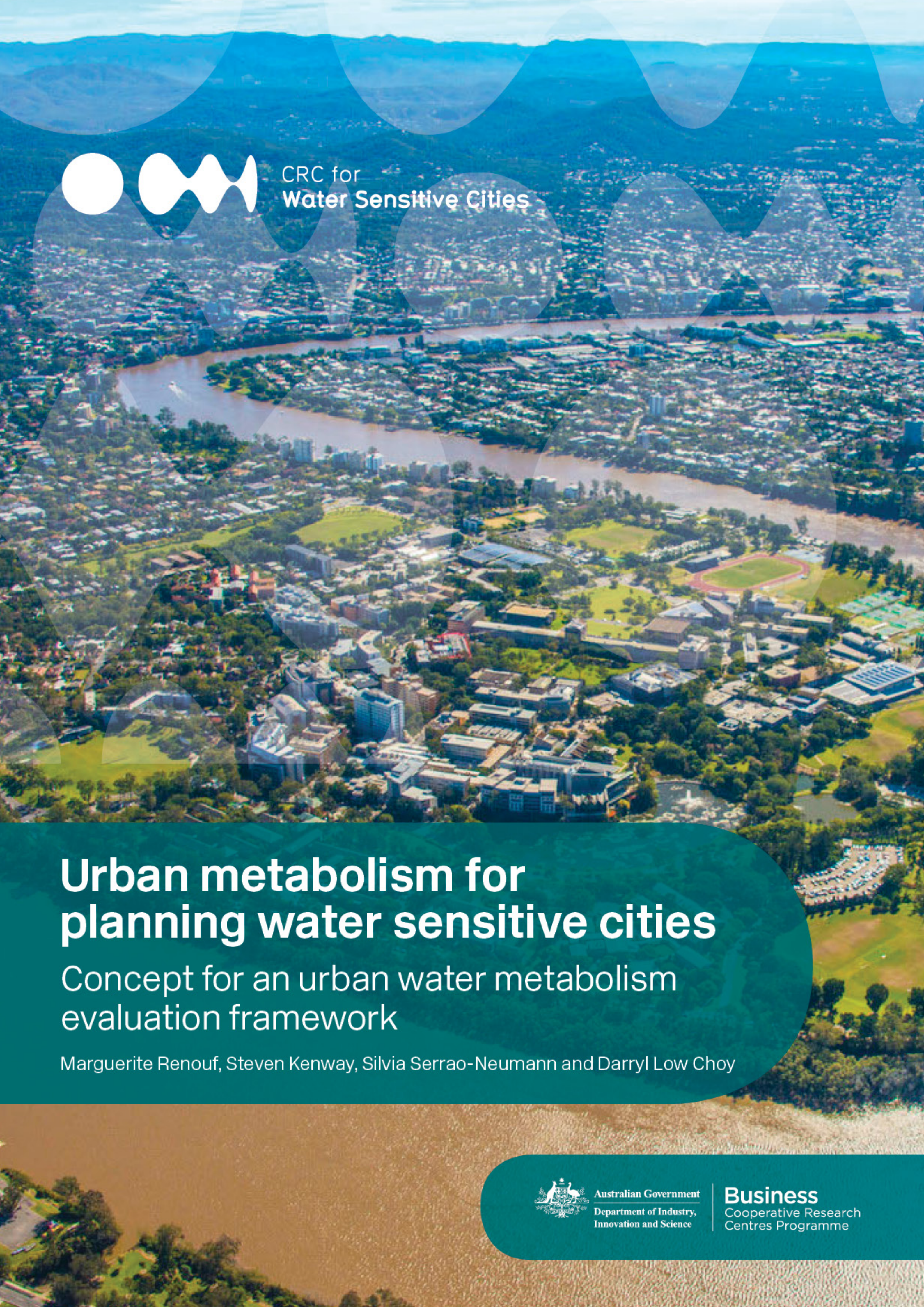

CRC for
Water Sensitive Cities

Urban metabolism for planning water sensitive cities

Concept for an urban water metabolism evaluation framework

Marguerite Renouf, Steven Kenway, Silvia Serrao-Neumann and Darryl Low Choy

Australian Government
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Urban metabolism for planning water sensitive cities
Concept for an urban water metabolism evaluation framework
Catchment scale landscape planning for water sensitive city-regions (Project B1.2)
B1.2 – 1 - 2016

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Glossary

Aquacycle	Aquacycle is a daily time step urban water balance model which simulates the total urban water cycle for investigating the use of stormwater and wastewater as a substitute for imported water. (http://www.toolkit.net.au/Tools/Aquacycle). (Mitchell et al., 2001).
AURIN	Australian Urban Resource Information Network (http://aurin.org.au/)
AWRA-System	Australian Water Resources Assessment System is a nationally consistent landscape water balance model used to generate estimates of landscape flows and storages across a region.
BOM	Bureau of Meteorology
catchment	In the context of urban planning, it is the area and population that supports the city. In the context of hydrology, it is an area of land where surface water converges to a single point (drainage basin). In this report it is referred to in the urban planning context unless specified as a hydrological catchment.
city-region	The population catchment of a city.
conurbation	An amalgamation of connected cities or urbanised areas.
CRCWSC	Cooperative Research Centre for Water Sensitive Cities
CRCWSC Modelling Toolkit	The software platform that integrates stormwater management research from the CRC for Water Sensitive Cities, and applies this knowledge to urban planning. The model supports catchment / regional scale planning and conceptual design through the modules covering stormwater management, local rainfall variability, stream health and urban micro-climate.
DAnCE4Water	Dance4Water (Dynamic Adaptation for eNabling City Evolution for Water) is a scenario-based urban water tool for assessing the dynamics of urban infrastructure in response to social and environmental drivers of change on the water system (Urich et al., 2013).
efficiency / efficient	Achieving maximum productivity with minimum waste (of effort, expense, natural resources).
E-IO	Environmentally-extended Input-Output analysis is a quantitative technique that models the flow of resources through the economy using uses input-output tables. See page 16.
evapotranspiration	The combination of evaporation from soil and transpiration from vegetation.
framework	A conceptual framework used to make conceptual distinctions and organize ideas.
hydrological performance	We refer to hydrological performance in the context of urban systems. See urban hydrological performance.

integrated urban water modelling	Models interactions between urban drainage, water supply and other urban water flows. For examples see Bach et al. (2014). See page 16.
LCA	Environmental life cycle assessment – the quantification of environmental impact across the life cycle of a product or service. See page 16.
macro-urban scale	On the continuum of urban spatial scales (micro, meso, macro), macro- is a large urban scales, such as a city or city-region.
mass balance MFA	A type of material flow analysis (MFA) that generates a comprehensive account of the flows of a resource into and out of an entity / system (sum of the inflow = 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.
material flow analysis	An analytical method of quantifying flows and stocks of materials in a defined entity / system.
meso-urban scale	On the continuum of urban spatial scales (micro, meso, macro), meso- is a medium urban scale, such as a precinct or hydrological catchment.
metabolise	In the context of urban systems, the sourcing, consumption and transformation of resources to achieve the required functionality.
metabolic efficiency	In the context of urban systems, the sourcing, consumption and transformation of resources to achieve maximum functionality with minimum waste (of natural resources).
MFA	See Material Flow Analysis
micro-urban scale	On the continuum of urban spatial scales (micro, meso, macro), micro- is a small urban scale, such as a neighbourhood or household.
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 (http://www.toolkit.net.au/Tools/MUSIC.
peri-urban	Areas located at the fringe of consolidated urban centres (Malano et al., 2014, p. 4). These areas present fuzzy boundaries between both urban and rural areas; and can also be defined by their socio-economic characteristics and activities which are clearly not classed as rural production.
planning	In the context of this report, planning refers to urban and regional planning - the technical and political processes concerned with the use of land and design of the urban environment, including air, water, and the infrastructure passing into and out of urban areas.
precinct	An area within a perceived boundary of a place. In the context of this project it refers to an urban area within a city.
rural	Areas that have predominant economic activities classed as rural production (e.g., livestock, crops, etc.). In some cases, they might also hold mining production.

supply-demand balance	In the context of hydrology, it is the balancing of water supplies to match water demand.
supply diversification	In the context of water, the sourcing of water from more than one sources, for example rainwater, stormwater runoff or recycled wastewater.
supporting region	In the context of this report, supporting regions are the peri-urban, adjacent rural areas and multiple catchments that directly service the needs of an urban settlement in terms of water supply and waste assimilation.
territorial MFA	A type of material flow analysis (MFA) that generates an inventory of the range of resource flows into and out of cities, without necessaries ensuring a mass balance.
UMEF4Water	Urban Metabolism Evaluation Framework for Water
urban	A location characterised as population clusters of 1000 or more people, with a density of at least 200/km^2 (Australian Standard Geographical Classification, 2001).
urban boundary	A three-dimensional land area containing urban areas centred around a single / multiple economic centre(s).
urban footprint	In the context of urban and regional planning systems, the Urban Footprint establishes a boundary for urban development, containing urban growth and promoting a higher density urban form.
urban hydrological performance	It refers to how water is circulated, distributed and utilised by the urban system as a whole. It can encompass aspects such as how well urban systems make use of available water, the overall water efficiency, extent of departure from natural hydrological flows etc.
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 in it (Renouf and Kenway, accepted).
urban metabolism evaluation	The quantification of the metabolic characteristics of an urban area, based on analysis of direct resource exchanges between an ‘urban are and its ‘supporting region’ (Renouf and Kenway, accepted).
urban water cycle	The natural and anthropomorphic movement and use of water within a city, including rainfall, storage, treatment, use, disposal, stormwater flows, evapotranspiration and groundwater movement.
urban water cycle services	The services provided by the urban water cycle that describes the diverse function of water in the urban landscape, including water supply and drainage, maintenance of eco-system services, amenity, flood mitigation, etc. The term was coined by Prof. Kees van Leeuwan of the KWR Water Cycle Research Institute and Utrecht University.
urban water mass balance	A water mass balance in the context of urban systems. See water mass balance.
water-energy nexus	The inter-relationship between water and energy, i.e. water used for energy and energy used for water.

water footprint	The total volume of freshwater used to produce the goods and services consumed in the supply chain of a product, or by an individual, community, business or settlement. See page 17.
water mass balance	In the context of hydrology, it is an equation that describes the flow of water in and out of a entity / system (sum of the inflow = sum of the outflows and the change in storage), with the change in storage acting as a check for the conservation of mass.
water related energy	Energy used to supply, use and dispose of water throughout the water supply chain.
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).

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Executive summary

This report compiles and summarises the research activities leading up to the first milestone for the urban metabolism component of the CRC for Water Sensitive Cities (CRCWSC) project on '*Catchment-scale landscape planning for water sensitive city-regions in an age of climate change'* (Project B1.2) - the conceptualisation of a city-region scale urban metabolism evaluation framework. A concept for a novel *Urban Metabolism Evaluation Framework for Water (UMEF4Water)* is presented with explanation of how it can be used to conceptualise urban water management more holistically, quantify urban hydrological performance, and understand the connection between urban areas and their supporting regions. The project brings together the science of urban metabolism with urban and regional planning, to develop a means for generating urban water performance information that can inform strategic urban and regional planning.

The problem this project addresses is a lack of frameworks and methods for evaluating urban hydrological performance, particularly at macro scales (for example city-region), which can account for the diverse functions of water, and consider the water connections between urban areas and their supporting regions. Just as the concept of 'water sensitive cities' has been an evolution in the way we view and value water in cities, this work proposes an evolution in the way we evaluate it, and for this we hypothesise a framework based on urban metabolism.

In this first phase, the research objectives were to 1) review past research on the urban metabolism of water to understand the methods used, information generated, and its potential utility; and 2) develop a concept for an evaluation framework that can generate metrics and knowledge for informing urban planning towards water sensitive cities. Concept development progressed to the point of defining the design elements of the framework.

We established a definition for urban metabolism evaluation to clarify some confusion around the use of the term, and to differentiate it from other evaluation approaches. Our synthesis of literature, the first to specifically explore urban metabolism applied to water, revealed the gaps in conceptualising and evaluating water metabolism that can be addressed by this project. We reviewed various approaches for evaluating urban water to identify the most appropriate method for the framework. In parallel, pathways for feeding urban metabolism science into strategic urban planning were reviewed, to identify the desired utility of the framework for informing planning.

The outcomes of this phase of the research were as follows:

1. Urban metabolism evaluation is defined for our purposes as the quantification of the metabolic characteristics of urban areas based on resource exchanges between a particular urban unit and its supporting regions.
2. The urban Water Mass Balance method offers a good foundation for urban metabolism evaluation, due to its capacity for generating indicators of metabolic performance. It is more holistic than traditional supply-demand balance, as it measures the performance of the urban system in relation to water, rather than the performance of the water supply and drainage system.
3. The desired utility of the framework for informing urban and regional planning and advancing water sensitive cities has been defined. It aims to: i) frame indicators of urban hydrological performance, ii) account for the diverse sources and functions of water in the urban landscape to maximize multi-functionality of water, iii) link urban areas to their supporting regions to understand potential competition for water, and iv) account for water-related energy use to understand potential energy trade-offs of water management.
4. A concept for the *Urban Metabolism Evaluation Framework for Water (UMEF4Water)* has been developed using urban water mass balance as the method, and the key elements defined.

The innovation is in the operationalisation of the urban metabolism concept into a method for evaluating urban hydrological performance, particularly at the city-region scale, and insights into how it can facilitate science-led planning.

Introduction

Researchers from the University of Queensland's Water-Energy-Carbon Research Group and Griffith University's Urban Research Program are using the concept of urban metabolism to evaluate the hydrological performance of urban areas. Urban metabolism considers the flows of resource into, through and out of urban areas similar to biological organisms or ecosystems, with the intent of replicating the higher resource efficiencies of natural systems. The intention is to feed the hydrological performance information into urban and regional planning process to facilitate better integration between land-use and water planning.

This research is a component of the CRC for Water Sensitive Cities' Project B1.2 (Figure 1). The output is an *urban water metabolism evaluation framework* (UMEF4Water), which helps us conceptualise urban water management more holistically and generate information about metabolic efficiencies to inform urban and regional planning. In subsequent phases of the project the framework will be used to evaluate hydrological performance of three Australian city-regions.

The intended outcome is knowledge that enables urban and regional planners, managers and policy-makers to understand and monitor the hydrological performance of urban areas, so as to better integrate water science into planning decisions. It brings together the science of urban metabolism and the discipline of urban and regional planning to foster science-led planning.

The framework extends existing urban water models to be more holistic by i) accounting for all water flows (natural and managed), ii) accounting for the diverse functions of water in the urban landscape, iii) linking urban areas hydrologically to their supporting regions, and iv) considering the energy interconnection. These aspects of urban water management have not been evaluated to date.

Just as the Water Sensitive Cities concept is an evolution in the way we value water in urban areas, the framework will be an evolution in the way we evaluate urban water management.

In the first year (June 2014–June 2015) the researchers developed the concept for the framework (described in this report), and in the second year (June 2015–June 2016), the concept will be proved by applying it to selected Australian city-regions. Beyond that, it may be operationalised into a model for future scenario analysis to inform planning policies and processes.

This report compiles and summarises the research activities leading up to the first milestone for the urban metabolism component of the project, i.e., the conceptualisation of a city-region scale urban metabolism evaluation framework. The research findings from this phase are described more fully in Renouf and Kenway (in press), Serrao-Neumann et al. (in press), Farooqui (2015) and King (2015).

Cooperative Research Centre for Water Sensitive Cities

Program A Society

Program B Water Sensitive Urbanism

B1 Catchment-scale landscape planning for water sensitive cities in an age of climate change

B1.1 Cities as water supply catchments

B1.2 Catchment-scale landscape planning for water sensitive cities in an age of climate change

Regional-scale values-led planning

Greenspace framework

Urban metabolism for planning water sensitive cities

Milestone 1 – Concept for an urban water metabolism evaluation framework – This report

Milestone 2 – Current water metabolism of Australian city-regions

Milestone 3 – Future water metabolism of Australian city-regions under climate

B4 Building socio-technical flood resilience in cities and towns

B5 Statutory planning for water sensitive cities

Figure 1. Position of this research to date within the CRCWSC research framework

Problems addressed

Urban areas draw on local / regional water sources for direct use, and on global water sources for indirect or virtual water (that embodied in goods and services consumed by urban dwellers). Both are important, but have different governance arrangements and different management solutions (Renouf and Kenway, in press). As our research is interested in the interface between water management and urban planning, we focus on the direct water use extracted from local / regional supplies. It is because urban and regional planning have a role in the governance of direct water use, but not indirect water use.

Local water supplies that directly sustain urban areas are increasingly stressed (McDonald et al., 2014, Richter et al., 2013). Commonly cited causes are external factors such as growing urban populations, competition with agricultural production, and more erratic supply due to climate change (OECD, 2015). However, internal factors make urban areas vulnerable to these external stresses, such as reliance on a single water source, non-utilisation of available water generated within the city itself, the linearity of urban water flows (Renouf and Kenway, in press). We could say that our urban areas are metabolically-inefficient in how they use water, and hence they struggle to be resilient to external pressures.

Urban and regional planners will increasingly deal with more frequent water shortages, competition for water between urban and regional uses (agriculture, energy production, ecosystem services), and conflict between urban functions during times of water shortages. This is the underlying driver for this research – the need to better understand how urban areas metabolise water so planners can make better-informed strategic decisions.

Hand in hand with water stress are the energy implications of urban water (water-energy nexus), which are substantial (Kenway et al., 2011b). The topic is receiving considerable attention due to concerns about problem shifting, when solutions to water issues impact energy solutions and vice versa (WBCSD, 2009, PMSEIC, 2010). There is also a nexus between water and nutrients, as nutrients are mobilised in water, and water management can influence nutrient outcomes, and vice versa. It will be increasingly important for urban water managers to consider the points of intersection with energy and nutrients to avoid problem-shifting. This project makes a start towards this by considering water-related energy, but is a secondary driver for the project. The main focus is on water metabolism.

The more specific research gap addressed by this research is a lack of frameworks and methods for holistically evaluating the hydrological performance of urban areas to enable them to become metabolically-efficient. The visions of water institutions increasingly emphasise principles such as "resource neutrality, recognising the many values of water, harmonisation with the environment" (IWA, 2010). However, we don't have a framework to monitor or inform progress.

Existing urban water evaluation approaches are not holistic, often focusing on water supply and drainage systems within urban areas rather than evaluating the hydrological performance of the urban area as a whole (Renouf and Kenway, accepted). We currently do not account for the multiple functions of water across the urban landscape, and do not consider the water connections between urban areas to their supporting regions. This constrains how well we can design and manage urban areas for overall water efficiency, security, resilience, and ultimately sustainability. We currently may be able to show how components of urban areas' water systems are performing in these regards, but how do we know how the urban system as a whole is performing?

This research hypothesises that an evaluation framework based on urban metabolism can fill this gap by generating information for monitoring overall hydrological performance of urban areas, informing the optimisation of urban water systems, and planning urban development within environmental constraints.

Research aims and objectives

The research question of Project B1.2 is "*Can an urban metabolism framework extended to the city-region scale, be incorporated into an evaluation process to support scenario planning which seeks to highlight strategic options for future growth in greenfield, peri-urban and rural landscapes for growing city-regions in an environment and uncertainty with particular regard to climate change adaptation, leading to resilient landscapes?"*

The more specific objectives of the urban metabolism component of Project B1.2 are:

1. Review past applications of urban metabolism evaluation, specifically in the context of water, to understand the current state of knowledge, methods, and applications, and in particular its utility for informing planning.
2. Develop a concept for an 'urban metabolism water framework' for a city-region that allows us to conceptualise urban water management holistically and generate information about city-scale metabolic efficiencies, to inform urban and regional planning.
3. Prove the concept by applying the framework to a selection of Australian city-regions (South East Queensland, Greater Melbourne and Greater Perth) to generate a base case evaluation of urban hydrological performance.
4. Model the future water metabolism of Australian city-regions under projected growth and climate change scenarios. Will Australian city-regions be able to achieve water security whilst maintaining ecological and liveability objectives?
5. Identify the most appropriate mechanisms for feeding the information and metrics generated by metabolic analysis into urban and regional planning processes. How can planning facilitate the consideration of city-region metabolism in a science-based planning approach?

This report addresses objectives 1 and 2.

Urban metabolism for evaluating urban hydrological performance

Background to urban metabolism

Urban metabolism is a metaphor for conceptualising the way urban systems function and has been adopted by a range of disciplines (Rapoport, 2011). Our use of urban metabolism is for evaluating resource exchanges between urban areas and the environment, as you might observe it in ecosystems or biological organisms (Pincetl et al., 2012, Newman, 1999, Fischer-Kowalski, 1998). Adapting the definitions of others (Baccini and Brunner, 1991, Kennedy et al., 2007, Wolman, 1965), we define urban metabolism as “the process of resources flowing through and being transformed and consumed in urban areas to sustain all the technical and socio-economic processes that occur within in it” (Renouf and Kenway, in press).

The concept of urban metabolism has been traced back to the ideology of Marx (Foster, 2000), but was first presented as an evaluation approach by Wohlman (1965), in his foundational analysis of a hypothetical U.S. city in the 1960s. Since then it has been applied in a range of guises, to generate information and metrics about urban resource consumption. For comprehensive reviews see Kennedy et al., (2011), Yetano Roche et al., (2014) and Zhang (2013).

We define urban metabolism evaluation as the quantification of the metabolic characteristics of an urban area, based on analysis of direct resource exchanges between the ‘urban area’ and its ‘supporting region’. It has been applied at various urban scales (city, precinct, neighbourhood, and household).

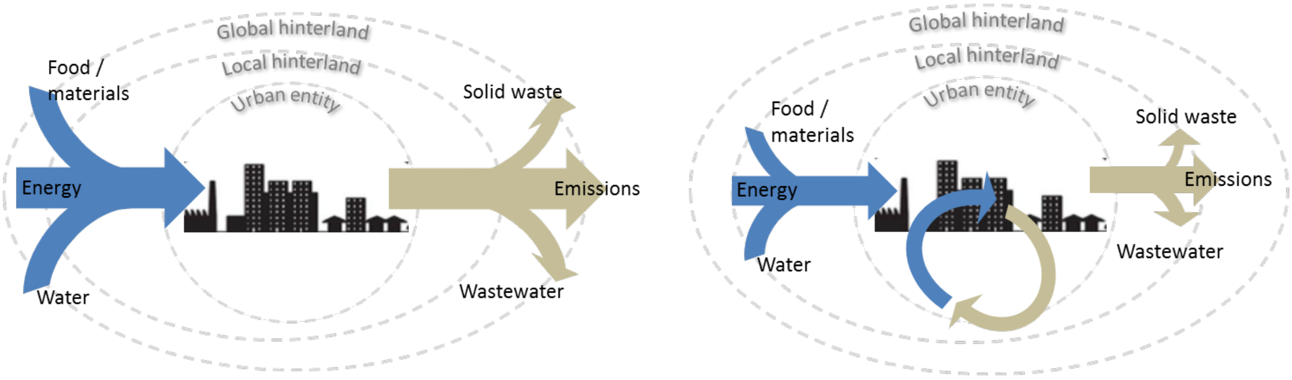
Outcome #1:

Urban metabolism evaluation is defined for our purposes as the quantification of the metabolic characteristics of urban areas based on resource exchanges between a particular urban unit and its supporting regions.

The implied intent of urban metabolism evaluation is to guide urban planning towards more metabolically-efficient urban systems (Chrysoulakis et al., 2015). Natural systems are highly resource-efficient, by conserving mass and energy through internal recycling and adapting to the supply capacity of their environment. In contrast urban systems have linear metabolisms that are open and unsustainable (Grimm et al., 2008). Urban metabolism evaluation can generate information to help us replicate the higher resource efficiencies of natural systems (Figure 2).

In relation to water, urban systems traditionally import externally-sourced water, use it once and discharge the resulting wastewater back to the environment. Urbanisation also changes the hydrology by increasing imperviousness (causing more runoff, less evapotranspiration and less infiltration). Hence urban ‘metabolism’ of water is far removed from pre-development conditions (Haase, 2009), and the intent of concepts such as ‘water sensitive cities’ is to revert it to being closer to natural conditions (Figure 3).

A metabolically-efficient urban area, with respect to water, tries to emulate natural systems by making optimal use of internal water sources, maximising functionality per unit of water input, reducing water wastage, recycling not only water but nutrients and energy carried in it, and avoiding unintended consequences for energy and nutrient efficiency.



a) current metabolism of urban areas (linear resource flows of high magnitude with an increasingly distant reach into distant / global hinterlands)

b) desired metabolism of urban areas (circular resource flows and reduction in the magnitude and reach of resource inflows)

Figure 2. The concept of urban metabolism (adapted from Pamminger and Kenway (2008))

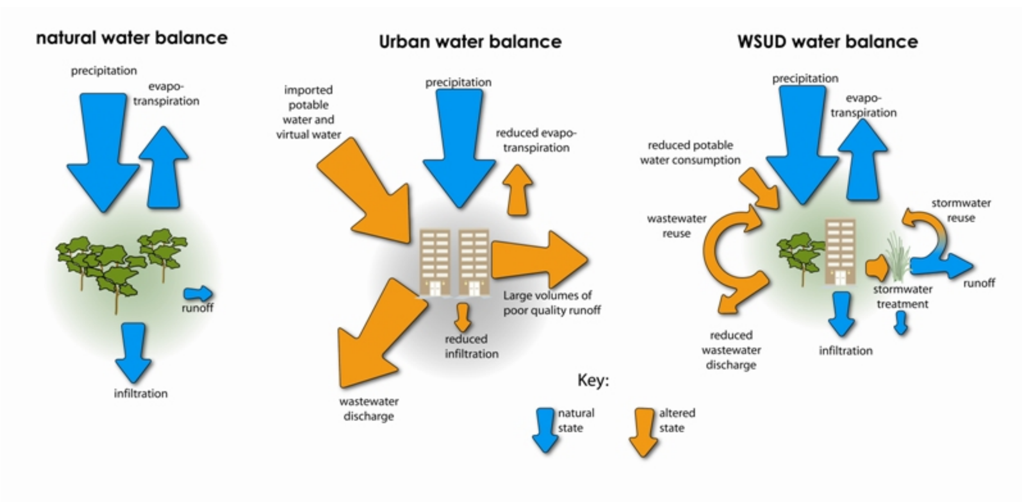


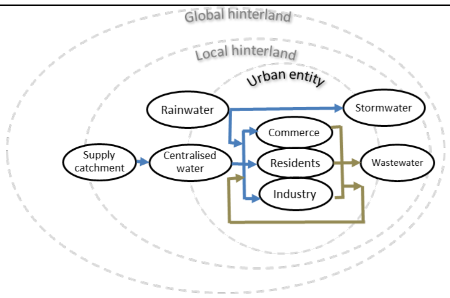
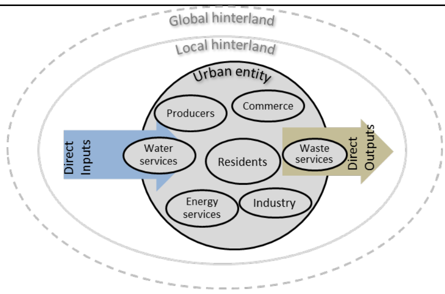
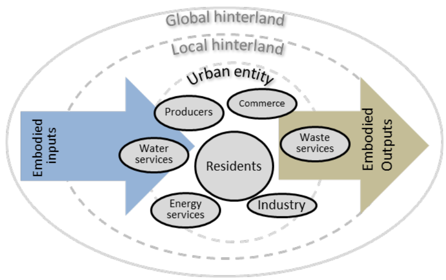
Figure 3. Urban metabolism of water (Source Healthy Waterways Ltd.)

How does urban metabolism differ from other evaluation approaches?

A range of approaches for evaluating urban resource sustainability are described in academic literature. The most common ones are categorised as *metabolism* and *consumption* approaches[1] (Zhang, 2013, Yetano Roche et al., 2014, Daniels and Moore, 2001, Baynes and Wiedmann, 2012) (Table 1). To this list we add *integrated urban water modelling*, as it is a well-established approach for evaluating water supply and drainage system (Bach et al., 2014). All these approaches quantify resource flows through urban systems, but with different perspectives and scopes – resource systems within the city, the city as an entity, the city as a consumer, or consumers within the city (Renouf and Kenway, in press).

[1] Complex systems approaches (ecological network analysis and systems dynamics) are also described. However we do not discuss them here, and the reader is instead referred to Renouf and Kenway (in press)

Table 1. Urban resource evaluation approaches (adapted from Renouf and Kenway (in press))

Evaluation approach	System definition and boundaries	Features	Utility
Integrated urban water modelling For examples see Bach et al. (2014)		Considers DIRECT water flows managed by urban water infrastructure Precinct-scale Bottom-up analysis	Balancing supply against demand Integrating diversified water supplies Evaluating the influence of urban form on stormwater runoff
Urban metabolism For examples see Kennedy (2014), Kenway et al (2011) and Theriault and Laroche (2009)		Considers all DIRECT water flows (managed and natural) Various urban scales – city, neighbourhood, household. Top-down analysis	Indicators of urban hydrological performance Connecting city to its supporting region Understanding local water scarcity impacts of cities
Consumption-based approaches – Water footprinting (WF). For example see Vandam (2012) – Input-output analysis (IO). For example see Lenzen (2009)		Considers INDIRECT water flows (i.e., those embodied in goods and services) Various scales (consumer, economic sector, city, nation, etc.) Bottom-up (WF) or Top-down (IO)	Understanding global water impacts

These varying approaches have at times been described collectively under the banner of *urban metabolism* (Pincetl et al., 2012) by adopting a broad interpretation of the term, which causes confusion as to what urban metabolism is. To address we apply a tighter interpretation, regarding it as an approach focused on the direct flow of resources through the urban areas as a whole. In comparison, other approaches examine sub-components of urban areas or 'systems' that cut across the urban boundary (*urban water cycle modelling)*, or indirect (virtual) resource exchanges with the global hinterland (*consumption* approaches) (see Text Box 1).

Urban metabolism is an appropriate approach for our purposes, because it is suited to application at larger macro-scale (e.g. the city or city-region), it addresses direct flows, and has the potential for linking these flow to their regional implications. There has been interest in coupling urban metabolism with environmental life cycle assessment (LCA) and water footprinting (Goldstein et al., 2013, Chester et al., 2012) to effectively represent the 'global metabolism' of cities, rather than the 'local metabolism' of cities. However, as we are interested the water supplies that directly sustain urban areas, we focus on 'local water metabolism'.

Text Box 1. Other evaluation approaches

Environmental life cycle assessment (LCA) characterises the environmental impacts of urban water systems (e.g., resource depletion, global warming and pollution impacts) (Fagan et al., 2010, Foley et al., 2010) or quantifies the water embodied in the goods and services consumed in the city, as in a water footprint.

Environmental footprinting has its origins in LCA but generates a single metric for a specific resource issues such as greenhouse gas emissions (carbon footprint), land requirements (ecological footprint) or water extraction (water footprint). Water footprints have more commonly used for products, but there are a few examples for cities (Hoff et al., 2014), regions (Lenzen, 2009, Vanham, 2012), and nations (Mekonnen and Hoekstra, 2011). Water footprints applied to geographic entities represent the total amount of water used in the life cycles of goods and services consumed by the inhabitants, (Hoekstra and Wiedmann, 2014).

Environmental input-output analysis (E-IO) uses 'top-down' economic input-output tables (instead of 'bottom-up' data used in LCA and footprinting) to quantify resource flows through whole economies, which can be disaggregation to regional (Lenzen, 2009), city (Zhang et al., 2011), or household scales (Lenzen et al., 2008, Lenzen and Peters, 2009). As it captures the whole economy it is very useful for quantifying both direct and indirect flows.

Integrated water cycle modelling considers the water system within an urban entity, but not the urban entity as a whole. It integrates water flows managed by urban water infrastructure (potable water, wastewater, stormwater and rainwater etc.) usually at the precinct scale (Bach et al., 2014), but does not give a complete picture of the urban entity. Some models have the capacity to be scaled up to city scale (Urich et al., 2013, Willuweit and O'Sullivan, 2013).

Past applications of urban metabolism to water and gaps in knowledge

Studies of urban metabolism (as we define it) have usually employed the method of material (or substance or energy) flow analysis, which we collectively refer to as materials flow analysis (MFA). MFA quantifies resource flows through an urban system, and can be *territorial* MFA or *mass balance* MFA.

Territorial MFA generates an inventory of the diverse range of urban resource flows (water, energy, carbon, materials, pollutants etc.) to understand the scale and trends of resource utilisation over time (Kennedy et al., 2007), and to compare cities (Kennedy et al., 2015). Applied to water, it offers a snapshot of centralised water use (i.e., easily measureable) at the city level and can be useful in state of environment reporting (Newman et al., 1996, Newton et al., 2001) and benchmarking (EIU, 2011). However its capacity for analysing urban water to inform better management is limited, because it rarely examines individual resources comprehensively enough to derive detailed insights. In the context of water, generally ignores the natural hydrological flows of water available to urban areas, and just focuses on centralised, potable water inflows (Renouf and Kenway, in press).

In comparison, water mass balance MFA focuses only on water to generate a more comprehensive account and affect a mass balance (i.e., inflow = outflows + storage) (Kenway et al., 2011a, Thériault and Laroche, 2009). This method enables greater analysis of resource utilisation and efficiency. Kenway et al. (2011a) advanced this approach to support urban metabolism evaluation by using the water mass balance data to generate indicators for water use intensity, supply centralisation, and supply diversification potential. In an application to four Australian cities they found that large flows of rainfall, stormwater, and wastewater pass through the urban areas untapped, highlighting the underutilisation of water sources available to urban areas. They also experimented with the use of turnover rate to compare the metabolic efficiencies of urban areas to that of biological organisms.

Urban water mass balance offers considerable scope for developing indicators of urban hydrological performance, but indicator development is still in its infancy (Renouf et al. (accepted). Kennedy et al. (2014) proposed an indicator set for urban metabolism based on territorial MFA, but for water it is limited to centralised water input only. Indicators reporting the water performance of cities have been proposed in city benchmarking programs such as City Blueprint (van Leeuwen et al., 2012), the Asian Water Development Outlook (ADB, 2013) and Green City Index (EIU, 2011). Indicators typically relate to elements of urban water systems (per capita consumption, leakage) or are based on ‘water footprints’ (a measure of the water embodied in goods and services consumed in the city). These existing indicators are useful for comparing cities, tracking progress over time, and for community engagement. However they don’t give a picture of a city’s overall hydrological performance, or enough information to guide planning decisions.

What we know from past research is the magnitude of direct, centralised flows of water through cities (Kennedy et al., 2015), but mostly for megacities and far less for mid-sized cities where most urban growth is expected to occur (Yetano Roche et al., 2014). We have models for evaluating flows managed by water supply and drainage infrastructure, and have gone some way towards their integrated assessment (Bach et al., 2014), and also towards integrating the dynamic factors that influence urban water (Urich and Rauch, 2014). Early efforts to evaluate the city water mass balance show how urbanisation affects natural hydrology (Haase, 2009), and highlight the considerable scope for efficiency improvements (Kenway et al., 2011a).

The gap is that we have not gone far enough to understand and quantify the overall hydrological performance of urban water systems, different urban typologies, and the influence of water sensitive interventions. In particular we do not currently account for all the components needed to understand the water metabolism of urban areas, namely the diverse sources and functions of water in the urban landscape, the water connections between urban areas and their supporting regions, and the inter-relationship between water and other resources (energy, carbon and nutrients). These aspects of urban water management have not been modelled or monitored to date.

There are also limitations in the methodology of urban metabolism evaluation to be addressed before it can be effectively operationalised (Baynes and Wiedmann, 2012, Yetano Roche et al., 2014, Zhang, 2013):

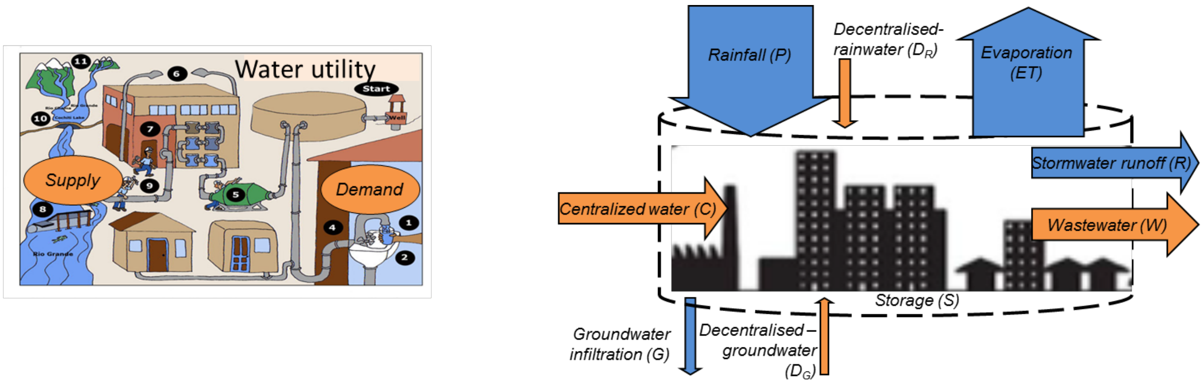
- a lack of uniformity in methods, including urban boundary definition, and the identification of meaningful indicators of urban hydrological performance;
- limited methods specifically related to water metabolism (there has been far more work done on energy and greenhouse gas emissions);
- paucity of data and lack of templates for repeatable and consistent data collection over time for monitoring and benchmarking, which is a limitation for all urban water studies not just metabolism;
- the static (‘black-box’) nature of metabolism analysis which doesn’t enable analysis of the drivers that influence resource flows (such as population, climate fluctuations, and socio-economic factors).

A more holistic framework for conceptualising urban water

Our traditional framework for urban water systems has been centred on centralised water and wastewater systems, where the system is managed by matching supply to demand (Figure 4a). This framework has been extended in recent times to integrate diversified water supplies (rainwater, stormwater, recycled wastewater) into the centralised system. In doing so, it also endeavours to restore pre-development hydrological flows. This framework has tended to be applied at micro- or meso-urban scales.

A future framework envisaged by this research and based on urban metabolism offers a more holistic view of urban hydrology (Figure 4b), by:

- measuring the hydrological performance of the urban area with a holistic mass balance framework rather than the water supply and drainage system with a supply-demand framework;
- considering the hydrological performance of urban areas as a whole, so that planning can optimise outcomes overall and avoid unintended problem shifting between components of urban areas; and
- being outward-looking, considering how urban areas link to and influence its supporting regions, rather than focusing just on what's happening within urban areas.



a) Supply Demand Balance: Supply = Demand

b) Water Mass Balance: C + D + P = W + R + G + ET + ΔS

Figure 4. Traditional supply-demand balance versus a water mass balance

Outcome #2:

Urban Water Mass Balance method offers a good foundation for urban metabolism evaluation, due to its capacity for generating indicators of metabolic performance.

It is more holistic than traditional supply-demand balance, as it measures the performance of the urban system, rather than the performance of the water system infrastructure.

There are examples from other sustainability fields where frameworks have evolved to be more holistic. The environmental management of product systems has changed from a framework based on managing and regulating individual industries within a product supply chain, to one based on the supply chain as a whole. This framework of 'product life cycle thinking' which emerged in the 1990s (UNEP, 1999) has now developed into methods for LCA and footprinting. They are governed by international standards (Finkbeiner, 2014) which now underpin environmental regulations and certification standards for products. It is likely that urban systems will be the next candidate for more holistic evaluation, and urban metabolism would be a suitable framework.

Utility of urban metabolism

How can urban metabolism advance water sensitive cities?

The concept of ‘water sensitive cities’ has been an evolution in how we view and value water in urban areas (Brown et al., 2009), in terms of diversifying water supply, recognising the wider functions of water in the urban landscape, integrated management of a more complex urban water system, and resource efficiency. Accordingly, there is a need to evolve how we evaluate urban water to monitor these objectives.

The need for **supply diversification** to address **supply security** is a central theme of water sensitive cities. It has emerged as centralised supplies become prone to water shortages due to climate change and growing demand. This makes the picture of supply and demand more complicated, from one based on a single source of water with uniform quality feeding all uses, to one based on multiple sources of varying fit-for-purpose qualities directed to different functions (Renouf et al. in press). Therefore, supply security now needs to be evaluated in this context, matching diverse supplies to diverse functions to maximise the functionality that water delivers, and within the constraints of environment to supply water. There is currently no evaluation framework for doing this.

The water sensitive cities concept recognise the **diverse function of water** beyond its primary value for sustaining life, health and productivity, to also include liveability (amenity, recreation, etc.), environmental and cultural services. For example water for irrigation to maintain vegetation is central to mitigating urban heat island effects for improved amenity (Coutts et al., 2014), maintaining natural water flows in urban streams is needed for environmental services (IWA, 2015), irrigation of sports fields can be important for community recreation and hence health and liveability. We don’t currently have an evaluation framework that accounts and budgets for these functions so we can evaluate the significance, feasibility and multifunctional benefits of directing water to these functions (Renouf et al. in press).

The above calls for **integrated management** of the diverse sources and uses of water in the urban landscape. Existing integrated urban water models (such as Aquacycle, Dance4Water and the CRCWSC Modelling Toolkit) enable integrated evaluation mostly at micro- and meso-urban scales, and mainly for the supply side of the water system. However integration needs to be scaled-up to the macro urban scale (i.e., city-region), and linked to the demand side of the water system to account for the diverse uses.

Resource efficiency is currently tackled through efficiency measures at the end user (potable water), supported by quantification of per capital water use. However, we don’t understand or quantify the water efficiency of urban areas overall (Renouf et al. in press), and this is the aspect that urban metabolism can make the greatest contribution to. Energy efficiency is another aspect of resource efficiency. However the energy implications of water are currently not an element of a water sensitive city, except in relation to energy-efficient wastewater treatment (Batstone et al., 2015). We propose that broader consideration of water-related energy will enhance what the ‘water-sensitive cities’ can deliver. This is because many – but not all – water sensitive opportunities can generate significant energy savings, both for water utilities and for urban dwellers. It will also ensure that pursuing water-sensitivity does not come at the expense of energy and climate change objectives.

How can urban metabolism inform planning?

Urban metabolism methods per se will not lead to the design and management of water-sensitive cities. To have effect it needs to align with existing decision making processes, particularly urban and regional planning processes. So the conceptualisation of the urban water metabolism framework is informed by parallel research about how metabolism science can inform planning policies and processes. In doing so, it will contribute to improving integration of decisions concerning land-use and water planning, which are often carried out separately (Serrao-Neumann et al., accepted, Plummer et al., 2011). The impacts of urbanisation on hydrological systems call for better integration between them to ensure the sustainability and resilience of cities and their regions. This is particularly important for the Australian context where water resources management is undertaken by multiple government and non-government agencies without being coordinated and/or integrated to address the total water cycle (Plummer et al., 2011). For example, it is common to find government agencies working separately and independently to manage water supply and distribution, wastewater and stormwater.

There is a growing body of academic literature that explores the potential of urban metabolism to improving planners' understanding of resources flow through, and exhaustion by, urban systems (Chrysoulakis et al., 2015, Chrysoulakis et al., 2013). In particular, urban metabolism studies may support decision making in urban and regional planning as they enable the description and analysis of how materials flow into and out of urban areas (Kenway, 2013, Kennedy et al., 2011). Specifically, urban metabolism studies may provide planners with a range of useful information, including guiding the selection of sustainability indicators through to urban greenhouse gas accounting, identification of holistic solutions to environmental issues beyond 'end of pipe' approaches, and as a design tool (Chrysoulakis et al., 2013).

To date, urban metabolism studies have been predominantly academic exercises. To increase applicability in the urban and regional planning context, there needs to be translation of the technical and quantitative information in a way that can influence urban and regional planning (González et al., 2013, Chrysoulakis et al., 2013). A number of initiatives have explored this:

- The BRIDGE project[2] produced a Decision Support System (DSS) for evaluating the influence of planning alternatives on sustainability aspects, including the urban metabolism of energy, water, carbon and pollutants (Chrysoulakis et al., 2013).

- The SUME project[3] analysed the impacts of existing urban forms on resource use and estimated the future potential to transform urban form to significantly reduce resource and energy consumption (EC, 2011).

- The City of Barcelona adopted urban metabolism to guide its vision for a sustainable future (Rueda, 2007).

- The urban metabolism concept has been adopted in a number of city reporting frameworks, such as the Australian State of Environment Report (Newman et al., 1996, Newton et al., 2001), the Asian and European Green Cities Index (EIU, 2011), and the City BluePrint program (Van Leeuwen, 2013).

These past efforts have cut across a wide range of urban resource issues (energy, greenhouse gases, materials etc.), and have not considered water in much detail. Further work is needed to advance the translation of water metabolism information into planning processes. A key challenge in this is the spatial scale at which water metabolism is evaluated. Water flows need to be considered in the context of the entire urban and peri-urban landscape, beyond the limits of the urban footprint (Dakhia and Berezowska-Azzag, 2010). So larger, macro urban scales (city-regions) may be the appropriate scale of application, but this needs to be tested as part of the research.

Linking urban areas to their supporting regions

Urban areas are not isolated entities; they exist within and ultimately depend on their surrounding landscapes which extend far beyond their built edge. The water sensitive city needs to be understood in relation to the landscape of their supporting regions (Serrao-Neumann et al., in press) and their water-related needs. The contribution offered by the urban metabolism concept is intrinsically linked to its central notion of conceiving the urban area as an ecosystem –which recognises how different components interact and affect one another. Understanding the way an ecosystem functions requires looking at the relationships and interactions between different elements of the landscape, including water. It also highlights the importance of considering landscape

[2] Sustainable urban planning decision support accounting for urban metabolism (www.bridge-fp7.eu/)
[3] Sustainable Urban Metabolism for Europe (www.sume.at/)

connectivity in decision making concerning water resources and how urban areas depend upon and impact their surrounding landscapes.

Landscape connectivity can be understood from a range of perspectives. From an ecological perspective, Meiklejohn et al. (2009) distinguishes between two different terminologies of landscape connectivity. The structural connectivity implies a physical connection within the landscape, whereas the functional connectivity implies facilitating the movement of organism and processes though the landscape. From a geomorphological perspective, connectivity refers to how water and sediments are transferred between landforms (Baartman et al., 2013) or two different compartments of a catchment (Fryirs, 2013). There are three main types of geomorphological connectivity: (i) landscape connectivity that refers to physical coupling of landforms; (ii) hydrological connectivity which involves the flow of water through the catchment; and (iii) sedimentological connectivity which comprises the transfer of sediment through a basin (cf. Bracken and Croke cited in Baartman et al., 2013, p.1457).

In the context of water sensitive cities, landscape connectivity implies both structural and functional connectivity. The key principles underpinning the design of water sensitive cities are based 'on considerations of minimizing the import of potable water, and the export of wastewater, from and to areas outside of the boundaries of the city, and optimizing the use of water resources within a city' (Wong and Brown, 2009 p. 680). Urban metabolism evaluation can improve our understanding of how water flows in and out of urban areas (and associated landscape connectivity); thereby supporting urban and regional planning decisions that address connectivity.

Additionally, there are similarities between the concepts of landscape connectivity and urban metabolism. Urban metabolism focuses on circularity of processes (e.g., water cycle, carbon and nutrient cycles, etc.) and as Giradet (2008) argues 'The long term viability and sustainability of cities is reliant on them shifting from a linear to a circular metabolism in which outputs are recycled back into the system to become inputs' (cited in Rapoport 2011a, p.11). Applying the principles of water sensitive cities to urban water management by utilising the concept of landscape connectivity could therefore help achieve this so-called 'circularity'. By embracing the concept of circular metabolism, whereby energy and materials are considered throughout their lifecycle, planners are likely to pay more attention to the connections between the different elements of the urban environment and its surrounding; thus producing more sustainable and holistic urban systems (Kavournis, 2015).

However, the natural water cycle and associated landscape connectivity have been significantly disrupted by urbanisation. The loss of permeable surfaces and the artificial channelization of runoff have contributed to changes to ecosystems as well as increased risks of flooding and transport of pollution in urban areas and its surroundings. Urban metabolism provides the conceptual framework to assess whether the current water related processes are functioning optimally compare to the way they would have functioned prior to development. This information provides a benchmark to examine what needs to be done to improve the efficiency of water management in our cities (Kenway et al., 2013). By taking a landscape connectivity approach complex systems involving water transportation, evaporation, and infiltration could be assessed comprehensively rather than locally, thereby ensuring that the complicated interaction across the landscape is considered. This includes the establishment and/or rehabilitation of greenspaces throughout the landscape. Including the diverse functions of water in our understanding urban water metabolism provides a mechanism for valuing greenspace and the connectivity it provides to support water resources and water sensitive cities. To this end, a greenspace framework is being developed in parallel to the urban metabolism evaluation framework (Serrao-Neumann et al., 2015).

Informing planning policy

Urban metabolism evaluation can inform planning policy by:

- characterising the metabolic characteristics of different settlement typologies within the urban landscape, i.e. urban, peri-urban, and the rural supporting region (Figure 5);

- monitoring the influence of urban and regional planning policies;
- designing for the multi-functionality of water in the urban landscape;
- evaluating, through scenario analysis, the changing hydrological performance of urban areas under population and climate change;
- understanding the competition between the diverse urban functions of water.

Figure 5. An example of defining settlement typologies in the urban landscape
(urban and peri-urban boundaries and the scale of water flows indicated by the arrows are provided for example only, and are not accurate. Dotted line indicates fuzzy boundary between peri-urban and urban areas)

Feeding science into planning processes

Typically, urban and regional planning processes have followed the rational planning model which predominantly bases land-use decisions and development controls on scientific evidence and expertise knowledge (Alexander, 1984, Alexander, 2000). By contrast, emerging alternative approaches to planning processes are centred on greater engagement of stakeholders, whereby planning decisions are a result of governance frameworks beyond government ranks and expertise knowledge (Renn, 2006, Healey, 2006). Under these governance frameworks, planning decisions have to capture the multi-scale jurisdictional nature of policy-making which requires improved horizontal and vertical integration within and across tiers of governments as well as the involvement of interested parties (van de Meene et al., 2011). Specifically, multi-scale governance examples have flourished in the last decades as a response to environmental change and need to better understand and manage social-ecological systems (Smith, 2007, Bisaro et al., 2010). However, taking Australia as an example, current decision making processes involved in land-use planning are heavily influenced by political motivations which are largely driven by private sector interests and economic considerations and not necessarily by best available scientific information (Measham et al., 2011, Taylor et al., 2013). Regardless of the availability and quality of science or level of stakeholder engagement, decisions involving environmental change tend to be guided by short-term electoral cycles rather than long-term needs (Bulkeley, 2006, Wilson, 2006).

Pathways for feeding urban metabolism science into planning need to be clearly articulated to enable its uptake by the planning process. Dilling and Lemos (2011) noted conflicting perspectives between what scientists think is useful and what is actually usable from a stakeholder/practice perspective, often determined by a ‘pull-push’ process. Typically the push end of the process is represented by the research agenda set by scientists while the pull end is characterised by the priorities raised by stakeholders. These authors suggest that to strike a balance in the ‘pull-push’ process, knowledge needs to be co-produced through continuous iteration between the two groups. Our project has adopted a number of stakeholder engagement strategies (e.g., project reference group and stakeholder workshops) that attempts to address Dilling and Lemos’ concern and therefore maximise opportunities for urban metabolism studies to inform planning decisions. Additionally, we identify key planning processes that could be supported by the urban metabolism concept (see Figure 6).

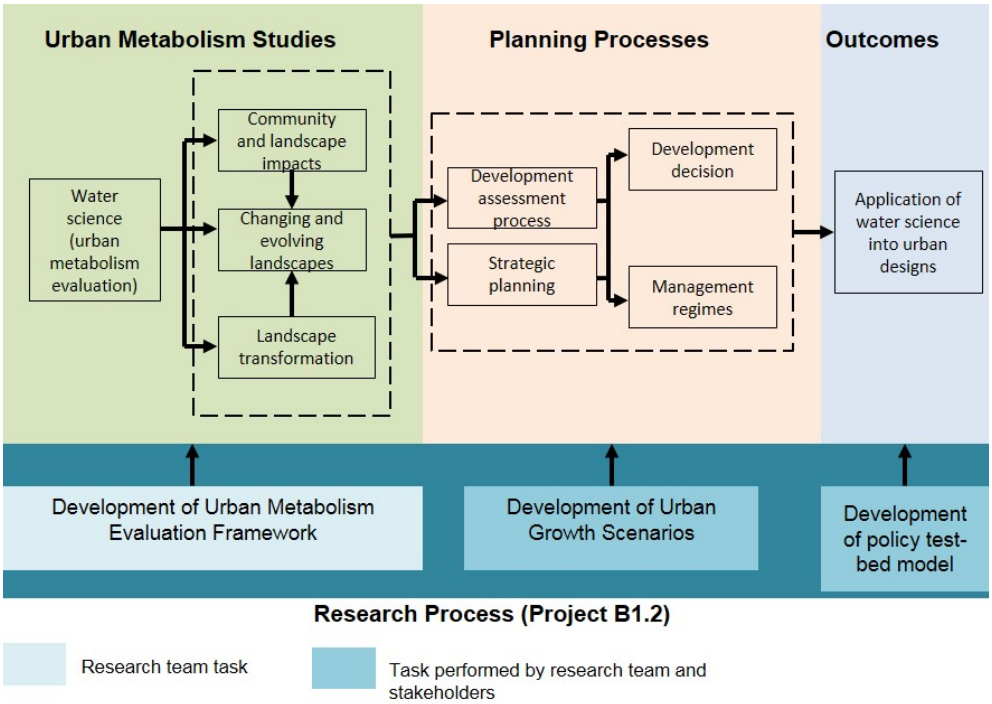


Figure 6. Pathways for feeding urban metabolism science into planning processes.

Desired utility of the urban water metabolism evaluation framework

Bringing together the information needs for informing urban and regional planning and for advancing water sensitive cities (Table 2), we propose that the desired utility of the framework is to:

- frame indicators of urban hydrological performance;
- account for the diverse sources and functions of water in the urban landscape to maximize multi-functionality of water;
- link urban areas to their supporting regions to understand potential competition for water; and
- account for water-related energy use to understand potential energy trade-offs of water management.

Outcome #3:

The desired utility of the framework for informing planning and advancing water sensitive cities has been defined to guide its further development.

These will be guide the further development and application of the framework in subsequent phases of the research.

Table 2. Utility of framework for informing planning and advancing water sensitive cities (derived from Renouf et al. in press)

Framework utility	Advancing water sensitive cities					Informing planning	
	Supply security	Supply diversification	Integrated management	Engagement	Resource efficiency	Linking urban areas to supporting regions	Informing planning policy
Frame indicators of urban hydrological performance to:							
- monitor the influence of urban and regional planning policy							×
- characterise / compare / benchmark cities and urban typologies							×
- report resource efficiencies as part of the Water Sensitive Cities Index				×			
- reporting urban hydrological performance in state of environment reports				×			
and national accounts				×			
Account for the diverse sources and functions of water to:							
- design for the multi-functionality of water			×		×		×
- holistically evaluate opportunities for supply diversification, resource efficiency and supply security	×	×	×		×		
- evaluate through scenario analysis the changing hydrological performance of urban areas under population and climate change							×
- understand the competition between the diverse urban functions of water							×
Link urban areas to their supporting regions to:							
- understand the competition between the urban and regional water use						×	×
- evaluate the city's reliance and drain on regional water supplies and competition with other users in the supporting region	×					×	×
Account for water-related energy use to:							
- understand potential energy trade-offs of water management					×		

A conceptual framework for evaluating urban water metabolism

There is currently no single recognised framework for urban metabolism evaluation. Various approaches are described in the academic literature, but methods vary in terms of the urban scale assessed, the system scope (i.e., the water flows included) and information generated (Renouf and Kenway, accepted).

A material flow accounting (MFA) approach has been developed by Kennedy et al. (2014) and used in a large study to quantify the urban metabolism of megacities (Kennedy et al., 2015). This could be seen as a template method, but it covers a very wide range of urban resource flows (energy, greenhouse gases, food, materials etc.) and the evaluation of water flows isn't developed enough for our purposes. It is limited to per capital potable water consumption. The Eurostat method for national material flow accounting (EC Eurostat, 2001) is a standardised MFA method that has been adapted to urban metabolism evaluation at the city scale (Barles, 2009, ADB, 2014), but does not consider water flows.

So in summary, existing frameworks / methods are not sufficiently developed to meet our needs for holistically evaluating urban water, and it was necessary to conceptualise a new framework that focuses on water. However it will be important to be cognisant of the above-mentioned emerging international protocols so the developed framework can be consistent wherever possible.

The aim of the new framework is:

"*to generate indicators and knowledge about the hydrological performance of urban areas, using urban metabolism as the conceptual framework and urban water mass balance as the method".*

It is referred to as an *urban water metabolism evaluation framework* (UMEF4Water).

Concept development progressed to the point of defining the design elements of the framework (Table 3), which are briefly described in this section. It has been informed by our review of existing evaluation methods (Renouf and Kenway, accepted), and our previously-described analysis of its utility for advancing water sensitive cities and informing planning. The operationalisation and testing of the framework will occur in next phase of the project.

Outcome #4:

A concept for an *Urban Metabolism Evaluation Framework for Water (UMEF4Water)* has been developed using urban water mass balance as the method, and the key elements defined.

Table 3. Elements of Urban Metabolism Evaluation Framework for Water (UMEF4Water)

Aim:	To generate indicators and knowledge about the hydrological performance of urban areas, using urban metabolism as the conceptual framework and urban water mass balance as the method.
Urban scale:	Applicable to various urban scales (household, neighbourhood, precinct, catchment, city, city-region).
Method:	The core method is urban water mass balance described in Kenway et al (2011a) and further developed by Farooqui (2015). It quantifies all water flows (natural and managed) into and out of an urban area with a defined urban boundary. This method will be extended to also account for the diverse uses of water in the urban landscape, and account for water-related energy (see Figure 7). The quantified water flows are used to generate indicators of urban hydrological performance. The quantities of water exchanged between the urban area and its supporting region can be used understand the drain and impact of the urban system on supporting regions (still under development).
System boundaries:	**Spatial extent of urban area:** For a given urban scale, the urban area is defined by a three-dimensional boundary (see Figure 7). Criteria for defining the spatial extent of urban area is still to be established, but could include: – built-up or heavily urbanised areas, i.e. those with imperviousness factor >x or a population density > y; – areas serviced by the centralised water supply / sewerage system; – alignment as far as practicable with hydrological catchment or sub-catchment boundaries. For macro-scale analysis of cities or city-regions, the urban boundary should also align as far as possible within the statutory 'Urban Footprint'. The vertical extent of the urban area extends from the roofline and tree canopy, to a point above the groundwater table (i.e. not including groundwater tables), typically to a depth of 1m below ground. **Spatial extent of supporting region** The supporting region is the 'environment' directly surrounding the urban area that services the water needs of the urban area in terms of water supply, and assimilation of wastewaters and stormwater runoff. Criteria still to be established. **Technical boundary of the urban system**: The urban system includes all natural water flows (precipitation, evapotranspiration, groundwater infiltration, and overland runoff, and all managed flows (centralised water supplies (potable water) from surface water or groundwater, decentralised water supplies (rainwater, groundwater, etc.), wastewater and stormwater drainage).
Analysis objectives:	– Framing indicators of urban hydrological performance – Accounting for the diverse sources and functions of water in the urban landscape to maximize multi-functionality of water – Linking urban areas to their supporting regions to understand potential competition for water – Accounting for water-related energy use to understand potential trade-offs
Outputs:	Indicators of hydrological performance (see Table 4 for preliminary examples).

Elements of the framework

Urban scale of application

What is regarded as 'urban' can have different scales – from households, to urban precincts (suburb, neighbourhood), up to the larger scale of cities[4] and city-regions (the population catchment of the city). In relation to hydrological performance, Haie and Keller (2012) define these as micro, meso and macro urban scales.

The urban metabolism evaluation framework could be applied at any of these scales. For informing planning, application at the macro urban scale may be most useful, hence application at the city-region scale will be emphasised.

To date, urban metabolism studies reported in academic literature have been undertaken at the household-, neighbourhood- and city-scale. City-scale has been the most common particularly for comparing and benchmarking cities (Renouf and Kenway, accepted). It has not been applied at the city-region scale to date, or to characterise the metabolic characteristics of the settlement typologies across city-regions (urban, peri-urban, rural). So its application at macro-scales will be an innovation in this field.

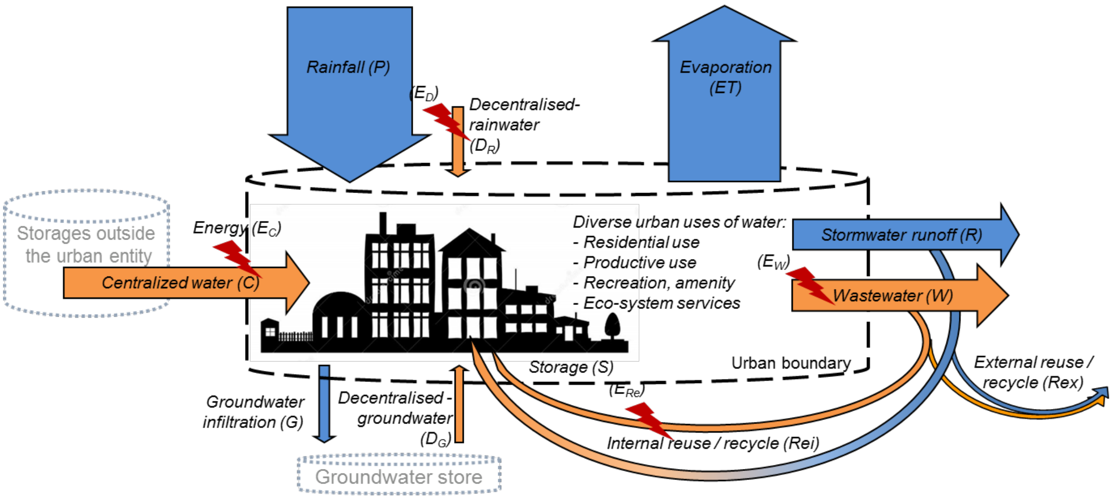
Method – urban water mass balance

The method found to be a good foundation for urban water metabolism evaluation is urban water mass balance (Renouf and Kenway, in press). This technique accounts for all water flows into and out of an urban area to achieve a mass balance (i.e., inflows = outflows + change in storage). The approach can be applied to urban water supply and drainage systems to inform infrastructure design (Bach et al., 2014), or to hydrological catchments to understand the influence of urbanisation on natural hydrological flow (Haase, 2009). However for urban metabolism applications, we are interested in its application to the urban system as a whole (Kenway et al., 2011a, Thériault and Laroche, 2009), and refer to it as an *urban water mass balance* to distinguish it from the others.

An urban water mass balance gives a complete account of all urban water flows, both natural and managed (see Figure 7). Water flows refer to the annual inputs and outputs, consistent with the terminology used in national environmental accounting (EC Eurostat, 2001). At the macro urban scale (i.e., whole of city or city-region), it can be a top-down analysis using primary data from national accounts, such as in the framework proposed by Kenway et al. (2011a), or a bottom-up analysis using modelled data for sub-catchments within an urban area which are aggregated up to a larger scale, such as in the SWITCH City Water Balance model (Mackay and Last, 2010) and Dance4Water (Urich et al., 2013).

For the urban metabolism evaluation framework we propose to use the top-down water balance method of Kenway et al. (2011), which has been developed further to account for reuse and recycle pathways (Farooqui, 2015). This is because the comprehensiveness and accuracy that the mass balance drives enable a wide range of performance indicators to be derived. See Text Box 2 for an example application of the method.

[4] A city can be a single city or polycentric – in planning, this term is used in relation to urban nodes not amalgamation of cities – (an amalgamation of connected cities–conurbation).



Urban water Mass Balance:

$$\text{Sum of inflow} = \text{Sum of outflows} + \text{change in storage}$$

$$C + D + P = W + R + Re_x + G + ET + \Delta S$$

Water-related Energy:

$$\text{Total system energy input} = E_C + E_D + E_W + E_{Re}$$

Figure 7. Urban water mass balance method (adapted from Kenway et al (2011a) and Farooqui (2015))

Table 4. Example indicators of hydrological performance derived from the urban water mass balance (adapted from Farooqui 2015)

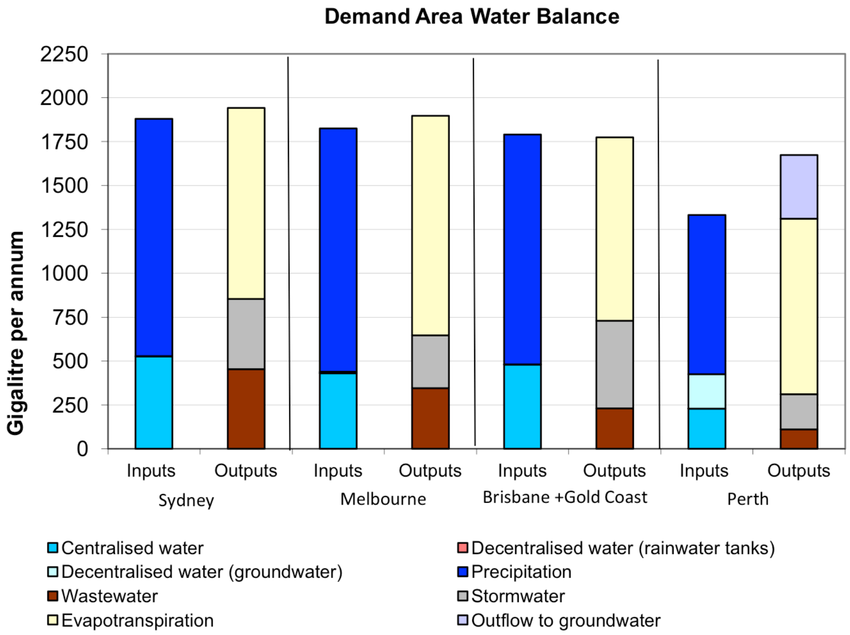
Theoretical internal supply capacity from various sources	
Proportion of total urban water demand that could potentially be met by internal (decentralised) sources [1]	Amount of harvestable water / Total demand
Degree of internal sufficiency	
Proportion of total urban water demand that is actually met by internal (decentralised) sources	D_R + Rei / Total demand
Degree of departure from pre-development hydrological flow	
Percentage change in the scale of hydrological flows (at time *t*), relative to the pre-development state	
– Stormwater runoff	$Rs_{(t)} / Rs_{(0)}$
– Total stream discharge	$(W_{(t)} + Rs_{(t)}) / Rs_{(0)}$
– Groundwater infiltration	$G_{(t)} / G_{(0)}$
– Evapotranspiration	$ET_{(t)} / ET_{(0)}$

[1] Harvestable wastewater, stormwater runoff and rainfall

Text Box 2. Urban water mass balance case study – Australian cities

A city water mass balance of four Australian cities (Figure 8) identified large flows of rainfall, stormwater, and wastewater passed through the cities underutilised, with very low recycle rates, confirming that cities are not metabolically efficient (Kenway et al., 2011a):

- rain falling on the cities was at least 250% of water demand, but only 0.1-22% is harvested;
- treated wastewater could potentially meet 26–86% of demand, but only 1–4% is recycled;
- stormwater recycling could potentially meet 47–104% of demand, but is currently zero.



	Supply centralisation (C/(C+D))	Reuse of anthrogenic input (Re/(C+D))	Rainfall Harvesting (D/P)	Replaceability	
				Storm-water (S/(C+D))	Waste-water (W/(C+D))
Brisbane (SEQ)	100%	2%	0.1%	104%	48%
Sydney	100%	1%	0.1%	76%	86%
Melbourne	98%	4%	1%	68%	79%
Perth	54%	1%	22%	47%	26%

Kenway et al. (2011) Urban water mass balance analysis. J. Ind. Ecol, 15(5)

Figure 8 . Example results from an urban water mass balance for Australian cities (2004-2005) (Kenway et al. (2011a))

System boundary

As urban metabolism is concerned with resources exchanges between ‘urban’ areas and the ‘supporting region’ (the environment), we need to define what we mean by these terms. Our boundary definitions will define what flows are included in the urban water mass balance, and what flows are not. Consistent boundaries are important when comparing urban areas, typologies or scenarios.

In relation to the spatial extent of ‘urban areas’, there is no universally agreed protocol for defining what is ‘urban’. There are a few interpretations based on population density and a common commuter shed. The OECD (2012) for example, define urban areas as ‘functional economic units’, and use population density to identify urban cores and travel-to-work flows to identify the outer areas whose labour market is highly integrated with the cores. In a large-scale urban metabolism study of megacities, Kennedy et al. (2015) notes that in practice, the availability of data will determine boundaries applied by researchers, and hence used administrative boundaries in their analysis. In the absence of an established protocol, this research will explore criteria for defining the spatial extent of urban areas that best align with urban metabolism informing planning. This task is ongoing, but preliminary criteria are described in Table 3 as examples.

Using an urban water mass balance approach, we need to define the urban area in three-dimensions (spatial area as well as a depth). This is because water moves through urban areas in three dimensions, including rainfall, surface flows, flows through water supply and drainage infrastructure, and flows to and from groundwater. Storage changes within the three-dimensional volume also need to be considered. Flows passing through urban areas via natural waterways (i.e., flows originating from and discharging to outside the urban area) are not included.

Bulk surface water storages and groundwater aquifers are considered part of the supporting region, as including them in the urban boundary would internalise many urban-environment flows and lead to them being non-consequential for the water balance. Adopting a tight system boundary in this way increases accuracy in the water mass balance. It helps detect smaller difference in the independently measurable system inputs and outputs, and hence drives greater accuracy.

We define the ‘supporting region’ as the environment directly surrounding the urban area that provides its direct water services, in terms of water supply and assimilation of wastewaters and stormwater runoff. We stress our focus on direct water services from the local environment, as opposed to indirect water services from more distant hinterlands (as in ‘water footprints’). The framework quantifies the exchange of water between urban areas and the local supporting region.

Analysis outputs

– Framing indicators of urban hydrological performance

The framework will aim to generate urban hydrological performance indicators from the urban water mass balance, which can be used for both informing planning policy and monitoring progress towards water sensitive cities in relation to resource efficiency (Table 2).

The scoping of indicators has only recently commenced (Renouf et al., in press). Examples of possible indicators are shown in Table 4, which represent the utilisation of water sources within the city catchment, and re-establishment of natural hydrological flows. There remains considerable scope to derive further indicators, for example overall water use efficiency (i.e., extent of urban liability delivered per unit of net water use), and drain on regional resources (i.e., degree to which the supplying region can accommodate urban water demands).

– Accounting for the diverse sources and functions of water

The comprehensiveness of an urban water mass balance means that the diverse sources of natural and anthropogenic water available to the city can be quantified, so the capacity for supply diversification across urban areas at the macro-scale can be better understood.

As well as quantifying the in-flows and out-flows across the urban boundary, the framework will aim to extend the urban water mass balance to also quantify through-flows of water, i.e. the flows of supplied water to various uses. This will allow for the diverse functions of water within the urban landscape to be accounted and budgeted for. In addition to the primary consumptive uses, which are already well accounted for, it will aim to also include water used for amenity, heat island mitigation, maintenance of greenspace, and environmental and cultural services, etc. This will enable analysis of the significance, feasibility and multifunctional benefits of directing water to these functions.

– Linking urban areas to their supporting regions

The in-flows of water from ‘supporting regions’ to ‘urban’ areas, quantified by the urban water mass balance, can be compared against the water supply capacity of the supporting region, and demands to sustain other activities in supporting regions. This will allow us to understand the drain of urban areas on water resources and what constraints on future urban expansion may be required to manage potential conflicts.

– Accounting for water-related energy use

The framework will focus on urban water flows. However in recognition of the importance of the nexus between water and other resources (energy, greenhouse gas emissions and nutrients), the framework will build in capacity for overlaying the analysis of these other water-related resource flows. In this initial phase of the research, it will only be possible to integrate water-related energy. Future iteration of the project may extend this to account for water-related greenhouse gas emissions and nutrient flows.

The framework will estimate water-related energy inputs to the urban water system, for water treatment and pumping for centralised and decentralised water supplies, water use, and wastewater treatment. This will enable energy implications to be considered alongside water. See an example of the value this provides in Text Box 3.

Text Box 3. The value of considering water-related energy in water planning

City 1 has the most energy-efficient pumping and water treatment, but draws on water from 100km away, and uses little of the rain falling on the urban area. City 2 has more energy-intensive pumping and treatment, but harvests rainwater which falls directly on the city and uses it to irrigate green spaces to mitigate urban heat island effects. The reduction in household air-conditioning demand in City 2 results in an overall better energy efficiency than City 1. City 1, based on traditional urban development creates enormous volumes of stormwater runoff, which is unutilised, but at the same time pumps water from distant sources.

The above example would purport that the use of stormwater, rainwater, and wastewater as water supplies will have favourable energy intensity. However, system design is also critical for energy efficiencies, as the energy use for some decentralised or inefficient systems can be high (Retamal et al. 2009). The current average energy use for water from rainwater tanks is 1.5 kWh/m^3, not much different to water and wastewater services in Australian capital cities (1.6 kWh/m^3) (Kenway et al., 2010). However rainwater tank systems can be designed to use less than 0.2 kWh/m^3 if they utilise header tanks, low pressure pumps, and reconfigure toilet valves to operate under low pressure (Cunio & Sproul 2009). Consequently, for cities using a large proportion of decentralised water supply (such as Perth where 46% of water supply is sourced from decentralised ground-water) consideration of energy-efficiency is essential.

Data sources

The framework will require data for water flows making up the urban water mass balance (Figure 7), for a selected time period, and to align with the selected urban boundary. Data may need to be drawn from a range of different datasets. This can be challenging, as datasets can have inconsistent frameworks, with differences in geographic scopes and flow characterisation. Potential data sources are as follows (Table 5):

- The Bureau of Meteorology's (BOM) Urban Water Accounts compiles much of the required data in a uniform format from 2010 onwards. The challenge will be to align the data, which is currently reported at a larger regional scale, to the tighter urban scale required for this research.
- The National Performance Reports prepared by the National Water Commissions (NWC), and now managed by BOM, compiles data from water utilities.
- Data for natural hydrological flows (stormwater runoff, etc.) can be generation of using 'bottom-up' models such as MUSIC and the Australian Water Resources Assessment System (AWRA-System).
- Australian Urban Resource Information Network (AURIN) collates data spatially (at the suburb or statistical area scale) and could allow for easier alignment of data with the required urban boundary. The population of data into AURIN has only just commenced and it may be some time before the full scope of required data is available.

Preference will be given to drawing on existing compiled data sets (such as the BOM Urban Water Accounts) so that data collation efforts are not duplicated. The value of this research is in extracting meaningful information and metrics about urban water metabolism, not in the data collection itself. As such it can provide an interpretive overlay to existing data collation and modelling activities. Furthermore, other urban water evaluation frameworks, such as the Dance4Water and the CRCWSC Toolkit, have similar data requirements. So consideration will be given to co-ordination that allows the frameworks to draw on a common data pool.

The data servicing plan described thus far will suit 'static' analysis for given time period and fixed parameters. More dynamic evaluation may be possible by drawing on the data generated from Dance4Water, which models the influence of changing bio-physical and socio-economic on water system parameters (Figure 6).

A future vision for data acquisition will be to align with evolving 'smart cities' and 'big data' sources (Gemma and Mc Intosh, 2014), such as the Australian Water Resources Information System (AWRIS,) the Australian Urban Resources Infrastructure Network (AURIN), and cloud-based economic flow models such as the Industrial Ecology Virtual Laboratory (Lenzen et al., 2014).

Table 5. Potential data sources

Data item		**Potential source**
In-flows	Precipitation (P)	BOM Climate Data or Urban Water Accounts
	Centralised water supplies (C)	BOM Urban Water Accounts or NWC National Performance Reports
	Decentralised water supplies (D)	BOM Urban Water Accounts
Out-flows	Evapotranspiration (ET)	BOM Climate Data or Urban Water Accounts
	Groundwater infiltration (G)	BOM Urban Water Accounts
	Stormwater runoff (S)	Generated using AWRA model (for larger catchment scales) or generated using MUSIC (or smaller sub-catchments)
	Wastewater (W)	BOM Urban Water Accounts or NWC National Performance Reports

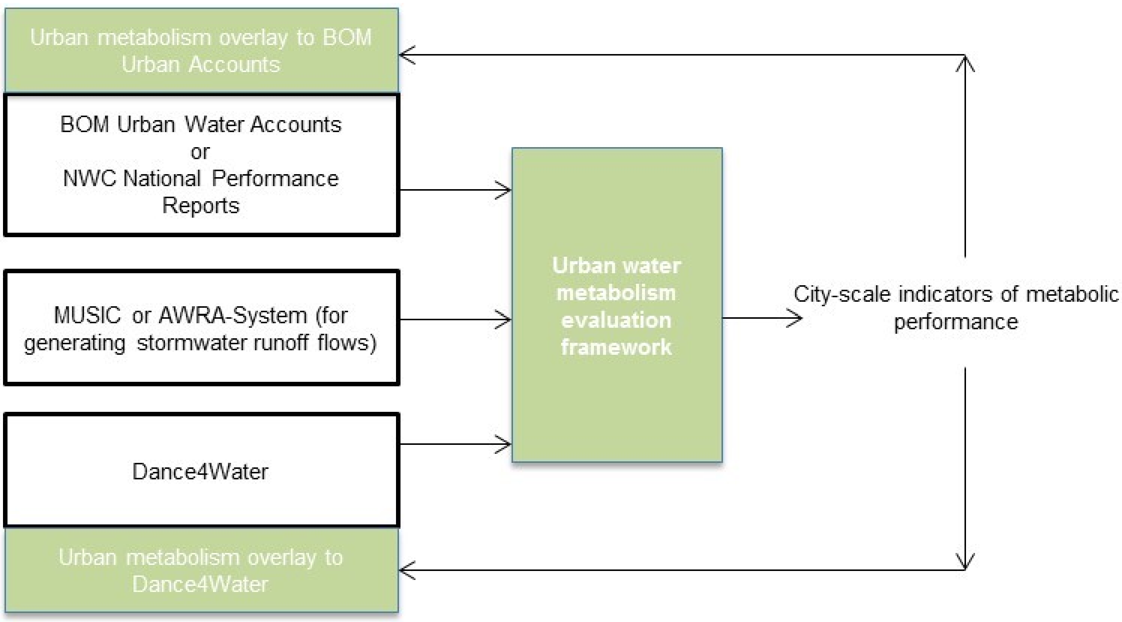


Figure 9. Proposed data flows

Link to other projects

As the framework aims to be holistic, by capturing multiple aspects of the urban system within a 'big-picture' framework (water sources, water functions, interactions with supplying environments, energy interactions), it has the capacity to draw in research outputs from other CRC Program B projects:

– *'Cities as Water Supply Catchments – Urban rainfall in a changing climate'* (Project B1.1) – Rainfall projections at appropriate (urban) scales by downscaling precipitation models

– *'Hydrology and Nutrient Transport Processes in Groundwater/Surface Water Systems'* (Project B2.4) – Groundwater and surface water interactions

– *'Cities as Water Supply Catchments – Green Cities and Microclimate'* (Project B3.1) – Urban microclimates, in relation to urban heat mitigation

– *'Social-Technical Flood Resilience in Water Sensitive Cities – Quantitative spatio-temporal flood risk modelling in an urban context'* (Project B4.1) – Socio-technical flood resilience, in relation to the intersection between stormwater capture for supply and flood mitigation

The outputs from the framework could feed into other CRCWSC programs, for instance:

– *'Engaging communities with Water Sensitive Cities'* (Project A2.3) – The Water Sensitive Cities Index could use the urban hydrological performance indicators generated by the framework as part of its 'resource efficiency' indicators

– *'Cities as Water Supply Catchments – Integration and Demonstration through Urban Design'* (Project D1.1) – The framework could be integrated into the CRCWSC Toolkit

The framework may draw on city-scale data compiled by the other urban water modelling activities, such as:

– *'Socio-technical modelling tools to examine urban water management scenarios'* (Project A4.3) – Dance4Water model

Conclusions

The research objectives for this initial phase of the 'Urban Metabolism for Planning Water Sensitive Cities' project were to review past applications of urban metabolism evaluation and its utility in the context of water, and develop a concept for an *urban metabolism evaluation framework for water (UMEF4Water)*.

To clarify some confusion around the use of the term *urban metabolism*, and to differentiate it from other evaluation approaches, we clarified urban metabolism evaluation for our purposes. We define it as the quantification of the metabolic characteristics of an urban area, based on analysis of direct resource exchanges between the 'urban area' and its 'supporting region'.

Existing evaluation frameworks / methods were found to be not sufficiently developed to meet our needs for holistically evaluating the hydrological performance of urban areas, and it was necessary to conceptualise a new framework that focuses on water. We identified the urban water mass balance method as a good foundation for the framework, due to its capacity for generating indicators of urban hydrological performance. It differs to a traditional supply–demand balance by measuring the performance of the urban area, rather than the performance of the urban water supply and draining system.

Based on a review of the information that can be generated, and how it could inform planning and advance water sensitive cities, the desired utility of the framework where identified to be:

- framing indicators of urban hydrological performance;
- accounting for the diverse sources and functions of water in the urban landscape to help maximize multi-functionality of water;
- linking urban areas to their supporting regions to understand potential competition for water; and
- accounting for water-related energy use to understand potential energy trade-offs of water management.

A concept for the *urban metabolism evaluation framework for water (UMEF4Water)* is proposed and its key elements are developed, including the urban scale of application, the evaluation method, spatial definition of system boundaries, and data sources. The framework can be applied at various urban scales, but we hypothesise that the macro urban scales (for example, city-regions) may be the appropriate scale of application, as water flows need to be considered in the context of the entire urban landscape, beyond the limits of the urban footprint.

The framework will draw on existing data sets so existing data collation efforts are not duplicated. The most likely dataset is the Bureau of Meteorology's (BOM) Urban Water Accounts, but also datasets compiled within the Danece4Water model. The value of this research is in extracting meaningful indicators about the hydrological performance of urban areas based on available data. As such it can provide an interpretive overlay to existing data compilation efforts.

The next phase of the research will aim to prove the concept by evaluating the baseline water metabolism of a selection of Australian cities, and then evaluate it under future scenarios of population growth and climate change.

There are many next steps necessary for improving our knowledge and operationalising of urban metabolism and the related concept of the water-energy nexus. Necessary action includes development of methods, standards, integrated water and energy plans, integrated water and energy education programs and training. Particularly important next steps to operationalise urban metabolism as one component contributing to the evaluation and management of the water sensitive city are:

- Progressing from frameworks to methodologies, and eventually standards (eg., for undertaking a mass balance evaluation of a city or proposed development).
- Enabling data requirements for urban metabolism evaluation by shifting toward consistent structures for urban water data reporting (across all flows) and eventually inter-operable datasets for urban water, energy and related flows (eg, nutrients).
- Progressing the development of metabolic indicators that can advance water sensitive cities.
- To-date metabolic (mass balance) analysis has only been undertaken as "snapshots". There is a need to shift towards dynamic assessment and to incorporate the critical function of water storage.
- There is an opportunity to use metabolic analysis to compare scenarios across all scales of development (from household to city-scale).

- Progressing multi-disciplinary groups and enabling uptake of metabolic/mass balance principles into reporting, strategies, local and strategic plans and eventually governance arrangements.

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