CRC for
Water Sensitive Cities

Water Sensitive Outcomes for Infill Development

Infill Performance Evaluation Framework

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Water Sensitive Outcomes for Infill Development: Infill Performance Evaluation Framework
Milestone Report
Water sensitive outcomes for infill developments
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Table of Contents

Tables and Figures

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).
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.
AWB	Australian Water Balance Model (Boughton, 1993).
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
detention storage	Detention storage basins hold runoff for short periods to reduce peak flow rates. They release the stored volume in a controlled manner to make the volume available for the next storm event and to mimic ‘natural’ hydrology. Refer to book 9 chapter 5 of Australian Rainfall and Runoff guide for more detail explanation (Ball et al., 2016).
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 three dimensional 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.
field capacity	The amount of soil moisture or water content held in the soil after excess water has drained away and the rate of downward movement has decreased.
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, 1 m 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 (Walsh et al., 2005b, Walsh and Kunapo, 2009, McIntosh et al., 2013). 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.
Integrated Water Management (IWM)	IWM is defined by the Global Water Partnership (2000) as “a process which promotes the coordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems”.
infill area	A two-dimensional area planned for development. See also ‘urban entity’.
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 recharge	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.
mass balance	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 (man-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.
recharge	Water that infiltrates through the soil beyond the urban area boundary (i.e. 1 m 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).
retention storage	Retention storage basins or ponds are designed to hold stormwater for considerable periods allowing water to infiltrate, percolate, evapotranspire, and be reused. Only overflows are discharged downstream. Refer to book 9 chapter 5 of Australian Rainfall and Runoff guide for more detailed explanation and comparison with detention basins (Ball et al., 2016).
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. Refer to Moravej et al. (in prep.) for more information.

supply internalisation	The sourcing of water from within the urban system, to reduce reliance on water sourced from the supporting environment.
total impervious area (TIA)	The total impervious area (TIA) is a summation of all impervious covers in the assessed site. There are many methods for estimating TIA of existing urban areas including remote sensing (e.g. Geoscape), land use categories with categorical TIA estimates, a generalised percent developed area, and relations between population density and TIA.
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. (See Renouf et al., 2017b.)
urban	A location characterised as population clusters of 1,000 or more people, with a density of at least 200/km^2 (ABS, 2017).
urban area	The two-dimensional (area-based) boundary of the 'urban entity (three-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 area boundary	The physical three-dimensional envelope surrounding the urban area being evaluated, to the height above the tree line and to a depth of 1 m below the ground surface.
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 entity	The three-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 1 m depth of soil) and associated land surfaces and vegetation, and related water storage/s. This term is used interchangeably with 'urban area' in this report and framework.
urban design typology	The taxonomic classification of (usually physical) characteristics commonly found in buildings and urban places.
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. 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 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 man-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 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 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 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.
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 mass balance	A water mass balance in the context of an urban area. See 'water mass balance'.
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, 2009).
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.

Executive summary

Most major Australian (and many global) cities expect intensified infill development over the coming decades. Infill development is promoted nationwide as a way of accommodating growing urban populations by increasing urban densities (densification) rather than allowing urban sprawl. Currently, the bulk of infill development occurring in Australian capital cities involves subdivisions of single suburban lots into denser single- and multi-unit dwellings, and apartment buildings around transport nodes. This pattern achieves higher density targets but increases building footprint and thus imperviousness of the redeveloped lot, most often at the expense of usable greenspace.

Without significant intervention, 'business as usual' redevelopment will have a considerable negative influence on urban hydrology, resource efficiency, urban heat, liveability and amenity. The water sensitive city approach aims to resolve these challenges. This document is prepared as a component of Integrated Research Project 4 (IRP4): Water Sensitive Outcomes for Infill Developments. It sets out the Infill Performance Evaluation Framework, which is intended to help guide the assessment and design of water sensitive cities. Specifically the Framework assesses the performance of an 'urban entity' defined as the components within a three-dimensional physically bounded system including all flows and storage of piped and natural water flows.

The performance evaluations generated by the Framework are intended to inform governance mechanisms that drive urban development and residential design. This includes planning policies, guidelines and codes, development approval processes, precinct, and building rating and certification schemes.[1] The Framework can be used to compare different planned designs, generate metrics that feed into broader economic evaluations or building approval processes, identify targets and objectives for infill development, and predict the impact of new developments. As such, it can be useful for planning, including use by sustainability officers, design engineers, climate change adaptation practitioners, planners, architects, designers, landscape architects, builders, developers, policy makers, water consultants and water utilities. At this stage of development, the Framework is intended to guide the broad screening of design options (e.g. rather than detailed engineering design). It would need further development to use it to size infrastructure etc., but it is well positioned to enable this in future.

The Framework (Figure ES 1) builds on and develops the concept of water sensitive cities and demonstrates how key elements can be applied at finer urban scales. Specifically, it fills a gap in available methods for evaluating the water sensitivity of urban designs at both precinct, and, for the first time, site scale. The Framework consists of four elements that:

- define the principles and criteria for good performance of infill/new developments
- define the design variables that influence that performance
- define indicators for reporting performance
- describe the methods for quantifying performance indicators at different urban scales.

Principles and criteria. Water sensitive infill development design is defined through three groups of performance criteria: (i) water performance (which includes hydrology, water demand and supply, greening), (ii) urban heat, and (iii) architectural and urban spaces quality. The framework has limited indicators for water quality and waterway health, principally because a strong focus on water quantity management was perceived as particularly important, and that addressing current water quantity challenges would also contribute to addressing water quality management. Further attention to water quality performance criteria are anticipated to be necessary.

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[1] Planning processes and instruments are considered in more detail in the CRCWSC's Integrated Research Project 3: Guiding Integrated and Urban Water Planning.

Performance principles describe what well considered and designed infill should aim to achieve. Water sensitive infill designs:

1. do not further adversely alter the natural hydrology of the development area, and ideally aim to mimic the pre-urbanised hydrological water balance
2. incorporate water storages to facilitate the availability of supplementary water supply, and slow/retain/detain runoff for reducing flooding
3. facilitate soil moisture storage through permeable surfaces that promote infiltration (where beneficial)
4. reduce reliance on imported water by facilitating the use of locally-sourced supplementary water supplies, by making space for water storage and/or connections to supplementary supplies
5. enable irrigation of vegetated areas to support greening for cooling and amenity
6. include space and deep root zones for vegetation and large trees, to provide greening for cooling and amenity
7. enable passive mitigation of outdoor urban heat through building orientation and tree canopy shading
8. include dwellings and urban spaces which are efficiently designed and equipped to enable improved amenity, usability and flexibility.

Design variables. The Framework provides a method to assess a range of alternative designs in various climatic and soil conditions. Thus it incorporates models that have the capacity for modelling water flows depending on determined design and climatic variables. These variables include environmental parameters (e.g. rainfall, soil), built form parameters of dwellings (e.g. building footprint and resulting surface types and imperviousness, occupancy rates), urban design parameters at precinct scale (e.g. density of built form, areas of greenspace and vegetation types), and water servicing parameters (e.g. indoor water demand, recycled water demand).

Indicators and methods. The Framework includes a set of methods and indicators of water, urban heat and architectural and urban space performance which can be used to assess infill development at both site and precinct scale. Performance indicator selection should be guided by aims or targets for managing the hydrology of the region or sub-catchment. Findings from site-scale analysis of designs can inform infill development scenarios at the precinct scale, and vice versa.

1. Water performance

   An urban water mass balance is used to quantify the water performance of urban areas. It is operationalised in the Site-Scale Urban Water Mass Balance Assessment (SUWMBA) Tool for site-scale analysis, and the Aquacycle tool for precinct-scale analysis. The analysis includes four groups of indicators that evaluate (i) hydrology, (ii) ecological function of urban waterways and water quality, (iii) water demand and supply, and (iv) greening. Due to scope and time we have not specifically analysed water quality impacts. However, moving hydrology of catchments much closer to pre-development (pre-urbanised) conditions is highly likely to also improve water quality.

2. Urban heat performance

   For the urban heat analysis the Framework uses the Universal Thermal Climate Index (UTCI) which represents the subjective experience and thermal stress of heat on a person in an outdoor area. It is assessed using the Solar Long Wave Environmental Irradiance Geometry model (SOLWEIG) module from the Urban Multi-scale Environmental Predictor (UMEP) model, which calculates the mean radiant temperature experienced by a human body at each modelled point in site-scale dwelling typologies. The performance indicator for urban heat is the fraction of areas in the precinct that have a ‘feels like’ (UTCI equivalent) temperature on very hot summer day that is less than a certain threshold, e.g. 42ºC UTCI.

3. Architectural and urban space quality

   Architectural and urban space quality relates to the extent to which space, both indoor and outdoor, is efficiently designed and organised for improved amenity, usability and flexibility. In the Framework these features are defined following the four categories of architectural and urban spaces: dwelling interiors, outdoor private, public and communal space. Performance of these spaces is judged against seven qualitative performance criteria:

   a) availability and diversity
   b) size and proportions
   c) accessibility and connectivity
   d) privacy through balanced transition between spaces
   e) multifunctionality, adaptability, flexibility
   f) solar access and cross-ventilation, and
   g) outlook to gardens, vegetation, canopy trees.

The performance of different infill development design scenarios across multiple selected performance criteria outlined earlier can be compared using a radar chart, where the area within the line represents overall performance of a given design.

The findings of applying this Framework in designing and assessing water sensitive precincts, sites and design typologies can be seen in the related documents including:

1. Infill Typologies Catalogue (Revision A)

2. Water Sensitive Outcomes for Infill Development: Salisbury Case Study – Final Report

3. Water Sensitive Outcomes for Infill Development: Knutsford Case Study – Final Report

4. Water Sensitive Outcomes for Infill Development – Final Report

5. SUWMBA Tool and User Manual.

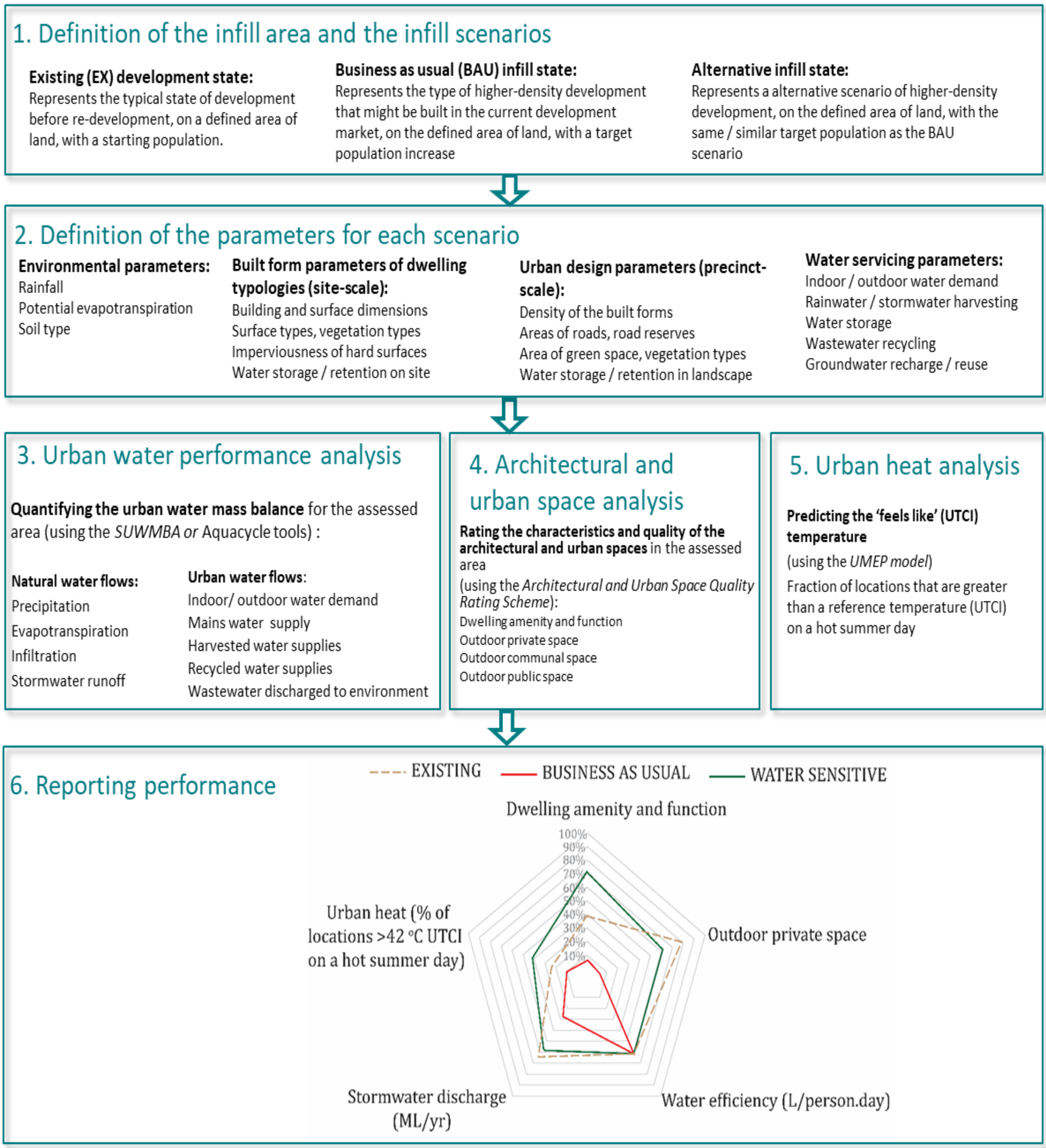


Figure ES 1: Components of the Infill Performance Evaluation Framework

1 Introduction

Most major cities in Australia expect intensified infill development over the coming decades (Commonwealth of Australia, 2017). Without significant intervention, 'business as usual' development practice is expected to have a considerable negative influence on the hydrology, resource efficiency, liveability and amenity of our cities (Brunner and Cozens, 2013, Jacobson, 2011). The water sensitive city approach (Wong and Brown, 2009) aims to support higher density communities while enhancing the environmental performance of Australian cities. It recognises the substantial effect of intensified residential infill development on metropolitan water and urban heat performance due to its scale and proliferation.

Medium density infill development, utilising efficient design strategies, presents an opportunity to transition towards water sensitive city outcomes (Newton et al., 2012, Newton and Glackin, 2014). Efficient and compact housing design can yield more outdoor space, valuable stormwater infiltration and large tree canopy area. If planned well, the housing can generate higher quality outdoor space facilitating optimised use of resources, eventually reducing overall water and energy demand per dwelling/person (Newton et al., 2012). Additionally, climate sensitive urban design can be applied to mitigate increases in urban heat associated with higher urban density (Bowler et al., 2010, Coutts et al., 2012). However, current infill practices, in this paper are referred to as ‘business as usual’ (BAU) (Thomson et al., 2017). Large building footprints (e.g. a high percentage of the site area) and low-rise developments often result in residual and often unusable open spaces; inadequate tree canopy, solar access and cross-ventilation; and, typically, poor water and urban heat performance. While it is possible to have low-rise development and good open space, it often is viewed as more costly.

This document describes the Infill Performance Evaluation Framework, developed as part of Work Package 5 of the CRC for Water Sensitive Cities’ (CRCWSC) Integrated Research Project 4 (IRP4): Water Sensitive Outcomes for Infill Developments. The IRP4 project aimed to:

- develop methods for quantifying the impacts of urban development (in terms of hydrology, water demand and supply, urban heat, and architectural and urban space quality), and for rating performance of urban designs
- understand these impacts in the contexts of residential densification (infill) in different Australian cities, and how design influences performance to understand how it can be improved
- generate design ideas that mitigate the adverse impacts, and potentially enhance the water sensitive performance of, urban environments by taking advantage of the urban renewal opportunity that urban densification represents
- generate evidence of the above that can guide urban planning and governance mechanisms.

The Framework fulfils the first of these aims.

1.1 Aim of the Framework

The Framework is a compilation of methods used to answer the specific research questions of the IRP4 project, which are summarised in Table 1. This report focuses on the questions in column 1, and Section 1.2 discusses potential ‘users’ of the Framework.

Table 1: IRP4 research questions

Performance assessment methods	Infill design	Governance
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 does it 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?

The Framework fills a gap in available methods for evaluating the water sensitivity of urban designs with specific attention to quantitative performance analysis of existing and future infill development areas (i.e. a three-dimensional 'urban entity'). A review of literature and consultation with industry partners found a few existing performance frameworks that include aspects of water sensitivity (see Box 1). These provide part of the picture for answering the IRP4 research questions, but a more systematic and comprehensive approach to performance evaluation was needed.

In this work 'performance' relates to the following bio-physical aspects of a water sensitive city (WSC) (see Appendix 1):

- hydrology
- water demand and supply
- greening
- urban heat
- architectural and urban spaces quality.

Water quality it is an important part of the WSC concept. However, it is beyond the scope of the current version of the Framework noting though that improved water quantity management (e.g. less flooding and greater restoration of natural hydrology) are anticipated to support improved water quality outcomes. Water quality and other attributes could be included in the Framework with further development.

The IRP4 research hypothesised that well designed urban densification can enable good performance across all these aspects. The Framework describes how performance can be evaluated for testing this hypothesis, by:

- defining the principles and criteria for good performance
- defining the design variables that influence performance
- defining indicators for reporting performance
- describing the methods for quantifying performance indicators at different urban scales.

The Framework has been considerably informed by input from the IRP4 Project Steering Committee (see Acknowledgements), feedback received from participant organisations, and the case study applications (London et al., 2020, Renouf et al., 2020).

Box 1: Existing frameworks related to the performance of urban development

Evaluation frameworks:

- The Danish Framework, An SDG-based framework for assessing urban stormwater management systems, is an SDG-based process to evaluate the services nature-based solutions for stormwater management deliver with reference to targets and indicators of the United Nations Sustainable Development Goals (Sørup et al., 2019). It considers the performance aspects of flood resilience, natural resource management, and liveability.

Design principles for good urban development and infill design:

- The Western Australian Residential Design Codes for Apartment (WA Planning Commission, 2019)
- NSW Building Sustainability Index (BASIX) (Ding, 2010) – indoor water demand per person
- National Australian Built Environment Rating System (NABERS) (Department of Planning, 2019)
- Green Star Communities (See Department of Infrastructure and Transport (2011))
- Enviro Development (UDIA, 2019).

Methods and tools for quantifying urban water flows:

- Aquacycle (Mitchell, 2005, Mitchell et al., 2001)
- Insite (WaterSensitiveSA, 2018)
- Water Balance Express (The Partnership for Water Sustainability, 2020)

Performance indicators used in:

- Deltares Adaptation Support Tool (AST) (van de Ven et al., 2016) – normative runoff; aquifer recharge; effective water storage capacity
- One Planet Goals and Guidance for Communities and Destinations (Bioregional, 2016) – ratio of permeable to impermeable area that accommodates infiltration; water supply internalisation (% of demand met by internal source); percentage of site area used for rainwater harvesting; percentage of outdoor area providing deep root zone for canopy trees
- CSIRO's AccuRate model (CSIRO, 2008) for energy efficiency buildings – percentage of outdoor area providing deep root zone for canopy trees
- Environmental Benefits Index (Fletcher et al., 2011) – number of days of runoff; indoor water demand; volume of harvested rainwater/stormwater; annual nitrogen loads
- Urban harvest approach (Agudelo-Vera et al., 2012) – demand minimisation, waste output, self-sufficiency, resource export
- Urban Water Mass Balance – Kenway et al. (2011) and Ghosh et al. (2019) – Water supply internalisation (% of demand met by internal source; turnover rate)
- Urban Metabolism Evaluation Framework for Water (Renouf et al., 2017a)
- WSC Scenario Tool (at May 2019) (CRCWSC, 2020) – volumes of stormwater runoff (total, from roof, residential, commercial, industrial, schools, parks, community areas, other); infiltration; evapotranspiration; indoor water demand; harvested rainwater/stormwater; recycled water supply; wastewater generated.

1.2 Uses for, and users of, the Framework

A core aim of this Framework was to improve the water sensitive outcomes from infill development – and enable the design and creation of more liveable, water secure, cooler and efficient cities. The performance evaluations generated by the Framework can inform governance mechanisms that drive urban development and residential design – planning policies, guidelines and codes, development approval processes, and building rating and certification schemes (See Table 2). The knowledge generated by the Framework can also influence the awareness of designers, architects and developers to improve the water sensitive outcomes of design. Answering the research questions identified for the IRP4 project was necessary to enable this aim.

Therefore, the audiences for the knowledge generated by the Framework are development assessment engineers, design engineers, climate change adaptation practitioners, planners, architects, designers, landscape architects, builders, developers, policymakers, water consultants and water utilities. Banks can also be a big influencer of what is built.

Table 2: Uses for the Framework

Uses	**Site-scale**	**Precinct-scale**
Compare the performance of individual design typologies (See Section 3.1)	✓	
Devise and validate 'deemed to satisfy' examples for development approval processes	✓	
Enhance existing building/design standards and guidelines with more detailed quantification of performance criteria (i.e. beyond the water demand assessed by BASIXs and SA's Insite tool)	✓	
Compare the performance of infill scenarios to understand the broader impacts of urban densification, or the benefits of better infill design		✓
Identify water sensitive objectives and targets for areas experiencing infill, e.g. in Local Government Integrated Water Management Plans		✓
Identify target populations and dwelling densities that will not compromise water sensitive objectives[1]		✓
Predict how urban design typologies at the site scale may contribute to water sensitive outcomes at the precinct scale and vice versa	✓	✓
Generate performance metrics that can feed into planning, design and development approval processes, e.g. building codes	✓	
Generate design parameters that can feed into evaluations of capital and operating expenditure for private developments and public infrastructure	✓	
Improve the awareness of influential agents in the development world, including architects, designers, landscape architects, banks and financiers	✓	✓

[1] This analysis was not undertaken in this project. However, key elements of such an analysis could be expected to include (a) establishing clear performance criteria – i.e. outcomes of runoff, groundwater, supply, wastewater, urban heat, liveability, quality spaces etc., and (b) provision of flexibility to designers to create designs that meet those criteria.

1.3 Scope of infill development evaluated by the Framework

The Framework focuses on urban densification that occurs through infill development, principally for residential dwellings. This is the process of redevelopment within established urban areas, typically using previously undeveloped or underutilised parcels of land (greyfield) or redeploying previously developed land (brownfield).

Significant population growth and urban development is expected to continue in Australian capital cities. Densification of residential areas, through infill development, will be the dominant form of growth as opposed to urban sprawl (Commonwealth of Australia, 2017). Densification is important for managing population growth in a resource-efficient and sustainable way, and most Australian states have infill targets. Infill in the suburbs of Australian capital cities typically aims to increase dwelling density from around 15 dwellings/hectare to around 30–55 dwellings/hectare (Chandler, 2016).

The modes of urban densification range from suburban lot subdivisions to major urban renewal (see Table 3). The bulk of infill development occurring in Australian capital cities involves subdivisions of single suburban lots into denser single- and multi-unit dwellings, and apartment buildings around transport nodes. The Framework focuses on those modes shaded in Table 3. In particular, the Framework is designed to evaluate residential infill typologies that are described in Figure 1, e.g. through residential design codes. The ‘missing middle’ is the medium density housing which is not simply high rise. They are low rise medium density multi-unit typologies (around 3-4, maximum 5, storeys) not currently well represented in the Australian housing market (Chandler, 2016).

Other building types or public urban features are also associated with infill development, such as mixed-use developments, public open space, and road corridors. Road corridors are a large part of the urban form (when road reserves, intersections and carparks are also considered), and can have a considerable influence on the performance of an urban area (Meng and Kenway, 2018). Public spaces can be important for offsetting the adverse impacts of urban densification. Therefore, the Framework can evaluate road corridors and public spaces as well as residential dwellings. It is expected to be widely beneficial for precinct planning when water sensitive outcomes are intended. The Framework focuses on quantifying outcomes. It is highly adaptable to consider a diverse range of future potential technologies and land use patterns, e.g. by quantifying their influence on target outcomes.

Water servicing and water management technologies are an important part of designing water sensitive infill. Table 4 summarises the suite of options that could be integrated into infill developments, and evaluated by the Framework. Some options require further research before they can be modelled within the Framework, such as water sensitive urban design (WSUD) features that retain/detain water (green walls, green roofs, grass swales, retention/detention basins) and smart tanks that optimise the management of rain tanks for both storage and flood storage (South East Water, 2014). Methods to capture these interventions are being considered in PhD research linked to the IRP4 project.

Performance evaluation of infill considers changing dwelling densities (dwellings per hectare) and dwelling occupancy (occupants per dwelling), as well as the urban form and water servicing. This is a point of difference from greenfield urban development, which may not be constrained by population and dwelling density targets. The lessons about better infill design could be translated to other development contexts, but perhaps not the other way around. The CRCWSC’s Integrated Research Project 3 (IRP3): Guiding Integrated Urban and Water Planning, investigates planning processes for water sensitive urban development and has considered greenfield development in its case studies.

Table 3: Modes of infill that can be evaluated by the Framework (shaded)

Mode	Description	Australian examples
Suburban lot subdivision	Backyard redevelopment model, 'dual occupancy'	Norman Creek, QLD
Small infill combinations	Small groups of dwellings on small to medium scale lots (possibly amalgamated)	Elwood, VIC
Block-scale infill	Medium scale developments (with additional public value) on large lots (e.g. ex-commercial)	Arden Macaulay, VIC
Suburban precinct	Dispersed precinct in suburban residential setting	Aquarevo, VIC Maroondah Council, VIC (Brysons Rd, Warranwood, Larissa Avenue, Ringwood) Melbourne Water Pipe Track, Croydon, VIC
Mixed-use precinct	Larger scale mixed use development or redevelopment within a structured plan	Southbank, QLD
Employment cluster	Large dispersed cluster of amenities and employment opportunities within a state government framework (often too large to be in structure plan), e.g. See National Employment Innovation cluster)	Tonsley Park, SA
Major urban renewal	Large high-density urban development sites designated for large population and employment opportunities (often scrap and rebuild)	Barangaroo, NSW Green Square, NSW Subiaco East, WA East Perth Power Station, WA, Fisherman's Bend, VIC

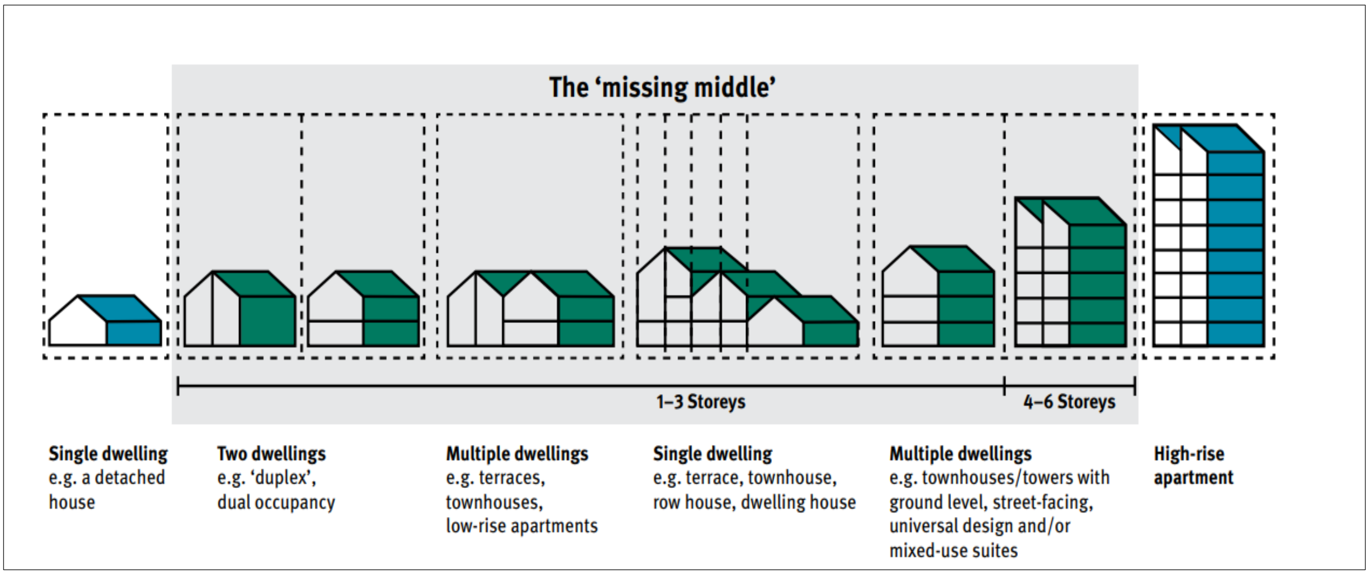


Figure 1: Infill dwelling typologies (QLD Government, 2009)

Table 4: Scope of water servicing options that can be evaluated by the current version of the Framework (shaded) with existing tools and models

Water servicing options	Site scale	Precinct scale	Australian examples
Rainwater harvesting and storage (above-ground or in-ground)	✓	✓	Numerous
Stormwater harvesting and storage (above-ground or in-ground including under roadways)		✓	Aquarevo, VIC
Stormwater harvesting and aquifer storage and recovery (ASR)		✓	Salisbury, SA
Greywater capture, storage and reuse	✓		Aquarevo, VIC
Wastewater treatment / sewer mining and recycling		✓	Central Park, NSW
Stormwater detention devices*		✓	Rainbank, QLD
Smart systems for water storage and irrigation[1]	✓	✓	Fisherman's Bend, VIC Aquarevo, VIC

* These options cannot currently be considered by the models used the Framework. Water detention devices refer to those that hold water for a period of time and then slowly release it for stormwater quality management (green walls, green roofs, grass swales, retention/detention basins). This is different to water retention / harvesting for storage. Smart systems for water storage and irrigation (smart tanks) optimise the management of rain tanks by holding and releasing water for both storage and flood mitigation outcomes. Both of these require more sophisticated modelling than is possible in the models used in the Framework.

1.4 Spatial scale of analysis

A strength of the Framework is that is can be applied at different urban scales (single sites, precincts, suburbs, towns, hydrological catchments and sub-catchments, and cities). However, different data, tools and models are typically needed at different scales. To answer the IRP4 research questions, the focus was on site- and precinct-scale evaluations.

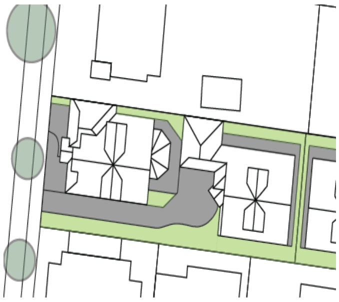
'Site' refers to an individual parcel of private land being developed for single or multiple residential dwellings, or an area of public land whose development is associated with urban densification or renewal such as a road or street corridor or park. Site-scale evaluation provides the detailed resolution needed to understand how the form and layout of the urban design and water servicing options influence performance criteria (see glossary).

'Precinct' refers to the scale at which infill is often planned and managed by local authorities, e.g. in 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 examines how performance is influenced by the extent and distribution of densification, WSUD in the public realm, and precinct-scale water servicing options.

The spatial scale of analysis depends on the purpose of the evaluation (see Table 5). The methods (models) and data used to evaluate performance are also influenced by the analysis scale (Table 5). For example, site-scale analysis can account for the site-specific characteristics of the built form (impervious factors of individual surfaces, household appliances, vegetation types, on-site water reuse/recycling) using details from architectural design plans. Precinct-scale analysis considers the general nature of the urban typologies/land uses present in the precinct and uses land use data, and typology-average design parameters.

The Framework enables site- and precinct-scale analyses to inform each other, such that findings from site-scale analysis of designs can inform infill development scenarios at the precinct scale, and vice versa. The approach is to first conduct site-scale analysis of individual design typologies to define typology-average design parameters. These can be used in precinct-scale analysis, to show how improved performance at the site scale might translate to the performance of the large urban area. As a further extension, parameters developed with the Framework at either site or precinct scale can be used for much larger scales of analysis using the CRCWSC's WSC Scenario Tool.

Table 5: Models and methods used in the Framework to evaluate performance at different spatial scales

	Site-scale	**Precinct-scale**
		
Methods for water analysis	IRP4's SUWMBA* tool (Moravej et al., in prep.), which estimates flows as follows: - rainfall/runoff model (adapted from MUSIC) using site-specific surface analyses from architectural drawings - indoor household water demand model, based on (Makki et al., 2015), using details of household demographics, appliance efficiency and use modes - outdoor water demand (irrigation) model based on evapotranspiration potential of the vegetation type - rainwater harvesting and use model.	Aquacycle tool (Mitchell et al., 2001), which estimates flow as follows: - a rainfall/runoff model, based on the AWBM model (Boughton, 1993), which is a three bucket model, partial area saturation over land flow model. Inputs to the model use typology-average fractions of roof, garden and pavement - indoor household water demand models using fixed per person water demand factors - outdoor water demand (irrigation) model based on average evapotranspiration values - detailed model of a wide range of water servicing options (RW and SW harvesting, greywater reuse, wastewater recycling, ASR) at different scales (site, cluster, catchment)
Methods for urban heat analysis	UMEP[2] model: a process-based QGIS plug-in that estimates urban climate processes.	Results from site-scale UMEP** analysis aggregated over the larger area based on distribution of typologies
Methods for architectural and urban space quality analysis	Urban Space Quality Rating Scheme is applied to dwelling interiors, outdoor private space and outdoor communal space.	Urban Space Quality Rating Scheme is applied to outdoor communal space and outdoor public space only (not dwelling interiors).

* SUWMBA = Site-scale Urban Water Mass Balance Assessment (see Section 3.3).
** UMEP = Urban Multi-scale Environmental Predictor (Lindberg et al., 2018).

1.5 Conceptual frameworks

The Framework is underpinned by the following concepts.

At the broadest level, this work can be framed by the *Sustainable Development Goals* (SDGs) that relate to water in the urban context. It sits at the intersection between SDG6, which aims to ensure available and sustainable management of water and sanitation for all, and SDG11 which aims to make cities and human settlements inclusive, safe, resilient and sustainable.

It is also framed by the umbrella concept of *integrated water management* (IWM) which ‘promotes the coordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (Global Water Partnership, 2000).

The *Water Sensitive Cities* (WSC) concept (Wong and Brown, 2009), along with the similar concepts of *Water Wise Cities* (IWA, 2016) and *Sponge Cities* (China), *Low Impact Development* (USA), *Nature Based Solutions* (EU), operationalises the above broad concepts for the urban context. A water sensitive city is defined as a place that serves as a water supply catchment (producing and using fit-for-purpose water supplies), provides and protects ecosystem services and a healthy natural environment, and consists of water sensitive communities where citizens make wise choices about water. Its goals, articulated in the Water Sensitive Cities Index (CRC WSC, 2018, Rogers et al., 2020), relate to governance, community capital, equity, adaptive infrastructure, quality urban spaces, water resource efficiency and productivity, and ecological health (see Appendix 1). This underpins the water sensitive performance we aim to promote for infill development, and hence evaluate with the Framework.

A new conceptual framework linking urban design variables to the water sensitive performance criteria by framing their cause and effects was developed for this research (Figure 2). The developed Framework frames the performance evaluation of urban designs. It provides a systematic structure for understanding how design variables influence performance. The performance criteria (on the right of Figure 2) were derived initially from an earlier CRCWSC review of international and national visions for good urban water management (Renouf et al., 2017a), but evolved iteratively over the course of the research to reflect performance attributes that are important to the industry partners. The influencing design variables (on the left of Figure 2) and their effects were compiled from known relationships reported in literature and industry knowledge. Indicators that are useful in describing the effects (in the centre of Figure 2) were compiled from prior urban water metabolism research and conceptual framing (Renouf et al., 2017a, Kenway et al., 2011), a review of other evaluation frameworks, and suggestions from the research team and industry partners.

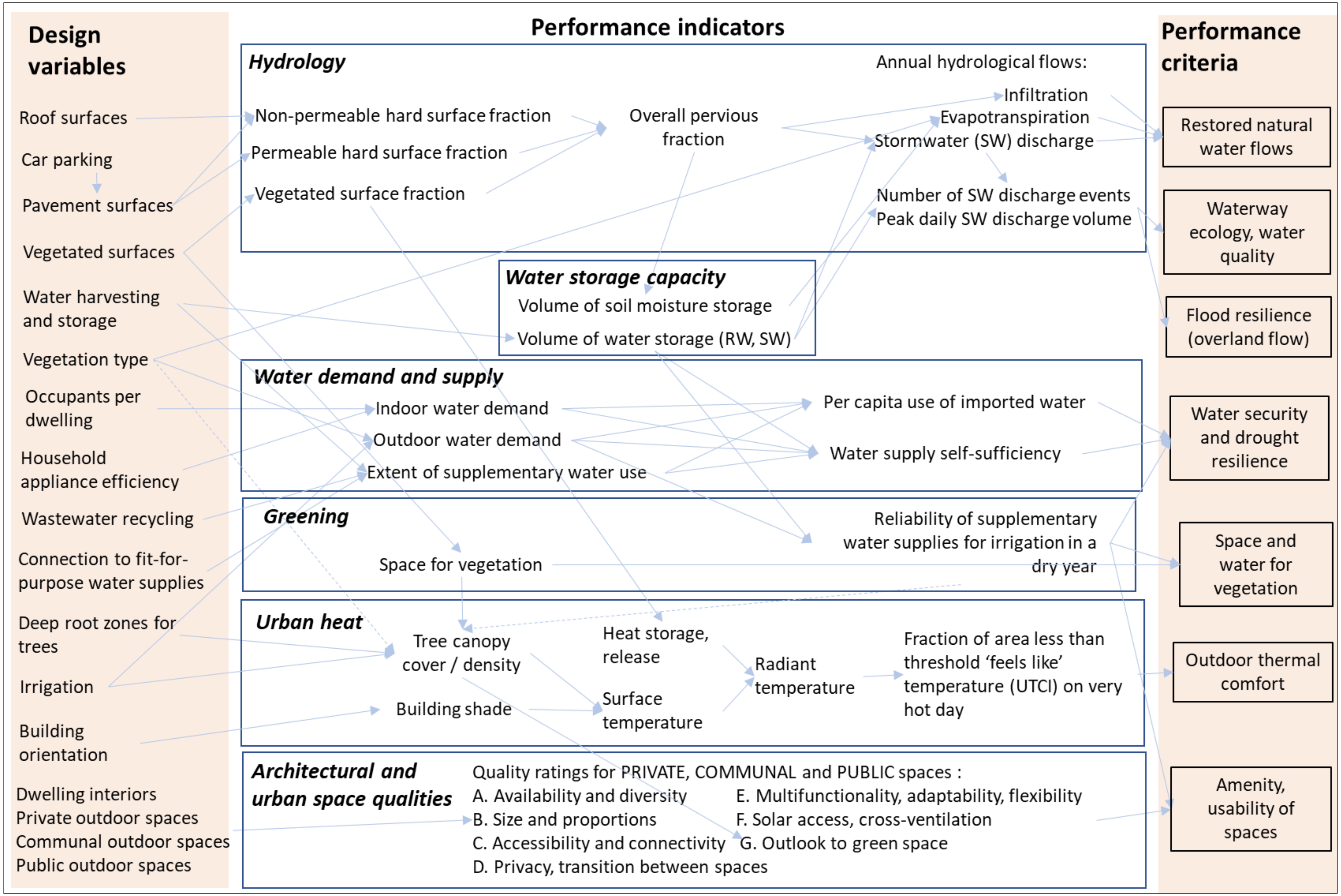


Figure 2: Cause and effect framework linking urban design parameters to water sensitive performance criteria

2 Performance principles, criteria and indicators

Performance principles lay the groundwork for the Framework by describing what good infill should aim to achieve, in terms of hydrology, water demand and supply, urban heat, and architectural and urban space quality (see Box 2). They evolved iteratively out of the lessons from IRP4's practical case studies (Renouf et al., 2020, London et al., 2020).

The intent is that the Framework offers indicators across a range of performance criteria, from which users can select those most relevant for the context and spatial scale of the analysis. For example, water storage to hold back overland flow will be important for flood-prone areas, urban heat will be important for hot, dry regions, water self-sufficiency will be important for areas with stressed water supplies, and ecological condition will be important where protecting natural water bodies is important. The selected set of indicators can be reported together on a multi-criteria chart (see Figure 2).

Performance indicators should ideally represent the performance criteria at or close to the end-point of the cause-and-effect chain (Figure 2), which are referred to as 'end-point' indicators. Other performance indicators that represent contributing factors along the cause-and-effect chain could also be used as proxies, or 'mid-point' indicators. End-point indicators can be difficult to measure because they may require modelling tools. If more easily measurable indicators are needed, then mid-point indicators may be useful. It is recognised that easily measurable performance indicators are important for supporting validation (Gabe et al., 2009). Performance principles and indicators are summarised below and in Table 6.

Box 2: Principles of water sensitive infill design

1. Infill design does not further adversely alter the natural hydrology (infiltration, evapotranspiration and stormwater discharge) of the development area, and ideally aims to mimic the hydrological water balance of a reference state[2]

    a. Maintenance/restoration of annual stormwater discharge volumes towards a reference state can contribute to protecting the ecological condition of waterways and water quality.[3]

    b. Maintenance/restoration of annual stormwater discharge volumes towards a reference state, coupled with 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 enable reduced reliance on imported water by 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[4] 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.

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[2] Reference state can be defined by the user. It can be a target state, the pre-urbanised state, or an altered pre-urbanised stat (where receiving water bodies adapted to 'urbanised' water balance and reached an equilibrium). See Section 2.1. for further clarification.
[3] See Section 2.1. for further clarification.
[4] Indoor heat is not captured in the Framework.

2.1. Water performance indicators

Hydrology

It is recognised that urbanisation significantly alters hydrological flows (i.e., stormwater runoff, infiltration and evapotranspiration), with subsequent impact on the morphology and ecology of receiving waters (Fletcher et al., 2013, Shuster et al., 2005, Klein, 1979, Walsh et al., 2004). Indicators should help to represent how much the natural hydrology is altered due to infill, as evolving water sensitive urban design guidelines are including objectives related to 'mimicking more natural flow regimes' (Government of South Australia, 2019).

Past research and existing evaluation frameworks commonly focused on how stormwater runoff is influenced by urbanisation. This Framework aims to consider all hydrological flows, evapotranspiration and infiltration as well as stormwater runoff, because they directly influence each other in the overall mass balance.

Indicators that the Framework can generate to represent changed hydrological flows and degree of restoration towards more natural flows are:

- **annual volumes** of infiltration, evapotranspiration and stormwater discharge (ML/year or mm/year)

- **fraction of rainfall** that evapotranspires, infiltrates or becomes runoff. It is a useful indicator because it relates to the climatic context, so that performance objectives can match to the regional condition.

- **naturalness** of infiltration, evapotranspiration and stormwater discharge, relative to a reference state, expressed as a ratio. The reference state could be the existing developed condition, the pre-urbanised condition (to represent the degree of 'naturalness') or a benchmark or target state. This work uses the pre-urbanised state as the reference case. It is expressed as a ratio of post-urbanised flows to pre-urbanised flows. A ratio >1 means the volume of the annual flow is larger than the reference state, and a ratio <1 means it is smaller. Using the pre-urbanised state as the reference state is not always useful in cases where the reference flows are zero or very low. For instance, in contexts where the pre-urbanised flow of stormwater or infiltration are low or zero (e.g. in very dry areas or soils that are naturally very impervious), the post-development flow will be divided by zero to generate an error.

Ecological function of urban waterways and water quality

Many factors influence the ecological function of urban waterways and water quality, and rating the performance of urban designs in this regard is complex and was not attempted within this Framework.

However, water quality deterioration in urban creeks and waterways is largely driven by changes in flow velocity, erosion and sedimentation. In temperate climates (e.g. Melbourne) there is evidence that the frequency of stormwater discharge is a strong predictor of the ecological condition of small streams (Walsh et al., 2005a, Walsh et al., 2009). In sub-tropical climates, McIntosh et al. (2013), citing Sheldon et al. (2012), found that the hydrological changes following urbanisation are not significant degrading factors in themselves, rather, the water quality variables, particularly temperature range, are more likely to be important.

Annual or monthly volumes of stormwater runoff may be only partially useful proxies for water quality. The frequency, volume, velocity of **peak flows** are likely to be more useful indicators. Quantifying the frequency, volume and velocity of **peak stormwater runoff flows** requires sub-daily rainfall-runoff modelling, which is not currently used in the water mass balance tools used by the Framework (IRP4's SUWMBA Tool, Aquacycle). A proxy indicator which avoids the need for sub-daily modelling is the **highest peak volume** of stormwater discharge during the assessed timeframe (e.g. a year).

This can be generated by the Aquacycle tool for precinct-scale analyses, but not by the SUWMBA tool for site-scale analysis[5]. This is similar to a proposed target in South Australia's new WSUD policy (Government of South Australia, 2019), which is to 'manage the rate of runoff discharged from the site so that it does not exceed the pre-urban development 1 year average recurrence interval (ARI) peak flow'.

Indicators that the Framework can generate as proxies of ecological function of urban waterways and water quality are:

- number of peak daily stormwater discharge events in a wet year
- volume of peak daily stormwater discharge events in a wet year.

If more direct indicators of the water quality impacts of stormwater runoff are required, pollutant loads can be estimated using tools such as the InSite tool for site scale (Organica Engineering, 2018) or MUSIC (eWater, 2017) for precinct-scale. The RESTORE tool (Beesley et al., 2019), developed by the CRCWSC could also be used in parallel with this Framework to rate the severity of stress (i.e. departure from reference) that adversely affects waterway ecosystem function (hydrology, geomorphology, connectivity, riparian, water quality, biota).

Water demand and supply

In relation to water supply the Framework distinguishes between water sourced from outside the urban system, referred to as 'imported' (dams, rivers, groundwater, etc.), and water sourced from within the urban system (harvested rainwater, harvested stormwater, recycled greywater, recycled wastewater, recharged aquifers). In relation to groundwater extraction, the Framework distinguishes between water extracted from groundwater resources for potable water schemes and private bores (which are considered to be imported water), and water extracted from shallow aquifers where there is evidence of managed aquifer recharge (which are considered to be sourced from inside the urban system) (Hoar, 2018).

Urban water efficiency can be achieved through a combination of (i) reducing water demand, and (ii) utilising supplementary water sourced from within the urban system (i.e. internalisation of supply) (Agudelo-Vera et al., 2013).

Indicators that the Framework can generate to represent efficient water demand and supply are:

- water supply self-sufficiency

- per capita use of imported water.

Greening

Outdoor water use for irrigation is often the first to be restricted during drought periods. However, the concept of water sensitivity promotes the importance of water for greening for cooling, amenity, even in hot, dry times when the need for cooling is most important. This challenges the need to reduce water demand for irrigation. The objective is to not constrain outdoor water use for irrigation, but instead to make supplementary water for irrigation. Therefore, in addition to the water demand and supply indicators (above) the Framework also includes

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[5] This requires an additional rainfall dataset that can be requested from BOM at a cost for each location. This may be acquired for the IRP4 case studies (Adelaide, Perth, Brisbane), but may be costly and hence not feasible, to have this additional data in the SUWMBA to support analysis for multiple regions. Similar datasets derived from satellite data (2000–2018) are available for free, but there will be a mismatch between the volumetric flows derived from BOM rainfall data and the peak flow volumes derived from the satellite data.

indicators for greening, where the emphasis is on making space for vegetation and trees, and optimising the availability of supplementary water to support vegetation, rather than constraining outdoor irrigation for efficiency.

The indicators are:

- fraction of area that can support vegetation
- fraction of area with deep root zone
- volumetric-reliability of supplementary water supplies for irrigation in a dry year. (We have adopted a volume-based reliability which is commensurate with the planning/screening function intended for this Framework. Time-base reliability indicators are also relevant and maybe even more applicable for analysis of detailed designs, e.g. the percentage of time in a dry year that demand can be met).

2.2. Urban heat indicators

The SOLWEIG module from the Urban Multi-scale Environmental Predictor (UMEP) model (Lindberg et al., 2018) was used to calculate mean radiant temperature (T_{mrt}) values for each point in the modelling domains. T_{mrt} is the average of radiant heat of an imaginary enclosure (a human body in this case). Using these values, a human thermal comfort index can be calculated for each point in the domains (at ground level, 1.5 m). The Universal Thermal Climate Index (UTCI) was calculated using the formula of Brode et al. (2009). UTCI gives equivalent temperatures of heat stress.

UMEP was chosen as the modelling tool for this project because of its ability to calculate T_{mrt}, a necessary parameter for calculating UTCI temperatures. UTCI quantifies the subjective experience and thermal stress of heat on persons in outdoor areas. Also, UMEP allows the scenario areas to be modelled at a micro-scale. Because micro-climates are highly variable and extremely localised, using a model with a lower resolution will capture only average effects across the wider area and does not show the effects of specific infrastructure changes.

The spatial results of these UTCI calculations were plotted for each area for each scenario. To best communicate the results (given the high variability and localisation as well as scenarios that contain differing layouts and are not directly comparable) the distributions of UTCI temperatures (heat stress categories) were calculated for each scenario. For the precinct-scale, the mix of typologies across the precinct was used to aggregate each distribution up to an overall distribution across the entire precinct.

The performance indicator for urban heat is the fraction of areas in the precinct that have a ‘feels like’ (UTCI equivalent) temperature on very hot summer day that is less than a certain threshold. For this case study the threshold temperature was taken to be 42ºC UTCI, where thermal stress crosses from the strong heat stress category to very strong heat stress.

2.3. Architectural and urban space quality indicators

Architectural and urban space quality relates to the extent to which space, both indoor and outdoor, is efficiently designed and organised for improved amenity, usability and flexibility. Current infill development practice demonstrates poor performance due to the low site usability and overall amenity (Thomson et al., 2017). Analysis of urban and architectural characteristics is an important part of performance evaluation. It is essentially a qualitative evaluation, even though many aspects of the design could be quantified.

Architectural and urban spaces aim to improve the liveability of higher density living without compromising on amenity and function. High quality infill typologies have internal and external spaces with the following features:

- appropriately sized, proportioned and positioned for the purpose

- accessible to all residents with appropriate transition between spaces, considering privacy and noise
- multifunctional and adaptable to different uses and living arrangements over time
- provide adequate access to sun, natural ventilation and outlook to greenery.

In the Framework, these features are defined following the four categories of architectural and urban spaces. The key to delivering good outcomes is through thoughtful spatial organisation across all of these categories.

1. Dwelling interiors

Dwelling amenity and function refer to interior design strategies for delivering quality higher density living, while leaving sufficient well-considered space for both private and communal outdoor areas. In general, building footprints are reduced and the number of floors increased, allowing more deep soil space to accommodate large canopy trees. Reduction in parking spaces from the usual two car bays to one per dwelling makes additional usable space available. Further space is gained by grouping parking on site, with open carports, grouped or individual, allowing for permeable paving areas.

Flexibility in internal spatial arrangements is crucial for increasing usability, supporting a range of occupancies and adapting to changing requirements over time. Flexible internal space is designed to support a diversity of uses, e.g. a room with separate services adjacent to a street could be used as a home office, games room or additional bedroom. Internal spatial amenity and functionality are enhanced by direct physical and visual connection to quality outdoor spaces, achieved by designing living areas adjacent to courtyards, terraces and other outdoor areas. Position and orientation of a dwelling on the site will improve site usability, thermal comfort and energy efficiency. Facing windows to the north and north east will provide favourable solar orientation, and windows in two walls of a room allow good cross-ventilation. Adequate shading on the east and west is achieved with well positioned greenery or by using a variety of shading systems.

2. Outdoor private space

Quality outdoor private space refers to courtyards, terraces, rooftop terraces, balconies and similar, providing good solar access, natural ventilation, outlook and space for large canopy trees. High quality outdoor private space is flexible and adaptable, designed to facilitate a variety of uses. Multiple uses are supported when such spaces are considered in terms of their length and width, and in relation to the height of surrounding walls with their effect on sun and ventilation throughout the year.

Courtyards adjacent to living and dining areas may be used as an extended living room, guest entertainment area, garden, and transitionary space between different house zones. An open carport may also be used as an outdoor living space. Landscaping solutions, including well-positioned large canopy shade trees, pergolas and trellises offer shade for improved thermal comfort, and can provide sound and visual privacy barriers when private areas face communal and public spaces.

3. Outdoor communal space

Communal space refers to shared areas. Consideration of shared facilities and quality communal outdoor space becomes significant in higher density infill development. To increase overall site amenity and reduce individual water and energy demands necessary for upkeep, shared BBQs, vegetable gardens, play areas and grouped car and bicycle parking areas may be included. Efficient design strategies, including compact design and organisation of buildings on site, allow provision of quality communal spaces that are functional and accessible to all residents, and adaptable to multiple uses. Certain common spaces, when well-designed, could serve multiple purposes; e.g. shared driveways may also be used for play and other recreational activities. To maintain a sense of privacy and individuality, while ensuring adequate sound and visual barriers, a balanced transition between private and communal spaces is important. Adequate setbacks, positioning of balconies and windows, and choice of screens and fences will help minimise overlooking from more activated street frontages.

4. **Outdoor public space**

Provision of and access to quality outdoor public spaces, such as parks, reserves and plazas, becomes essential at higher densities with more compact living. Considered design strategies for residential precincts, with a range of suitable dwelling typologies allowing a diversity of household types, can complement and encourage use of public open spaces. Higher densities and mixed-use typologies, with home/work options, can generate additional services and diversity of functions over time. Public spaces designed to allow different activities maximise their use. For example, 'slow' streets may be used as access to residences, for bicycle connectivity and, as linear parks with tree canopy cover, allowing communal recreational activities in a pleasant and comfortable environment able to be occupied at different times of the day and year. Pedestrian and cyclist-friendly infrastructure (including designated paths, bicycle racks, and rest and recreational areas) reduce car dependence while encouraging connectivity and use of public open spaces. Higher performing design strategies may be included in public spaces allowing precinct-scale solutions to stormwater and reduction of urban heat, benefitting whole precincts and also individual lots. This could include a precinct-scale water storage, recycling and reuse facility; or a blue-green network that incorporates water elements in landscaping such as retention ponds and green swales.

Outdoor space is important for stormwater and urban heat management. Large building footprints and low-rise developments result in residual and often unusable open spaces, with inadequate tree canopy cover and cross-ventilation, and poor solar access. At the other extreme, larger outdoor spaces, if not planned well, may result in increased water and energy demand for irrigation and maintenance. One typical example would be large outdoor areas covered with lawn requiring high upkeep demands while doing little to reduce urban heat, especially in drier and hotter climates. The effective performance of available outdoor space is an outcome of design strategies increasing its usability and amenity. The overall quality of both indoor and outdoor spaces depends on their functionality and usability, which in turn depend on spatial organisation and design features that afford favourable use.

2.4. Other performance aspects

A range of other performance aspects were identified and discussed through the IPR4 project, but, were outside the scope able to be considered at the time:

- **Affordability, marketability and cost-effectiveness** of infill designs are important for developers and buyers, who ultimately need to be convinced of the practicalities of alternative infill designs. While these aspects are not specifically assessed by the Framework, affordability and marketability can be accounted for by selecting evaluation designs that have been pre-tested for both criteria by stakeholders. This approach was used in the case studies (London et al., 2020, Renouf et al., 2020). In relation to cost-effectiveness, the design parameters defined as part of the evaluation process can be used to calculate capital and operating costs in a parallel benefit–cost analysis. Costings of a representative sample of IRP4 typologies versus BAU could be used to validate a generic statement such as 'alternative designs can achieve better liveability and sustainability outcomes with minor additional costs, between 0% to 5%'. See an example of an apartment design policy testing and economic study issued by WA Department of Planning Lands and Heritage. The CRCWSC's Integrated Research Project 2 (IRP2): Comprehensive economic evaluation framework, has developed a range of economic analysis tools and resources for water sensitive cities; see INFFEWS.

- **Energy efficiency** is an important consideration, which the Framework does not currently capture. Harvesting, recycling and supplying supplementary water supplies requires energy (for pumping and treatment), and energy use and associated greenhouse gas emissions can be unintended trade-offs.

Similarly, enhancing vegetation in urban areas for cooling and amenity has direct energy requirements for mowing grass, clearing leaf litter and trimming trees. WSUD can also support reduced use of air conditioners by providing shade. However, this was not considered here due largely to the lack of quantitative models and science necessary. In addition, the Framework does not capture the energy requirements for heating, ventilation and air conditioning. The energy efficiency performance criteria should be added to the Framework in future iterations. Generally, water sensitive design could be expected to require less energy for water supply (given its local sourcing), and also reduce space cooling and ventilation due to the influence of water sensitive practices. However, this remains to be quantified and local context and design (particularly infrastructure) could have significant influence.

Table 6: Performance principles, criteria and indicators

Aspect	Principle	Performance criteria		Performance indicators
Hydrology	1. Infill design does not further adversely alter the reference state hydrology (infiltration, evapotranspiration and stormwater discharge) of the development area, and ideally aims to mimic the reference state hydrological water balance	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 harvesting, storing and using 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*
	a. Restoring stormwater discharge volumes towards a reference state can contribute to protecting the ecological condition of waterways and water quality	Waterway and wetland ecology, water quality	Peak daily stormwater discharges 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*
	b. Restoring stormwater discharge volumes towards a reference state, coupled with capacity for water storage (see principle 2), can contribute to reduced flood risk	Flood resilience (overland flow)		
Water storage capacity	2. Infill designs incorporate water storages to facilitate the availability of supplementary water supply, and slow/retain/detain runoff for reducing flooding		Water storage capacity (in tanks, basins, etc.) within the infill development is optimised	Volume of on-site constructed water storage, relative to optimal storage volume
	3. Infill designs facilitate soil moisture storage through permeable surfaces that promote infiltration (see principle 1).		Soil moisture storage capacity is maximised through permeability	Volume of soil moisture storage capacity, relative to reference state*

Aspect	Principle	Performance criteria		Performance indicators
Water demand and supply	4. Infill designs enable reduced reliance on imported water by facilitating the use of supplementary water supplies by making space for water storage and/or connections to supplementary supplies	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 and 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. Infill designs facilitate the irrigation of vegetated areas using supplementary water supplies, to enable greening for cooling and amenity**	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. Infill designs include space and deep root zones for vegetation and large trees, to enable greening for cooling and amenity		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. Infill designs enable passive mitigation of outdoor urban heat through building and tree canopy shading	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 hot day
Architectural and urban space qualities	8. Dwellings and urban spaces are efficiently designed and equipped to enable improved amenity, usability and flexibility	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	See Section 3.5

* Reference state can be defined by the user. It can be a target state, the pre-urbanised state, or an altered pre-urbanised stat (where receiving water bodies adapted to 'urbanised' water balance and reached an equilibrium). For example, hydrological flows of the 'pre-urbanised state' are the flows expected for the site in question if there was no development present. See Section 2.1 for further clarification.

** The objective is to not constrain outdoor water use for irrigation, but instead to optimise the harvesting and use of supplementary water for irrigation.

*** Reliability (and security) can be defined as time-based reliability and/or volume-based reliability and consider either centralised and or decentralised sources (see also Hashimoto et al. (1982)). The above definitions are commensurate with planning-level analysis. Additional details will be required for detailed designs.

3 Methods

The methods used in the Framework are summarised in Figure 3, and described in subsequent sections.

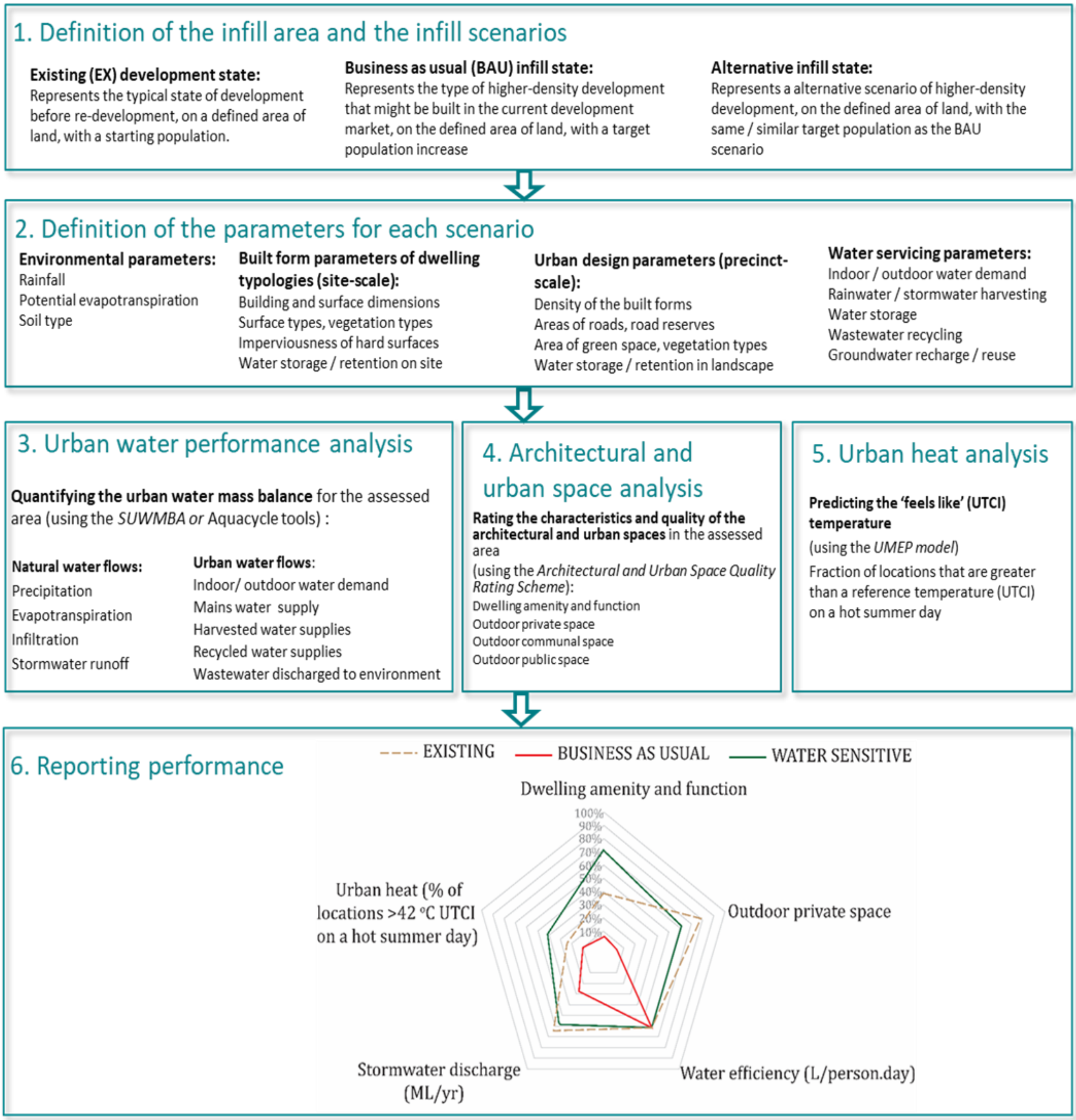


Figure 3: Components of the Infill Performance Evaluation Framework

The evaluation can be performed in multiple ways (e.g. using detailed models or by using customised tools (e.g. Aquacycle, SOLWEIG; see Appendix 2). While developing specific tools was outside the scope of this research project, we did create a site-scale excel sheet to support water mass balance analysis which is at the core of the method. Two case studies (Salisbury and Knutsford) demonstrate how to use various tools to populate the Framework and influence designs. The Framework and steps which can be followed and performed in multiple platforms suited to the context and situation of individual sites, and pending the scale (area) of the system in question. IRP4's final report provides details about these tools.

3.1. Definition of the infill area and infill scenarios

Because infill development is a process of change, performance evaluation is most useful when it compares the impacts before and after infill. A set of scenarios are defined representing the existing development state before infill (EX), and after infill for one or more development scenarios. For example, business as usual (BAU) and water sensitive (WS) infill may be the options being compared. The scenarios are defined in terms of the size of the infill area and population accommodated in the area.

The performance of the infill options (BAU, WS) is considered relative to the existing (EX) development state before infill. This approach illustrates how the design choices can influence and mitigate the impacts of infill development. For effective comparison, scenarios being compared (e.g. BAU and WS) should be approximately equivalent in terms of the functions they provide. We define basic functionality in terms of the number of people that can be accommodated in the assessed area. Ideally, scenarios being compared should also have approximately equivalent dwellings or populations. However, if this is not possible or desirable, then these differences should be considered when interpreting the performance results.

The population of infill scenarios can be estimated from the assumed dwelling density or yield (dwellings/hectare) and the assumed dwelling occupancy (number of people per dwelling). There is considerable uncertainty in the dwelling occupancy. Residential dwellings are designed around the number of bedrooms, from which a likely occupancy can be estimated (1 bedroom = 2 occupants, 2 bedrooms = 3 occupants, 3 bedroom = 4 occupants). However, actual occupancy can differ, with a tendency for lower than design occupancy in Australia. Therefore, it is recommended that dwelling occupancy be based on ABS statistics of numbers of people per household for the study area.

Some of the performance indicators (for hydrology) are reported relative to a reference state. The reference state could be the pre-urbanised (PRE) condition to represent the 'natural' condition, or it could be a benchmark or target. Therefore, the performance of the reference state will need to be evaluated also.

3.2. Definition of parameters for each scenario

The Framework aims to assess a range of alternative designs in various climatic and soil conditions. Therefore, the ability to define different design variables and climatic variables is an important feature (Table 7). The parameters for these variables are the inputs to the models the Framework uses (see Table 5). These models have the following capacity for modelling those variables:

- Simulation of natural hydrological flows using a rainfall-runoff model using parameters related to surface types and imperviousness, and climate and soil, etc. Currently, the Framework cannot model water sensitive urban design features, such as green walls, green roofs, grass swales, retention/detention basins.
- Simulation of indoor water demand, using parameters of occupancy rates, occupant demographics, and the types of appliances and modes of operation
- Simulation of irrigation water demand, based on extent and type of vegetation, and climate and soil
- Simulation of rainwater/stormwater harvesting yields, using parameter of storage volume, rainfall, and uses. Using water storage for flood retention is only partially considered, by virtue of storage capacity.

Currently, retention/detention basins specifically designed to modulate stormwater flows and manage water quality cannot be modelled.

- Simulation of how alternative water sources (rainwater, stormwater, greywater, wastewater, recharged aquifer water) are matched to different water demands (only in Aquacycle and similar models and tools). Currently, smart tanks cannot be modelled, except by using appropriate weather-based criteria for emptying tanks.
- Simulation of urban thermal comfort, based on the built form, amount of shade, air flow, etc.

Table 7: Variables that can be modelled by the Framework

Aspect	Variables
Occupancy	Dwelling occupancy (people per dwelling)
Environmental	Rainfall Soil type Potential evapotranspiration Slope (not modelled in this work)
Built form	**Influencing hydrology** Areas and imperviousness of built surfaces (roofs, driveways, paths, roads, verges/nature strips, car parks) Areas of vegetative cover Type of vegetation (grass, shrubs, trees) Water harvesting (rainwater/stormwater) **Influencing architectural outdoor space quality** Area of outdoor space for private use Connection between indoor areas and private outdoor space Functionality, usability and amenity of outdoor private space Areas of outdoor communal spaces for social engagement Functionality, usability and amenity of communal spaces Areas of outdoor public spaces for community connectivity Functionality, usability and amenity of public spaces **Influencing urban heat** Tree canopy cover (leaf area index) Sky view factor (shade from trees/buildings) Area of vegetated surfaces (irrigated) Average albedos of wall and ground surfaces (influencing reflected energy)[6] Area of impervious surfaces (including roofs) Airflow, wind mixing, heat trapping Longwave trapping (at night under canopy) Cooling plumes off water bodies
Water demand	**Influencing indoor water demand (residential dwellings only)** Design occupancy Demographics of occupants Household income Appliances efficiency including type, capacity, mode of operation **Influencing outdoor irrigation water demand** Area irrigated Type of vegetation **Influencing water use** Extent rainwater and stormwater harvest Extent of greywater reuse or wastewater recycling Storage volumes Uses for supplementary water

[6] Type of building material can be accounted for by virtue of the amount of reflected energy generated, but not their energy storage capacity. Other anthropogenic heat sources (air-conditioner compressors, traffic etc.) can’t be modelled.

3.3 Urban water mass balance and water performance analysis

An urban water mass balance helps to quantify the water performance of urban areas. The water balance concept (as depicted in Figure 4) shows how water flows into, through and out of urban areas, how urbanisation alters those flows, and how they need to be changed to mimic a more natural hydrological water balance. An urban water mass balance quantifies the volumes of the flows in Figure 4(Hoban and Wong, 2006). Urban water mass balance has long been advocated as the key method for studying water in the urban landscape (McPherson, 1973). It has been used in urban metabolism studies to generate the water flow data needed to quantify water performance indicators (Kenway et al., 2011, Renouf et al., 2016, Renouf et al., 2017b). It was adapted in the IRP4 project to quantify the water performance of infill development and is operationalised in the SUWMBA Tool and user manual (Moravej et al., in prep., Moravej et al., 2020) for site-scale analysis, and the Aquacycle tool (Mitchell et al., 2001, Mitchell, 2005) for precinct-scale analysis.

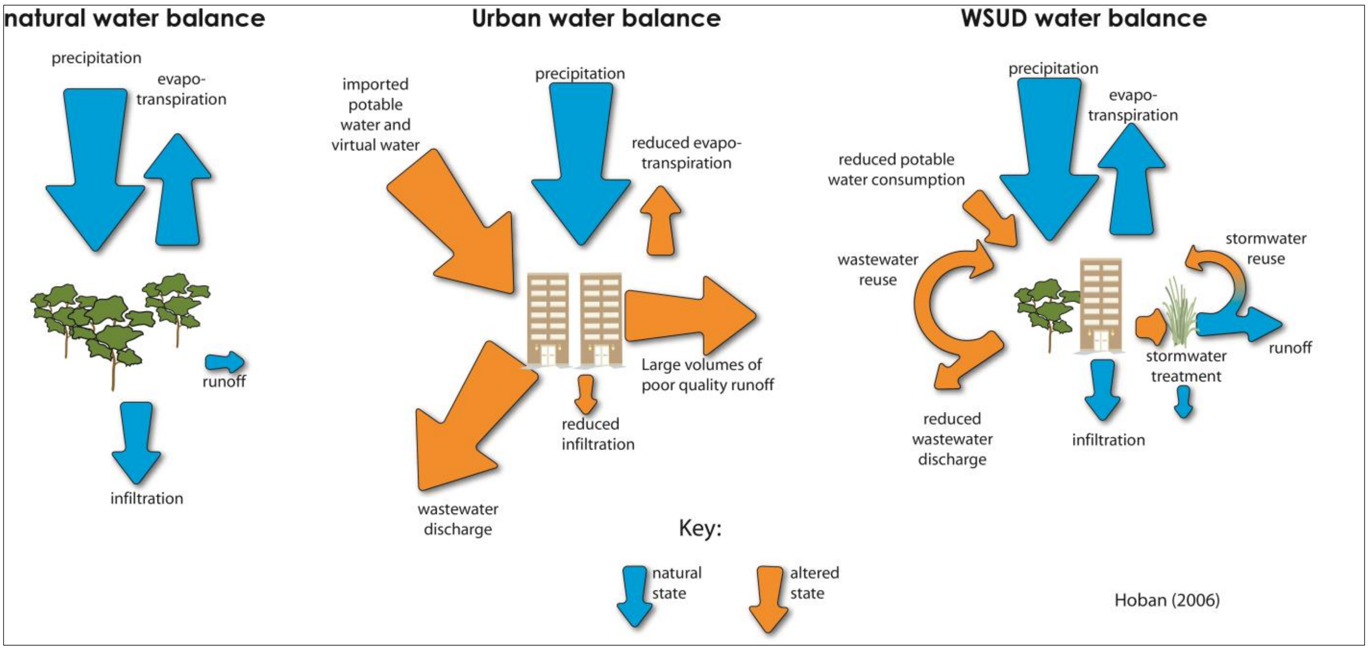


Figure 4: Urban water mass balance

Figure 5 depicts how Framework conceptualises the urban water mass balance. Features of this approach, which are different to other methods, are summarised below. Appendix 2 describes the differences between the water balance tools used in this research and other tools.

- Water flows are estimated for a defined urban area, a three-dimensional physical area. The urban system boundary is defined to delineate the exchanges of water between the urban system and the environment.
- Water flows are defined to align with the urban metabolism conceptual framework, which differentiates water from within the urban system and from outside the urban system (imported water).
- Water flows are defined in a way that can be used to derive the desired water performance indicators.
- Water flows are defined to represent conditions in different parts of Australia. For example, it captures the recharge of treated stormwater and wastewater to aquifer storages for subsequent use and interactions between the urban system and aquifer systems in contexts with high groundwater tables.
- Methods for estimating water flows are parameterised so they can be estimated for varying design variables.

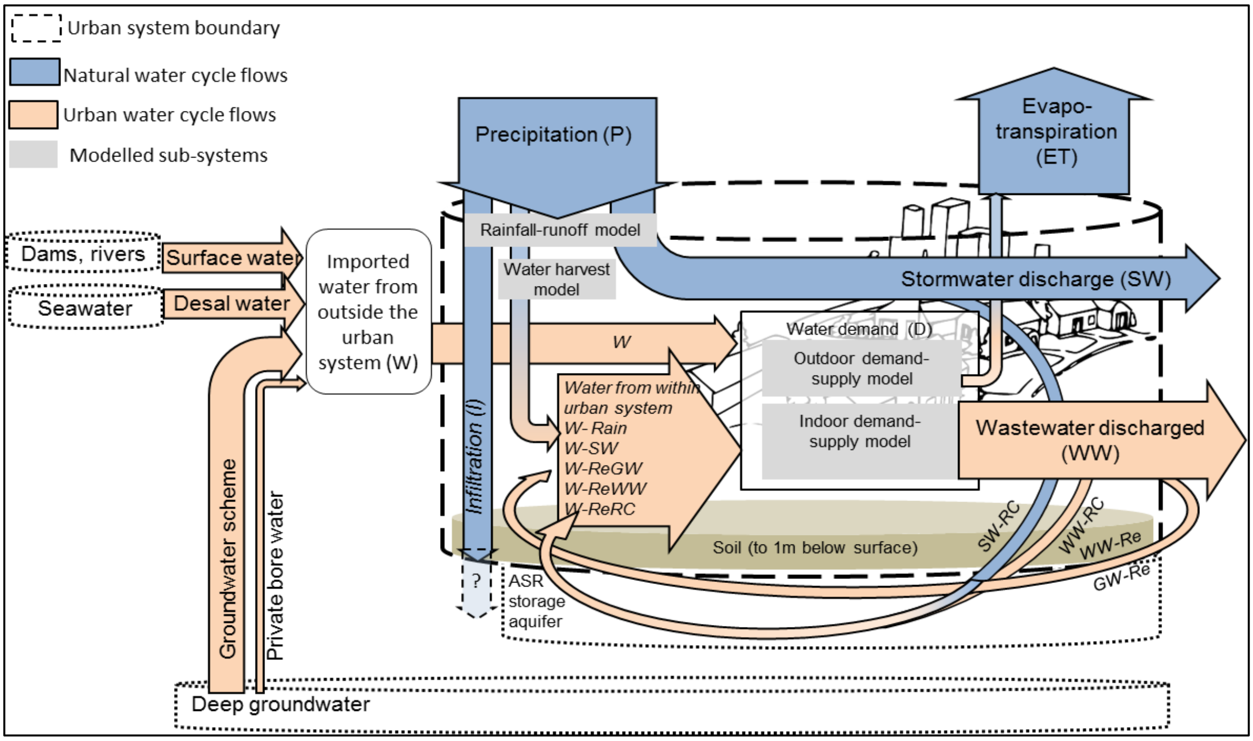


Figure 5: Urban water mass balance – "urban system" components, boundary and water flows

Flows in the natural water cycle:

P	= precipitation (minus harvested rainwater and stormwater)
I	= infiltration through 1m soil profile
ET	= evapotranspiration
SW	= stormwater discharged from the urban system
ΔS	= change in storage (soil moisture and stored water)

Flows in the urban water cycle:

D	= water demand
W	= water imported from outside the urban system (mains water)
W-Rain	= water from rainwater harvesting
W-SW	= water from stormwater harvesting
W-ReGW	= water from recycled / reused greywater
W-ReWW	= water from recycled wastewater
W-ReRC	= water recovered from recharged aquifer storage
SW-RC	= stormwater recharged to storage aquifer
SW	= stormwater discharged from the urban system
GW-Re	= greywater collected for recycling / reuse in the urban system
WW-Re	= wastewater collected for recycling / reuse in the urban system
WW-RC	= wastewater recharged to storage aquifer
WW	= wastewater (including greywater) discharged from the urban system

Water mass balance:

Sum of water inflows	= Sum of water outflows + change in storage
P+W+W-Rain+W-SW+W-ReGW+W-ReWW+W-ReRC	= I+ET+(SW-RC+SW)+(GW-Re+WW-Re+WW-RC+WW)+ΔS

Site-scale water balance analysis

The SUWMBA Tool developed for the IRP4 project is suited to site-scale water performance analysis because it can examine details of built form at high resolution and some site-scale water servicing options (rainwater harvesting). The urban water flows calculated by the SUWMBA Tool are converted directly into water performance indicators within the tool. Other urban water mass balance tools suited to site scale, for example InSite (WaterSensitiveSA, 2018) can also be used to generate a water balance from which the performance indicators can be generated. However, some conversions may be needed to align with how they are used in this Framework.

The SUWMBA Tool employs the following methods to estimate flows in the natural water cycle and flows in the anthropogenic water cycle:

- Indoor demand–supply is estimated using residential indoor water end-use demand forecasting algorithms developed by Makki et al. (2015), and based on observed household predictors of indoor water use in south east Queensland (n=210 households with 557 occupants). Since the influence of these predictors is fairly consistent across Australia, these algorithms were assumed to be transferable to other regions.

- Infiltration, evapotranspiration and stormwater discharge are estimated using the rainfall-runoff algorithm adapted from the MUSIC surface runoff model (eWater, 2017). This algorithm was used for three reasons. First, MUSIC is a widely used model in Australia. Its algorithm is trusted by most professionals and it requires well-known inputs which reduces ambiguity. In addition, its parameters have been calibrated for different locations (i.e. most Australian cities except for Perth) and can be readily used. Second, the algorithm allows for a landscape perspective rather than an infrastructure perspective (e.g. SWMM, MIKE URBAN). Because MUSIC does not account well for surface water–groundwater interaction, it is not suitable for analysis in areas impacted by shallow or perched groundwater aquifers (such as Perth). Finally, the simple representation of hydrological processes enables integrating natural with anthropogenic flows.

- The inputs to this algorithm are the surface types and areas present in the urban area being assessed, and their imperviousness fractions. Other hydrological parameters needed for the analysis are set within the tool based on the selected climate and soil context. Flows are estimated using a daily time step, and can be aggregated to appropriate time-steps (e.g. annual flows suggested but higher resolution possible) to determine the indicators presented in Table 6. Key assumptions are:

    - Hard surfaces are assumed to have an imperviousness factor of 0.95.

    - Permeable paving is assumed to have an imperviousness factor of 0.4.

    - Soil beneath an impervious surface is assumed to be impervious, and water infiltrating under pervious surfaces is assumed to not migrate horizontally into the soil under impervious surfaces.

    - Effective imperviousness is interpreted differently in this model, which can be more interesting in estimating peak flows rather than annual flows. Effective impervious surfaces respond much faster to precipitation than non-effective surfaces due to longer paths to reach the drainage system. So effective impervious surfaces are the main contributor to peak flows. However, because annual stormwater runoff is being considered here, regardless of when it was produced, stormwater runoff from the effective impervious surfaces (fast response) and non-effective impervious and pervious surfaces (slow response) are totalled together.

    - Base flow is not accounted for, and so all water flowing through the soil profile to 1 m below the surface (the basis of the urban system boundary) is counted as ‘infiltration’ and does not subsequently flow to the surface to join stormwater runoff.

- For site-scale evaluations, 10% leakage and consumptive use of water was assumed, which means the wastewater generated is 90% of supplied water in case where there is no irrigation, unless defined otherwise by the user (i.e. a return flow ratio of 90%). When there is irrigation, wastewater generation will be even, because the water directed to irrigation will be lost to evapotranspiration, not to the wastewater system.

- Irrigation demand is estimated using a model based on vegetation characteristics, and assuming irrigation is triggered when soil moisture drops to below the field capacity of the soil profile (using local potential evapotranspiration and rainfall data). The irrigation goal in the model is to keep soil moisture at a fraction of field capacity called irrigation-trigger-factor determined as an input. This means that irrigation is assumed to be needed to keep soil moisture at a certain level and to prevent plants to start to wilt. Irrigation is maximised when the irrigation-trigger-factor is set to 1. This would keep soil moisture high for high evapotranspiration and urban cooling but gives an unrealistic picture of irrigation demand when wanting to represent a typical existing condition.

- Rainwater (and stormwater) harvesting and use are estimated using a continuous water mass balance model for rainwater tanks developed by Fewkes and Butler (2000).

- The assignment of fit-for-purpose water supplies (rainwater, stormwater, greywater, etc.) to various water uses is modelled using an approach similar to (Zeisl et al., 2018).

Current urban water mass balance methods do not adequately account for estimate exchanges between urban systems and groundwater (Renouf et al., 2017b). This becomes a problem in cities and communities that are groundwater dependent, such as Perth, because it is difficult to represent the performance of water sensitive interventions that influence groundwater exchanges. It is very difficult to adequately account for interchanges between the urban system and groundwater at the small urban scales considered in this work (site scale and precinct scale). This is because groundwater systems such as those in Perth need to be observed at the regional scale to account for the horizontal movements of groundwater over the groundwater catchment, which is the approach used in Perth's main hydrological mode (PRAMS – Perth Regional Aquifer Modelling System).

A Masters student project conducted in parallel with the IRP4 project (Hoar, 2018) investigated how the hydrological model and mass balance approach used in the SUWMBA Tool could be adapted to better account for the water exchanges between the urban areas and the groundwater systems in the Perth context. The identified solution was to redefine the urban system boundary to account for water exchanges between the urban system and both the shallow groundwater (unconfined aquifer) and deep groundwater (confined aquifer) as shown in Figure 5:

- infiltration of water through the soil profile into the shallow groundwater
- abstraction of water from the shallow groundwater, such as in aquifer storage and recovery (ASR) schemes or private groundwater bores
- abstraction of water from the deep groundwater, such as used in mains water supply
- infiltration of water from the urban system into deep groundwater was not considered.

Precinct-scale water balance analysis

The Aquacycle tool (Mitchell, 2005) is suited to water performance analysis at the precinct scale because it can perform the more complex computations required for examining precinct-scale water harvesting and recycling and transfers of water between different parts of an urban precinct. The model defines the nature of the built form but not in as much detail.

Aquacycle is a daily urban water balance model for simulating flows in the natural water cycle and the anthropogenic water cycle, and is especially suited to investigating supplementary water sources (rain and stormwater harvesting, and grey and wastewater recycling). The calibration factors used in Aquacycle assume no base flow, so 'base flow recession constant (ratio)' is set to zero.

City-scale water balance analysis

The CRCWSC's WSC Scenario Tool (CRCWSC, 2020) is suited to water performance analysis at the city scale, because it can extrapolate urban design variables over very large urban scales.

For all analysis scales, the water balance data are used to generate the water performance indicators using the algorithms in Table 8.

Table 8: Derivation of water performance indicators from water mass balance

Aspect	Performance indicator	Equation
Hydrology	Evapotranspiration naturalness	$\frac{ET_{\text{Post-urbanised}}}{ET_{\text{Pre-urbanised}}}$
	Infiltration naturalness	$\frac{I_{\text{Post-urbanised}}}{I_{\text{Pre-urbanised}}}$
	Stormwater naturalness	$\frac{SW_{\text{Post-urbanised}}}{SW_{\text{Pre-urbanised}}}$
	Highest peak stormwater runoff naturalness	$\frac{\max\left(SW_{\text{Post-urbanised}}\right)}{\max\left(SW_{\text{Pre-urbanised}}\right)}$
	Evapotranspiration fraction of precipitation	ET/P
	Infiltration fraction of precipitation	I/P
	Stormwater fraction of precipitation	SW/P
Storage	Volume of on-site constructed water storage	$\frac{\sum_q V_{\max}^q}{V^{opt}}$
	Volume of soil moisture storage capacity	$\frac{SMSC_{\text{post-urbanised}}}{SMSC_{\text{pre-urbanised}}}$
Water demand and supply	Per capita use of imported water	$\frac{W}{Pop}$
	Self-sufficiency	$\frac{W_{Rain}+W_{SW}+W_{ReGW}+W_{ReWW}}{D}$
Greening	Volumetric-based reliability of supplementary water supplies in a dry year	$\vartheta = 1 - \frac{\sum_{t\in f} D_t - \sum_{t\in f} D_t^*}{\sum_{t\in T} D_t}$

Where, post- and pre-urbanised represents developed and pre-urbanised conditions, respectively.

$V_{\max}^q$ = storage capacity (tank size) of store *q.* V^{opt} = optimal storage. *SMSC* = soil moisture store capacity. *Pop* = total number of people within urban system boundary. D = demand. *f* = number of failures in the dry year. T = total number of time steps in the dry year. D_t^* = supplied demand at *t* time step.

3.4 Urban heat and heat stress

In urban areas, replacing pervious and vegetated surfaces with impervious surfaces, reducing shading and tree canopies, and reducing amounts of available water can increase urban heat and reduce human thermal comfort. Weighing the heat impact of different scenarios of urban redesign is best assessed with modelling. Many types of temperatures can be modelled and calculated to show the thermal performance of different designs, such as air temperature and surface temperatures. The models within CRCWSC's Scenario Tool use is approach to report land surface and air temperatures. Air temperatures will only show small variations across wide areas which makes this metric more suitable for showing average differences between scenarios. Surface temperatures can show detailed spatial variability but provide only one component of heat stress.

To assess the impacts on human health, a thermal comfort index best captures the subjective experience and thermal stress of heat on a person in an outdoor area. One of these indexes, the UTCI is calculated from the combination of air temperature, wind speed, humidity levels, and mean radiant temperature (T_{mrt}), the summation of heat surrounding a human form from nearby surfaces and solar exposure, using the formula of Brode et al. (2009). This results in a categorised equivalent temperature derived from a thermo-physiological model coupled with a behavioural clothing mode (

Figure 6). More simply, UTCI values represent the equivalent temperatures of heat stress, which we refer to in this framework as a 'feels like' temperature.

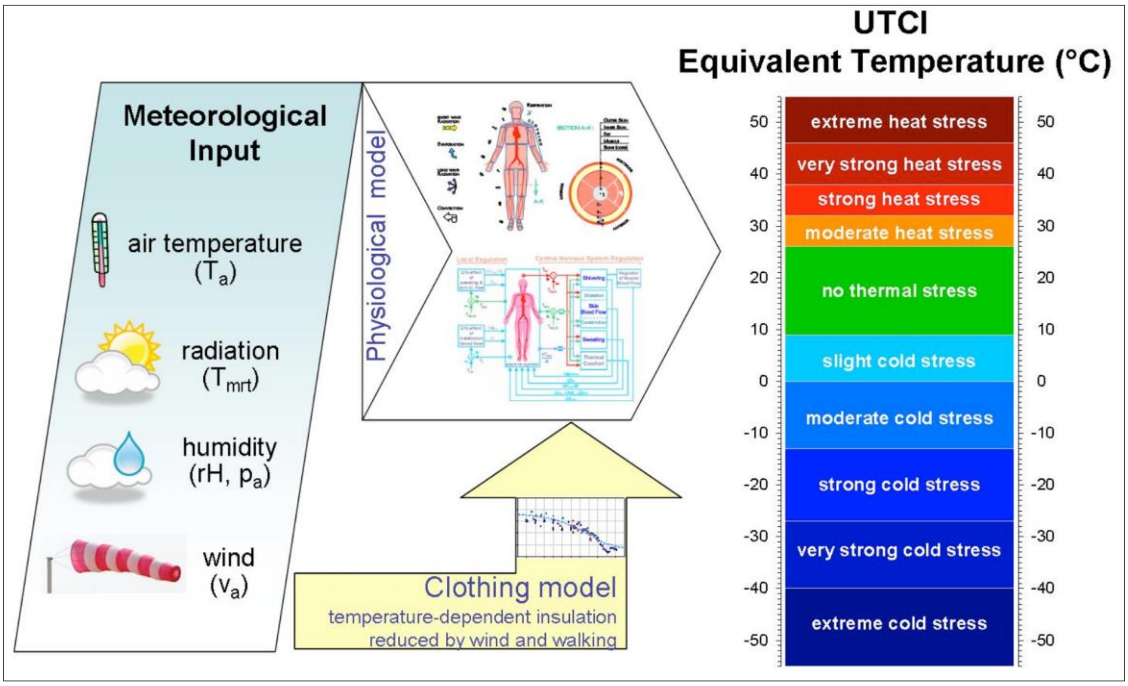


Figure 6: Universal Thermal Climate Index (UTCI) from Brode et al. (2011)

A case study of Salisbury (in Adelaide) demonstrates how to apply heat modelling using UTCI to the Framework. We used the SOLWEIG module from the Urban Multi-scale Environmental Predictor (UMEP) model (Lindberg et al., 2018), performed at the site-scale for each of the dwelling and street typology site plans (refer to figure A11 in the appendix of the Salisbury case study final report) on a typical hot summer day (2:00 pm, February 12 2004). This provides heat maps of T_{mrt} for each modelled point in site-scale dwelling typologies. UTCI values can now be calculated for each point using the modelled T_{mrt} values and the forcing values used to drive the model (Table 9).

Table 9. Forcing values for scenario modelling

Parameter	Value
Air temperature	37.4ºC
Relative humidity	29.6%
Global radiation	833.0 W/m^2
Di_use radiation	92.0 W/m^2
Direct radiation	925.0 W/m^2
Wind speed	2.5 m/s

The visual representations of heat outcomes in the site-scale heat maps can be translated into quantitative distributions of the UTCI (a ‘feels like’) temperatures for each typology. Additionally, because UTCI values are highly localised, distributions of temperatures across site-scale typologies can be aggregated up to a wider precinct scale based on the distribution and quantity of the mix of typologies for each development scenario. This distribution plots the number of locations within the precinct that can be expected to have UTCI temperatures in each of the heat stress ranges shown in

Figure . The performance indicator for urban heat is the fraction of areas in the precinct that have a ‘feels like’ (UTCI equivalent) temperature on hot summer day that is less than a certain threshold. For the case studies which applied this method (see Salisbury and Knutsford case studies), the threshold temperature was 42ºC UTCI.

The modelling within this Framework (and of the use of vegetation in urban cooling in general) assumes the vegetation of the garden areas (grass and trees) are in good health and have sufficient irrigation. Without healthy vegetation, sparse tree canopies and struggling lawns will not provide the shading benefits and cooling benefits reported in the performance results. The analysis aimed to capture the heat performance of the different infill designs and that irrigation indirectly contributes to cooling by supporting vegetation vigour.

Irrigation can also provide an additional direct cooling effect at the microscale through heat exchange with the air when water is sprinkled or misted above ground. Research shows sprinkled irrigation can reduce air temperature by 2˚C with applications of 20L/m^2/day (Broadbent et al., 2017), and that watering the roads during a heatwave can deliver a substantial cooling benefit (Hendel et al., 2014). However, direct cooling strategies are independent of the urban form, reflecting how the urban design scenario is maintained rather than how it is designed. Further, irrigation is commonly applied subsurface to reduce evaporative losses for water efficiency, and most likely in a water sensitive scenario. Consequently, this Framework does not model direct cooling effects, because the aim was to quantify the performance of the designs for passive cooling, and not the role of purposeful above-surface sprinkling of water for active cooling.

The additional direct cooling benefits of irrigation can be added to a performance evaluation, if irrigation was proposed to be above-ground. However, it would need to be evaluated using a different model to that used in this work, such as SURFEX (Masson et al., 2013). Such modelling requires defining the specific watering (spraying) regime (volume of water applied per day, whether daytime or night-time watering, continuous watering or not), because each can deliver very different results. However, the effects of irrigation were not included in this analysis.

4.4 Architectural and urban space analysis

Analyses of architectural and urban space quality can be performed on a site level or a precinct level, depending on the scale of infill development. Site-scale performance analysis is conducted on two or more consolidated lots with groups of dwellings typically planned as one development. Such developments typically do not include urban spaces such as streets, laneways and parks, so the performance assessment does not evaluate outdoor public space. Precinct-scale analysis is performed on consolidated sites and precincts with a combination of several infill dwelling typologies and urban space types. The emphasis is on quality and access to outdoor spaces, in particular communal and public open spaces, resulting in modified streets, parks and plazas**.** Access and appropriate connections to high quality outdoor private space add to the performance of the precinct, especially in terms of establishing good connections and balanced transitions between private, communal and public spaces. For the precinct-scale analysis, due to the magnitude and complexity of analysed area, the quality assessment of interior organisation and spaces is not included. The indicators in the Framework are designed to be as scale-independent as possible, as they are built on the urban water mass balance. This also enables comparisons across scale (e.g. site, precinct and city).

Performance is judged against the following qualitative performance criteria:

A. **Availability and diversity**

Availability and diversity are assessed against the overall number and the number of different types of dwellings/outdoor spaces on the examined site.

For dwelling diversity, the number of dwelling sizes (number of bedrooms and bathrooms in a dwelling) as well as a dwelling typology (e.g. apartment, townhouse, etc.) is assessed. For outdoor space diversity, the number of different outdoor spaces, in terms of their type and position, is calculated. For private outdoor space this could be, for example, a balcony, courtyard, rooftop terrace and garden, with different orientations to support use at different times of the day. A variety of communal/shared spaces are possible, such as garden, BBQ, play area, with supporting shared facilities such as storage or communal room adjacent to a shared BBQ area. A range of publicly accessed areas – such as a linear park, nature reserve and sports field, and additional public facilities – support the diversity of uses.

B. Size and proportions

Appropriate size and proportion of available space depend on the intended use.

For the internal spaces, minimal recommended dimensions should at least be met (such as minimum height for living areas, etc.). Irregular and ‘broken’ shapes (e.g. sharp corners and unusually angled walls) typically do not show high usability and adaptability and are regarded less appropriate. Elongated spaces are generally not found to be appropriate, except linear parks and connectors. For outdoor space, appropriate size is estimated based on the intended use and number of potential users (e.g. a balcony accessed from a bedroom is expected to be smaller in size than a terrace used by all dwelling occupants). An ‘appropriately-proportioned’ courtyard could be defined by the ratio of its boundary lengths, where a square-shaped space supports more diverse uses and may be deemed more functional than a long narrow courtyard. An elongated space such as a linear park may be evaluated as ‘appropriately-proportioned’ as well when it supports its intended uses.

C. Accessibility and connectivity

High levels of accessibility and connectivity are best achieved with the direct physical and visual connection between interior and exterior spaces.

For interior spaces direct connection between, for example, kitchen and dining area, or between services and bedrooms, is adequate. Private outdoor space is accessible to all occupants when it is directly accessed from living areas, and well-connected with communal spaces. Additional access from public spaces for visitors contributes to the usability of private and communal outdoor spaces (e.g. to a BBQ area). Public outdoor spaces are accessible to all residents from the precinct with direct bicycle, pedestrian and public transport connectivity, supported by quality infrastructure, e.g. designated bike paths, benches, and similar.

D. Privacy through balanced transition between spaces

A balanced transition considering privacy and noise between spaces of different use type or ownership is established when ‘overlooking’ is minimised, with appropriate choice and positioning of windows, screens and fences (e.g. bedrooms are not directly facing communal outdoor space used by all occupants). Similarly, a balanced transition between private and communal/public outdoor spaces is achieved with adequate organisation of buildings on site, and positioning of windows, screens, trees and fences.

E. Multifunctionality, adaptability, flexibility

This refers to the extent of adaptability of spaces to a variety of uses and user groups. Adaptable internal spatial arrangement accommodates a range of occupancies and uses, with appropriate positioning and connection between spaces (e.g. separate living from sleeping areas), multiple access points (e.g. car from pedestrian access), and with a multifunctional room/space that is adaptable to several uses (e.g. office space adaptable to granny flat). The number of potential uses and/or users is used to determine the usability, e.g. balcony accessed from a master bedroom is more likely to be used by one to two occupants, and a garden accessed from living room by all occupants. Similarly, multifunctionality and adaptability of outdoor spaces consider the number of potential uses and/or user groups, as well as the extent of adaptability of spaces (e.g. a sports field could be adapted for a variety of events and celebrations). For the precinct analysis, the diversity of dwelling typologies allowing a range of household occupancies is an important factor.

F. Solar access and cross-ventilation

North and north east orientation are preferable for adequate solar access throughout the year. Proportion, position and distance of surrounding structures, including trees and screens are important factors to determine the adequate sun access. Shade gained from surrounding structures is not appropriate on the north side, but is desirable on the east and west sides. Cross-ventilation refers to the extent to which natural ventilation (airflow) is established. For the dwelling interior, positioning, distance and obstacles between windows are important factors, e.g. unobstructed airflow can be established between windows on opposite sides of a dwelling, even when on different floor levels connected through an open staircase. For outdoor spaces, appropriate organisation of buildings, shades and trees on site allows adequate airflow and avoids ‘wind tunnels’, which are subject to local microclimates and prevailing wind directions at the specific location.

G. Outlook to gardens, vegetation, canopy trees

This is assessed against the available area (m^2) for vegetation and large canopy trees (deep root zone) and the appropriate positioning in relation to usable outdoor spaces, and windows and balcony doors for the indoor spaces.

A qualitative rating scheme is used to evaluate the desired architectural and urban space qualities (Table 10). Each performance indicator across the seven criteria (A-G in Table 10) are rated and scored as absent (0), low (1), medium (2) or high (3), to generate a total score out of a maximum of 21 for each category.

Table 10: Performance indicators for architectural and urban space quality criteria

Performance criteria	Performance indicators for each category			
	Dwelling interiors (only for site-scale analysis)	**Outdoor private spaces**	**Outdoor communal spaces**	**Outdoor public spaces** (only for precinct-scale analysis)
A. Availability and diversity	Dwelling diversity on site, a range of dwelling sizes (number of bedrooms and bathrooms) and types (e.g. townhouse, apartment and other)	Adequate number and types of private outdoor space, (e.g. garden, courtyard, balcony, rooftop terrace) Spaces of different orientation and levels of exposure/ protection	Adequate number and types of shared facilities (e.g. vegetable garden, play area, BBQ area)	Number and variety of open public spaces (e.g. linear park, pocket park, sports fields, nature reserve)
B. Size and proportion	Adequate internal spatial arrangement (size, proportion, and position appropriate for the use)	Appropriately sized and proportioned in length, width and height for usability	Appropriately sized and proportioned in length, width and height for usability	Appropriately sized and proportioned in length, width and height for usability
C. Access and connectivity	Appropriate accessibility (e.g. multiple access points separating residential from office, or pedestrian from car access); and appropriate internal connection between spaces	Accessible to all occupants (e.g. direct accessibility from living areas vs accessibility from a master bedroom only)	Accessible to all residents, with physical connections between private and communal spaces	Adequate bicycle and pedestrian accessibility and connectivity (i.e. walking distance; pedestrian and cycling infrastructure; multiple access points) Public transport provision
D. Privacy and noise – balanced transition	Privacy and noise proofing through positioning of windows, screens, fences (e.g. bedrooms not directly facing private open space used by all occupants or communal/ public space)	Balanced connection between private and communal/public spaces, considering privacy and noise (e.g. shades, screens, fences)	Balanced connections between communal and public open spaces considering privacy and noise (e.g. shades, screens, fences)	Balanced connections between public and residential spaces, considering privacy and noise (e.g. commercial/office space facing streets; setbacks; access points)
E. Multifunctionality, adaptability, flexibility	Supports a range of occupancies (e.g. flexible space on ground floor could be adapted as office space, granny flat)	Supports a number of uses and users (e.g. balcony accessed from master bedroom will have less users/uses compared with a terrace accessed from living area)	Supports a number of uses and users	Supports a number of uses and users, being suitable for a wide demographic and social mix (appropriate for the dwelling diversity of the surrounding area)
F. Solar access, cross-ventilation	Adequate solar access (including positioning of surrounding buildings and deep root zones for trees), avoiding excessive westerly exposure, adequate cross-ventilation to all living areas	Adequate solar access (including positioning of surrounding buildings and deep root zone for trees), adequate cross-ventilation, avoiding ‘wind tunnels’	Adequate solar access (including positioning of surrounding buildings and deep root zone for trees), adequate cross-ventilation, avoiding ‘wind tunnels’	Adequate solar access (including positioning of surrounding buildings and deep root zone for trees), adequate cross-ventilation, avoiding ‘wind tunnels’
G. Outlook to gardens, vegetation, canopy trees	High quality visual connection to open space, gardens, canopy trees	Deep root zone providing sufficient space for and adequate positioning of large canopy trees/ vegetation	Deep root zone providing sufficient space for and adequate positioning of large canopy trees/ vegetation	Deep root zone providing sufficient space for and adequate positioning of large canopy trees/ vegetation

4.5 Reporting performance

The Framework aims to report the performance of infill development across multiple selected performance criteria. A radar chart, also referred to as a spider diagram, is a way of reporting multiple indicators on a single graph (see Box 3 for an example). In doing so, it can inform the design process towards urban forms and water servicing options that perform well across the board with minimal trade-offs.

There is no limit to the number of indicators that can be included in the multi-criteria assessment. However, a large number of indicators makes interpreting the graph more difficult. We recommended reporting the set of indicators that are most relevant and important for the case. The relative importance of each performance criteria will depend on local conditions (and e.g. whether downstream flooding, water security, urban heat, or other aspects are important). If these conditions and their relative importance are quantified, additional multi-criteria analysis and optimisation could be undertaken.

Each axis represents the performance of an indicator, scaled from bad performance (0% in the centre) to good performance (100% at the perimeter), so all axes have the same scale. The results for each indicator axis are connected to produce a performance envelope. The larger an envelope size, the better the performance.

Presenting the results in this way necessitates defining what good performance is for each criterion and what might be achievable. This process is useful for considering and testing targets that may be operationalised in urban planning policies and design codes.

Box 3: Example of multi-indicator performance reporting

The radar chart shows example results for a performance evaluation of three different dwelling designs on a development site – existing dwellings (EX), business as usual infill (BAU) and water sensitive (WS) infill.

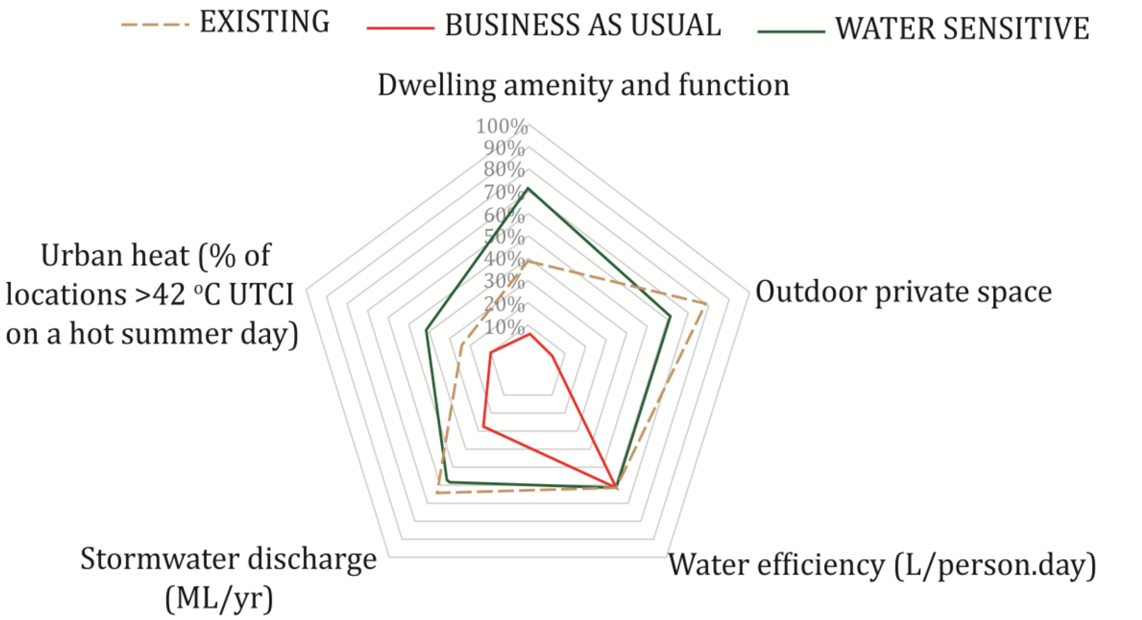
Compared with the existing dwellings, BAU design has reduced performance in terms of increased stormwater runoff, reduced outdoor thermal comfort, and reduced quality of private and communal outdoor space. By contrast, the WS infill design maintains stormwater runoff at a similar level to existing, slightly improves outdoor thermal comfort, does not erode outdoor private space as much as BAU and increases communal outdoor space. The three designs have similar urban water efficiency.

The Framework is useful not only for screening the performance differences of designs, but also for guiding planners, designers and developers towards setting performance objectives and targets for infill development. For more detailed analysis of these typologies with the Framework, see the case study analysis of Salisbury and Knutsford.

EXISTING DWELLINGS

BUSINESS AS USUAL INFILL

WATER SENSITIVE INFILL



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Appendix 1: Water sensitive cities index

The performance aspects addressed by the Framework that align with those goals of Water Sensitive Cities Index (CRC WSC, 2018, Rogers et al., 2020) are highlighted below:

Good governance
1.1 Knowledge, skills and organisational capacity
1.2 Water is a key element in city planning and design
1.3 Cross-sector institutional arrangements and processes
1.4 Public engagement, participation and transparency
1.5 Leadership, long-term vision and commitment
1.6 Water resourcing and funding to deliver broad societal value
1.7 Equitable representation of perspectives

Increase community capital
2.1 Water literacy
2.2 Connection with water
2.3 Shared ownership, management and responsibility of water assets
2.4 Community preparedness and response to extreme events
2.5 Indigenous involvement in water planning

Achieve equity of essential services
3.1 Equitable access to safe and secure water supply
3.2 Equitable access to safe and reliable sanitation
3.3 Equitable access to flood protection
3.4 Equitable and affordable access to amenity values of water-related assets

Improve productivity and resource efficiency
4.1 Benefits across other sectors because of water-related services
4.2 Low GHG emission in water sector
4.3 Low end-user potable water demand
4.4 Water-related economic and commercial opportunities
4.5 Maximised resource recovery

Improve ecological health
5.1 Healthy and biodiverse habitats
5.2 Surface water quality and flows
5.3 Groundwater quality and replenishment
5.4 Protect existing areas of high ecological value

Ensure quality urban space
6.1 Activating connected urban green and blue space
6.2 Urban elements functioning to mitigate heat impact
6.3 Vegetation coverage

Promote adaptive infrastructure
7.1 Diverse fit-for-purpose water supply
7.2 Multifunctional water system infrastructure
7.3 Integration and intelligent control
7.4 Robust infrastructure
7.5 Infrastructure and ownership at multiple scales
7.6 Adequate maintenance

Appendix 2: Comparison of urban water balance modelling approaches

Aspect	Attribute	SUWMBA	Aquacycle	CRCWSC WSC Scenario Tool's urban water cycle model[1]
Purpose and applications		Evaluating water performance of design alternatives at site scale Providing detail picture of interactions of design and WSUD technologies at site scale	Providing a holistic view of urban water system by linking water supply, wastewater discharge, and stormwater drainage Understanding the impacts of alternative water supplies on urban water catchment	Exploring alternative development scenarios by quantifying the impact of different urban form and blue/green infrastructure initiatives on urban water catchment
Scale	Spatial	Site scale	Urban catchment represented in three nested scales: unit block, cluster, and catchment	Flexible and user-defined Can be as small as 30 m×30 m or the entire city
	Temporal	Daily calculations reported as user-defined single-month or single-year	Daily calculations reported as monthly or annual time series	Daily calculations reported as single year
Source of data	Precipitation (P) and potential evapotranspiration (PET)	In-built libraries developed from BOM climate data for the financial year (July-June)	User input of a climate file Aquacycle reports annual P and ET for the calendar year (Jan-Dec)[2]	Automatic retrieval from BOM depending on the site's centroid location
	Land cover characteristics	User-defined, detailed depending on the design	User-defined, simplified and clustered	Automatic retrieval from Geoscape for existing case, user-defined for scenarios
	WSUD technologies	User-defined	User-defined	User-defined
Outputs		Absolute volumes of urban water flows, water performance indicators	Absolute volumes of urban water flows, reliability of alternative water supplies	Absolute volumes of urban water flows, annual water saving from alternative water supplies
Hydrology	Model	Based on MUSIC rainfall-runoff model executed for each land cover zone	Based on AWBM model	Simple catchment model that uses Horton's equation for infiltration, runoff generation is limited to impervious areas
	Flow routing	None	None	None

Aspect	Attribute	SUWMBA	Aquacycle	CRCWSC WSC Scenario Tool's urban water cycle model[1]
Water demand	Indoor residential	Modelled	Fixed values	Fixed values
	Indoor non-residential	None	None	Fixed values
	Outdoor (i.e. irrigation)	Modelled (as fraction of field capacity) Vegetation types are accounted for	Modelled (as fraction of field capacity) Single vegetation type	Modelled (to fulfil potential evapotranspiration). Short and tall vegetation (factor of 1.78 of potential evapotranspiration)
Alternative water supplies (e.g. rainwater harvesting)	Model	Daily storage behaviour model	Daily storage behaviour model	Daily storage behaviour model
	Store size	User-defined	User-defined	Fixed 2 KL for lot-scale interventions and 20 ML for catchment-scale interventions
	Spatial representation of stores (i.e. required space for implementing the storage)	Implicit	Implicit	Implicit
	Configurations of harvesting surfaces to the store	User-defined for each land cover zone	User-defined for within or between clusters	User-defined as a percentage of area
	Configurations of alternative supplies to demand	User-defined and flexible	Fixed	Fixed

[1] The CRCWSC's WSC Scenario Tool's urban water cycle module was updated and released in September, 2020.

[2] The result of Aquacycle cannot be directly compared with SUWMBA due to this timeframe difference.

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