CRC for
Water Sensitive Cities

Urban metabolism for planning water sensitive city-regions

Proof of concept for an urban water metabolism evaluation framework B1.2 Milestone Report

Marguerite Renouf, Beata Sochacka, Steven Kenway, Ka Leung Lam, Silvia Serrao-Neumann, Ed Morgan and Darryl Low Choy

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Urban metabolism for planning water sensitive city-regions
Proof of concept for an urban water metabolism evaluation framework
Catchment scale landscape planning for water sensitive city-regions (Project B1.2)
B1.2 – 2 - 2017

Authors
Marguerite Renouf[1,3], Beata Sochacka[1,3], Steven Kenway[1,3] and Ka Leung Lam[1,3]
Silvia Serrao-Neumann[2,3], Ed Morgan[2,3] and Darryl Low Choy[2,3]

[1] The University of Queensland, School of Chemical Engineering, Water-Energy-Carbon Research Group
[2] Griffith University, School of Environment, Urban Research Program
[3] CRC for Water Sensitive Cities

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Cooperative Research Centre for Water Sensitive Cities
Building 75, Clayton Campus
Monash University
CLAYTON VIC 3800

p. +61 3 9902 4985
e. admin@crcwsc.org.au
w. www.watersensitivecities.org.au

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Abbreviations

BOM	Bureau of Meteorology
CRCWSC	Cooperative Research Centre for Water Sensitive Cities
GIS	Geographic Information System
HFP	Hydrological flow partitioning
MEL	Melbourne metropolitan region
OECD	Organisation for Economic Co-operation and Development
PER	Perth metropolitan region
SEQ	South East Queensland metropolitan region
WSC	Water Sensitive Cities
WSUD	Water Sensitive Urban Design
UMEF4Water	Urban Metabolism Evaluation Framework for Water

Glossary

anthropogenic water flows	Water flows managed by urban water infrastructure, including (water supply and use, wastewater collection, treatment, recycling and disposal), as distinct from natural water flows.
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	A metropolitan area that encompasses cities and their surrounding regions and can include multiple administrative districts.
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, 2011).
efficiency / efficient	Achieving maximum productivity with minimum use and wastage of effort, expense, natural resources.
framework	A conceptual way of thinking used to make conceptual distinctions and organise ideas.
hydrological flow partitioning factors	Factors that represent the partitioning of natural flows (precipitation, runoff, infiltration to groundwater and evapotranspiration) for the various land uses, regional climates and topographies (Renouf et al., in prep).
hydrological performance	We refer to hydrological performance in the context of urban systems. See urban hydrological performance.
integrated urban water models	Models that stimulate interactions between urban drainage, water supply and other urban water flows. For examples see Bach et al. (2014).
macro-urban scale	On the continuum of urban spatial scales (micro, meso, macro), macro- is a large urban scale, such as a city or city-region.
meso-urban scale	On the continuum of urban spatial scales (micro, meso, macro), meso- is a medium urban scale, such as a master planned community/development.
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, it is a way of sourcing, consumption and transformation of resources that achieves maximum functionality with minimum waste (of natural resources).
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	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).
National Performance Reports	National performance reports benchmark the pricing and service quality of Australian water utilities. Indicators include water resource supply and usage, financial operations, bills and pricing, assets, water quality compliance and customer performance. Published annually and prepared independently by the Bureau of Meteorology, State and Territory governments, and the Water Services Association of Australia, the reports support commitments under the National Water Initiative (http://www.bom.gov.au/water/npr/).
National Water Account	The National Water Account contains a set of water accounting reports for eight nationally significant water management regions collated on an annual basis since 2010. Currently it includes data on Adelaide, Canberra, Melbourne, Perth, South East Queensland and Sydney (http://www.bom.gov.au/water/nwa/2016/).

natural water flows	Water flows in the natural water cycle, ie, precipitation, stormwater runoff, infiltration to groundwater and evapotranspiration, as distinct from anthropogenic water flows.
peri-urban	Areas located at the fringe of consolidated urban centres (Malano, 2014, p. 4), forming a fuzzy periphery between urban and rural areas. They can be defined based on multiple criteria (eg, economic activities of residents, mobility, access to infrastructure services, etc) (Maheshwari and Thoradeniya, 2016).
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 a spatially defined urban area.
supply diversification	In the context of water, it is the sourcing of water from multiple supplies, for example surface waters, groundwaters, rainwater, stormwater runoff, recycled wastewater, desalinated water.
supply internalisation	In the context of water, it is the sourcing of water from within the urban system boundary, to reduce reliance on water sourced from the supporting environment.
supporting environment	In the context of this report, supporting environments are the hydrological catchments that directly service the needs of an urban settlement in terms of water supply and waste assimilation. Determining the distinction between “urban system” and “supporting environment” is an important step of setting the urban system boundary (Renouf et al., submitted 2017).
urban	Location characterised as population clusters of 1,000 or more people, with a density of at least 200 km^2 (Australian Standard Geographical Classification, 2001).
urban system boundary	For the purpose of this research, the urban system boundary is a three-dimensional volume (an area with a depth) containing settlements. In this study urban and peri-urban areas within this boundary are included.
urban footprint	In the context of urban and regional planning systems, the Urban Footprint is defined in strategic regional plans as the agreed extent of urban development for a given planning horizon (around 25 years), which establishes a spatial boundary for future urban development, containing urban growth and promoting a more compact urban form.
urban hydrological performance	The extent to which urbanisation alters the natural hydrological flows (precipitation, runoff, infiltration, evapotranspiration) relative to the pre-urbanised state or some other reference state.
urban metabolism	For the purpose of this research, we define urban metabolism as 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 et al., 2016a). This is derived from prior definitions of Baccini and Brunner (1991), Kennedy, Cuddihy and Engel-Yan (2007) and Wolman (1965).
urban metabolism evaluation	The quantification of the metabolic characteristics of an urban area, based on analysis of direct resource exchanges between an ‘urban area’ and its ‘supporting environment’ (Renouf et al., 2016a), (Renouf et al., 2016b).
urban water cycle	The movement and use of anthropogenic water (ie, managed by urban water infrastructure) within a city, including water supply and use, wastewater collection, treatment, recycling and disposal.
urban water mass balance	A water mass balance in the context of urban systems. See water mass balance.
urban water metabolism	The process of water and associated resources (water-related energy and nutrients) flowing through and being transformed and consumed in urban areas. Water mass balance (see below) is a method that allows its assessment.

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 (Kenway et al., 2011; Farooqui et al., 2016).
water related energy	Energy used to supply, use and dispose of water throughout the water supply chain.
water related nutrients	Nutrients (mainly nitrogen and phosphorous) mobilised in wastewater and stormwater runoff.
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, 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.

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Executive summary

This report summarises and compiles research activities 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 problem this project addressed was a lack of frameworks and methods for evaluating urban metabolic performance, particularly at macro scales (for example city-region), and quantifying this performance through indicators of holistic urban water performance.

A concept for an *Urban Metabolism Evaluation Framework for Water (UMEF4Water)* was developed in the first phase of the project and presented in the previous Milestone Report (Renouf et al., 2016). In this second phase of the project, the objective was to test and prove the UMEF4Water concept. The evaluation framework was applied at a number of urban scales to generate baseline water metabolism performance indicators for these urban regions. The framework was applied to three city-regions in Australia: South East Queensland, Greater Melbourne and Greater Perth, and to a meso-urban scale of a master plan development (Ripley Valley Development Area). By doing so, it tested if the indicators and knowledge that it generates can inform urban planning towards water sensitive cities. The relevance and value of the generated information was validated through consultation with water sector practitioners and planners in the case study regions.

The outcomes and findings from this second phase of the research were as follows:

- **A set of indicators that represent the holistic water performance of urban areas were devised**. These are underpinned by the desired objectives of Water Sensitive Cities, **which capture what we refer to as the urban water metabolism**. This includes: (1) resource efficiency (water, energy, nutrients), (2) supply diversification and internalisation, (3) effectiveness of protection of water resources and hydrological flows, (4) diverse functionalities of water that go beyond just meeting the needs for potable water.
- UMEF4Water was applied at the macro- (city-region) and meso- (master planned community or development) urban scales. It was proven **useful for understanding current water metabolism performance** and the influence of **water sensitive interventions**. UMEF4Water can also help with the setting of urban water performance targets.
- Application of the framework involved the compilation of water flow data from various sources, to match the scale of application. The establishment of a clear urban system boundary, and the alignment of the compiled data to the defined boundary identified was important. New methods for implementing such analysis using the framework were developed.
- Practitioners recognised the **usefulness** of the framework **for strategic resource and urban planning, and development assessment**. The proposed set of indicators could help align planning policies with long-term goals envisioned for Water Sensitive Cities. It could also facilitate integration of water and land use planning.
- The potential of urban water metabolism might be compromised by **poor general understanding of the concept**. Lack of common method was recognised as one of the main sources of confusion and frustration. UMEF4Water addresses that barrier by providing a rigorous urban water metabolic evaluation method. Additionally, the understanding can be improved by a broader use of visualisation tools for concept communication and data representation.

The innovation of this work is twofold. Firstly, the work refined methods of defining urban system boundary, estimating natural hydrological flows and gauging urban water performance through a set of indicators. Secondly, it combines urban planning and urban water cycle modelling perspectives to provide an evaluation approach that can help urban planners and water managers in Australia.

Introduction

Researchers from The University of Queensland's Water-Energy-Carbon Research Group and Griffith University's Urban Research Program further developed and used the concept of urban metabolism to evaluate the water resource management at city-region and meso-urban scales.

Urban metabolism is a concept which considers the flows of resources into, through and out of urban settlements. At its simplest, metabolism focusses on mass balances of water and materials and related energy flows. However, metabolism can also be used to understand how ecosystems or organisms function, with the intent of guiding us towards the higher resource efficiencies of natural systems. We are interested specifically in the urban metabolism of water. The aim of the research was to develop an evaluation framework that can generate indicators and knowledge of urban water metabolism to inform urban and regional planning.

The research is part of Project B1.2 of the Cooperative Research Centre for Water Sensitive Cities' Program on Water Sensitive Urbanism. This report describes the second phase of the urban metabolism component of Project B1.2 (Figure 1). The first phase developed the concept for the *Urban Metabolism Evaluation Framework for Water* (UMEF4Water) (Renouf et al., 2016). In this second phase, the framework was applied to a sample of Australian city-regions (macro-urban scale) to test that the information generated can inform urban and regional planning towards more 'water sensitive cities'.

This report summarises the research outcomes to demonstrate achievement of Milestone 2. Further details of the research have been published in Farooqui et al. (2016), Renouf et al. (2017), Renouf et al. (submitted), Serrao-Neumann et al. (in press), Serrao-Neumann et al. (2017), King et al. (2015), and Lamb (2016).

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 city-regions**
        - Milestone 1 – Concept for an urban water metabolism evaluation framework
        - Milestone 2 – Baseline water metabolism of three Australian city-regions
        - Milestone 3 – Future water metabolism of Australian city-regions
  - B2 Planning, design and management to protect and restore receiving waters
  - B3 Water sensitive urban design and urban micro-climate
  - B4 Building socio-technical flood resilience in cities and towns
  - B5 Statutory planning for water sensitive cities
- **Program C Future Technologies**
- **Program D Adoption Pathways**

Figure 1: Position of this research within the CRCWSC research framework.

Problems addressed

Urban areas draw on local and regional water sources for direct use. They also draw on global water sources for indirect or virtual water (embodied in goods and services consumed by urban dwellers), however, as this research is interested in the interface between water management and urban planning, the focus is on the direct water use extracted from local/regional supplies.

Local water supplies that directly sustain urban areas are increasingly stressed (McDonald, 2014; Richter, 2013). Factors (such as growing urban populations, competition with agricultural production, and more erratic supply due to climate change (OECD, 2015)) and internal factors (such as reliance on a single water source, non-utilisation of available water generated within the city itself, the linearity of urban water flows) make urban areas vulnerable to these external stresses (Renouf et al., 2016a). Urban and regional planners need to deal with not only the traditional challenges of managing stormwater runoff, deteriorating water quality and flooding, but increasingly, more frequent water shortages leading to competition for water between urban and regional uses, and between urban uses. Yet, the tools they have to deal with these challenges may not be sufficient. The existing urban water evaluation approaches are not holistic, often focusing on water supply and drainage systems within urban areas rather than evaluating the urban area as a whole (Renouf et al., 2016a), not accounting for the multiple functions of water in the urban landscape or the water connections between urban areas to their supplying regions. This constrains how well we can design urban areas for water efficiency, security and resilience.

The research gap addressed by this work is a lack of frameworks and methods for holistically evaluating the water metabolism of urban areas, ie, how water is consumed and transformed by urban settlements. The visions of future urban water management increasingly emphasise principles such as “resource neutrality, recognising the many values of water, harmonisation with the environment” (IWA, 2010). However, we do not have a framework to guide decisions about how to achieve this and make urban areas more metabolically-efficient (Renouf et al., 2016a). Therefore, the overarching aim of the work is to establish an evaluation framework and methods for better understanding how urban areas metabolise water so land use and water resource management planners can make better-informed strategic decisions.

Urban water metabolism

This research hypothesised that an evaluation framework based on the urban water metabolism concept can satisfy this gap by providing a ‘bigger picture’ of how our urban areas consume and transform water in the context of their supporting environments, for informing the optimisation of urban water systems, and for planning and managing urban development within environmental constraints.

Urban metabolism can be defined 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 et al., 2016a). Urban water metabolism focuses on water as the central resource and other resource flows associated with water, eg, energy and nutrients. The proposed UMEF4Water evaluates urban water metabolism, not the entire metabolic performance in an urban area.

In that sense, **urban metabolism** is a broader concept than urban water metabolism. Urban metabolism embraces all aspects of urban sustainability – it includes stocks and flows of water, energy, or materials that enter and leave the urban area. **Urban water metabolism**, on the other hand, beyond water flows, analyses only the trajectories and magnitudes of flows of energy and nutrients that are created in the process of water treatment or pumping. **Water mass balance** is a narrower term that includes only stocks and flows of water, excluding any energy or nutrient efficiency considerations (Figure 2).

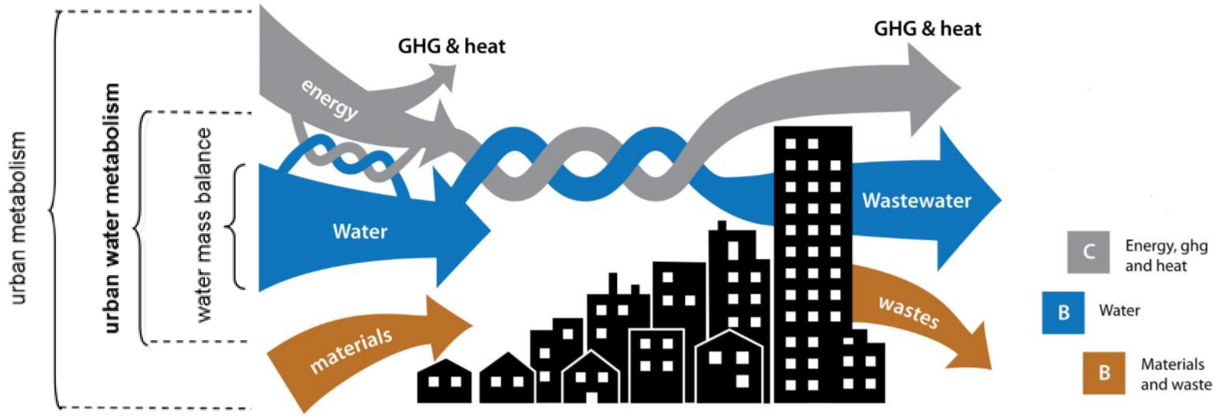


Figure 2: Urban metabolism, urban water metabolism, water mass balance – Differentiation of concepts. Adapted from Renouf et al., (2016b) and Kenway et al., (2013)

Research aims and objectives

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

The 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 usefulness 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. <u>Prove the concept by applying the framework to a selection of Australian city-regions (South East Queensland, Greater Melbourne and Greater Perth) to generate baseline water metabolism evaluations.</u>
4. <u>Strategic assessment of future scenarios for each case study region in terms of urban water metabolism performance.</u>

The findings from Objectives 1 and 2 were reported in Milestone Report B1.2 – 1 - 2016 (Renouf et al., 2016).

This report addresses Objectives 3 and 4.

The objective was to test that the UMEF4Water conceptualised in Phase 1 of the research can be operationalised to generate indicators and knowledge to aid the holistic conceptualisation of water management at the city-region scale, and to guide urban and regional planning processes towards the goals of a water sensitive city.

The research questions addressed here were:

1. What new insights about urban water management does urban water metabolism evaluation provide? What is the usefulness of the framework?
2. What indicators can be generated by the UMEF4Water framework to provide a useful measure of urban water metabolism?
3. How can the information generated from urban water metabolism evaluation inform decisions about urban water management at the city-region scale?
4. How can the framework be used for informing planning?

Figure 3 summarises the structure of the report and the sections which cover the answers to the research questions outlined above.

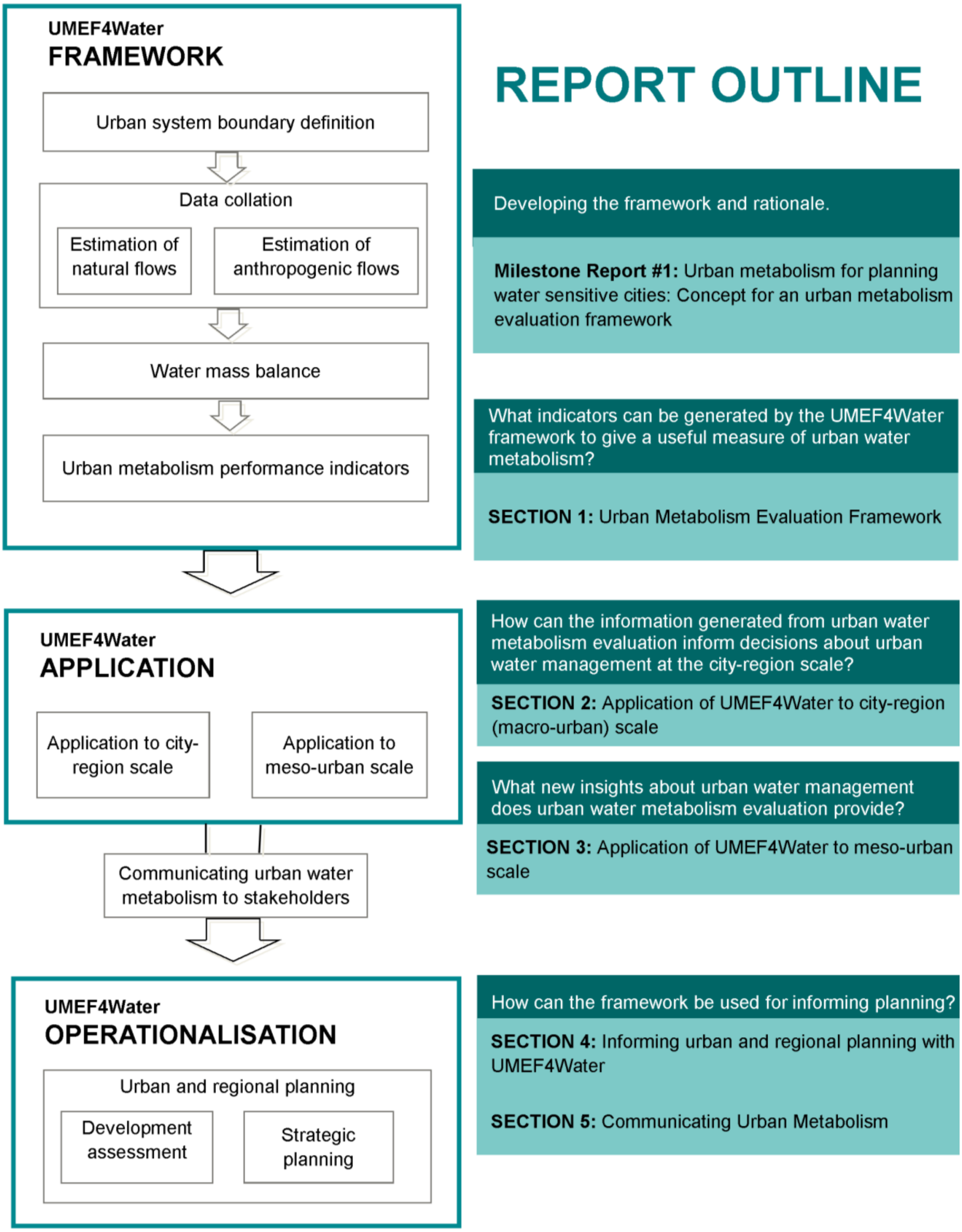


Figure 3: Structure of the report with research questions.

1. Urban Metabolism Evaluation Framework (UMEF4Water)

UMEF4Water uses urban metabolism as the conceptual foundation and urban water mass balance as the method. An initial concept for the framework was described in the previous Milestone Report (Renouf et al., 2016b). This section provides a summary of how it functions as an introduction to UMEF4Water application results.

More details can be found in:

Kenway, S., Gregory, A., and McMahon, J. (2011). Urban water mass balance analysis. *Journal of Industrial Ecology, 15*(5), 693-706.
Renouf, M.A., and Kenway, S.J. (2016a). Evaluation approaches for advancing urban water goals. *Journal of Industrial Ecology 10.1111/jiec.12456*.
Renouf, M.A., Kenway, S.J., Serrao-Neumann, S., and Low Choy, D. (2016b). *Urban metabolism for planning water sensitive cities. Concept for an urban water metabolism evaluation framework*. Melbourne, Australia: Cooperative Research Centre for Water Sensitive Cities. Retrieved from https://watersensitivecities.org.au/wp-content/uploads/2015/12/TMR_B1-2_UrbanMetablolismPlanningWSC.pdf.
Renouf, M.A., Serrao-Neuman, S., Kenway, S.J., Morgan, E.A. and Low Choy, D. (2017). Urban water metabolism indicators derived from water mass balance - bridging the gap between vision and performance assessment of urban water resource management. *Water Research 122 (2017), pp. 669-677*.

UMEF4Water can be applied at different scales, for different performance parameters, to assess a range of scenarios. The project focused its application on the city-region scale, and water resource management issues, to evaluate a selection of typical water-sensitive interventions. However, the broader potential of the framework for evaluating other urban scales and other performance parameters was also explored.

- **Urban scale –** The framework may be used at different scales – this report demonstrates city-region (macro) scale and master-planned community development (meso) scale.
- **Scope of performance parameters –** The framework is underpinned by a water mass balance for quantifying water resource performance. However, it can also serve as a basis for considering water-related energy and water-related nutrients. While the research focused on water evaluation, demonstration of the relevance of the framework to characterise water-related energy was also explored in a preliminary way.
- **Range of analysed options for intervention –** The framework was used to evaluate current performance (baseline), but also to forecast how performance may change under a range of water-sensitive interventions. Current performance was also compared with pre-development conditions to show the extent to which natural hydrology has changed and to explore the scale of measures that may be necessary to restore it.

Noting the choice of urban scale, scope and range of scenarios influence the way the system boundary is set and what data sources are used.

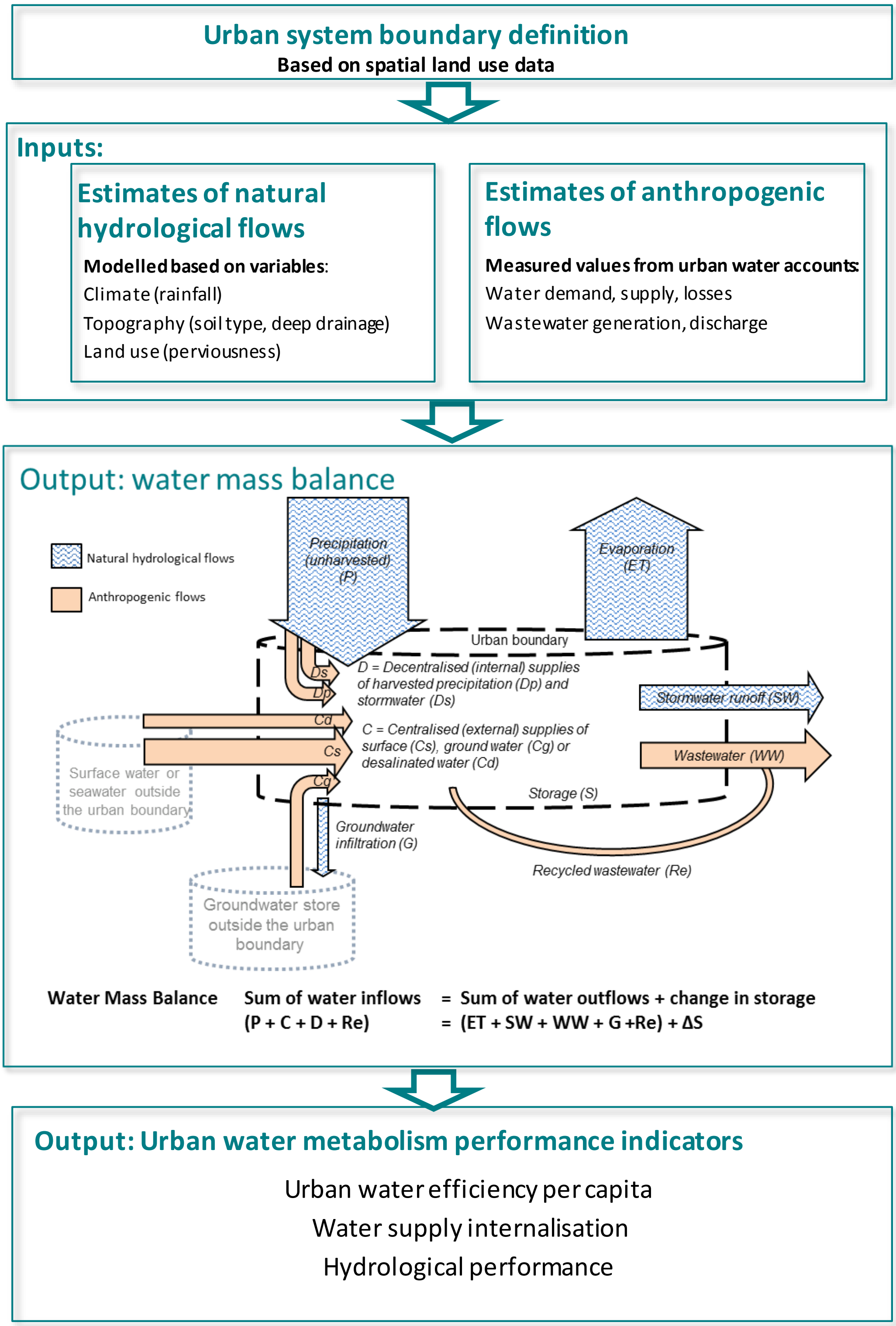


Figure 4: Urban Metabolism Evaluation Framework for Water (UMEF4Water). Reproduced from Renouf et al., (submitted 2017)

Overview of the framework

UMEF4Water evaluation consists of four steps as outlined in Figure 4 above and discussed below:

1. Determining urban system boundary
2. Collecting data for natural and anthropogenic flows
3. Collating the data into a water mass balance
4. Deriving water metabolism performance indicators from the water mass balance data

1. Urban system boundary definition

The spatial boundaries of the city-regions were defined according to current strategic regional plans, and include multiple local government administrative areas. Urban water supplies are sourced from catchments within these boundaries, hence the city-region also represent the supporting environments from which water supplies are drawn.

The urban systems within these city-region areas were then defined, and include urban and peri-urban areas. The spatial extent of the urban systems was defined by using spatial (GIS - Geographic Information System) land use data to identify areas that would be regarded as urban and peri-urban in nature. At the city-region scale, this was combined with the ‘urban footprints’ defined in strategic planning documents to ensure alignment with planning processes.

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 the groundwater table) typically to a depth of one metre below ground (Farooqui, 2016).

A technical boundary also distinguishes water that is part of the ‘environment’ from water considered to be part of the ‘urban system’, in order to define the flows of water between the ‘urban system’ and the ‘environment’. Both anthropogenic flows (i.e. those managed by urban water infrastructure) and natural flows (those part of the natural water cycle) are considered. Natural water flows are precipitation, evapotranspiration, groundwater infiltration, and stormwater runoff. Anthropogenic flows are centralised water supplies (potable water) from surface water or groundwater, decentralised water supplies (rainwater, groundwater, etc), and wastewater discharged or recycled.

2. Data collation

The framework requires data for annual water flows making up the urban water mass balance, for a selected time, and to align with the selected urban boundary. Data may need to be drawn from a range of different datasets, as the evaluation requires estimation of both natural and anthropogenic flows. This can be challenging, as datasets can have different spatial scope and flow characterisation methods (Renouf et al., 2016b). The data sources used in the city-region and meso-urban scale applications were:

City-region scale:

- Annual volumes of anthropogenic water flows were derived from the Australian Bureau of Meteorology’s (BOM) National Water Accounts database (BOM, 2016).
- Annual volumes of natural water flows were estimated by using hydrological flow partitioning (HFP) relevant to different land use type in the respective city-region, which were multiplied by the areas of respective land use types present within the urban system boundary.

Master-planned development (meso-urban) scale:

- Annual volumes of anthropogenic water flows were derived from bottom-up estimates of water demand, water use, etc.
- Annual volumes of natural water flows were estimated using the MUSIC hydrological model (Renouf et al., 2016b).

3. Water mass balance

The core method of UMEF4Water is the urban water mass balance described in Kenway et al. (2011) and further developed by Farooqui (2015) and Renouf et al. (submitted 2017). It quantifies all water flows (natural and anthropogenic) into and out of an urban area with a defined urban system boundary (Figure 4). The quantified water flows are used to generate indicators of urban metabolic performance.

4. Urban water metabolic performance indicators

The following urban water metabolism performance indicators were derived from the water mass balance data.

Urban water efficiency is an indicator of the overall efficiency of 'environmental' water use for the whole urban system and expressed as a rate of environmental water withdrawal per inhabitant per year (kL/capita/yr). It is an outcome of both the urban water demand, and the degree of supply internalisation (rainwater and stormwater collection, or wastewater recycling).

Hydrological performance is an indicator of the degree to which natural hydrological flows have increased or decreased relative to a defined pre-urbanised reference state. It is the ratio of post- to pre-urbanised annual flows for stormwater runoff, evapotranspiration, and infiltration to groundwater, and therefore is dimensionless. A ratio of greater than one means that the magnitude of the annual flow/flux is larger than pre-developed landscape, and a ratio of less than one means it is smaller. In this work, the pre-urbanised reference state was taken to be an undeveloped natural landscape.

Development of the urban water metabolism indicators

Urban water metabolism indicators derived from water mass balance bridge a current gap between vision and performance assessment of urban water resource management. Research undertaken by Renouf et al (2017) generated quantitative indicators related to the water metabolic characteristics of urban water management: resource efficiency (for water, water-related energy and nutrients), supply diversification and internalisation, hydrological performance and sustainable management of water resources within a regional safe operating space (Table 1). This is a broad set of indicators that can be used for the assessment of water metabolic performance and for identifying opportunities for improvement.

The new indicators were not driven by data availability (which has been the case in the past), but instead by urban water management objectives inferred from the vision statements of water management agencies. They were developed by:

- reviewing and categorising water-related resource management objectives for urban areas
- deriving indicators that can gauge performance against these objectives
- assessing how they can be quantified using urban water mass balance
- validating the indicators with water, urban and regional planners.

The reviewed vision statements and principles that underpin the indicators, advocate for a new paradigm for water management. They are the concept of Water Sensitive Cities, the International Water Association's Smart Cities program, the Organisation for Economic Co-operation and Development's (OECD) framework for city-level water management, the Asian Development Bank's Water Development Outlook, and the United Kingdom Water Partnership.

Key objectives inferred from these were broadly categorised into themes of urban water metabolism performance, risk management (e.g. resilience and flood risk) and institutional aspects of water management (e.g. economic sustainability, governance standards). This study focused only on urban water metabolism and categorised the objectives expressed in that area into four overarching goals:

1. **Resource efficiency** – understood as the efficient use of water-related resources, comprising water, energy used for treating and pumping water, and nutrients mobilised in water. The efficiency in that sense refers to the efficient use of a resource within the urban area and is not limited to water use efficiency of end users.
2. **Supply diversification and internalisation** – understood as augmentation of the supply while decreasing reliance on water drawn from the environment. This can be achieved through utilisation of water sources within the urban area (internalisation), e.g. harvesting rainfall from urban areas (rainwater, stormwater) or recycling of used water (wastewater, greywater).
3. **Protection of water resources and hydrological flows** – understood as sustainable management of water resources in terms of stocks, qualities and flows. It is achieved through: (i) managing the volumes of water drawn from the environment for urban uses within the region's capacity to supply, (ii) limiting the discharge of pollutants to the environment to maintain the quality of waterways, and (iii) restoring natural hydrological flows (stormwater runoff, groundwater infiltration, evapotranspiration) altered by increased imperviousness.
4. **Recognising the diverse functions of water** beyond just meeting primary needs for potable water – understood as the valuation of benefits derived from water that include: social functions (e.g. urban liveability, recreation), sustaining habitat ecosystem health and biodiversity, enabling economic activities, supporting a range of urban spaces (e.g. green infrastructure).

Some indicators identified were able to be quantified using the data generated from an urban water mass balance. This is demonstrated in the work of Farooqui (2016) and Renouf et al. (submitted 2017), and discussed in Sections 2 and 3 of this report. The other aspirational indicators will require further method development, to generate data currently not available: water-related energy and nutrient data, urban water functionality index with efficiency indicators to express per unit of function, and understanding the sustainable water yields and assimilative capacities of supporting environments.

Future directions: Refining the method

UMEF4Water was developed to enable systematic assessment of urban water metabolism. However, as urban water metabolism is a concept which is developing quickly, UMEF4Water can be further advanced and refined by:

- Integrating the framework with existing software and modelling packages, for example Dance4Water and testing the extent to which the calculations that underpin the water mass balance method can be automated.
- Calibrating the model through longitudinal application and comparison with real hydrological data gathered from different geographical locations and different urbanisation patterns. This would be particularly useful for verifying assumptions that underpin natural hydrological flows estimation (for more details see Section 2).
- Operationalising the concept in planning practice (e.g. by feeding it into the Water Sensitive Cities Index). The main opportunity seem to lie in the fact that UMEF4Water can be used to rapidly estimate urban water flows at various urban scales, for the initial screening of the scale and type of water sensitive interventions that may be needed to achieve desired objectives.
- Developing data visualisation and communication tools for effective representation of the results generated by application of UMEF4Water to different urban scales.

The concept of urban water metabolism can be further developed by:

- Incorporating estimation methods for water-related energy (including thermal energy) and nutrients.
- Developing further indicators based on time-based testing (e.g. monthly/daily or multi-annual (over a period of 10-20 years)) water mass balances.
- Incorporating estimation methods for water storage.

Table 1: Proposed urban water metabolism indicators. Reproduced from Renouf et al. (2017)

Key objectives of urban water performance		**Performance indicators and their quantification**	
		Currently achievable	**Aspirational**
Resource efficiency	Water efficiency	**Urban water efficiency per person** - total use of 'environmental' water per person $\frac{C}{\text{Population}}$	**Urban water efficiency per unit of functionality** - total use of 'environmental' water per unit of urban function $\frac{C}{\text{Functionality index}}$
	Energy efficiency (water-related)	**Water-related energy efficiency per person** - total energy use for the water system per person $\frac{E_{TOT}}{\text{Population}}$	**Water-related energy efficiency per unit of functionality** - total energy use for the water system (including the use phase) per unit of functionality $\frac{E_{TOT}}{\text{Functionality index}}$
	Nutrient efficiency (water-related)		**Nutrient recovery from urban water** - proportion of the nutrient load in wastewater that is beneficially used $\frac{N_{Re}}{N_{WWin}}$
Supply internalisation		**Water supply internalisation** - proportion of total water demand met by internally harvested/recycled water $\frac{D + Re}{D + Re + C}$	
Protecting water resources and hydrological flows	Water stocks (quantity)	**Water use within safe operating space** - rate of surface and groundwater drawn from supplying catchments relative to the sustainable urban water allocation $\frac{C}{\text{Sustainable urban water allocation}}$	
	Water quality		**Water pollutant load within safe operating space** - point-source and diffuse nutrient loads discharged to surface and ground waters relative to sustainable discharge rates $\frac{W_{Wout} + N_{SW}}{\text{Sustainable discharge rate}}$
	Restoration of natural hydrological flows (runoff, infiltration, evapotranspiration)	**Hydrological performance** - post-urbanised hydrological flows/fluxes relative to pre-urbanised flows/fluxes (o)$\frac{SW_i,\ G_i,\ ET_i}{SW_o \quad G_o \quad ET_o}$	
Recognising the diverse functionality of water	Social Environmental Economic Urban spaces		**Supporting diverse functions** - water needed to maintain desired functions relative to water budgeted for the functions $\frac{W_{allocated}}{W_{needed}}$

2. Application of UMEF4Water to city-region scale

UMEF4Water was applied to a sample of city-regions to explore the framework's usefulness for macro-urban scale applications. The research conducted by Renouf et al. (submitted 2017) used urban metabolism evaluation to understand the current urban water performance and the impacts of some conceptual water sensitive interventions in three Australian city-regions: South East Queensland (SEQ), Melbourne (MEL) and Perth (PER) metropolitan areas. The selected case studies face similar challenges of growth management under similar climate change induced conditions: reduced and erratic water supply due to increasing average temperatures, change in average annual rainfall and increased intensity of extreme rainfall events (Risbey, 2011; Schandl, 2008; Gooda, 2012).

More details can be found in:

Renouf, M.A., Kenway, S.J., Lam, K.L., Weber, T., Serrao-Neumann, S., Low Choy, D., and Morgan, E.A. (submitted 2017). Understanding urban water performance at the city-region scale using an urban water metabolism evaluation framework. *Manuscript submitted for publication*.

Water metabolic performance improvements that could be obtained from conceptual water sensitive interventions were quantified using water mass balance method and compared using indicators of urban water efficiency and hydrological flows performance. Assessed conceptual water sensitive interventions included: reduced demand, internal harvesting, recycling and increased perviousness (Figure 5).

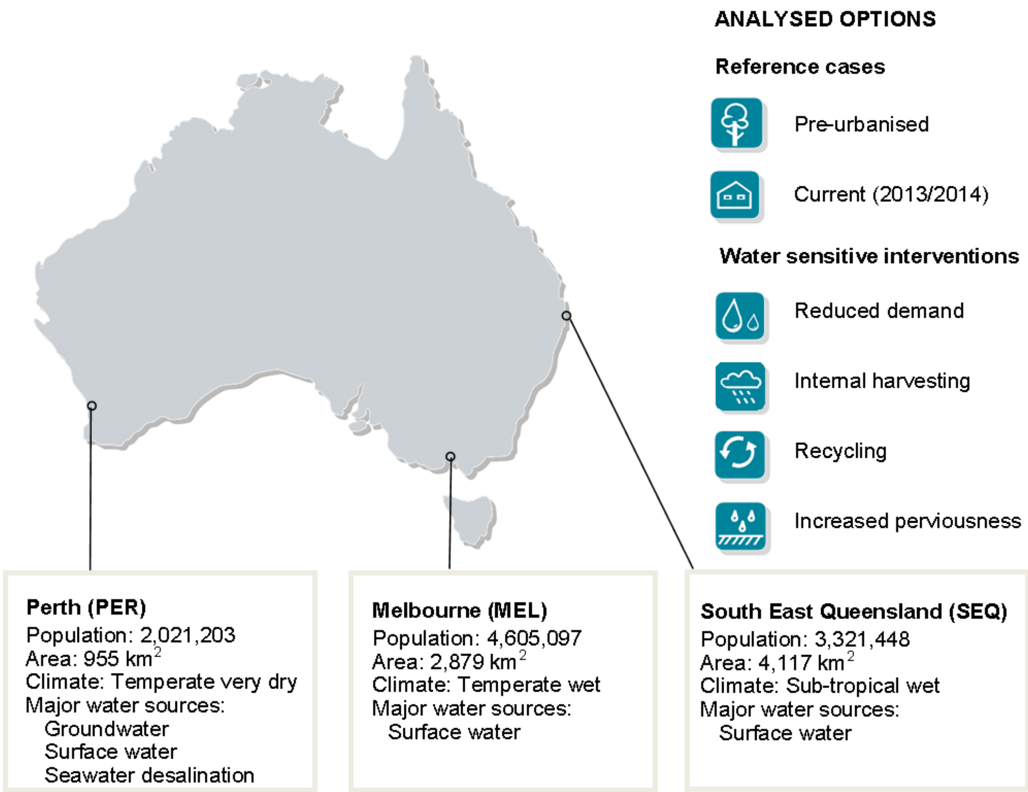


Figure 5: Characteristics of the assessed cities and the range of evaluated scenarios.

UMEF4Water application city-region scale

STEP 1

1. Defining urban system boundary

The spatial extend of "urban system boundary" comprised urban and peri-urban areas and was defined through a process of overlaying boundaries determined by land use (sourced from Catchment Scale Land Use in Australia (CLUM 2015) and based on Australian Land Use and Management Classification system), population density and "urban footprint" (area pre-defined for development in strategic policy documents). Vertical boundary was set to extend from rooftop and tree tops, to the root zones of trees.

STEP 2

2. Collating data for:

   A. natural flows

   B. anthropogenic flows

Data on anthropogenic flows was mostly obtained from the Australian Bureau of Meteorology's Urban National Water Accounts (BOM UWA) database. Decentralised supplies for rainwater, stormwater and bore water were estimated on the basis of published reports.

Natural hydrological flows were estimated based on BOM annual rainfall data, the Australian Landscape Water Balance, land use data, and the derived hydrological flow partitioning (HFP) factors.

STEP 3

3. Water mass balance

Urban water mass balance brings together estimates of the managed and natural flows. It is calculated based on the equation developed by Kenway (2011):

$$(P' + C + D + Re) = (Et + SW + WW + G + Re) + \Delta S$$

The inflows sum total unharvested precipitation (P), total centralised (C) and decentralised (D) supply as well as recycled water (Re). Outflows include evapotranspiration (Et), stormwater runoff (SW), wastewater (WW), groundwater infiltration (G), water flows that are recycled (Re). ΔS is the change in the stored water volume within the defined urban system boundary in a given time period (eg, depletion of the reservoir).

STEP 4

4. Deriving water metabolism performance indicators

To assess the metabolic performance of the explored scenarios a set of metabolic indicators was used:

Urban water efficiency per person– proportion of total use of 'environmental' water per person per year (kL/p/yr).

Water supply internalisation– proportion of total urban water demand met by internally harvested / recycled water.

Hydrological performance– ratio of post (i) to pre (o) urbanised annual flows/fluxes of stormwater runoff, evapotranspiration, and infiltration to groundwater.

The city-region scale refers to metropolitan areas that encompass cities and multiple administrative districts. It was determined to be optimal scale for answering the question of how different water sensitive interventions can be brought together to optimise water performance on a macro urban scale. On a smaller scale there is a risk that interventions of relatively moderate overall benefit will be selected, while initiatives that can offer overall benefits for the city-region scale as a whole will be overlooked. Additionally, the city-region scale corresponds to the scale of strategic planning and the scale at which urban water supply and catchment-based water resources can be managed in an integrated way. Conducting water mass balance at the city-region scale has until recently been difficult due to immature methods and fragmented data. The recent centralisation of data collation for urban water systems, eg, due to National Water Accounts, and the refining of urban hydrological models in Australia made this analysis possible.

Urban water metabolic performance evaluation of three city-regions

Urban water metabolic performance was assessed using three indicators: (1) urban water efficiency, (2) water supply internalisation, and (3) hydrological performance. It revealed and gauged the extent to which the natural, pre-development hydrological performance of the site was altered by the development. Under the baseline (business as usual) post-development conditions the stormwater runoff increased to 200-580% of the pre-urbanised flows. The indicators also helped to assess the four conceptual water sensitive interventions and their potential for improving the current hydrological performance and urban water efficiency and internalisation (Figure 6 and Figure 7). The dark green spaces indicate the most beneficial intervention for every indicator.

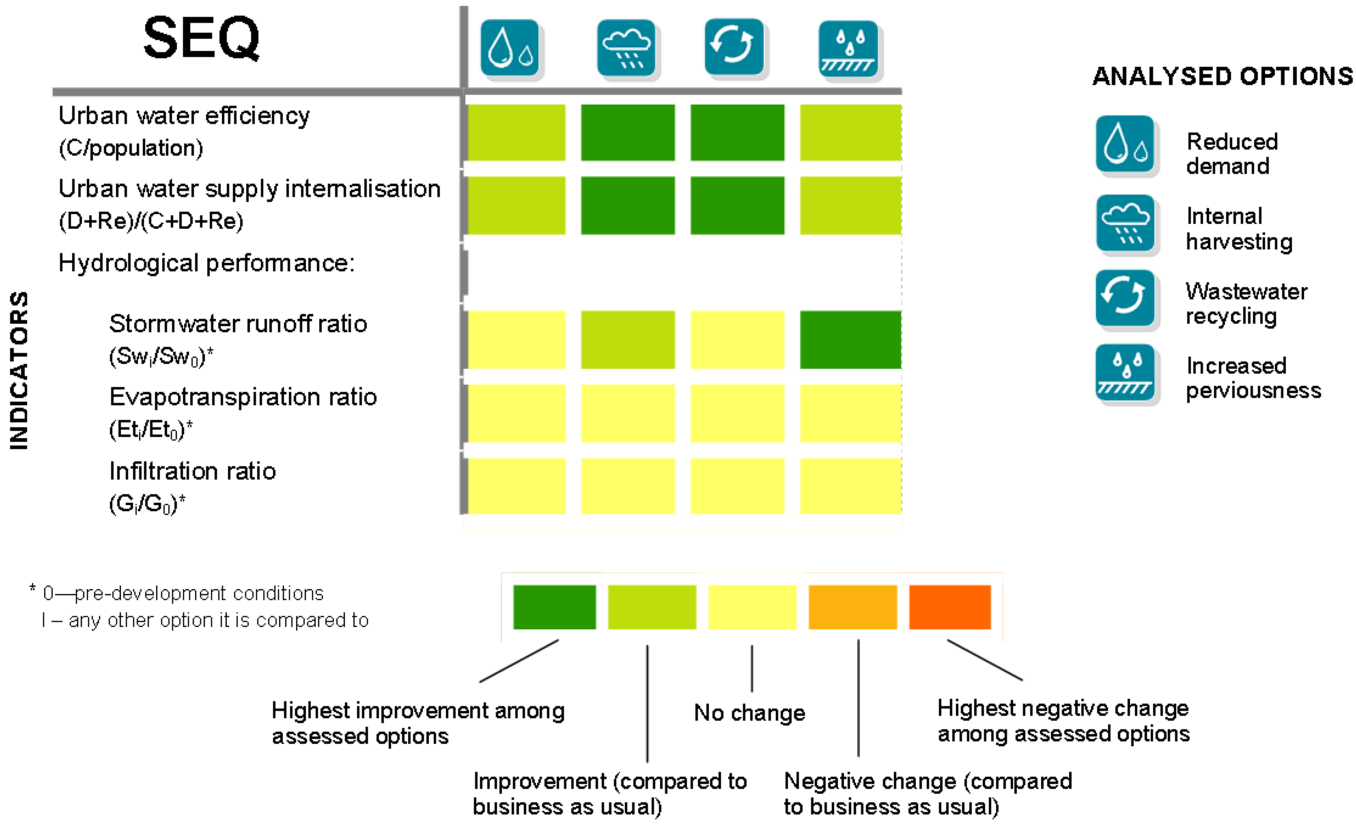


Figure 6: Urban water metabolic indicators for SEQ.

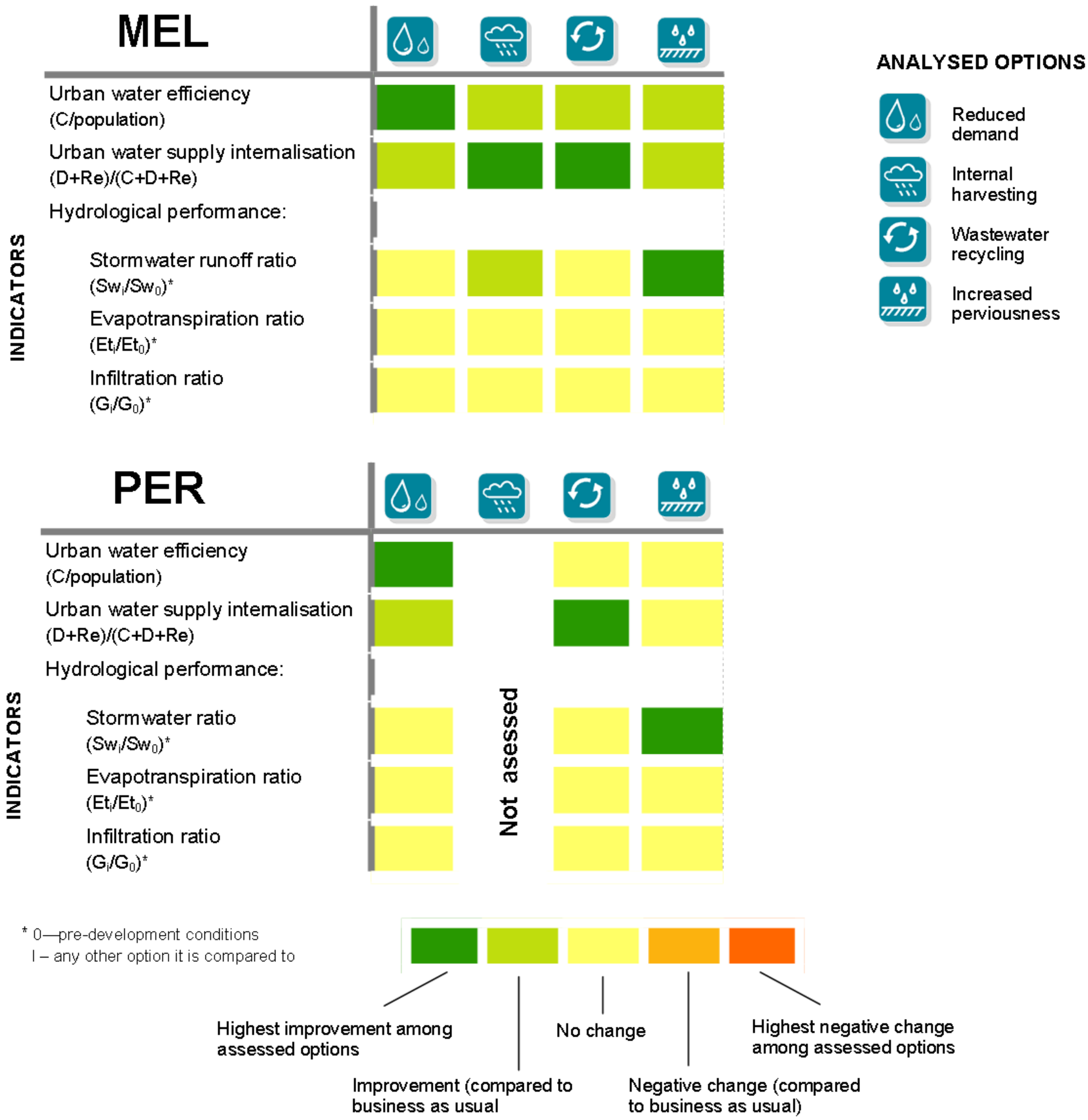


Figure 7: Urban water metabolic indicators for MEL and PER.

South East Queensland (SEQ)

In the current case, SEQ has the lowest per capita urban water demand amongst the three city-regions. This is largely due to the water efficiency improvement through the Millennium Drought (2001-2009). Additionally, more than 10% of its supply is sourced internally through water recycling and rainwater or stormwater harvesting. This further reduces the volume of water sourced from the environment. Compared to pre-urbanised hydrological flows, surface water runoff has doubled, while groundwater infiltration and evapotranspiration have slightly reduced.

Water sensitive intervention scenarios:

Urban water efficiency and supply internalisation

Further internal **harvesting of rainwater or stormwater** as well as **wastewater recycling** offer the most significant opportunities to reduce the urban extraction of environmental water. On the other hand, the potential of further reducing urban water demand through residential demand management may be low because the current urban water efficiency is already relatively high. Combined effect of all the interventions could reduce the urban extraction of environmental water by over 40%.

Hydrological performance

Increasing perviousness for urban residential areas could moderately reduce the overall stormwater runoff, while slightly increase evapotranspiration and groundwater infiltration.

Melbourne (MEL)

In the current case, MEL also has a relatively low per capita urban water demand amongst the three city-regions. While its per capita urban water demand is higher than SEQ, MEL has a greater proportion of internally-sourced water. Stormwater runoff has been highly elevated by urbanisation as compared to the pre-urbanised state, while there have been slight reductions in groundwater infiltration and evapotranspiration.

Urban water efficiency and supply internalisation

Reducing demand through residential water demand management offers the greatest opportunity to reduce the use of external water supply. This may offer a greater reduction than rainwater/stormwater harvesting, or wastewater recycling scenarios modelled. Combined effect of all the interventions could reduce the urban extraction of environmental water by nearly 40%.

Hydrological performance

Increasing perviousness for urban residential areas could moderately reduce the overall stormwater runoff. Similar to the case of SEQ, the impacts on groundwater infiltration and evapotranspiration are insignificant.

Perth (PER)

Compared to SEQ and MEL, PER has the highest per capita urban water demand. Approximately 40% of its centralised water supply is from seawater desalination. PER has amongst the three city-regions the highest internal supply because of significant use of decentralised local bores. Similar to MEL and SEQ, urbanisation has significantly increased stormwater runoff, while it has slightly reduced groundwater infiltration. The high outdoor water use may have increased the evapotranspiration compared to the pre-urbanised state.

Urban water efficiency and supply internalisation

Reducing demand in the residential sector and **wastewater recycling** offer similar potential for reducing external water supply. Using both interventions may reduce the current demand for external water by nearly 25%. Since these interventions could displace desalinated water supply, they would also improve water-related energy efficiency.

Hydrological performance

Increasing perviousness for urban residential areas may greatly reduce the overall stormwater runoff because of the relatively high perviousness and sandy soil type in PER, compared to SEQ and MEL. Groundwater infiltration and evapotranspiration would increase slightly as a result of reducing stormwater runoff.

Conclusions on macro urban scale application

Using the UMEF4Water to understand the potential urban water performance impacts of four conceptual water sensitive interventions in the three city-regions revealed that:

- The framework is suited to performance monitoring, priority setting, and initial screening of water sensitive interventions to identify the types and scale of implementation necessary to achieve desired water performance objectives for a city-region.
- The work also highlights the current absence of established performance objectives and prompts the need for urban planners and water managers to consider targets for improvements.
- The values of the approach are the city-region perspective (important for informing strategic land use planning), compilation of all urban water flow data into a single framework (for comprehensiveness and understanding interconnections), and consistency in system boundary definition (important for comparing between urban systems and over time).

Future directions: Extending the scope of evaluation

The study highlighted avenues for further enquiry that could improve the assessment of the three city-regions urban water metabolism. Adoption of more robust set of indicators, including the ones discussed in Table 1 as aspirational, could offer further insights into the improvement opportunities for Australian city regions. In particular, further research could extend the scope of evaluation by including indicators that evaluate water use within safe operating space as well as water-related energy and nutrient efficiency. This requires:

- identifying ways to define sustainable rates of water extractions against which to evaluate the sustainability of ‘environmental’ water extraction
- estimating water-related energy and nutrient flows.

UMEF4Water application to city-region scale also emphasised elements of the method that could be refined to provide a more robust urban water metabolism evaluation. For example, while the study assessed hydrological performance of the three city-regions under different scenarios, the usefulness of this indicator could be enhanced if there was a suitable reference case against which hydrological performance could be normalised. Future research would also be necessary to validate the established HFP factors by comparing the results they generated with those generated from full hydrological modelling.

3. Application of UMEF4Water to meso-urban scale

The work undertaken by Farooqui et al., (2016) was a pilot application of the UMEF4Water to a real case example at meso-urban scale - a semi-hypothetical case study of the Ripley Valley Development Area, which is a proposed new master planned development in SEQ of an area of 3,002 ha. The analysis enabled comparison of the performance of six alternative conceptual water servicing options, scoped by earlier studies (CRCWSC, 2015) for the area (Figure 8), judged against a set of indicators for hydrological performance, resource efficiency and supply internalisation. Each alternative water servicing option was assessed under two scenarios: conservative and maximised implementation.

More details can be found in:

Farooqui, T.A., Renouf, M.A., and Kenway, S.J. (2016). A metabolism perspective on alternative urban water servicing options using water mass balance. *Water Research, 106*, 415-428.

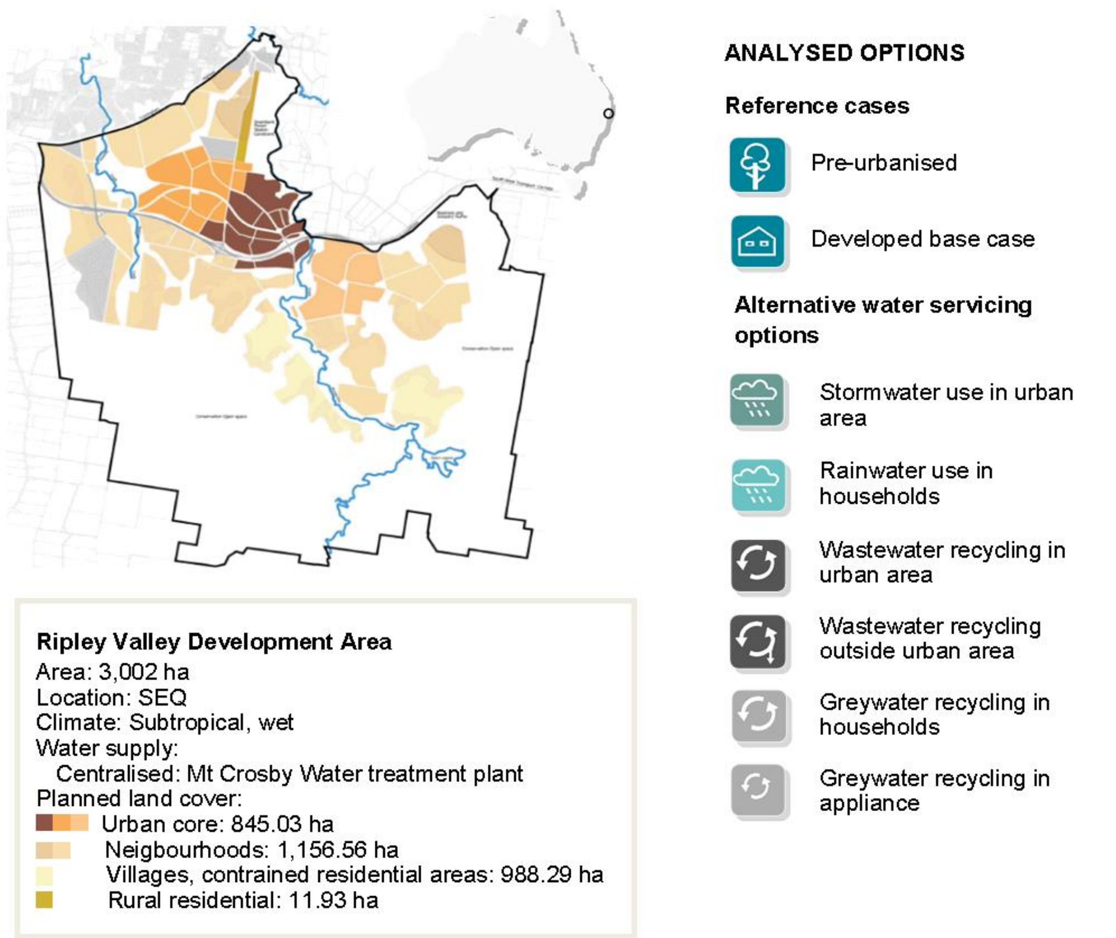


Figure 8: Characteristics of the Ripley Valley Development Area with a range of assessed options.

UMEF4Water application meso-urban scale

STEP 1

1. Defining urban system boundary

The urban system boundary defined for the purpose of the analysis covered an area of 3,002 ha, delineated by the edge of the built-up development, according to the Ipswich Planning Scheme. The urban boundary excluded the natural reserves that surround the planned development. Vertical boundary spanned from the rooftops to root zones of trees approx. 1 m below the ground. The Mt Crosby Water Treatment Plant is located outside the system boundary whereas the planned sewage treatment plant is proposed to be located inside the urban boundary.

STEP 2

2. Collating data for
   A. natural flows
   B. anthropogenic flows

Anthropogenic lows were estimated on the basis of average residential (per person) and commercial (per m^2) water demand in SEQ, projected population and planned land use of the area.

Natural flows were estimated with the use of MUSIC software and prior hydrological modelling for this area (McIntosh, 2013). Imperviousness of different land use clusters was determined based on the equation developed by (McIntosh, 2013):

$$\text{Imperviousness} = 0.0649 \times \ln(\text{housing density}) + 0.1822$$

The ratios of 25% groundwater infiltration and 75% evaporation (Chrysoulakis, 2015) were adopted for outdoor irrigation and leakages.

STEP 3

3. Water mass balance

Urban water mass balance was calculated based on the equation developed by Kenway (2011):

$$(P' + C_{tot} + D_{tot} + Re) = (Et + Rs + W + G + Ri + Re) + \Delta S$$

The inflows sum total unharvested precipitation (P'), total centralised (C_{tot}) and decentralised (D_{tot}) supply as well as recycled water (Re). Outflows include evapotranspiration (Et), stormwater runoff (Rs), groundwater infiltration (G), water flows that are recycled internally (Ri) and externally (Re). ΔS is the change in the stored water volume within the urban boundary.

STEP 4

4. Estimation of water-related energy

The total water-related energy is a sum of energy used for extracting, treating and conveying previously calculated volumes of different flows of water: centralized supply (Ec), rainwater (E_{Dp}), stormwater (E_{Ds}), groundwater (E_{Dg}), wastewater (E_w), greywater recycled internally (E_{ri}) and externally (E_{re}). ΔE_U is the change in household energy use.

$$E_{tot} = Ec + (E_{Dp} + E_{Ds} + E_{Dg}) + (E_{ri} + E_{re}) + E_w + \Delta E_U$$

STEP 5

4. Deriving water metabolism performance indicators

To assess the metabolic performance of the explored scenarios a set of eight metabolic indicators was used.
Resource efficiency - (a) ratio of water extracted from external sources and population, (b) ratio of water-related energy and population; (c) proportion of water harvested per total demand, and (d) proportion of water recycled internally per total demand.

Hydrological performance - ratio of post- to pre-urbanised annual flows/fluxes of (a) stormwater runoff, (b) total stream discharge, (c) infiltration, and (d) evapotranspiration.

Novel contributions to this research was associated with quantifying energy implications of the alternative water servicing options by estimating water-related energy on the basis of the water mass balance. The calculations in Farooqui's work were based on energy-intensity estimations derived in previous research (Kenway et al., 2015; Memon, 2015). Water treatment and distribution, wastewater treatment and operation of rainwater tanks was based on the water-related energy report for SEQ developed by Kenway et al. (2015). Greywater recycling related energy on household level was adopted from Memon's (2015) research of United Kingdom households. The data for stormwater treatment and pumping was estimated based on assumed treatment procedures (sand filtration and chlorine disinfection) and delivery heads. Greywater recycling within an appliance and the energy saved due to heat recovery was also included.

Urban metabolic performance comparison of different water servicing options

Metabolic-efficiency is understood as an urban water performance that is (1) resource efficient, i.e. energy and water-efficient, which means it reduces demand for water extracted from external sources by augmenting supply, e.g. with harvested stormwater or recycled wastewater, and (2) maintains the hydrological conditions closest to the pre-development condition. The set of eight indicators used for this comparative analysis covers these two dimensions of metabolic efficiency.

The assessment revealed that the extent of alternation of natural hydrological performance of the area under post-development conditions. The water mass balance showed that stormwater runoff is likely to increase 2.5 fold as compared to the pre-development case. Indicators highlighted also the potential for water supply augmentation with alternative sourcing options. Maximalised implementation of alternative sourcing options with rainwater, stormwater and wastewater could each individually supply respectively 37%, 45% and 45% of total projected demand. Conservative implementation of the options where non-potable uses are only considered, could satisfy 5%, 15% and 5% respectively of the total demand. The energy efficiency indicator shows that rainwater use and greywater recycling at household scale can increase energy use (Figure 9). Greywater recycling in appliances offers significant energy use reductions at household scale due to heat recovery that far exceeds the increased energy use for pumping.

The findings highlight the importance of more careful considerations of energy implications of alternative servicing options. Farooqui (2016) found that rainwater and greywater harvesting at household scale had significant energy trade-offs increasing the water-related energy by 31% and 67% respectively. At larger (urban) scales this energy use can be reduced by up to 10% as compared to base case conditions. Heat recovery through greywater recycling in appliances also offers considerable energy savings to household energy use.

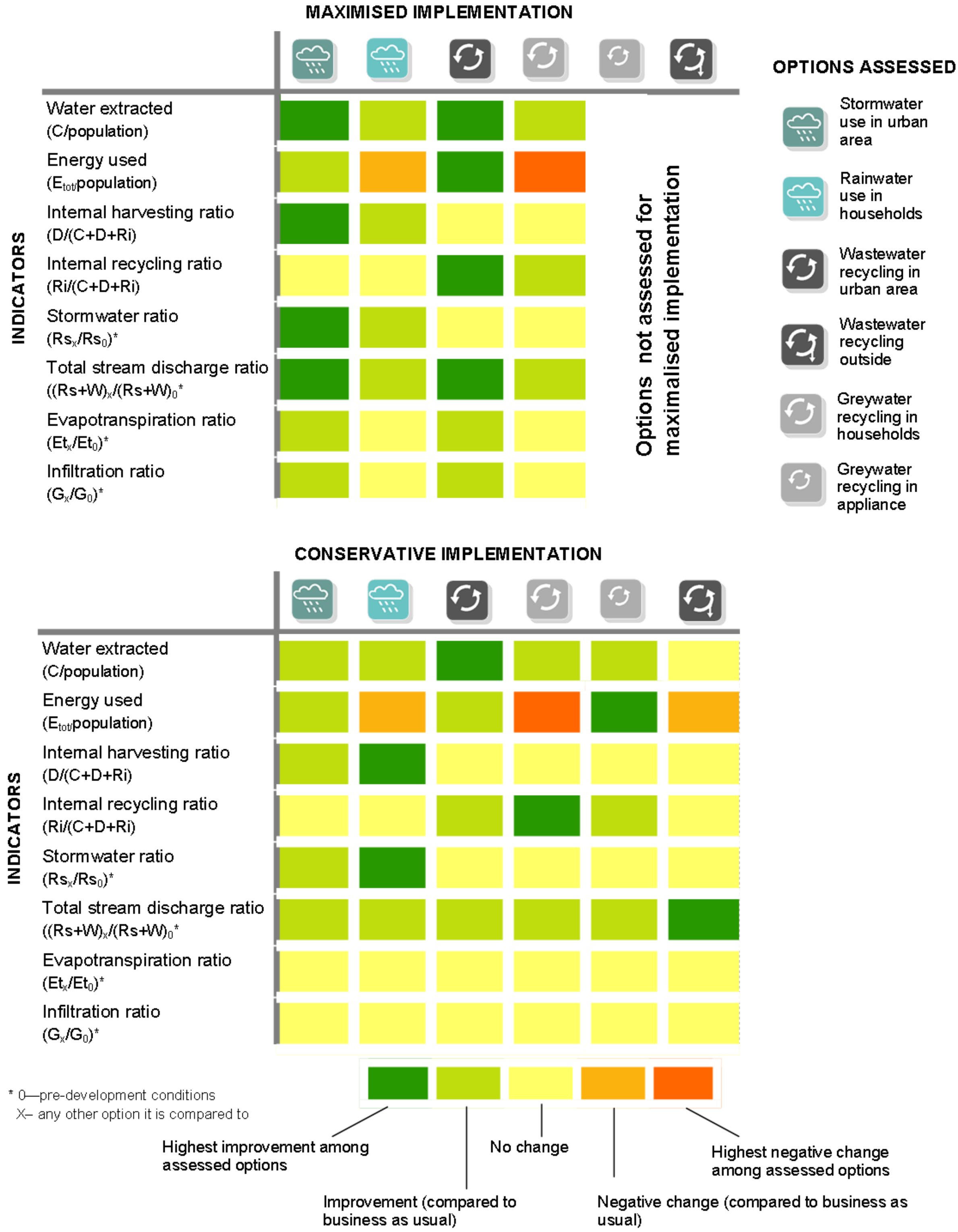


Figure 9: Urban water metabolic performance. Indicators for maximised and conservative implementation of alternative sourcing options.

Overall the analysis of the Ripley Valley case study showed that harvesting rainwater or stormwater might offer more metabolism benefits than wastewater recycling, mainly due to the benefits for hydrological performance from reduced stormwater runoff. The study also demonstrated that harvesting stormwater or rainwater offers significant improvements to water efficiency only when utilisation is maximised.

Resource efficiency

Rainwater and stormwater harvesting could decrease external water extraction from 95 kL/p/yr to 56-60 kL/p/yr under maximised implementation and to 82-92 kL/p/yr under conservative implementation. However, due to energy intensity of household rainwater pumps, the energy savings obtained from displacing centralised supply with rainwater will be offset by increased energy use by end users (households). Stormwater harvesting could produce minor energy savings under the maximised implementation.

Hydrological performance

Rainwater or stormwater harvesting under a conservative implementation (water used for garden irrigation and toilet flushing) could reduce stormwater runoff by up to 2.5 fold. If stormwater harvesting was maximised to cover all legal sub-potable uses, it has the potential of restoring near pre-development volumes of stormwater runoff. However, this assumes equal distribution of rainfall throughout the year. With intense sub-tropical storms, it is possible that stormwater collection ponds will often overflow.

Other hydrological flows will most likely not be restored. Total stream discharge will remain high due to external water supply that is later discharged as wastewater. The scale of urban vegetation and irrigation are too small to bring significant changes to evapotranspiration and groundwater infiltration rates.

Resource efficiency

Wastewater and greywater recycling could reduce water extraction from 95 kL/pr/yr to 56-63 kL/pr/yr under maximised implementation, and 78-92 kL/pr/yr under conservative implementation. Wastewater recycling also reduces water-related energy use, but greywater recycling at household scale tends to increase energy intensity on the site of the end user. However, greywater recycling within the appliance may provide significant energy savings for the end user if it is combined with heat recovery.

Hydrological performance

Wastewater or greywater recycling do not have any restorative effect on stormwater runoff, evapotranspiration, or groundwater infiltration rates. However, they decrease total stream discharge.

Conclusions on meso-urban scale application

The study demonstrated the usefulness of UMEF4Water for water servicing options assessment. Comparison of resource efficiency and hydrological performance of different interventions at master planned development scale may be useful for decision making by providing the following information:

- quantifying and comparing the degree to which urban areas are moving towards reduced reliance on external centralised supplies
- estimating the extent of intervention needed to maintain or restore pre-development hydrological flows
- bringing together the consideration of both anthropogenic and natural water cycles and highlighting the interactions between them to draw attention to the untapped potential (underutilisation of available water sources) and unintended consequences of their interconnectedness
- informing cost-benefit analysis that considers both the water and energy efficiency.

The outcomes highlight considerations that should be made in other locations for water-sensitive interventions screening. These considerations should stress:

- hydrological performance differences between wastewater recycling and stormwater harvesting options
- the scale of implementation of alternative water servicing options have to reach to produce significant benefits
- energy-related trade-offs of alternative water supply.

It should be noted, however, that the framework should be considered a complementary tool for robust assessment of water servicing options. To obtain best results, additional considerations could include:

- indirect implications of urban water management (can be assessed, e.g. through life cycle assessment)
- constraints obscured by the spatial and temporal scale of the analysed system (e.g. feasibility of rainwater harvesting with highly variable seasonal rainfall)
- other resources, beyond water and energy, that require more efficient use (e.g. nutrients).

Future directions: Micro-urban scale applications and thermal energy estimations

While the UMEF4Water is designed for city-region scale applications, analytical procedures that underpin its methods can be applied to smaller scales to assess local-scale technologies. Some of these technologies, such as greywater recycling, may be cost prohibitive if only water savings are considered, and estimation of energy use reductions might be necessary to justify their implementation.

Lamb (2016) refined the estimation of energy intensity for decentralised greywater recycling scenario at household scale discussed by Farooqui et al. (2016) by researching additional benefits obtained through coupling greywater reuse with heat recovery systems. The study assessed its economic viability by quantifying water demand savings and water-related energy use reduction obtained from thermal energy. Unlike Farooqui et al. (2016), the analysis was not specific to a particular geographic location, but the data on temperature, water usage and population were selected to reflect a range of typical conditions in Australia. Lamb's analysis was applied to a smaller scale, ranging from one household to a cluster of 10 apartment buildings. The technologies used for the scenario analysis were: recirculating showers (for one apartment scale) and rotating biological contactor with reuse for toilet flushing (for one apartment building and 10 apartment buildings scales).

The analysis of the amount of thermal energy that can be recovered from greywater reuse at different scales demonstrated variability that originated from different scales of implementation, the different technological solution adopted and their efficiency limitations, and differences in temperature of mains water supply. The estimation of both energy and water savings informed a lifecycle cost assessment that can complement cost-benefit analysis. Application of greywater recycling alone provided 19-23% reductions of mains water supply. However, the savings from water alone were not enough to cover the capital cost.

The results indicated that profitability relied on the scale of implementation and technology chosen by the investor as well as factors independent from the end user such as: supply mains water temperature, energy prices and proper insulation of pipes between the buildings. The findings indicated that benefits increased with the lower temperature of supplied water, higher energy prices and larger scale of implementation. The largest scale – cluster of 10 apartment buildings – was discovered to be optimal. In the analysed conditions economic viability was obtained if the supplied mains water temperature was equal or lower than 23°C and energy price was higher than $0.15/kWh. Additionally, when the energy price was higher than $0.25/kWh it was considered economically viable for a single apartment when the main's temperature was equal to or lower than 18°C. This highlights the role of local mains water temperature and energy policy in creating conditions for greywater recycling at household level in Australia.

Since end use water-related energy, especially energy used for water heating, comprises a significant, but often under-recognised (Kenway et al., 2013) proportion of total water-related energy, Lamb's (2016) findings have broader implications for water infrastructure and urban sustainability planning. Future research could explore further the usefulness of methods and indicators developed under UMEF4Water for micro-urban scale applications that provide a more precise estimate of end user energy use.

4. Informing urban and regional planning with UMEF4Water

Current institutional and legislative frameworks have been recognised as a barrier in transitioning to the new urban water management paradigm envisioned by Water Sensitive Cities. UMEF4Water and the set of indicators it proposes could be instrumental in facilitating transitions to Water Sensitive Cities as it addresses sector integration problems that undermine its successful realisation.

More details can be found in:

Serrao-Neumann, S., Morgan, E., Schuch, G., Renouf, M., Kenway, S., and Low Choy, D. (in prep.). *Towards Water Sensitive City-regions– Part 1 Pathways for rapidly growing metropolitan regions*. Melbourne, Australia: Cooperative Research Centre for Water Sensitive Cities.

Serrao-Neumann, S., Renouf, M., Kenway, S.J., and Low Choy, D. (2017). Connecting land-use and water planning: Prospects for an urban water metabolism approach. *Cities, 60, pp.* 13-27.

Research conducted by Serrao-Neumann et al. (2017) explored how the current statutory and non-statutory planning instruments support the integration of land use and water planning. The outcomes from a review of 113 documents, which included plans, policies, and strategies from three Australian city-regions: metropolitan Melbourne, metropolitan Perth and SEQ, revealed that this integration is yet to be accomplished. In particular, the current planning instruments (i) did not widely consider hydrological and environmental connections between cities and regions; (ii) had limited consideration of future change and uncertainties for water resources; and (iii) were sector-oriented rather than taking a whole of landscape perspective to account for policy synergies and trade-offs.

These findings suggest there is a need for performance assessment measures that address these gaps, and UMEF4Water indicators have the potential to address this gap. Specifically, the framework could be helpful in facilitating understanding of the reliance of urban systems on surrounding regions, framing urban hydrological performance indicators, and accounting for diverse sources and functions of water in urban systems. Information provided by urban water mass balance could be included in statutory and non-statutory strategic plans, implementation guidelines and land-use planning development assessments.

Current policies and urban metabolic performance

The utility of UMEF4Water was further explored with the purpose of highlighting pathways for feeding the information from the framework into urban and regional planning through a series of scenario planning workshops and semi-structured interviews carried out in the three city-regions (MEL, PER, SEQ) (Serrao-Neumann et al., in prep). Existing policies were found to be insufficient to achieve metabolic performance objectives and water sensitive city-regions that the framework is advocating for. In particular, we found that:

Supply internalisation may be hampered by the existing policies, legislation, and codes of practice that do not fully support alternative water sources. Additionally, while current urban planning systems promote compacted urban forms to limit further urban sprawl, there are limitations relating to implementing water supply internalisation. In particular, to some extent, the implementation of alternative water sources is enabled in greenfield but is difficult in infill developments and retrofitting existing built up areas.

Protecting water resources and hydrological flows is not fully supported by the existing policies and regulations. Specifically, it was noted that:

- Maintaining water extraction rates within sustainable limits was somewhat addressed, especially with respect to groundwater extraction, but at the same time there was little support for augmentation from more sustainable sources.
- Preservation and restoration of natural hydrological flows is hampered by problems associated with centralised management, limited collaboration between agencies, low public understanding, urban areas excluded from water management mandates (e.g. foreshore in Perth). There were efforts to improve existing integration of land use planning and water management, but these still faced barriers due to the siloed nature of agencies and institutions.
- Improving and maintaining water quality was hampered by problems that arise from lack of cooperation between agencies, future land use development, centralisation that may hinder innovative projects, low priority of environmental objectives, and policies focusing on water quantity (in terms of supply/demand) rather than quality, including the absence of targets for the latter in some cases.

Recognition of diverse functions of water was also not well embedded in urban and regional planning:

- Achieving multi-functionality of blue-green spaces was limited by low community awareness of the value of such places and limited funding. Additionally, there are complex governance arrangements (e.g. concerning health risks) that limit innovation in these areas. Multi-functionality of blue-green spaces is supported by some existing policies, but this excludes privately owned land and native habitats, which limits outcomes in terms of environmental objectives.
- Liveability was poorly integrated with water resource management, highlighting a potential policy gap.

The potential of urban metabolic performance indicators

Further interviews with 17 stakeholders highlighted pathways to enable water sensitive practices in the city-regions that could be informed by UMEF4Water (Serrao-Neumann et al., in prep). The findings reveal that both currently achievable and aspirational indicators could better inform urban and regional planning in SEQ, MEL and PER.

1. Resource efficiency

Water efficiency indicators could provide information that could be useful for:

- evidence-based policy planning and implementation (e.g. green/open space planning, human health, land-use control and development, integrated water management, building design)
- metrics to benchmark both for development and water resource management performance (e.g. water management objectives, clarification of agencies roles and responsibilities, fit-for-purpose water demands, identification and avoidance of policy trade-offs).

Stakeholders working in the sectors of urban and regional planning, urban water management and natural resource management stressed the need for higher resolution data that enables tracking of water usage patterns of different consumer groups or even households. This would support better strategies to decrease demand by allowing for context-specific tailoring of interventions. Water efficiency as an indicator was seen as particularly useful in Perth due to its arid climate and the resulting strong policy focus on bulk water resource management (eg, for managing groundwater recharge and environmental flow allocation). Specific applicability of the indicator for urban and regional planning in each city-region is presented on page 38.

Information about **water-related energy efficiency** can be useful for:

- investment strategies (more robust cost-effectiveness estimation of water supply options)
- cross-agency collaboration (especially between water and energy sectors)
- policy innovation (e.g. holistic approach to water and energy planning, including understanding of embedded social and environmental outcomes in maintaining water flows with the use of energy)
- public communication messages (e.g. promoting more efficient use of resources).

The interest in the indicator was fuelled by a growing recognition of the greenhouse gases footprint as a result of the water-energy nexus and the potential for renewable energy to offset that footprint as a key endeavour relating to corporate social responsibility of water utilities.

The indicator that assesses **water-related nutrient efficiency** was recognised as useful for:

- water quality policy: better monitoring of the effectiveness of nutrient reduction strategies (e.g. nutrient schemes) that aim to protect/improve supply water quality (both surface and groundwater) and setting pollution reduction targets
- investment strategies and policy innovation, in particular related to the potential of recovering nutrients from wastewater and fit-for-purpose treatment of sub-potable demand (irrigation)
- metrics to benchmark development performance (e.g. nutrient removal target)
- cross-agency collaboration.

2. Supply internalisation

The indicator can be useful for:

- informing investment strategies (e.g. business cases for alternative water sources, stormwater infrastructure prioritisation)
- technological innovation (e.g. fit-for-purpose design)
- metrics to benchmark water resource management performance (e.g. efficiency at different spatial scales, targets for fit-for-purpose supply augmentation)
- policy planning and implementation (e.g. regulatory options, identification of trade-offs, decentralisation of water supply)
- public communication messages (e.g. increasing public acceptance of recycled water) and shifting the dominant urban water management paradigm towards more diversified water supplies.

Depending on the region and its climatic conditions, the indicator may serve particularly for measuring efficiency of stormwater (MEL, SEQ) or recycled water (PER, SEQ) schemes.

3. Protecting water resources and hydrological flows

The indicator that assesses **water stocks** (maintaining the water extraction rates to within sustainable limits) can inform:

- water allocation for multiple water functions, including setting targets and monitoring of environmental flows
- policy planning and implementation (ensuring water security amid climate variability and population growth through regulatory options, land use planning, etc)
- Benchmarking development performance, especially in regard to urban runoff management.

UMEF4Water

Informing planning

URBAN PLANNING MECHANISMS / INDICATORS	Resource efficiency			Supply diversification and internalisation	Protecting water resources and hydrological flows			Recognising the diverse functionality of water
	Urban water efficiency per person or unit of efficiency	Water-related energy efficiency per person or per unit of functionality	Nutrient recovery from urban water	Water supply internalisation	Water use within safe operating space	Water pollutant load within safe operating space	Hydrological perfor-mance	supporting diverse functions
Evidence-based policy planning and implementation	●			●	●	●	●	●
Metrics to benchmark water resource management	●			●	●			
Metrics to benchmark development assessment	●		●					●
Investment strategy		●	●	●		●	●	●
Cross-agency collaboration		●	●					●
Policy innovation		●	●			●	●	●
Public communication		●		●				
Offset schemes			●					●
Setting targets for water management			●		●			●
Technological innovation				●				●

The indicator that measures **water quality** (water pollutant load within safe operating space) is particularly useful for:

- investment strategies (e.g. building business cases for multi-functional spaces, assessing interventions and programs that try to improve water quality and inform capital investments)
- policy planning and implementation (e.g. regulatory options, better environmental outcomes by improving the understanding of natural freshwater and groundwater systems, including environmental flows)
- policy innovation (e.g. urban design - informing design and maintenance of stormwater infrastructure especially underground stormwater basins, bio-retention systems and flood mitigation infrastructure)
- shifting the current water management paradigm from one focused on water quantity to one focused on quantity and quality.

4. Recognising the diverse functions of water

The indicator could be especially useful for:

- policy planning and implementation (e.g. urban design, including blue-green infrastructure, land use development and control, multi-functional urban spaces)
- policy and technological innovation (e.g. blue-green infrastructure, alternative water supplies)
- cross-agency collaboration (e.g. planning for the whole catchment, defining future roles of current agencies)
- investment strategies (building a business case for, and providing a more robust estimation of cost-effectiveness of, green infrastructure and WSUDs)
- water allocation for multiple water functions (e.g. purposes other than human consumption)
- offset schemes (e.g. water levy programs)
- metrics to benchmark development performance (e.g. landscape and open space design).

This indicator could also inform long-term water planning that takes into account liveability benefits derived from water and support a paradigm shift to embrace broader environmental and social values of water beyond economic gains and water efficiency.

Conclusions on UMEF4Water relevance for urban and regional planning

The interviews confirmed the utility of the framework for urban and regional planning. UMEF4Water can be particularly useful for:

- Informing strategic planning aligned with the vision of WSC

The new paradigm of urban water management that is enshrined in the concept of WSC has not yet been operationalised in performance indicators. UMEF4Water fills that gap by offering indicators that better respond to changes in the way performance is perceived within this new paradigm. Findings from the interviews with stakeholders demonstrated that UMEF4Water can be particularly useful for strategic planning that does not only focus on water supply and demand, but recognises new challenges of urban water management. These challenges include limits to natural resources, increased uncertainty related to climate change, and the need for a shift to deriving the highest environmental, social and economic outcomes from water, rather than simply managing its allocation.

- Informing development assessment

UMEF4Water was recognised as helpful in development assessment and water resource management – it enables the development of rigorous targets scalable to different areas, from the lot/precinct to city-region scale, and more robust sustainability performance assessments. UMEF4Water can be useful in measuring localised impacts and contextualising them within the broader performance of the whole city-region. Thus, it helps to align regulatory provisions (such as e.g. erosion and sediment control standards) with strategic, long-term water planning objectives. Translating city-region policies to lower scale targets is likely to become even more important as the financial mechanisms for water management that aim at changing private sector practices and consumer behaviours (e.g. nutrient offset schemes, water pricing) become increasingly preferred policy instruments. Additionally, UMEF4water can provide ampler assessment of trial water sensitive interventions that can create both a business case for WSC projects and a benchmark for innovative and conventional practices.

- Facilitating collaboration between different stakeholders (e.g. multiple agencies, levels of government, industry peak bodies, non-government organisations and communities) and indicating ways to further integrate existing institutional frameworks

Difficulties with collaboration between different agencies appear to be one of the most important barriers in the short-term realisation of WSC. The set of indicators available through UMEF4water operationalise the concept of various nexuses embedded in water management. For example, indicators measuring nutrient and energy efficiency of water management enable quantification of improvements that can be designed to strengthen sustainability performance of water infrastructure and processes. Water mass balance, the principal method behind UMEF4Water, facilitates discussion about the interrelations between natural and managed water flows (i.e. the landscape connectivity of water). It models how interventions focused on different water flows (e.g. stormwater) can impact other water flows (e.g. water supply) and therefore it highlights opportunities for collaboration across different agencies.

Future directions: UMEF4Water and sustainable urban water management approaches

The research conducted by Serrao-Neumann et al. (in prep) focused on how urban water metabolism can support urban and regional planning that is better aligned with the principles of WSC. The framework may also facilitate the transition to a more holistic and sustainable urban water management approach.

Findings from this research point to at least five key planning strategic initiatives that could promote water sensitive city-regions objectives and features, and be supported by best available information potentially being generated by metabolism science as evidence for recommending policy implementation (Serrao-Neumann et al., in prep). These are: (i) sustainability benchmarking for urban developments (e.g. mandatory targets); (ii) tailoring programmes that promote resource efficiency (e.g. nutrient offset schemes); (iii) making a business case for regional blue-green spaces; (iv) small and large-scale infrastructure innovation; and (v) social and institutional innovation in urban water management (e.g. integrated water resource management perspective). Further research could investigate pathways for the implementation and monitoring of these initiatives, including their contribution to the consolidation of innovative, sustainable urban water management approaches.

5. Communicating urban metabolism

Urban metabolism has been studied for decades, but it is still not a mainstream term. It is used in the vernacular of academics, but remains poorly understood by water practitioners (Dean et al., in press). The research undertaken by King (2015) explored how urban metabolism has been communicated and interpreted to date.

More details can be found in:

King, S. (2015). *How has urban metabolism been interpreted and communicated?* Unpublished final project thesis realised under Master of Integrated Water Management programme, International WaterCentre / University of Queensland. The report is available upon request from the International WaterCentre.

The research consisted of two elements: a literature review and structured interviews with urban metabolism experts. The literature review analysed the discourse, imagery and research focused on urban metabolism that has been presented in sources spanning from academia to business contexts. The structured interviews with nine urban metabolism practitioners from Australia, Europe and North America explored how urban metabolism communication has been received and interpreted by practitioners. It found a need for a common framework which this report is putting forward. Findings of the study also highlight the need to direct communication efforts to specific target groups and the role visualisation can play in advancing the understanding of the concept.

Current understanding of urban metabolism

To date, urban metabolism research has been mostly regarded as an academic "accounting exercise" (Kennedy et al., 2011). However, with more availability of detailed data due to the advancement of information and communication technologies, urban metabolism's usefulness for urban planning has been rediscovered (Kennedy and Hoornweg, 2012). This is evidenced by urban metabolism research projects undertaken by organisations worldwide, with examples such as the Public Interest Energy Research Program of the California Energy Commission, the European Union's Seventh Framework for the Sustainable Urban Metabolism of Europe and BRIDGE projects, as well as by The World Bank for its Eco2 Cities initiative. However, research undertaken in Australia shows that urban metabolism is the least understood term among water practitioners who also identify it as a concept that triggers their frustration (Dean et al., in press).

The concept of urban metabolism has not been communicated consistently. The literature review conducted by King revealed a lack of a standardised definition or a common method for urban metabolism analysis. In fact, although the concept of urban metabolism rests on an analogy to resource efficiency and sustainability of natural systems, it is not clear which system constitutes a more appropriate analogy – an ecosystem or an organism (Golubiewski, 2012; Pincetl, 2012). Discrepancies in the choice of metaphors are not a minor issue as they result in different evaluation approaches that further exacerbate different outcomes and create more potential confusion.

The thematic analysis of expert responses provided insights into the limitations of the current communication of urban metabolism. It highlighted four areas of particular relevance to the effectiveness of communication efforts.

Target audiences

The study confirmed that urban metabolism is not a widely understood term even among academic audiences. The general public was not perceived as the target audience among urban metabolism experts, and while its importance was expressed none of the interviewees expressed the capacity to engage the citizens directly. The targeted audiences that were mentioned by the interviewees included: local and state governments, urban planners and research funding institutions. Communicating the concept to city mayors was also seen as a useful application, as it could be used for comparison between cities sharing metabolic similarities and could drive inter-city collaboration.

Awareness and understanding among target audiences

One interviewee attributed low awareness of urban metabolism among experts to urban planning curriculum that lack components which provide an integrative perspective for analysis of complex urban systems (e.g. systems theory). Some interviewees also emphasised that the concept of urban metabolism is not widely used in urban planning and that the idea behind it is specialised and thus difficult to understand for non-specialists.

The broad range of definitions, methods and metaphors increases the difficulty of explaining urban metabolism to end users. Thus, interviewees asserted the need for scientific rigour and consistency. One interviewee was also concerned with the lack of audiences' understanding of the scientific basis of urban water metabolism methods (such as mass balance), while another drew more attention to the comprehension of the socio-economic system that should be coupled with urban metabolism, but currently that understanding may be lacking.

The language of urban metabolism

The majority of the interviewees claimed that language was not a barrier, as the concept is easily understood. This is not confirmed by larger scale, nationwide research undertaken by Dean et al. (in press) that shows that Australian water practitioners report low understanding of the concept. King's study also recognises the possible contradiction between what respondents report and their actual comprehension of the term. The differences in the actual understanding of the terminology resulting from the use of different metaphors and methods seem to suggest that language can, in fact, hinder effective communication.

City and ecosystem or organism analogies can be misleading. Two interviewees emphasised the limitations of the use of a metaphor, stating that it is important to communicate not only similarities but also differences between a city and an organism. The choice of the method for urban metabolism assessment can also influence the concept's understanding as evaluation methodology determines data requirements and uses. Interviewees pointed to material flow analysis as the most popular method, however sustainable life approach, mass balance, self-sufficiency, network analysis and life cycle assessment were also mentioned. Finally, the implicit use of the concept may obscure the imprecise definition of the term and cause further confusion. European interviewees mentioned that they are familiar with cases of urban policies that implicitly adopt urban metabolism principles without explicitly referring to it.

Effective means of representing urban metabolism

Interviewees agreed that visual representation was critical for communicating urban metabolism, but there was not consensus on the most effective method. One interviewee stated that the balance lies within simplifying complex information without being overly simplistic. Mapping was cited by a majority of interviewees as one of the most effective diagrammatic representations for urban metabolism, mainly because of the ability to layer data and that people generally understand maps.

Conclusions on urban water metabolism communication

The study highlighted the need to find a common language and a common working definition of urban metabolism. Interviewees, especially those from Australia, emphasised the importance of a rigorous method which this Milestone Report is starting to develop. Their concerns also included insufficient or inconsistent data at different scales.

There is a potential for urban metabolism to be used as a benchmarking tool, but Australian respondents were the most sceptical about its applicability for this and called for more evidence of its usefulness. This concern is also addressed by this publication in Sections 2, 3 and 4 that present the application of the framework and its usefulness for urban planning.

Regarding urban metabolism communication, this research shows that in order to advance urban metabolism understanding it will be necessary to:

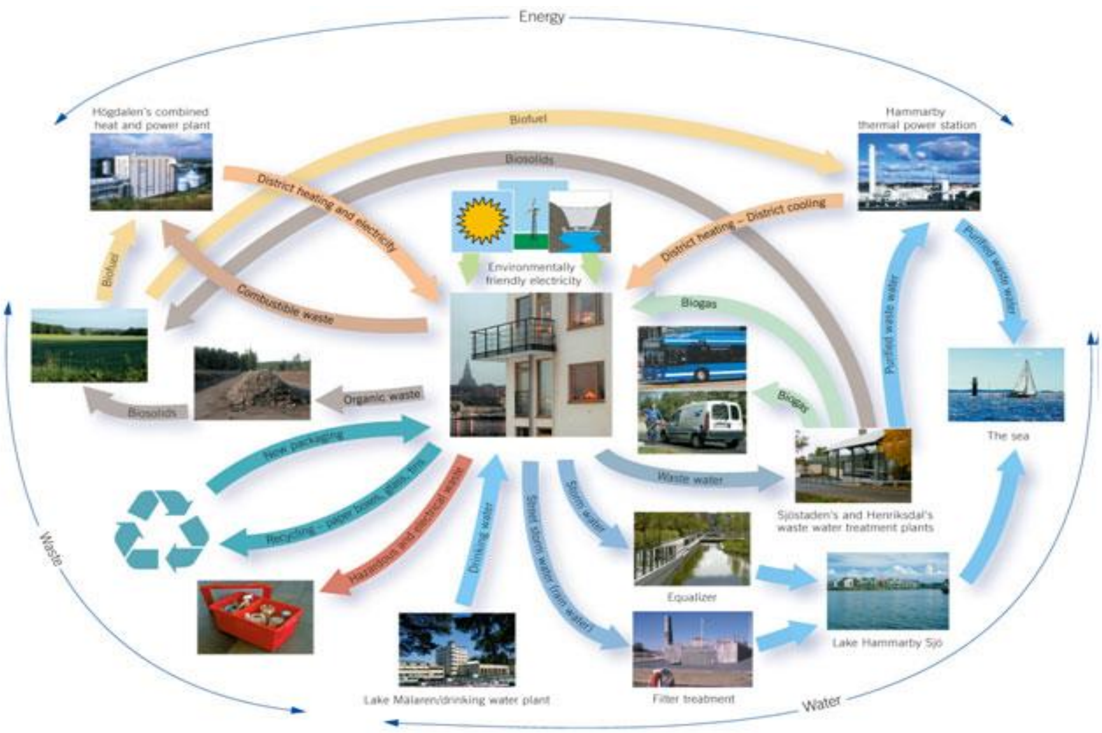
i) develop a shared and common understanding about what it means in relation to water, and consolidate methods used to evaluate it

ii) direct communication efforts and meaningful dialogue with target audiences, that have an interest in strategic urban water planning, most likely planners and water managers

iii) employ visualisation techniques to use and communicate urban metabolism information, including spatially linked such as mapping tools.

Future directions: Visual representation – data visualisation and concept communication

The research undertaken by King (2015) included a study of imagery used to communicate urban metabolism. The diversity of representations reflects differences in understandings of the concept and confirms findings of the literature review. But it also points to the potential, recognised also by the respondents, of using visual representation to communicate urban metabolism as a concept more clearly but also represent the outcomes of the evaluation.



A genuine attempt at moving towards a circular uban metabolism: Hammarby Sjostad, Stockholm.

Figure 10: Circular urban metabolism (Suzuki and Dastur 2010).

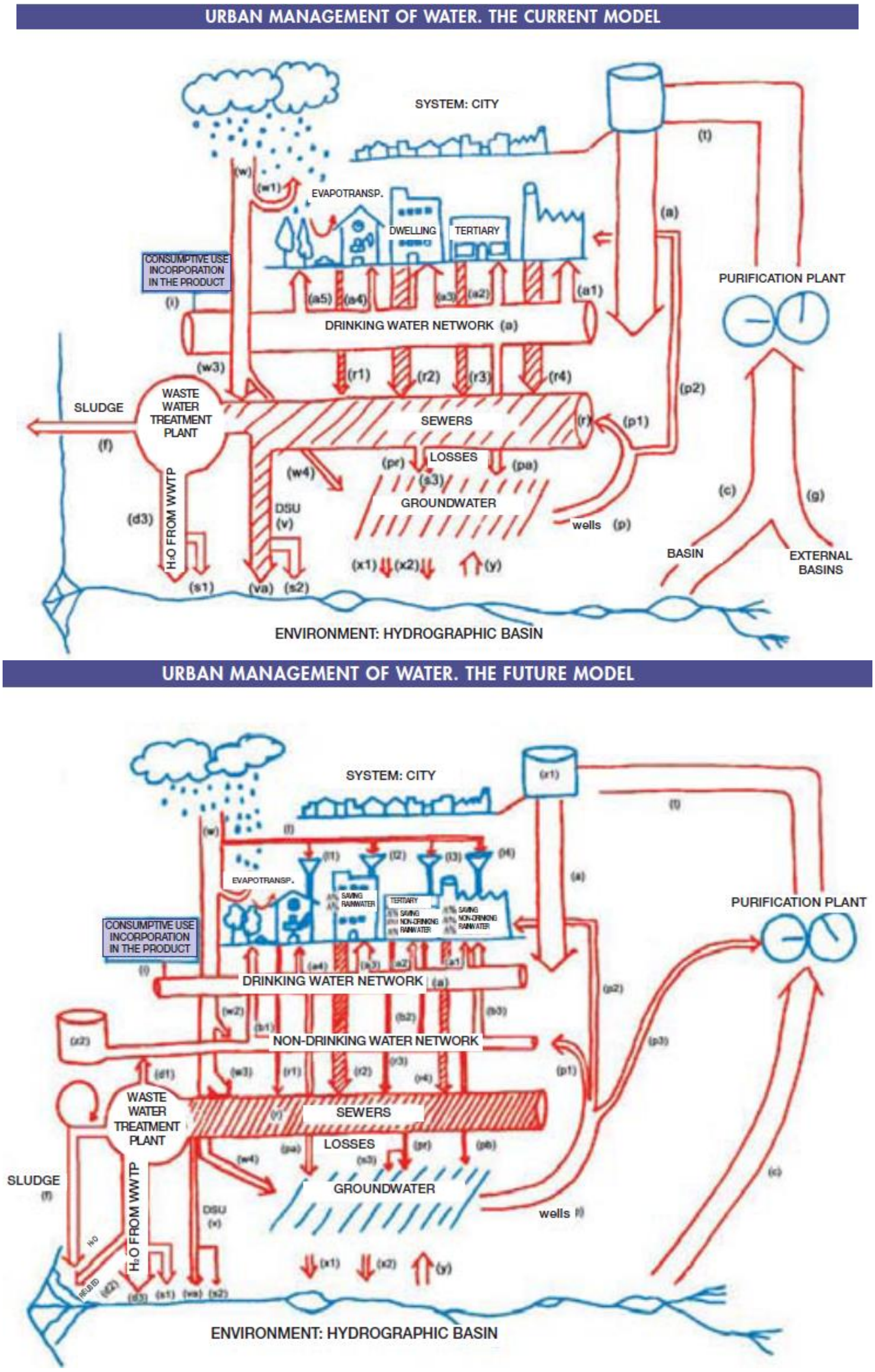


Figure 11: Urban water metabolism – current (top) and future (bottom) (Rueda, 2007).

Concept representation focuses on the underpinning metaphor and showing how different flows are connected. For example, Figure 10 depicts a Hammarby Model and illustrates how cyclic metabolism can help “cities in developing countries achieve greater ecological and economic stability” (Suzuki and Dastur 2010, p. 1). Figure 11 focuses on water flows and illustrates the comparison of a current urban water model to that of a potential future model. The representation includes input and output arrows of varying width to represent reduced consumption, and additional arrows to show reuse of resources.

Data visualisation tools allow representation not only of water flow trajectories but also their volumes. Sankey diagrams are one of the most common ways of depicting quantified flows (Figure 12). Some data visualisation techniques also include an element of spatial representation and are linked with GIS.

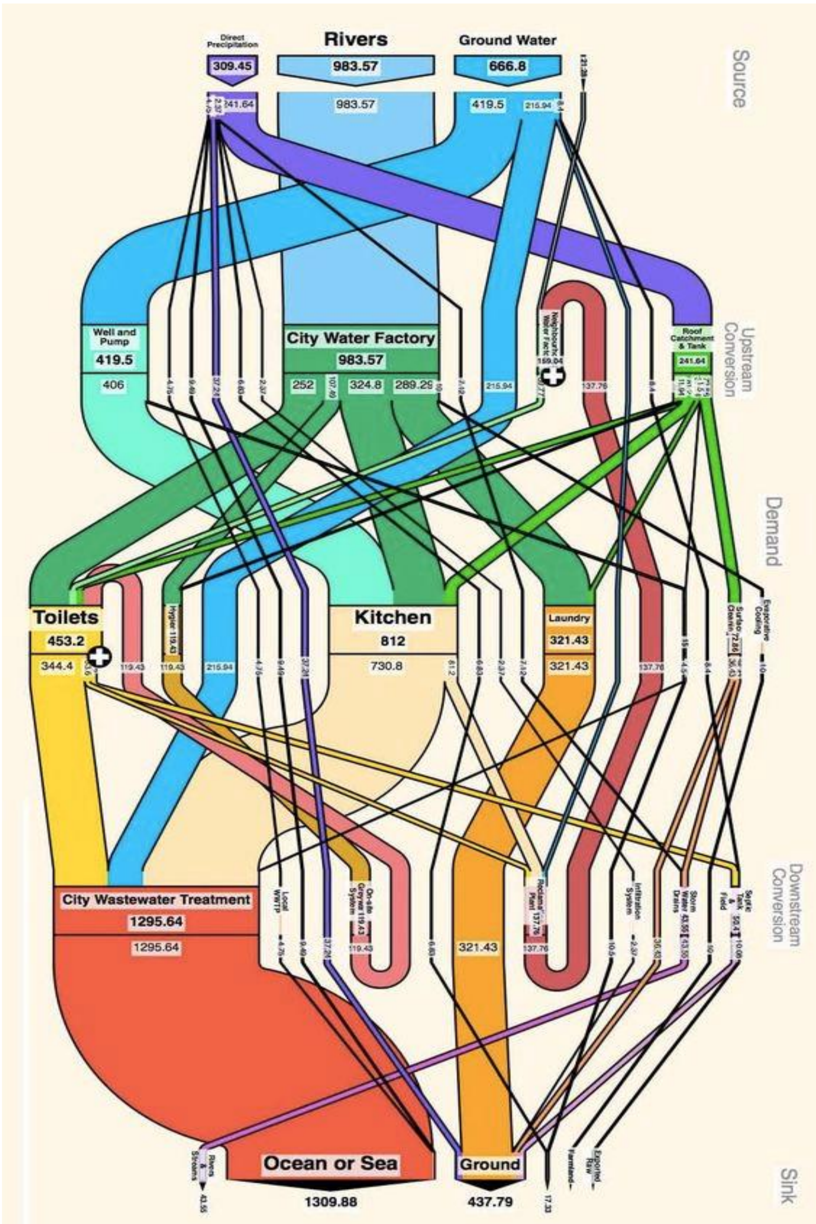


Figure 12: Water flows in the city of Vancouver. Example of a Sankey diagram (Eberlein 2014).

Synthesis

The aim of the research was to develop an evaluation framework that can generate indicators and knowledge of urban water metabolism to inform urban and regional planning. In the second phase of the research, UMEF4Water was applied to macro- and meso-urban scale and evaluated for its usefulness for urban and regional planning. We answered the following research questions:

What new insights about urban water management does urban water metabolism evaluation provide? What is the usefulness of the framework?

There is a need for indicators that can quantify targets for the water management objectives envisioned in the concept of Water Sensitive Cities and gauge the impact of water sensitive interventions. The evaluation approach explored in this work provides a mechanism for doing this. For example, the findings from the analyses suggested that implementation of water sensitive interventions might have to be conducted at a much larger scale to achieve envisioned improvements, especially those related to stormwater (e.g. restoration of natural hydrological flows).

Differences between urban water metabolism evaluation at macro- and meso-urban scale emphasise the importance of the scale of the assessment and the need for caution in generalising solutions recognised as working on a smaller scale to the larger scale. The differences between the impact of rainwater harvesting on stormwater runoff in the Ripley Valley and SEQ case studies, shows that interventions that might bring a localised improvement on a meso-urban scale, may not in fact be the most effective strategies at the city-region scale.

Application of UMEF4Water to city-region scale highlighted differences between the assessed city-regions in terms of their current urban water performance. The evaluation approach may be useful for comparing advancements made by different cities, and for benchmarking their performance against each other, and bringing attention to areas of urban water management that could be improved.

Urban water metabolism evaluation might also facilitate the transition to a new paradigm of urban water management that goes beyond water allocation to delivering the highest value per unit of extracted water (e.g. through diverse functionalities of water indicator). However, there is a need for further research as some indicators that could play the most important role in that transition are currently aspirational, their assessment is limited by the insufficient understanding of relevant environmental mechanisms (e.g. sustainable water yields and assimilative capacities of supporting environments) and lack of data to populate equations (e.g. urban water functionality index with efficiency indicators to expressed per unit of function). Further research in those areas could advance the transition to Water Sensitive Cities.

What indicators can be generated by the UMEF4Water framework to give a useful measure of urban water metabolism?

A set of indicators proposed for UMEF4Water allows more holistic evaluation and quantification of the four objectives of urban water management: (1) resource efficiency (water, energy, nutrients), (2) supply diversification and internalisation, (3) effectiveness of protection of water resources and hydrological flows, (4) diverse functionalities of water that go beyond just meeting the needs for potable water. Ten indicators, proposed as part of the UMEF4Water framework are outlined in Table 1. The novelty of these indicators is that they are driven by the objectives of urban water management, rather than by data availability. Hence, while some indicators can already be quantified with data generated from a water mass balance, other aspirational indicators will require further research.

How can the information generated from urban water metabolism evaluation inform decisions about urban water management at the city-region scale?

The framework is suited to performance monitoring (e.g. of current and proposed systems), priority setting, and initial screening of water sensitive interventions to identify the types and scale of implementation that would be needed to achieve desired water performance objectives for a city-region. For example, the case study analysis suggested that multiple interventions (stormwater/rainwater harvesting, wastewater recycling, increasing perviousness) may be required to achieve a tangible improvement in city-scale performance. The work also highlights the current absence of established performance objectives and prompts the need for urban planners and water managers to consider targets for improvements that are sought at the city-region scale. The values of the approach are the city-region perspective (important for informing strategic land use planning), compilation of all urban water flow data into a single framework (for comprehensiveness and understanding interconnections), and consistency in system boundary definition (important for comparing between urban systems and over time).

How can the framework be used for informing planning?

There is relatively little evidence that consideration regarding hydrological and environmental connectivity is being extensively enabled by current urban and regional planning statutory and non-statutory mechanisms in Australian capital city-regions. Urban and regional planners have access to various tools to assist in their decision-making and policy implementation processes concerning land-use and water planning, especially tools related to water infrastructure. However, many of these tools do not enable the integration of different aspects of water (e.g. stormwater, wastewater, drinking water) nor take into account larger spatial scales known to be important for strategic planning purposes. The UMEF4Water has the potential to fill this gap by setting indicators that can both inform strategic planning and development assessment, and promote integration between the sectors of land use and water resource planning.

For example, the UMEF4Water links the principles articulated in several visions related to water sensitive city-regions with available indicators for quantifying performance against these visions. Additionally, it can help urban and regional planners evaluate how urban areas are currently performing in terms of water resource efficiency and set desired levels of performance for existing and future developments. Spatial scale wise, the UMEF4Water focuses on the city-region and therefore aligns with the scale commonly adopted by strategic regional planning endeavours. The framework can also focus on the meso-urban scale, thereby allowing the evaluation of a range of water-sensitive interventions that are applicable to smaller spatial scales and intended to provide localised overall improvements of hydrological performance of, but not limited to, greenfield and brownfield developments.

For governance regimes similar to the one governing Australian capital city-regions, the full benefits from UMEF4Water for land use planning can be enhanced if provisions for improved integration between land use and water resource planning are enabled through statutory and non-statutory policies across several sectors and government levels (state and local). The framework can aid such integration by facilitating collaboration between different stakeholders and sectors. This includes different agencies that govern managed and natural flows at both state and local government levels, natural resource management organisations, water corporations and utilities, and the private sector.

The potential of the urban water metabolism might, however, be compromised by poor general understanding of the concept and this confusion may undermine adoption of the framework. Therefore, it is recommended that visualisation tools are used for improved concept communication and data representation.

Advancing the framework

Future research can refine UMEF4Water by addressing limitations related to:

Urban boundary – Delineation of the urban boundary posed difficulties that needed to be overcome in the work presented in this report. Land use data, planning schemes and development plans as well as information on population densities both current and future were all needed to be considered when setting the boundary. The boundary also required adjustment to data resolution of different layers. For example, while actual land use GIS data may have very high resolution, the data on water usage or population density tends to be aggregated to more coarse units (e.g. districts). Additional difficulty lies in the fact that the actual boundary tends to be 'fuzzy', particularly at the urban edges and the decision to exclude certain areas in order to create a consistent urban area development "envelope" may need to be made by the researcher. Determining the boundary between urban and peri-urban is also challenging as the boundary is dynamic and changes with urban growth, but also as the change from urban to peri-urban is gradual and requires decisions distinguishing the two. Future research could provide further methods for overcoming some of these challenges.

Spatial and temporal variability – The work undertaken and described in this report focused on relatively large temporal and spatial scales – it assessed water metabolic performance based on a single year and relied on averages for a given urban scale that disregarded spatial variability. Future work could provide more refined assessments that for example take into account the temporal variations of water flows that may be particularly important for storage capacity within cities. Assessment of water metabolic performance at finer time scales and comparison of multiple years may also allow capturing localised effects of water sensitive interventions under climate change conditions characterised by more common weather extremes and changing rainfall patterns. The work presented in this report relied on spatial averages (e.g. average value of rainfall across the whole city). Since the assessed urban scales (macro and meso) were large, as an example, the spatial variability of rainfall within the urban boundary could be substantial. Partitioning cities or meso-scales (development areas) into smaller zones or assessing urban water metabolic performance at finer scales (micro-urban) could complement large scale (macro-urban) assessment. It can be more useful for informing decisions on water sensitive interventions in the context of infill development and urban renewal projects that tend to be implemented at smaller than meso- or macro-urban scales.

Data sources and data governance – While more data on centralised, anthropogenic flows has been made publically accessible in recent years, data availability remains a challenge for the advancement of UMEF4Water. Natural flows estimation relies on hydrological flow partitioning factors that need to be understood better and calibrated against real hydrological data. Decentralised supply is not well monitored and thus its estimation often is based on existing case studies in academic literature. Additionally, there is little data on decentralised supply from boreholes and surface water, which may lead to its underestimation particularly if the urban boundary includes large peri-urban or even rural areas that are not serviced by utilities. Finally, even data available for anthropogenic flows is often aggregated in a way that hinders more precise estimation of water efficiency at smaller, e.g. household levels, as urban planners from all three cities remarked. BOM's role, in enabling access to relevant data and overcoming fragmentation of data presents an obstacle for robust analyses, needs to be recognised. However, there is still potential for improving data governance through high-level data sharing agreements between agencies and encouraging open data that is spatially explicit at a resolution useful to different stakeholders.

Scales – Application of UMEF4Water at different scales draws attention to the importance of selection of the scale for metabolic evaluation. City-region scale evaluation may be useful for strategic planning, while smaller scales may help to inform regulations and assess developments. The two may be most effective if conducted together - city-region evaluation can contextualise smaller scale performance and benchmark it against city average, while meso-urban scale assessment may provide a more nuanced picture of whole city metabolic water performance which allows for intra-city comparison and prioritisation of areas with the poorest results. The challenge lies, however, in identifying the conditions that need to be met to be able to conduct such intra-city comparison (e.g. consistent and tight urban boundary).

Opportunities for impact – future directions

This research shed light on the opportunities that UMEF4Water creates for a more holistic urban water management that is better equipped to respond to future uncertainties. The opportunities lie in:

1. Embracing more integrated urban water management

Recognition of multi-functionality of water – Recognising the diverse functions of water beyond just meeting primary needs for potable water is a recurring objective in the new, more holistic paradigms of urban water management. Yet, there is little consideration so far of how these competing functionalities could be compared to each other and what metrics could be used to inform decisions of prioritising one function (e.g. recreation) over another (e.g. ecosystem health). Some of the proposed aspirational indicators are measured against the delivered functionality. They envision that with a growing understanding of the value of benefits derived from water (functionality index) proposed indicators could inform decision making that prioritises delivering the highest value of water, rather than its allocation.

Understanding sustainable extraction rates – The framework represents the overall water efficiency of an urban area in terms of the amount of water extracted from the environment. This could be extended by putting those estimates in the context of what may be sustainably extracted from supporting regions. This would help planners and water managers understand the extent to which urban areas are stretching the capacity of the regions to supply; but would require methods for defining water sustainable extraction rates.

Consideration of water-related energy and nutrient flows –There is an opportunity to add water-related energy and nutrient flows as an overlay to the urban water mass balance, to enable the generation of indicators related to these other important water-related resource efficiency aspects. As the stakeholders remarked, understanding energy implications of supply augmentation technologies and water sensitive interventions can inform decisions on future investments and help avoid mal-adaptation to climate uncertainties. They may also be useful for reducing greenhouse gases emissions and the carbon footprint of water sector operations. Water-related nutrient efficiency on the other hand can build support for innovations in wastewater treatment technologies.

2. Receptive and enabling institutional environment

Advancing robust science informed planning – the development and application of UMEF4Water provides a good example of how the technical aspects of land use and natural resource management planning can be enhanced. It provides an avenue for the planning process and its outputs in terms of land use locational decisions and planning policy generally can be better informed through the consideration of science thereby providing a more robust platform upon which to consider environmental aspects and the consequential impacts of proposed developments. In particular, it provides an example of how a science based framework can be used in the important components of the planning process, namely the evaluation of alternative courses of action leading to the final planning decision in both the strategic and development assessment aspects of planning.

Cross-agency collaboration – UMEF4Water aligns with the trend to promote more collaborative work in urban water management. As the framework brings together natural and anthropogenic flows it can highlight interconnections and facilitate dialogue between agencies dealing with different parts of the city water cycle (stormwater versus water supply).

3. Information and communication advancements

Information and Communication Technologies – There are opportunities to automate the urban water metabolism evaluation, for example through integration with other CRC tools/products such as DANCE4Water, and developing software solutions that are linked to BOM data for natural and anthropogenic flows.

Data visualisation and communication with non-experts – Water mass balance that constitutes the core method of UMEF4Water can easily be visualised using simple tools for Sankey diagram creation. Data visualisation can be a useful tool to facilitate decision making for urban and regional planners, by providing a concise and systematic representation of complex hydrological modelling. But data visualisation may also be useful for communicating urban water metabolism to lay audiences. With the trend to engage communities with water management tools that enhance systemic and holistic understanding of the urban water cycle among non-experts are of particular value. Macro- and meso-urban scale water mass balance visualisation can, e.g. be used to reduce water demand or strengthen support for alternative water sources.

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CRC for
Water Sensitive Cities

Cooperative Research Centre for Water Sensitive Cities

Level 1, 8 Scenic Boulevard
Monash University
Clayton VIC 3800

info@crcwsc.org.au

www.watersensitivecities.org.au