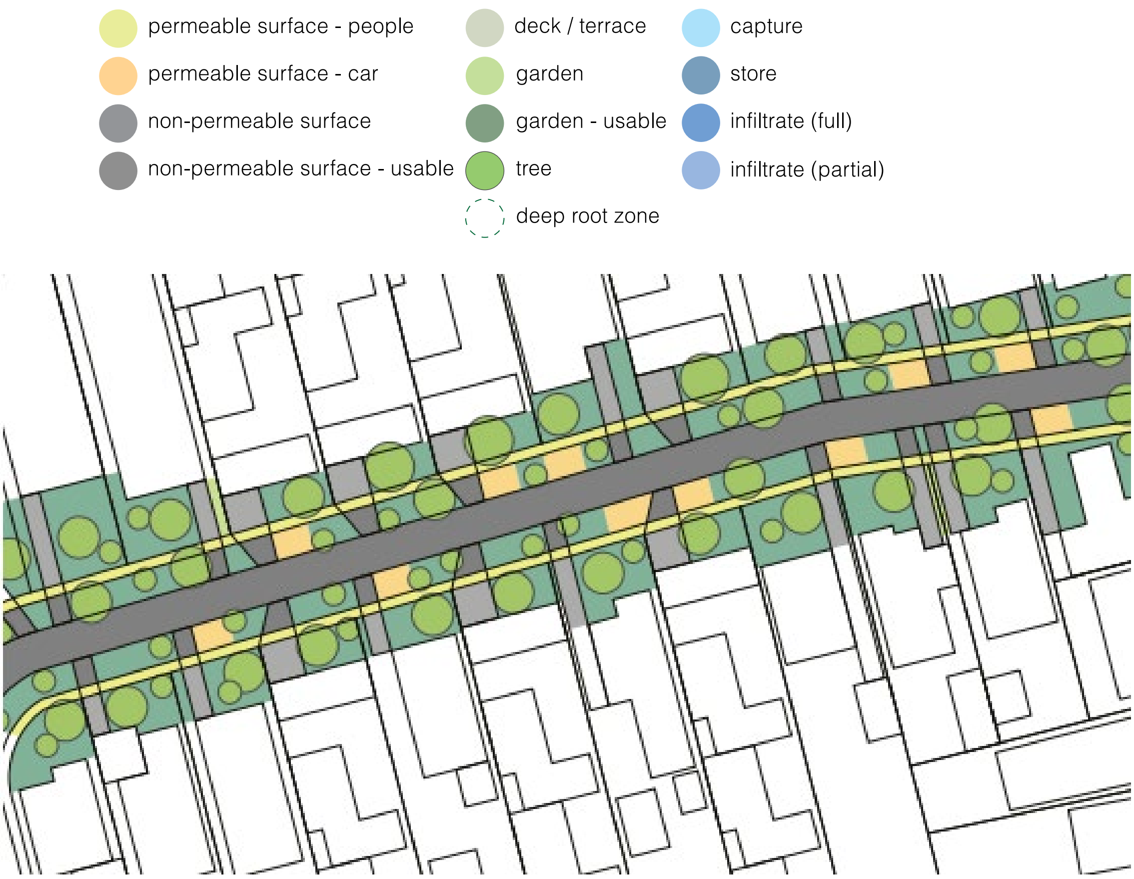


Figure 9. Example of water sensitive streetscape design. As found by (Meng and Kenway 2018) road design can have significant impact on overall precinct water performance. (London et al. 2020b, p. 44.)

5. Water sensitive infill case studies: findings

While the site-scale analysis of housing typologies (Chapter 4) gives initial insights into water impacts of different infill development scenarios, the precinct-scale assessment provides a nuanced view of water sensitive performance of the redevelopment sites in their broader context. A precinct-scale assessment allows understanding of the impact of streetscape and public open space (POS) design (Meng and Kenway 2018), or alternative water servicing technologies at larger scales (e.g. shared rainwater tanks between multiple households). But it also highlights the constraints to which new housing has to adapt, the scale of its impacts compared with the existing development and the opportunities for mitigating the impacts it produces on site (e.g. stormwater runoff). Urban heat analysis and urban space quality are also assessed at this scale. Thus, in the next step of our analysis, we focused on precinct-scale analysis which allowed us to explore how housing typologies perform in real-life circumstances.

Precinct-scale evaluation used two case studies – Salisbury in South Australia (part of Greater Adelaide) and Knutsford in Western Australia (site in Fremantle, part of Greater Perth). Through a collaborative and iterative process involving a multidisciplinary team of researchers and local stakeholders, the project team identified potential sites that may be subject to infill development in the next years. The team created designs of infill housing and precinct design, which were then evaluated using the Infill Performance Evaluation Framework. The case studies highlighted the local constraints in promoting water sensitive designs and demonstrated (London et al. 2020a, Renouf et al. 2020a):

- Water sensitive design can simultaneously enable densification (accommodate more residents), retain or improve natural hydrology and create more liveable built forms.
- Much of the influence of cities on stormwater and cooling can be addressed with good building design, and related land use and vegetation management. The shading effects of vegetation canopies and buildings are the most significant sources of cooling and they are directly related to the design. If there is sufficient green space to irrigate, that can provide cooling on top of the shading effects.
- However, consideration of water servicing options and hybrid infrastructure is also critical to cater for additional water supplies needed for growing populations and to make local contributions of water supply to water security and also deal with related wastewater flows.
- Site and precinct context (climate, soil, etc.) proves to be very important. Typologies perform differently in different environments.

5.1. Case studies context

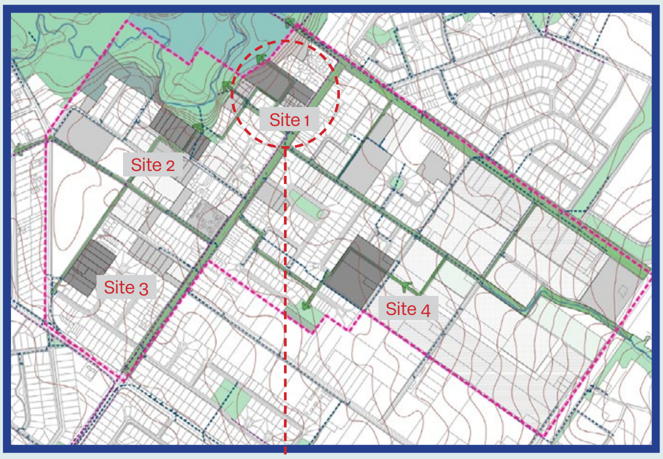
The selected case studies differ on a range of aspects and hence allow examination of the role of context (Figure 10). The precinct nominated in the City of Salisbury is quite large and has a number of vacant lots as well as land currently occupied by commercial operations (e.g. warehouses) which may become available for residential redevelopment (26 out of 130 ha likely available for redevelopment). Knutsford is a small site nominated within the City of Fremantle which has an industrial legacy but is surrounded by medium density residential areas, including the neighbouring award winning White Gum Valley estate, praised for its sustainability performance.

While both areas lie within the middle suburbs (10–30 km from CBD, both around 20 km) (Newton et al. 2011), they differ significantly in terms of urban character and demographics. The Salisbury site displays typical characteristics of middle suburbs which are likely to be redeveloped – dormitory, low density layout with a growing number of commercial land conversions as commerce moves to the outer suburbs. Underutilisation of land is becoming visible with several vacant lots. Residents represent the lowest quantile of socio-economic advantage with median household income of $837/week (~$44,000/year), which is 30% lower than the Australian median. In contrast, Knutsford represents a high socio-economic context with median household income in Fremantle being $1,548/week (~$80,000/year), which is 7% higher than the Australian median (ABS 2016). The adjacent area has already undergone rejuvenation with innovative architectural designs. Thus, the case study proponents expect they would be able to attract buyers interested in purchasing smaller dwellings in multi-residential buildings for a relatively higher price in exchange for features that improve housing sustainability e.g. smart water appliances, electric vehicle charging stations, communal rainwater harvesting schemes.

	SALISBURY East precinct	**KNUTSFORD street precinct**
DIFFERENCES		
Area of whole precinct	Large (130 ha)	Small (23 ha)
Area to be redeveloped (% of precinct)	26 ha (20%)	3 ha (13%)
Vacant land in the area to be redeveloped	13.79%	100%
Impervious fraction of land (EX)	41%	41%
Population (2016)	1,900 residents	90 residents (→100 residents* with typical low density housing)
Socio-economic profile of the precinct (2018)	Low (1 IRSAD)	High (4–5 IRSAD)
Rainfall (average)	536 mm/yr (ranges from 300–800)	807 mm/yr (ranges from 467–861)
SIMILARITIES		
Dwelling occupancy (precinct)	Low (2.3 people)	Low (2.1. people)
Potential evapotranspiration	1,200–1,800 mm/yr	1,468–1,542 mm/yr
Soil permeability	Low (clay)	Low (thin layer of soil on limestone ridge)
Climate	Mediterranean with wet winters, dry, hot summers	Mediterranean with wet winters, dry, hot summers

Figure 10. Case studies context comparison. * Typical existing conditions, projected from surrounding areas.

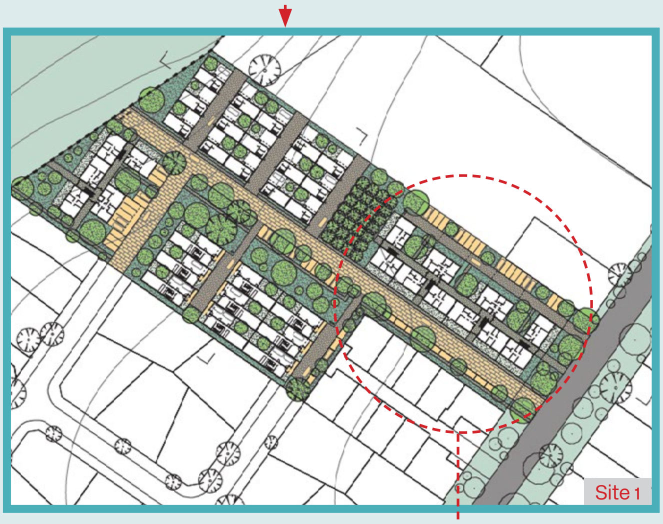
How to design a water sensitive precinct using infill development/urban regeneration?



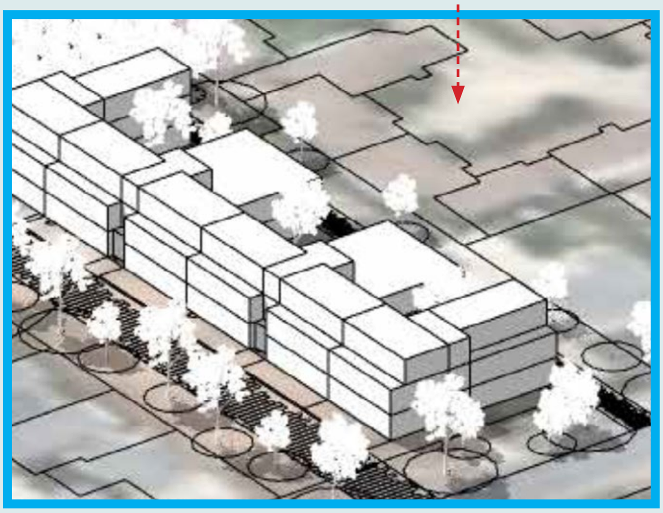
1. Identification of sites likely to be redeveloped

2. Understanding local context, history, community and developer's expectations

Principle 1:
Establish public realm connectivity and enhance its quality and amenity. Retain significant remnant trees, local character, and topography, and allow these elements to contribute to the overall site logic.



3. Site-scale WS intervention:
   - WS housing mix: apartments, townhouses, courtyards
   - Green laneways
   - New and existing greenspaces
   - Improved access to existing greenspace
   - New trees
   - Permeable surfaces
   - WS technologies: e.g. rainwater tanks integrated with housing design



4. Take a holistic view of the precinct: Understand changes these interventions will cause at the precinct scale (Table 6)

5. Explore aspirational, maximised water sensitive visions for the precinct

Principle 2:
Include a range of building typologies that allow a mix of scale, height, household types and the potential for work/living. Consider spaces between buildings as multi-use public and semi-public areas: allowing circulation, solar access, privacy, safety and delight.

Figure 11. WS Infill design – precinct-scale opportunities (example from Salisbury Case Study (Site 1) and Knutsford Case study) (All imagery from (London et al.))

5.2. Water sensitive precinct designs

The projected BAU infill housing designs for Salisbury and Knutsford are similar – a house on large block relaced with two single-storey houses on a sub-divided lot. However the mix of WS precinct designs and WS housing typologies mix for the two case studies are different. Community expectations, development parcel scale and affordability threshold influenced different choices of alternative water servicing options. The WS scenario provides two design variants: conservative (WS-Con) and where water sensitive benefits are maximised (WS-Max).

5.2.1. Knutsford designs

The areas surrounding Knutsford Street precinct, which is currently vacant post-industrial land, are characterised by a mix of housing types that includes single-storey residential buildings on large blocks, and higher density housing typologies (e.g. 3-storey mid-rise apartment blocks). Given this wide range and variety of surrounding housing, and for the purposes of comparison with the Salisbury case study, the base BAU development scenario for Knutsford was the same as that used for Salisbury – i.e. single-storey housing with a built cover of 58% roof and 34% pavement and a net dwelling density of 45 dwellings per hectare. The WS alternative design used three different typologies – apartment units, townhouses, and warehouse units.

Compared with BAU, WS apartment units increase building height to 3 to 4 storeys, thus creating space for additional dwellings while limiting building footprint and maximising pervious site area. WS Max describes a development scenario that has the same footprint as WS, but differs in the number of stories, and delivers additional dwellings. Although stakeholders recognised this approach as a preferable long-term outcome, current market conditions inhibit its realisation in the short term. The redevelopment also included an additional green public space planned at the north of the precinct, connected to the precinct 'Green Spine'.

The water sensitive technologies explored in Knutsford include rainwater harvesting through large communal under-building rainwater tanks with capacities of 110–220 m^3 (10 m^3 per dwelling) and total capacity of 2 ML. Wastewater recycling is achieved through onsite treatment and use of household wastewater from a sewer-mining scheme with assumed storage capacity for treated wastewater of 200m^3. The landscape plan for the WS scenario includes construction of raingardens to treat stormwater and infiltration galleries underneath the internal roads.

Table 6. Comparison of redevelopment scenarios for Knutsford and Salisbury

	Knutsford				Salisbury			
	Typical EX	BAU	WS-Con	WS-Max	EX	BAU	WS-Con	WS-Max
Density (dwellings/ha)	0/ 16	45	81	105	14.3	24	31	58
Population (residents)	90	225	323	420	1,900	5,000	5,000	11,000
Imperviousness	0.41	0.75	0.49	0.49	0.41	0.52	0.42	0.41
Redeveloped area (ha)	0	3	3	3	0	35	26	78

5.2.2. Salisbury designs

The Salisbury East precinct is currently characterised by 3- and 4-bedroom detached houses on large (~1,500m²), medium (675 m²) and small (500m²) lots. BAU infill development is projected to remain 1–2 storey townhouse-type dwellings on smaller allotments and thus with a significantly higher fraction of building to open space. WS alternatives to BAU housing typologies included a mix of apartments, townhouses and terrace houses on four different sites with total area of 26 ha (London et al. 2020b). In the WS-Max scenario, these different site designs were hypothetically tested across all developable land in the precinct, on approximately 78 ha which is 60% of its land (Table 6). As is common in infill development, scattered pockets of underutilised residential and vacant industrial–agricultural land will be developed throughout the precinct. This meant that BAU, WS and WSMax redevelopment scenarios resulted in changes to land use. WS Con and WS Max designs also include redevelopment of streetscape and conversion of vacant land into green open space.

In terms of water supply, analysis of representative EX or BAU developments assumed no use of alternative water servicing options. However, we recognise that approximately. 20% of existing houses in the Salisbury precinct have rainwater tanks, presumably due to a combination of financial incentives (rebates, subsidies), regulation (mandated rainwater tanks for new developments after 2006) and impact of water restrictions (which in 2010 were replaced with water wise measures that allow sprinklers for irrigation in the morning and evening only). Even though recycled stormwater (purple pipe) is currently available in the study area from the ASR scheme, it was assumed to not be in use in the EX case due to the absence of a distribution network to individual houses and lower cost of mains water, which is subsidised for some establishments that could be irrigated with aquifer storage and recovery (ASR) scheme otherwise (e.g. schools). The WS-Con and WS-Max scenarios assumed all new buildings will use a combination of rainwater and stormwater (through purple pipe) with capacities of 3 ML and 9 ML respectively for rainwater storage, and that all greenspace, excluding creek corridor reserve, will be irrigated using stormwater.

5.3. Evaluation of development scenarios

The assessment of 8 scenarios (4 scenarios for each case study: EX, BAU, WS-Con and WS-Max) confirmed initial hypotheses about the differences in the influence on water performance and liveability between standard industry practice (BAU) and water sensitive alternatives to infill development. These differences are predominantly driven by a change to surfaces and overall imperviousness on the one hand (Figure 12), and the effect of alternative water servicing options (e.g. rainwater tanks, stormwater and wastewater recycling schemes at precinct scale) on the other.

5.3.1. Water performance

WS designs accommodated more people on the same area of land as BAU, while improving water performance of the precincts for all of the evaluated indicators. WS designs significantly reduced stormwater runoff, which is one of the main issues with infill developments. In both Knutsford and Salisbury, WS designs retained more stormwater than both BAU and existing, low density development (EX). Analysis of the Knutsford precinct design showed that 24% of rainfall volume was converted to runoff in the EX scenario, compared with 60% in BAU and 13% in WS-Con/WS-Max. In Salisbury these differences were smaller but still significant with values of 42% (EX), 50%(BAU) and 31–39% (WS-Max and WS-Con). These results suggest BAU infill developments could be intensifying localised pluvial flooding while WS designs could ameliorate some of these effects in areas that are experiencing overland flow. This outcome is attributable to design of the built form which promotes more evapotranspiration – and to a lesser degree – infiltration, but the main driver of this reduction is by reusing rainwater as an alternative water source.

Knutsford's soil characteristics meant the EX scenario had 0 storage capacity, and the 1.5. ML storage obtained in WS was due solely to rainwater tanks. In Salisbury the additional water storage – due rainwater tanks and aquifer recharge and a small additional storage in soil moisture due to improved designs – was more than triple in the WS-Con and WS-Max scenarios, compared with the EX or BAU scenarios (Figure 13). In terms of restoring natural hydrology of the area, the Knutsford case study demonstrated WS mid-rise housing designs improved infiltration by 1% compared with typical low density development and almost triple the amount of water that replenishes groundwater when compared with BAU.

WS scenarios also provide improvements which would be particularly relevant to areas with periodic water stress. While water demand will be higher in WS scenarios than in BAU even holding the population constant (in Salisbury case), WS and WS Max achieve higher water use efficiency – a higher number of people whose demand is covered per 1 kL of imported water. The BAU scenario also improves in that respect when compared with EX conditions, although not as significantly as for the WS scenarios. For example, in Knutsford 1kL of imported water satisfies demand of 3 people in EX, 6 in BAU and 11 in WS scenarios. This result most likely reflects reduced use of imported water for garden irrigation (due to smaller greenspace in BAU and replacement of water supply with alternative local sources in WS), water efficient appliances installed in new dwellings, and indoor water use patterns of larger households to whom the designs cater.

Importantly, in Salisbury, rainwater tanks alone would not meet the additional water demand for irrigation, and thus use of stormwater from the ASR scheme will be necessary to reduce imported water demand efficiency below BAU. However, with these two alternative water servicing options water demand per capita from imported water could be reduced to 141 L/person/day in the WS-Con scenario (29% of all water demand met from alternative sources) and 116 L/person/day in the WS-Max scenario (34% of all water demand met with alternative servicing options) despite year-round irrigation of private and public greenspace and common water stress in South Australia during the dry season. This is a significant finding, because it is significantly lower than average water use in Adelaide of 190 L/person/day, and reduces residential demand within Australia's most water stressed city where imported water is sourced from the highly constrained Murray–Darling River and desalination. BAU could also reduce water demand to 166 L/person/day (from 251 L/person/day in EX) however at the expense of reduction in greenspace when compared with EX or WS.

In Knutsford, per person use of imported water for the EX case was estimated to be 325 L/person/day. The BAU scenario reduced this amount to 161 L/person/day. However, by incorporating wastewater recycling and rainwater tanks, water demand for imported water could be reduced further to 110 L/person/day (for WS Max, where alternative sources could meet as much as 60% of all demand) or 86L/person/day in WS (where alternative sources could meet

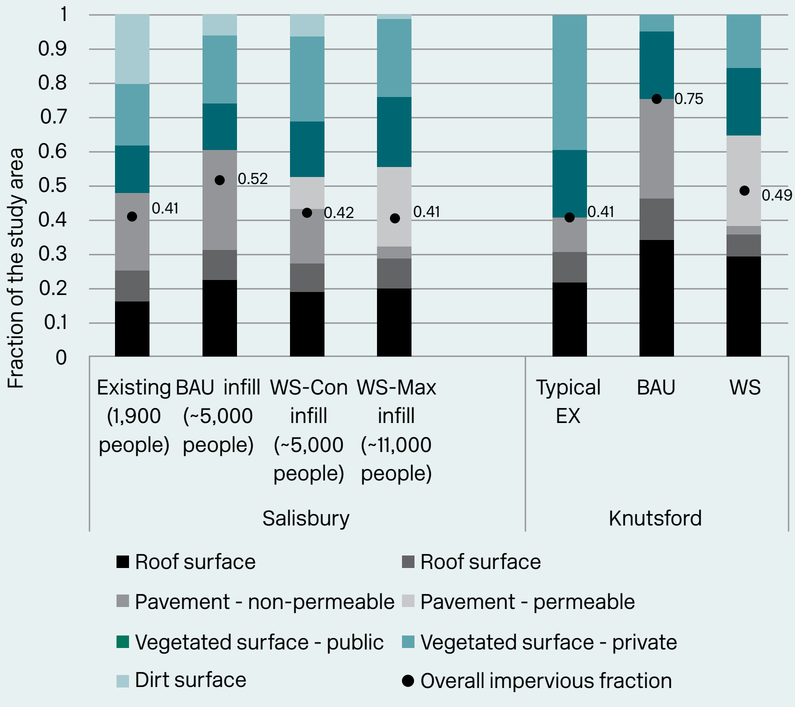


Figure 12. Assumed changes in surfaces and imperviousness in Salisbury (left) and Knutsford (right)

57% of all demand). This demand is significantly lower than average water demand of 290L/person/day in Perth (Water Corporation 2010) or 246 L/person/per day (Wynne E. 2017). This finding is especially relevant to the local context. In Perth, many houses rely on groundwater bores to irrigate their gardens, but the case study site has groundwater contamination issues due to the legacy of industrial land use and so cannot tap this resource. Reducing the per capita water demand and outperforming not only Perth but other Australian cities, without compromising aesthetics of the gardens, may appeal to residents interested in sustainability outcomes. This will be particularly important in the future. Approximately 30% of Perth's water supply comes from desalination, and climate change is projected to make Perth increasingly water stressed with yields from groundwater and surface water to fall by almost half by 2030 (WaterCorp 2009).

Garden irrigation is often the first to be restricted during drought. However, water sensitive infill promotes maintaining green vegetation even in the hot, dry times, because these green spaces help mitigate the urban heat island effect. So, understanding how alternative water sources can help new designs meet this challenge was imperative. The Water for Greening indicator in the Infill Evaluation Framework was calculated as the percentage of irrigation demand that can be met by supplementary water supply in a dry year. (In both Knutsford and Salisbury, 2006 was the representative dry year.)

In Knutsford, wastewater recycling met 100% of the irrigation demand in the WS-Max scenario, and 94% in the WS-Con scenario. Rainwater tanks alone could meet only 30–40% of the irrigation demand in WS-Max and WSCon scenarios. So, a combination of rainwater and wastewater reuse in WS scenarios met all irrigation demand.

In Salisbury, rainwater tanks in a dry year could only meet 20% of irrigation demand in both WS-Con and WS-Max scenarios. The recycled stormwater supplied through purple pipe had a much higher reliability in the WS-Con scenario (100%), but only 40% in the WS-Max scenario. This result reflects the much larger area of irrigated greenspace assumed in the WS-Max scenario. While this indicator assumes water harvested from within the precinct will also be used for aquifer recharge, in practice residents would probably use recycled stormwater to meet 100% of their green irrigation water demand, unless there are restrictions due to prolonged drought conditions.

For both case studies, the analysis reveals the importance of accompanying rainwater tanks with rainfallindependent sources (wastewater recycling) or large storage options (ASR) to achieve enough reliability for greenspace irrigation during drought. In Salisbury, where rainwater tanks have been mandated for new buildings since 2009 and water restrictions were replaced with water wise measures post Millennium Drought, this finding poses challenges for community engagement in setting realistic expectations about the reliability of household-scale water saving measures during droughts.

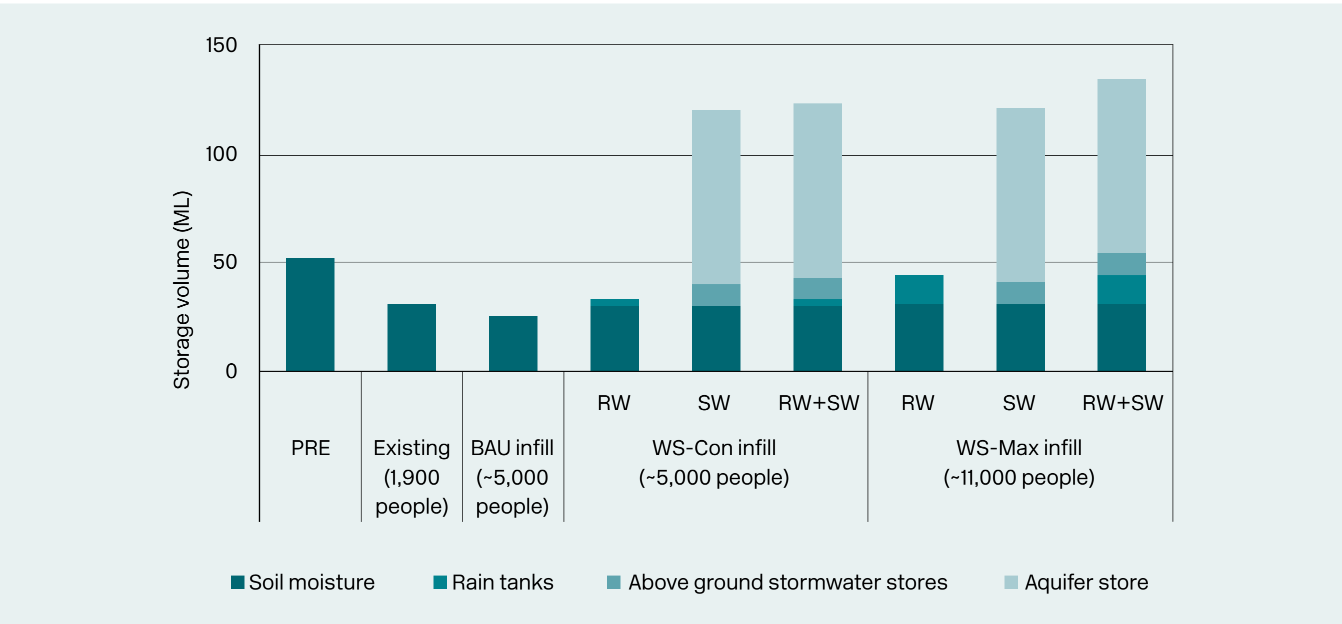


Figure 13. Water storage capacity in the study area (tank storage and soil moisture storage) – Salisbury case study

5.3.2. Thermal comfort and architectural and urban space quality

WS designs were created via principles of quality architectural and urban space (outlined above in Figure 8) and they have demonstrated their superiority to BAU in ratings using performance criteria contained in the Infill Evaluation Framework. In both Salisbury and Knutsford, WS design significantly improves the outlook to gardens, vegetation and trees and solar access and cross-ventilation of the outdoor private space. In Knutsford, WS designs also improve availability and diversity of outdoor private space by consolidating the available ground space and maximising its useability. The designs include roof terraces, balconies of useable size and generous private courtyards. In Salisbury, WS designs also change the size and proportion of outdoor communal spaces and the outlook to vegetation they provide. In Knutsford, WS designs improve the availability and diversity of communal space and its connectivity by responding to existing patterns of movement, and land subdivision scale, utilising topography, and increasing pedestrian access through well-shaded shared laneways. Designing at precinct scale improves public open space: its availability and diversity, size and proportion, access and connectivity, multi-functionality and outlook to vegetation. These benefits are more significant in Knutsford than Salisbury because Knutsford does not currently have public open space within its boundary. WS designs in both precincts are characterised by more flexible rooms and internal relationships, which improve a dwelling's adaptability over time.

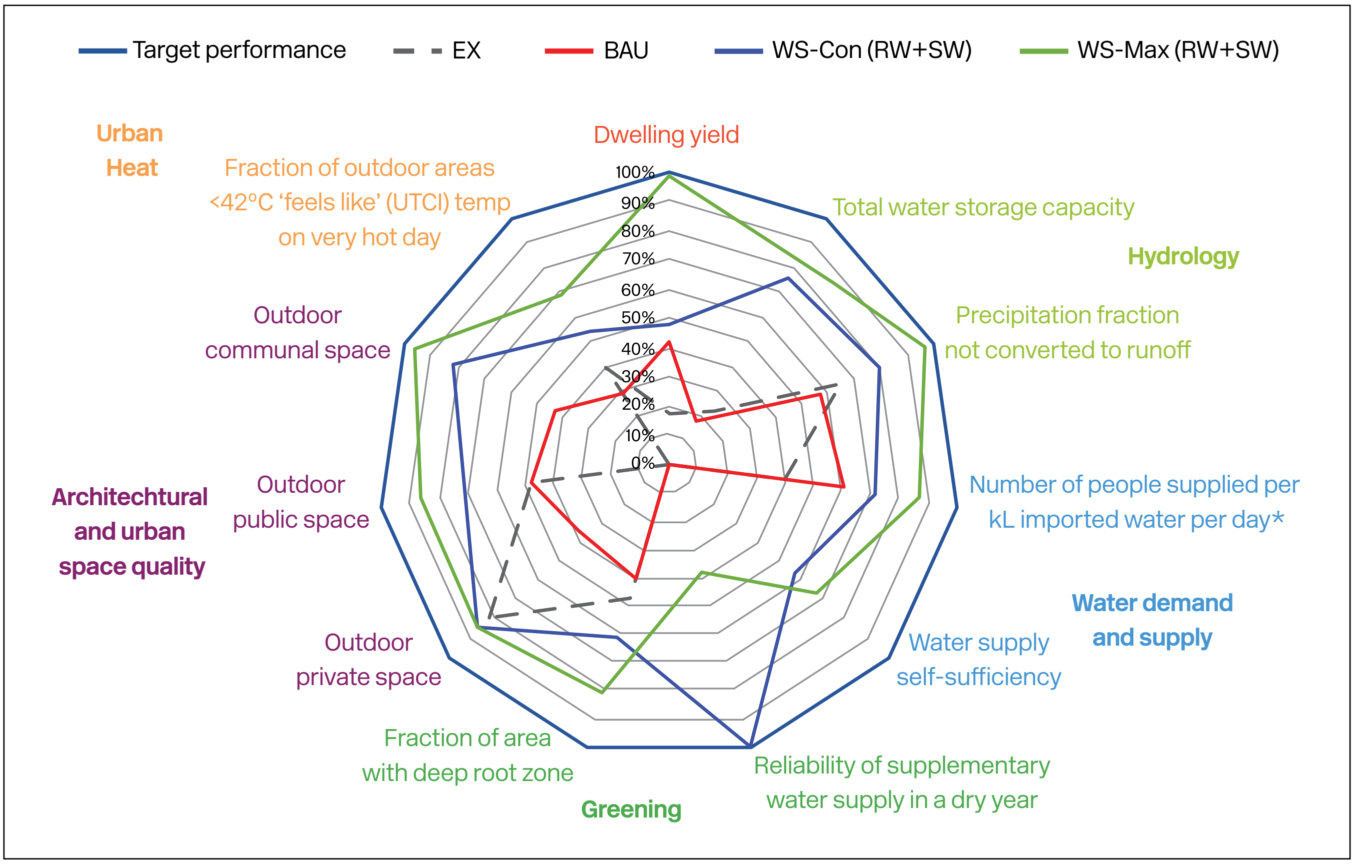
Thermal comfort plays an important role in arid, hot climates and greenspace can help mitigate the urban heat island effect which tends to be exacerbated in higher density developments. The indicator used was the fraction of outdoor areas that are above 42°C UTCI (Universal Thermal Climate Index 'feels like' temperature), representing a 'very strong' level of heat stress. In the microclimate analysis, the two most important elements were the amount of shading provided by buildings and trees and the reduction of hard impervious surfaces in favour of vegetated (irrigated) surfaces. That is because reductions in UTCI are largely driven by reductions in surface temperatures and the radiated heat off of those surfaces. Because heat at a micro-scale is highly variable and highly localised, all of the designs had some very hot elements (generally an unshaded road or concrete path) but the areas that performed the best saw the distribution of heat (and thermal stress) across the area shift from many very hot areas to a higher percentage of cooler areas. In Salisbury in the existing case, 77% of the study area exhibits temperatures above 42°C UTCI on a high heat day. With BAU this increases to 83%, while WS designs can reduce this to 68% for WS-Con or 59% for WS-Max. In Knutsford, similar findings were obtained with WS scenarios outperforming BAU and EX (Zhu et al. 2020). This result does not include the potential additional effect of active watering to further suppress heat. Vegetation that creates a mosaic across the area maximises the cooling effect by spreading it as widely as possible.

This finding is particularly important for cities that experience many hot days and where climate change is likely to exacerbate their frequency and severity. For example, Adelaide, where Salisbury is located, broke its record for heat with the temperature of 46.6°C in January 2019. But this finding has special bearing in Salisbury which is characterised by high social disadvantage, with many pensioners and elderly living in the area. Consistent with previous research, the urban heat island effect is especially prevalent in suburbs where most vulnerable populations reside, including Salisbury (Seed Consulting Services et al. 2018). Less affluent households may struggle to meet the costs of higher electricity use (for air conditioning) and be more affected by the heat outdoors. WS design that provides both more shade and more water for irrigation is likely to contribute to better health outcomes for residents and lower mortality during heatwaves.

5.3.3. Multi-criteria assessment

Radar graphs represent the multiple benefits provided by WS-Con and WS-Max designs compared with EX or BAU developments (Figure 14). They compare the scenarios to an established target and so may be more useful in tracking achievement of an assumed 'management goal' or overall vision for a site in terms of its urban water performance (Figure 15). This project demonstrates that there are very few clear, quantifiable, site-specific 'visions' for water that can be used to establish performance across all dimensions.

Incorporating a reference state or baseline can facilitate comparison of the development options to established policy targets, but can also highlight some of the trade-offs they imply. For example, Figure 14 demonstrates how in Knutsford, BAU infill development would provide benefits in terms of density and water efficiency per capita, but at the expanse of greenspace for the residents and hydrological effects on site and beyond it. In Salisbury, BAU infill development would not affect the hydrology as much as in Knutsford, but it would compromise outdoor private space for residents and exacerbate urban heat impacts. While the proposed WS designs outperform BAU infill development in every aspect, they can imply trade-offs when compared with EX. For example, WS designs tend to perform similarly or slightly worse in terms of the quality of outdoor private space (gardens) than EX. In some cases (e.g. Knutsford) they may also provide less space for deep-rooted trees.



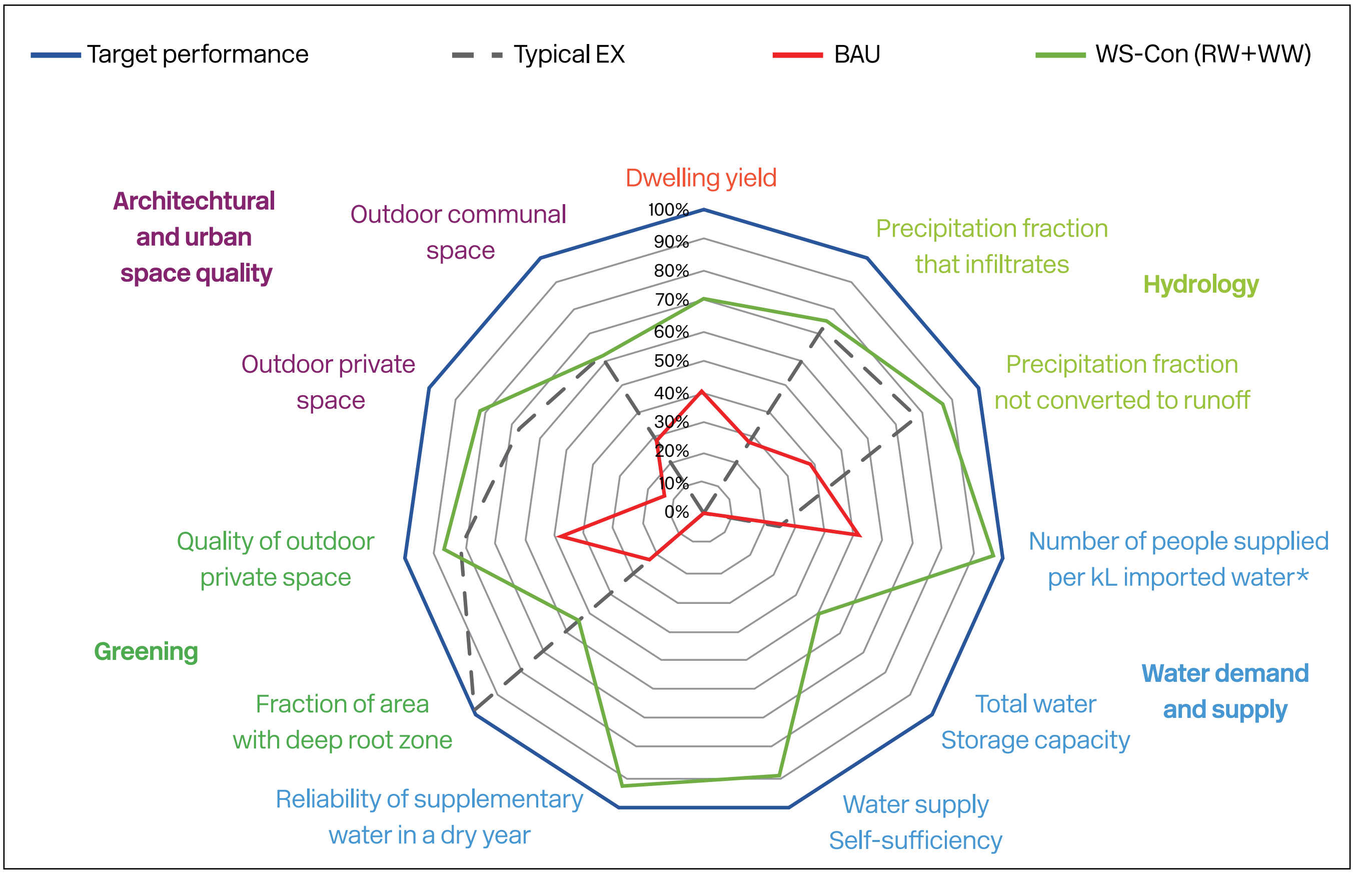


Figure 14. Multi-criteria assessment for Salisbury (top) and Knutsford (bottom)

How indicators and targets reflect local priorities?

The evaluation framework is an adaptive tool that can be tailored to a given context. It can assist in decision making and monitoring of the progress towards an established management goal. The elements of the framework – design variables, performance indicators and performance criteria – are causally linked (as established through the analysed case studies). Therefore, it is envisioned that depending on the management goal (or priority concern from criteria list) different lists of indicators, and subsequently targets, will be selected for assessment. This presupposes the following sequence of steps, which may happen at different urban scales (e.g. goal set for city, but assessed at precinct scale):

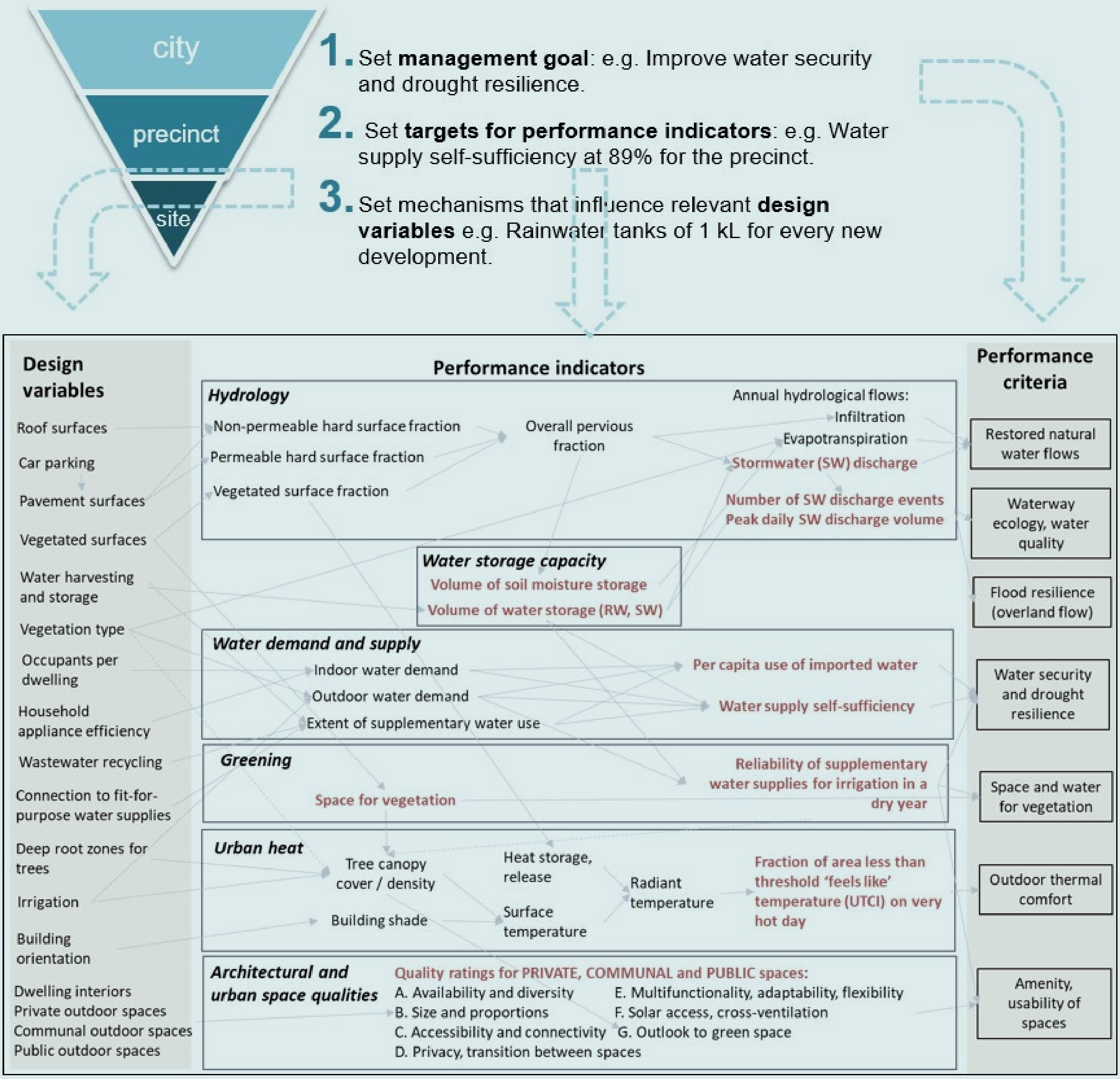


Figure 15. Cause-and-effect relationships between design parameters and performance criteria for the Infill Performance Evaluation Framework (Renouf et al. 2020b, p. 26.)

5.4. Influence of design

The analysis confirms the influence of housing and public open space design on water performance and ambient heat. The differences between EX, BAU and WS designs was primarily driven by:

1. **Occupancy and number of dwellings per hectare.** This directly affects number of residents, which leads to higher total water demand and wastewater discharge. This relationship was not strictly proportional – BAU and WS had lower per capita demand due to measures increasing water efficiency (e.g. water efficient appliances) and smaller greenspace area. In infill contexts, this is particularly important since it may put an additional strain on existing water servicing and sewage infrastructure that were designed based on different urban densities. While outdoor water demand can be lowered using a range of alternative water servicing options (e.g. rainwater tanks, purple pipe), wastewater discharge can be lowered only through wastewater recycling technologies.

2. **Compactness of built form and low built cover**. This had a major effect on overall impervious fraction of the area which in turn led to higher stormwater runoff and reduced infiltration and evapotranspiration. Sealing surfaces contributed to reduced soil moisture storage capacity and higher temperature during heatwaves from radiating surface heat. The adverse influence of BAU was mostly linked to single storey built form, large building footprint compared with the whole site, and extensive area of concrete driveways and pathways. So, reducing building footprint on the ground level proved more important than roof area or number of storeys. In WS designs, compactness of building form and orientation that reduced driveways lowered imperviousness as evident in the typologies assessment. The WS designs also included outdoor areas that are structural parts of the building and that do not elevate imperviousness on the ground (e.g. balconies. terraces). On a precinct scale, the imperviousness was elevated when compared with the site scale because it also included the road system, which was not assumed to change with the infill redevelopment and so comprised a large area of impervious surface. Water sensitive streetscape designs reduced the overall imperviousness by approximately 25% in Knutsford and 10% in Salisbury (Figure 12).

3. **Surface materials and their permeability** influenced overall imperviousness, driving differences in stormwater runoff, water storage in soil moisture and ambient temperature. WS designs replaced a share of the impervious concrete and asphalt with permeable surfaces used for driveways and payment. Where possible without compromising space function, soil was not covered with any material.

4. **Landscape design and area of vegetated cover** influenced ambient temperature and overall imperviousness but also changed hydrology due to increased evapotranspiration. The impact of vegetation on hydrology includes increasing soil moisture capacity and removing stored water (stored precipitation) from soil which in turn reduces stormwater discharge. Also more vegetated areas enable more pervious areas boosting infiltration, again reducing stormwater discharge. So, creating new greenspaces in the WS-Max scenario in Salisbury further improved stormwater runoff. Converting previously vacant land to buildings with gardens affected local hydrology positively in both BAU and WS scenarios, even though the impact was small in the BAU scenario and was overwritten by vast area of concrete surfaces. Irrigating the vegetated area can facilitate reversion to natural hydrology, by increasing evapotranspiration and infiltration to close to pre-developed levels despite higher imperviousness (Moravej et al. 2021). At the same time, it increases outdoor water demand, so in situations where gardens are mostly irrigated, the WS designs (which have larger vegetated area than BAU) are likely to raise total water demand of the precinct, particularly in dry season. However, this increase does not necessarily need to be met by potable water.

   Vegetation has also a significant effect on ambient temperature. This effect depends on the type of vegetation planted; large canopy trees that provide shade are the primary drivers of the cooling effect observed at precinct scale. The effect of irrigation can provide further although smaller temperature reductions. The temperature of dry grass or soil is similar to that of concrete and can reduce the benefits expected from greenspace.

5. **Building orientation** influences ambient temperature by creating shade and sunlight exposure. While this potential is often constrained due to site dimensions, building orientation can improve thermal comfort by creating shade over outdoor spaces.

The analysis highlighted a number of trade-offs that should be carefully considered in WS designs:

1. **More compact building form and higher density** were achieved in some WS designs by increasing **building height** and number of storeys. Although this increase was modest and within planning envelope controls for the case study areas (Salisbury and Knutsford), in some other instances it may change the suburban character or feel of the precinct. The increased shade from taller buildings can be seen as both an advantage during hot, sunny days and a disadvantage in winter. Multi-storey buildings can also increase the cost of construction and thus reduce affordability per m^2 of floor area.

2. More **compact building form** and improved accessibility was also achieved by reducing the area allocated for **driveways and garages**. WS designs, in line with leading Australian examples of this type of development scenario, assumed lower private car use with generally only one private parking spot for each dwelling. This may increase the need for on street parking if the preference for car-dependent mobility persists. On the other hand, if the societal trends toward more sustainable mobility (such as car-share options) become more dominant, this will be a more efficient use of land.

3. The larger area of **green space** is likely to require more water for irrigation, which may increase **household water demand**, particularly during prolonged drought when rainfall-dependent WS alternative sources are either stretched or not available. In this case, residents turn to mains supply. However selecting appropriate, water-tolerant and endemic species can greatly reduce water demand for irrigation after the initial 12–18 months if properly established.

5.5. Influence of water servicing options

The analysis quantified the impact of water servicing options on water demand, storage capacity, hydrology and urban greening. Its main drivers related to assumptions about:

1. Rainfall-dependent alternative water servicing options (household **rainwater tanks**) which increased water storage, and reduced stormwater runoff and dependency on imported water especially for irrigation. Rainwater tanks were implemented at household scale, although WS scenarios also included communal rainwater tanks. Overall, they generated modest benefits when compared with other technologies, but they seemed particularly easy to promote and integrate with the housing design. Their reliability for urban greening during dry season was also low and their capacity (1,000 kL per dwelling in Salisbury) most of the time was not fully utilised. Since the analysis did not account for the area of roof serving as water catchment, the current assessment may overestimate this value, which may be even lower.

2. Rainfall-independent alternative water servicing options (**wastewater recycling** in Knutsford) supplemented water supply, reducing demand for imported water (also for irrigation) thus significantly improving reliability for greening. However, it did not improve local hydrology. An additional benefit which was not quantified but identified in water mass balance was lower wastewater discharge from the site (assuming sewer is accessed onsite). This was an important bonus to the land developer who would otherwise pay fees to upgrade the existing sewer network.

3. Increasing rainfall-fed water storage (purple pipe with **treated stormwater from Salisbury's ASR scheme**) significantly increased reliability of water for greening. But it did not improve local hydrology, (e.g. by reducing stormwater runoff), because the aquifer is outside of system boundary. The runoff needs to flow down to wetlands located downstream of the precinct where it is treated and captured. At the precinct scale, ASR operated as imported water supply – bringing water from outside the precinct through the distribution network.

4. Water efficient **appliances** reduced imported water demand. Due to modelling assumptions, their effect was directly proportional to precinct population. In Knutsford, appliances reduced per capita demand by almost half (from 325 to 161 L/person/day) while supplementary sources used for irrigation (rainwater tanks, wastewater recycling, treated stormwater) reduced demand by 50 L/person/day.

The case studies revealed trade-offs that may be related to implementing these technologies:

1. **Occupancy** rates (people per dwelling) and appliance **water efficiency** both influence **water demand**. The potential for lower occupancy in smaller dwellings may lower the overall water efficiency of households (use of imported water per capita). However, it is also likely that more water efficient appliances will be installed in new dwellings and that overall they will reduce water demand per capita when compared with EX or BAU.

2. Optimising **alternative water servicing technologies efficiency** may compete with optimising **WS design.** When there are good stormwater harvesting and storage opportunities, there may be competition between favouring hard surfaces to increase the volume harvested versus favouring pervious surfaces to promote infiltration for moisture for trees. This was observed in the Salisbury case study.

3. **Different water servicing options** may compete with each other and the choice may be related to factors other than water performance. This occurred in Salisbury (with purple pipe and rainwater tanks). The selection of a given technology comes with its benefits and trade-offs (e.g. rainwater tanks may help reduce runoff but at the same time are not a highly reliable source to water gardens during drought).

4. Different water servicing options are viable at **different scales** (household/precinct/city), and their impacts and benefits will relate to these scales and can be localised (in the precinct) or externalised (to outside of the precinct). So, there can be trade-offs between improving local hydrology (through rainwater tanks) but reducing stormwater yield (for stormwater ASR) downstream, outside the precinct. Similarly, combining wastewater recycling with rainwater tanks may create a variability in demand for recycled water and so compromise the system.

5.6. Influence of the local context

The two case studies allowed us to explore in more detail local context and the constraints it may impose on implementing WS infill designs and their performance:

1. **Influence of climate and soil.** Local environmental conditions changed the water performance of the analysed designs, in particular, for hydrology and reliability of supplementary supply for greening. Rainfall patterns proved important for the amount of water that can be captured, used and thus reduced from imported water demand. This was apparent in the reliability of the supply for greening provided by rainwater tanks. Prolonged periods of drought or rain and intense rainfall events reduced the volume of water which rainwater tanks could provide for irrigation, regardless of their capacity. Soil characteristics – its permeability and soil water holding capacity – were important for determining what fraction of rainfall is converted to runoff (e.g. clay soils in Salisbury limit infiltration regardless of vegetated areas). Differences between the same set of infill housing typologies applied across sites in a number of cities in Australia driven is described in more detail in (Moravej et al. 2021).

2. **Influence of infill development extent**. Knutsford's study area was much smaller and tighter than Salisbury's – it covered several sites all of which were redeveloped. This meant we could observe the effects on infill development more clearly because it magnified the adverse impacts on hydrology that were partially ameliorated by retained low density development in Salisbury. In comparison, the precinct boundary adopted in Salisbury meant we could test the effects on water sensitive interventions that involve greenspace, particularly converting previously commercial land to vegetated public open space.

3. **Local determinants of WS designs.** Development and selection of WS designs was guided by the existing housing stock and precinct character of the case study areas, allowing for higher density typologies in Knutsford. It also involved a guess about the potential buyers of these new dwellings based on the precinct's current socio-economic profile, which translated into predicted occupancy of the new infill developments.

4. **Local determinants of alternative water servicing options choice**. The viability of water servicing options was determined by local conditions (rainfall patterns), existing infrastructure (e.g. purple pipe), the anticipated readiness of future residents to adopt certain technologies and their costs, as well as scale. Analysis revealed certain alternative water servicing technologies require minimum urban densities to be feasible (in terms e.g. of wastewater yield) and that they become economically viable at certain scales (e.g. communal versus household rainwater tanks).

5. **Influence of the previous land use: greyfield versus brownfield developments**. There are two major types of infill: greyfield and brownfield development, both of which were explored. Greyfield can be defined as 'ageing but occupied tracts of inner and middle ring suburbia that are physically, technologically and environmentally failing and which represent under-capitalised real estate assets' (AHURI 2020). Greyfield refers to redeveloping previously residential land, while brownfield refers to repurposing land used for industrial and commercial purposes. These two types of infill are characterised by different challenges and opportunities, with brownfield offering larger sized lots but sometimes requiring remediation of pollution caused by industrial operations and struggling with lack of services and infrastructure associated with residential land use. Greyfield infill development happens within already residential precincts, but, faces challenges related to small, scattered lots which make tapping opportunities for multi-residential housing designs and strategic planning difficult. Greyfield development tends to be driven by opportunistic land acquisition by small-scale developers who maximise dwelling number while appealing to customer taste for suburban housing typologies. This played a role in Salisbury, where conversion of commercial and industrial land to residential and greenspace changed imperviousness in both the BAU and WS-Max scenarios. Knutsford as a brownfield site had legacy of groundwater contamination which influenced the choice of water servicing options.

6. Enabling water sensitive infill: pathways and learnings

Case studies tested the concept of water sensitive infill and demonstrated the opportunity it creates for urban regeneration that delivers improved environmental and liveability outcomes simultaneously. Reflecting on the drivers that underpin superior performance of WS precinct design, as opposed to industry standard practice (BAU) and the trade-offs they may imply, highlighted critical enablers for bringing water sensitive infill to practice:

- integrating housing and public space design with water planning to manage conflicts between different objectives (e.g. architectural quality and water performance)
- integrating alternative water servicing technologies and hybrid infrastructure with conventional infrastructure, particularly bringing stormwater and wastewater related impacts and opportunities into water planning through whole-of-cycle water management
- coordinating planning across different spatial scales to share benefits and costs, tapping synergies that could otherwise be missed
- acknowledging community and market preference for better infill design, which may mean acceptance of higher density housing typologies
- recognising infill development as a precinct regeneration opportunity in policy, planning and design.

6.1. Barriers related to governance

One of the early tasks of the IRP4 project was a literature review to identify barriers to water sensitive infill, an issue that was further explored as part of the CRCWSC's Integrated Research Project 3: Guiding integrated urban and water planning (IRP3). IRP3 sought to advance water sensitive outcomes by guiding urban growth and renewal at a range of scales and in different contexts by applying a conceptual framework for integrated urban and water planning. The project used the Salisbury case study to explore how South Australian planning system facilitates the implementation of water sensitive typologies designed in IRP4.

The review undertaken under IRP4 found:

(1) the effectiveness of governance instruments that reward good water sensitive designs is currently low (and disincentives for poor performance are limited)

(2) some compliance-based regulations and codes may limit innovation in housing design and choice of most suitable alternative water servicing options

(3) there are limited governance instruments for precinct-scale planning for established residential areas that could guide urban regeneration

(4) coordination of precinct-scale planning is obstructed by scattered ownership and agencies' (e.g. water management) jurisdictions operating at different scales.

Water sensitive infill could be promoted by mechanisms that penalise poorly designed infill development or developments that adversely affect local hydrology. But currently infill development is not heavily regulated and much of BAU practice fits well into conventional planning and development approval systems. Currently, development, plumbing and building codes cover adverse effects such as increased stormwater runoff (e.g. maximum built cover), but do not make increase of imperviousness of the site through new construction a venture which is cost prohibitive or unsuitable. The goal of constraining urban growth to the existing urban footprint is articulated in metropolitan strategies and often includes targets. However, this is not translated into planning scheme (e.g. density zoning tends to prescribe the maximum rather than the minimum density). Small infill development is not necessarily regulated by the same controls as placed on greenfield (legacy, environmental impact of existing buildings, lack of PSP), although it does require a development and building approval (except for minor redevelopment). But this is not enough to address cumulative impacts of infill development from lots and clusters of lots scattered around the city. These incremental changes are not monitored, so there are no policies to address them systematically.

In contrast, water sensitive infill could be encouraged by governance instruments that reward implementing alternative water supplies and decentralised stormwater infrastructure (e.g. wetlands). But currently governance instruments for alternative water sources and hybrid infrastructure (generally referred to as WSUD) are discretionary (guidelines and non-binding policies). Performance-based targets that could encourage water sensitive infill are not mandatory. The planning framework for WSUD in Australia's cities (CRCWSC project B5.1(Choi and McIlrath 2017)), revealed disparities between the states in their planning legislation and execution, and gaps that made implementation difficult. In particular, infill development lacks sufficient coverage in WSUD planning frameworks. In general, WSUD is supported through discretionary planning policies and guidelines. An exception is Victoria where clause 56.07 is incorporated into all new residential subdivisions (but not infill developments, although some local councils have developed local WSUD policies that apply the clause to redevelopment as well).

Augmenting supply with alternative sources is sometimes obstructed with existing regulations. For example, the mandatory inclusion of 1kL rainwater tank in every new residential building in Salisbury displaced water demand that could have been met by a more reliable source – e.g. recycled stormwater from the purple pipe. Existing subsidies may make alternative sources less competitive. In Salisbury, the mains water price was lower for some institutional water users than purple pipe supply, due to subsidies awarded to religious organisations. This may be compounded by broader policies and regulations that prevent all servicing options from being assessed – for example, recycled wastewater or treated stormwater cannot be used directly to augment potable water supply (Productivity Commission 2020).

Water sensitive infill could be implemented through precinct-scale planning, where the benefits and trade-offs of urban and water planning are considered together. Precinct structure planning (PSPs, also called 'neighbourhood plans', 'detailed master plans' and 'structure plans') refers to plans established for a parcel of land that needs special planning: which could be either a strategic infill site, or a new development site greenfield. The sites that are subjected to PSPs vary across states. In Queensland PSPs apply to either state-identified 'Priority Development Areas' or precincts nominated for Master Plans by the councils. In New South Wales, PSPs are developed for 'Growth Centres', but may also be identified by councils. In Victoria, PSPs are developed for Urban Growth Zone (UGZ), although councils may also develop them for strategic activity centres or redevelopment sites. PSPs in Victoria can also be prepared and funded by landowners and developers in accordance with PSP Guidelines. South Australia does not identify land for PSPs at state level; instead councils that declare precincts pursuant to the Urban Renewal Act must develop a PSP for it. In Western Australia, PSPs are developed for (a) areas identified as suitable for urban or industrial development, (b) other areas identified in the scheme prior to subdivision or development of land, (c) if they are required under State Planning Policy, (d) if required by the Western Australian Planning Commission. In practice, PSPs are typically developed for large greenfield or brownfield sites, with amalgamated lots and single land ownership, rather than greyfield infill development contexts characterised by piecemeal asynchronous redevelopment. PSP implementation in established residential precincts is likely to be obstructed by scattered and fluctuating ownership as well as the legacy of existing infrastructure. Precinct scale also does not align with typical scales of water planning, which tend to be local-scale and system-wide (Productivity Commission 2020). This creates additional obstacles to collaborative planning at that scale with different agencies involved.

Water sensitive housing designs are not only not encouraged in any existing planning documents, some of the regulations obstruct innovation with housing form. Compactness of the form and reduced built cover may require new housing typologies to create medium density and small site options, which have not been the mainstream practice in Australia. Some building codes restrict more innovative housing designs due to limitations on building setback, form (particularly at the second storey level) and overlooking requirements (Murray et al. 2011). Parking space requirements are another barrier (Rowley and Phibbs 2012).

6.2. Barriers related to community and market

The majority of greyfield infill development is undertaken by small private landholders often through subdivision and rebuild of single lots. So, not surprisingly, some barriers relate to community and market preferences. Potential buyers, investors and developers favour familiar housing typologies. New homeowners seek dwellings with ensuite bedrooms and double garages (Murray et al. 2011) preferably resembling detached houses typical of low density. Designs developed for Salisbury confirmed this barrier with one of the initial housing typologies rejected due to its low marketability to potential buyers. Overcoming this barrier will likely involve identifying factors influencing preferences for single level houses across different demographic cohorts and testing how alternative designs could cater to them.

Another barrier is the real estate development industry's preference for single house redevelopment, reflecting the anticipated return on investment and the additional time needed to approve unconventional designs (Murray et al. 2011). Infill development tends to occur in places with underutilised land and ageing housing stock, so often occurs in places that pose significant risk in terms of marketability and where developers may be hesitant to build higher density, multi-storey housing due to construction costs (Rowley and Phibbs 2012).

6.3. Opportunities for mainstreaming water sensitive infill

The case studies and the meetings with local stakeholders that informed them identified opportunities that may enable water sensitive infill in other locations.

Knutsford and Salisbury as examples of integrated water and land planning. Case study proponents were organisations that exemplified efforts to integrate water, built form and energy planning and expertise. In Salisbury, the stormwater ASR scheme means the Council is also responsible for water distribution from the purple pipe. This made linking stormwater with water servicing options and new infill housing typologies which reduce stormwater runoff relevant for the Council. The Knutsford case study proponent was LandCorp (now DevelopmentWA), the state's land development agency which has a long history of renewal projects aiming for sustainability. This role gives the agency a role in how residential developments are planned. It also has a history of collaborating with the Water Corporation, integrating land and water planning.

Strategy, management goal and targets. Land and water planning can be better integrated through strategic documents, rather than institutional consolidation. Setting a management goal and targets that span aspects important to water management, architectural design and land use planning (e.g. target density, water supply self-sufficiency) can help to coordinate benefits, synergies, trade-offs and impacts. These strategic documents can also strengthen collaboration between different departments and organisations. The Infill Performance Evaluation Framework was developed with this in mind – the performance is assessed against target reference values which are derived from existing policies or set specifically for a given context.

Local context: its water constraints and environmental pressures. The two case studies demonstrated the value of local constraints to conventional infill development. The contamination of groundwater in Knutsford (due to industrial use legacy) was an impulse to look for alternatives. Additionally, the developer faced having to upgrade the wastewater system to accommodate increased density, which prompted it to look for options to reduce wastewater discharge without reducing the population. In Salisbury, underutilisation of stormwater supply (purple pipe) and the effects of heatwaves on vulnerable populations seemed an important consideration in looking for housing design alternatives.

Existing mechanisms that support WS infill or that could be used for WS infill. The governance review identified voluntary (incentives) or mandatory (compliance-based) instruments for stormwater management in the development process – e.g. stormwater offset fees, building code mechanisms for encouraging whole-of-water-cycle planning (e.g. Victorian Integrated Water Management Plans), whole-of-precinct planning (PSP) or integrated planning at city scale, or incorporation of multi-criteria assessment tools with sustainability targets that are required as part of development approval (BASIX in New South Wales). Additionally, the case studies showed that voluntary sustainability certification schemes (e.g. One Planet Living in Knutsford) and public open space planning at precinct scale (e.g. City of Salisbury Landscape Plan) can help progress water sensitive infill.

Planning reforms. Planning reforms, such as those occurring in Adelaide to building codes and in Perth to the Medium Density Design Code, create opportunities for current industry standard practice (BAU) review. The evidence showing how BAU changes local hydrology, ambient temperature during heat waves and green space availability was met with interest. Applying the Framework allowed us to test assumptions about performance criteria that could be used to set performance targets for impervious fractions, areas set aside for trees, volumes of rainwater storage, etc. There is already a signal that several local and state governments are seeking and using this information to improve urban water management.

Role of residents as agents of change. In Knutsford, it was evident that residents' positive response to innovative housing designs fuelled LandCorp's ambition to deliver cutting edge designs that strive for ambitious sustainability goals. The neighbouring area of White Gum Valley being awarded Best Planning Ideas Small Project by Planning Institute of Australia set expectations about the quality of the new development and the context it would need to fit into. It seemed that obtaining sustainability certification (One Planet Living) and generous multifunctional communal space helped legitimise the cost of higher density construction. The promise of an 'urban community' was reflected in shared services and strata titles, and perhaps this is the selling point for medium density in Australia. Economic valuation methodologies and tools (IRP2) can be useful in understanding what residents would be willing to pay for in terms of alternative housing designs and additional greenspace.

Legacy of innovation and local champions. Both Knutsford and Salisbury case studies were supported by organisations innovating in water harvesting and recycling in the past – ASR stormwater recycling scheme in Salisbury (Salisbury Water) and shared rainwater harvesting schemes in White Gum Valley developed by LandCorp. This seems to have set water sensitive aspirations for the precincts' design. Local champions from WA organisations (LandCorp, WA Department of Planning, Lands and Heritage) and SA organisations (City of Salisbury and Water Sensitive SA, who were involved in the project's planning and execution) took leadership in bringing different stakeholders to a single table, which started the conversation about the possibility of water sensitive infill.

Table 7. Barriers and opportunities for implementing WS infill development – governance

	Existing mechanisms and instruments (examples)	Barriers	Opportunities
Conducting housing and public space design together with water planning	POS policies, subsidies for retrofit of rainwater tanks, stormwater fees, environmental targets as part of development application (e.g. BASIX in NSW), prescriptive measures for stormwater management in planning schemes (e.g. Victorian Planning Provisions), practice guidelines	WSUD policies are discretionary, WSUD and POS planning not integrated	Stormwater schemes run by councils State agencies which combine water and property development capacities POS policies on suburb scale Urban heat and cooling goals Local constraints in water availability Cost of stormwater/wastewater network upgrade
Coordinating water servicing options and hybrid infrastructure	Integrated water management plans (VIC), best practice guidelines and manuals (e.g. QUDM), stormwater quality and flow targets	Mandated technologies which disregard local context Stormwater governed separately from other sources	Precinct scale urban regeneration where single organisation delivers public space, road and housing design and construction Local constraints in water availability Cost of stormwater/wastewater network upgrade
Coordinating planning across different scales to share benefits and costs thus tapping synergies that could otherwise be missed	Stormwater offset schemes (VIC), levies for changes to imperviousness/increase of stormwater runoff, planning schemes, Precinct Plans (e.g. priority Development Areas Plans in QLD or Urban Growth Zone in VIC), Water Plans	Precinct does not align well with water management Scattered and fluctuating ownership (public, private, body corporate)	Redevelopment agencies responsible for planning and property development Cooperative arrangements (strata title)
Recognising community and market preference for better infill design	Building codes, mandated densities in zoning, masterplans for large infill, designation and planning of Growth Zone Areas	Risk aversion of developers and investors Community preferences for low density and car-dependent mobility Mandatory provisions in development code limit innovation	State agencies as property developers for cutting edge developments Community involvement in co-design and co-funding Demonstration high-end precincts elevating community expectations
Recognising infill development as a precinct regeneration opportunity	Building codes that cover infill (e.g. BASIX) Metropolitan strategies which cover medium density redevelopment and growth areas (e.g. 30-year Plan for Greater Adelaide, State Planning Strategy in WA) Precinct Plans, Masterplans for large brownfield redevelopment, Planning and Design Codes	Small infill is not regulated (sometimes does not require a building permit), when general housing codes apply, they tend to exempt infill from water targets Scattered ownership of land	Medium density policies Demonstration precincts developed by state agencies Design awards for precincts Market interest in premium locations with uses that became obsolete Market segments interested in mixed-use socially diverse community precincts

How can the Infill Performance Evaluation Framework be useful in mainstreaming Water Sensitive Infill Design?

There are multiple pathways using for the performance evaluation presented in this report, and methods that accompany it, to influence water sensitive outcomes on the ground. In particular, it could:

Strengthen existing governance and planning mechanisms related to residential development, public open space and water management:

- *Indicators and targets* could be built into building, development or plumbing codes (e.g. for impervious fractions, areas set aside for trees, volumes of rainwater storage), practice guidelines related to stormwater management, urban policies on infill development, landscape planning, and urban density, metropolitan urban growth strategies and long-term water planning, as well as voluntary sustainability building accreditation schemes (similar to One Planet Living for example).
- *SUWMBA* could be used to inform development and building approvals, as well as public open space (POS) and stormwater offset schemes.
- *Infill housing and streetscape designs* could be used as prototype development options in masterplans and precinct plans (PSPs); they could also illustrate what quality medium density could look like in infill policies and metropolitan growth strategies. Streetscape design could be included in POS policies and landscape planning.

Replace prescriptive building codes based on compliance, which may obstruct innovative housing designs (e.g. setbacks, building heights restrictions), with a process for demonstrating benefits and impacts of alternative designs.

Replace mandatory water sensitive technologies (e.g. mandatory rainwater tanks in building codes) with a process for identifying a combination of technologies that is most suitable to local context.

Leverage enablers of water sensitive infill design by facilitating **integration of planning silos (e.g. water and urban planning), water flows and scales**:

The framework together with the accompanying methods and WS designs can be used to coordinate efforts of multiple departments and organisations working in the area of water, urban planning, landscape design and architecture under a common management goal.

- *SUWMBA* as a water mass balance tool can be also useful in integrating different water flows and informing decisions regarding water servicing options.
- Precinct- and site-scale assessment tools may help plan at different scales.

Leverage enablers related to **community and market acceptance**:

- *Case studies* promote water sensitive urban regeneration as a design approach by demonstrating architectural and ambient benefits of specific designs as well as adverse cumulative effects of BAU redevelopment practice.
- The *Infill Typologies Catalogue* can inspire ambitious architectural visions and challenge cultural preferences for single detached houses by appealing to sustainability aspirations of potential residents and 'community feel' more compact built form and denser precinct can foster.
- Assessment of water performance and thermal comfort of specific designs can feed into cost-benefit analyses of different designs, and thus support a business case for water sensitive housing developments.

7. Synthesis and recommendations

7.1. Synopsis of research findings

In response to the research questions outlined at the beginning, IRP4 found the following:

Research question	Finding
How can the water sensitive performance of urban development (and associated water servicing) be defined?	Water sensitive infill development can be defined through a set of principles and criteria. It is a well-designed residential redevelopment that features quality dwellings and urban spaces that offer improved amenity, usability and flexibility, while at the same time provides a number of water and thermal comfort-related benefits: minimises impact on natural hydrology, improves water storage and soil moisture, enables use of substitute water resources, facilitates irrigation of vegetated areas and passive mitigation of outdoor urban heat, and provides spaces for deep-root vegetation (trees in particular).
Which urban design and water servicing variables influence performance?	The water sensitive performance of a given site or the precinct in which redevelopment occurs depends on several design and water servicing variables: number of dwellings and assumed occupancy, building compactness and built cover, surface materials (i.e. permeable concrete), vegetation (i.e. canopy trees), building orientation as well as the adopted combination of water servicing options, their storage capacity, and efficiency of household water-using appliances. Increased density affects water demand and wastewater discharge, but part of this effect can be remediated with appropriate combination of water servicing options. Building compactness and the associated ratio between built cover and vegetated area influence local hydrology while building orientation and large canopy trees improve thermal comfort.
How can the performance of urban densification (infill) be measured and represented?	The performance of infill development can be assessed using a set of indicators related to (i) water performance (hydrology, water demand and supply, water for greening, water storage, self-sufficiency), (ii) thermal comfort, and (iii) architectural quality of housing designs and urban space. These indicators can be measured using existing tools for urban water mass balance modelling at site and precinct scale (Aquacycle, SUWMBA) as well as scoring through qualitative appraisal. To compare performance of different designs, we have chosen radar diagrams.
What are the water-related impacts of urban densification (infill), and how does it vary in different contexts (e.g. climate, land, infrastructure, demographic and design) in Australia?	The assessment of standard industry practice (BAU) in terms of infill housing design confirmed its adverse impact on almost all aspects of urban water performance, however those on local hydrology, particularly stormwater runoff, and water demand seem most significant. BAU housing typologies almost tripled the volume of stormwater runoff compared with pre-developed conditions and almost doubled it compared with current low density development. With approximately 20% of the precinct redeveloped (in Salisbury) this translated to increasing stormwater runoff volume by 19% (or 8% of annual rainfall volume) when compared with current low density development. While BAU increased the total water demand, the smaller area of private green space which could be irrigated meant that water demand per person decreased (by almost two-thirds in Salisbury and almost half in Knutsford). So even though the population increased by more than two fold, the total water demand rose by only 80% in Salisbury and 60% in Knutsford.

	The variation between the case studies was caused by different climate (rainfall patterns, potential evapotranspiration) and soil characteristics (e.g. soil moisture storage capacity), the extent of likely redevelopment compared with the whole precinct, the density of current development (EX) and the characteristics of land to be redeveloped (vacant, industrial or residential) (Moravej et al. 2021).
What are the urban heat impacts of urban densification (infill) in Australia and what role can water play in heat mitigation?	While the research evaluated only one case study (Salisbury) in terms of the impact of BAU design on thermal comfort, the evidence suggested this impact is significant. With only 20% of the precinct redeveloped with BAU housing designs, we found that on a very hot day the area which exhibits temperatures above 42°C UTCI would rise from 77% (EX) to 83% (BAU) of the precinct area. The analysis focused on the effect of the design parameters (e.g. vegetated area, large trees, shade). This does not include the potential additional effect of active watering to further suppress heat.
How do water servicing alternatives influence performance in different contexts?	We evaluated the impact of water servicing alternatives on site and precinct scale. In both cases it was evident that no single alternative servicing option can meet 100% of demand and that performance of the alternative servicing options varies depending on the context. Onsite-scale water servicing alternatives could reduce water demand but the results varied depending on rainfall patterns, water source used (e.g. rainwater, wastewater), technology's storage capacity and the ranking of usages chosen when multiple water sources are available. 'Self-sufficiency' (the volume of water use that alternative water supply can meet annually) varied from 10% to 36% depending on the year and technology. Precinct analysis demonstrated incorporating alternative water servicing options could significantly reduce per capita water demand while almost doubling the greenspace area (both private gardens and public parks) irrigated. However, irrigation demand could not be met by rainwater tanks alone, which could meet only 20–40% of this demand. A combination of rainwater tanks with rainfall-independent technology (wastewater recycling, ASR) satisfied close to 100% of the irrigation demand, but still varied depending on the rainfall characteristics of the year and extent of greenspace irrigated. Incorporating alternative water servicing options delivered other benefits related to water performance. Rainwater tanks mitigated some of the negative impacts of densification on stormwater runoff by reducing it by almost a half in Knutsford and by 8–27% in Salisbury. Similarly, wastewater recycling reduced the pressure on the wastewater network from the increased population in Knutsford.
Which design and water servicing variables should guide design solutions?	The following variables played a significant role in water performance and should be considered when designing water sensitive precincts: • Density (dwellings per ha) and dwelling occupancy: when these are high alternative sources should be considered for reducing water demand and wastewater discharge • Building compactness and built cover: lower built cover reduces stormwater runoff, but the potential reduction of rainwater harvesting yield is a trade-off that should be considered • Surface materials (especially for paved surfaces): use of permeable materials can improve performance related to hydrology, but can also reduce potential for stormwater harvesting • Vegetation area and choice (including space of canopy trees): large areas of greenspace can improve hydrology but can require more water for irrigation which may be a problem in dry climates

	• Rainfall-dependency of water servicing options: options should consider local rainfall conditions; some cases may require rainfall-independent options to secure supply • Storage capacity: storage capacity of water servicing options influences their reliability and, in most cases, large storage provides better outcomes • Efficiency of household appliances: this can help to further reduce indoor water demand but reductions are less than for alternative water servicing options.
What water performance objectives or targets might be appropriate for infill development?	The performance evaluation can be the first step in establishing targets for specific indicators, either by using water sensitive designs (WS) as a baseline or by setting a desired degree of remediation of adverse impact of infill development anticipate in typical redevelopment (BAU). The evaluation framework can also incorporate already established targets. Based on the analysis, the following targets seem to be particularly powerful in preventing adverse effects of infill development: • imperviousness or built cover of new developments • storage capacity of alternative water servicing options and their reliability in a dry year • areas set aside for mature trees.
What design typologies give good performance in different Australian contexts?	A set of water sensitive housing typologies has been developed, characterised by more compact built form and with priority given to greenspace area and useability. These typologies were found to provide benefits in terms of water performance – particularly minimising the effect on local hydrology – when compared with standard industry practice (BAU) across a number of locations in Australia. While water performance varied across Australian cities, these differences were small compared with the impact of housing design. However, context is important for selecting the water sensitive housing typology (e.g. courtyard, townhouse or apartment building) that replaces existing housing, and deciding which water management goals (e.g. reduction of water demand or stormwater runoff) to prioritise.
How might performance evaluation influence governance and planning mechanisms (policy, planning processes, design codes, etc.) across a range of contexts?	Performance evaluation can be incorporated into the current planning mechanisms as follows: • *Indicators and targets* could be built into building, dwelling, development or plumbing codes (e.g. for impervious fractions, areas set aside for trees, volumes of rainwater storage), practice guidelines related to stormwater management, urban policies on infill development, landscape planning, urban density, metropolitan urban growth strategies and long-term water planning, as well as voluntary sustainability building accreditation schemes (similar to One Planet Living). • *SUWMBA* could be used to inform development and building approval processes, as well as POS and stormwater offset schemes. • *Infill housing and streetscape designs* could be used as prototype development options in masterplans and precinct plans. They could also demonstrate quality medium density designs in infill policies and metropolitan growth strategies. Streetscape design could be included in POS policies and landscape planning.

7.2 Discussion

This report summarises the findings of the CRCWSC Integrated Research Project 4 and demonstrates how it quantified the adverse effects of business as usual (BAU) infill development on water performance, thermal comfort and urban amenity. The project proposed a set of water sensitive housing typologies that increase density while minimising the negative impacts associated with BAU development. Our findings challenge established practices hinting to broader debates and questions relevant for practice and theory:

1. *Why site and precinct scale? WSUD beyond stormwater technology*

Initially, water sensitive urban design (WSUD) was envisioned as an interaction between two components: 'urban design' and 'water sensitive(ity)'. As such, it sought to reconcile water management objectives with urban planning priorities, thus suggesting a holistic approach to urban design in which water is an important consideration (Wong and Brown 2009a). In practice, WSUD is still often defined as a set of stormwater treatment and rainwater harvesting technologies. So, housing design and broader precinct planning has been missing from the range of options discussed as WSUD. This project brings back the question of what 'water sensitive urban design' could mean and how considerations related to urban water performance can inform not only punctuated infrastructure interventions across urban landscape (e.g. stormwater wetlands, bioswales and rainwater tanks), but planning at site, precinct and city scale where architecture interacts with water servicing options to realise optimal result for local catchments and urban residents.

This project focused specifically on site and precinct scale, which align with urban planning and design. The simultaneous assessment at site and precinct scale offers complementary perspectives which can be relevant to development approval processes (and therefore, developers) and broader urban planning, including land use zoning and allocation of land for greenspace. Choosing precinct as the assessment scale also helps embed water sensitivity in urban regeneration as a broader approach to urban growth.

2. *Whole-of-water-cycle analysis: benefits in constrained environments*

The benefits of whole-of-water-cycle approaches to urban water management have been long recognised, but infill development brings them to the forefront. Redevelopment of pockets of land across a precinct generates cumulative impacts for local hydrology, water demand and wastewater discharge simultaneously. Without joint assessment and management of these different water flows, measures that could ameliorate multiple issues at once may be missed. For example, our findings suggest rainwater and stormwater harvesting not only help to meet additional water demand but also ameliorate the effects of increased stormwater runoff. Recycling wastewater becomes a much more attractive option in infill development contexts not just due to the additional water demand it can satisfy but also wastewater discharge it can reduce. Finally, whole-of-water-cycle assessment highlights trade-offs otherwise hard to notice. For example, prioritising reduction of stormwater runoff may mean higher water demand due to larger area of potentially irrigated greenspace. At the same time, more greenspace reduces the area of impervious surface that acts as catchment for stormwater and rainwater harvesting technologies.

3. *Better infill development design: role of innovation and context*

The debate around urban infill has been dominated by concerns about the impacts of higher density urban forms on traditional suburban liveability. What's missing from that debate is a clear understanding of (i) what the standard industry practice in infill development is, (ii) which of its features generate the adverse impacts that are associated with densification and consequently (iii) what alternatives could be developed to meet density targets without these negative impacts. The water sensitive infill housing typologies demonstrate there are under-explored avenues for innovation in medium density housing which could provide multiple benefits. However, innovation may be constrained by existing regulations and market preferences for familiar housing typologies. So, a question emerges about whether the current criticism of general infill development is biased by lack of quality and diversity in built outcomes, caused in part by the above factors. Further, innovation in design approach must be matched by equal innovation in financing, land tenure and procurement pathways to deliver quality infill development outcomes that are also affordable.

One of the learnings from this project has been that innovation requires understanding the full context in which it occurs: for example, legacy-related constraints of infill settings, the nature of existing housing stock and infrastructural capacity, and local environmental and ecological factors. More broadly, both the openness to innovation and recognition of the context are underpinned by a due appreciation for long-term perspectives in design approaches to built form. Infill development requires considering the full lifetime of the new housing and its capacity to adapt to changing future needs.

4. *Interdisciplinary cooperation and common language*

More broadly, this project demonstrated the value of interdisciplinary collaboration in urban water, planning, modelling, engineering and design. It showcases a new way of thinking about assessing the performance of urban infill and provides a new language and tools highly relevant to the major challenge of sustainable, resilient urban water, and associated water sensitive development. Part of the effort of integrating management silos lies in developing conceptual frameworks that scaffold understanding of different disciplinary perspectives.

Learnings from this project also bring to light the importance of sufficient time to negotiate the framework meaning and its theoretical assumptions in building that mutual understanding. We found the iterative process of developing the framework acted as a catalyst for discussions which improved our understanding and appreciation for complexities of the different disciplinary perspectives. Building a common language – agreeing on terms to call concepts labelled differently in engineering, planning and design (e.g. impervious fraction, permeability, built cover) – was an important part of this process.

5. *Urban water mass balance as a conversation starter*

The urban water mass balance that underpins the evaluation framework appeals to a common mental model of moving liquid between two containers. So, its visual representation can be a powerful tool for starting a dialogue between members of the general public, planners, developers, architects and engineers. This is especially true because water flows and 3-dimensional system boundary fit well with the 3-dimensional architectural designs. This visual aspect of urban water performance can be a conversation starter particularly when the extent of the change is an important part of the message. Insights and outputs from this research could be used and adapted for community engagement to demonstrate the impacts of incremental changes caused by infill housing design on local water cycle, and to trigger discussion about community expectations regarding redevelopment of established suburbs and their sustainability.

6. *Advancing the concept of urban water metabolism*

The Infill Performance Evaluation Framework built on the findings of project B.1.2, which developed and tested the concept of urban water metabolism. The new methods developed for this research improve the precision of urban water performance quantification of specific designs through:

- more precise quantification of imperviousness fraction, by increasing the resolution from land use to land cover. In B1.2, land use was used as a proxy of impervious fraction, while IRP4 uses specific housing and streetscape designs to measure the actual imperviousness at site scale. While B.1.2. assumed imperviousness averages for residential land use, IRP4 captures differences between low and medium density, and specific housing designs.
- higher temporal resolution. IRP4 calculates water mass balance in daily timesteps which are aggregated at the end to annual water mass balances, while B1.2. used annual totals. This improvement is particularly important where rainfall-dependent water servicing options with storages (e.g. rainwater tanks) are incorporated.
- higher spatial resolution. New methods quantify an impact of individual lot redevelopment using a new urban water mass balance tool developed precisely for this purpose (SUWMBA). The site-scale evaluations are then used to inform precinct-scale assessments (using Aquacycle).
- more precise water demand estimation. The water demand model in SUWMBA aggregates water use from specific appliances for indoor water use, but allows for adjusting the water use for appliance efficiency and sociodemographic parameters of the household (e.g. number of family members, income). Outdoor water demand for irrigation is modelled based on daily soil moisture levels.
- use of daily rainfall and evapotranspiration data from BOM
- better integration of architectural design and technologies. The exploratory modelling capacity of the evaluation framework developed in B1.2. for in depth analysis of what-if scenarios has been limited due to lack of this integration. IRP4 removed this limitation by developing methods that explicitly link different urban water streams that flow through landscape impacted by architectural design and technologies.

The evaluation framework proposed here uses some of the indicators nominated in B1.2. but also a range of new indicators for evaluating architectural and urban space design quality as well as thermal comfort. Using radar diagrams to represent the results is also a new improvement which visually represents performance across a number of criteria.

Overall, the project tested urban water metabolism on real precinct-scale case studies. The refined methods demonstrate urban water metabolism can be integrated with specific tools used to assess urban water performance and can be used to evaluate water sensitivity of specific architectural designs. This showcases its value for urban planning and design processes, as an approach to facilitate integrated management of urban water resources and land.

7. *Applicability nationally and beyond Australia*

The research evidenced the adverse impacts of typical infill development on hydrology, resource use and liveability in several Australian cities (Brisbane, Adelaide and Melbourne). Case studies from Greater Adelaide (Salisbury) and Greater Perth (Knutsford) further evidence the potential impact infill development can have on the whole precinct performance in these aspects. While we have not evaluated the impact of infill development in the tropics characterised by heavy seasonal rainfall (Darwin), or in dry but cooler oceanic climate (Hobart), the effects of stormwater runoff will likely be higher in the former and comparable to Adelaide (though without the urban heat effect) in the latter. SUWMBA has in-built libraries for both and water performance evaluation could be conducted to verify these initial predictions. However, overall this research builds a strong case for embedding mechanisms to prevent negative impacts of typical infill development in policies and regulation.

The catalogue of infill typologies was developed based on the analysis of suburban areas of Australian cities. It is a snapshot of what low density looks like and what types of housing replaces these low density dwellings through infill development. This can be used as a basis for forecasting the future landscape of Australian cities and quantifying the effects this change is likely to bring not just for water management but other aspects of sustainability as well (e.g. energy consumption, traffic, air and water quality).

Both the Infill Performance Evaluation Framework and water sensitive housing typologies have been developed as tools to be used, adapted and extended. The framework, its criteria and indicators, can be adjusted to the local context, while the WS typologies were purposefully left at schematic representations of a broader range of possible variations in built form, allowing space for customisation. Both can inspire more ambitious policies and designs that chart the way forward for urban sustainability. And while this research focused specifically on infill development, housing designs and evaluation methods are also applicable to greenfield developments.

Chapter 6 diagnosed some of the obstacles that implementing water sensitive urban design is likely to face and ways in which local, state and federal government can foster its use. Many of the barriers and opportunities identified in this research point to mechanisms vested in local governments' mandate (e.g. rules for obtaining development approval or council's dwelling codes, POS policies, zone planning, metropolitan growth strategies), state (e.g. departments or agencies tasked with oversight or delivery of key redevelopment sites, state building and plumbing codes) and federal government (e.g. Building Code of Australia). Re-evaluating the current technical provisions stipulated in these documents may be necessary for promoting water sensitive infill development.

While this research is focused on Australia and uses Australian case studies, it may be useful for other contexts where high and medium density housing design generates problems related to water demand, flooding or liveability. It also resonates with other concepts such as Sponge Cities and Water Wise Cities since it also aims to redesign cityscape to capture more stormwater runoff (Sponge Cities) and implement modular and regenerative system solutions to respond to growing pressures on the water resources of cities (Water Wise Cities).

7.3. Recommendations

These recommendations build on the results which demonstrated (i) water sensitive design can simultaneously enable densification and improve liveability, (ii) impact on stormwater runoff and cooling can be reduced with good building design, and related land use and vegetation management, (iii) water servicing options and hybrid infrastructure are critical to cater for growing populations and to make local contributions to water security, and (iv) site and precinct context (climate, soil, etc.) are very important and need to be considered locally. Guided by this, the main recommendations are:

Short term

- Stronger attention should be made for **quantified performance** (e.g. in water, liveability and heat management) supported by appropriate analysis. This is needed to reduce, or slow the acceleration of, negative impacts of conventional infill development, and to guide improved design. It will also create opportunities for densification that do not compromise water performance outcomes. Quantified performance should be preferenced over recommendations for specific water servicing options or designs, which as proven by the analysis may be insufficient to mitigate the negative impacts of BAU infill.

- To improve water performance and architectural quality simultaneously, **housing design** should prioritise:
  - consolidating open space into useable 'outdoor rooms' for trees, people and sun
  - the amount of site available to other use than vehicles and enabling permeable multi-use surfaces
  - retention of all existing mature trees and addition of new large canopy tree spaces within each site, together with associated water harvesting
  - more adaptable and therefore sustainable spaces for a range of uses: ageing-in-place, multi-household, multi-generation.

- To achieve superior water performance outcomes and improved quality of urban spaces, **precinct design** should:
  - include a range of building typologies that allow a mix of scale, height, household types and the potential for work/living
  - establish public realm connectivity and enhance its quality and amenity
  - retain significant remnant trees, local character, and topography, and allow these elements to contribute to the overall site logic
  - consider spaces between buildings as multi-use public and semi-public areas: allowing circulation, solar access, privacy, safety and delight
  - iteratively analyse performance with a screening tool (such as SUWMBA) to guide design.

- The **range of tools and methods developed** in this project could be used much more widely in assessing and designing water sensitive development. This includes use of the performance framework and site-scale analysis (e.g. with the SUWMBA Tool and typologies catalogue). It also includes longer-term precinct-scale analysis and design (e.g. with tools such as Aquacycle and the Scenario Tool), and related heat management analysis. This would help embed water sensitive infill development principles in current redevelopment practice and inspire further development of water sensitive design alternatives. Further training, application and support of developed resources would help this.

- Foster **multidisciplinary cooperation** and integration between planning and design silos especially in engineering, architecture, hydrology and urban climate. As a component of this, we recommend bringing community, developers and designers on board with more compact housing which is water sensitive. Multidisciplinary cooperation can improve outcomes where sustainability and liveability are not trade-offs, but rather outcomes achieved simultaneously.

Medium term

- Ideally **implement the precinct- and site-scale designs** as suggested to create proof of concept and demonstrate the multiple benefits achieved with good design supported by quantitative analysis.
- As a component of design, stronger attention in future should be made to **establishing city-scale, and related precinct-scale targets**, informed by a management goal. The general lack of quantified goals (e.g. for self-supply of water, or heat management or greenspace retention) creates uncertainty for design. Without targets, it is harder for designers to know when solutions have reached required levels of performance.
- **Monitor** progress.

Long term

- **Regulation and legislation** should recognise the potential for positive outcomes from infill development as well as the current adverse impacts in the planning and development assessment process. Doing so can encourage better redevelopment designs and improve poor design, by elucidating the currently hidden impacts. There is a need to implement better measures to manage this:
  a. Consider impacts of new developments on water demand and stormwater runoff (and flooding) and ways of meeting the demand with alternative supplies.
  b. Consider impacts of new developments on wastewater discharge and the benefits of recycling for avoiding network upgrade costs.
  c. Include targets for impervious fractions, areas set aside for trees, and volumes of rainwater storage in development approval process.
  d. Assess impacts of new developments on local hydrology.

- **Support or create more flexible processes to enable amalgamation of allotments** (e.g. merging two or three sites to create a single larger site) due to the impact this has on flexibility of design and function of 'the wider water performance' system.

- **Reconsideration and progressive reform of prescriptive compliance-based codes** related to all elements of water sensitive design and development including (a) building heights/setbacks which may limit more innovative water sensitive housing design, and (b) mandatory car parking spaces due to the significant influence on development. This could allow more innovation in architectural design and development of more water sensitive alternatives for housing in denser urban environments.

- **Implement precinct-scale planning** for existing neighbourhoods subject to redevelopment at the earliest stage possible. In general, there is a need retain greenspace, make space for deep-rooted trees and consider trade-offs in design and planning. Precinct-scale planning can recognise cumulative impacts of housing designs, and potential opportunities to mitigate them in the private and public realms.

7.4. Future research

Many new venues for future research emerged throughout the project.

Evaluation framework and process

The Infill Performance Evaluation Framework could be extended further to include a wider array of management goals, derived from broader urban policy and water planning objectives. The conceptual linkages and possible indicators related to water-related liveability outcomes and water security were explored through two research projects (see Appendix B):

Design and optimisation

The architectural designs and the water servicing option combinations that accompany them can inspire further research that investigates their economic viability and affordability, as well as adjusts them further to specific geographical contexts in Australia and beyond. Two research projects explored some of these questions (see Appendix B).

Performance analysis

Further research could quantify the performance of different BAU versus water sensitive housing designs in other Australian cities and other countries (see Appendix B). There is also a significant opportunity to quantify energy use, nutrient loads or food implications of water use, using the urban metabolism framework.

Appendix A: IRP4 Project team and process

The project was delivered by an interdisciplinary team, which comprised architects, urban climate modelers and water engineers across four Australian universities.

IRP4 was led by:

Prof. Steven Kenway (Project Leader) Steven Kenway has worked with urban water, wastewater and stormwater, and related energy and greenhouse gas issues since 1990. Steven is an international leader in quantifying the links between water, energy and carbon. He creates tools and models of all flows of water – and related energy into, out of, and within cities. His interests include (i) managing water impacts of urban design and infrastructure, (ii) net zero water cycle, (iii) performance of hybrid, decentralised and integrated systems, (iv) water security, and (v) urban design.

Dr Marguerite Renouf (deputy Project Leader) Marguerite Renouf contributed to this project while a Senior Research Fellow at The University of Queensland (2018–2020). Much of her research career over the past 20 years has been directed to evaluating environmental impacts and eco-efficiency opportunities for production and urban systems using method such as environmental life cycle assessment (LCA) and urban metabolism.

Prof. Nigel Bertram (Project Lead: Design) Nigel Bertram is a Director of NMBW Architecture Studio and Practice Professor of Architecture at Monash University. Nigel's current research with the Monash Urban Laboratorytests design-led processes for suburban regeneration and infill redevelopment, seekingnew relationships between natural and human-made systems.

Prof. Geoffrey London (Project Lead: Design) Geoffrey London is an Emeritus Professor of Architecture at The University of Western Australiaandan Adjunct Professor at Monash University.His key research interests are in the field of higher density housing and alternative forms of project delivery. He previously held the positions of Victorian Government Architect and Western Australian Government Architect.

IRP4 was based on broad stakeholder engagement and included elements of co-design and consultation with representatives of planning and water agencies, local government and engineers responsible for the site's design at various stages of the project implementation The research team acknowledge the valuable contributions of past and current Project Steering Committee members, and other CRCWSC industry partners:

Mellissa Bradley	Water Sensitive SA
Matt Stack	Department of Planning, Lands and Heritage, WA
Greg Ryan	Development WA (formerly LandCorp, WA)
Sadeq Zaman	NSW Department of Planning, Industry and Environment (formerly Inner West Council, NSW)
Peter Newton	Swinburne University, VIC
Pam Kerry	South East Water, VIC
Chris Tancheff	South East Water, VIC
Cintia Dotto	Water Technology
Nigel Corby	City West Water, VIC
Andrew Allan	Manningham Council, VIC
Phil Young	Brisbane City Council, QLD
Scott Beard	Brisbane City Council, QLD
Nick Morgan	Brisbane City Council, QLD
Chris Tanner	CRC Water Sensitive Cities, QLD
Jurg Keller	CRC Water Sensitive Cities, QLD

Appendix B: IRP4 PhD and MPhil projects

- *Contribution of alternative water sources to urban water security* – Shenbagameenal Surendran (MPhil project) developed indicators for urban water security employing alternative water sources at precinct scale using Knutsford as a case study.
- *Understanding the relationship between water and liveability* – Beata Sochacka (PhD project) explored liveability benefits attributable to water and ways of quantifying them through indicators.
- *Applying an integrated framework to help manage and inform infill water impacts* – Owen Hoar (Masters thesis, completed) conducted a preliminary water mass balance for a Perth location focusing on groundwater impacts.
- *Water sensitive infill development: a case study for the Norman Creek Middle Catchment* – Xuli Meng (Masters thesis, completed) compared different water sensitive technologies through a water mass balance using MUSIC software and found that reducing road width had the largest effect on water performance of a precinct in Brisbane.
- *Water performance evaluation of infill development* – Mojtaba Moravej (PhD project) developed and tested the SUWMBA Tool.
- *Conceptualisation of urbanization and stormwater management effects on hydrology in catchment scale* – Niloo Tarakemehzadeh (PhD project) explored in more detail stormwater impacts of infill development on a case study in Brisbane.
- *Towards repair in the biodiversity–urbanisation hotspot: frameworks and design studies for ecological and housing regeneration* – Daniel Jan Martin (PhD project) explored precinct design studies for achieving ecological regeneration *with* housing regeneration in areas of projected conflict between urbanisation and biodiversity in Perth.
- *Decentralised wastewater systems across scale* - Bosco Chow (Masters thesis, completed) explored scales of feasibility for alternative water servicing options that use wastewater.

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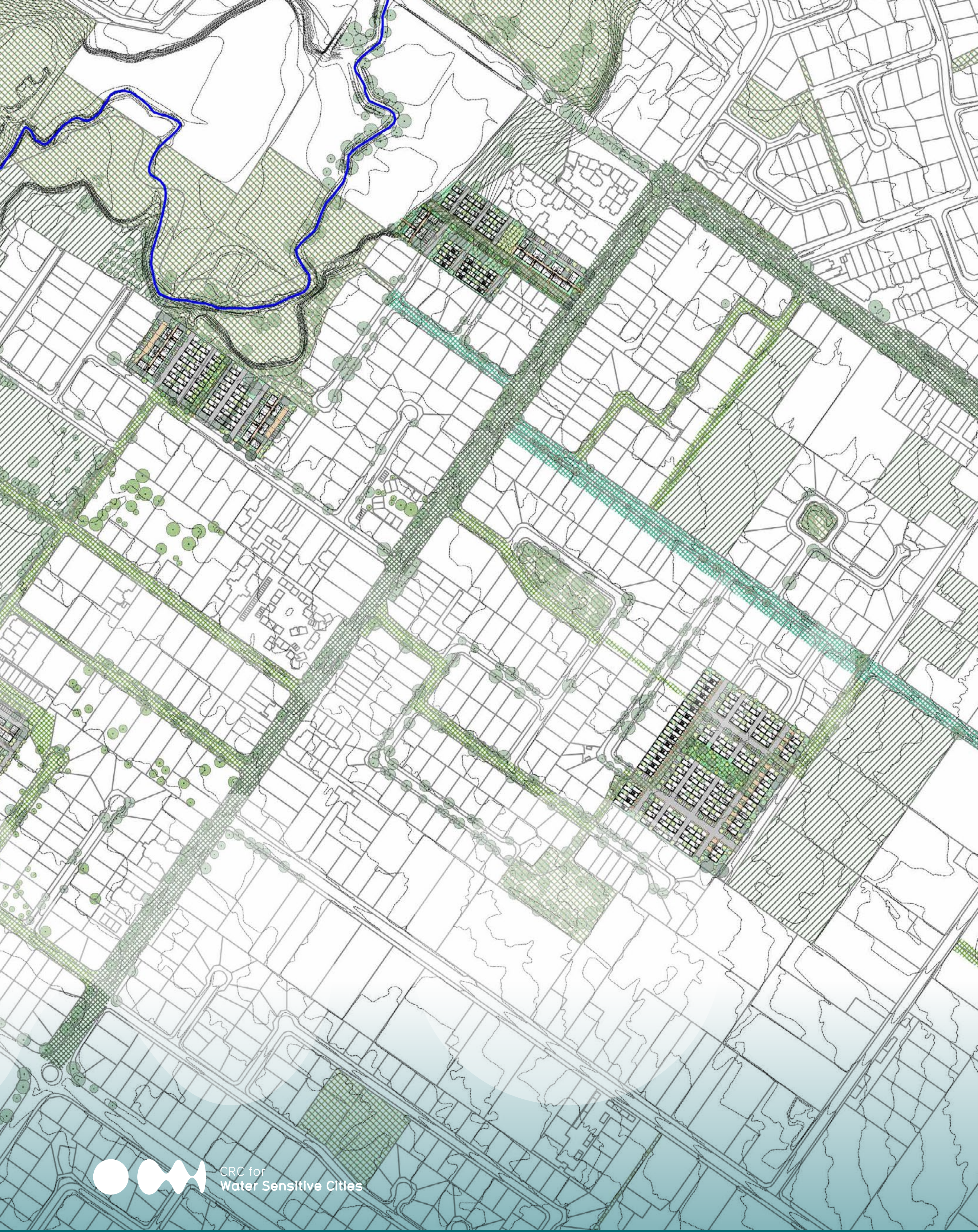

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