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Energy Implications of Water Management in Cities

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Abstract

Energy is used in every stage of the urban water cycle, from water abstraction, treatment, distribution, to end use and wastewater treatment. In recent years, increasing energy consumption for providing water services, rising energy costs, recognising the water-energy nexus and the need for mitigating climate change have been drivers for better management of the energy use in urban water systems.

The primary goal of this thesis is to improve our understanding of the energy implications of urban water management. This thesis considers water management activities that balance supply and demand of water in cities, and provide water-related services to municipal water end users. It uses multi-city analysis, time-series analysis, deterministic modelling, data mining, comparative case study, life-cycle assessment and marginal cost curve to explore the energy implications. The existing body of "energy for water" research has i) limited analysis and no consistent framework comparing "energy for water" in different cities, ii) no time-series historical analysis of "energy for water" in cities, iii) limited energy implication assessment of implemented water management strategies, and iv) no analysis and framework comparing cost implications of water-related energy management in water utilities to that of water end users.

This thesis starts with a global multi-city analysis to quantify and compare the energy use for water supply performance of cities (Objective 1). The analysis reveals high spatial and temporal variations of energy use for water supply in the 30 cities studied. A novel time-based water-energy profiling approach is developed and used to illustrate these variations. Per capita energy use for water supply shows high spatial variation, ranging from 10 kWh/p/a (Melbourne in 2015) to 372 kWh/p/a (San Diego in 2015). In terms of temporal variations between 2000 and 2015, there was a general reduction in per capita energy use for water supply in most of the 17 cities with time-series data. Climate, topography, water use pattern and system operational efficiency are some of the factors contributing to these variations. The high spatial and temporal variation, and the study of the contributing factors provide insight for inter-city learning of water-related energy management.

The multi-city analysis also identifies four Australian regions for detailed case studies of their water-related energy lessons from the Australian Millennium Drought (Objective 2). The case studies demonstrate significant long-term energy saving benefits for water utilities from the large scale adoption of water conservation strategies in Melbourne, South East Queensland (SEQ) and Sydney. This energy saving within the water supply systems has partly (for Sydney) or fully (for Melbourne and SEQ) offset the negative energy consequence

of utilising energy-intensive alternative water sources such as seawater desalination and inter-basin water transfers during the drought. In addition, this energy saving extends beyond water utility boundary to water end use, mostly in the form of hot water savings. Furthermore, the comparative case study between SEQ and Perth illustrates that a different emphasis on supply versus demand side management can drive regions towards very different long-term water-related energy use pathways.

The case studies also show how water management has different water-related energy influences in various components of urban water systems: water supply system, sewage system, residential water end use and decentralised water source. For instance, the water conservation strategies implemented during the drought have led to significant water-related energy saving in residential water end use, with much greater energy saving than that of water supply systems (e.g., 30-fold in Melbourne). Large-scale uptake of rainwater tanks in SEQ through the drought added over 10% of life-cycle energy use to the regional water supply system, but contributed an estimate of only 2% of urban water supply.

Following on from the different water-related energy influences shown in the three case studies, this thesis uses a marginal cost curve approach to help address the question of where management effort should be directed from the perspectives of both cost-effectiveness and energy saving potential (Objective 3). The current paradigm for water-related energy management is primarily focused on opportunities within water utilities.

This thesis clearly shows that such a utility-focused paradigm would lead to sub-optimisation of the urban water system. More specifically, focusing solely on managing the energy use within the utility would miss substantial non-utility water-related energy saving opportunities. By broadening the current scope of water-related energy management beyond the system boundary of water utilities and valuing their management from a city perspective, some water end-use options with more significant energy saving potential and cost-effectiveness would stand out, instead of being neglected in the utility perspective management. This would create opportunities where the same capital investment could achieve far greater energy savings in an urban water system. In the Australian context, this thesis shows that many water-related energy management solutions at water end users can be more cost-effective and having greater energy saving potential than water utility options. However, there is a need to create the right incentives for water utilities to look beyond their system boundaries to engage in water-related energy management at water end users.

The work in this thesis has improved our understanding of the energy implications of water management in cities – in particular, energy impacts of geospatial conditions, historical trends of various cities, energy impacts of drought adaptation, relative energy influences in various components of urban water systems, and cost implications for water-related energy management. It clearly shows that cities can improve energy management in urban water systems through greater water efficiency and exploring opportunities in water end use.

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my research higher degree candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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Publications during candidature

Peer-reviewed papers

Lam, K.L., Lant, P.A., Kenway, S.J. (2017) Energy implications of the millennium drought on the urban water cycles in southeast Australian cities. *Water Science and Technology: Water Supply* (Accepted on 25th May, 2017).

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Lam, K.L., Lant, P.A., O'Brien, K.R., Kenway, S.J. (2016) Comparison of water-energy trajectories of two major regions experiencing water shortage. *Journal of Environmental Management* 181, 403-412.

Kenway, S.J., **Lam, K.L.** (2016) Quantifying and managing urban water-related energy use systemically: case study lessons from Australia. *International Journal of Water Resources Development* 32(3), 379-397.

Kenway, S.J., Binks, A., Lane, J., Lant, P.A., **Lam, K.L.**, Simms, A. (2015) A systemic framework and analysis of urban water energy. *Environmental Modelling and Software* 73, 272-285.

Conference paper

Lam, K.L., Lant, P.A., Kenway, S.J. (2016) Energy implications of the millennium drought on the urban water cycles in southeast Australian cities. *IWA World Water Congress & exhibition*, Brisbane, Australia, October, 2016.

Conference abstracts

Lam, K.L., Kenway, S.J. (2016) Adapting the urban water systems in three Australian regions to droughts. *SIWI World Water Week*, Stockholm, Sweden, August, 2016.

Lam, K.L., Lant, P.A., Kenway, S.J. (2015) Historical Energy Implications of Urban Water Management Options in South East Queensland, Australia. *9th IWA Symposium on Systems Analysis and Integrated Assessment*, Gold Coast, Australia, June, 2015.

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Contributor	Statement of contribution
Ka Leung Lam (Candidate)	Designed the study (80%) Data collection (95%) Results analysis and interpretation (80%) Wrote and edited the paper (80%)
Steven J. Kenway	Designed the study (10%) Data collection (5%) Results analysis and interpretation (10%) Wrote and edited the paper (10%)
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Ka Leung Lam (Candidate)	Designed the study (100%) Data collection (100%) Results analysis and interpretation (100%) Wrote and edited the paper (90%)
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Ka Leung Lam (Candidate)	Designed the study (85%) Wrote and edited the paper (90%) Data collection and model development (100%) Results analysis and interpretation (90%)
Steven J. Kenway	Designed the study (10%) Wrote and edited the paper (5%) Results analysis and interpretation (5%)
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Contributions by others to the thesis

Contributions by all co-authors for the publications included in this thesis. Steven Kenway and Paul Lant commented on this thesis.

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Keywords

energy management, urban water system, water-energy nexus, drought, water utility, water end use, multi-city analysis, time-series analysis, least cost analysis, life-cycle assessment

Australian and New Zealand Standard Research Classifications (ANZSRC)

ANZSRC code: 050204, Environmental Impact Assessment, 10%

ANZSRC code: 050205, Environmental Management, 60%

ANZSRC code: 090702, Environmental Engineering Modelling, 30%

Fields of Research (FoR) Classification

FoR code: 0502, Environmental Science and Management, 70%

FoR code: 0907, Environmental Engineering, 30%

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List of Figures & Tables

List of Abbreviations used in the thesis

$CAPEX_{City}$	Capital expenditure from water utility/government and end users ($)
$CAPEX_{Utility}$	Capital expenditure from water utility ($)
E_{EU}	Energy saving at water end use as quantified by the data source (MWh/year)
$E_{EU,t}$	Energy saving at water end use in *t* th year (MWh)
$E_{EW,t}$	Energy saving at water utility in *t* th year (MWh)
$E_{O,WU}$	Energy saving at water utility (non-water saving related) (MWh/year)
$EC_{EU,t}$	Electricity price at water end use in the *t* th year ($/MWh)
$EC_{WU,t}$	Electricity price at water utility in the *t* th year ($/MWh)
$ECS_{EU,t}$	Energy cost saving at water end use in the *t* th year ($)
$ECS_{WU,t}$	Energy cost saving at water utility in the *t* th year ($)
EI_{EU}	Energy intensity for water end use activities (MWh/ML)
$EI_{WS,t}$	Energy intensity for water supply in the *t* th year (MWh/ML)
$EI_{WW,t}$	Energy intensity for wastewater treatment in the *t* th year (MWh/ML)
EP_{City}	Energy saving potential of an option from the city perspective (MWh)
$EP_{Utility}$	Energy saving potential of an option from the water utility perspective (MWh)
$i_{EC,EU}$	Electricity price annual change rate at water end use (%)
$i_{EC,WU}$	Electricity price annual change rate at water utility (%)
$i_{EI,WS}$	Energy intensity for water supply annual change rate (%)
$i_{EI,WW}$	Energy intensity for wastewater treatment annual change rate (%)
i_{WC}	Water price annual change rate (%)
kWh/p/a	Energy use expressed as kilowatt-hour electricity use per person per year
kWh/kL	Energy intensity expressed as kilowatt-hour electricity use per kilolitre water supplied
L/p/d	Water use expressed as litre of water use per person per day
MC_{City}	Marginal cost of an option from the city perspective ($/MWh)
$MC_{Utility}$	Marginal cost of an option from the water utility perspective ($/MWh)
n	Monte Carlo run
N_{max}	Total number of Monte Carlo simulation
t	Year
t_{option}	Lifetime of option
T_{max}	Number of assessment year
TC_{City}	Net cost of an option from the city perspective ($)
$TC_{Utility}$	Net cost of an option from the water utility perspective ($)
V_w	Water saving from the mains (ML/year)
WC_t	Water price ($/ML)

PART I:

INTRODUCTION

1. Introduction

1.1. Background

Recent years have seen increasing interest by both practitioners and researchers in energy management in urban water systems. It is driven by the concerns regarding increasing uptake of alternative water sources with higher energy requirement (Stokes and Horvath, 2006), environmental sustainability (Čuček *et al.*, 2012), rapidly increasing energy costs (Talebpour *et al.*, 2014), water-energy nexus (Bartos and Chester, 2014) and climate change mitigation needs (Rothausen and Conway, 2011).

On a city level, water-related energy use can be a significant part of urban energy demand. For instance, the water-related energy use in an average Australian city in 2007 was determined to be 13% of total electricity and 18% of the total natural gas (Kenway *et al.*, 2011a). In California, 19% of the state's electricity use and 32% of its non-power station natural gas use in 2005 was water-related (Klein *et al.*, 2005). In 2010, 13% of annual primary energy consumption in the residential sector in the US is for water heating (Sanders and Webber, 2012). Therefore, any changes on the supply-side or demand-side of urban water systems may have considerable energy implications on the water utilities, the water end-users and collectively, the cities. For example, in South East Queensland, new water supply sources introduced during a prolonged drought consumed approximately 40% of the total energy use for the water supply system, but contributed only 10% of the water supply in 2009/10 (Cook *et al.*, 2012). In California, it was estimated that in order to meet the regional water demand entirely with desalination, it would consume 52% of the state's electricity (Stokes and Horvath, 2009).

Another driver for improving energy management of urban water systems is the rapidly increasing energy costs. In Australia from 2003 to 2013, real electricity prices for businesses increased on average by 60% for electricity and 29% for gas, and for households increased on average by 72% for electricity and 54% for gas (Swoboda, 2013). For water utilities, energy costs are a major operating expense and are rapidly becoming a business risk (Victorian Water Industry Association, 2011).

Energy use is also a major contributor of greenhouse gas (GHG) emissions in most urban water systems as electricity and gas supply in a lot of cities is mostly fossil-based. A better understanding of the relationship between water and energy is therefore essential for the management of water-related GHG emissions. This improved understanding, especially the possible energy implications of different options for future scenarios, can help develop water strategies that do not compromise climate change mitigation efforts.

The inter-dependency of water and energy resources (or the so-called water-energy nexus) has been gaining recognition in recent years. Energy is needed for providing water services (i.e., "energy for water", the subject of study in this thesis), while water is needed for fuel production and cooling of thermal power plants (i.e., “water for energy”). Such an integrated perspective can allow the assessment of co-benefits of conservation efforts in both water and energy sectors (Bartos and Chester, 2014) and can reduce the risk that a strategy or policy implemented in one area undermines a policy goal in another (Howells *et al.*, 2013).

This PhD project aims to improve our understanding of the energy impacts associated with urban water system management. The “water management” referred to in this work includes activities on balancing supply and demand of water in cities, and providing water-related services to municipal water end users. For the urban water system, this work considers centralised water supply, centralised wastewater collection and treatment, water end use and decentralised water supply.

1.2. Motivation and objectives

This PhD research project is composed of three major research objectives. These research objectives and research questions addressed some gaps in the current body of “energy for water” research (reviewed in Chapter 2).

Research objective 1: Quantify and compare the performance of cities for their energy use for water supply

This research objective studies the energy use of urban water supply systems in 30 cities from 13 countries. It was motivated by some previous multi-regional studies (Mo *et al.*, 2014; Siddiqi and Anadon, 2011; Venkatesh *et al.*, 2014). These earlier studies examined a small sample of cities for the water-related energy impacts of geospatial conditions. My work aims to address the following research questions.

1. How and why does energy use for water supply differ across cities? (Chapter 3)
2. What are the historical trends for some of the cities? (Chapter 3)
3. How can we compare and track the energy for water performance of cities consistently? (Chapter 3)
4. What have been some of the lessons learned for managing energy use for water supply? (Chapter 3)

Research objective 2: Quantify and understand the energy impacts of droughts on urban water systems

This research objective investigates the energy impacts of a prolonged drought (the Millennium Drought) on the urban water systems of four Australian urban regions – Melbourne, South East Queensland (SEQ), Sydney and Perth. It was motivated by an observation from the multi-city study (research objective 1) that these four regions had significant changes in energy use for water supply during the drought. In addition, it is well documented how these regions responded to this worst drought on record, but relatively little is known about the energy implications of the drought and the implemented water management strategies on the urban water systems. This objective investigates the energy impacts at different parts of the urban water systems – water supply system, wastewater system, and residential water end use. The work aims to address the following research questions.

1. What have been the long-term changes in water use and associated energy use for two major urban areas (SEQ, Perth) encountering water stress? (Chapter 4)
2. How much can water management options influence long-term water use and associated energy use in cities? And what are the lessons learned from the four regions? (Chapters 4-6)
3. What is the relative energy impacts of the drought and implemented strategies on water supply, wastewater treatment and residential water end use in Melbourne? (Chapter 5)
4. What is the life-cycle energy impacts of the alternative water supply strategies introduced in SEQ? (Chapter 6)

Research objective 3: Investigate the least cost solutions for water-related energy management in wider urban water systems

This research objective conducts a least cost analysis of energy management in wider urban water systems. It was motivated by an earlier finding that water end use (including residential, commercial and industrial use) accounts for 86% of total water-related energy use in an average Australian city (Kenway *et al.*, 2011a), and its management is generally not within the scope of water planners (WSAA, 2012). This objective therefore develops marginal cost curves to prioritise and visualise the cost effectiveness and energy saving potentials of 18 water-related energy management options (both water utility options and water end use options) that have been implemented or evaluated in Australia. It compares cost curves developed from two perspectives, namely the (typical) water utility perspective, and the city perspective. It also discusses the policy implications.

The work aims to address the following research questions.

1. If we draw a wider urban water system boundary which considers both water utility and water end use instead of just water utility in conventional analysis, how would that impact on the least cost analysis of water-related energy management? (Chapter 7)
2. How are the cost effectiveness and energy saving potential of water end use options compared to water utility options? (Chapter 7)

1.3. Structure of the thesis

This thesis is composed of three parts – Part I: Introduction, Part II: Research outcomes, and Part III: Discussion and conclusions.

Part I sets the scene for this thesis.

- Chapter 1 gives the background and motivations behind this work. It also outlines the research objectives and research questions.
- Chapter 2 provides a literature review on i) energy studies for urban water systems, ii) methods used by some previous studies, and iii) the Australian Millennium Drought context for which the case studies in Chapters 4 to 6 are based on. It identifies research gaps and connects the research outcomes in Part II to the literature.

Part II is the main body of this thesis. It is a collection of five journal papers that advance our understanding of the energy implications of urban water management (the theme of this thesis).

- Chapter 3 analyses the energy use for water provision in 30 cities. The work identifies four Australian cities for more in-depth studies in Chapters 4 to 6.
- Chapter 4 is case study 1. It quantifies and compares the trend of energy use for water provision of South East Queensland and Perth in response to water shortage.
- Chapter 5 is case study 2. It quantifies the time-series energy use of water supply systems and wastewater systems in Melbourne and Sydney through the Millennium Drought. It also compares the changes in water-related energy use in the water supply system, wastewater system and residential water end use in Melbourne before and after the drought.
- Chapter 6 is case study 3. It quantifies the life-cycle energy impacts of four alternative water supply strategies introduced in South East Queensland during the Millennium Drought.
- Chapter 7 is a least cost analysis of water-related energy management in Australian cities. It compares the cost-effectiveness and energy saving potential of both water utility options and water end use options.

Part III synthesises the research outcomes of this thesis.

- Chapter 8 presents an overall discussion on the research outcomes in Part II.
- Chapter 9 concludes this work and provides some recommendations.

Additional details for the work in Chapters 3 to 7 are given in the appendices.

2. Literature Review

2.1. Previous studies on energy implications of urban water management

A considerable amount of work has evaluated the energy implications of different urban water management strategies. These strategies range from different centralised water sources (Lundie *et al.*, 2004; Shrestha *et al.*, 2011; Stokes and Horvath, 2006) to alternative decentralised water sources (Anand and Apul, 2011; Devkota *et al.*, 2013; Lee and Tansel, 2012; Racoviceanu and Karney, 2010) to wastewater treatment technology change (Anand and Apul, 2011; Lundie *et al.*, 2004) to water demand management (Bartos and Chester, 2014; DeMonsabert and Liner, 1998; Racoviceanu and Karney, 2010; Willis *et al.*, 2010) and to household water-related energy management (Kenway *et al.*, 2012; Sanders and Webber, 2015). Their energy implications have been studied from different perspectives such as to understand direct energy impacts on centralised systems (Hall *et al.*, 2011; Shrestha *et al.*, 2011), to quantify the embodied energy impacts (Amores *et al.*, 2013; Mo *et al.*, 2014; Stokes and Horvath, 2006) and to explore future scenarios (Lundie *et al.*, 2004; Shrestha *et al.*, 2011; Twomey Sanders, 2016).

Table 1 covers 30 of these studies that explored energy implications of urban water management. It categories each study based on i) the type of urban water management strategies being studied, ii) where the water-related energy influence was quantified, iii) the evaluation scale, iv) the nature of the study, and v) whether cost implications were considered or not. This systematic literature review helps identify some gaps in the current body of "energy for water" research.

Firstly, most of the published work comprises studies of a single region. There are very few multi-regional studies on energy for water. Siddiqi and Anadon (2011) assessed the inter-dependence of the water and energy systems in the Middle East and North Africa, and Sanjuan-Delmás *et al.* (2015) statistically analysed a sample of 50 municipalities in Spain to assess their energy use in water supply networks. A multi-regional study is valuable because it can help to identify best practice and support inter-city learning, especially between cities with similar geophysical environments (Kennedy *et al.*, 2009). Multi-regional studies also provide a better understanding of the impacts of geospatial conditions on water management decisions (Mo *et al.*, 2014). Decker *et al.* (2000) emphasised the need to broaden the study of individual cities into systematic cross-city comparisons.

Gap: <u>Lack of multi-regional "energy for water" studies</u> that can explore the influences of geospatial conditions on water-related energy use and support inter-city learning (*addressed by Objective 1 and Chapter 3*)

Table 1 A list of studies focusing on evaluating energy implications of urban water management

Study	Category															
	Urban water management strategy [1]				Water-related energy impacts on [2]				Evaluation scale			Nature				
	CWS	**DWS**	**WWT**	**EU**	**WS**	**EU**	**WW**	**EX**	**Centralised system**	**End user: individual**	**End user: regional**	**Static/ dynamic**	**Scenario comparison**	**Historical impacts**	**Actual/ hypothetical system**	**Cost implications**
(DeMonsabert and Liner, 1998)				✓	✓	✓	✓			✓		Static			Hypothetical	✓
(Lundie *et al.*, 2004)	✓		✓	✓	✓		✓	✓	✓			Static	✓		Actual	
(Lundie *et al.*, 2005)	✓		✓	✓	✓		✓	✓	✓			Static	✓		Actual	
(Stokes and Horvath, 2006)	✓				✓			✓	✓			Static	✓		Actual	
(Stokes and Horvath, 2009)	✓				✓			✓	✓			Static	✓		Hypothetical	
(Racoviceanu and Karney, 2010)		✓		✓	✓	✓		✓		✓		Static	✓		Hypothetical	
(Rozos *et al.*, 2010)		✓				✓				✓		Static	✓		Hypothetical	✓
(Willis *et al.*, 2010)				✓		✓					✓	Static		✓	Actual	✓
(Stillwell and Webber, 2010)		✓		✓	✓		✓		✓			Static	✓		Actual	
(Anand and Apul, 2011)		✓	✓	✓	✓	✓	✓	✓		✓		Static	✓		Actual	✓
(Proença *et al.*, 2011)		✓		✓	✓		✓		✓			Static			Actual	✓
(Shrestha *et al.*, 2011)	✓				✓				✓			Dynamic	✓		Actual	✓
(Hall *et al.*, 2011)	✓	✓		✓	✓		✓		✓		✓	Dynamic			Actual	
(Poussade *et al.*, 2011)	✓				✓			✓	✓			Static		✓	Actual	
(Chang *et al.*, 2012)	✓				✓			✓	✓			Dynamic	✓		Actual	✓
(Shrestha *et al.*, 2012)	✓			✓	✓				✓			Dynamic	✓		Actual	
(Kenway *et al.*, 2012)				✓		✓				✓		Static	✓		Actual	✓
(Lee and Tansel, 2012)				✓	✓	✓	✓	✓		✓		Static			Hypothetical	
(Amores *et al.*, 2013)	✓		✓		✓		✓	✓	✓			Static	✓		Actual	
(Cook *et al.*, 2013)		✓				✓				✓		Dynamic			Actual	
(Devkota *et al.*, 2013)		✓	✓		✓	✓	✓	✓		✓		Static			Hypothetical	✓
(Stokes *et al.*, 2013)	✓				✓		✓	✓	✓			Static		✓	Actual	✓
(Willuweit and O'Sullivan, 2013)	✓	✓		✓	✓		✓	✓	✓			Dynamic	✓		Actual	✓
(Umapathi *et al.*, 2013)		✓				✓				✓		Dynamic		✓	Actual	
(Siddiqi and De Weck, 2013)	✓			✓	✓	✓	✓			✓		Dynamic	✓		Actual	
(Talebpour *et al.*, 2014)		✓				✓				✓		Dynamic		✓	Actual	
(Bartos and Chester, 2014)				✓	✓	✓	✓		✓		✓	Dynamic	✓		Actual	✓
(Mo *et al.*, 2014)	✓				✓			✓	✓			Static	✓		Actual	
(Lane *et al.*, 2015)	✓	✓	✓		✓		✓	✓	✓			Static	✓		Actual	
(Sanders and Webber, 2015)				✓		✓					✓	Static	✓		Actual	

[1] CWS: centralised water supply system; DWS: decentralised water supply source; WWT: wastewater treatment method; EU: water end user (including water conservation, energy management)

[2] WS: water supply system; EU: water end user (including decentralised supply sources); WW: wastewater system; EX: externality (i.e., life-cycle energy impact)

Secondly, most of the studies reviewed present a "snapshot" result of a single year. Studies considering the influence of time on water-related energy use are less evident in the literature (Kenway *et al.*, 2011b). Some dynamic studies were looking at real-time energy consumption for rainwater tanks (Cook *et al.*, 2013; Talebpour *et al.*, 2014; Umapathi *et al.*, 2013) or long-term future scenarios of centralised water systems (Bartos and Chester, 2014; Hall *et al.*, 2011).

Gap: <u>No time-series historical analysis of "energy for water" in cities</u> to quantify the current trends, understand historical changes, and explore possible water-related energy lessons (*addressed by Objective 1 and Chapter 3*)

Thirdly, the review clearly shows that there are very few studies that evaluate the energy implications of past implemented water management strategies. A lot of studies focus on scenario comparison for future or hypothetical systems. The Australian Millennium Drought (to be discussed in Section 2.3) offers rich sources of information and data to explore energy implications of a wide range of adopted urban water management strategies.

Gap: <u>Lack of energy implication assessment of implemented water management strategies</u> to demonstrate their actual energy influence and offer insights which may not necessarily be unveiled by studies that focus on future scenarios and hypothetical systems. More specifically, these aspects were less explored in the literature, especially for historical analysis:

- Energy saving potential of water conservation
- Long-term energy impact of drought adaptation
- Relative energy influence on different components of urban water systems
- Regional energy impact of rainwater tanks

(*addressed by Objective 2 and Chapters 4 - 6*)

Lastly, while there is an increasing recognition of the significant energy influence of water end use (Kenway *et al.*, 2011a; Sanders and Webber, 2012), it is not clear whether it is also cost-effective to focus on managing this water-related energy use. In the literature, cost implications for water-related energy management are relatively less studied (Table 1). They also focused on the financial performance on either water utilities or individual water end users, but not both.

Gap: <u>No comparison between cost implications of water-related energy management in water utilities and water end users</u> to understand where effort on water-related energy management should be directed in urban water systems from an economic perspective in addition to energy saving potential
(*addressed by Objective 3 and Chapter 7*)

2.2. Methodologies for studying energy implications of urban water management

In the literature, a wide range of approaches has been used to study energy implications of water management in cities. For example, they include deterministic static modelling (DeMonsabert and Liner, 1998), system dynamic modelling (Bartos and Chester, 2014), direct measurement (Talebpour *et al.*, 2014), multi-regional analysis (Venkatesh *et al.*, 2014), material flow analysis (Kenway *et al.*, 2012), life-cycle assessment (Lundie *et al.*, 2004), marginal abatement cost curves (Stokes *et al.*, 2014). These approaches can be complementary to each other and in some cases share certain characteristics. For example, life cycle assessment is also considered to be a modelling approach, but with a more standardised methodology than other approaches. While most of the reviewed articles can be categorised into a distinct methodology type, a number conducted their studies by combining features from multiple approaches.

Direct measurement approaches involve making instrumental measurements and observations directly, or conducting surveys and interviews. This is a comparatively straightforward method for quantifying the energy implications. On the supply-side, the approach is commonly used as water utilities directly meter the energy consumption of their system components. On the other hand, for the demand-side, direct measurement of energy consumption for water use is often not feasible in practice as building-level metering commonly includes non-water related energy uses. Instead, other parameters such as water use patterns and system stock profiles are used to determine the energy implications of different options (Kenway *et al.*, 2012; Willis *et al.*, 2010). Nevertheless, a number of studies reviewed measured the energy intensity of rainwater tanks (Cook *et al.*, 2013; Talebpour *et al.*, 2014; Umapathi *et al.*, 2013).

Both static modelling approaches and system dynamic modelling approaches describe the subjected system (whether it is an urban water supply system or an individual household) mathematically and provide a possible platform for options comparison and scenario studies. Static modelling deals with time independent quantification of the energy implications of supply and management options, while system dynamic modelling simulates the behaviour of a system in response to time dependent changes and is a common approach to study a system with stocks, flows, time delays and causal relationships (Dawadi and Ahmad, 2013). In the literature, system dynamic modelling approaches are more commonly applied to simulate the behaviours of centralised water supply systems (Chang *et al.*, 2012; Shrestha *et al.*, 2011; Shrestha *et al.*, 2012). The majority of modelling studies utilised parameters from multiple academic or grey literature sources, while some were based on data from direct measurement (Cook *et al.*, 2013; Kenway *et al.*, 2012; Poussade *et al.*, 2011; Umapathi *et al.*, 2013; Willis *et al.*, 2010).

Life cycle assessment (LCA) is a structured, comprehensive and internationally standardised approach (Čuček *et al.*, 2012) for quantifying different categories of environmental impacts of processes, products or activities over their whole life cycle. LCA studies generally consider a broader system boundary than the other three approaches described above and can be viewed as a static modelling approach in some cases. In energy studies of urban water management, the externalities being considered by LCA can, for example, include the energy embedded in manufactured chemicals used in water treatment or in construction materials embedded in water supply infrastructure, and the supply of electricity for operation. The system boundary for the analysis strongly dictates the energy impacts identified.

Multi-regional analysis draws on multiple regions for analysis in a single study. As previously discussed, the approach can help to identify best practice, support inter-city learning and understand the impacts of geospatial conditions. There are only a few examples of this type of analysis for water-related energy studies (Siddiqi and Anadon, 2011; Smith *et al.*, 2015; Venkatesh *et al.*, 2014). The possible barriers to conduct multi-regional analysis are lack of data for multiple regions/cities, and consistent frameworks to compile, present and analyse the data.

> **Gap**: <u>No approach to illustrate the performance of multiple regions for their water-related energy use</u> in a consistent framework for clear comparison and presentation
> (*addressed by Objective 1 and Chapters 3*)

Marginal Abatement Cost Curves (MACC) have been used to support least cost planning for energy and greenhouse gas management in various disciplines. The approach graphically illustrates the relative cost-effectiveness and mitigation potential of different measures. Meier *et al.* (1982) is an early work of using the cost curve approach (i.e., called supply cost curves at that time) to populate energy saving options in the residential sector. Sydney Water Corporation (the water services provider for the Greater Sydney region) has developed a Cost of Carbon Abatement (CCA) tool for managing energy and GHG emissions based on the marginal abatement cost curve approach (WSAA, 2012) and licensed the tool to 19 water utilities across Australia as of 2014 (Sydney Water Corporation, 2014). Stokes *et al.* (2014) constructed a life-cycle carbon abatement cost curve for water utilities to account for pressure and leakage management strategy. While there is an increasing use of marginal cost curves for water-related energy management, the curves have only been developed from the perspective of the water utility, but not for a city perspective that considers and values options in both utility and water end use domains. Furthermore, water management options on the supply-side (i.e., within the system boundary of the water utility) and the demand-side (i.e., outside the system boundary of the water utility) are not typically compared on the same basis. The development of a city cost curve for the water sector can provide a platform to compare options across the boundary between water suppliers and water consumers.

> **Gap**: <u>No marginal cost curve for water-related energy management in city</u> to compare cost-effectiveness and energy saving potential for different water-related energy management strategies in both utilities and water end use
> (*addressed by Objective 3 and Chapter 7*)

2.3. Australian Millennium Drought and urban water management responses

From 2001 to 2009, south-eastern Australia experienced the longest uninterrupted series of years with below median rainfall on record (Van Dijk *et al.*, 2013). This was a part of a prolonged period of dry conditions occurring in much of southern Australia from late-1996 to mid-2010 (Bureau of Meteorology, 2015a). This prolonged severe drought, known as the Millennium Drought, had substantial impacts on agriculture, economy, ecosystem and urban water sector in much of southern and eastern Australia. This review focuses on three urban regions in southeast Australia – Melbourne, South East Queensland and Sydney.

Previous studies on the urban context of this drought have focused primarily on examining the adaption process of individual cities. For instance, for South East Queensland, Head (2014) examined the decision-making processes in policy responses, while Laves *et al.* (2014) studied the effectiveness and future risks of implemented adaptation strategies. Grant *et al.* (2013) discussed how urban water demand in Melbourne changed through the drought. The only comprehensive multi-regional study is by Turner *et al.* (2016), who summarised the policy responses and unveiled lessons learned from the drought experience in four regions – Melbourne, South East Queensland, Sydney and Perth. More recently, Horne (2016) examines preparedness for extreme weather events (including droughts, floods and extreme storm events), as well as policy responses and remaining challenges in six major Australian cities.

The three regions responded to the drought by implementing a range of demand-side and supply-side responses at various points during the escalating (and resolving) water “crisis” (Table 2) (Grant *et al.*, 2013; Head, 2014; Turner *et al.*, 2016). The timing of some responses are shown in Figure 1 (Lam *et al.*, 2017b; Melbourne Water, 2016b; Seqwater, 2016; WaterNSW, 2016). It also shows the major dam storage levels (i.e., as a proxy of the level of water stress) and the per capita urban water use (i.e., showing how the urban water demand responded to both policies and drought conditions).

Table 2 Policy responses to the drought in Melbourne, South East Queensland and Sydney

Policy responses	Melbourne	South East Queensland	Sydney
Demand-side			
Water restrictions	✓	✓	✓
Water conservation rebate schemes	✓	✓	✓
Business water efficiency program	✓	✓	✓
Consumption targets	✓	✓	
Educational campaign on water efficiency	✓	✓	✓
Supply-side			
Operating the existing inter-basin water transfer system			✓
Investigating on building new dams		✓	
Increasing the capacity of existing dams		✓	
Building an inter-basin water transfer system	✓		
Connecting segregated water supply systems		✓	
Increasing use of non-potable recycled water	✓	✓	✓
Building an indirect potable water recycling system		✓	
Building a seawater desalination plant	✓	✓	✓
Pressure management and leakage program	✓	✓	✓
Promoting decentralised water sources (e.g., rainwater tank)	✓	✓	✓

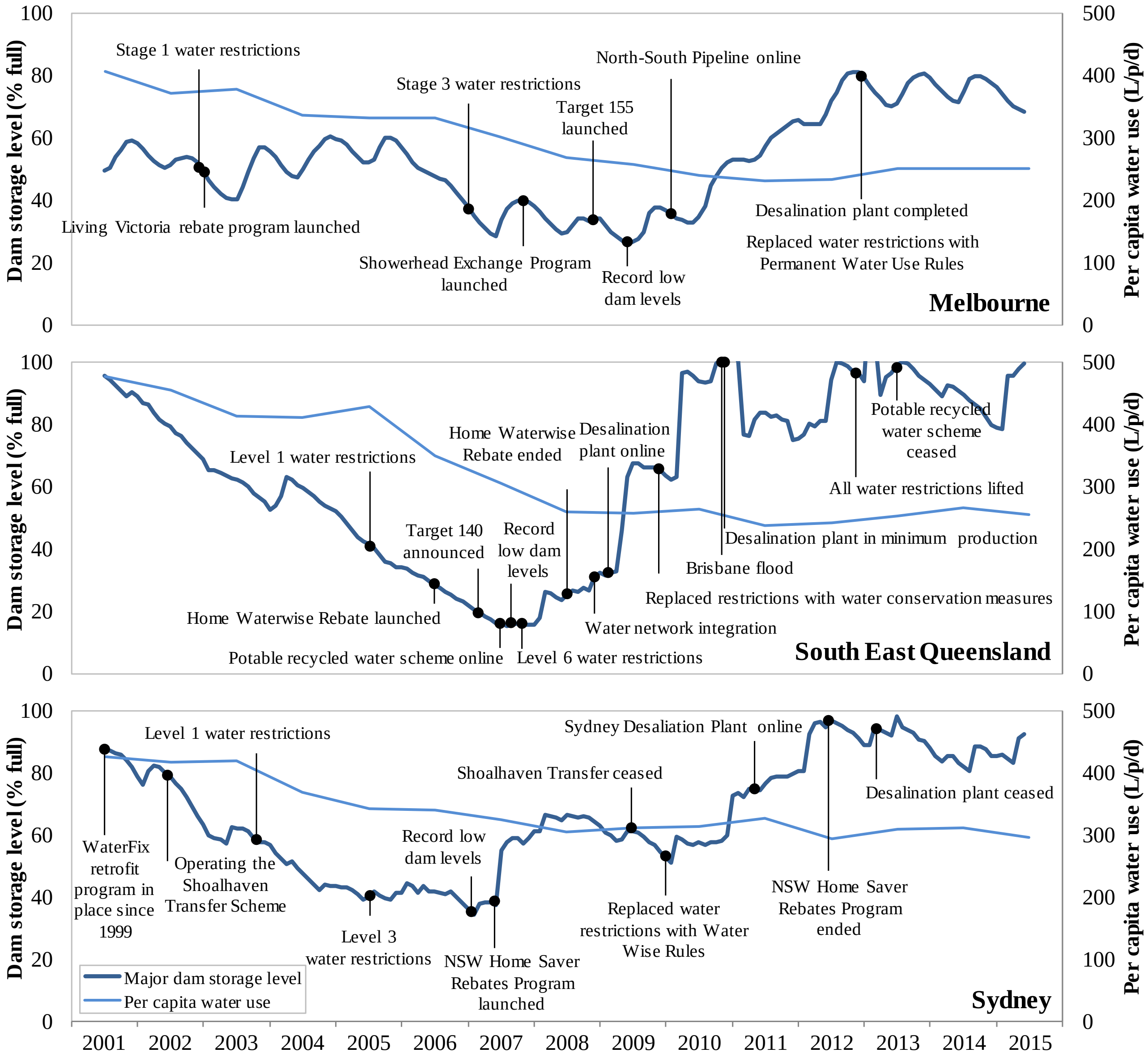

Figure 1 Dam storage level and per capita total urban water use in Melbourne, South East Queensland and Sydney from 2001 to 2015 with key events and policy responses

Since the water supply systems in the three regions are characterised by a relatively high carry-over capacity (e.g., in SEQ, the dam capacity was estimated to be 6 times the total annual urban water demand (Marsden and Pickering, 2006)), much of the policy focus was on managing the water demand in the early stage of the drought. All the three regions progressively imposed different levels of water restrictions, offered various water-efficient device rebates and launched water conservation promotion campaigns. Many of these responses targeted residential water use, which represented approximately 60% of the total urban water demand.

Water restrictions were imposed to limiting outdoor water use in a stepped system (4 stages in Melbourne; 7 stages in SEQ; 3 levels in Sydney). The measures included for example, limiting or banning the use of sprinklers or hoses for watering gardens, banning watering of lawns, limiting car washing to buckets only, prohibiting washing of paved surfaces, and restricting the filling of swimming pools. In addition to that, high volume residential water users in SEQ were also identified and given personalised notice to limit their water use.

Water efficient device rebate programs were another major demand-side measure implemented. In Sydney, a household retrofit program (WaterFix) was first launched as early as 1999. The program offered a visit from a plumber to fix leakages and replace showerheads with more efficient ones. In SEQ, a $321 million program (Home Waterwise Rebate scheme) was launched to offer households rebates on water-efficient devices such as low-flow showerheads, water-efficient clothes washers, dual-flush toilets, and rainwater tanks (mostly for external use, only a small portion were internally plumbed).

Water conservation promotion campaigns were used to induce water use behaviour change. Public education through the media messages was one of the tools effective in driving behaviour-led reduction in water use (Grant *et al.*, 2013; Head, 2014). One such campaign was Target 140 in SEQ. It encouraged residents to reduce their water usage rate to 140 litres per person per day (L/p/d), targeting indoor water use behaviour in particular (as previous water restrictions had focused mostly on outdoor water use).

As a result of these demand-side interventions, urban water demand dropped significantly in all three regions within a few years (Figure 1), largely due to the contribution of residential sector. For example, the per capita urban water use in Melbourne reduced from 408 L/p/d in 2001 to 241 L/p/d in 2010 (residential water use from 247 L/p/d to 152 L/p/d). These measures considerably lowered the risk of dam storages running out before alternative supply arrangements could be made.

As the drought worsened, dam levels in the three regions approached “trigger points” for planning and building new supply sources. Trigger responses included planning for new dams, increasing the capacity of existing dams, accessing the dead storage of reservoirs, building seawater desalination plants, constructing inter-basin water transfer systems, increasing the use of recycled water, and promotion of decentralised water sources. Most of these supply-side responses involved significant infrastructure investments.

Noticeably, each of the three regions built a reverse osmosis seawater desalination plant. In addition, in South East Queensland, an indirect potable water recycling system was constructed, which is designed to purify treated sewage effluent to a quality suitable to be fed into the main supply storage (Wivenhoe Dam). However, due to a steady increase in rainfall in 2008 and a lack of public support for potable water recycling, no recycled water has yet been fed into the dam. The potable recycled water was used primarily as cooling water for two power stations in the region. The drought also led to the building of a bulk water supply network to connect eight discrete water supply systems (Queensland Water Commission, 2010). This has increased regional flexibility, and reduces the need for water restrictions in one region while dams are full in adjacent regions.

In Melbourne, an inter-basin water transfer pipeline (the North–South Pipeline) was constructed for transferring water from the Goulburn River to Melbourne's catchment systems. The easing of drought conditions and the timing of the state election cycle in 2010 led to the shutdown of this $750 million asset.

Most new infrastructure was commissioned in the later stages of the drought, due to the long timeframes required to plan and implement supply-side responses. Some such as the Sydney Desalination Plants and the North South Pipeline in Melbourne, did not even come online until the drought broke in 2010.

In the literature, it is relatively well documented how the Australian urban regions responded to this drought (Grant *et al.*, 2013; Head, 2014; Horne, 2016; Laves *et al.*, 2014; Morgan, 2015; Newman, 2014; Turner *et al.*, 2016), but relatively little is known about the energy implications of the drought and the implemented water management strategies on the urban water systems. Retrospective studies based on the experiences of these regions can demonstrate how cities perform in practice and provides insights into managing energy use in urban water systems. It is particularly relevant to urban areas that are facing water stress and increasing energy costs, and starting to utilise more energy-intensive water sources.

Gap: Lack of water-related energy study of the Australian Millennium Drought to analyse water-related energy implications of drought adaptation experience in Australian cities
(*addressed by Objective 2 and Chapters 4 - 6*)

PART II.

RESEARCH OUTCOMES

3. Energy use for water provision in cities

This chapter is composed of a paper that addresses the first objective of this thesis – to quantify and compare the performance of cities on their energy use for water supply. This multi-city study provides an up-to-date comprehensive analysis of current status, trends and drivers of energy use for water supply in 30 cities from 13 countries. It also identified four Australian cities (where major shifts of energy use for water supply were observed) for detailed studies in the next three chapters.

Lam, K.L., Kenway, S.J., Lant, P.A. (2017) Energy use for water provision in cities, *Journal of Cleaner Production* 143, 699-709.

Abstract

Energy demand for urban water supply is emerging as a significant issue. This work undertakes a multi-city time-series analysis of the direct energy use for urban water supply. It quantifies the energy use and intensity for water supply in 30 cities (total population of over 170 million) and illustrates their performance with a new time-based water-energy profiling approach. Per capita energy use for water provision ranged from 10 kWh/p/a (Melbourne in 2015) to 372 kWh/p/a (San Diego in 2015). Raw water pumping and product water distribution dominate the energy use of most of these systems. For 17 cities with available time-series data (between 2000 and 2015), a general trend in reduction of per capita energy use for water provision is observed (11% - 45% reduction). The reduction is likely to be a result of improved water efficiency in most of the cities. Potential influencing factors including climate, topography, operational efficiency and water use patterns are explored to understand why energy use for water provision differs across the cities, and in some cities changes substantially over time. The key insights from this multi-city analysis are that i) some cities may be considered as benchmarks for insight into management of energy use for water provision by better utilising local topography, capitalising on climate events, improving energy efficiency of supply systems, managing non-revenue water and improving residential water efficiency; ii) energy associated with non-revenue water is found to be very substantial in multiple cities studied and represents a significant energy saving potential (i.e., a population-weighted average of 16 kWh/p/a, 25% of the average energy use for water provision); and iii) three Australian cities which encountered a decade-long drought demonstrated the beneficial role of demand-side measures in reducing the negative energy consequences of system augmentations with seawater desalination and inter-basin water transfers.

3.1. Introduction

Energy is used in every stage of water supply, abstraction, conveyance, treatment and distribution. In future, more energy is expected to be required to adapt water systems to meet increasing demand, regulatory requirements and the effects of climate change (Rothausen and Conway, 2011). In places with increasing water scarcity, alternative water sources such as inter-basin water transfers, desalination, potable water recycling and decentralised sources are being considered or utilized to meet increasing water demands and/or to cope with drought (Hussey and Pittock, 2012). Most of these alternative supply sources are more energy-intensive than traditional options such as dams and aquifers (Stokes and Horvath, 2006). This can represent a significant increase in greenhouse gas emissions and therefore, may be inconsistent with climate change mitigation policies. In addition, rising energy use can represent a financial risk to water utilities and communities (Kenway and Lam, 2016). For instance, the electricity cost for providing urban water services in Australia was forecast to increase five-fold over 2010 levels by 2030 (Cook *et al.*, 2012).

Energy use for urban water provision has been studied extensively from different perspectives such as to understand direct energy impacts (Nogueira Vilanova and Perrella Balestieri, 2015; Sanjuan-Delmás *et al.*, 2015), to quantify the embodied energy impacts (Amores *et al.*, 2013; Mo *et al.*, 2011; Stokes and Horvath, 2006) and to explore future scenarios (Lundie *et al.*, 2004; Shrestha *et al.*, 2011; Twomey Sanders, 2016). In addition to these particular studies, energy use in urban water systems has been previously reviewed in literature. Plappally and Lienhard (2012) reviewed energy use for the whole water cycle, while Loubet *et al.* (2014) provided a review of LCA studies for urban water systems.

Most of the published work comprises studies of a single region. There are very few multi-regional studies on energy for water. Siddiqi and Anadon (2011) assessed the inter-dependence of the water and energy systems in the Middle East and North Africa, and Sanjuan-Delmás *et al.* (2015) statistically analysed a sample of 50 municipalities in Spain to assess their energy use in water supply networks. A multi-regional study is valuable because it can help to identify best practice and support inter-city learning, especially between cities with similar geophysical environments (Kennedy *et al.*, 2009). Multi-regional studies also provide a better understanding of the impacts of geospatial conditions on water management decisions (Mo *et al.*, 2014). Decker (2000) emphasised the need to broaden the study of individual cities into systematic cross-city comparisons. Furthermore, most of the studies reviewed present a “snapshot” of a single year. Studies considering the influence of time on water-related energy use are not currently evident in the literature (Kenway *et al.*, 2011b).

This multi-city study quantifies, compares and analyses the direct energy use of water supply systems (i.e., source to tap) for a sample of 30 cities (including time-series for 17 of the cities studied). It aims to i) illustrate the historical performance of water use and direct energy use for water provision in the sampled cities using a new water-energy profiling approach, and ii) improve our understanding of some of the determining factors (i.e., climate, topography, water use pattern and operational efficiency) for variations between cities and temporal changes in some cities.

The major contributions of this work are i) Compilation and analysis of the most up-to-date energy use for water provision data (where available) in a large set of cities, ii) Performance of a time-series water-energy analysis for a sub-set of these cities to explore the trends and lessons learned, iii) New insights from a rare multi-city analysis, and iv) Illustration of the results with a water-energy profiling approach. Collectively, the work could support inter-city learning and help guide benchmarking of urban water systems, helping cities to transition towards greater water and energy efficiency.

3.2. Materials and Methods

3.2.1. Data collection and compilation

Urban water use, energy use or energy intensity of water supply systems and population data were collected for 30 cities (Table 3). These cities, with a range of population size (>500,000) and water supply sources, were chosen based on availability of data, especially the energy demand for water provision. The most up-to-date data and time-series data, were collected, where available. To enable analysis of variation in energy use for water provision across the sample of cities (more details in section 3.2.2), data for annual average precipitation, elevation information, water use by sector and energy use by system component (i.e., raw water pumping, water treatment and water distribution) for most of the cities were acquired. All data were obtained from public sources (mostly water utilities) and academic literature. Detailed lists of the data sources are available in Tables A1-1, A1-6, A1-7, A1-8 and A1-9 (Appendix A1). All years (even if data sources are in fiscal year) are expressed as calendar year. Information on data quality control can be found in Appendix A1.

Energy use for water provision considered in this work includes the direct on-site electricity use for raw water abstraction and conveyance, drinking water treatment and drinking water distribution (not including private booster pumping). Electricity use is the predominant energy source for most water supply systems (Cook *et al.*, 2012; Olsson, 2012). The energy results are expressed in the unit of kilowatt-hours (kWh), which provides a common unit for comparison across cities and is not affected by spatial variation in the electricity mix and generation efficiency (compared to the use of primary energy units). Some energy figures reported by the utilities on which this study depends may include energy uses outside the system (e.g., for transportation, office). These are typically negligible (Lemos *et al.*, 2013) and their inclusion was not considered significant enough to influence the findings.

Energy intensity is commonly reported by water agencies. This is the electricity consumption of a water supply system (from source to tap) per unit volume of water produced (e.g., kWh/ kL). The quantification approaches for every city and the characteristics of primary data are summarised in Table A1-1 and Table A1-2 (Appendix A1) respectively. To aid the analysis of city performance, the energy intensities for 17 cities have been segregated into raw water pumping, water treatment and water distribution where possible.

This work considers mostly the metropolitan regions of cities that are served by water utilities. Therefore, water use is for urban consumption with no or limited agricultural use. Total urban water use includes residential use, commercial use, industrial use, public sector use and non-revenue water (i.e., system water loss and unmetered water use). In this work, urban water use refers to the total volume of water produced and distributed by water suppliers to the cities. It does not account for decentralised water supply such as harvested rainwater, recycled greywater and well water (in most cities, these sources account for a small fraction of total water supply (Hering *et al.*, 2013)). Using total water produced by the water suppliers to account for the total urban water use has a high certainty for cities from developed countries, where very high percentages of the population are connected to the water mains. Only a few of the cities in the sample (e.g., Bangalore, Delhi) have limited access to public water supply.

The data have been compiled into the forms of per capita water use per day (L/p/d) and per capita energy use for water provision per year (kWh/p/a). Per capita water use for all the cities are based either on the figures directly reported by local water agencies (e.g., water utilities, water departments, government bodies) or by dividing the total urban water supplied by the serving population. For most of the cities, the per capita energy use for water provision has been calculated by multiplying its per capita water use by the energy intensity of its water supply system.

3.2.2. Multi-city analysis

This work introduces a water-energy profiling approach to provide a snapshot of the energy use for water provision performance of 30 cities, and a time-series tracking of 17 cities. The approach builds on previous work by the authors (Lam *et al.*, 2016). It provides a visual illustration of a city's relative performance in terms of per capita water use (L/p/d), related energy use (kWh/p/a) and energy intensity for water provision (kWh/kL) to track how cities have "moved" historically, in order to aid inter-city comparison and learning.

In the literature, several studies have analysed the factors influencing energy use for water provision. These have been summarised in Table 4. The list is not intended to be exhaustive, but instead synthesises some of the key factors that have been discussed in the context of understanding and managing energy use in urban water supply systems. This work explores the variation in energy use for water provision, based on the available data and contextual information related to some of the influencing factors in each category. It studies i) the relationship between energy intensity and average annual precipitation, ii) the energy implications of climate events in some cities, iii) the relationship between raw water pumping energy intensity and infrastructure elevation change, iv) the energy implications of non-revenue water, and v) the change of energy intensity in some cities. In the analysis, some of the cities can be identified as potential benchmarks for other cities to learn from.

This study does not aim to investigate all factors that contribute to the level of energy use for water provision in the 30 cities. It only accounts for some possible factors, where data and contextual information are more abundant for the comparison and discussion among those cities. Specific insights are then drawn from these selected possible factors. One of the goals of this work is to provide a large-scale compilation of city-scale energy use for water provision data in a systematic framework, which has not been previously achieved. The compiled data may be useful for further studies on detailed analysis of specific cities and drawing additional insights from exploring other influencing factors.

Table 3 List of cities studied

City/ region[1]	Country	Studied year(s)[2]	Population[3]	Major water sources[4]				
				River/ lake	Constructed reservoir	Inter-basin water transfer	Groundwater	Desalination
Brisbane	Australia	2002-2014	2,275,000		✓			O
Melbourne	Australia	2001-2015	4,377,000		✓	O		O
Perth	Australia	2002-2015	1,961,000		✓		✓	✓
Sydney	Australia	2002-2014	4,755,000		✓	O		O
Rio de Janeiro	Brazil	2014	5,913,000		✓			
Salvador	Brazil	2014	2,700,000		✓			
São Paulo	Brazil	2003-2014	26,075,000		✓			
Toronto	Canada	2006, 2011-2013	2,772,000	✓				
Beijing	China	2011	18,585,000		✓		✓	
Tianjin	China	2011	12,648,000		✓		✓	
Copenhagen	Denmark	2008-2010, 2012-2014	575,000				✓	
Berlin	Germany	2010	3,438,000				✓	
Ahmedabad	India	2009	5,578,000	✓				
Bangalore	India	2013	8,444,000			✓		
Bhopal	India	2009	1,798,000	✓	✓		✓	
Delhi	India	2009	16,788,000	✓				
Jamshedpur	India	2005-2009	860,000	✓				
Osaka	Japan	2005-2014	2,686,000		✓			
Sapporo	Japan	2007-2014	1,928,000		✓			
Tokyo	Japan	2000-2003, 2005, 2009-2014	13,257,000		✓			
Yokohama	Japan	2004-2007, 2009-2014	3,712,000		✓			
Mexico City	Mexico	2013	8,894,000			✓	✓	
Oslo	Norway	2001-2010	584,000	✓				
Cape Town	South Africa	2010	3,655,000		✓			
Bangkok	Thailand	2004-2011	8,001,000	✓				
Denver	U.S.A.	2007-2014	1,172,000		✓			
Los Angeles	U.S.A.	2003-2015	3,988,000			✓	✓	
San Diego	U.S.A.	2003, 2007-2015	1,326,000			✓		
San Francisco	U.S.A.	2014	837,000		✓			
Tampa	U.S.A.	2010	657,000		✓			

[1] Considering metropolitan regions, Table A1-1 (Appendix A1) includes the regions considered for some of the cities

[2] Depending on data availability

[3] Considering population served by water mains in the latest studied year. References can be found in Table A1-1.

[4] Water sources are considered to be major if they contribute to more than 10% of the local water supply. River/ Lake: with natural water bodies; Constructed reservoir: with artificial water bodies upstream; Inter-basin water transfer: sourcing water from distant river basins; Groundwater: with underground aquifers; Desalination: reverse osmosis; O to be operated in dry years. References can be found in Table A1-1.

Table 4 Summary of key literature focusing on four categories of influencing factors on energy use for water provision

Category	Factors [1]	Sources
Climate	Precipitation	(Venkatesh *et al.*, 2014)
	Temperature	(Venkatesh *et al.*, 2014)
	Climatic behaviour	(Plappally and Lienhard V, 2012)
Topography	Distance of water source	(Plappally and Lienhard V, 2012; Venkatesh *et al.*, 2014)
	Raw water pumping power	(Carlson and Walburger, 2007)
	Water source type	(Carlson and Walburger, 2007; Venkatesh *et al.*, 2014)
	Source elevation change	(Plappally and Lienhard V, 2012)
	Distribution elevation change	(Carlson and Walburger, 2007; Plappally and Lienhard V, 2012; Venkatesh *et al.*, 2014)
	Distribution main length	(Carlson and Walburger, 2007; Plappally and Lienhard V, 2012; Venkatesh *et al.*, 2014)
Operational efficiency	System condition	(Plappally and Lienhard V, 2012; Venkatesh *et al.*, 2014)
	Pumping efficiency	(Carlson and Walburger, 2007; Nogueira Vilanova and Perrella Balestieri, 2014; Plappally and Lienhard V, 2012)
	Distribution pressure	(Carlson and Walburger, 2007; Nogueira Vilanova and Perrella Balestieri, 2014)
	System operational rule	(Nogueira Vilanova and Perrella Balestieri, 2014)
	Energy management system	(Cherchi *et al.*, 2015)
Water use pattern	Population served	(Carlson and Walburger, 2007; Venkatesh *et al.*, 2014)
	Service area	(Carlson and Walburger, 2007; Venkatesh *et al.*, 2014)
	Water demand	(Carlson and Walburger, 2007)
	Income/ affluence	(Venkatesh *et al.*, 2014)
	Economic composition	(Venkatesh *et al.*, 2014)
	Water loss	(Carlson and Walburger, 2007; Nogueira Vilanova and Perrella Balestieri, 2014; Venkatesh *et al.*, 2014)

[1] The factors that were discussed in the context of energy for water in the literature.

3.3. Results

3.3.1. Overall results of the 30 cities

Per capita energy use for water provision in the 30 cities ranges from 10 kWh/p/a for Melbourne to 372 kWh/p/a for San Diego (Figure 2). It is notably higher in Los Angeles, San Diego and Perth than in the other cities. The large difference in the per capita energy use between Melbourne and San Diego is mainly attributed to the facts that i) the Melbourne water supply system is predominantly gravity-fed, while San Diego obtains most of its water from two energy-intensive inter-basin water transfer systems (See section 3.4.1.2 and Table 5 for more details), and ii) Melbourne (251 L/p/d) has a lower per capita water use than San Diego (488 L/p/d). The energy intensities of the water supply systems (indicated by the “wedges”) range from 0.11 kWh/kL for Melbourne to 2.31 kWh/kL for Bangalore. Five of the cities (Bangalore, Los Angeles, Mexico City, San Diego and Perth) have significantly higher energy intensity for supplying water (i.e., > 1 kWh/kL).

Per capita total water use varies from 109 litre per person per day (L/p/d) for Bangalore to 588 L/p/d for Bangkok (Figure 2). A huge range of energy use for water provision is observed both at the low and high end use of water. Wherever data are available, the water and related-energy use levels of the latest year are presented. The results associated with this figure are included in Tables A1-3, A1-4 and A1-5 (Appendix A1).

3.3.2. Historical trends of 17 cities

For a sub-sample of 17 cities with time-series data, their water-energy trajectories are shown in Figure 3. A general trend for most of the cities over the past decade has been a reduction in both the per capita energy use for water provision and per capita total water use. In terms of per capita energy use for water provision, 12 of these 17 cities reduced by 11–45% (e.g., 22% in Yokohama (2004-2014) and 45% in Melbourne (2001-2015)). In terms of per capita water use, almost all cities (including cities with only time-series water use results, Table A1-3 in Appendix A1) show a downward trend. For energy intensity of water supply systems, 5 of these cities had a minor to moderate reduction (6–17%), while 7 cities increased by a broad range (6% for Tokyo (2000 to 2014) to 222% for Perth (2001 to 2015)). Reduction of per capita water use enabled some cities (e.g., Brisbane, Melbourne, Sydney, Tokyo) to reduce their per capita energy use for water provision, even though the energy intensity of their water supply systems increased.

Despite a reduction in long-term per capita water use for all cities (2001–2014), the last few years have seen increases for some (Figure 3). A slow "rebound" of water use can be observed for the three southeast Australian cities (e.g., Brisbane, Melbourne, Sydney) after a prolonged drought ended and water restrictions were lifted (to be discussed in section 3.4.1.1). In the U.S.A., water use reduced during and after the recession (2007-2009) and rebounded afterwards for many cities (Kiefer, 2014).

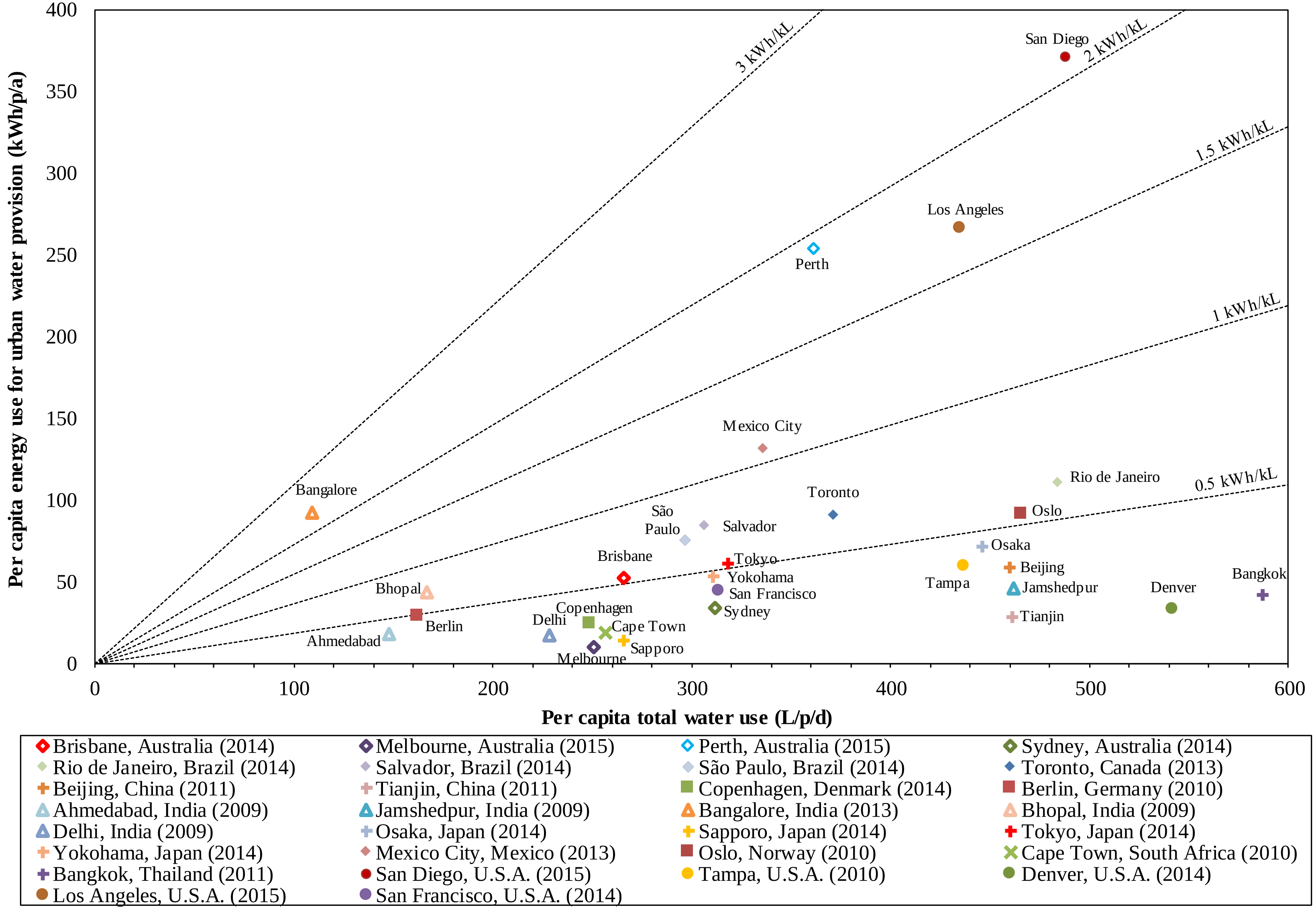

Figure 2 Water-energy profile of 30 cities, showing their per capita energy use for water provision and per capita total water use

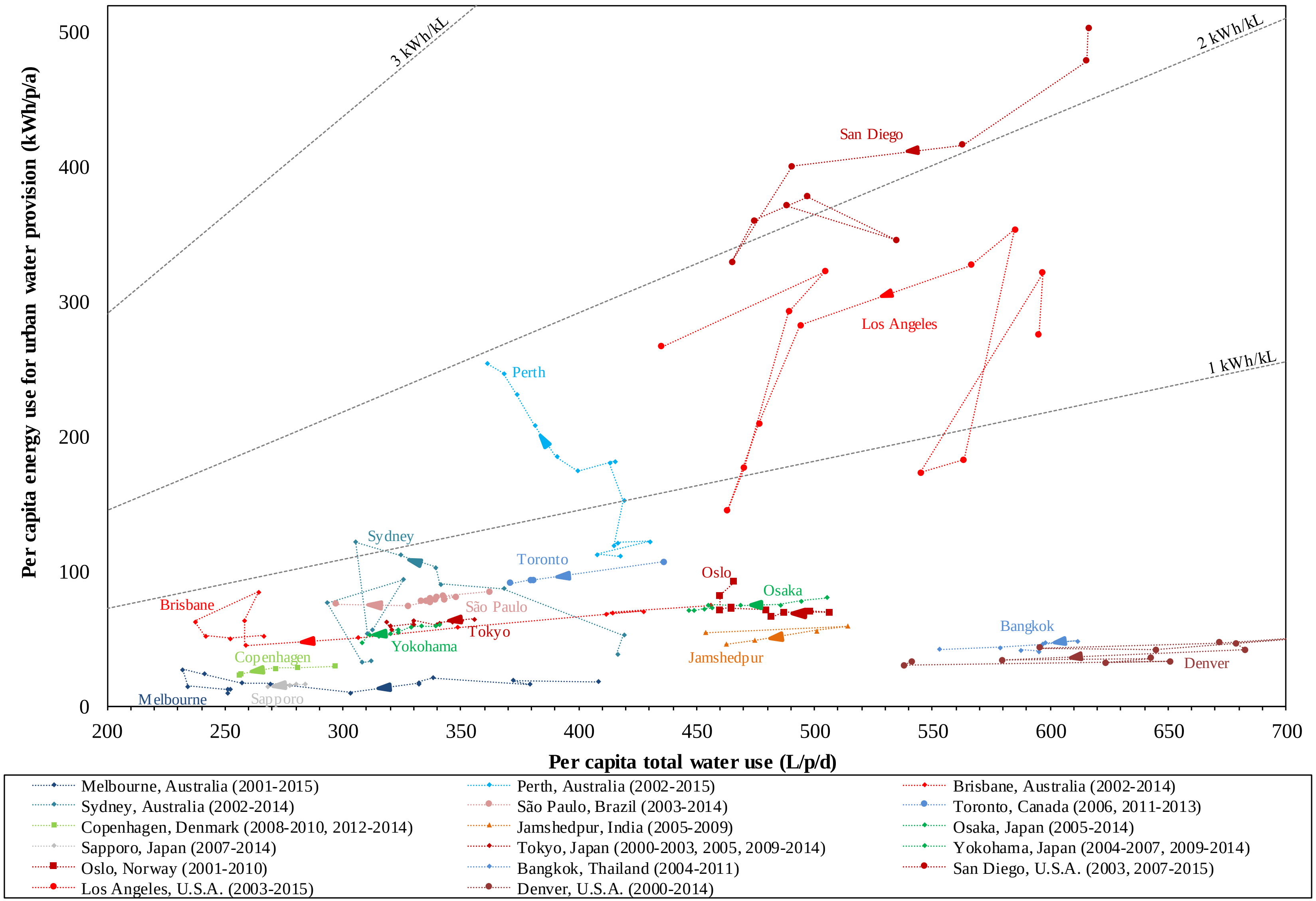

Figure 3 Water-energy profile for a sub-sample of 17 cities, showing their trajectories

3.3.3. Energy use breakdown by system component

The energy intensities of some of the water supply systems have been segregated into raw water pumping, water treatment and water distribution (Table 5). This gives an indication of the relative energy use in different parts of the water supply systems. Energy intensity figures are consistent with those reported in the literature.

Water pumping (including raw water and drinking water) account for a major portion of the energy use in the water supply systems of the cities with segregated data. Energy intensity of raw water pumping ranges from 0.006 to 2.624 kWh/kL (average of 1.086 kWh/kL and median of 0.889 kWh/kL from 8 sources/cities), while that of water distribution ranges from 0.010 to 0.341 kWh/kL (average of 0.167 kWh/kL and median of 0.169 kWh/kL from 15 cities). Surface water abstraction and treatment is in the range of 0.048 – 0.335 kWh/kL (for 10 cities without significant inter-basin water transfers), groundwater abstraction and treatment is 0.240 – 0.430 kWh/kL (for 2 cities).

Compared to raw water pumping or drinking water distribution, conventional water treatment has relatively low energy intensity, ranging from 0.027 to 0.204 kWh/kL (average of 0.076 kWh/kL and median of 0.041 kWh/kL from 8 cities). Alternative water treatment approaches such as potable water recycling and seawater desalination are much more energy-intensive.

Table 5 Breakdown of energy intensities for components within the water supply system - raw water pumping, water treatment and water distribution, for a sub-sample of cities

City/ Region/ Country	Energy intensity, kWh/kL			Data source
	Raw water pumping	Water treatment	Water distribution	
Energy figures from this work				
Brisbane, Australia	Conventional: 0.307 Seawater desalination: 3.82 [a]		0.211	Refer to Table A1-6 in Appendix A1
	-	Potable water recycling: 1.14 [a]		
Melbourne, Australia	0.109		0.030	
Sydney, Australia	Shoalhaven drought transfer: 1.93 Other sources: - [b]	Conventional: - [b]	- [b]	
	Seawater desalination: 3.38			
Toronto, Canada	0.335		0.341	
Copenhagen, Denmark	0.240		0.010	
Bangalore, India	2.100 [c]		0.210	
Delhi, India	- [b]	0.204	0.017	
Sapporo, Japan	0.032	0.040	0.058	
Tokyo, Japan	0.055	0.168	0.305	
Yokohama, Japan	0.155	0.029	0.169	
Oslo, Norway	0.216		0.135	
Bangkok, Thailand	0.006	0.042	0.169	
Denver, U.S.A.	0.074		0.114	
Los Angeles, U.S.A.	Los Angeles Aqueduct: 0 [d] California Aqueduct - West branch: 2.092	0.027	0.159	
	California Aqueduct - East branch: 2.624 Colorado River Aqueduct: 1.622			
	Local groundwater: 0.430 [c]			
San Diego, U.S.A.	California Aqueduct - East branch: 2.624 Colorado River Aqueduct: 1.622	0.029	0.336	
San Francisco, U.S.A.	0.146		0.244	
Energy figures from literature				
Australia	Surface water/ groundwater: 0.25-3.3	Conventional: 0.2–1 Seawater desalination: 3.3-8.5	-	(Plappally and Lienhard V, 2012)
U.S.A.	Surface water: 0.035-3.59	Conventional (primary): 0.07 Seawater desalination: 2.58-5.49	0.18-0.32	
Northern California, U.S.A.	0.04	-	-	(Olsson, 2012)
Southern California, U.S.A.	2.3	-	-	
Sweden	0.24	0.12	0.1	
Copenhagen, Denmark	0.18		0.1	(Loubet *et al.*, 2014)
Sydney, Australia	0.08		0.24	

[a] Supplying to the South East Queensland region; [b] Data not available; [c] predominantly used for raw water pumping; [d] Along the aqueduct, there are multiple hydropower plants.

3.4. Discussion

3.4.1. Factors influencing energy use for water provision

This section discusses some potential influencing factors that contributed to the high variation in energy use (kWh/p/a) and energy intensity (kWh/kL) for water provision in the 30 cities (as observed in Figure 2). It also explores how some of these influencing factors led to the time-series changes in some of the cities (as observed in Figure 3).

3.4.1.1. Climate

The relationship between long-term annual average precipitation for the 30 cities and their energy intensity, and per capita total water use have been examined (Figure 4). The long-term annual average precipitation (from 24 to 115 years) gives a rough characterisation of the regional rainfall pattern and was used as a proxy for water availability in this work. Data sources are included in Table A1-7 (Appendix A1).

For the relationship between energy intensity and precipitation, most of the cities with higher energy intensity water supply systems (e.g., Los Angeles, San Diego and Mexico City) are located in regions with lower average annual precipitation. Other than this higher energy intensity group, there does not seem to be a strong correlation between average annual precipitation and energy intensity. For the relationship between per capita water use and precipitation, there seems to be no correlation. Some regions with lower precipitation still have a relatively high water usage rate.

In addition to longer-term climate patterns, energy intensities of some of the water supply systems are subject to the influence of shorter-term climate extremes such as drought. A recent example is the Australian Millennium Drought, which was most profound during 2001-2009 in southeast Australia (Van Dijk *et al.*, 2013). The energy intensity for the three cities in the region increased by 96% (in 2010), 129% (in 2011) and 325% (in 2008) from 2002 level in Brisbane, Melbourne and Sydney respectively (Figure 3). In Brisbane (within a part of the water supply network in the South East Queensland region), it was attributed to the operation of a desalination plant and an indirect potable water recycling system during 2008 to 2012. In Melbourne, the new inter-basin water transfer scheme and additional pumping from the Yarra River were used to relieve water shortage. In Sydney, a drought water transfer scheme was operating from 2003 to 2009, followed by a newly-built desalination plant from 2010 to 2012. Operating these supply sources in the dry years would result in a substantial increase in energy use. For instance, based on the energy intensity figures, having 10% of desalinated water in the supply mix in Brisbane would double the energy use of the water supply system. In total, six seawater reverse osmosis desalination plants were commissioned in five major Australian cities between 2006 and 2012. As of 2015, only Perth still had a high throughput from desalination, contributing to over 40% of its water supply (Water Corporation, 2015). This has resulted in Perth having the most energy-intensive urban water supply system in Australia and a steep water-energy trajectory (Figure 3).

In terms of opportunity, cities with greater annual rainfall could potentially improve use of urban runoff to satisfy part of their non-potable water demand. In response to a severe drought (2001–2009) and some rebate schemes, there was a significant increase in the uptake of rainwater tanks for both indoor and outdoor water use in some Australian cities. Between 2007 and 2013, the percentage of households with a rainwater tank installed increased from 18.4% to 47%, from 11.6% to 31.1%, and from 10.3% to 19% in Brisbane, Melbourne and Sydney respectively (Australian Bureau of Statistics, 2013). These cities receive different levels of annual rainfall (i.e., Brisbane: 1094 mm/a; Melbourne: 602 mm/a; Sydney: 1223 mm/a). Depending on the design of rainwater harvesting systems, the energy intensity can vary substantially. In their review, Vieira *et al.* (2014a) found that the median energy intensity of these systems to be 0.20 kWh/kL and 1.40 kWh/kL from theoretical and empirical studies respectively. This indicates a potential of supplementing the centralised water supply system with a lower energy intensity water source in some of the cities, but these systems have to be carefully designed to consider their energy implications.

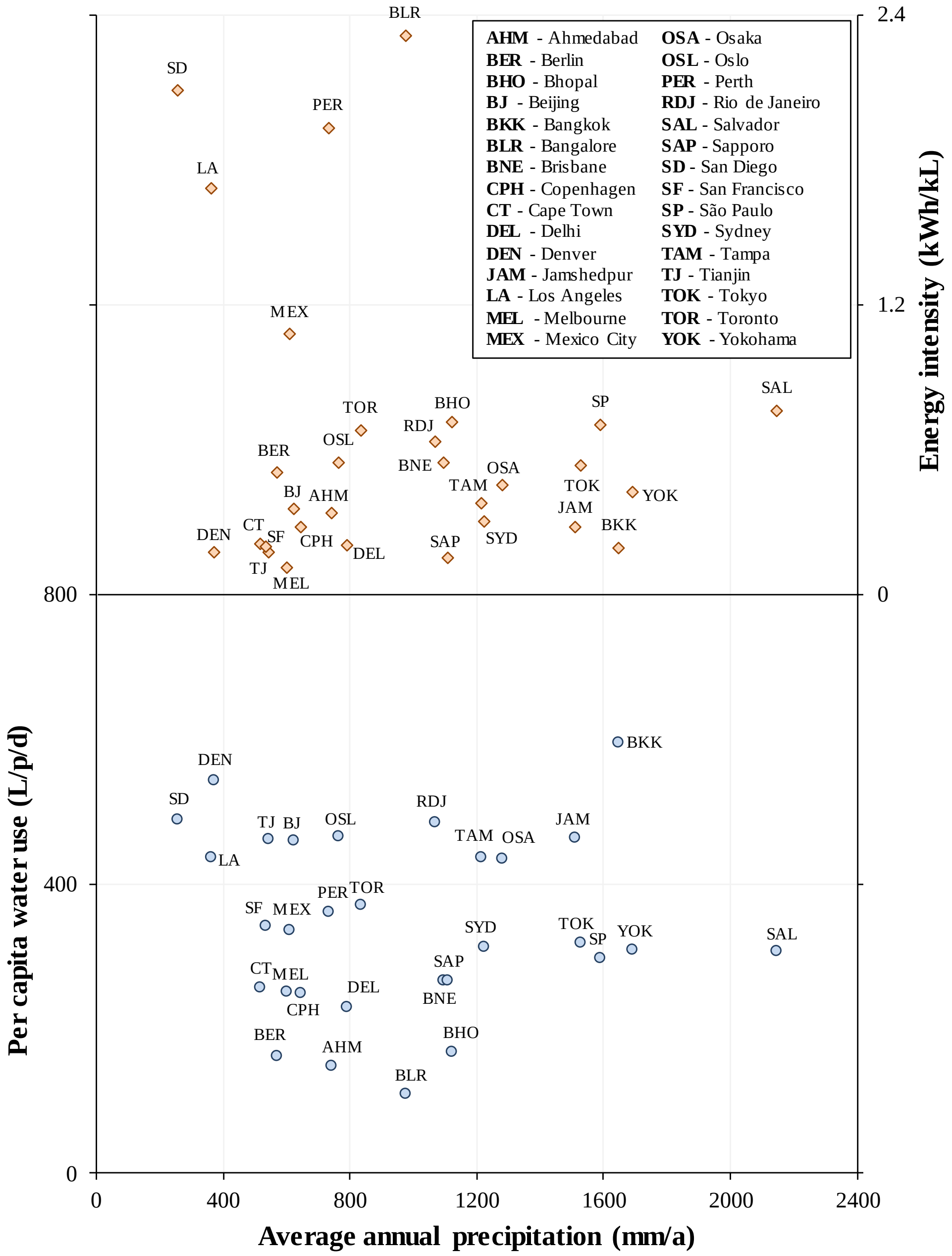

Figure 4 Average annual precipitation, per capita water use and energy intensity of water supply systems of 30 cities

3.4.1.2. Topography

Local topography can strongly influence the distance and lift required to abstract, convey, and distribute water, and hence the pumping energy (Cook *et al.*, 2012). Here, the relationship between elevation difference involved in transferring water in some of the systems (i.e., elevation difference = destination elevation – water source elevation) and the associated energy intensity (Table 5) has been assessed. Data sources are summarised in Table A1-8 (Appendix A1).

The results clearly illustrate the nearly linear correlation between elevation difference and energy intensity for water transfer systems (Figure 5). One of the largest transfer systems is the California State Water Project, which transfers water from Northern California to Southern California (including cities like Los Angeles and San Diego), home to nearly two-thirds of the state's population. The whole aqueduct including all the branches is over 1100 km and has the largest single lift of nearly 600 m over the Tehachapi Mountains (California Department of Water Resources, 2013). Hydroelectricity is used downstream of the aqueduct to recover some of the energy.

Some cities with relatively low raw water pumping and water distribution energy intensity (Table 5) may be considered to have taken advantage of their local topography in building their water supply systems. An example is Sapporo with an energy intensity of only 0.15 kWh/kL. Their water supply system was built in a way that each water supply system component is situated in a lower elevation than the previous component (i.e., dam, raw water extraction point, water treatment plant, treated water reservoirs, distribution network) to minimise pumping energy use. With that, approximately 80% of the city's water supply is gravity-fed (Sapporo City Waterworks Bureau, 2015). While it is not feasible for most cities to reconfigure their existing water supply systems with the idea of utilising excess hydraulic energy, the concept should be better acknowledged in new planning or re-development of urban water supply systems. For instance, it is recently included in the energy efficiency plan of the water utility in Tokyo (Tokyo Metropolitan Government Bureau of Waterworks, 2014). In addition to that, it has become more common for water utilities to establish mini-hydro generation schemes to capture excess hydraulic energy (Cook *et al.*, 2012).

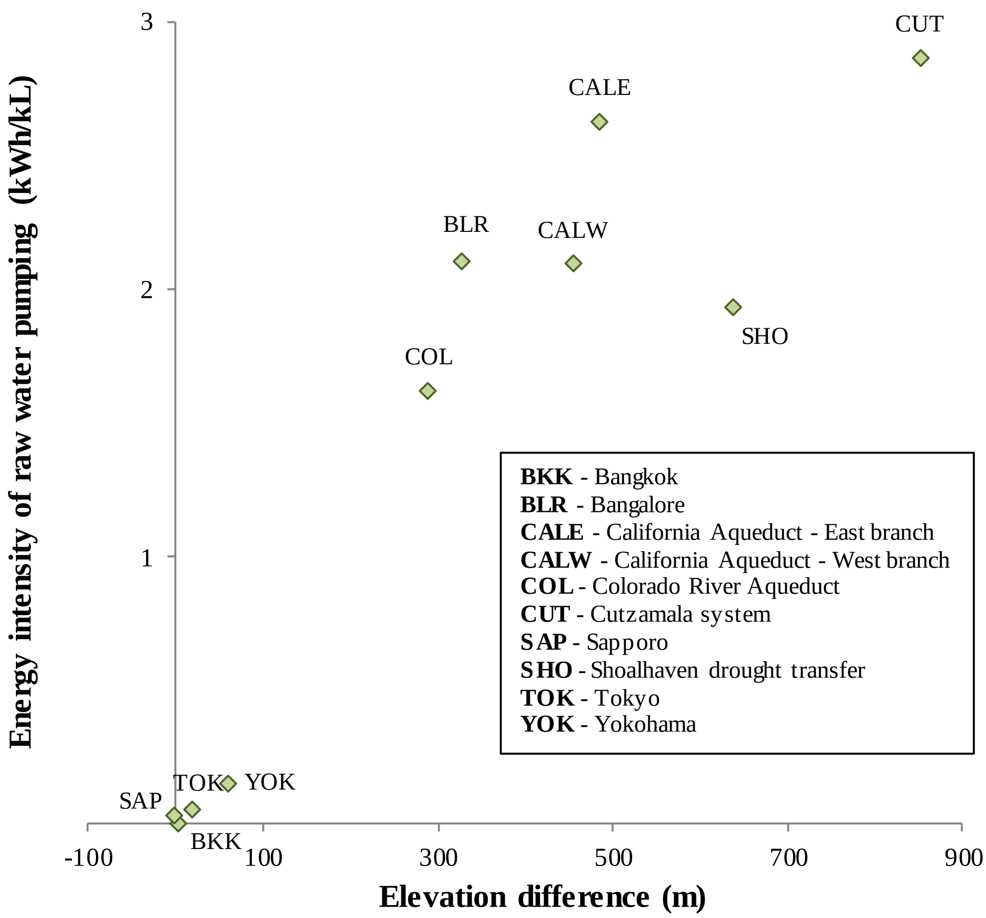

Figure 5 Energy intensity and elevation difference of different raw water transfer infrastructure

3.4.1.3. *Water use pattern*

In order to understand the results in Figure 2, the per capita water use of 22 cities (mostly in 2013 and 2014) have been broken down into residential water use, non-residential water use and non-revenue water (Figure 6). Data sources are included in Table A1-9 (Appendix A1). There is a body of literature identifying factors that influences urban water use (Inman and Jeffrey, 2006; Saurí, 2013). Consequently, this discussion focuses more on the energy implications of the water use pattern.

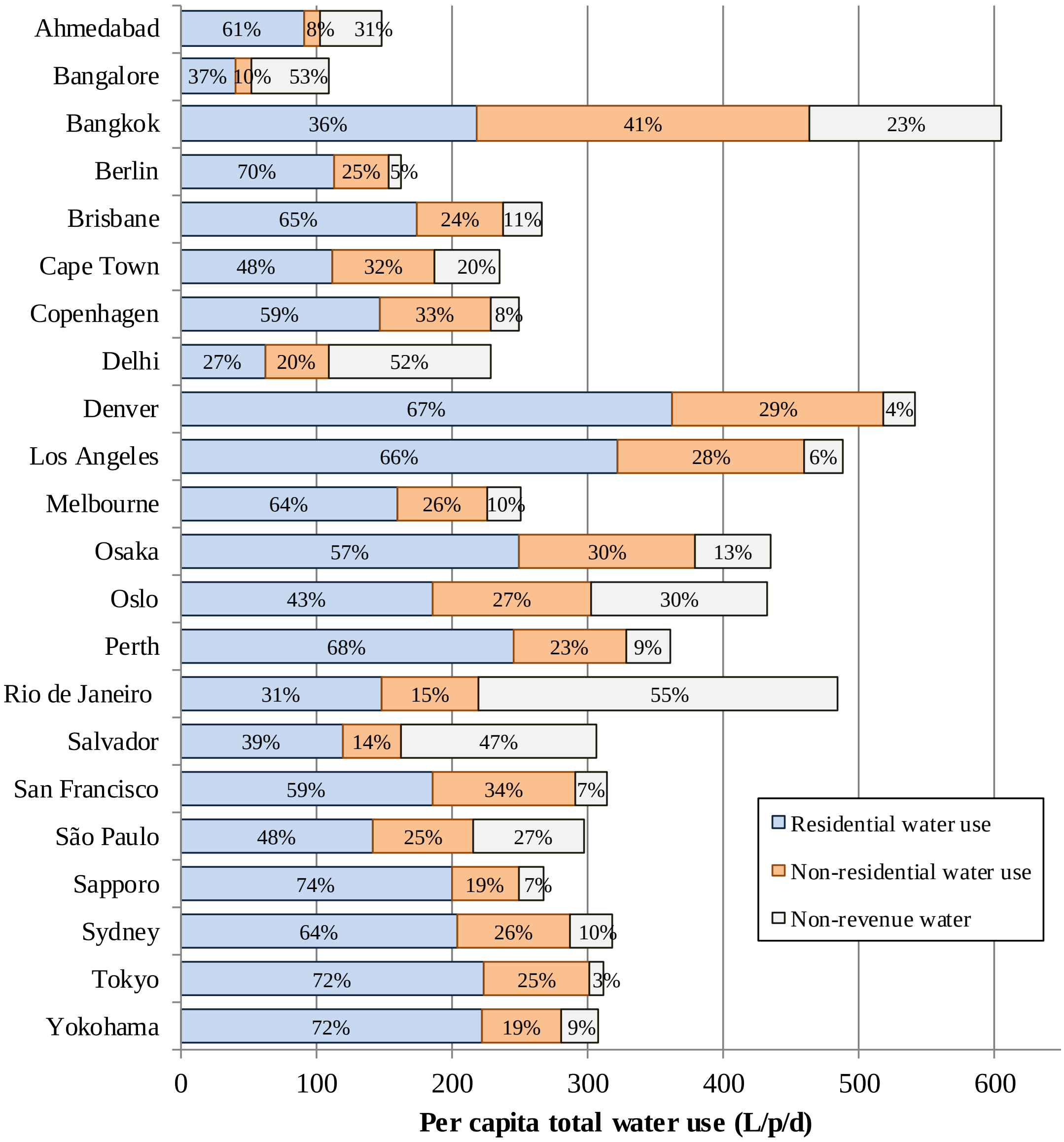

Figure 6 Breakdown of per capita total water use of 22 cities, showing the scale of residential water use and non-revenue water

In the majority of the cities in developed countries, residential water use represents over half of the total urban water use (Figure 6). Residential water use varies from 113 L/p/d for Berlin to 363 L/p/d for Denver. Historically, the residential sector is a typical point of intervention in managing urban water demand, particularly during drought (Mini *et al.*, 2015; Turner *et al.*, 2016). For instance, through the Millennium Drought in Australia, the per capita residential water use in Melbourne reduced by 35% from 247 L/p/d (2001) to 160 L/p/d (2014) (Melbourne Water, 2014a) with the aid of water demand management strategies. The state government and the water industry reported the latest water storage levels in the media, provided advice on how to save water, imposed different levels of water restrictions and modified the tariff structure (Grant *et al.*, 2013). Brisbane and Sydney both shared the same reduction trend in residential water use (Turner *et al.*, 2016). In Brisbane, with strong support by the mass media, marketing campaigns aimed at reducing residential water use to a target of less than 140 L/p/d were very successful during the most water stressed period (Head, 2014). In these three cities, the energy saving from water use reduction offset part of the additional energy use from the change in supply mixes discussed in section 3.4.1.1 (e.g., desalination, potable water recycling, inter-basin water transfer) (Lam *et al.*, 2016).

In contrast to Australian cities, some cities (e.g., Japanese cities) that were not facing severe water stress only show moderate reduction of water use. East coast Australian cities have demonstrated that improving water efficiency in residential end use can have significant long-term water and energy impacts. Consequently, they could be a good reference case for cities that are developing long-term water management strategies. For instance, rebate schemes launched during the drought in Australia offered great incentives for residents to invest in water-efficient devices. Among the cities in developed countries, Berlin, Melbourne and San Francisco have a remarkably low per capita residential water use. They may act as benchmarks (i.e., achievable targets) for other cities (e.g., within the same country, similar cities) to improve residential water use efficiency and to subsequently save energy.

Non-revenue water is the difference between treated water input into a water supply system and billed authorised consumption. It generally includes water system losses from leaks and mains breaks, unauthorised water use and unbilled authorised water use (Alegre *et al.*, 2000). It is usually a consequence of aging pipeline and unmetered water use. Although some of the non-revenue water is actually used by inhabitants in the urban areas, the unmetered nature of its usage may prohibit better water demand management (Inman and Jeffrey, 2006).

The percentage of non-revenue water ranges from less than 5% of the total water supply in Berlin, Denver and Tokyo to over 50% in Delhi, Rio de Janeiro and Salvador (Figure 6). From an energy perspective, the energy associated with the non-revenue water from these 22 cities is 1.9 TWh (or a population-weighted average of 16 kWh/p/a, see Table A1-10 in Appendix A1 for the details of the estimation) based on the current energy intensities of their water supply systems. To put it into perspective, the population-weight average per capita energy use for water provision in these 22 cities was 62 kWh/p/a. Although the benefits of reducing non-revenue water are well known, the results have shown that it still remains as a significant issue for many cities, particularly in developing countries. It is suggested to be due to underestimating both the technical complexity of non-revenue water management and the potential benefits (Frauendorfer and Liemberger, 2010). The better performers in this respect (e.g., Berlin, Tokyo, Denver, and Copenhagen) can possibly offer insights regarding the regulatory framework, financial incentives and technical approaches necessary to better manage non-revenue water. As an example, Tokyo managed water loss through replacing aged water mains systematically, conducting active leak detection, improving detection devices and conserving the legacy of leak detection skill in the utility (Ashida, 2014). As a result, the city reduced its water loss rate from over 10% in 1990 to less than 3% in 2010 (Ashida, 2014).

3.4.1.4. Operational efficiency

Many utilities in the studied cities reported to have invested in improving energy efficiency through approaches such as improving pump efficiency, building mini hydro plants, recovering excess hydraulic power, and reducing pressure and leakage (Berliner Wasserbetriebe, 2011; Chiplunkar *et al.*, 2012; Cook *et al.*, 2012; Tokyo Metropolitan Government Bureau of Waterworks, 2015).

In the time-series results (Figure 3 and Table A1-5 in Appendix A1), 5 cities have seen a more significant reduction in energy intensity (> 5 %) of the water supply system, possibly indicating improvements in energy efficiency. For instance, Berlin reported a reduction of the energy intensity of its water supply system from 0.536 kWh/kL in 2006 to 0.505 kWh/kL in 2010 through hydraulic optimization of groundwater abstraction, improving water pump efficiency, and designing water distribution networks with minimum elevation difference (Berliner Wasserbetriebe, 2011). Jamshedpur improved through energy auditing and pump replacement (Chiplunkar *et al.*, 2012). Optimising bore pump management, and upgrading discharge and booster pumps are possibly the sources of improvement for Copenhagen (Danish Water and Waste Water Association, 2013). A reduction in energy intensity cannot be seen in other cities, possibly because other events occured (e.g., introduction of new supply sources, expansion of water distribution networks) concurrently. More segregated time-series energy data (e.g., raw water pumping, treatment, distribution) would be needed to evaluate any energy efficiency improvements in these systems.

3.4.2. Lessons from the multi-city analysis of energy use for water provision

Based on the multi-city analysis of the studied cities, pumping energy (for water extraction, conveyance and distribution) dominates the energy use for water provision (Table 5). Therefore, within water supply systems, the major opportunities for utilities to improve energy efficiency (illustrated by arrow *A* in Figure 7) would be to optimise pumping operation (e.g., Berlin, Copenhagen) and the use of excess hydraulic energy such as considering mini-hydro and maximising gravity-fed supply (e.g., Melbourne, Sapporo). When the water supply system has become more energy efficient over time (i.e., reducing energy management potential within utilities), further energy saving in the long term has to be achieved through improving urban water efficiency such as managing water end use and non-revenue water (e.g., Melbourne, Sydney, Tokyo). Improving urban water efficiency would mostly drive a city down the “energy intensity wedge” (arrow B_1). In some systems with multiple supply sources of different energy intensity (e.g., Los Angeles, San Diego), a larger scale of water efficiency improvement can also have a marginal effect to reduce both energy use and energy intensity (arrow B_2). On the other hand, meeting future water demand primarily by augmenting the systems with new supply sources would likely move the city toward a higher energy intensity wedge (arrow *C*) (e.g., Perth). In addition, considering alternative water sources such as non-potable water recycling and stormwater harvesting with energy in mind can potentially reduce future growth in energy intensity for supplying water.

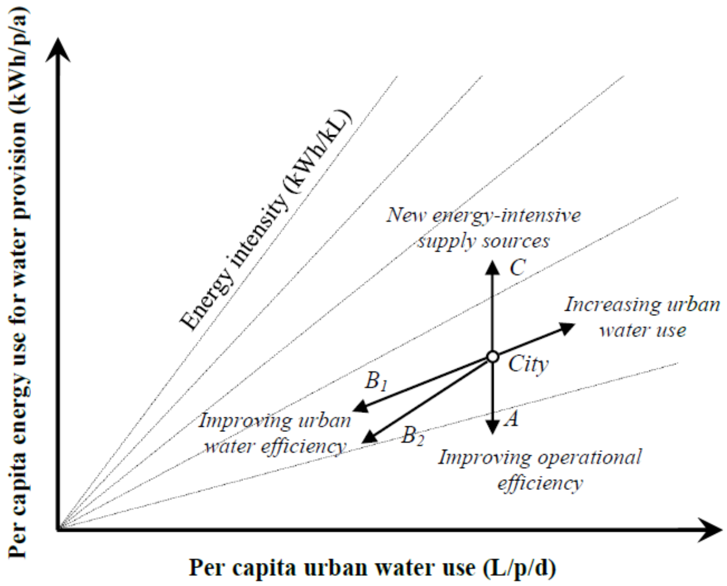

Figure 7 Illustration of where a city can transform

It is evident from the Australian drought experience that a significant long-term shift in residential water demand is achievable (Grant *et al.*, 2013; Head, 2014) (e.g., reduction by 35% in Melbourne (Melbourne Water, 2014a)), which also results in a significant energy benefit. The studied Australian cities (i.e., Brisbane, Melbourne, Sydney) are good references for i) what water demand-side management can achieve, ii) what approaches (e.g., media campaigns, rebate schemes) are effective for improving water use efficiency, iii) how cities can capitalise on climate events to induce long-term changes, and iv) demonstrating that water demand-side management can provide energy savings to counteract the negative energy impacts of new supply sources (i.e., inter-basin water transfer and seawater desalination). This also illustrates the importance of balancing supply-side and demand-side strategies in maintaining long term water security, while managing associated energy use.

From this multi-city analysis, it can be observed that energy saving from water conservation can vary significantly between different cities. For instance, per unit volume of water saving in San Diego would yield a greater energy saving benefit (i.e., 2.09 kWh/kL) than that of Melbourne (i.e., 0.11 kWh/kL). In addition, water conservation can also have potential marginal energy use reduction benefits. It can reduce the frequency of operating energy-intensive sources and possibly deferring the building of new infrastructure which is generally more energy intensive. When a water supply system has become more energy efficient over time, further energy savings on a larger scale must be achieved through better managing water demand and non-revenue water (i.e., improving urban water efficiency). This would cap or even reduce future energy use for water provision, even in cases where water supply systems are becoming more energy intensive.

Into the future, cities with energy use trajectories moving toward the higher energy intensity wedge should consider advancing their water conservation initiatives and further developing energy management programs. This not only helps to mitigate greenhouse gas emissions, but also reduces the cost risk to water utilities and communities associated with rising electricity costs. (for example, an anticipated five-fold increase in electricity expenditure for water services in Australia over a 20-year period (Cook *et al.*, 2012)). Furthermore, water utilities or cities can compile their own historical data into the water-energy profile to see how they compare with other cities and what their trajectories have been. Understanding the water-energy history of water supply systems can be vital for developing future scenarios for better management.

This study also reveals that segregated, time-series energy data, for multiple sequential years is currently a rarity in water statistics for most cities. Not all cities have complete time-series data, meaning time-series comparative conclusions need to be made cautiously. Further, this lack of data is a hindrance to benchmarking cities and utilities. Many utilities or national water statistical reporting agencies (in addition to the 30 cities studied in this work) have established performance indicator frameworks and are reporting the utility performance results annually. However, energy use is often not within the scope of this reporting or not being reported annually. The absence of energy in performance indicators, and the lack of transparency, may be barriers for improving energy use in these utilities. An improved global effort to create more reliable and regular datasets covering energy use in urban water supply would be of high value.

3.5. Conclusions

Water provision in the 30 cities demonstrates a huge range of per capita energy use, from 10 to 372 kWh/p/a. Between 2000 and 2015, in the 17 cities with time-series data, a general trend of reducing per capita energy use for water provision is observed (a reduction by 11 - 45% in 12 of them), even though the water supply systems in nearly half of these cities have become more energy intensive on a per unit volume of water supplied basis. Most of these cities have become more water efficient (on a per capita basis), which contributed to the reduction in per capita energy use for water provision. Among the studied cities, energy use for raw water pumping and drinking water distribution dominate the energy use of water supply systems.

There are three key insights from exploring four categories of potentially influencing factors, namely climate, topography, water use pattern and operational efficiency. Firstly, some cities can act as potential benchmarks to learn about managing energy use for water provision through manipulating factors such as energy efficiency in the supply systems (e.g., Berlin, Copenhagen), non-revenue water (e.g., Berlin, Tokyo and Denver) and residential water efficiency (e.g., Sydney, Melbourne) or through capitalising on factors such as climate events (e.g., Brisbane, Melbourne) and local topography (e.g., Melbourne and Sapporo). Secondly, energy associated with non-revenue water is found to be very substantial in many of the cities studied (i.e., a population-weighted average of 16 kWh/p/a for 22 cities, 25% of the average energy use for water provision) and therefore represents a significant energy saving potential. Thirdly, the three Australian cities which encountered a decade-long drought demonstrate the beneficial role of demand-side measures in reducing the increased energy consequences of system augmentations, especially with seawater desalination and inter-basin water transfers.

The water-energy profiling approach is applied to track how cities have performed historically and relatively to each other in terms of per capita water use, per capita energy use for water provision and energy intensity for water provision. Understanding the water-energy history of urban water supply systems can be vital for establishing future scenarios for better management.

4. Comparison of water-energy trajectories of two major regions experiencing water shortage

This chapter is the first of the three papers that address the second objective of this thesis – to quantify and understand the energy impacts of droughts on urban water systems. The case study presented in this chapter compares the water use and energy use for water provision trajectory of two Australian urban regions – South East Queensland and Perth in response to water stress. The two regions are included in the multi-city analysis in Chapter 3 and are explored in detail in this chapter.

Lam, K.L., Lant, P.A., O'Brien, K.R., Kenway, S.J. (2016) Comparison of water-energy trajectories of two major regions experiencing water shortage. *Journal of Environmental Management* 181, 403-412.

Abstract

Water shortage, increased demand and rising energy costs are major challenges for the water sector worldwide. Here we use a comparative case study to explore the long-term changes in the system-wide water and associated energy use in two different regions that encountered water shortage. In Australia, South East Queensland (SEQ) encountered a drought from 2001 to 2009, while Perth has experienced a decline in rainfall since the 1970s. This novel longitudinal study quantifies and compares the urban water consumption and the energy use of the water supply systems in SEQ and Perth during the period 2002 to 2014. Unlike hypothetical and long-term scenario studies, this comparative study quantifies actual changes in regional water consumption and associated energy, and explores the lessons learned from the two regions. In 2002, Perth had a similar per capita water consumption rate to SEQ and 48% higher per capita energy use in the water supply system. From 2002 to 2014, a strong effort of water conservation can be seen in SEQ during the drought, while Perth has been increasingly relying on seawater desalination. By 2014, even though the drought in SEQ had ended and the drying climate in Perth was continuing, the per capita water consumption in SEQ (266 L/p/d) was still 28% lower than that of Perth (368 L/p/d), while the per capita energy use in Perth (247 kWh/p/a) had increased to almost five times that of SEQ (53 kWh/p/a). This comparative study shows that within one decade, major changes in water and associated energy use occurred in regions that were similar historically. The very different "water-energy" trajectories in the two regions arose partly due to the type of water management options implemented, particularly the different emphasis on supply versus demand side management. This study also highlights the significant energy saving benefit of water conservation strategies (i.e., in SEQ, the energy saving was sufficient to offset the total energy use for seawater desalination and water recycling during the period.). The water-energy trajectory diagram provides a new way to illustrate and compare longitudinal water consumption and associated energy use within and between cities.

4.1. Introduction

This study quantifies the urban water consumption and the energy use of the urban water supply system in South East Queensland (SEQ) and Perth from 2002 (the early period of the Millennium Drought) to 2014 (the post drought period). It then explores the difference in the long-term water and energy use for water provision pathways of the two regions.

The water sector worldwide is facing a range of challenges including increasing water demand from population growth, droughts, groundwater depletion, surface water pollution, rising energy use from increasing uptake of energy-intensive alternative water sources, rapidly increasing energy cost, and the need for climate change mitigation and adaptation. For example, the combination of ongoing population growth and lower than average rainfall has generated significant water shortage/stress in many parts of Australia over the past two decades. From late 1996 to mid-2010, a prolonged dry period was experienced in much of the southern part of Australia (Bureau of Meteorology, 2015a; Grant *et al.*, 2013). It is known as the Millennium Drought and was particularly severe in densely populated south-eastern Australia and south-western Australia.

Both south-eastern Australia (where SEQ is located) and south-western Australia (where Perth is located) experienced a dry period during the Millennium Drought. South-eastern Australia had uninterrupted below median rainfall from 2001 to 2009 and entered a wet period afterwards as a result of La Niña-Southern Oscillation (Van Dijk *et al.*, 2013). On the other hand, south-western Australia has encountered a “stepping down” decline in rainfall since 1975 with several major short-term meteorological droughts in 2001, 2002, 2004, 2006 and 2010 (State of the Environment 2011 Committee, 2011), and the drying climate (attributed considerably to human-induced climate change (State of the Environment 2011 Committee, 2011)) has continued after 2010.

In response to their water stress situations, both regions implemented some water management options on both the supply-side and demand-side. In SEQ, the water shortage crisis (the combined dam storage dropped to 16% (Laves *et al.*, 2014)) was addressed by some adaptive responses from the water sector on the demand-side, commencing in the earlier stage of the drought (e.g., water restrictions, water conservation campaigns), and followed by building new-supply sources in the later stage of the drought (i.e., seawater desalination, water recycling). In Perth, water stress was concurrently tackled by outdoor water restrictions, water conservation campaigns and augmenting the system with new supply sources (e.g., desalination). The adopted supply-side and demand-side options in the two regions have significant long-term urban water consumption implications and energy implications to the water supply systems, which have not been well studied.

The major contributions of this work are the use of rare comparative time-series case studies, and the development of a water-energy trajectory diagram to explore the changes in the long-term water consumption and associated energy use in two major regions encountering water stress. A considerable amount of work has quantified and evaluated the energy implications of different water management options, ranging from centralised water sources (Lundie *et al.*, 2004; Shrestha *et al.*, 2011; Stokes and Horvath, 2006) to alternative decentralised water sources (Anand and Apul, 2011; Devkota *et al.*, 2013; Lee and Tansel, 2012; Racoviceanu and Karney, 2010) and to demand management (Bartos and Chester, 2014; DeMonsabert and Liner, 1998; Racoviceanu and Karney, 2010; Willis *et al.*, 2010). Most of these studies focus on long-term projections of energy use of individual systems through scenario analysis (Bartos and Chester, 2014; Hall *et al.*, 2011; Lundie *et al.*, 2004; Shrestha *et al.*, 2011; Stokes and Horvath, 2006) or on quantifying energy use with hypothetical cases (Anand and Apul, 2011; DeMonsabert and Liner, 1998; Racoviceanu and Karney, 2010). In addition, it is well documented how SEQ (Head, 2014; Laves *et al.*, 2014; Poussade *et al.*, 2011) and Perth (Morgan, 2015; Newman, 2014) responded to their water stress situation, but relatively little is known about the energy implications of the drought and the implemented options on the urban water systems. A retrospective comparative study based on the experiences of the two regions can demonstrate how cities perform in practice and provides insights into managing energy use in urban water systems. This work is particularly relevant to urban areas that are facing water stress and increasing energy costs, and starting to utilise more energy-intensive water sources.

In the context of urban water supply management, there are a wide range of factors that influence both the water supply system operation and water demand, which in turn have energy implications (Figure 8). This work focuses on the long-term impacts of changes in supply system operation and water demand on the energy use of centralised water supply systems (enclosed by the dashed line). This study examines the collective water and energy consequences of the implemented water management options and specifically, addresses the following research questions.

1. What have been the long-term changes in water consumption and associated energy use for two major urban areas (i.e., SEQ, Perth) encountering water stress?
2. How much can water management options influence long-term water consumption and associated energy use in cities? And what are the lessons learned from the two regions?

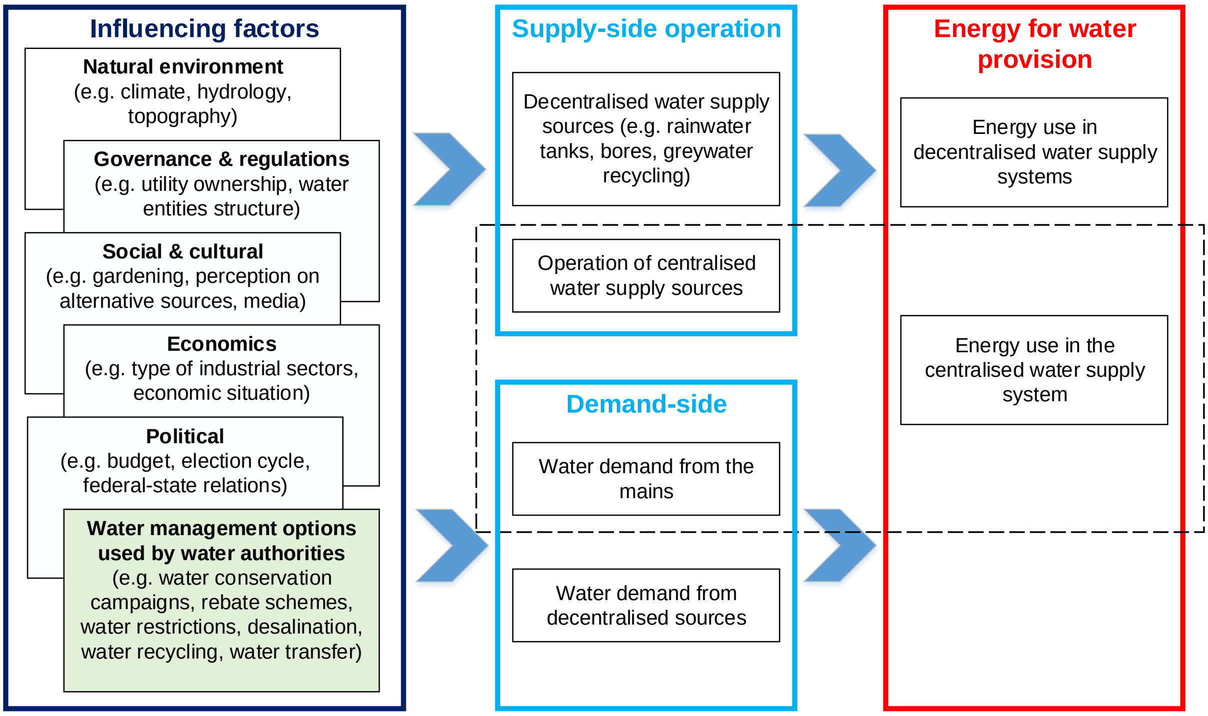

Figure 8 Illustrative diagram for the context of energy use for urban water provision. Dashed line is the primary scope of this work and the water management options implemented are discussed.

4.1.1. The water situation in South East Queensland

South East Queensland (SEQ) is the most urbanised and populated region of the Australian state of Queensland. It consists of ten local government areas (LGAs) - Brisbane, Gold Coast, Sunshine Coast, Redland, Logan, Ipswich, Moreton Bay, Lockyer Valley, Scenic Rim and Somerset. This work focuses on the first seven LGAs which accounted for approximately 97% of SEQ population of over three million in 2013 (Australian Bureau of Statistics, 2014a) and are connected to the SEQ bulk water supply network (Seqwater, 2013a). The region obtains water from its main water source, Lake Wivenhoe and Lake Somerset (together contributing to approximately 60% of the total storage capacity of 26 dams managed by Seqwater (Seqwater, 2014b)), in addition to some smaller reservoirs such as the Hinze Dam situated in the Gold Coast region and the North Pine Dam located north-west of Brisbane. During the Millennium drought, the main water supplies dropped to 16% of capacity (Laves *et al.*, 2014), seriously jeopardising the regions water supply. A diagram of the bulk water supply system can be found in Appendix A2. The water context of SEQ is summarised in Table 6.

In SEQ, the water shortage crisis caused by the Millennium Drought triggered major changes in the configuration of the urban water supply system, the structure of urban water services and the way that water resources were being managed (Table 6). The Queensland Government provided AUD$321 million for rebate schemes of water efficient devices and rainwater tanks to the region (Walton and Holmes, 2009). Approaching the end of the drought, two climate-independent sources – Gold Coast Tugun desalination plant and the Western Corridor Recycled Water Scheme were commissioned. Regional bulk water pipelines called the Southern Regional Water Pipeline (SRWP), Northern Pipeline Interconnector (NPI) and Eastern Pipeline Interconnector (EPI) were constructed to connect previously segregated regional water supply systems to form a bulk water supply network.

4.1.2. The water situation in Perth

Perth is the capital city of the state of Western Australia. The Greater Perth region had a population of approximately two million people in 2014, 79% of the state's total population (Australian Bureau of Statistics, 2015a). The water supply and wastewater treatment services of Western Australia are managed entirely by the Water Corporation. Unlike SEQ, Perth relies heavily on groundwater for water supply with less carry-over surface water capacity. The Gnangara Mound is a major groundwater source for Perth. The water context of Perth is summarised in Table 6.

In response to the drying climate and growing water demand, stage 4 water restrictions have been imposed since 2001, limiting the use of sprinklers by householders and businesses to only two days per week. In addition, some studies were conducted in the early 2000s for augmenting the system with new supply sources. Noticeably, one of them is the study of extracting water from South West Yarragadee aquifer (the largest freshwater aquifer in Western Australia) to supply Perth (Newman, 2014). In 2004, a decision was made to construct a seawater desalination plant instead because of reducing cost of desalination technology and a concern that long-term sustainable yields from groundwater may not be achieved. Two desalination plants, namely the Perth Seawater Desalination Plant (Engineers Australia, 2010) and the Southern Seawater Desalination Plant (Water Corporation, 2012), were commissioned in 2006 and 2011 respectively. Since then, desalinated water has become one of the major water sources for the region. As of 2013-14, the supplies were from surface water, groundwater and desalinated water 18%, 43% and 39% respectively (Water Corporation, 2014). In recent years, a groundwater replenishment scheme is being considered (Water Corporation, 2014). It is a form of indirect potable water recycling that recharges the groundwater system with highly treated wastewater.

Table 6 Summary of the water context, pressure and major water management options implemented in SEQ and Perth from 2002 to 2014

	SEQ	Perth
Context		
Major water sources in 2002	Dam water	Dam water (~40%)[a] Groundwater (~60%)
Institution	Multiple water utilities	Single water utility
Pressure		
Population growth[b]	~33% 2.33 million (2002) to 3.09 million (2014)	~37% 1.47 million (2002) to 2.02 million (2014)
Climate	Millennium drought from 2001 to 2009, followed by wet years	Decline in rainfall since 1975
Major water management options implemented		

Supply-side[d]	• Built the Gold Coast Desalination Plant (GCDP) (supplying <1% of demand[c])
	• Built the Western Corridor Recycled Water Scheme (WCRWS) (now supplying 0% of demand[c])
	• Built a bulk water supply network to connect previously segregated networks with regional network interconnectors:
	  ◦ Southern Regional Water Pipeline (SRWP)
	  ◦ Northern Pipeline Interconnector (NPI)
	  ◦ Eastern Pipeline Interconnector (EPI)
	• Rainwater tank rebate
	• Pressure management and leakage program
		• Built the Perth Seawater Desalination Plant and the Southern Seawater Desalination Plant (supplying ~40% of demand[c])
		• Completed a groundwater replenishment trial scheme (using potable recycled water)
		• Rainwater tank rebate
		• Pressure management and leakage program

Demand-side[e]	• Residential water restrictions • Water conservation rebate schemes • Business water efficiency program • Consumption targets and educational campaign on water efficiency	• Irrigation water use restrictions • Water conservation rebate schemes

[a] Source: (Water Corporation, 2002)

[b] Estimated numbers from the Australian Bureau of Statistics (Australian Bureau of Statistics, 2015a; b)

[c] Based on the total urban water demand in 2013-14 (Seqwater, 2014a; Water Corporation, 2014)

[d] Sources: (Gold Coast City Council, 2013; LinkWater, 2009; Seqwater, 2014b; Walton and Holmes, 2009; WaterSecure, 2009)

[e] Sources: (Fyfe *et al.*, 2015; Price *et al.*, 2010; Queensland Water Commission, 2010; Walton and Holmes, 2009)

4.2. Method

4.2.1. Data mining and literature reviews

Data mining and literature reviews of the regional water situation in SEQ and Perth from 2001-2002 to 2013-2014 were conducted to collect a wide range of data and information such as water production data, water demand data, population data, centralised water supply system development history, regional water service reform history, regional drought management history and system operation history. Data or information sources include (but are not limited to) the Australian Bureau of Statistics, Bureau of Meteorology, National Water Commission, CSIRO, UWSRA, Seqwater, the Water Corporation, some city councils and other historical water agencies. Since most data sources were reported as fiscal year (starts on 1 July and ends on 30 June), all the annual results in this work are expressed in Australian fiscal years.

There is a great difference in the way water services were and are managed in SEQ and Perth. In SEQ, the water supply system management and governance structure changed remarkably during the period of interest. The Millennium Drought triggered significant reforms in the regional urban water service. Some water agencies in SEQ were merged, reformed or ceased operation. Therefore, information and data on historical urban water use in SEQ are fragmented. Time-series historical energy use of the water supply systems (mostly segregated in the past) was not available and had to be modelled in this work. There are only two public reports (Cook *et al.*, 2012; Kenway *et al.*, 2008) providing a partial snapshot for the energy use of some of the SEQ water utilities in year 2006-07 (2 out of over 10 utilities) and 2009-10 (5 out of 6 utilities). Energy use by most of the water utilities in SEQ has not been reported or disclosed. On the other hand, the water services in Western Australia (including the capital city Perth) were managed solely by the Water Corporation, which published annual figures on water consumption and energy use in water supply services.

4.2.2. Quantification of urban water consumption

The historical annual urban water consumption rates (i.e., total urban water consumption, residential water consumption, and per capita water use) in SEQ and Perth from 2002 to 2014 were compiled from published water data sources and Seqwater. The primary dataset is the National Performance Report – Urban Water Utilities, which was published annually by the Water Services Association of Australia (before 2007-08), the National Water Commission (from 2007-08 to 2012-13) and the Bureau of Meteorology (in 2013-14) to report on the performance of most of the water utilities in Australia. For Perth, water consumption data were sourced from the National Performance Reports. For SEQ, supplementary data sources were needed and they included water data from Seqwater, city councils reports and utilities reports, and population data from the Australian Bureau of Statistics. The urban water consumptions for the studied seven local government areas (LGAs) in SEQ were quantified individually. This formed the inputs for the energy modelling work described in the following section. Most of the LGAs (i.e., Gold Coast, Redland, Logan, Brisbane, Ipswich) have the exact data for all the years, while Sunshine Coast and Moreton Bay do not have the total regional data for some years and require to be estimated from the per capita water use of some of their sub-regions.

The total urban water use quantified includes residential use, non-residential use and system loss. This work does not consider water consumption from decentralised sources (e.g., rainwater tanks, greywater recycling, bores), which are in most of the cases neither metered nor managed by the water utilities.

4.2.3. Quantification of energy use for water supply services

For SEQ, a bottom-up approach was used to quantify the annual energy use by the water supply system based on the modelled historical water balance and energy intensities of key system components. A cost optimization model, namely the Decision Support System Optimiser (DSSO), was utilised to model the historical water balance of SEQ. The DSSO model is owned by Seqwater – the bulk water agency in SEQ. It is primarily designed for evaluating long-term water security implications of different future climate, demand and bulk water supply infrastructure change scenarios. Its objective function aims to obtain the most cost-effective supply and demand configurations of the supply network. The model represents the seven major local government areas in SEQ by 40 demand zone nodes. It captures the main components of SEQ urban water supply system including 16 water treatment plant nodes, 21 catchment nodes, the desalination plant node, the recycled water scheme node, the associated key pipelines, pumps, reservoirs and junctions. Water production data such as throughputs from the desalination plant and regional bulk water transfer were predominantly sourced from utilities public reports.

The time-series annual energy use of the water supply system was quantified based on the generated water balance and the energy intensities of some key system components such as water treatment plants, pump stations and the desalination plant. Energy intensities (fixed and flow dependent use) of major water treatment plants were obtained from statistical analysis of historical electricity use recorded from Seqwater. Energy intensities of key pump stations, water distribution, desalination and water recycling were estimated from data from Seqwater and some public sources. Since electricity is the major energy source for the water supply system, all energy results are expressed in electricity units (i.e., kWh, GWh). The modelled energy use profile was validated by comparing with available energy use figures reported by utilities or literature. In addition to quantifying the historical energy use of the system, the model can also be utilised to simulate some hypothetical cases. For instance, a hypothetical case for which water conservation strategies were not implemented was modelled in this work and compared against the historical baseline to quantify the energy saving from water conservation. More details of the method can be found in Appendix A2.

For Perth, the time-series energy use for water provision was quantified based on the energy intensity of water supply in Western Australia (for each year) published in the Water Corporation's annual reports and the total urban water consumption. Because energy intensity data for water supply in Perth is not available, the energy intensities for water provision in the state of Western Australia were used instead (As of 2014, 84% of the state's total population was in Perth (Australian Bureau of Statistics, 2015a).)

4.3. Results & discussion

4.3.1. Quantification of urban water use and energy use for water provision in SEQ

From 2002 to 2014, urban water consumption in SEQ and energy use in the urban water supply system varied substantially (Figure 9). Some of the key events that influenced the water consumption and the energy use of the supply system are marked on Figure 9. The urban water consumption reduced continuously from the implementation of water restrictions in May 2005, followed by a series of measures including the promotion of water efficient devices and rainwater tanks (e.g., Home WaterWise Rebate), setting of residential water consumption targets (e.g., Target 140), and pressure and leakage management in the water supply network. Some of these measures had an ongoing water use reduction effect even after the drought. The post-drought total urban water use is still significantly lower than that of the pre-drought period, even though regional population has increase continuously throughout the past decade (Australian Bureau of Statistics, 2014a).

The result highlights that energy use of the water supply system is strongly affected by both water conservation strategies and the introduction of alternative water sources. In the pre-drought period, the urban water supply system in SEQ consumed 169 GWh energy in 2002. In the most severe period of the drought in 2007, when the combined dam storage dropped to 16% (Laves *et al.*, 2014) and strict water restrictions were imposed, energy use reduced by over 30% to 117GWh. In the later stage of the drought, the energy use doubled to 237 GWh in 2010 when some key infrastructure including the Western Corridor Recycled Water Scheme (WCRWS), Gold Coast Desalination Plant (GCDP) and regional network interconnectors (SRWP, NPI, EPI) came online. Between 2008 and 2010, the overall dam storage returned to the pre-drought level. Decisions were made to reduce the production from the two energy-intensive climate independent supply sources. In year 2010-11, both were placed in "standby" mode. As of May 2014, the Western Corridor Recycled Water Scheme has ceased production completely and would only be operated when the combined system storage falls below 40% of its full capacity (Seqwater, 2014b). The time-series results can be found in Appendix A2.

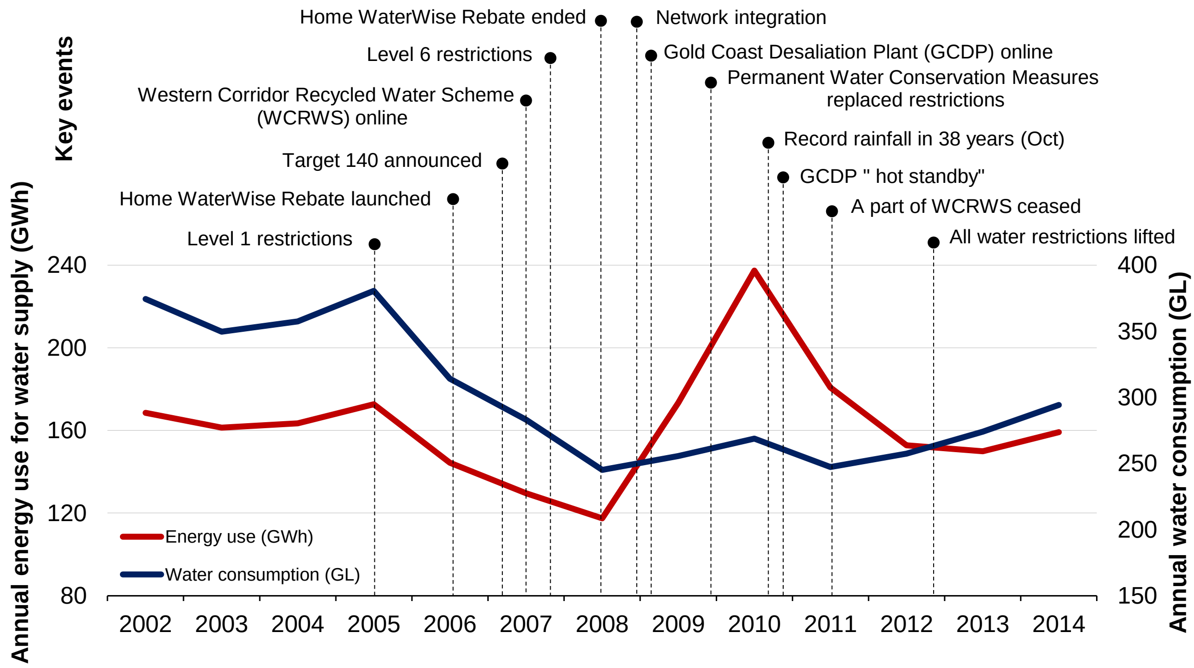

Figure 9 Water consumption and modelled energy use of SEQ urban water supply system from 2002 to 2014 with key events

4.3.2. Quantification of urban water use and energy use for water provision in Perth

From 2002 to 2014, Perth's water consumption and energy use in the urban water supply system increased continuously (Figure 10). Stage 4 water restrictions have been imposed in Perth since 2001 to limit outdoor water use. During the Millennium Drought period, Perth did not raise the level of water restrictions further as the region did not get into a severe water shortage crisis as in the case of SEQ. The "stepping down" decline in rainfall since 1970s might have given the water authority a longer time frame to plan and augment the supply system, and therefore, the water management approach could be less demand-side focused than SEQ. The most distinctive adaptive responses to the drying climate were the introductions of the Perth Seawater Desalination Plant (Engineers Australia, 2010) (i.e., the first seawater desalination plant in Australia for urban water use) and the Southern Seawater Desalination Plant (Water Corporation, 2012) in 2006 and 2011 respectively. The impacts of desalination can be clearly seen from the two significant increases in the energy use for water supply services in Figure 10. The energy intensity for water provision in the state of Western Australia increased from 0.73 GWh/GL in 2002 to 1.84 GWh/GL in 2014. As of 2013-14, the two desalination plants supplied 39% of the total water use in Greater Perth (Water Corporation, 2014) and are expected to increase further to above 40% in the future (Water Corporation, 2013). The time-series result can be found in Appendix A2.

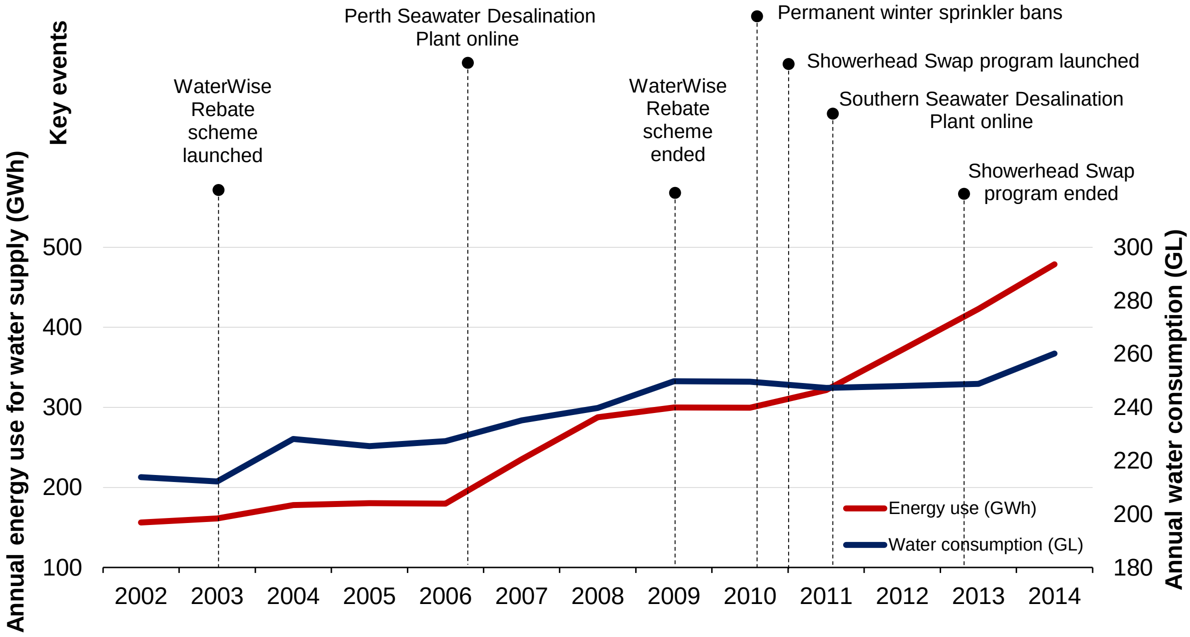

Figure 10 Water consumption and energy use of Perth urban water supply system from 2002 to 2014 with key events

4.3.3. A comparison between SEQ and Perth

In 2002, Perth had a similar per capita water consumption rate to SEQ, and 48% higher per capita energy use in the water supply system than SEQ. By 2014, the per capita water consumption in SEQ became 28% lower than that of Perth, while the per capita energy use in Perth had increased to 470% of that of SEQ (Figure 11).

The water consumption rate in SEQ reduced significantly from 2005, while there has been only a moderate reduction in Perth since 2008 (Figure 11). As stated above, the Millennium Drought in SEQ was most pronounced during 2005 to 2008. It led to the implementation of strict water restrictions and water conservation schemes (Table 6). This explains the distinct reduction in the per capita water use in Figure 11. The average residential water consumption in SEQ greatly reduced from 282 litres per person per day (L/p/d) in 2005 (Queensland Water Commission, 2010) to 143 L/p/d in 2012 (Queensland Water Commission, 2012), while the total urban water use dropped from 450 L/p/d in 2005 to 240 L/p/d in 2012. Remarkably, there has yet to be a significant rebound in water use after the drought ended in 2010. In addition to changes in water use behaviours and built-in fixtures, other factors such as smaller lot developments and changes to tariff structures are suggested to reduce the rebound of water use (Beal and Stewart, 2014). In contrast, even with short-term meteorological droughts in 2001, 2002, 2004, 2006 and 2010 (State of the Environment 2011 Committee, 2011), Perth still had among the highest residential water consumption rate in Australia after these droughts (Australian Bureau of Statistics, 2014b). As of 2012-13, Western Australia (78% of its population was in Perth) had the highest household water consumption per person of 362 L/p/d, while the Australian average was 219 L/p/d (Australian Bureau of Statistics, 2014b). Nevertheless, a progressive reduction in per capita water use since 2008 can be noticed. It can be attributed to the increasing water conservation effort and rising water prices.

For SEQ, as discussed in the earlier section, the trend of the energy profile is the consequence of the Millennium Drought and followed by the augmentation of the supply system with energy-intensive sources. For Perth, the increase in the share of desalinated water in the supply mix has doubled the per capita energy use for water supply services in 8 years. The geographical setting (i.e., relying more heavily on groundwater), drying climate (i.e., increasing the use of desalinated water) and water use pattern (i.e., relatively higher water consumption rate in Australia) result in Perth having almost five times the per capita energy use for water supply services than SEQ in 2014.

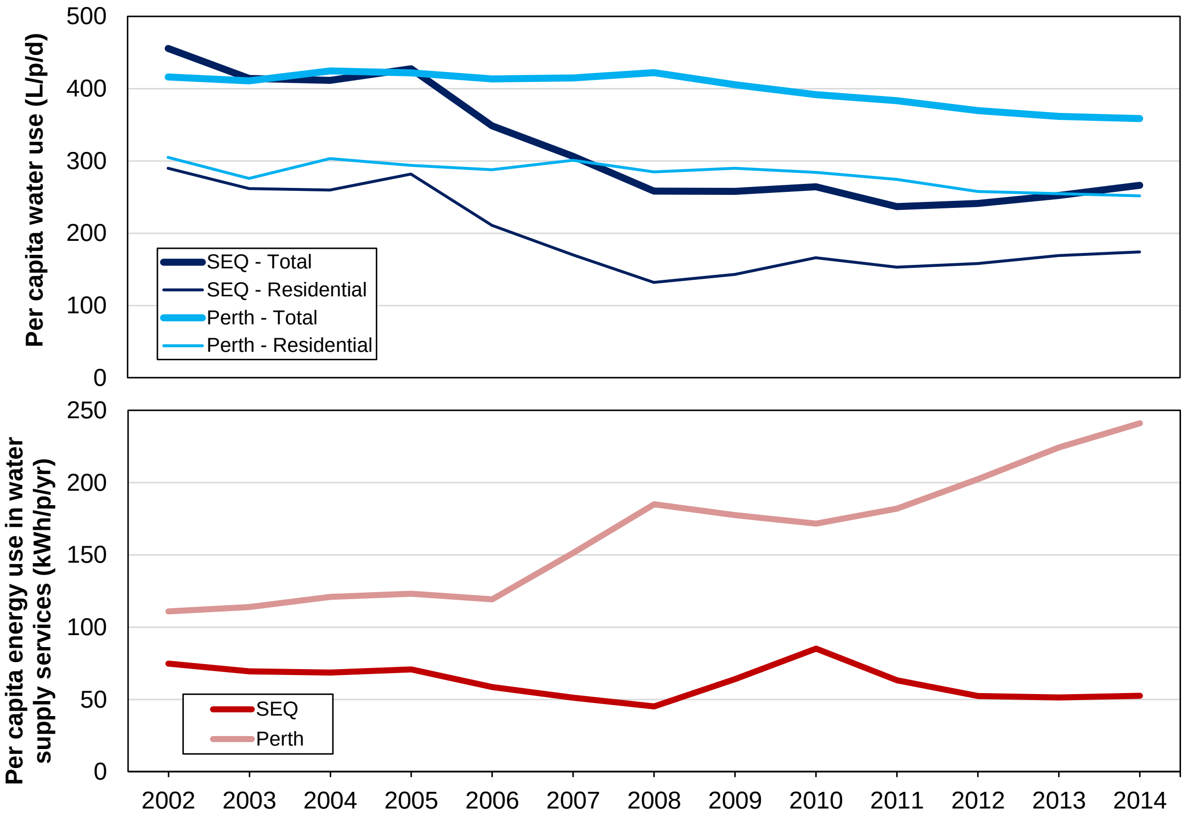

Figure 11 Per capita total urban water use, residential water use and energy use for water supply services in SEQ and Perth

The great difference in the residential water consumption rate between the two places is mainly attributed to the household stock, and water use pattern in showering and irrigation (Table 7). The percentages of households having a water-efficient shower head and a dual flush toilet in Queensland increased more than that of Western Australia between 2001 and 2013. For indoor water use, residents in SEQ took a shorter shower on average than in Perth. For outdoor water use, the increased uptake of rainwater tanks in SEQ, triggered by the rebate scheme, played a key role in reducing the reliance on mains water for gardening in SEQ.

Table 7 Water use pattern and household stock comparison

Water use pattern and household stock	SEQ	Perth	Sources
Households having a water-efficient shower head in 2001 (by state)	36.9%	40.1%	(Australian Bureau of Statistics, 2001)
Households having a water-efficient shower head in 2013 (by state)	72.7%	64.4%	(Australian Bureau of Statistics, 2013)
Households having a dual flush toilet in 2001 (by state)	62.1%	71.3%	(Australian Bureau of Statistics, 2001)
Households having a dual flush toilet in 2013 (by state)	92.2%	91.6%	(Australian Bureau of Statistics, 2013)
Average shower duration in 2010 (Brisbane)/ 2009 (Perth) (min)	5.7	6.7	(Beal and Stewart, 2011; Water Corporation, 2009)
Households with a garden using mains water for gardening in 2001 (by state)	86.2%	76.7%	(Australian Bureau of Statistics, 2001)
Households with a garden using mains water for gardening in 2013 (by state)	32.0%	69.0%	(Australian Bureau of Statistics, 2013)
Households installed with rainwater tanks in 2013 (by capital city)	47.0%	9.3%	(Australian Bureau of Statistics, 2013)

The current difference in water and associated energy consumption between the two regions can be attributed to very different “water-energy” trajectories over the past decade (Figure 12). The water-energy trajectory diagram plots the annual per capita urban water use and per capita energy use for water supply services in SEQ and Perth from 2002 to 2014. Both regions had quite similar per capita water use and energy use in 2002. Since 2002, SEQ followed a trajectory that had a significant reduction in water use and a slight drop in energy use, while Perth’s trajectory was a moderate reduction in water use and a substantial rise in energy use. The plot also demonstrates the difference in the consequences of the “supply-side focused approach” and the “integrated approach with both demand and supply-side options” in water resources management. The supply-side approach is to meet increasing demands through building large infrastructure, while the integrated approach emphasises improving water use productivity and complementing centralised supply systems with small-scale decentralised sources (Gleick, 2003). While Perth was not entirely focused on the supply-side approach, the result does suggest that the more a region depends on the supply-side approach, the more likely it follows a higher energy increase and lower water reduction trajectory. For regions that face increasing water stress, it is a good time for them to shift toward a more demand-side focused approach. The decisions will dictate the future long-term “water-energy” pathway of those regions. Often, it is not only an issue about energy usage, but also about the related greenhouse gas emissions (i.e., non-renewable fossil fuel is still the major energy source for today’s power generation sector around the world) and capital investment for building new infrastructure (i.e., reducing water demand can defer the building of new infrastructure.

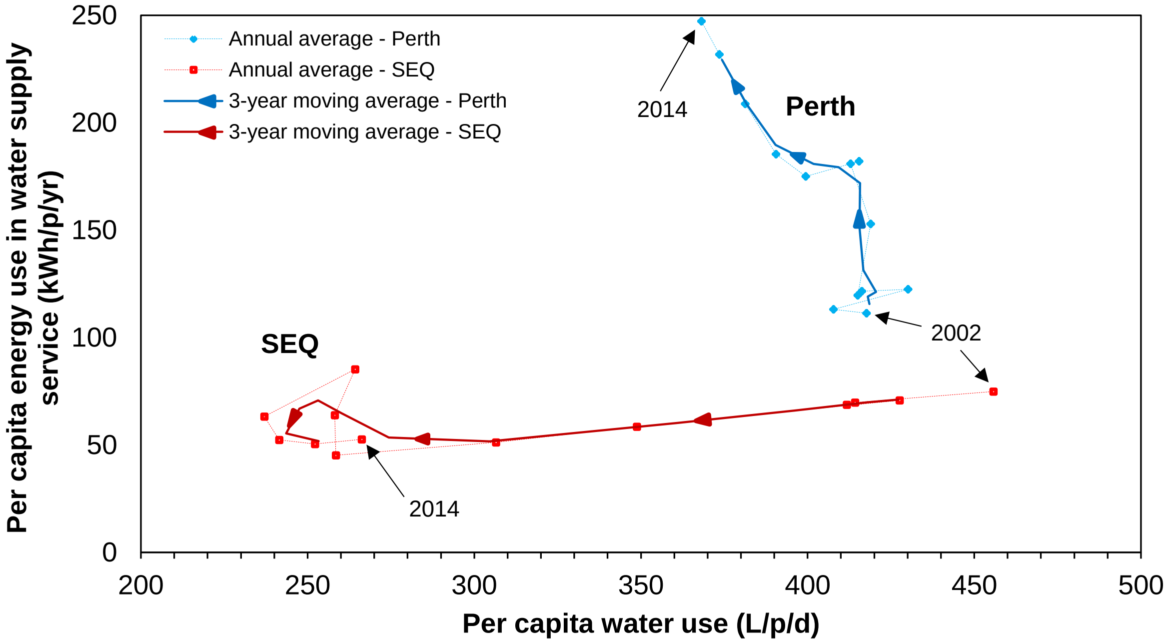

Figure 12 Water-energy trajectories (per capita total urban water use and per capita energy use for water supply services) of SEQ and Perth

4.3.4. Energy implications of adopted options in SEQ

This section specifically discusses the energy implications of adopted options in SEQ as more details are available for the region. In 2010, nearly half of the energy use in the water supply system was used by the new infrastructure - Gold Coast Desalination Plant (GCDP), Western Corridor Recycled Water Scheme (WCRWS) and regional network interconnectors (SRWP, NPI, EPI) (Figure 13). The category of "WTPs & network" includes water treatment plants, bulk water supply network and water distribution network. In that year, GCDP contributed less than 10% of water supply, but attributed 34% of the total energy use of the water supply system. WCRWS did not contribute to urban water supply, but supplied approximately 6% of water relative to urban demand to power stations.

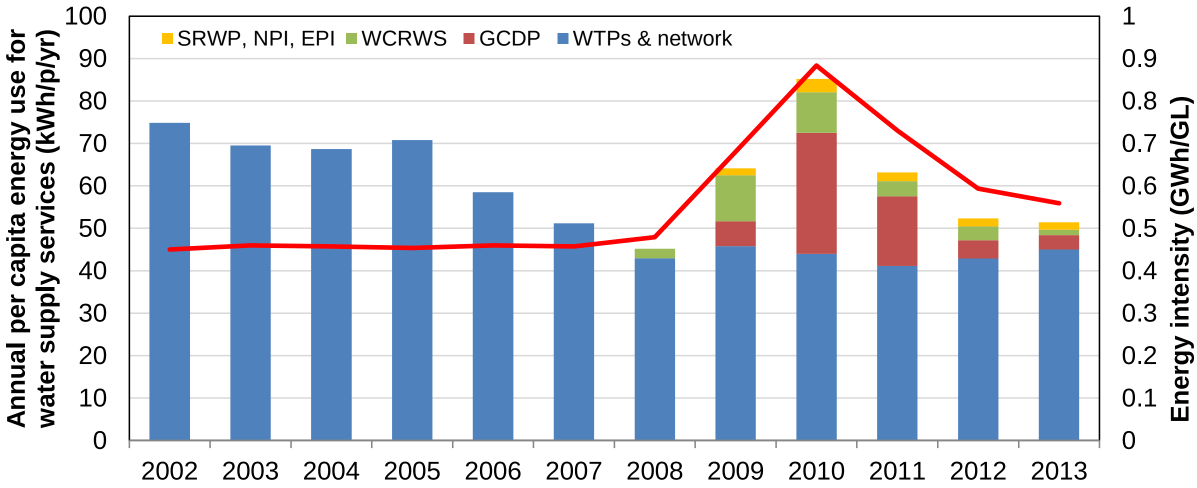

Figure 13 Modelled energy intensity of SEQ urban water supply system (line) and annual per capita energy use for water supply services with breakdown by system component (bar).

It is estimated that urban water use reduction has saved 790 GWh electricity for the urban water supply system over the period of 2005 to 2014 in SEQ. This estimate is obtained by comparing the actual energy use of the supply system against a modelled hypothetical historical energy use baseline considering the absence of all urban water use reduction measures. The urban water use reduction is a collective result of imposing water restrictions, promoting demand management, increasing uptake of rainwater tanks, implementing pressure and leakage management of the water supply network, and possibly passive conservation, with residential water conservation being the major contributor (Walton and Holmes, 2009). Even after the drought with water restrictions lifted, the energy saving benefit of past implemented options persists. It should be noted that during the same study period, seawater desalination (GCDP) and potable water recycling (WCRWS) consumed 260 GWh electricity. The energy saving from urban water use reduction has clearly offset the energy use of the energy intensive supply sources (which were not in full operation).

4.3.5. Lessons from the two regions

The SEQ case study provides quantitative evidence of the significant energy saving benefit of water use reduction strategies on the centralised water supply system. The benefit from energy saving through water use reduction is cumulative and will likely only grow over time, considering the significant increase in the energy price in the region in recent years (Quezada *et al.*, 2014). In Australia, real electricity prices for businesses increased on average by 60% from 2003 to 2013 (Swoboda, 2013). The increasing electricity cost also creates a stronger incentive for water utilities to better manage the energy efficiency of their assets and peak & off-peak electricity use. In both the SEQ and Perth water supply systems, the marginal energy saving benefit of having water conservation is substantial. Considering the high energy intensities of new infrastructure, reducing the frequency in which the desalination plant, water recycling scheme and regional water transfer pipelines have to be operated can greatly reduce the energy use of the systems. In addition to the energy saving benefit experienced by the centralised supply system, there are also some externality benefits (e.g., postponing the building of new infrastructure and reducing chemicals use in water treatment) and potential downstream energy saving benefits in residential end use and wastewater treatment systems, which are beyond the scope of this work and will be studied in future work.

This longitudinal comparative study suggests that a water shortage crisis created an opportunity for changing urban water use pattern, which in turn, yielded long-term benefits in water and energy savings. In SEQ, the drought was an acute rainfall decline leading to a water shortage crisis during 2005 and 2008, whereas in Perth the drought was part of a much longer (i.e., chronic), “stepping down” decline in rainfall since 1970s. While the water management responses of the two regions were also a collective result of other factors (e.g., political, institutional, cultural, geospatial factors), the water context (i.e., acute/ chronic) under which the water management responses were made might play a role. A possible explanation is that augmenting the water supply system with new supply sources requires a relatively long time frame that may not be available for an acute water crisis and as a result, the water agency has to rely more on demand-side intervention in the early stage of the crisis. For the water sectors in regions that are facing increasing water demand or encountering droughts, water stress situations may be windows of opportunity to induce changes in water use pattern for achieving long-term water and energy saving benefits (i.e., shifting to a lower “water-energy” trajectory).

This historical case also shows that regions with similar water and associated energy use historically can change differently in a relatively short timeframe. It demonstrates that some alternative supply-side options (e.g., seawater desalination, potable water recycling) can result in surging energy use in the water supply systems (i.e., a short-term increase in SEQ, a long-term increase in Perth). For regions with periodic droughts (and a large carry-over capacity as in SEQ), they should consider carefully the necessity of building centralised infrastructure that has a “lock-in” impact and prioritise less energy intensive options. Furthermore, while the reduction of urban water demand cannot be attributed solely to the water conservation effort imposed by the water authorities, demand management options do show to have significant water and energy saving benefits in the case of SEQ (similar to other eastern coast cities (Grant *et al.*, 2013)). In particular, rebate schemes for water efficient devices have provided a stronger incentive for people to improve water use efficiency.

The water-energy trajectory diagram (Figure 12) is proposed in this work as an approach to illustrate longitudinally the water and associated energy use performance of cities or regions and is particularly suitable for comparative and benchmarking studies. Other cities or regions can potentially plot their own water-energy trajectory diagrams to see how their water consumption and associated energy use have changed over time and benchmarking with similar cities for identifying areas for improvement and sharing lessons learned.

4.3.6. Limitations and uncertainties

One of the limitations of this work is that the water consumption and associated energy use from decentralised water supply sources such as rainwater tanks, bores and greywater recycling are not considered. Based on some rainwater tank studies in SEQ (Cahill and Lund, 2013; Chong et al., 2011; Walton and Holmes, 2009), it can be roughly estimated that as of 2013, the regional water use from rainwater tanks was not more than 5% of total urban water consumption from the mains. While there can be a high variation in the energy intensity of rainwater tank systems, in an Australian study (Umapathi et al., 2013), the average energy intensity of internally plumbed rainwater tanks was estimated to be 1.52 kWh/kL. Based on this estimate, the total regional energy use for rainwater tanks was unlikely to exceed 10% of the energy use in the centralised water supply system. Therefore, the water-energy trajectory of SEQ in Figure 12 would still remain similar even if the water and energy impacts of decentralised water sources are considered.

This work does not aim to prove any causality of various influencing factors on the supply-demand balance (Figure 8). Instead, it focuses more on the energy consequence of the supply-demand balance. Nevertheless, the energy implications of the new supply-side options (i.e., seawater desalination, water recycling, and bulk water transfer) implemented in both regions are evident. In addition, it has been suggested in the literature that water conservation effort played a key role in reducing urban water consumption in SEQ (Head, 2014; Laves et al., 2014; Walton and Holmes, 2009). In order to respond to water stress situation in a sustainable manner, it is recommended that water stressed regions have to better understand how the various factors can affect their long-term water-energy trajectories.

4.4. Conclusions

This paper presents the first longitudinal comparative study that explores the long-term changes in the water consumption and associated energy use in the water supply systems for two Australian regions (i.e., SEQ and Perth) that encountered water stress situations in their past decade. In 2002, both regions had a similar per capita water consumption and energy use for water provision. A strong effort of water conservation could be seen in SEQ during the drought (especially during the water shortage crisis between 2005 and 2008), while Perth has been increasingly relying on seawater desalination. As of 2014, even though the drought in SEQ had ended and the drying climate in Perth was continuing, the per capita urban water use in SEQ was 28% lower than that of Perth, while the per capita energy use for water provision in Perth is about five times that of SEQ. This historical case clearly shows that the water and associated energy use in regions that were similar historically can change drastically and differently in a relatively short timeframe (i.e., following distinct “water-energy” trajectories). It demonstrated the significant long-term water and energy consequences of some of the water management options.

The experiences of the two regions encountering water stress situations can be lessons for other regions that are facing increasing water stress and energy cost. For instance, this study reveals the significant energy saving benefit from the large-scale adoption of water conservation strategies. In the centralised water supply system in SEQ, this energy saving was sufficient to offset the total energy use for seawater desalination and water recycling during the period. In addition, the empirical result in this study may suggest that times of water stress (especially under an acute context as in the case of SEQ) can be windows of opportunity to induce changes in water use patterns, thereby shifting the region to lower long-term “water-energy” trajectories.

In term of the contributions of this work, in addition to the use of longitudinal comparative case studies to explore the water and energy consequences of water management options, this paper also introduced the water-energy trajectory diagram as a way to illustrate and benchmark cities for their water and associated energy performance.

5. Energy implications of the Millennium Drought on the urban water cycles in southeast Australian cities

This chapter is the second of the three papers that address the second objective of this thesis – to quantify and understand the energy impacts of droughts on urban water systems. The case study presented in this chapter examines the energy use of the water supply systems and sewage systems in Melbourne and Sydney through the Millennium Drought. In addition, the energy impacts of the Drought and implemented demand-side measures on the water supply system, sewage system and residential water end use in Melbourne are compared. The two regions are included in the multi-city analysis in Chapter 3 and are explored in detail in this chapter.

> **Lam, K.L**., Lant, P.A., Kenway, S.J. (2016) "Energy implications of the millennium drought on the urban water cycles in southeast Australian cities", *IWA World Water Congress & Exhibition 2016*, Brisbane, Australia, 9-14 October, 2016. Accepted for publication in *Water Science and Technology: Water Supply* on 25th May, 2017.

Abstract

During the Millennium Drought in Australia, a wide range of supply-side and demand-side water management strategies were adopted in major southeast Australian cities. This study undertakes a time-series quantification (2001-2014) and comparative analysis of the energy use of the urban water supply systems and sewage systems in Melbourne and Sydney before, during and after the drought, and evaluates the energy implications of the drought and the implemented strategies. In addition, the energy implications of residential water use in Melbourne was estimated. The research highlights that large-scale adoption of water conservation strategies can have different impact on energy use in different parts of the urban water cycle. In Melbourne, the per capita water-related energy use reduction in households related to showering and clothes-washing alone (46% reduction, 580 kWh_{th}/p/yr) was far more substantial than that in the water supply system (32% reduction, 18 kWh_{th}/p/yr). This historical case also demonstrates the importance of balancing supply and demand-side strategies in managing long-term water security and related energy use. The significant energy saving in water supply systems and households from water conservation can offset the additional energy use from operating energy-intensive supply options such as inter-basin water transfers and seawater desalination during the dry years.

5.1. Introduction

In recent years, concerns about environmental sustainability, rapidly increasing energy cost and climate change mitigation, together with the increasing uptake of energy-intensive alternative water sources, have driven a growing interest in understanding and managing the energy use and greenhouse gas emissions in the urban water cycle.

The Millennium Drought was a prolonged period of dry conditions occurring in much of southern Australia from late-1996 to mid-2010 (Bureau of Meteorology, 2015a). In southeast Australia, the dry condition was most profound between 2001 and 2009 (Van Dijk et al., 2013). The region has some of the most populated Australian cities, including Adelaide, Brisbane, Melbourne and Sydney. At the height of the drought, the total water use in the region reduced by over 50% (from 2001 level) (Australian Bureau of Statistics, 2006; 2015d). The agricultural sector was most severely affected, followed by the urban water use (i.e., the percentage of water use by household sector was on average less than 10% of the total state-wide water use). The drought led to a series of policy responses from the water sectors. A wide range of supply-side (e.g., inter-basin water transfers, desalination, rainwater harvesting) and demand-side strategies (e.g., water conservation campaigns, water restrictions) were implemented. It is well documented how the region responded to this worst drought on record (Grant *et al.*, 2013; Turner *et al.*, 2016), but relatively little is known about the energy implications of the drought and the implemented water management strategies on the urban water cycles (i.e., water supply systems, sewage systems, residential water end use). In addition, most of the studies in the literature present a "snapshot" analysis of a single year. Studies considering the influence of time on water-related energy use are less evident in the literature (Kenway *et al.*, 2011b). This study therefore aims to fill this gap.

This study explores the energy implications of the Millennium Drought on the urban water cycles in two southeast Australian cities – Melbourne and Sydney. It quantifies longitudinally the energy use of the water supply systems and the sewage systems in the two cities from 2001 to 2014, and estimates the residential water-related energy use in Melbourne before and after the drought. The energy implications of the drought, and the implemented supply and demand-side strategies (Table 8) on the water supply systems, sewage systems and residential water end use are then discussed. The major contribution of this work is to provide a case study on analysing the temporal water-related energy impacts of drought on different parts of the urban water cycle.

Table 8 Major supply and demand-side strategies implemented in Melbourne and Sydney in responses to the Millennium Drought

Supply-side	**Demand-side**
Melbourne	
Building the North-South Pipeline	Water restrictions
Building the Victorian Desalination Plant	Target 155 campaign[1]
Leakage and pressure management	Living Victoria Rebate Program[2]
	Showerhead Exchange Program
	waterMAP Program[3]
Sydney	
Operating the Shoalhaven Drought Transfer Scheme	Water restrictions
Building and operating the Sydney Desalination Plant	NSW Home Saver Rebates Program[4]
Leakage and pressure management	Business water efficiency programs

[1] Promoting a voluntary household water use target of 155 L/p/d (Turner *et al.*, 2016).

[2] Providing rebates for water efficient products such as washing machines, showerhead and dual-flush toilet (Fyfe *et al.*, 2015).

[3] High water use businesses to prepare water efficiency improvement plans (EPA Victoria, 2008).

[4] Providing rebates for water-related products such as water-efficient washing machines, hot water systems and rainwater tanks (Fyfe *et al.*, 2015).

5.2. Case Study Background

Melbourne (the capital city of the Australian state of Victoria) had 4.5 million residents as of 2015 (Australian Bureau of Statistics, 2015c). It obtains water from an interconnected system of 10 storage reservoirs with a total storage capacity of 1810 GL (Melbourne Water, 2013b), which is more than three times the total urban water demand in 2001 (500 GL) (Melbourne Water, 2014a). The water supply system is mostly gravity-fed. During the Millennium Drought, the average inflow into Melbourne's main water supply reservoirs (1997-2009) was only 376 GL/year, compared to the long-term average of 615 GL/year (Melbourne Water, 2016a). For the sewage system, all sewage was treated to a secondary level before the introduction of tertiary treatment in one of the treatment plants in 2012.

Sydney (the capital city of the Australian state of New South Wales) is the most populous city in Australia (4.9 million as of 2015) (Australian Bureau of Statistics, 2015c). Prior to the drought, it already had an inter-basin water transfer pipeline (Shoalhaven Transfer Scheme) that can transfer water from the Shoalhaven River to Sydney's catchments in the dry years. During 1991 to 2012, the total average inflow to major catchments for Sydney was only 673 GL/year, compared to the long-term averages of 2153 GL/year during 1948 to 1990 respectively (Water Services Association of Australia, 2013). For the sewage system, 74%, 3% and 23% of sewage were treated to primary level, secondary level and tertiary/advanced level respectively in 2014 (Bureau of Meteorology, 2015b).

5.3. Material and Methods

The time-series (2001-2014) per capita total urban water use, total energy use in the water supply system, total energy use in the sewage system in Melbourne and Sydney were quantified based on the collected and compiled historical data for urban water use, population served by the water utilities, energy use of water supply systems and energy use of sewage systems. The major data sources are the National Performance Reports in Australia (Bureau of Meteorology, 2015b; National Water Commission, 2011; Water Services Association of Australia, 2008) and numerous public reports published by the water utilities in Melbourne (i.e., City West Water, Melbourne Water, South East Water and Yarra Valley Water) and Sydney (i.e., Sydney Catchment Authority and Sydney Water Corporation). Most water utilities report their operational energy use or energy intensity annually. Literature review was used to unveil the historical context of the two cities' responses to the drought.

In this work, the energy implications of some of the supply-side strategies (i.e., Shoalhaven Drought Transfer, Sydney Desalination Plant) and demand-side strategies (i.e., collective impact) implemented during the drought were quantified. For the energy implications of supply-side strategies, the annual electricity consumption by the two major supply-side strategies in Sydney were obtained from various utility reports and compiled in an early work (Lam *et al.*, 2017b). For the energy implications of demand-side strategies, estimates were made on the energy saving associated with water demand reduction in Melbourne and Sydney. For each city, the per capita total water use in 2001 was used as the baseline. The energy saving for a specific year was calculated by multiplying the volume of water saved (against the baseline) with the energy intensity for water supply in that year (i.e., energy saving in year x = (per capita water use in year x - per capita water use in 2001) × population in year x × energy intensity for water supply in year x).

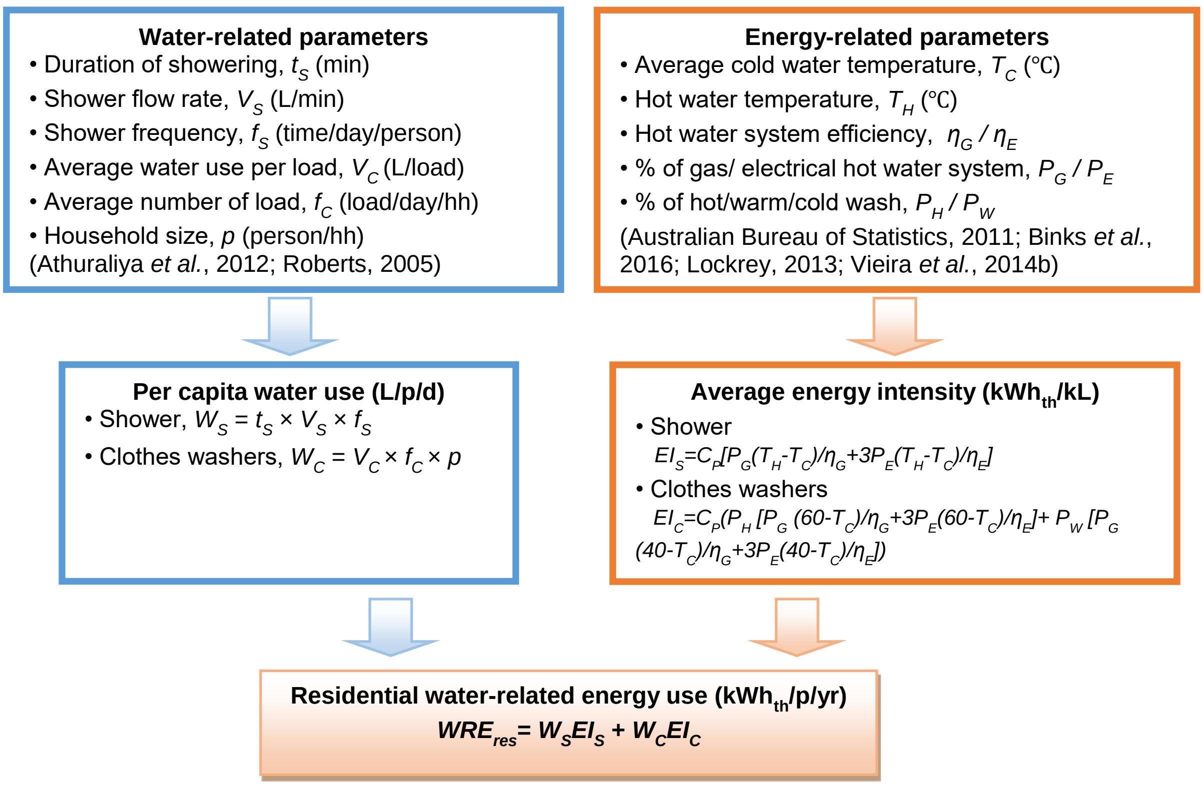

Figure 14 Overview of the quantification of residential water-related energy use

Previous works have shown that residential water-related energy use is dominated by hot water use (Kenway et al., 2011a) with showers and clothes washers contributing the dominant fraction in households studied in Melbourne (Binks et al., 2016). Consequently, this work considers the water-related energy use associated with showering and clothes washing to represent the residential water-related energy use. Two residential end use studies (Athuraliya et al., 2012; Roberts, 2005) conducted by one of the water retailers in Melbourne (i.e., Yarra Valley Water) in 2004 and 2012 were used to estimate the change in the residential water-related energy use through the drought (Figure 14). The results are expressed in per capita primary energy equivalent use (kWhth/p/a) to compare with that of the centralised water systems. It is assumed that three unit of kWh_{th} (thermal) is equivalent to one unit of kWh_e (electrical) (Gleick and Cooley, 2009).

5.4. Results and Discussion

5.4.1. Quantification of urban water use and energy use in the centralised water systems

The per capita total urban water use (L/p/d), total energy use in the water supply systems (GWh) and total energy use in the sewage systems (GWh) between 2001 and 2014 for Melbourne and Sydney are shown in Figure 15 and Figure 16 respectively. Some of the key events that possibly had impacts on the water use and the energy use of the supply systems are marked on the figures.

The results show that there was a significant reduction in urban water use in both Melbourne and Sydney through the drought. On a per capita basis, it reduced by as much as 43% (2011) and 31% (2010) from the levels of 2001 respectively for Melbourne and Sydney. Even after the drought has ended in 2010, there was only minor “rebound” in the water use. The urban water efficiency gained through the drought seems to have been preserved.

The energy use for water supply in both Melbourne and Sydney was greatly influenced by the drought and the implemented supply and demand-side strategies. Before the drought, the Melbourne’s water supply system did not have an inter-basin water transfer pipeline as in Sydney, the energy use for water supply was therefore much more stable compared to that of Sydney during the drought. The only significant increase in the energy use was observed in 2011 when an inter-basin pipeline (i.e., the North-South Pipeline) came online. The pipeline was built in response to the drought, but commissioned after the drought ended. Similar to the new desalination plant (i.e., the Victorian Desalination Plant), it ceased operation shortly after commissioning.

In Sydney, as the Shoalhaven Drought Transfer started operating in 2002 to transfer water from the Shoalhaven River to Sydney’s catchments, the energy use of the water supply system rapidly increased. By the time the transfer was at its peak in 2008, the energy use was over three times that of the pre-drought level. As the drought came to an end in 2010, the energy use reduced back to a lower level for around two years, before a newly-built seawater desalination plant operated for around two years.

The time-series of energy use in the sewage systems were relatively stable in both cities, in contrast to the energy use in the water supply systems. The drought and the significant urban water demand reduction seem to have little impact on the sewage systems in term of their energy use. The only significant change in the energy use was in Melbourne from 2012 to 2014 when one of their major wastewater treatment plant (i.e., Eastern Treatment Plant) was upgraded to raise the treatment standard both for improving discharge quality and providing non-potable water recycling (Melbourne Water, 2014b).

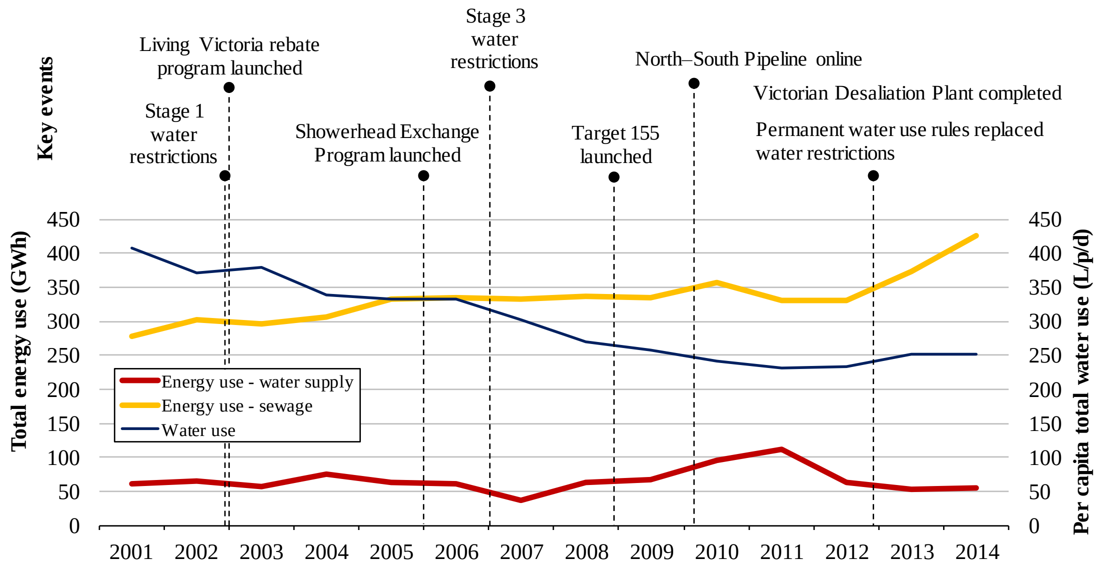

Figure 15 Per capita total urban water use and total energy use of urban water supply system and sewage system in Melbourne from 2001 to 2014 with key events

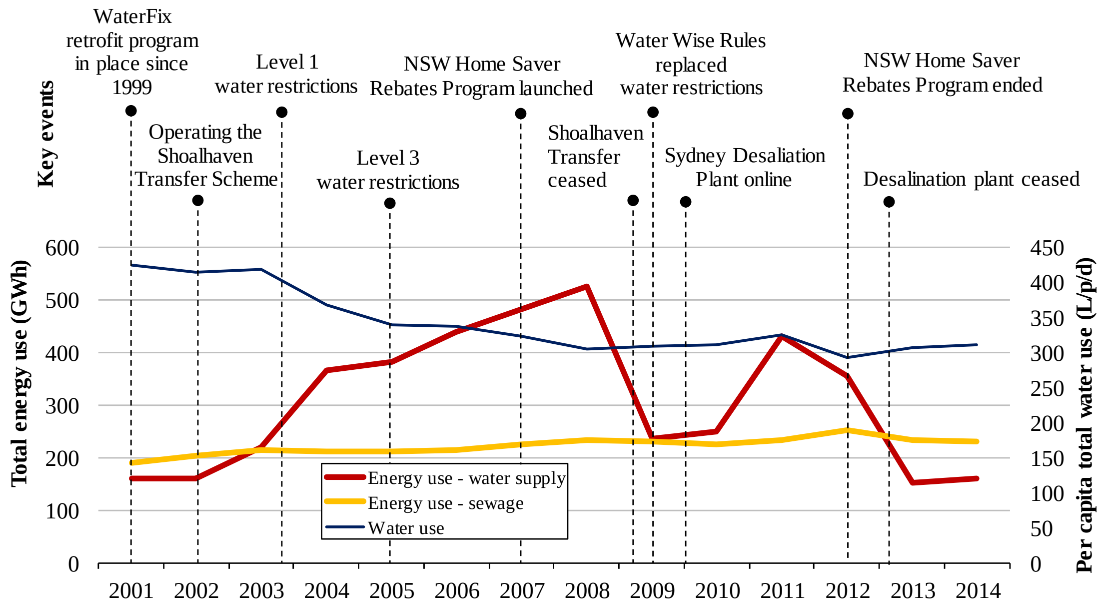

Figure 16 Per capita total urban water use and total energy use of urban water supply system and sewage system in Sydney from 2001 to 2014 with key events

5.4.2. *Energy implications of adopted strategies on the centralised water systems*

In term of the energy implications of the supply-side strategies in Melbourne, the two new supply-side options (i.e. the North-South Pipeline, the Victorian Desalination Plant) only came online after the drought ended, and operated for a short period of time. Data are not available for quantifying their energy implications.

In Sydney, the Shoalhaven Drought Transfer consumed 1616 GWh of electricity in total between 2003 and 2009 (Sydney Catchment Authority, 2006; 2010) to provide approximately 30% of the supply to Sydney through the drought (Metropolitan Water Directorate, 2014). To put it in perspective, this total energy use was ten times the annual energy use of the water supply system in the normal year (i.e., 161 GWh in 2014). Another key supply-side strategy was the construction and operation of the Sydney Desalination Plant, it used 535 GWh electricity between 2010 and 2012 at an average energy intensity of 3.38 kWh/kL (Bureau of Meteorology, 2015b; Sydney Water Corporation, 2012c).

In term of the energy implications of the demand-side strategies, it is estimated in this study that from 2001 to 2014, 404 GWh and 1212 GWh of electricity were saved in the water supply systems in Melbourne and Sydney respectively as a result of urban water demand reduction. While the water use reduction can be a result of both active conservation (e.g., imposing water restrictions, promoting water end use efficiency, increasing the use of decentralising sources, managing leakage) and passive conservation (i.e., water use reduction without demand-side strategies), the significant water demand reduction has been mostly attributed to the change in water use behaviour and the increased use of water efficient devices (Grant et al., 2013; Turner et al., 2016). This energy saving can help offset the extra energy use by the supply-side strategies during the drought. This offset has also been observed in the South East Queensland region which experienced the same drought (Lam *et al.*, 2016).

The energy impacts of the drought and the implemented strategies on the sewage systems in both cities were less distinct as the energy use was concurrently influenced by other factors such as upgrading treatment processes. The amount of sewage collected generally reduced as a result of a reduction in water demand. However, because of stormwater infiltration, the amount of sewage collected increased for those years with more urban rainfall.

5.4.3. *Quantification of the energy impacts in the residential water end use in Melbourne*

The residential water-related energy use before and after the drought were estimated to be 1272 kWh_{th}/p/a and 692 kWh_{th}/p/a respectively (46% reduction). This energy use only includes the hot water energy use for taking showers and using clothes washers, which are the top two household water-related energy use activities. The significant reduction can be mainly attributed to the increased uptake of water-efficient showerheads and water efficiency improvement in clothes washers. In the Victorian state, where Melbourne situated, the percentage of household with water efficient shower head increased from 31.7% (2001) to 71.4% (2013) (Australian Bureau of Statistics, 2004; 2013). Comparing the residential water end use studies in 2004 and 2012 also found that there was a slight reduction in the average shower time and shower frequency, which also contributed to a reduction in per capita hot water use. For the use of clothes washer, there was an increased percentage of households using cold water over warm/hot water between 2003 and 2012 (Athuraliya et al., 2008; Smart Water Fund, 2013). Energy statistics for the state of Victoria show a reduction of per capita primary energy consumption (including conversion loss) by nearly 15% in the residential sector between 2001 and 2014 (Department of Industry and Science, 2015a). This can be attributed to factors such as improving household energy efficiency, change in hot water systems and the reduction in hot water use as quantified in this study.

5.4.4. Implications for managing water-related energy use in urban water cycles

Through the drought between 2001 and 2009, the water-related energy use in the water supply system, sewage system and residential water end use in Melbourne have changed by different extents. The results are expressed in per capita primary energy equivalent use ($kWh_{th}/p/a$) for comparison (Figure 17).

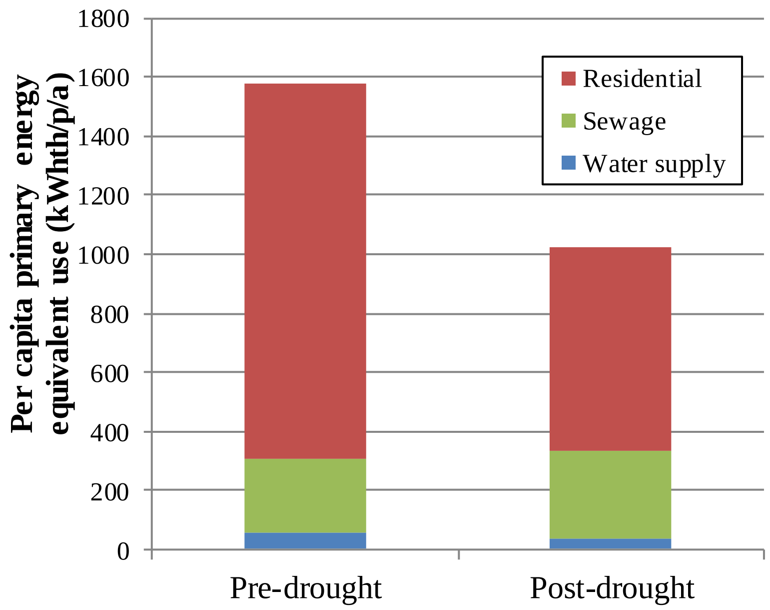

Figure 17 Per capita primary energy use of urban water supply system, sewage system and residential water end use in Melbourne before and after the drought

The change in the per capita water-related energy use in the residential water use was far more substantial than that of water supply system and sewage system. Comparing the pre-drought and the post-drought per capita residential water-related energy use can see a significant reduction of 46% (580 $kWh_{th}/p/a$). For the water supply system, per capita energy use reduced by 32% (18 $kWh_{th}/p/a$) between 2001 and 2014. For the sewage system, even though the per capita volume of sewage collected has reduced through the drought, the per capita energy use has increased as a result of raising treatment standard as discussed in the earlier section.

Because of the significant difference in the magnitude of water-related energy use between the residential side and water supply system (i.e., as shown in Figure 17 and literature (Kenway *et al.*, 2011a)), demand-side strategies that have strong influence on hot water use can provide far more significant energy saving, especially in the residential sector, to offset the additional energy use for operating energy-intensive supply-side strategies (on top of the supply system energy saving benefit as quantified in the earlier section). This demonstrates the need of balancing supply-side and demand-side strategies in managing long-term water security and water-related energy use.

To put the estimated water-related energy use in perspective (including only urban water supply, urban wastewater treatment and a part of the residential water-related energy use), it is approximately 2% of per capita total primary energy consumption in the state of Victoria (Department of Industry and Science, 2015a).

5.5. Conclusions

This work provides a rare time-based analysis of water-related energy use of two major cities through a severe drought. It shows how water-related energy use can change so rapidly within a decade timeframe. The historical case demonstrates the significant energy impacts of some supply-side strategies (e.g., inter-basin water transfers, seawater desalination) and large-scale adoption of water conservation strategies (e.g., water restrictions, conservation campaigns and rebates, leakage management). The energy impacts experienced by the water supply systems, sewage systems and residential water end use different considerably both in magnitude and temporal sense. Operating infrastructure for relieving water shortage resulted in nearly 50% and over 200% increases in the per capita energy use in the water supply systems in Melbourne and Sydney respectively during the dry years. In contrast, water demand reduction (mostly as a result of the drought and implemented water conservation strategies) offered significant long-term energy saving in both the water supply systems and the residential water end use. This reflects the importance of considering the balance of supply-side and demand-side strategies in managing long-term water security and water-related energy use.

6. Life-cycle energy impacts for adapting an urban water supply system to droughts

This chapter is the last of the three papers that address the second objective of this thesis – to quantify and understand the energy impacts of droughts on urban water systems. It builds on the understanding of the urban water supply system in SEQ (Chapter 4) to explore specifically the life-cycle energy impacts of four alternative water supply strategies introduced in SEQ during the Millennium Drought.

Lam, K.L., Stokes-Draut, J.R., Horvath, A., Lane, J.L., Kenway, S.J., Lant, P.A. (To be submitted) Life-cycle energy impacts for adapting an urban water supply system to droughts.

Abstract

In recent years, cities in some water stressed regions have explored alternative water sources such as seawater desalination and potable water recycling. There are concerns over increasing energy consumption for urban water systems. In this study, we evaluated the current and future life-cycle energy impacts of four alternative water supply strategies introduced during a decade-long drought in South East Queensland (SEQ), Australia. These strategies were: seawater desalination, indirect potable water recycling, network integration, and rainwater tanks. Our work highlights the energy burden of alternative water supply strategies which added approximately 25% life-cycle energy use to the existing supply system in SEQ even for a post-drought low utilisation scenario. This research provides insights for developing more realistic scenarios to evaluate and compare life-cycle energy impacts of drought-adaptation infrastructure and regional decentralised water sources. Long-term scenarios should consider i) climate variability (and therefore infrastructure utilisation rate), ii) potential under-utilisation for both installed centralised and decentralised sources, and iii) the potential energy penalty for operating infrastructure well below its design capacity. This study also demonstrated that managing long-term water demand is as important as acknowledging the energy-intensive nature of some alternative water sources. In SEQ, a 20% increase in per capita water use "consumes" more energy than all the four alternative strategies. In addition, a long-term low utilisation of the desalination system and the water recycling system has greatly reduced their actual energy burden (reducing from adding 87% life-cycle energy use to existing centralised system in a higher utilisation scenario to 13% in a lower utilisation scenario). It illustrates that evaluating the energy implications of these type of supply sources without considering their realistic long-term operating scenario can potentially distort their energy implications and misplace the focus of water-related energy management.

6.1. Introduction

Recent years have seen regions such as southeast Australia (Van Dijk *et al.*, 2013) and southwest United States (Prein *et al.*, 2016) face serious water stress. Some of the cities in these regions explored and introduced alternative water sources to cope with their water crises *(Aghakouchak et al.*, 2014). These water sources include seawater desalination, potable water recycling, inter-basin water transfers, and decentralised water sources. Most of them are more energy-intensive than conventional water sources (Rothausen and Conway, 2011; Wakeel et al., 2016), and have significantly increased the long-term energy footprint of some water supply systems (Lam *et al.*, 2016; Li *et al.*, 2016).

An example of these water-stressed regions is South East Queensland (SEQ) in Australia, which encountered a decade-long drought, known as the Millennium Drought (Van Dijk *et al.*, 2013). The drought was most profound between 2001 and 2009 with the average annual inflow to the major dams that was less than 20% of the long-term average (Water Services Association of Australia, 2013). A wide range of supply-side and demand-side responses were used to cope with the drought (Head, 2014). On the supply-side, there were noticeably four major alternative supply strategies – i) building a seawater desalination plant, ii) building an indirect potable water recycling system, iii) integrating systems with bulk water transfer pipelines, and iv) promoting a large scale uptake of residential rainwater tanks.

Prior research in SEQ has examined the energy impacts of some of these supply-side changes. Poussade *et al.* (2011) quantified the life-cycle energy impact of some parts of the newly commissioned desalination system and indirect potable water recycling system. Hall *et al.* (2011) performed a future scenario analysis based on a water strategy set out during the drought. Lane *et al.* (2015) conducted a detailed life-cycle assessment of a subset of the SEQ urban water system. These studies were based on empirical data and information available during the drought. More recently, Kenway (2015) conducted a systemic analysis of water-related energy use in SEQ and Lam *et al.* (2016) quantified the direct energy use of the SEQ's water supply system through and after the drought. Building on these earlier efforts, this paper aims to address two gaps in literature concerning life-cycle energy implications of alternative water sources based on the post-drought SEQ context and new empirical data.

Firstly, previous studies mostly defined and compared scenarios based on high utilisation of specific alternative water sources (Lundie *et al.*, 2004; Mo *et al.*, 2014; Shrestha *et al.*, 2011). They often did not account for possible influence of climate/water variability over an assessment period on long-term operation scenarios. While an "upper bound" scenario can capture the maximum impact of using a specific alternative water source, some more realistic scenarios (which are often missing) should also be evaluated to understand the more likely long-term energy impacts on urban water systems. For instance, most new desalination plants in Spain were idle as of 2012 (March *et al.*, 2014) and only two out of the six desalination plants built in Australia during or shortly after the drought were still in high utilisation as of 2016 (Turner *et al.*, 2016). Drawing on some of these past experiences can potentially offer insights on developing more-likely scenarios for evaluating the long-term energy impacts of introducing new water supply infrastructure.

Further, limited research has been conducted on regional life-cycle energy impacts of a large-scale uptake of rainwater tanks. Previous studies focused predominantly on evaluating single rainwater harvesting systems (Cook *et al.*, 2013; Devkota *et al.*, 2013; Racoviceanu and Karney, 2010). It is not known how these individual results would scale in a regional evaluation. In addition, few studies compare the regional life-cycle energy use of decentralised systems (i.e., typically rainwater harvesting in SEQ) with that of the centralised systems. It is important to understand how much they can contribute to the overall energy use of urban water supply systems. Decentralised systems have gained popularity in recent years and a number of empirical studies have found that rainwater harvesting systems are more energy intensive than conventional centralised water supply systems (Vieira *et al.*, 2014a). The rapid implementation of rainwater harvesting in SEQ provides a wealth of empirical data to explore these two aspects.

This work presents a life-cycle energy assessment of the urban water supply system in SEQ. The goal is to assess the relative life-cycle energy impacts of the four alternative water supply strategies introduced during the Drought. Current post-drought and future energy impacts of the strategies under various utilisation and water demand scenarios are quantified. This study provides insight for i) developing more realistic scenarios to evaluate the life-cycle energy impacts of drought-adaptation infrastructure and regional decentralised water sources, and ii) informing policy priorities for energy management in urban water systems. The discussion focusing on the experience in SEQ is highly relevant to other water-stressed regions where they may be exploring future alternative water supply strategies to cope with supply constraints (e.g., drought) or increasing water demand.

6.2. Case study background

South East Queensland (SEQ), where the Queensland state capital Brisbane is situated, is an urbanised region on the eastern coast of Australia. It has more than 60% of the state's population. Its traditional water source is surface water from major dams such as Wivenhoe Dam, North Pine Dam and Hinze Dam. Its water supply system was designed to have a high carry-over capacity (i.e., the total storage capacity was estimated to be over six times the annual urban water demand (Marsden and Pickering, 2006)). Between 2001 and 2009, the region experienced its longest recorded continuous period with below average rainfall (more than 80% lower than the long-term average). The unprecedented low catchment inflows led to a water crisis. Four water-supply strategies were introduced to the regional water supply systems to augment the supply (Turner *et al.*, 2016).

Firstly, three bi-directional bulk water transfer pipelines were built to connect previously segregated water supply systems. They are the Southern Regional Water Pipeline that connects the Greater Brisbane system to the Gold Coast system; the Northern Pipeline Interconnector that connects the Greater Brisbane system to the Sunshine Coast system; and the Eastern Pipeline Interconnector that connects the Brisbane-Logan system to the Redland system. Forming a bulk water supply network increased the system flexibility and was estimated to increase the overall regional system yield by 14% compared to without network integration (Queensland Water Commission, 2010).

Secondly, a 125 ML/day capacity reverse osmosis seawater desalination plant (the Gold Coast Desalination Plant) was built. The system also includes a 25 km product water pipeline. The produced potable water is fed into the Gold Coast system and can be transferred to the other parts of the SEQ system through the newly-built Southern Regional Water Pipeline. As of 2010, the desalination system increased the system yield by approximately 9% (Queensland Water Commission, 2010).

Thirdly, a 232 ML/day capacity indirect potable water recycling system (the Western Corridor Recycled Water Scheme) was built. The system includes three advanced water treatment plants and over 200 km of bulk water pipelines. The system is linked to two major power plants in the region. It also has an option to feed the highly-treated potable recycled water into Wivenhoe Dam (the major dam in SEQ). However, due to easing of the drought and political pressure, the indirect potable water use option was not implemented. In 2010, the water recycling system increased the system yield by approximately 16% (Queensland Water Commission, 2010).

Lastly, over 250,000 new rainwater tanks were installed between 2006 and 2008 through the Home WaterWise Rebate Scheme (Walton and Holmes, 2009). The tanks were required to be 3,000 L or greater in size to fulfil the rebate requirement. In addition, the Queensland Development Code Mandatory Part 4.2, introduced in 2007 and enforced until late-2012, requires any new development to have higher water efficiency (Siems and Sahin, 2016). One way to meet the requirement is to install an internally-plumbed rainwater tank of at least 5,000 L capacity. As a result of both measures, the percentage of households considered suitable for installation that own a rainwater tank increased from 18.4% (2007) to 47% (2013) in Brisbane (Australian Bureau of Statistics, 2013).

The Drought ended with a return of more normal rainfall patterns in 2009. Between 2010 and 2011, reservoir elevations returned to the pre-drought levels, and both the desalination system and the recycled water system were placed in “standby” mode. As of 2014, the desalination plant was in its minimum operation mode, while the potable water recycling system was expected to remain idle for the next decade (Seqwater, 2013b).

6.3. Methods

6.3.1. Scope of study

This study conducted a life-cycle energy assessment on the urban water supply system in SEQ with a focus on the four alternative supply strategies introduced during the Millennium Drought. The study is divided into two parts. In the first part, the current post-drought life-cycle energy use of the system was quantified based on the operation status of the system in the 2013-14 fiscal year (referred as 2014 throughout). That year was chosen for study because the actual water balance and operation data are available, and the water demand is representative of the post-drought volume. In the second part, future scenario modelling was utilised to quantify the potential long-term average life-cycle energy use of the system between 2014 and 2033 under three different scenarios. The future water balances under different scenarios were simulated from a utility's water balance model (Section 6.3.3). The regional water yield from rainwater tanks was estimated from a local rainwater tank model and water use surveys (Section 6.3.2). The water balances form the basis for the energy assessment (Table 9).

Table 9 Summary data for water balances

Component	**Year [a]**	**Volume (ML/year)**			**Source**
		"Normal" scenario	**"Dry" scenario**	**"High water demand" scenario**	
Urban water demand from water mains	2014	295,877	295,877	295,877	(Bureau of Meteorology, 2016)
	2023	364,000	332,000	437,000	DSSO model (Section 6.3.3)
	2033	422,000	385,000	506,000	DSSO model (Section 6.3.3)
Desalinated water	2014	1,435	1,435	1,435	(Bureau of Meteorology, 2016)
	2014-2033	1,400	28,400	7,600	DSSO model (Section 6.3.3)
Potable recycled water	2014	1,282	1,282	1,282	(Bureau of Meteorology, 2016)
	2014-2033	1,300	41,300	5,200	DSSO model (Section 6.3.3)
Bulk water transfer (through NPI, EPI and SRWP)	2014	22,053	22,053	22,053	Operation data from utility
	2014-2033	21,700	18,800	25,000	DSSO model (Section 6.3.3)
New rainwater tanks	2014	6,700	6,700	6,700	See Section 6.3.2
	2014-2033	6,700	3,100	6,700	See Section 6.3.2

[a] The water balance of 2014 was used to represent the current status. The volumetric throughput shown for 2014-2033 is the annual average over the period.

This life-cycle energy assessment of the SEQ water supply system considers the direct and indirect energy use in the construction phase and the operation phase of five system components - the conventional system and the four alternative water supply strategies. The conventional system can be referred to as the "baseline" system without the four alternative supply strategies. It includes water treatment plants and water distribution networks. Table 10 gives an overview of the key components included in the inventory and the data sources. Detailed inventories can be found in the Appendix A3.

For the construction phase, the infrastructure specifications of the three centralised system strategies were based mostly on utility, government and material supplier documents which are listed in the Supplementary Material. Data gaps were filled using previously published literature (Lane *et al.*, 2015). For the operation phase, data were obtained directly from the infrastructure operators or from local studies based on data from operators. Data for second-order inventories (e.g., electricity supply, material supply, material transportation) were based predominantly on the Australasian LCI database (lifecycles, 2015) which adapted Ecoinvent data (Hischier and Weidema, 2010) to the Australian context, unless noted in Table 2. The regional estimation of the current rainwater tank usage in SEQ was based on a national water survey (Australian Bureau of Statistics, 2013) and a detailed rainwater study in SEQ (Siems and Sahin, 2016). The estimation is detailed in the Appendix A3.

Table 10 Key inventory included and data sources

Component	**Construction phase** [a]	**Operation phase** [a]
Conventional system	Water supply network [d]; Water treatment plants (SEQ capacity) [e]	Electricity use for raw water abstraction and water treatment [f]; Water distribution (Lam *et al.*, 2016); Chemicals use [f]
Bulk water transfers [b]	Three bulk water transfer pipeline systems [e]	Electricity use [f]
Seawater desalination system [b]	Desalination plant [e]; Product water pipeline [e];	Electricity use [f]; Chemicals use (Lane *et al.*, 2015);
Water recycling system [b]	Three advanced wastewater treatment plants [e]; Feed water pipelines [e]; Product water pipelines [e]	Electricity use (Poussade *et al.*, 2011); Chemicals use (Lane *et al.*, 2015);
Rainwater tanks [c]	New tanks; Small pumps; Plumbing adjustment	Electricity use (Siems and Sahin, 2016); Tank water usage (Siems and Sahin, 2016); Percentage of tanks in use (Australian Bureau of Statistics, 2013); Percentage of internally plumbed tanks (Australian Bureau of Statistics, 2013)

[a] Assumed 100 km distance for all material transportation, unless specific data are available. Energy use estimated from Australasian LCI database (lifecycles, 2015). See Appendix A3.

[b] Considered excavation work. Energy use estimated from Stokes and Horvath (2010). See Appendix A3.

[c] The regional estimation of new rainwater tanks installation and operation status is based on several key references (Australian Bureau of Statistics, 2013; Moglia *et al.*, 2014; Siems and Sahin, 2016; Walton and Holmes, 2009). The detailed description of the estimation can be found in Appendix A3.

[d] Based on the length of water mains in SEQ in 2013-14. Energy use scaled from the Gold Coast system (Lane *et al.*, 2015). See Appendix A3.

[e] Specifications from utility, government and/or material supplier documents. See Appendix A3.

[f] Measured operations data provided by the infrastructure operators.

6.3.2. Rainwater tanks

This study quantified the number of new rainwater tanks being installed in SEQ in response to two government strategies introduced during the drought – Home WaterWise Rebate Scheme and Queensland Development Code Mandatory Part 4.2. The total number of new tanks (at least 3,000 L) that were rebated through the Scheme between July 2006 and December 2008 was 257,094 (only 17,025 of them were reported to be internally plumbed) (Walton and Holmes, 2009). The number of new rainwater tanks (at least 5,000 L) installed in response to the Queensland Development Code

Mandatory Part 4.2 (in effect 2007 until late 2012) was estimated to be 37,800. The estimation was obtained by scaling the increase in the number of tanks between 2010 and 2013 in Brisbane to that of South East Queensland based on their population ratio (Australian Bureau of Statistics, 2013). For all the new rainwater tanks (294,894), it is assumed that the percentage of these tanks plumbed into dwellings was 31.7% (the figure for Brisbane in 2013 (Australian Bureau of Statistics, 2013)). Among these new rainwater tanks, it can be estimated that approximately 77% of them were still in use as of 2013 (i.e., percentage of household with rainwater tank in Brisbane: 40.2%; percentage of household using rainwater tank as a source of water in Brisbane: 31.0%) (Australian Bureau of Statistics, 2013).

6.3.3. Scenario modelling

We utilised a cost optimisation model, namely the Decision Support System Optimiser (DSSO), to simulate long-term water balances of SEQ between 2014 and 2033 under different scenarios. The DSSO model is owned and used by Seqwater (the bulk water agency in SEQ) for long-term water security planning. The model operates through cost optimisation of the supply and demand configurations of the water supply system. It has been described and used in a previous study to quantify the historical time-series direct energy use of the SEQ water supply system (Lam *et al.*, 2016). A similar bottom-up approach was used in this current study for future life-cycle energy quantification. It involves coupling the generated water balance (a monthly water balance of SEQ from 2014 to 2033) with the life-cycle energy intensities of key system components including 12 major water treatment plants, key water transfer and distribution pipelines to 40 demand zones, the three bulk water transfer pipelines, the seawater desalination plant and the potable recycled water system. Rainwater tanks are not included in the DSSO model and were modelled separately.

We evaluated the life-cycle energy impacts of three different scenarios, defined as “Normal”, “Dry” and “High water demand”, over a 20 year period.

- The “Normal” scenario continues the low utilisation status of the desalination system and the water recycling system observed in 2014. It includes both normal and dry hydrological periods over the study period. It is also based on the most likely demand scenario forecasted by the water utility (Seqwater, 2014b). The demand forecast considers population growth, commercial and industrial usage, water leakage, regional variation, seasonal variation and a long-term urban water demand of 285 litre per person per day (Seqwater, 2014b).
- The “Dry” scenario assumes an unlikely extended period of dry conditions (i.e., worse than the Millennium Drought) with all the catchments receiving just 25% of the inflows in the “Normal” scenario. Based on the DSSO model simulation, the seawater desalination system and the potable water recycling system would have to operate on average at 62% and 49% of their design capacities, respectively. The unsatisfied water demand from rainwater tanks is assumed to be double the value presented in a SEQ study that modelled the average annual yield of rainwater tank over 20 years with both dry and wet periods (Siems and Sahin,

2016). Urban water demand is assumed to reduce to 260 litres per person per day (the Millennium Drought's level) as a result of outdoor water restrictions and water conservation campaigns.

- The "High water demand" scenario is similar to the "Normal scenario", but with a 20% higher urban water demand. This scenario aims to compare the long-term energy impacts of increased water demand with that of the four alternative water strategies.

6.4. Results & discussion

6.4.1. Current life-cycle energy impact of alternative supply strategies

Adapting the urban water supply system in SEQ to the Millennium Drought with four alternative supply strategies increased its life-cycle energy use by approximately 25% (Figure 18). Nearly half of this increased energy use was contributed by the rainwater tanks. To the local water utilities, the three alternative supply strategies in the centralised system has increased the total direct operational energy use by approximately 16%. The results were based on the post-drought, low-utilisation operation status of the system in 2014. This operation status is a likely scenario for the SEQ system for the coming decade because of a relatively high expected water security (Seqwater, 2015).

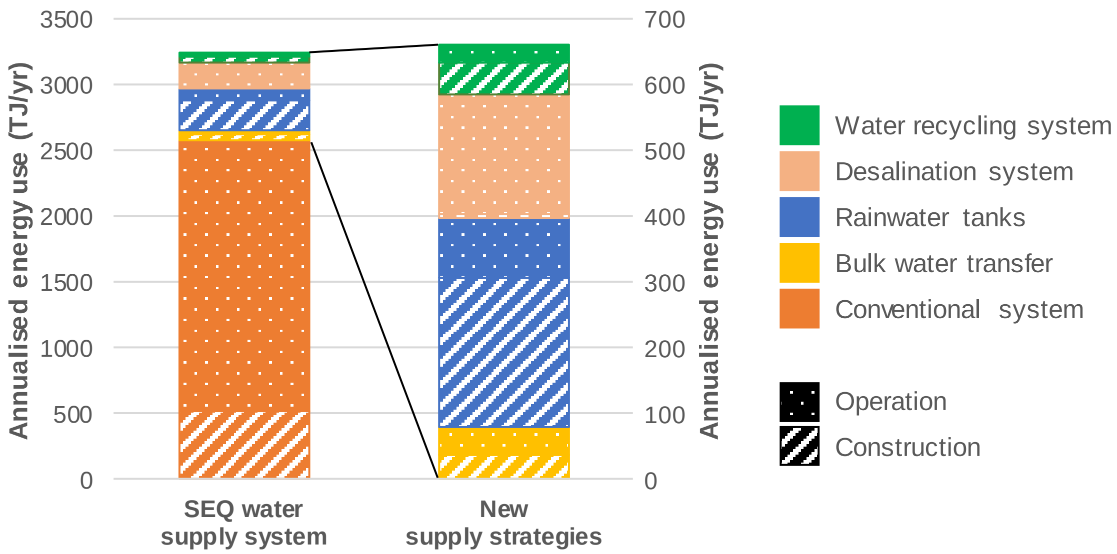

Figure 18 Breakdown of annualised life-cycle energy use of SEQ water supply system in 2014 with low utilisation of new supply infrastructure

With low utilisation of new infrastructure in 2014, the construction phase of the four supply strategies constituted nearly half of the additional life-cycle energy use. It was contributed mostly from the manufacturing of bulk water pipelines and rainwater tanks. The bulk water pipelines involved nearly 400 km of mild steel cement lined pipeline (mostly larger than 1,000mm in diameter). The more than 290,000 new rainwater tanks in the region are typically fabricated from polyethylene and have capacities predominantly between 3,000-5,000L.

In 2014, the direct energy use of the SEQ water supply system was 1,880 TJ/yr, while the embodied energy use was 1,358 TJ/yr. The two climate-independent sources – seawater desalination system and potable water recycling system – collectively provided approximately 1% of the total water supply in 2014. Rainwater tanks only contributed an estimated 2% of regional water supply, but added over 10% to the life-cycle energy use of the existing system.

The results also highlight that the energy use for the operation of seawater desalination system is high even under a minimum operating condition (less than 3% of its design capacity). The empirical operation data shows that the desalination system would have a higher energy efficiency (i.e., lower energy intensity, MJ/m^3) when operating with a higher throughput. This dynamic will be discussed further in the next section on scenario modelling.

Bulk water transfer pipelines have a relatively minor influence on the overall energy use of the whole system, even though they were utilised much more (in a design capacity sense) than the desalination system and the water recycling system. These pipelines are much less energy-intensive (MJ/m^3), particularly because some of the pipelines are gravity-fed.

6.4.2. Future life-cycle energy impact and the significance of scenario selection

The SEQ case study illustrates that the choice of long-term operation scenario has a significant impact on evaluating the life-cycle energy use of any alternative supply strategy and affects the prioritisation of new supply sources based on their energy consumption or energy intensity (which can subsequently influence GHG emissions or other environmental factors). Figure 19 presents a comparison of the average annualised life-cycle energy use of the SEQ water supply system over a 20-year period (between 2014 and 2033) for three different future scenarios. In addition to the water supply sources shown in Figure 18, the scenario analysis results (Figure 19) include the "Conventional system (demand growth between 2014 and 2033)" which is the additional future life-cycle energy use (i.e. including treatment, pumping, chemicals, expanded distribution network) to meet the increased demand with conventional surface water sources. "Conventional system (baseline demand in 2014)" is the baseline life-cycle energy use for the conventional section of the water supply system.

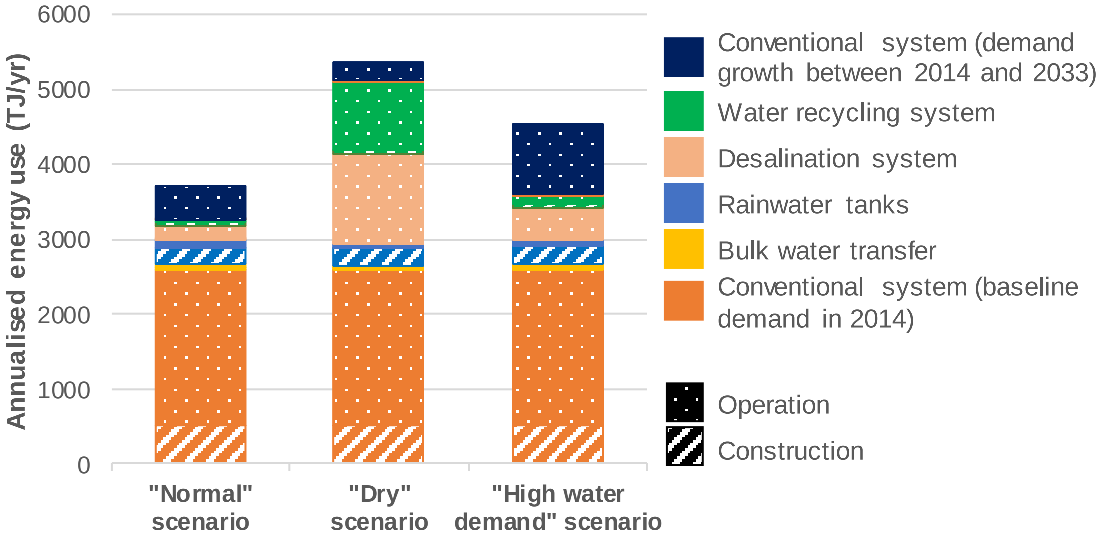

Figure 19 Breakdown of average annualised life-cycle energy use of SEQ water supply system between 2014 and 2033 under different scenarios

The scenario analysis shows that when the two energy-intensive new infrastructure are in high utilisation in the “Dry” scenario, the annualised energy use of the overall water supply system would be 44% more than that of the most likely “Normal” scenario. This additional energy consumption is mostly from the increased direct electricity use by desalination and water recycling processes. The annualised energy use in the “High water demand” scenario is between that of the “Normal” scenario and the “Dry” scenario. The modelled results in the high demand scenario also indicate the need of increasing production from the desalination system in some of the dry years to meet the increased demand. In the latest water strategy (Seqwater, 2015), the desalination system is given a higher priority for operation than the water recycling system.

A “Dry” scenario with high utilisation of the new supply infrastructure would almost double the life-cycle energy use compared to the conventional supply system. By contrast, alternative new supplies add less than 25% in the “Normal” scenario. Under the “Dry” scenario, the desalination system and the potable water recycling system supply 21% of total urban water demand. This type of high utilisation scenario is a “common” scenario in the literature. It clearly demonstrates the energy burden of operating some of these alternative water sources.

In a longer term, the life-cycle energy impact from future increased water demand (i.e., in the “Normal” scenario) would indeed be as significant as that of the four alternative supply strategies introduced in the Millennium Drought. In the case of “High water demand” scenario, this energy use associated with increased water demand (on a per capita water use basis, increased by 20%) would even contribute more to the total life-cycle energy use of the system than that of the alternative sources. It clearly illustrates the important role of water conservation on long-term water-related energy management. It should be recognised as important as the “energy-intensive” labels we often put on some of the alternative water sources.

The scenario analysis results can be presented in term of energy intensity (MJ/m^3) (Figure 20). Energy consumption per unit volume of water supplied is a functional unit commonly used by life-cycle energy assessment of urban water systems (Loubet *et al.*, 2014). For each water supply type, its life-cycle energy intensities for construction phase and operation phase are shown.

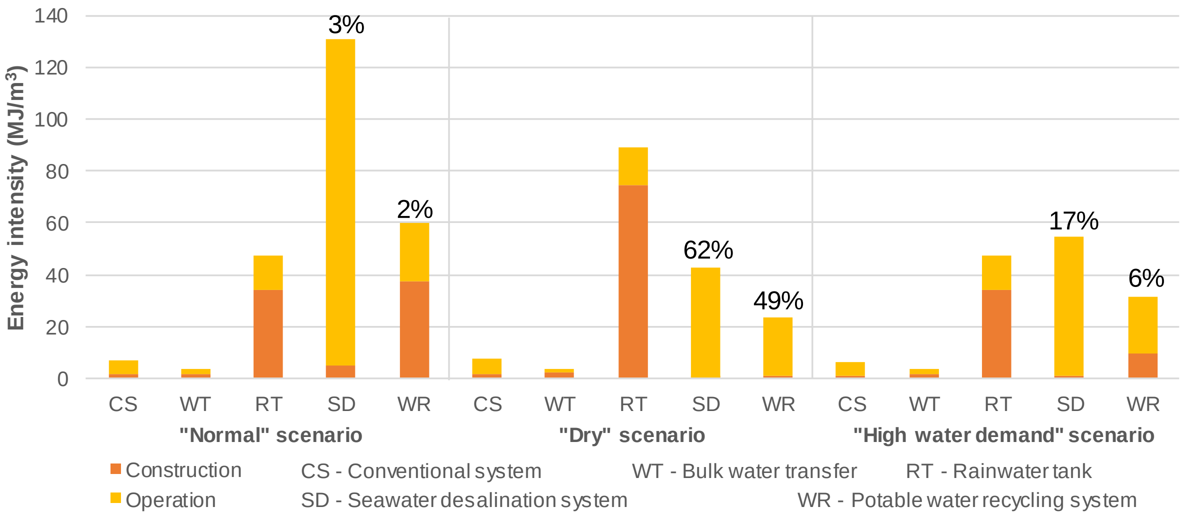

Figure 20 Energy intensity of SEQ mains water supply and the four water strategies under different scenarios. The percentage indicates the proportion of source's design capacity that is utilised in the scenario.

The results show that the life-cycle energy intensities of the four alternative water strategies strongly depend on operational conditions over their design lifespan. One major factor is how the embodied energy use in the construction phase is allocated over the lifespan on a per unit volume basis. In addition, the seawater desalination system is far more energy efficient on a per unit volume basis when it operates at a high output (i.e., comparing SD in "Normal" scenario (131 MJ/m^3 for 3% of design capacity) and "Dry" scenario (42 MJ/m^3 for 62% of design capacity)). In the "Dry" scenario, the average annual water yield of rainwater tanks would reduce, causing a relatively high energy intensity attributed to the construction phase. If alternative water sources are compared based on their energy intensity, this case study highlights that defining an appropriate long-term average water supply rate is critical.

6.4.3. The regional implications of rainwater tanks

From an energy intensity perspective, rainwater tanks are far more energy-intensive than the mains water supply in SEQ. On a life-cycle energy intensity basis (MJ/m^3), high regional uptake of rainwater tanks, estimated at 40% of all households in SEQ, would be as energy-intensive as seawater desalination, if a considerable portion of the tanks are under-utilised or their water yield reduces due to droughts (i.e., comparing RT and SD in the "Dry" scenario or the "High water demand" scenario in Figure 20). Under-utilisation of rainwater tanks is expected in normal conditions. A post-drought survey on water use and conservation in Brisbane and Queensland has shown that an estimate of 23% of these tanks in SEQ were no longer in use as of 2013 (Australian Bureau of Statistics, 2013) (i.e., estimated from the percentage of households with rainwater tanks installed and the percentage of households with sources of water from rainwater tanks in 2013).

In addition, a large portion of the new tanks (68%) were not internally-plumbed as of 2013 and, therefore, their usage is limited to outdoor water use. This can undermine their actual water yield for reducing mains water use because a detailed rainwater tank study in SEQ has suggested that 72% of water usage from internally-plumbed water tanks is for indoor water use (Siems and Sahin, 2016). Intuitively, if rainwater tanks can only be used outdoors, they are more likely to support thirsty plants than to offset necessary water use. It can also mean that a large portion of the tanks, which are limited to outdoor water use, may not have an optimised size. This SEQ case shows that whether rainwater tanks are under-utilised and internally-plumbed are important factors and should be included in any regional assessment of this type of alternative water source. Neither factor has been explored in previous single tank studies.

This scenario study was based on the latest available rainwater tanks usage data in 2013 (i.e., 5-7 years after most tanks were installed) to quantify their long-term regional life-cycle energy impact. It does not account for possible further reduction in the utilisation of the tanks (e.g., because of pump problems, usage pattern change). Therefore, the regional life-cycle energy intensity of these tanks can potentially be even higher than modelled in the scenario study. Retrofitting a large portion of the 68% of non-internally-plumbed rainwater tanks for indoor water use may help lower the overall life-cycle energy intensity.

6.4.4. The implications for other water-stressed regions

Centralised alternative water sources such as desalination, potable water recycling and inter-basin water transfers are often labelled as "energy-intensive" (Plappally and Lienhard V, 2012; Wakeel *et al.*, 2016). The SEQ case (along with other emerging cases in Spain (March *et al.*, 2014) and some other Australian cities (Barnett and O'Neill, 2010)) shows that for water-stressed regions with high climate variability, alternative water sources only have higher utilisation in dry years. Evaluating the energy implications of these supply sources without considering their long-term likely operating scenarios can potentially distort their energy implications relative to the whole water supply system and mislead the focus of water-related energy management. In fact, as in the case of SEQ, it may be worth paying more attention to other parts of an urban water system for water-related energy management. For example, low-hanging fruit for energy minimization may come from decentralised sources (as discussed in the previous section), wastewater systems (Lane *et al.*, 2015) or even water end use (with high water-related energy and cost saving potential in Australia found by Lam *et al.* (2017a)).

For other water-stressed regions considering new supply sources, they should carefully assess whether the new supply sources are mostly for drought adaptation (i.e., only operating in dry years) or not. As shown in this SEQ study, the classification would affect how the new supply sources are being evaluated for their long-term life-cycle energy impacts and compared against other strategies. While alternative water sources can diversify the supply portfolio and increase system flexibility during future droughts, it should be noted that a continuous operation of the desalination system under minimum production rate has shown to be highly energy inefficient in SEQ (i.e., three times more energy-intensive on a per unit volume basis than if it is operating at its design capacity).

The SEQ case highlights that, while desalination often dominates the water-related energy story, an unintended negative energy consequence is associated with rainwater tanks. Future energy evaluation of projected large-scale adoption of decentralised sources (e.g., rainwater harvesting, greywater recycling) should take into consideration of embodied energy use and potential under-utilisation scenarios. In the case of plastic rainwater tanks in SEQ, over half of the energy use is indirect. This would give a better quantification of energy (or subsequent GHG emissions or other environmental impacts) when comparing with other alternative water sources. Any scheme for promoting decentralised sources should also be carefully designed to find the optimum design capacities and minimise the issue of under-utilisation.

6.5. Conclusions

Life-cycle energy impacts of alternative water supply strategies were studied in this work. We focused on the current post-drought and future life-cycle energy impacts of four alternative water supply strategies introduced during the Millennium Drought in SEQ. The key insights are as follows.

- Our work highlights the energy burden of alternative water supply strategies compared to existing urban water supply systems. In SEQ, adapting its water supply system to the Millennium Drought with four alternative supply strategies (primarily from seawater desalination and rainwater tanks) has increased its annualised life-cycle energy use (TJ/a) by approximately 25% under post-drought conditions, when two of the centralised strategies were in minimum operation. Rainwater tanks only contributed an estimated 2% to regional water supply, but added over 10% life-cycle energy use to the existing system.
- The life-cycle energy assessment demonstrates the important role of defining appropriate long-term operating scenarios for life-cycle energy assessment of alternative supply strategies. More specifically, strategies used for drought adaptation (only operating in dry years) should be evaluated with consideration of climate variability over a long period. In addition, when evaluating decentralised sources, under-utilisation should be taken into account (e.g., in SEQ in 2013, only 77% of tanks were still in use and 68% of tanks were not internally-plumbed).
- The life-cycle energy-intensity (MJ/m^3) of an alternative supply strategy can differ significantly under various scenarios (depending on the utilisation rate of the strategy). This can have implications for comparing and selecting alternative water supply strategies based on energy

intensity (MJ/m^3), a common functional unit for life cycle energy assessment of urban water systems. For instance, a desalination system has a potential "energy penalty" when it operates at a low output. Based on empirical data, the results show that the SEQ desalination plant at low utilisation (131 MJ/m^3 for 3% capacity) is three times more energy-intensive on a per unit volume basis than if it is operating closer to its design capacity (42 MJ/m^3 for 62% capacity). In addition, regional uptake of rainwater tanks can be more energy-intensive than seawater desalination if a significant portion of the tanks are under-utilised (i.e., not internally-plumbed or reducing usage).

- The life-cycle energy burden for increasing per capita water use can be as significant as introducing alternative water supply strategies. This SEQ case demonstrates that focusing on managing long-term urban water demand is as important as acknowledging the energy-intensive nature of some of the alternative water sources. The scenario analysis shows that a 20% increase in per capita water use (816 TJ/a) would "consume" more energy than the four alternative water supply strategies (655 TJ/a).
- While centralised alternative water sources still have considerable energy impacts, this research demonstrates that long-term low utilisation of some of these sources has greatly reduced their actual energy burden (reducing from adding 87% life-cycle energy use to existing system in a higher utilisation scenario to 13% in a lower utilisation scenario). Evaluating the energy implications of these supply sources without considering their long-term more realistic operating scenario can potentially distort their energy implications relative to the whole water supply system and mislead the focus of water-related energy management. It may be worth placing more policy focus for water-related energy management on other parts of urban water systems such as decentralised sources, wastewater systems or even water end use.

7. City-scale analysis of water-related energy identifies more cost-effective solutions

This chapter is a paper that addresses the third objective of this thesis – to Investigate the least cost solutions for water-related energy management in wider urban water systems. It is based strongly on the Australian context, and the understanding of some of the Australian urban water systems explored in previous chapters.

> **Lam, K.L.**, Kenway, S.J., Lant, P.A. (2017) City-scale analysis of water-related energy identifies more cost-effective solutions, *Water Research* 109, 287–298.

Abstract

Energy and greenhouse gas management in urban water systems typically focus on optimising within the direct system boundary of water utilities that covers the centralised water supply and wastewater treatment systems, despite a greater energy influence by the water end use. This work develops a cost curve of water-related energy management options from a city perspective for a hypothetical Australian city. It is compared with that from the water utility perspective. The curves are based on 18 water-related energy management options that have been implemented or evaluated in Australia. In the studied scenario, the cost-effective energy saving potential from a city perspective (292 GWh/year) is far more significant than that from a utility perspective (65 GWh/year). In some cases, for similar capital cost, if regional water planners invested in end use options instead of utility options, a greater energy saving potential at a greater cost-effectiveness could be achieved in urban water systems. For example, upgrading a wastewater treatment plant for biogas recovery at a capital cost of $27.2 million would save 31 GWh/year with a marginal cost saving of $63/MWh, while solar hot water system rebates at a cost of $28.6 million would save 67 GWh/year with a marginal cost saving of $111/MWh. Options related to hot water use such as water-efficient shower heads, water-efficient clothes washers and solar hot water system rebates are among the most cost-effective city-scale opportunities. This study demonstrates the use of cost curves to compare both utility and end use options in a consistent framework. It also illustrates that focusing solely on managing the energy use within the utility would miss substantial non-utility water-related energy saving opportunities. There is a need to broaden the conventional scope of cost curve analysis to include water-related energy and greenhouse gas at the water end use, and to value their management from a city perspective. This would create opportunities where the same capital investment could achieve far greater energy savings and greenhouse gas emissions abatement.

7.1. Introduction

Energy is used in every stage of the urban water cycle, from water abstraction, treatment, distribution, to end use and wastewater treatment. In recent years, increasing energy consumption for providing water services, rising energy costs and the need for mitigating climate change have been drivers for better management of energy use and associated greenhouse gas (GHG) emissions in urban water systems. In the urban water context, a number of studies have shown that the water-related energy use in the water end use sector (i.e., residential, commercial and industrial) is far more substantial than that of water utilities (Kenway *et al.*, 2015; Plappally and Lienhard V, 2012).

Water utilities or regional water planners typically focus on optimising energy use and GHG emissions in their centralised water supply and wastewater treatment systems (including raw water abstraction and transfer, drinking water production, drinking water distribution, wastewater collection and wastewater treatment), despite a greater energy saving and carbon abatement benefit potentially present in the water end use. For instance, Cherchi *et al.* (2015), Conrad *et al.* (2010) and Frijns *et al.* (2013) showed cases in which cites focus on optimising the energy use of water utilities only. On the other hand, Zhou *et al.* (2013) acknowledged the energy saving potential of water conservation by considering a wider urban water system. Escriva-Bou *et al.* (2015) demonstrated the system-wide benefit of considering residential water-related energy use.

Marginal Abatement Cost Curves (MACC) have been used to support least cost planning for energy and GHG management in various disciplines. The approach illustrates graphically the relative cost-effectiveness and mitigation potential of different measures. Meier *et al.* (1982) is an early work of using the cost curve approach (i.e., called supply cost curves at that time) to populate energy saving options in the residential sector. MacLeod *et al.* (2010) developed MACCs for managing agricultural emissions in the U.K. In recent years, the cost curve approach has been applied in the water industry. Sydney Water Corporation (the water services provider for the Greater Sydney region) has developed a Cost of Carbon Abatement (CCA) tool for managing energy and GHG emissions based on the marginal abatement cost curve approach (WSAA, 2012) and licensed the tool to 19 water utilities across Australia as of 2014 (Sydney Water Corporation, 2014). Stokes *et al.* (2014) constructed a life-cycle carbon abatement cost curve for water utilities to account for pressure and leakage management strategy.

In the water sector, cost curves have been developed from the perspective of the utility, however, to the authors' knowledge, none have been published for a city perspective that considers and values options in both utility and water end use domains. Furthermore, water management options on the supply-side (i.e., within the system boundary of the water utility) and the demand-side (i.e., outside the system boundary of the water utility) are not typically compared on the same basis. The development of a city cost curve for the water sector can provide a platform to compare options across the boundary between water suppliers and water consumers. It can also help overcome the norm that water end use is not included in the agenda for energy and greenhouse gas management in regional water strategy planning (i.e., an issue of sub-system optimisation).

An example of comparing cost curves from different perspectives is the Low Carbon Growth Plan for Australia (ClimateWorks Australia, 2010). It illustrates that the choice of perspective can have a profound impact on the interpretation of the abatement performance of different options. The work quantifies the emissions reduction opportunity and costs for society as a whole and compares with the same opportunity from the perspective of business sectors. It has shown that for a portfolio of carbon management options in Australia, the cost-effective abatement potential (i.e., the GHG emissions reduction from implementing projects with a positive net present value) for the investor cost curves is 24% less than that of the societal cost curves. This is because of a difference in the way investors and society value a project. For instance, investors generally consider a higher discount rate, and have a different energy prices considering account taxes and direct or indirect subsidies.

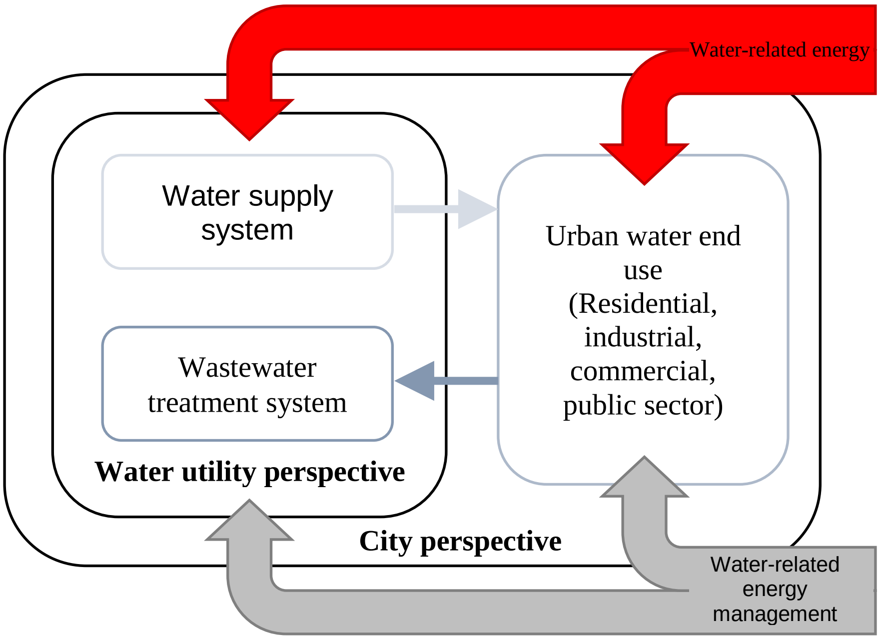

Figure 21 A system diagram showing the water utility perspective and the city perspective

This work aims to develop and compare cost curves for water-related energy from the “water utility” and “city” perspectives (Figure 21), for a hypothetical city based on average Australian data. The water utility perspective refers to the point of view of water managers who consider purchased energy use, and financial performance within their entities. The city perspective considers the purchased energy use and financial performance of making water-related energy management investments in the whole urban water system, including water supply system, water end use, and wastewater treatment system. The curves are based on a list of water-related energy management options that have been implemented and/or analysed for their energy saving potentials and cost-effectiveness in Australia. The developed curves can reflect the difference between optimising the energy use of urban water systems from water utility and city perspectives. The implications of both the water utility and city perspectives for water policies are discussed.

7.2. Material and methods

7.2.1. Overall approach

This work developed cost curves for energy management of urban water systems following four major steps:

Step 1: Identifying options for improved energy management and efficiency in water utilities and water end use

Step 2: Defining scenario for implementation of the options in an urban water system

Step 3: Quantifying the energy saving potential and marginal cost of all the options from both the water utility and city perspectives

Step 4: Presenting the results in the form of cost curves

7.2.2. Identifying the options

The list of options (Table 11) for improved energy management and efficiency of urban water systems was compiled based on a review from academic literature and water utility reports. Most of these options have been studied or implemented, and their water and energy saving benefits have been demonstrated in some Australian cities (i.e., Adelaide, Brisbane, Gold Coast, Melbourne, Sydney). The list of options is not intended to be exhaustive. Instead, it aims to capture a range of options to show how these options are valued differently from the water utility and city perspectives. Ten of the options are utility options that can be applied to the potable water treatment plants, water distribution network and wastewater treatment plants. Eight options relate to water end use. Further details of these options can be found in Table A4-1 in Appendix A4.

Table 11 Options related to water-related energy management

No.	Option	Scope [a]	City/ region implemented or studied	Nominal capital expenditure ($) [b]	Water saving from the mains (ML/yr)	Energy saving at utility (MWh/yr)	Energy saving at end use (MWh/yr)	Purpose	Source
1	Active leak detection and pressure management	DWD	Sydney	9,514,000	30,416	c	0	To reduce the frequency of leaks and the amount of water loss in the water distribution network	(Sydney Water Corporation, 2012b)
2	Scrubber ventilation efficiency	WWT	Sydney	203,464	0	1,044	0	To control the speed of ventilation fan based on the concentration of odour causing agents	(Sydney Water Corporation, 2013)
3	Sewage pumping efficiency	WWT	Sydney	58,500	0	562	0	To slow down the speed of some of the pumps to reduce frictional losses in the rising main	(Sydney Water Corporation, 2013)
4	Minimising the use of DAF	DWT	Sydney	78,700	0	500	0	To shift to the use of clarifier instead of dissolved air flotation (DAF) stage when raw water algae level is low	(Sydney Water Corporation, 2012a)
5	Most open valve aeration strategy	WWT	Sydney	220,000	0	2,000	0	To use control valves to optimise the pressure of aeration systems	(Sydney Water Corporation, 2012a)
6	Inverter speed control pump for bulk water transfer	BWT	Sydney	1,188,000	0	6,219	0	To control pumping by inverter speed control instead of by valves	(Sydney Catchment Authority, 2009)
7	Aeration optimisation	WWT	Melbourne	1,162,000	0	4,468	0	To reduce the continuous aeration for secondary treatment	(Melbourne Water, 2013a)
8	Plant upgrade for biogas recovery and electricity generation	WWT	Adelaide	25,875,000	0	31,450	0	To upgrade the existing wastewater treatment to efficiently utilise all available biogas	(Public Works Committee, 2011)
9	Existing STP reuse and minor recycling	WWT	Sydney	7,670,000	2,160	c	0	To reuse and recycle the effluent from sewage treatment plant (STP)	(Sydney Water Corporation, 2009)
10	Stormwater harvesting	DWS	Sydney	31,181,800	1,000	c	0	To capture and use stormwater at community scale	(Bush, 2015)
11	Water-efficient clothes washer rebate	RWE	South East Queensland	46,968,485	1,465	c	111,740 [d]	To incentivise the uptake of water-efficient clothes washer	(Beal *et al.*, 2012; Walton and Holmes, 2009)
12	Water-efficient shower head rebate	RWE	South East Queensland	868,508	475	c	19,807 [d]	To incentivise the uptake of water-efficient showerhead	(Beal *et al.*, 2012; Walton and Holmes, 2009)
13	Dual flush toilet rebate	RWE	South East Queensland	6,309,339	755	c	0	To incentivise the uptake of dual flush toilet	(Walton and Holmes, 2009)
14	Solar hot water system rebate	RWE	Queensland	25,900,000	0	c	67,067 [d]	To incentivise the uptake of solar hot water system	(2013; Beal *et al.*, 2012)
15	Alarming visual display monitors for shower	RWE	Gold Coast	7,500,000	1,491	c	60,200	To install alarming monitoring devices to induce a reduction in shower water use	(Willis *et al.*, 2010)
16	Plumber visit	RWE	Sydney	20,800,000	3,344	c	108,166 [d]	To have households visited by certified plumbers for offering services such as replacing inefficient showerheads, checking of leaks, and providing advice on water saving	(Turner *et al.*, 2005)
17	Cooling towers upgrade	IWE	Melbourne	4,430,000	220	c	4,400	To fund upgrading of cooling towers at manufacturing plants	(Lovell, 2013)
18	Irrigation and landscape efficiency program	OWE	Sydney	5,600,000	1,090	c	0	To improve water use efficiency for open space irrigation	(NSW Government, 2013)

Figures in the shaded boxes are based on the data sources.

[a] BWT: bulk water transfer, DWD: drinking water distribution network, DWS: decentralised water supply, DWT: drinking water treatment plant, IWE: industrial water end use, OWE: other water end use, RWE: residential water end use, WWT: wastewater treatment plant

[b] The figures were reported by the sources for the corresponding years in which the options were studied or implemented. They were the investment by governments or water agencies for implementing those options.

[c] It is a function of the energy intensity of the water systems and the volume of water saved from the mains.

[d] The energy saving at the end use was estimated based on a study of energy saving (i.e., electricity) from the use of water efficient devices and solar hot water system in Brisbane (Beal *et al.*, 2012).

7.2.3. The urban water system

A hypothetical Australian city was used in this work. The use of a synthesised hypothetical city enabled a more comprehensive list of water-related energy management options to be considered. The city was based on the water situation in four Australian capital cities - Brisbane, Melbourne, Sydney and Perth (collectively accounting for nearly 60% of the Australian population) (Table 12). The hypothetical city's water price, electricity prices, energy intensity for water services and characteristics were taken as the average of the four cities. All monetary terms are in Australian dollars.

The city has a population of nearly 3.4 million (population density of 360 people/km^2) with 70% of the dwellings being separate houses. It obtains water predominantly from dams (79%), supplemented with groundwater (9%), desalinated water (7%) and non-potable recycled water (5%). It has a humid subtropical climate with a mean temperature range of 16.3℃ to 26.5℃. Residential water use, commercial, municipal and industrial water use, and non-revenue water account for 65%, 24% and 11% of the total urban water demand respectively.

Table 12 Parameters used in the analysis pertaining to the hypothetical city

Context	**Average value [1]**	**Remark [2]**
Energy intensity of main water supply (kWh/kL)	0.57	Weighted-average of the energy intensity of centralised water supply systems of the greater capital city areas of Brisbane, Melbourne, Sydney and Perth in 2013-14. Water sources associated with this average energy intensity for water supply are 79% of surface water, 9% of groundwater, 7% of desalinated seawater and 5% of non-potable recycled water.
Energy intensity of wastewater treatment (kWh/kL)	0.83	Weighted-average of the energy intensity of wastewater treatment systems of the greater capital city areas of Brisbane, Melbourne, Sydney and Perth in 2013-14. 52% of the wastewater going through tertiary treatment, 30% for primary treatment and 18% for secondary treatment.
Water consumption charge ($/kL)	2.28	Average tier 1 water consumption charge of Brisbane, Melbourne, Sydney and Perth in 2013-14
Electricity price - Utility ($/MWh) (Industrial retail)	144	Average purchased electricity cost (including both the usage charge and the supply charge) of Yarra Valley Water (Melbourne), Queensland Urban Utility (Brisbane) and Sydney Water Corporation in 2013-14
Electricity price –End use ($/MWh) (Residential retail)	239	Average purchased electricity cost (the flat rate usage charge) of Victoria, Queensland and New South Wales as of 2016
GHG Emission factor of electricity generation (kg CO_2eq/kWh)	1.03	Average GHG emission factor of Victoria, Queensland, New South Wales and Western Australia in 2011-12. Considering the full fuel cycle (scope 2 and scope 3) emissions. Coal is the largest fuel source (61% as of 2013-14) for electricity generation in Australia, followed by natural gas (22%), renewable sources (15%) and oil (2%) (Department of Industry and Science, 2015b).
Annual increase in water price	2%	Similar to the percentage increase in the consumer price index in Australia
Annual increase in electricity price	2%	Similar to the percentage increase in the consumer price index in Australia
Annual increase in energy intensity of water system	1%	Assuming an increasing trend of energy intensity as in major Australian cities in recent years
Emission factor annual change rate	0%	The emission factor of electricity generation in Australia has remained stable in recent years. (Department of the Environment, 2014)
Discount rate	5%	Based on the discount rates used for public utility or societal studies (ClimateWorks Australia, 2010; Stokes *et al.*, 2014)

[1] See Table A4-3 and A4-4 (Appendix A4) for the values of the four Australian cities (Brisbane, Melbourne, Sydney and Perth) and the distribution shapes used

[2] See Table A4-3 for other contextual characteristics of the four cities and the hypothetical city

7.2.4. *Quantifying the energy saving potential and marginal cost of options*

Figure 22 shows the methodology for quantifying the total energy saving potential (GWh) and marginal cost ($/MWh) of an option over the assessment period. The quantification is based on the following general equations with some variations depending on the types of option (i.e., water saving, non-water saving, utility or end use).

For the water utility perspective,

$$EP_{Utility} = \sum_{t=1}^{t_{option}} \left(\left(EI_{WS,t} + EI_{WW,t} \right) \times V_{w,t} + E_{o,t} \right) \tag{1}$$

$$MC_{Utility} = \left(CAPEX_{Utility} - \sum_{t=1}^{t_{option}} \frac{\left(\left(EI_{WS,t} + EI_{WW,t} \right) \times V_{w,t} + E_{o,t} \right) \times EC_t - V_{w,t} \times WC_t}{(1+r)^t} \right) / EP \tag{2}$$

For the city perspective,

$$EP_{City} = \sum_{t=1}^{t_{option}} \left(\left(EI_{WS,t} + EI_{WW,t} + EI_{EU,t} \right) \times V_{w,t} + E_{o,t} \right) \tag{3}$$

$$MC_{City} = \left(CAPEX_{City} - \sum_{t=1}^{t_{option}} \frac{\left(\left(EI_{WS,t} + EI_{WW,t} + EI_{EU,t} \right) \times V_{w,t} + E_{o,t} \right) \times EC_t}{(1+r)^t} \right) / EP \tag{4}$$

where *EP* is the total energy saving potential (GWh), *t* is the year, t_{option} is the lifetime of the option (year), *EI* is the energy intensity of the associated activities in year *t* (MWh/ML) (i.e., water supply, wastewater treatment, hot water use), $V_{w,t}$ is the volume of water saved (ML/year), $E_{o,t}$ is other energy saving independent of water saving (MWh), *MC* is the marginal cost of an individual option ($/MWh), *CAPEX* is the capital expenditure of the option ($), EC_t is the energy cost ($/MWh) and *r* is the discount rate. In general, the energy saving potential of an option (equations 1 and 3) is quantified based on i) its water saving potential (if the option is a water saving one such as leakage prevention), ii) energy intensity for supplying drinking water and treating wastewater, and iii) other energy saving potential that is not water saving-related such as improving pump efficiency. The energy saving potential in the city perspective (equation 3) also includes energy intensity for water use activity such as hot water use. For each option, the marginal cost (equations 2 and 4) is its overall financial performance over its total energy saving throughout the assessment period. Utility perspective (equation 2) only account for the financial impacts (e.g., reducing energy expense, reducing revenue from water sales) experienced within the utility's organisation boundary.

Input parameters of the options include the lifetime, water saving potential, energy saving potential at water utility, unit energy saving potential at water end use and capital expenditure. Most of these parameters were based on the original data sources (Table 11). Several key assumptions were made to quantify the energy saving potential and marginal cost of all options:

1. All monetary terms of the options were adjusted to real terms in 2014 (reference year) based on the Australian Consumer Price Index (ABS, 2015) (Table A4-2 in Appendix A4).

2. All the options are technically feasible and they could achieve the same level of water and energy saving described in the original data sources.
3. A discount rate of 5% was used for all the options, over an assessment period of 20 years.
4. Potential interactions between options, marginal effect of energy use reduction, non-energy cost benefits and ongoing non-energy operating costs were not considered.

Other assumptions for quantifying the energy saving potential and marginal cost of each option are detailed in Table A4-1 in Appendix A4.

7.2.5. Constructing the cost curve

The quantified total energy saving potential (GWh) and marginal cost ($/MWh) for all the options were then used to construct the cost curve. The cost curve ranks the results from the most cost-effective option to the least cost-effective one from left to right based on the net cost per unit energy saved of each option. The height of the bar is the marginal cost of the option ($/MWh). Negative value means both monetary and energy saving (i.e., cost-effective), positive means energy saved in the expense of financial cost (i.e., not cost-effective). The width of the bar is the total amount of energy saved (GWh) over the assessment period, while the area of the bar is the net cost of the option.

Global input parameters

- Discount rate (r)
- Energy intensity – water supply ($EI_{WS,1}$)
- Energy intensity – wastewater treatment ($EI_{WW,1}$)
- Water price (WC_1)
- Electricity price – water utility ($EC_{WU,1}$)
- Electricity price – end use ($EC_{EU,1}$)
- Increase rates ($i_{EI,WS}$, $i_{EI,WW}$, $i_{EC,WU}$, $i_{EC,EU}$, i_{WC})

Input parameters (utility/ end use options)

- Lifetime (t_{option})
- Annual water saving potential (V_w)
- Annual energy saving in the utility ($E_{O,WU}$)
- Unit energy saving in the end use ($EI_{EU,1}$, E_{EU})
- Capital expenditure ($CAPEX_{Utility}$, $CAPEX_{City}$)

Computing the performance of options over the assessment period (T_{max}):

Year		***0***	***1*** ***st year***		**...**	***t*** ***th year***
Capital expenditure		*CAPEX*	-		...	-
Energy intensity – water supply	$EI_{WS,t}$	-	$EI_{WS,1}$		...	$EI_{WS,1} \times (1 + i_{EI,WS})^t$
Energy intensity – wastewater treatment	$EI_{WW,t}$	-	$EI_{WW,1}$		...	$EI_{WW,1} \times (1 + i_{EI,WW})^t$
Energy intensity – end use	EI_{EU}	-	EI_{EU}		...	EI_{EU}
Electricity price – water utility	$EC_{WU,t}$	-	$EC_{WU,1}$		...	$EC_{WU,1} \times (1 + i_{EC,WU})^t$
Electricity price – end use	$EC_{EU,t}$	-	$EC_{EU,1}$		...	$EC_{EU,1} \times (1 + i_{EC,EU})^t$
Water saving	V_w	-	V_w		...	V_w
Water price	WC_t	-	WC_1		...	$WC_1 \times (1 + i_{WC})^t$
Energy saving – water utility	$E_{WU,t}$	-	*Option no.2-8* *Option no.1, 9, 10* *Option no.11-13, 15-17* *Option no.18*	$E_{O,WU}$ $EI_{WS,1} \times V_w$ $(EI_{WS,1} + EI_{WW,1}) \times V_w$ $EI_{WS,1} \times V_w$	...	$E_{O,WU}$ $EI_{WS,t} \times V_w$ $(EI_{WS,t} + EI_{WW,t}) \times V_w$ $EI_{WS,t} \times V_w$
Energy cost saving – water utility	$ECS_{WU,t}$	-	$E_{WU,1} \times EC_{WU,1}$		...	$E_{WU,t} \times EC_{WU,t}$
Energy saving – end use	$E_{EU,t}$	-	*Option no.11, 12, 16* *Option no.14, 15, 17*	$EI_{EU,1} \times V_w$ E_{EU}	...	$EI_{EU,t} \times V_w$ E_{EU}
Energy cost saving – end use	$ECS_{EU,t}$	-	$E_{EU,1} \times EC_{EU,1}$		...	$E_{EU,t} \times EC_{EU,t}$

Quantifying the net cost:

For option no. 11-13, 15-17, $TC_{Utility} = CAPEX_{Utility} - \sum_{t=1}^{T_{max}} \frac{ECS_{WU,t} - (V_{w,t} \times WC_t)}{(1+r)^t}$

For all other options, $TC_{Utility} = CAPEX_{Utility} - \sum_{t=1}^{T_{max}} \frac{ECS_{WU,t}}{(1+r)^t}$

$TC_{City} = CAPEX_{City} - \sum_{t=1}^{T_{max}} \frac{ECS_{WU,t} + ECS_{EU,t}}{(1+r)^t}$

Quantifying the **energy saving potential**:

$$EP_{Utility} = \sum_{t=1}^{T_{max}} E_{WU,t}$$

$$EP_{City} = \sum_{t=1}^{T_{max}} (E_{WU,t} + E_{EU,t})$$

Quantifying the **marginal cost**:

$MC_{Utility} = TC_{Utility}/EP_{Utility}$

$MC_{City} = TC_{City}/EP_{City}$

Results for constructing the cost curves

Figure 22 Flow diagram showing the steps and equations for quantifying the energy saving potential and marginal cost

7.3. Results & discussion

7.3.1. Comparing the water utility cost curve and city cost curve

According to the utility curve (Figure 23(a)), the water utility in this hypothetical city can save approximately 1300 GWh over the 20 year period with respect to the baseline by implementing all the cost-effective options in its water supply and sewage systems (i.e., all the options with negative net cost). Improving pumping efficiency (no. 3) and aeration strategies (no. 4, 5) are relatively cost-effective, while active leak detection and repair (no. 1) is the most significant energy saving option.

The curve also shows that demand-side options (no. 9-13, 15-18) are highly unfavourable to the water utility in direct financial terms as a result of a loss of water sale revenue and relatively insignificant energy cost saving within utility. This is consistent with the GHG abatement cost curve developed by Sydney Water Corporation, which has indicated that none of the demand management options they evaluated are cost-effective to them (WSAA, 2012).

The city curve (Figure 23(b)) shows that approximately 5800 GWh can be saved cost-effectively through implementing most of the options studied. In particular, options related to hot water use (e.g., water-efficient shower head rebate (no. 12), plumber visit (no. 16)) are among the most favourable. It indicates that hot water use represents a significant portion of urban water-related energy use and is an important management opportunity. The most cost-effective option is water-efficient showerhead rebate (no. 12) and solar hot water system rebate (no.14) saves the most amount of energy.

Comparing the two cost curves (Figure 23) illustrates the difference between optimising the water-related energy use in the urban water system from the water utility and the city perspectives. One distinct difference is the magnitude of energy savings. The cost-effective energy saving potential from the city perspective (~5800 GWh, ~292 GWh/year) is 4.5 times that of the utility (~1300 GWh, ~65 GWh/year). This is consistent with the earlier finding that a significant portion of water-related energy use is in the water end use (Kenway *et al.*, 2015; Plappally and Lienhard V, 2012). This significant energy saving potential (from options no. 12, 15, 16, 14, 11) is not being captured by the utility curve as it only accounts for energy cost saving benefit within the utility.

For the city curve, some demand-side options (no. 12, 15, 16, 17, 14) can reduce energy use at lower cost than supply-side options (no. 1 – 7) which are very cost-effective in the utility curve. This illustrates that focusing solely on managing the energy use within the utility would miss out substantial non-utility water-related energy saving opportunities. The energy saving potential associated with the large-scale adoption of some of the demand-side options is clearly significantly greater than that of the supply-side options. In Australia, rebate schemes have been a popular approach to incentivise the uptake of water-efficient or energy-related appliances (e.g., water-efficient devices, solar hot water system) (Beal *et al.*, 2012; Walton and Holmes, 2009). One of main reasons for the higher cost-effectiveness of demand-side options is that the purchased electricity unit price of residential end use (23.9¢/kWh) is nearly double that of the utility (14.4¢/kWh).

By comparing supply and demand-side options in a consistent framework, like the city cost curve (Figure 23(b)), it can be found that some demand-side options (i.e., with energy benefit beyond the system boundary of utilities) have greater energy saving potential than the other supply-side options with similar capital expenditure for policy implementation. For example, for a similar capital cost, investing in solar hot water system rebates (no. 14, at a capital cost of $28.6 million (adjusted to 2014 dollars)) would save more energy (67 GWh/year against 31 GWh/year) and offer a greater financial return ($111/MWh saved against $63/MWh saved) than upgrading a wastewater treatment plant for biogas recovery (no. 8, at a capital cost of $27.2 million (adjusted to 2014 dollars)).

Some of the options (no. 9, 10, 13, 18) are not cost-effective from either utility or city perspective as the developed cost curves have not accounted for any non-energy cost benefits (e.g., deferment of infrastructure augmentation, managing urban runoff, reducing treatment costs).

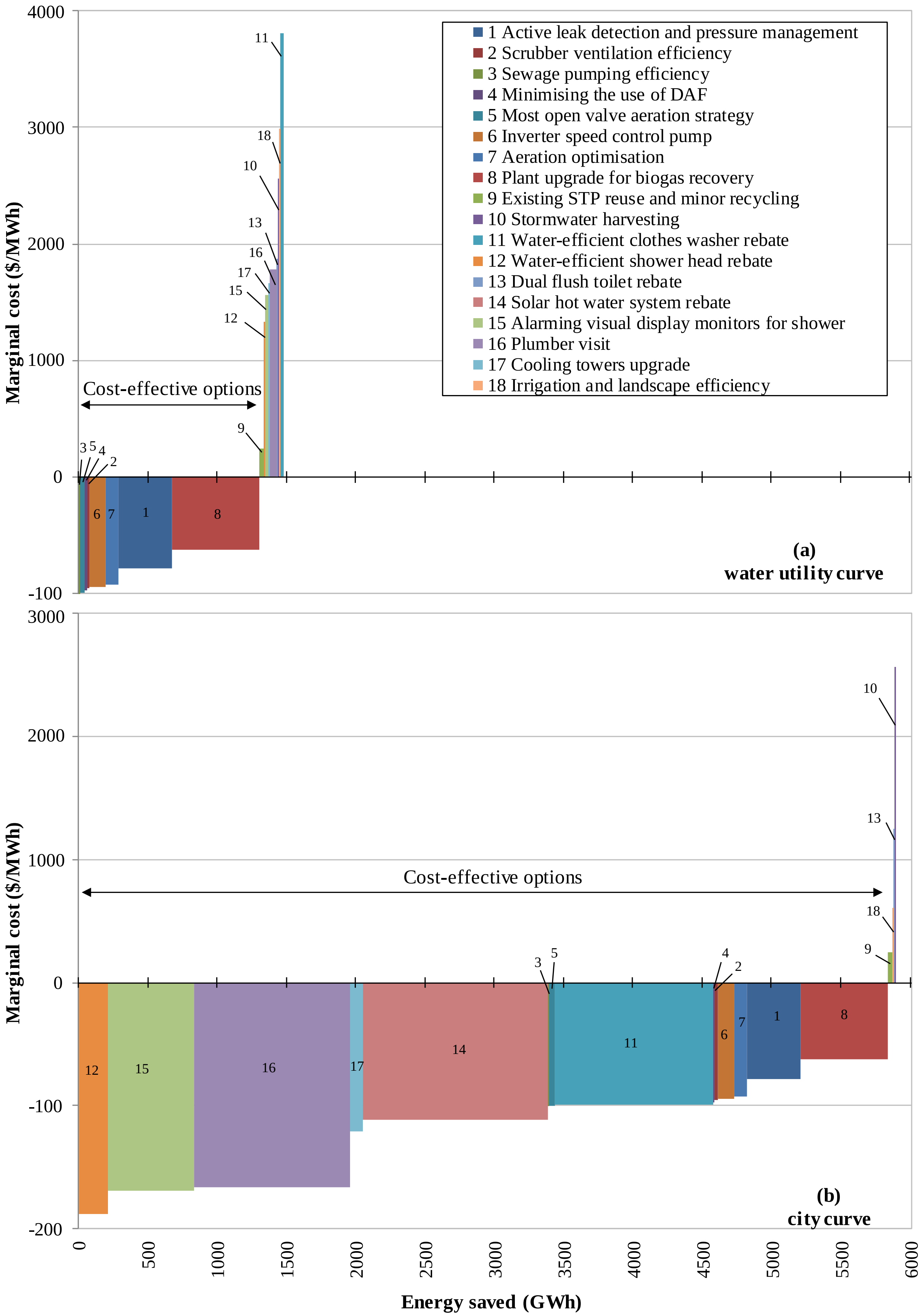

Figure 23 Cost curves for water-related energy management from (a) a water utility perspective and (b) a city perspective

7.3.2. *Implications for setting water-related energy and GHG management policies*

Energy use and GHG emissions of urban water systems are typically managed by utilities, but the water-related energy use and GHG emissions in the wider urban water system (which include residential water use, industrial water use, and decentralised water supply) are more loosely managed. Visions for managing water-related energy use and GHG emissions in urban water end use are scattered among different policy areas such as building efficiency, product energy efficiency, renewable energy targets, and water demand management programs. Water utilities are arguably the ideal agency for assisting end use water-related energy management because they have access to water use pattern data from water demand management programme (Turner *et al.*, 2005) and smart metering (Britton *et al.*, 2013). This information would enhance the quantification of the energy impacts of options and help customise the options based on the local context.

Based on the average GHG emission factor of electricity generation of the four Australian cities used for the hypothetical city, the corresponding marginal abatement cost curve for GHG emissions from the city perspective can be developed (Figure 24). Into the future, if the electricity mix becomes less carbon-intensive, the abatement potential (i.e., the width of the bar) will reduce and the magnitude of the marginal abatement cost (i.e., the height of the bar) will increase. Furthermore, if carbon is priced, the marginal abatement cost will become more negative.

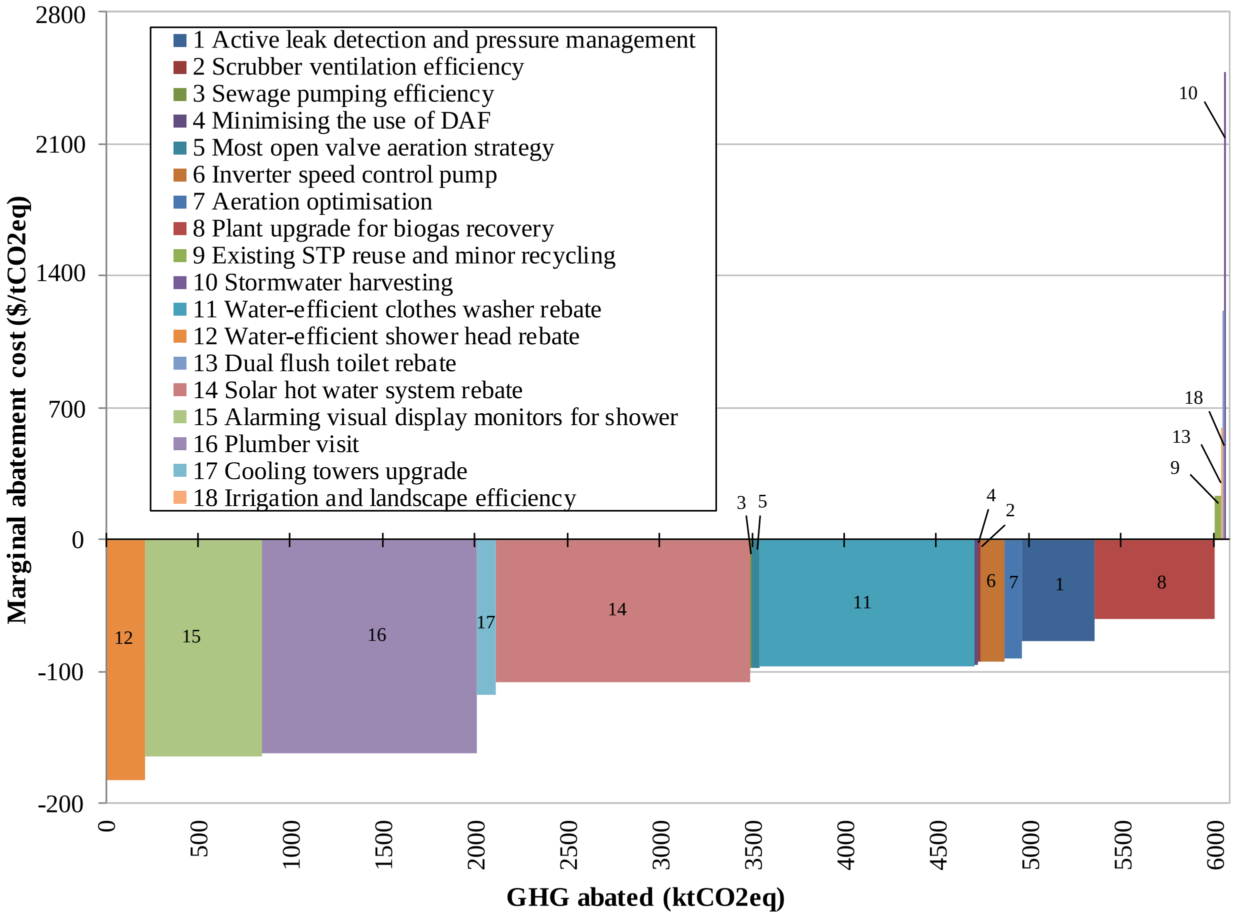

Figure 24 Marginal abatement cost curve from the city perspective

The utility curve (Figure 23(a)) has clearly shown that there is currently a lack of direct financial benefit for utilities to consider and support managing the water-related energy use and GHG emissions at the water end use. One way to overcome this barrier could be through some forms of carbon offset that creates a financial incentive. For instance, carbon management policy for water utilities could be designed to allow the purchase of non-utility water-related GHG emissions reduction to offset the emissions of the centralised systems. This would be similar to investing in external renewable energy generation to offset electricity use of desalination plants, or purchasing renewable energy credits (Cook *et al.*, 2012). As managing GHG emissions increasingly becomes a long-term goal for some water utilities, it would be a window of opportunity to include a wider range of water-related energy use management opportunities into the water agenda.

Some water utilities are aiming to make their systems "carbon-neutral" (Workman, 2015). They have encountered challenges to eliminate residual GHG emissions cost effectively. Taking a wider urban water system perspective would mean that instead of investing a significant amount of money for achieving carbon-neutrality within their organisation boundary, some of the budget would be allocated for options outside the utility, and would save more energy and abate more GHG for a city.

In recent years, water demand management has been one of the key elements in the water strategies of some utilities, especially regions encountering water stress. What they need to consider further is the energy consequence of their demand-side intervention and to include them in the energy and GHG management plan. Once these typically unaccounted for energy, GHG and cost benefits are included in cost-benefit analysis, this would provide policy makers a stronger incentive to promote wider-system options. This work demonstrates that the cost curve can be a decision support tool for water planners to prioritise options on both the water supply-side and the demand-side for long-term energy and GHG management of urban water cycle.

7.3.3. Sensitivity analysis

A sensitivity analysis was performed to determine how each input parameter influences the marginal cost and energy saving potential of each of the options. Percentage variations of -50% and +50% from the base values of input parameters were used. The sensitivity analysis results of the four most significant energy saving options in the city cost curve are presented in Figure 25 and all other results are included in Appendix A4. The sensitivity diagram shows the ranges of an output result (in Figure 25, it is the marginal cost) for the low (-50%) and high (+50%) values of all input parameters (Loucks *et al.*, 2005). The analysis shows that the marginal cost is more sensitive to the changes in the electricity price, discount rate, and the water and energy saving potential of an option. For instance, the higher the electricity price, the more cost-effective the options would be.

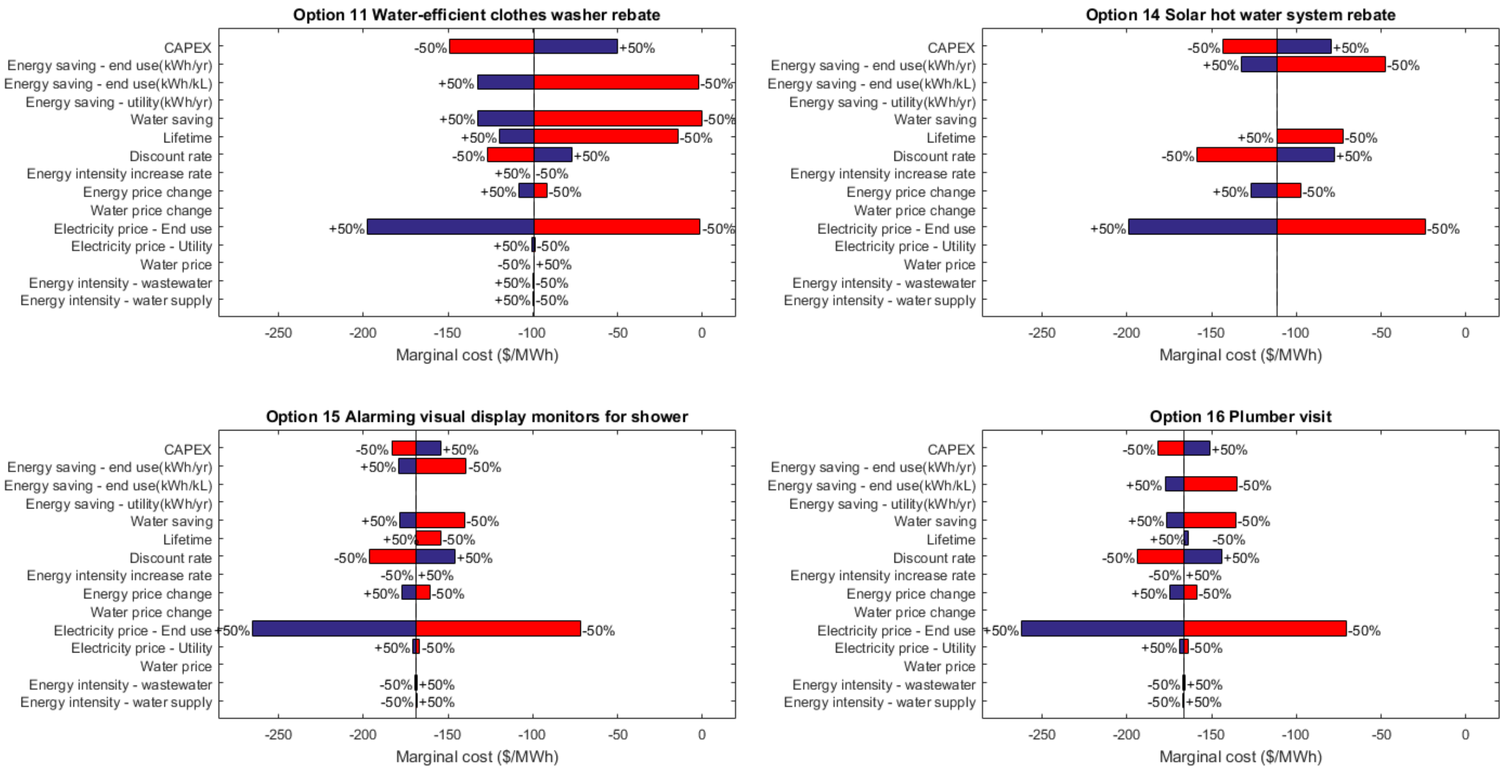

Figure 25 Sensitivity diagrams showing the ranges of the marginal costs of the top four significant options for low and high values of the input parameters

The sensitivity analysis reflects the performance of energy saving options if these options are applied to other cities with different water systems (e.g., systems with different energy intensity of supply, water pricing, etc.) and energy systems (e.g., energy price, energy mix). In general, cities with higher energy prices would find the options more cost-effective than they are in the hypothetical city, providing that the capital costs of the options are similar. On the other hand, cities with higher energy intensity in the water supply system (i.e., having a different water supply mix such as more desalinated water or imported water) would not find any significant improvement in the marginal cost for most of the options, especially the end use options (Figure 25 and 3S). This is because the energy and cost savings occurred in the end use is several magnitudes greater than that in the water utilities.

A range of factors can influence the performance of individual options. While this level of detail is beyond the scope of this paper, some examples are worth clarifying. For example, the temperature of delivered mains water in cities with different climate would influence the relative energy impacts of different options. In particular, it would impact the energy saving potential of options which involve water heating (no. 11, 12, 14, 15, 16) (i.e., a colder climate would likely result in a more negative marginal cost and a greater energy saving potential). Based on the sensitivity analysis (Figure 25 and Figure A4-3), this climatic factor (determining “energy saving – end use”) is less influential on the marginal cost (i.e., the height of the bar in cost curve) than other factors such as electricity price and discount rate. On the other hand, the energy saving potential (i.e., the width of the bar in cost curve) is strongly influenced by such a climate difference (Figure A4-5).

There are other behavioural, technological and environmental factors that are not directly captured by the sensitivity analysis can influence the cost curves in other cities. For example, shower duration, flow-rate, frequency and temperature all have significant impact on end use water-related energy (Kenway *et al*., 2016). Changes to these parameters in cities could have a marked impact on the relative size of options (e.g., options 11 (clothes washer rebate) and 12 (shower head rebate)). In addition, since some of the options used in this work are water conservation basis. Their saving potential would depend on the existing water-related household stock and water use behaviour (e.g., the efficiency of existing cloth washers, the average duration of showering time). For detailed sensitivity analysis of how technical, behavioural and environmental factors (including water temperature) influence household water-related energy use refer to Kenway *et al.* (2012; 2016).

7.3.4. Uncertainty and limitations

In order to understand the uncertainty of the results, a Monte Carlo simulation using 10,000 runs was carried out (Figure A4-1 in Appendix A4) based on an approach described in the literature (Stokes *et al.*, 2014). Probability distribution functions were assigned to all input parameters for the options and the hypothetical city. The distribution functions of input parameters used are listed in Tables A4-4 and A4-5 (Appendix A4). The simulation generated the output distributions of the marginal cost ($/MWh) for each option. These distributions give indications of the uncertainty of the results. Figure 26 shows the median, 10th percentile and 90th percentile of the marginal cost of all the options in the city perspective curve. Considering the error bars, the 10th percentile marginal costs of most of the significant cost-effective demand-side options (no. 12, 15, 16) are still lower than the 90th percentile marginal costs of all the cost-effective utility options (no. 1 -8). Options that are not cost-effective (no. 9, 10, 13, 18) appear to have higher uncertainty in the marginal cost. However, since their energy saving potential is relatively insignificant (as shown in Figure 23(b)), their uncertainties have little effect on the overall result of the cost curve.

The major limitations of this work are the use of a hypothetical city and the reliance of published data rather than mechanistic modelling to develop the cost curves. This approach was adopted to overcome data limitations and focus on conceptual and methodological questions. Despite its hypothetical nature, the city was still based strongly on the characteristics of four Australian cities – Brisbane, Melbourne, Sydney and Perth. In addition, all the water-related energy management options used were based on implemented or evaluated actual options across Australia. The methodology outlined in this work can be used by water planners to construct the cost curves for water-related energy and GHG emissions management in their cities or regions based on their water balance models and detailed options analysis. Using local contextual data and models to conduct detailed analysis can potentially overcome some of the limitations of this work by for example, conducting detailed scenario analysis on the impacts of city characteristics, accounting for the interactions between options and conducting more comprehensive economic assessment.

Other limitations are on the cost curve approach itself and have been extensively discussed by Kesicki and Ekins (2012). To partially address some of these limitations (namely uncertainty and transparency), a probabilistic model was used in this work to perform an uncertainty analysis. In addition, the assumptions and the methodology used in this work are detailed in section 7.2 and Appendix A4.

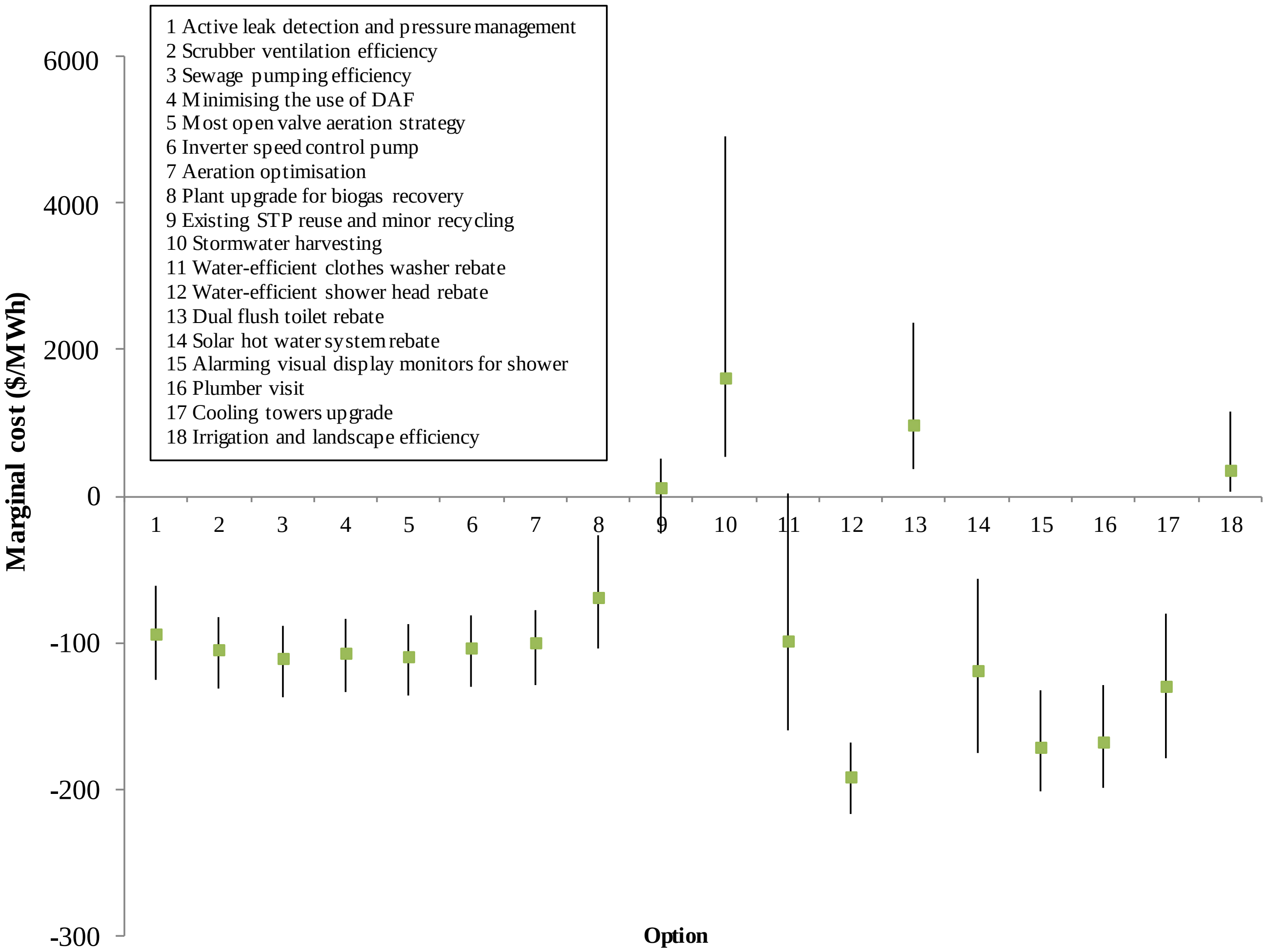

Figure 26 Median, 10th percentile and 90th percentile of the marginal cost of all the options in the city perspective curve from Monte Carlo simulation

7.4. Conclusions

The key contribution of this work is to develop and compare cost curves for water-related energy options in a hypothetical Australian city from two perspectives, namely the city and the water utility. The key insights are as follows.

- For the same set of water-related energy management options in the Australian context, the cost-effective energy saving potential experienced by the city is far more significant than that of the water utility. A significant portion of these additional energy saving comes from hot-water related energy use associated with water end use conservation.
- This work illustrates that focusing solely on managing the energy use within the utility would miss substantial non-utility water-related energy saving opportunities. By broadening the current scope of cost curves beyond the system boundary of water utilities and valuing their management from a city perspective, some options with more significant energy saving potential and cost-effectiveness would stand out, instead of being neglected in the utility curve. This would create opportunities where the same capital investment could achieve far greater energy savings and GHG abatement.
- There is a need to create the right incentives for water utilities to look beyond their system boundaries so as to achieve greater energy saving and GHG abatement in urban water systems. Under the current cost-benefit analysis approach, water end use options do not offer direct financial incentive to water utilities. One way to overcome this barrier may be through some form of carbon offset scheme that allows water utilities to purchase non-utility water-related GHG emissions reductions to offset the emissions of the centralised systems operated by utilities.
- This work also demonstrates that the cost curve can be a useful decision support tool to compare and rank options across the interface of the utility and water end use.
- While this study is based on the Australian context and some of the local characteristics have been shown to strongly influence what the more cost-effective or greater energy saving options for a city can be, water planners in different cities can use the outlined approach to assess what the better energy saving opportunities in their wider urban water systems are.

Abbreviations

$CAPEX_{City}$	Capital expenditure from water utility/government and end users ($)
$CAPEX_{Utility}$	Capital expenditure from water utility ($)
E_{EU}	Energy saving at water end use as quantified by the data source (MWh/year)
$E_{EU,t}$	Energy saving at water end use in *t* th year (MWh)
$E_{EW,t}$	Energy saving at water utility in *t* th year (MWh)

$E_{O,WU}$	Energy saving at water utility (non-water saving related) (MWh/year)
$EC_{EU,t}$	Electricity price at water end use in the *t* th year ($/MWh)
$EC_{WU,t}$	Electricity price at water utility in the *t* th year ($/MWh)
$ECS_{EU,t}$	Energy cost saving at water end use in the *t* th year ($)
$ECS_{WU,t}$	Energy cost saving at water utility in the *t* th year ($)
EI_{EU}	Energy intensity for water end use activities (MWh/ML)
$EI_{WS,t}$	Energy intensity for water supply in the *t* th year (MWh/ML)
$EI_{WW,t}$	Energy intensity for wastewater treatment in the *t* th year (MWh/ML)
EP_{City}	Energy saving potential of an option from the city perspective (MWh)
$EP_{Utility}$	Energy saving potential of an option from the water utility perspective (MWh)
$i_{EC,EU}$	Electricity price annual change rate at water end use (%)
$i_{EC,WU}$	Electricity price annual change rate at water utility (%)
$i_{EI,WS}$	Energy intensity for water supply annual change rate (%)
$i_{EI,WW}$	Energy intensity for wastewater treatment annual change rate (%)
i_{WC}	Water price annual change rate (%)
MC_{City}	Marginal cost of an option from the city perspective ($/MWh)
$MC_{Utility}$	Marginal cost of an option from the water utility perspective ($/MWh)
t	Year
t_{option}	Lifetime of option
T_{max}	Number of assessment year
TC_{City}	Net cost of an option from the city perspective ($)
$TC_{Utility}$	Net cost of an option from the water utility perspective ($)
V_w	Water saving from the mains (ML/year)
WC_t	Water price ($/ML)

PART III:

DISCUSSION & CONCLUSIONS

8. Discussion

This chapter synthesises the research outcomes in Chapters 3 to 7 which address the research objectives and questions set out in Chapter 1, and fills some gaps in the current body of “energy for water” research discussed in Chapter 2. It starts with a discussion on the spatial and temporal variations of energy use for urban water supply (Section 8.1). The spatial and temporal variations in major Australian cities through the Millennium Drought offer significant water-related energy lessons (Section 8.2). The analysis also demonstrates how water-related energy impacts of urban water management vary in magnitude across different components of urban water systems (Section 8.3). Based on the Australian context, the synthesis further discusses prioritising water-related energy management efforts in cities in terms of cost and energy saving potentials (Section 8.4).

8.1. Spatial and temporal variations of energy for water

The multi-city analysis (Chapter 3) reveals significant spatial and temporal variations of energy use for water supply in the 30 cities studied. A time-based water-energy profiling approach was developed and used to illustrate these variations. The profile plots per capita energy use for water supply against per capita water use for each city. With time series data, the profile can be used to track how cities have performed historically and relative to each other.

Per capita energy use for water supply shows significant spatial variation, ranging from 10 kWh/p/a (Melbourne in 2015) to 372 kWh/p/a (San Diego in 2015). The energy intensity of water supply systems is between 0.11 kWh/kL (Melbourne in 2015) and 2.31 kWh/kL (Bangalore in 2014). In terms of temporal variations between 2000 and 2015, there was a general reduction trend in per capita energy use for water supply in most of the 17 cities with time-series data. Four Australian cities (i.e., Brisbane, Melbourne, Sydney and Perth) and two Californian cities (i.e., Los Angeles, San Diego) had substantial changes in energy use for water supply over the studied period.

Climate, topography, water use pattern and system operational efficiency are some of the factors contributing to these variations. For instance, the large difference in the per capita energy use between Melbourne (10 kWh/p/a) and San Diego (372 kWh/p/a) is mainly attributed to the facts that i) the Melbourne water supply system is predominantly gravity-fed, while San Diego obtains most of its water from two energy-intensive inter-basin water transfer systems, and ii) Melbourne (251 L/p/d) has a lower per capita water use than San Diego (488 L/p/d).

The high spatial and temporal variation, and the study of the contributing factors provide insights for inter-city learning. Some cities can act as potential examples to learn about managing energy use for water supply through manipulating factors such as energy efficiency in the supply systems (e.g., Berlin, Copenhagen), non-revenue water (e.g., Berlin, Tokyo and Denver) and residential water efficiency (e.g., Sydney, Melbourne) or through capitalising on factors such as climate events (e.g., Brisbane, Melbourne) and local topography (e.g., Melbourne and Sapporo).

The time-series analysis shows that the historical reduction of energy use for water supply in most cities was predominantly contributed by enhancing water use efficiency instead of improving energy efficiency within water supply systems (i.e., energy intensity for water supply did not reduce in most cases). This can imply that future water-related energy management should put more effort on improving water use efficiency (e.g., reducing water leakage, promoting household water conservations). For instance, energy use associated with non-revenue water is very substantial in the cities studied and represents a significant energy saving potential (i.e., a population-weighted average of 16 kWh/p/a, 25% of the average energy use for water provision).

The multi-city analysis also identifies individual cities for more detailed analysis of their current status, trends and drivers for managing energy for water (in addition to energy use for water supply covered by the multi-city study). In particular, four Australian cities had high temporal variation of energy use for water supply for the studied period as a result of a decade-long drought. During the drought, the energy intensity for water supply in Brisbane, Melbourne and Sydney increased by 96% (in 2010), 129% (in 2011) and 325% (in 2008) from 2002 level respectively. In Perth, the latest energy intensity is 164% (in 2015) higher than that of 2002 level. The detailed energy for water case studies that offer water-related energy lessons include – long-term shifts in energy use for water supply (a comparative case study in Chapter 4), relative energy implications of drought on water supply system, sewage system and residential water end use (Chapter 5), and life-cycle energy impacts of supply-side drought responses (Chapter 6).

8.2. Water-related energy lessons from the Australian Millennium Drought

The Australian case studies (Chapters 4 and 5) demonstrate significant long-term energy saving benefit from the large scale adoption of water conservation strategies (e.g., water-efficient devices rebate, water use target, promotion campaigns, outdoor water restrictions) in Melbourne, South East Queensland (SEQ) and Sydney. This energy saving within the water supply systems has partly (for Sydney) or fully (for Melbourne and SEQ) offset the negative energy consequence of utilising energy-intensive alternative water sources during the drought. Furthermore, the benefit from energy saving through water use reduction is cumulative, considering there has only been little rebound of water use even some years after the drought. The benefit may even grow over time because of i) significant increase in the energy price in Southeast Australia in recent years and ii) marginal energy saving (i.e., reducing the frequency of using more energy-intensive supply sources).

In addition, the Melbourne case study (Chapter 5) shows that this energy saving extends beyond the water utility boundary to the water end use, mostly in the form of hot water saving (more details in Section 8.3). Even though data are not available for estimation in SEQ and Sydney, it is highly likely that there was also significant residential water-related energy saving from water conservations in the two regions. This is because distinct residential water use reduction was observed in both regions through the drought (i.e., from 286 L/p/d (2001) to 169 L/p/d (2013) in SEQ; from 255 L/p/d (2001) to 198 L/p/d (2013) in Sydney). This reduction can be partly attributed to some changes in hot water-related activities such as higher uptake of water-efficient showerheads, shorter showering time and higher uptake of water-efficient clothes washers.

Another lesson from the Australian Millennium Drought is that different emphasis of supply versus demand side management can drive a region to a very different long-term water-related energy use pathway. This is evident from the SEQ and Perth comparative study (Chapter 4). In 2002, Perth had a similar per capita total urban water use to SEQ and 48% higher per capita energy use in the water supply system. From 2002 to 2014, a strong effort of water conservation can be seen in SEQ during the drought, while Perth has been increasingly relying on seawater desalination. By 2014, even though the drought in SEQ had ended and the drying climate in Perth was continuing, the per capita total urban water use in SEQ (266 L/p/d) was still 28% lower than that of Perth (368 L/p/d), while the per capita energy use for water supply in Perth (247 kWh/p/a) had increased to almost five times that of SEQ (53 kWh/p/a).

The SEQ and Perth comparative study also suggests that times of water stress can be windows of opportunity to induce changes in water use patterns, which in turn, can yield long-term benefits in water and energy savings. Other water stressed regions can learn from how SEQ (and also Melbourne and Sydney) capitalised on the drought event to improve their water efficiency. For example, rebate schemes for water efficient devices have provided a stronger incentive for people to improve water use efficiency, which also provides water-related energy saving. Public education through media was also one of the effective tools to drive the reduction in water use.

The life-cycle energy assessment of the alternative water supply strategies introduced in SEQ during the Drought (Chapter 6) provides insights for other water-stressed regions to develop more realistic scenarios to evaluate and compare life-cycle energy impacts of drought-adaptation infrastructure and regional decentralised water sources. Long-term scenarios should consider i) climate variability (and therefore infrastructure utilisation rate), ii) potential under-utilisation for installed decentralised sources, and iii) potential energy penalty for operating infrastructure well below their design capacities. The study also demonstrates that focusing on managing long-term urban water demand is as important as acknowledging the energy-intensive nature of some of the alternative water sources. The 20-year period scenario analysis for SEQ shows that a 20% increase in per capita water use (816 TJ/a) would “consume” more life-cycle energy than the four alternative water supply strategies introduced (i.e., seawater desalination, potable water recycling, network integration and rainwater tanks) (655 TJ/a).

8.3. Different water-related energy influences in various components of urban water systems

In addition to the water-related energy lessons, the Australian case studies (Chapters 4 to 6) show how water management has different water-related energy influences in various components of urban water systems: water supply system, sewage system, residential water end use and decentralised water source. The "water management" referred to in this work includes activities on balancing supply and demand of water in cities, and providing water-related services to municipal water end users.

Supply-side and demand-side urban water management options are found to significantly influence the overall energy use of water supply systems. As discussed earlier, during a prolonged drought, the energy intensity for water supply in three Australian regions increased to 2-4 times the pre-drought levels as a result of meeting demand with energy-intensive alternative water sources (i.e., inter-basin water transfer, seawater desalination, indirect potable water recycling). On the other hand, demand-side options such as water restrictions, water conservation promotion campaigns and water-efficient device rebates alleviated some of the negative energy consequence of supply-side changes.

The Drought and the significant urban water demand reduction seem to have little impact on the sewage systems in Melbourne and Sydney in term of their energy use (where historical data are available). Because of stormwater infiltration, the amount of sewage collected increased for those years with more urban rainfall. That seems to be a stronger determinant for changes in energy use of sewage systems in the two cities than the demand-side options. In fact, the only significant change in the energy use of the sewage system in Melbourne from 2012 to 2014 was a result of a major wastewater treatment plant upgrade for improving discharge quality and providing non-potable water recycling.

The Melbourne case study has also shown that there is a significant difference in the magnitude of water-related energy savings in water supply systems compared to residential water end use as a result of the drought and implemented water conservation strategies. The per capita water-related energy use reduction in the residential water end use (46% reduction, 580 kWh_{th}/p/a) was far greater than that in the water supply system (32% reduction, 18 kWh_{th}/p/a). This has clearly identified that there is more water-related energy savings potential in water end use.

For decentralised water sources, new rainwater tanks introduced in SEQ only contributed an estimate of 2% of regional water supply, but added over 10% life-cycle energy use to the existing water supply system. In addition, the SEQ case study also shows that regional uptake of rainwater tanks can be more energy-intensive (kWh/kL) than seawater desalination if a significant portion of the tanks are under-utilised (i.e., not internally-plumbed or reducing usage).

8.4. Prioritising water-related energy management efforts

Section 8.3 has discussed the difference in the magnitude of water-related energy impacts in various components of urban water systems. The more important follow-up question is where we should then put our water-related energy management efforts in urban water systems from both cost-effectiveness and energy saving potential perspectives. My development of marginal cost curves for city-scale water-related energy management based on the Australian context (Chapter 7) helps address this question. More specifically, a range of utility and end use water-related energy management options which have been implemented or evaluated in Australia were evaluated and ranked for their cost-effectiveness.

Energy use of urban water systems is typically managed by utilities, but the water-related energy use in the wider urban water system (which includes residential water use, industrial water use, and decentralised water supply) is more loosely managed. The current paradigm for water-related energy management is still mostly focused on opportunities within water utilities. The cost curve study (Chapter 7) shows that this current paradigm would lead to sub-optimisation of urban water systems. More specifically, focusing solely on managing the energy use within the utility would miss substantial non-utility water-related energy saving opportunities. By broadening the current scope of water-related energy management beyond the system boundary of water utilities and valuing their management from a city perspective, some water end use options with more significant energy saving potential and cost-effectiveness would stand out, instead of being neglected when considered from the perspective of the utility. This would create opportunities where the same capital investment could achieve far greater energy savings in an urban water system. For example, in the studied scenario, upgrading a wastewater treatment plant for biogas recovery at a capital cost of $27.2 million would save 31 GWh/year with a marginal cost saving of $63/MWh, while solar hot water system rebates at a cost of $28.6 million would save 67 GWh/year with a marginal cost saving of $111/MWh.

In addition to cost-effectiveness, the energy saving potential in water end use is shown to be far more significant than that of the water utility in the Australian context (for a hypothetical city based on average Australian data). A significant portion of this water-related energy saving related to hot-water use. This finding from the cost curve study (Chapter 7) is consistent with the Melbourne case study (Chapter 5), which estimates that on a per capita basis, residential water end use has saved over 30 times more water-related energy than the water supply system through the Millennium Drought.

There is a need to create the right incentives for water utilities to look beyond their system boundaries so as to achieve greater energy savings and greenhouse gas abatement in urban water systems. Under the current industry cost-benefit analysis approach, water end use options do not offer direct financial incentive to water utilities. One way to overcome this barrier may be through some form of carbon offset scheme that allows water utilities to purchase non-utility water-related greenhouse gas emissions reductions to offset the emissions of the centralised systems operated by utilities. For instance, Sydney Water Corporation was given carbon offset credits by the NSW Government for its water conservation programmes during the Drought (Sydney Water Corporation, 2011).

9. Conclusions & Recommendations

9.1. Urban water management has significant energy implications

This work shows that urban water management has significant energy implications. “Water management” referred to in this thesis includes activities necessary for balancing supply and demand of water in cities, and providing water-related services to municipal water end users. One of the major contributions of this work is to use multi-city analysis, time-series approach and comparative case study to explore these energy implications.

One of these energy implications is on the use of energy-intensive alternative water sources such as inter-basin water transfers and seawater desalination in meeting urban water demand. During a prolonged drought, the energy intensity for water supply (kWh/kL) in Brisbane, Melbourne and Sydney increased by 96% (in 2010), 129% (in 2011) and 325% (in 2008) from 2002 level respectively as a result of using alternative water supply sources. In Perth, the increased use of desalinated seawater as a major supply source has made the energy intensity for water supply rose by over 160% (in 2015) of 2002 level. In addition to alternative centralised water sources, over 280,000 new rainwater tanks introduced in South East Queensland only contributed an estimate of approximately 2% of regional water supply, but added over 10% life-cycle energy use to the existing water supply system. The Australian experience clearly demonstrates that the overall energy use for water supply can be greatly influenced by supply-side changes within a relatively short timeframe.

Another energy implication is on the water efficient demand-side options. Reducing urban water demand not only helped some of the Australian regions managed through a decade-long drought, it also led to energy saving in the water supply system and helped partly (in Sydney) or fully offset (in Melbourne and South East Queensland) the negative energy consequence of using energy-intensive alternative water sources during the drought. This water-related energy saving did not confine to the water supply system only, it was also experienced in the water end users in a much higher magnitude.

The significant energy implications of water management in cities imply the need for better quantifying of the current and future influence of various water management approaches, inter-regional learning of water-related energy lessons and prioritising water-related energy management efforts. A better understanding of the energy implications is also critical for managing energy cost and GHG emissions for water utilities and water end users.

9.2. Water use efficiency is critical for water-related energy management

Current efforts of water-related energy management have been focused on water utilities energy use. The time-series analysis of energy use for water supply in multiple cities shows that historical reduction in this energy use (a reduction by 11-45% between 2000 and 2015 in 12 of 17 sampled cities) was mostly achieved by enhancing water end use efficiency instead of improving energy efficiency within water supply systems. This implies that future water-related energy management should put more effort on improving water use efficiency (e.g., reducing water leakage, promoting household water conservation). The Australian drought experience can provide a realistic urban water efficient target for other cities. Furthermore, energy associated with non-revenue water is found to be very substantial in multiple cities studied and represents a significant energy saving potential (i.e., a population-weighted average of 16 kWh/p/a, 25% of the average energy use for water provision).

This work also demonstrates that focusing on managing long-term urban water demand is as important as acknowledging the energy-intensive nature of some of the alternative water supply sources. For instance, in a scenarios analysis of South East Queensland for a 20-year period, a 20% increase in per capita water use (816 TJ/a) would “consume” more life-cycle energy than the four alternative water supply strategies introduced (i.e., seawater desalination, potable water recycling, network integration and rainwater tanks) (655 TJ/a).

Improving water end use efficiency also results in direct energy saving at the water end users. This water-related energy saving at the end use is much higher than that of water utilities (e.g., in Melbourne, it was 30 times more). Recognising such a difference in magnitude would better value the role of some water conservation strategies for water-related energy management in urban water system. A major contribution of this work is to make use of the actual experience in Australia to showcase the energy saving potential from water conservations and the difference in magnitude for water-related energy influence between water supply system and end use.

9.3. Water end use has some of the more cost-effective water-related energy management solutions with greater energy saving potential

In the Australian context (for a hypothetical city based on average Australian data), this work shows that many water-related energy management solutions targeting water end use (e.g., water-efficient shower heads, water-efficient clothes washers, solar hot water system rebates) are more cost-effective than water utility options (e.g., improving pump efficiency, reducing water leakage). In addition, end-use options often have a greater energy saving potential because water-related energy at end use is much higher than that of water utilities. One of the major contributions of this work is to make use of marginal cost curve approach to compare cost-effectiveness and energy saving potential for a range of water-related energy management opportunities in urban water systems.

9.4. The need for paradigm change of water-related energy management

A paradigm change of water-related energy management is needed to achieve a greater water-related energy saving. This involves expanding the conventional water-related energy option evaluation beyond water utilities to look at water-related energy management opportunities across the whole urban water system. In the studied scenario, the cost-effective energy saving potential from a city perspective (292 GWh/year) is far more significant than that from a utility perspective (65 GWh/year). This thesis shows that the current paradigm of utility-focused water-related energy management would lead to sub-optimisation of urban water system. More specifically, focusing solely on managing the energy use within the utility would miss substantial non-utility water-related energy saving opportunities. By broadening the current scope of water-related energy management beyond the system boundary of water utilities and valuing their management from a city perspective, some water end use options with more significant energy saving potential and cost-effectiveness would stand out, instead of being neglected in the utility perspective management. This would create opportunities where the same capital investment could achieve far greater energy savings in an urban water system. For example, in the studied scenario, upgrading a wastewater treatment plant for biogas recovery at a capital cost of $27.2 million would save 31 GWh/year with a marginal cost saving of $63/MWh, while solar hot water system rebates at a cost of $28.6 million would save 67 GWh/year with a marginal cost saving of $111/MWh.

9.5. Recommendations for future research

This thesis employs multi-city analysis, detailed historical water-related energy analysis of major Australian cities, and least cost analysis of water-related energy management to fill some gaps in the current body of research concerning the energy implications of water management in cities. It provides useful starting points for further research. Future investigation is recommended in the following areas:

- Scenario analysis should be conducted to evaluate and project the water-related energy impacts of different future water management strategies or scenarios (e.g., climate, demand) in some of the studied cities, where clear historical baselines have been established in this thesis.
- Understand why some cities/regions still have relatively high water use even though they have been water stressed and have energy-intensive water supply systems. This is important for water-related energy management because this thesis shows that higher water efficiency has been a major driving factor for a historical reduction in per capita energy use for water supply in most of the cities studied.
- Improve water-related energy data collection and analysis for water end use in individual cities to better design water-related energy management strategies that suit local contexts.

It is because this thesis clearly shows the water-related energy saving potential in the water end use is much higher than that in the water utilities.

- Greenhouse gas emissions are one of the drivers for better managing water-related energy use. Its management in the water context can be studied based on the comprehensive energy analysis conducted in this thesis. Future research can quantify the historical water-related greenhouse gas emissions trends for different cities and explore the role the urban water systems play in enabling cities to meet GHG reduction targets.
- Investigate how to develop and implement more consistent national or global energy reporting frameworks for water utilities to track and benchmark their performance. Currently, the lack of water-related energy performance indicators, continuous reporting and transparency may be barriers for improving energy use in some water utilities. An improved global effort is needed to create more reliable and regular datasets covering energy use in urban water supply.
- Explore how to create the right financial and regulatory incentives for water utilities to engage in water-related energy management at water end users. This represents an important step to drive the paradigm change of water-related energy management as discussed.
- Apply the city-scale water-related management cost curve evaluation methodology developed in this work to actual systems based on local contextual data and water balance models. This will allow more detailed scenario analysis on the impacts of city characteristics, consideration of the interactions between options and more comprehensive economic assessment. Ultimately, this could inform policy makers on how to prioritise the water-related energy management efforts in their systems.
- Future cost-effectiveness analysis of water-related energy management options should also include the indirect energy components or other externalities (e.g., life-cycle costs). This would provide a more holistic evaluation for water-related energy management strategies. This thesis shows that the indirect energy use for some strategies can be considerably significant.

References

(2013) QLD Government Solar Hot Water Rebate. http://web.archive.org/web/20130123225051/http://www.hotwaterrebate.com.au/p/qld-rebate-overview (accessed 01.02.16).

Aghakouchak, A., Feldman, D., Stewardson, M.J., Saphores, J.D., Grant, S. and Sanders, B. (2014) Australia's drought: Lessons for California. *Science* 343(6178), 1430-1431.

Alegre, H., Hirnir, W., Baptista, J.M., Parena, R. and International Water, A. (2000) Performance indicators for water supply services, IWA Publishing, London.

Amores, M.J., Meneses, M., Pasqualino, J., Antón, A. and Castells, F. (2013) Environmental assessment of urban water cycle on Mediterranean conditions by LCA approach. *Journal of Cleaner Production* 43, 84-92.

Anand, C. and Apul, D.S. (2011) Economic and environmental analysis of standard, high efficiency, rainwater flushed, and composting toilets. *Journal of Environmental Management* 92(3), 419-428.

Ashida, H. (2014) Pursuing water loss reduction, Tokyo.

Athuraliya, A., Gan, K. and Roberts, P. (2008) Yarra Valley Water 2007 Appliance Stock and Usage Patterns Survey. http://www.yvw.com.au/yvw/groups/public/documents/document/yvw1001675.pdf (accessed 13.10.15).

Athuraliya, A., Roberts, P. and Brown, A. (2012) Residential water use study volume 2 – summer 2012. http://www.yvw.com.au/yvw/groups/public/documents/document/yvw1003347.pdf (accessed 17.04.15).

Australian Bureau of Statistics (2001) Environmental Issues: People's Views and Practices • March 2001. http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/4602.0Mar%202001 (accessed 29.09.14).

Australian Bureau of Statistics (2004) 4602.0 Environmental Issues: People's Views and Practices • March 2004. http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/4602.0Mar%202001 (accessed 29.09.14).

Australian Bureau of Statistics (2006) Water Account, Australia, 2004-05. http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/4610.02004-05 (accessed 21.04.16).

Australian Bureau of Statistics (2011) Environmental Issues: Energy Use and Conservation, Mar 2011. http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/4602.0.55.001Mar%202011 (accessed 29.09.14).

Australian Bureau of Statistics (2013) 4602.0.55.003 Environmental Issues: Water use and Conservation, Mar 2013. http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/4602.0Mar%202001 (accessed 29.09.14).

Australian Bureau of Statistics (2014a) Population Estimates by Local Government Area (ASGS 2013), 2003 to 2013. http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/3218.02012-13 (accessed 06.09.14).

Australian Bureau of Statistics (2014b) Australia Water Account 2012-13. www.abs.gov.au/AUSSTATS/abs@.nsf/Latestproducts/4610.0Main%20Features32012-13 (accessed March, 2015).

Australian Bureau of Statistics (2015a) Estimated Resident Population by SA2 (ASGS 2011), 1991 to 2014. http://govhack.abs.gov.au/Index.aspx?DataSetCode=ABS_ANNUAL_ERP_ASGS (accessed 24.07.15).

Australian Bureau of Statistics (2015b) Population Estimates by Local Government Area (ASGS 2014), 2001 to 2014. http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/3218.02013-14 (accessed 24.07.15).

Australian Bureau of Statistics (2015c) 3218.0 Regional Population Growth, Australia, 2014-15. http://www.abs.gov.au/ausstats/abs@.nsf/mf/3218.0 (accessed 12.07.16).

Australian Bureau of Statistics (2015d) Water Account, Australia, 2013-14. http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/4610.02013-14 (accessed 17.05.16).

Barnett, J. and O'Neill, S. (2010) Maladaptation. *Global Environmental Change* 20(2), 211-213.

Bartos, M.D. and Chester, M.V. (2014) The conservation nexus: Valuing interdependent water and energy savings in Arizona. *Environmental Science and Technology* 48(4), 2139-2149.

Beal, C. and Stewart, R.A. (2011) South East Queensland Residential End Use Study: Final Report. http://www.urbanwateralliance.org.au/publications/UWSRA-tr47.pdf (accessed 26.05.14).

Beal, C.D., Bertone, E. and Stewart, R.A. (2012) Evaluating the energy and carbon reductions resulting from resource-efficient household stock. *Energy and Buildings* 55, 422-432.

Beal, C.D. and Stewart, R.A. (2014) South East Queensland Residential End-Use Study: Stage 2 final report and summary of water consumption trends from 2010 to 2014. http://www98.griffith.edu.au/dspace/bitstream/10072/65771/1/99889_1.pdf (accessed 17.04.15).

Berliner Wasserbetriebe (2011) Abschlussbericht zur Kooperationsvereinbarung Klimaschutz BWB 2006-2010 [Final report on the climate cooperation agreement BWB 2006-2010].

http://www.bwb.de/content/language1/downloads/BERICHT_Klimaschutzvereinbarung_BWB-SenGUV_2012.pdf (accessed 16.07.15).

Binks, A.N., Kenway, S.J., Lant, P.A. and Head, B.W. (2016) Understanding Australian household water-related energy use and identifying physical and human characteristics of major end uses. *Journal of Cleaner Production* 135, 892-906.

Bureau of Meteorology (2015a) Recent rainfall, drought and southern Australia's long-term rainfall decline. http://www.bom.gov.au/climate/updates/articles/a010-southern-rainfall-decline.shtml (accessed 05.05.15).

Bureau of Meteorology (2015b) National performance report 2013–14: urban water utilities, Part B. http://www.bom.gov.au/water/npr/docs/2013-14/National_Performance_Report_2013-14_PartB.xlsx (accessed 12.07.15).

Bureau of Meteorology (2016) National performance report 2014–15: urban water utilities, Part B. http://www.bom.gov.au/water/npr/docs/2014-15/National-performance-report-2014-15_part-B.xlsx (accessed 27.06.16).

Bush, C. (2015) Blacktown Stormwater Harvesting and Reuse scheme – Final Report. http://www.environment.gov.au/system/files/pages/0ff19ccf-31f0-4d4f-beaa-871e7b49041d/files/blacktown-final-report.pdf (accessed 11.02.16).

Cahill, R. and Lund, J. (2013) Residential water conservation in australia and california. *Journal of Water Resources Planning and Management* 139(1), 117-121.

California Department of Water Resources (2013) Bulletin 132-11, Management of the California State Water Project. http://www.water.ca.gov/swpao/docs/bulletins/bulletin132/Bulletin132-11.pdf (accessed 01.09.15).

Carlson, S.W. and Walburger, A. (2007) Energy Index Development for Benchmarking Water and Wastewater Utilities. http://www.waterrf.org/ExecutiveSummaryLibrary/91201_3009_profile.pdf (accessed 06.03.14).

Chang, N.B., Qi, C. and Yang, Y.J. (2012) Optimal expansion of a drinking water infrastructure system with respect to carbon footprint, cost-effectiveness and water demand. *Journal of Environmental Management* 110, 194-206.

Cherchi, C., Badruzzaman, M., Oppenheimer, J., Bros, C.M. and Jacangelo, J.G. (2015) Energy and water quality management systems for water utility's operations: A review. *Journal of Environmental Management* 153, 108-120.

Chiplunkar, A., Seetharam, K. and Tan, C.K.T. (2012) Good Practices in urban water management: Decoding good practices for a successful future, Asian Development Bank, Mandaluyong City, Philippines.

Chong, M.N., Umapathi, S., Mankad, A., Sharma, A. and T., G. (2011) A Benchmark Analysis of Water Savings by Mandated Rainwater Tank Users in South East Queensland (Phase 2). http://www.urbanwateralliance.org.au/publications/UWSRA-tr49.pdf (accessed 26.05.14).

ClimateWorks Australia (2010) Low Carbon Growth Plan for Australia. http://www.climateworksaustralia.org/sites/default/files/documents/publications/climateworks_lcgp_australia_full_report_mar2010.pdf (accessed 19.05.15).

Cook, S., Hall, M. and Gregory, A. (2012) Energy use in the provision and consumption of urban water in Australia: an update. http://publications.csiro.au/rpr/download?pid=csiro:EP122271&dsid=DS4 (accessed 27.03.14).

Cook, S., Sharma, A. and Chong, M. (2013) Performance Analysis of a Communal Residential Rainwater System for Potable Supply: A Case Study in Brisbane, Australia. *Water Resources Management* 27(14), 4865-4876.

Čuček, L., Klemeš, J.J. and Kravanja, Z. (2012) A review of footprint analysis tools for monitoring impacts on sustainability. *Journal of Cleaner Production* 34, 9-20.

Danish Water and Waste Water Association (2013) DANVA Benchmarking 2013 – process benchmarking and statistics. http://reader.livedition.dk/danva/134/ (accessed 17.07.15).

Dawadi, S. and Ahmad, S. (2013) Evaluating the impact of demand-side management on water resources under changing climatic conditions and increasing population. *Journal of Environmental Management* 114, 261-275.

Decker, E.H., Elliott, S., Smith, F.A., Blake, D.R. and Rowland, F.S. (2000) Energy and material flow through the urban ecosystem. *Annual Review of Energy and the Environment* 25, 685-740.

DeMonsabert, S. and Liner, B.L. (1998) Integrated energy and water conservation modeling. *Journal of Energy Engineering* 124(1), 1-19.

Department of Industry and Science (2015a) Australian Energy Statistics 2015. http://industry.gov.au/Office-of-the-Chief-Economist/Publications/Pages/Australian-energy-statistics.aspx (accessed 30.05.16).

Department of Industry and Science (2015b) 2015 Australian Energy Update. http://www.industry.gov.au/Office-of-the-Chief-Economist/Publications/Documents/aes/2015-australian-energy-statistics.pdf (accessed 27.09.16).

Devkota, J., Schlachter, H., Anand, C., Phillips, R. and Apul, D. (2013) Development and application of EEAST: A life cycle based model foruse of harvested rainwater and composting toilets in buildings. *Journal of Environmental Management* 130, 397-404.

Engineers Australia (2010) Western Australia Infrastructure Report Card 2010. http://www.engineersaustralia.org.au/sites/default/files/shado/Infrastructure%20Report%20Cards/Australian/2010%20Australian%20IRC%20Report.pdf (accessed 09.04.15).

EPA Victoria (2008) Environment and Resource Efficiency Plans (EREP) and Water Management Action Plans (waterMAP) http://www.epa.vic.gov.au/~/media/Publications/1212.pdf (accessed 28.07.16).

Frauendorfer, R. and Liemberger, R. (2010) The issues and challenges of reducing non-revenue water. http://www.adb.org/sites/default/files/publication/27473/reducing-nonrevenue-water.pdf (accessed 08.10.15).

Fyfe, J., McKibbin, J., Mohr, S., Madden, B., Turner, A. and Ege, C. (2015) Evaluation of the Environmental Effects of the WELS Scheme, report prepared for the Australian Commonwealth Government Department of the Environment by the Institute for Sustainable Futures, University of Technology, Sydney. http://www.waterrating.gov.au/system/files/resources/c679f9ae-3045-4c0c-9b1c-9c1b81f2036b/files/evaluation-wels-scheme-final-report.pdf (accessed 24.04.15).

Gleick, P.H. (2003) Global Freshwater Resources: Soft-Path Solutions for the 21st Century. *Science* 302(5650), 1524-1528.

Gleick, P.H. and Cooley, H.S. (2009) Energy implications of bottled water. *Environmental Research Letters* 4(1).

Gold Coast City Council (2006) Gold Coast City Council Annual report 2005-06.

Gold Coast City Council (2013) City of Gold Coast Water and Sewerage Network Service Plan Part A. http://www.gchaveyoursay.com.au/document/show/125 (accessed 18.09.14).

Grant, S.B., Fletcher, T.D., Feldman, D., Saphores, J.D., Cook, P.L.M., Stewardson, M., Low, K., Burry, K. and Hamilton, A.J. (2013) Adapting urban water systems to a changing climate: Lessons from the millennium drought in southeast Australia. *Environmental Science and Technology* 47(19), 10727-10734.

Hall, M.R., West, J., Sherman, B., Lane, J. and De Haas, D. (2011) Long-term trends and opportunities for managing regional water supply and wastewater greenhouse gas emissions. *Environmental Science and Technology* 45(12), 5434-5440.

Head, B.W. (2014) Managing urban water crises: Adaptive policy responses to drought and flood in Southeast Queensland, Australia. *Ecology and Society* 19(2).

Hering, J.G., Waite, T.D., Luthy, R.G., Drewes, J.E. and Sedlak, D.L. (2013) A changing framework for urban water systems. *Environmental Science and Technology* 47(19), 10721-10726.

Hischier, R. and Weidema, B. (2010) Implementation of Life Cycle Impact Assessment Methods Data v2.2. http://www.proyectaryproducir.com.ar/public_html/Seminarios_Posgrado/Material_de_referencia/EcoInvent%2003_LCIA-Implementation-v2.2.pdf (accessed 30.01.17).

Horne, J. (2016) Resilience in major Australian cities: assessing capacity and preparedness to respond to extreme weather events. *International Journal of Water Resources Development*, 1-20.

Howells, M., Hermann, S., Welsch, M., Bazilian, M., Segerström, R., Alfstad, T., Gielen, D., Rogner, H., Fischer, G., Van Velthuizen, H., Wiberg, D., Young, C., Alexander Roehrl, R., Mueller, A., Steduto, P. and Ramma, I. (2013) Integrated analysis of climate change, land-use, energy and water strategies. *Nature Climate Change* 3(7), 621-626.

Hussey, K. and Pittock, J. (2012) The energy-water nexus: Managing the links between energy and water for a sustainable future. *Ecology and Society* 17(1).

Inman, D. and Jeffrey, P. (2006) A review of residential water conservation tool performance and influences on implementation effectiveness. *Urban Water Journal* 3(3), 127-143.

Kennedy, C., Steinberger, J., Gasson, B., Hansen, Y., Hillman, T., Havránek, M., Pataki, D., Phdungsilp, A., Ramaswami, A. and Mendez, G.V. (2009) Greenhouse gas emissions from global cities. *Environmental Science and Technology* 43(19), 7297-7302.

Kenway, S.J., Priestley, A., Cook, S., Seo, S., Inman, M., Gregory, A. and Hall, M. (2008) Energy use in the provision and consumption of urban water in Australia and New Zealand. http://www.clw.csiro.au/publications/waterforahealthycountry/2008/wfhc-urban-water-energy.pdf (accessed 27.03.14).

Kenway, S.J., Lant, P. and Priestley, T. (2011a) Quantifying water-energy links and related carbon emissions in cities. *Journal of Water and Climate Change* 2(4), 247-259.

Kenway, S.J., Lant, P.A., Priestley, A. and Daniels, P. (2011b) The connection between water and energy in cities: A review. *Water Science and Technology* 63(9), 1983-1990.

Kenway, S.J., Scheidegger, R., Larsen, T.A., Lant, P. and Bader, H.P. (2012) Water-related energy in households: A model designed to understand the current state and simulate possible measures. *Energy and Buildings* 58, 378–389.

Kenway, S.J., Binks, A., Lane, J., Lant, P.A., Lam, K.L. and Simms, A. (2015) A systemic framework and analysis of urban water energy. *Environmental Modelling and Software* 73, 272-285.

Kenway, S.J. and Lam, K.L. (2016) Quantifying and managing urban water-related energy use systemically: case study lessons from Australia. *International Journal of Water Resources Development* 32(3), 379-397.

Kesicki, F. and Ekins, P. (2012) Marginal abatement cost curves: A call for caution. *Climate Policy* 12(2), 219-236.

Kiefer, J.C. (2014) Water Demand Forecasting in Uncertain Times: Isolating the Effects of the Great Recession WRF Project #4458. Water Research Foundation (ed), Denver, Colorado.

Klein, G., Krebs, M., Hall, V., O'Brien, T. and Blevins, B. (2005) California's Water–Energy Relationship – Final Staff Report. (accessed

Lam, K.L., Lant, P.A., O'Brien, K. and Kenway, S.J. (2016) Comparison of water-energy trajectories of two major regions experiencing water shortage. *Journal of Environmental Management* 181, 403-412.

Lam, K.L., Kenway, S.J. and Lant, P.A. (2017a) City-scale analysis of water-related energy identifies more cost-effective solutions. *Water Research* 109, 287-298.

Lam, K.L., Kenway, S.J. and Lant, P.A. (2017b) Energy use for water provision in cities. *Journal of Cleaner Production* 143, 699-709.

Lane, J.L., de Haas, D.W. and Lant, P.A. (2015) The diverse environmental burden of city-scale urban water systems. *Water Research* 81, 398-415.

Laves, G., Kenway, S., Begbie, D., Roiko, A., Carter, R.W. and Waterman, P. (2014) The research-policy nexus in climate change adaptation: Experience from the urban water sector in South East Queensland, Australia. *Regional Environmental Change* 14(2), 449-461.

Lee, M. and Tansel, B. (2012) Life cycle based analysis of demands and emissions for residential water-using appliances. *Journal of Environmental Management* 101, 75-81.

Lemos, D., Dias, A.C., Gabarrell, X. and Arroja, L. (2013) Environmental assessment of an urban water system. *Journal of Cleaner Production* 54, 157-165.

Li, Y., Xiong, W., Zhang, W., Wang, C. and Wang, P. (2016) Life cycle assessment of water supply alternatives in water-receiving areas of the South-to-North Water Diversion Project in China. *Water Research* 89, 9-19.

lifecycles (2015) Australasian LCI database version 2015.02. http://www.lifecycles.com.au/australasian-database (accessed 28.09.16).

LinkWater (2009) LinkWater Annual Report 2008-09. http://www.parliament.qld.gov.au/docs/find.aspx?id=5309T1426 (accessed 03.11.14).

Lockrey, S. (2013) Life Cycle Assessment of Hot Water Delivery. http://mams.rmit.edu.au/xogcg47u4b2s.pdf (accessed 13.10.15).

Loubet, P., Roux, P., Loiseau, E. and Bellon-Maurel, V. (2014) Life cycle assessments of urban water systems: A comparative analysis of selected peer-reviewed literature. *Water Research* 67, 187-202.

Lovell, A. (2013) Energy –Water Nexus The Australian Experience, San Francisco.

Lundie, S., Peters, G.M. and Beavis, P.C. (2004) Life cycle assessment for sustainable metropolitan water systems planning. *Environmental Science and Technology* 38(13), 3465-3473.

Lundie, S., Peters, G. and Beavis, P. (2005) Quantitative systems analysis as a strategic planning approach for metropolitan water service providers, pp. 11-20.

March, H., Saurí, D. and Rico-Amorós, A.M. (2014) The end of scarcity? Water desalination as the new cornucopia for Mediterranean Spain. *Journal of Hydrology* 519(PC), 2642-2651.

Marsden, J. and Pickering, P. (2006) Securing Australia's Urban Water Supplies: Opportunities and Impediments. http://www.environment.gov.au/system/files/resources/a4c27c83-6edd-4fc5-84a2-70e38b183fc4/files/urban-water-report.doc (accessed 08.07.16).

Melbourne Water (2013a) Energy Efficiency Opportunities Program - Public Report 2013. http://www.melbournewater.com.au/whatwedo/Liveability-and-environment/Documents/Energy%20Efficiency%20Opportunities%20-%206th%20public%20report%20(Western%20Treatment%20Plant).pdf (accessed 18.11.15).

Melbourne Water (2013b) Water storage reservoirs. http://www.melbournewater.com.au/whatwedo/supply-water/reservoirs/Pages/water-storage-reservoirs.aspx (accessed 12.07.16).

Melbourne Water (2014a) Water Outlook for Melbourne 1 December 2014. http://www.melbournewater.com.au/getinvolved/saveandreusewater/Documents/Water%20Outlook%20December%202014.pdf (accessed 21.05.2015).

Melbourne Water (2014b) Melbourne Water Annual Report 2013-14. http://www.melbournewater.com.au/aboutus/reportsandpublications/annual-report/documents/4977_mel_annual_report_2014_lr.pdf (accessed 19.06.15).

Melbourne Water (2016a) Inflow over the years. http://www.melbournewater.com.au/waterdata/waterstorages/Pages/Inflow-over-the-years.aspx (accessed 13.07.16).

Melbourne Water (2016b) Water storage data. http://www.melbournewater.com.au/waterdata/waterstorages/Pages/water-storages.aspx (accessed 26.04.16).

Metropolitan Water Directorate (2014) Shoalhaven Transfer Scheme. http://www.metrowater.nsw.gov.au/planning-sydney/dams/shoalhaven-transfer-scheme (accessed 23.07.16).

Mini, C., Hogue, T.S. and Pincetl, S. (2015) The effectiveness of water conservation measures on summer residential water use in Los Angeles, California. *Resources, Conservation and Recycling* 94, 136-145.

Mo, W., Zhang, Q., Mihelcic, J.R. and Hokanson, D.R. (2011) Embodied energy comparison of surface water and groundwater supply options. *Water Research* 45(17), 5577-5586.

Mo, W., Wang, R. and Zimmerman, J.B. (2014) Energy-water nexus analysis of enhanced water supply scenarios: A regional comparison of Tampa bay, Florida, and San Diego, California. *Environmental Science and Technology* 48(10), 5883-5891.

Moglia, M., Tjandraatmadja, G., Delbridge, N., Gulizia, E., Sharma, A.K., Butler, R. and Gan, K. (2014) Survey of savings and conditions of rainwater tanks. http://www.clearwater.asn.au/user-data/research-projects/swf-files/10tr4---001-rainwater-surveys-final-report.pdf (accessed 22.09.16).

Morgan, R.A. (2015) Running out? : water in Western Australia, Crawley, W.A. UWA Publishing.

National Water Commission (2011) National Performance Report 2009–10: Urban water utilities. http://archive.nwc.gov.au/library/topic/npr/npr-2009-10-urban (accessed 13.09.14).

Newman, P. (2014) The Story of Perth's Water Resilience Turnaround, pp. 24-26, Australian Water Association.

Nogueira Vilanova, M.R. and Perrella Balestieri, J.A. (2014) Energy and hydraulic efficiency in conventional water supply systems. *Renewable and Sustainable Energy Reviews* 30, 701-714.

Nogueira Vilanova, M.R. and Perrella Balestieri, J.A. (2015) Exploring the water-energy nexus in Brazil: The electricity use forwater supply. *Energy* 85, 415-432.

NSW Government (2013) Hawkesbury-Nepean River Recovery Program - Final Report. http://www.water.nsw.gov.au/__data/assets/pdf_file/0010/548506/recovery_hn-hnrrp-final-report-irrigation-and-landscape-efficiency-project-section.pdf (accessed 04.02.16).

Olsson, G. (2012) Water and energy: threats and opportunities, IWA, London.

Plappally, A.K. and Lienhard V, J.H. (2012) Energy requirements for water production, treatment, end use, reclamation, and disposal. *Renewable and Sustainable Energy Reviews* 16(7), 4818-4848.

Poussade, Y., Vince, F. and Robillot, C. (2011) Energy consumption and greenhouse gases emissions from the use of alternative water sources in South East Queensland. *Water Science and Technology: Water Supply* 11, 281-287.

Prein, A.F., Holland, G.J., Rasmussen, R.M., Clark, M.P. and Tye, M.R. (2016) Running dry: The U.S. Southwest's drift into a drier climate state. *Geophysical Research Letters* 43(3), 1272-1279.

Price, N., Renouf, M.A. and Pagan, R.J. (2010) Outcomes of mandatory water efficiency in business - A case study from South East Queensland, Australia, pp. 1-17, Colombo, Sri Lanka.

Proença, L.C., Ghisi, E., Tavares, D.D.F. and Coelho, G.M. (2011) Potential for electricity savings by reducing potable water consumption in a city scale. *Resources, Conservation and Recycling* 55(11), 960-965.

Public Works Committee (2011) Bolivar Wastewater Treatment Plant Energy Use Optimisation Final Report. http://www.parliament.sa.gov.au/HOUSEOFASSEMBLY/BUSINESSOFTHEASSEMBLY/RECORDSANDPAPERS/TABLEDPAPERSANDPETITIONS/Pages/TabledPapersandPetitions.aspx?TPLoadDoc=true&TPDocType=1&TPP=52&TPS=1&TPItemID=108&TPDocName=PWC%2B-%2BBolivar%2BWWTP%2BEnergy%2BUse%2BOptimisation.pdf (accessed 17.12.15).

Queensland Water Commission (2010) South East Queensland Water Strategy. http://www.dews.qld.gov.au/__data/assets/pdf_file/0019/32734/seqws.pdf (accessed 09.12.13).

Queensland Water Commission (2012) South East Queensland Water Strategy Annual Report 2012. http://www.dews.qld.gov.au/__data/assets/pdf_file/0020/32735/seqws-ar2012.pdf (accessed 09.02.14).

Quezada, G., Grozev, G., Seo, S. and Wang, C.H. (2014) The challenge of adapting centralised electricity systems: Peak demand and maladaptation in South East Queensland, Australia. *Regional Environmental Change* 14(2), 463-473.

Racoviceanu, A.I. and Karney, B.W. (2010) Life-cycle perspective on residential water conservation strategies. *Journal of Infrastructure Systems* 16(1), 40-49.

Roberts, P. (2005) Yarra Valley Water 2004 Residential End Use Measurement Study. http://www.yvw.com.au/yvw/groups/public/documents/document/yvw1001680.pdf (accessed 08.10.15).

Rothausen, S.G.S.A. and Conway, D. (2011) Greenhouse-gas emissions from energy use in the water sector. *Nature Climate Change* 1(4), 210-219.

Rozos, E., Makropoulos, C. and Butler, D. (2010) Design robustness of local water-recycling schemes. *Journal of Water Resources Planning and Management* 136(5), 531-538.

Sanders, K.T. and Webber, M.E. (2012) Evaluating the energy consumed for water use in the United States. *Environmental Research Letters* 7(3).

Sanders, K.T. and Webber, M.E. (2015) Evaluating the energy and CO2 emissions impacts of shifts in residential water heating in the United States. *Energy* 81, 317-327.

Sanjuan-Delmás, D., Petit-Boix, A., Gasol, C.M., Farreny, R., Villalba, G., Suarez-Ojeda, M.E., Gabarrell, X., Josa, A. and Rieradevall, J. (2015) Environmental assessment of drinking water transport and distribution network use phase for small to medium-sized municipalities in Spain. *Journal of Cleaner Production* 87(1), 573-582.

Sapporo City Waterworks Bureau (2015) 札幌水道ビジョンとは [Sapporo Water Vision]. http://www.city.sapporo.jp/suido/c03/c03third/suido_vision.html (accessed 14.01.16).

Saurí, D. (2013) Water conservation: Theory and evidence in urban areas of the developed world. *Annual Review of Environment and Resources* 38, 227-248.

Seqwater (2013a) Year 2013 Water Supply Asset Plan. http://www.seqwater.com.au/sites/default/files/PDF%20Documents/Publications/2013-Water-Supply-Asset-Plan.pdf (accessed 19.07.14).

Seqwater (2013b) Annual Report 2012 -13 For the Western Corridor Recycled Water Scheme - Recycled Water Management Plan. http://www.seqwater.com.au/sites/default/files/PDF%20Documents/Publications/2012-13%20WCRWS%20Annual%20Report.pdf (accessed 02.10.14).

Seqwater (2014a) Seqwater Annual Report 2013-14. http://www.seqwater.com.au/sites/default/files/PDF%20Documents/Annual%20Reports/Seqwater%20Annual%20Report%202013-14%20full%20report.pdf (accessed 08.12.14).

Seqwater (2014b) Annual Operations Plan May 2014. http://www.seqwater.com.au/sites/default/files/PDF%20Documents/Publications/Annual%20Operations%20Plan%20May%202014.pdf (accessed 14.07.14).

Seqwater (2015) Water for Life South East Queensland's Water Security Program 2015-2045. http://www.seqwater.com.au/sites/default/files/PDF%20Documents/Water%20for%20life_Water%20Security%20Program.pdf (accessed 15.07.16).

Seqwater (2016) Historical dam storage data. http://www.seqwater.com.au/water-supply/dam-levels (accessed 26.04.16).

Shrestha, E., Ahmad, S., Johnson, W., Shrestha, P. and Batista, J.R. (2011) Carbon footprint of water conveyance versus desalination as alternatives to expand water supply. *Desalination* 280(1-3), 33-43.

Shrestha, E., Ahmad, S., Johnson, W. and Batista, J.R. (2012) The carbon footprint of water management policy options. *Energy Policy* 42, 201-212.

Siddiqi, A. and Anadon, L.D. (2011) The water-energy nexus in Middle East and North Africa. *Energy Policy* 39(8), 4529-4540.

Siddiqi, A. and De Weck, O.L. (2013) Quantifying end-use energy intensity of the urban water cycle. *Journal of Infrastructure Systems* 19(4), 474-485.

Siems, R. and Sahin, O. (2016) Energy intensity of residential rainwater tank systems: Exploring the economic and environmental impacts. *Journal of Cleaner Production* 113, 251-262.

Smart Water Fund (2013) Water Appliance Stock Survey and Usage Pattern Melbourne 2012. https://www.yvw.com.au/yvw/groups/public/documents/document/yvw1004066.pdf (accessed 12.10.15).

Smith, K., Liu, S., Liu, Y., Savic, D., Olsson, G., Chang, T. and Wu, X. (2015) Impact of urban water supply on energy use in China: a provincial and national comparison. *Mitigation and Adaptation Strategies for Global Change*.

State of the Environment 2011 Committee (2011) Australia state of the environment 2011. Independent report to the Australian Government Minister for Sustainability, Environment, Water, Population and Communities. DSEWPaC (ed), Canberra.

Stillwell, A.S. and Webber, M.E. (2010) World Environmental and Water Resources Congress 2010, pp. 4093-4108.

Stokes, J. and Horvath, A. (2006) Life cycle energy assessment of alternative water supply systems. *International Journal of Life Cycle Assessment* 11(5), 335-343.

Stokes, J. and Horvath, A. (2010) Life-Cycle Assessment of Urban Water Provision: Tool and Case Study in California. *Journal of Infrastructure Systems* 17(1), 15-24.

Stokes, J.R. and Horvath, A. (2009) Energy and air emission effects of water supply. *Environmental Science and Technology* 43(8), 2680-2687.

Stokes, J.R., Horvath, A. and Sturm, R. (2013) Water loss control using pressure management: Life-cycle energy and air emission effects. *Environmental Science and Technology* 47(19), 10771-10780.

Stokes, J.R., Hendrickson, T.P. and Horvath, A. (2014) Save water to save carbon and money: Developing abatement costs for expanded greenhouse gas reduction portfolios. *Environmental Science and Technology* 48(23), 13583-13591.

Swoboda, K. (2013) Energy prices – the story behind rising costs. http://www.aph.gov.au/About_Parliament/Parliamentary_Departments/Parliamentary_Library/pubs/BriefingBook44p/EnergyPrices (accessed 11.09.14).

Sydney Catchment Authority (2006) Sydney Catchment Authority Annual Report 2005-06. http://www.opengov.nsw.gov.au/download/10837 (accessed 20.06.15).

Sydney Catchment Authority (2009) Energy Efficiency Opportunities Public Report. http://www.waternsw.com.au/__data/assets/pdf_file/0014/17015/SCA-Energy-Efficiency-Opportunities-Public-Report-2008-09-FINAL-250610.pdf (accessed 21.12.15).

Sydney Catchment Authority (2010) Sydney Catchment Authority Annual Report 2009-10. http://www.opengov.nsw.gov.au/download/11477 (accessed 20.06.15).

Sydney Water Corporation (2009) Water Conservation and Recycling Implementation Report 2008-09. http://www.sydneywater.com.au/Publications/Reports/AnnualReport/2009/docs/compliance/2008-09_WCRIR_Report_FINAL.pdf (accessed 04.02.16).

Sydney Water Corporation (2011) Sydney Water Annual Report 2011. http://www.sydneywater.com.au/Publications/Reports/AnnualReport/2011/annual_report/index.html (accessed 14.10.16).

Sydney Water Corporation (2012a) Sydney Water Annual Report 2012. http://www.sydneywater.com.au/Publications/Reports/AnnualReport/2012/assets/Sydney%20Water%20Annual%20Report%202012_web.pdf (accessed 20.12.15).

Sydney Water Corporation (2012b) Water Efficiency Report 2011-12. http://www.sydneywater.com.au/Publications/Reports/AnnualReport/2012/assets/Operating%20Licence%20Water%20Efficiency%20Report%202011-12.pdf (accessed 10.02.16).

Sydney Water Corporation (2012c) Sydney Water Operating Licence Environment Report: Environmental Indicators Report 2011–12. http://www.sydneywater.com.au/Publications/Reports/AnnualReport/2012/assets/Operating%20Licence%20Environment%20Report%202011-12.pdf (accessed 20.06.15).

Sydney Water Corporation (2013) Energy Efficiency Opportunities 2013 Public Report. http://www.sydneywater.com.au/web/groups/publicwebcontent/documents/document/zgrf/mdu2/~edisp/dd_056052.pdf (accessed 18.11.15).

Talebpour, M.R., Sahin, O., Siems, R. and Stewart, R.A. (2014) Water and energy nexus of residential rainwater tanks at an end use level: Case of Australia. *Energy and Buildings* 80, 195-207.

Tokyo Metropolitan Government Bureau of Waterworks (2014) 東京水道エネルギー効率化10年プラン [Tokyo Water Supply Energy Efficiency 10 Year Plan]. https://www.waterworks.metro.tokyo.jp/suidojigyo/torikumi/kankyo/pdf/energy_plan.pdf (accessed 09.07.15).

Tokyo Metropolitan Government Bureau of Waterworks (2015) Tokyo Waterworks 10 Year Plan for Energy Efficiency. http://www.waterprofessionals.metro.tokyo.jp/pdf/energy-1_01.pdf (accessed 25.10.15).

Turner, A., White, S., Beatty, K. and Gregory, A. (2005) Results of the largest residential demand management program in Australia. *Water Science and Technology: Water Supply* 5, 249-256.

Turner, A., White, S., Chong, J., Dickinson, M.A., Cooley, H. and Donnelly, K. (2016) Managing drought: Learning from Australia. http://www.allianceforwaterefficiency.org/WorkArea/DownloadAsset.aspx?id=9554 (accessed 14.03.16).

Twomey Sanders, K. (2016) The energy trade-offs of adapting to a water-scarce future: case study of Los Angeles. *International Journal of Water Resources Development* 32(3), 362-378.

Umapathi, S., Chong, M.N. and Sharma, A.K. (2013) Evaluation of plumbed rainwater tanks in households for sustainable water resource management: A real-time monitoring study. *Journal of Cleaner Production* 42, 204-214.

Van Dijk, A.I.J.M., Beck, H.E., Crosbie, R.S., De Jeu, R.A.M., Liu, Y.Y., Podger, G.M., Timbal, B. and Viney, N.R. (2013) The Millennium Drought in southeast Australia (2001-2009): Natural and human causes and implications for water resources, ecosystems, economy, and society. *Water Resources Research* 49(2), 1040-1057.

Venkatesh, G., Chan, A. and Brattebø, H. (2014) Understanding the water-energy-carbon nexus in urban water utilities: Comparison of four city case studies and the relevant influencing factors. *Energy* 75, 153-166.

Victorian Water Industry Association (2011) Electricity issues in the Victorian Water Sector, Melbourne.

Vieira, A.S., Beal, C.D., Ghisi, E. and Stewart, R.A. (2014a) Energy intensity of rainwater harvesting systems: A review. *Renewable and Sustainable Energy Reviews* 34, 225-242.

Vieira, A.S., Beal, C.D. and Stewart, R.A. (2014b) Residential water heaters in Brisbane, Australia: Thinking beyond technology selection to enhance energy efficiency and level of service. *Energy and Buildings* 82, 222-236.

Wakeel, M., Chen, B., Hayat, T., Alsaedi, A. and Ahmad, B. (2016) Energy consumption for water use cycles in different countries: A review. *Applied Energy* 178, 868-885.

Walton, C. and Holmes, K. (2009) How much water efficiency does $321 million buy?, Sydney, Australia.

Water Corporation (2002) Annual Report 2002. http://www.parliament.wa.gov.au/publications/tabledpapers.nsf/displaypaper/3620242af91f67d018b28d6e48256c3900114542/%24file/watercorp2002.pdf (accessed 02.05.15).

Water Corporation (2009) Perth Residential Water Use Study 2008/2009. http://www.water.wa.gov.au/__data/assets/pdf_file/0016/5272/98576.pdf (accessed 03.03.15).

Water Corporation (2012) Southern seawater desalination project performance and compliance report. http://www.watercorporation.com.au/~/media/files/residential/water-supply-and-services/desalination/ssdp/ssdp-performance-compliance-report-april-2012.pdf (accessed 09.04.15).

Water Corporation (2013) Annual Report 2013. http://www.watercorporation.com.au/-/media/files/about-us/our-performance/annual-report/2013-annual-report.pdf (accessed 22.03.15).

Water Corporation (2014) Annual Report 2014. http://www.watercorporation.com.au/-/media/files/about-us/our-performance/annual-report/annual-report-2014/water-corporation-annual-report-2014.pdf (accessed 27.03.15).

Water Corporation (2015) Annual Report 2015. http://www.watercorporation.com.au/-/media/files/about-us/our-performance/annual-report-2015/water-corporation-annual-report-2015.pdf (accessed 20.07.16).

Water Services Association of Australia (2008) National Performance Report 2006-07: Urban water utilities. http://archive.nwc.gov.au/library/topic/npr/npr-2006-07-urban (accessed 09.09.14).

Water Services Association of Australia (2013) WSAA Dams Information Pack One. https://www.wsaa.asn.au/sites/default/files/publication/download/WSAA%20Dams%20Fact%20Sheet%20Information%20Pack.pdf (accessed 13.07.16).

WaterNSW (2016) Archived verified storage reports. http://www.waternsw.com.au/supply/dam-levels/greater-sydneys-dam-levels/weekly-verified-storage-reports/archived-verified-storage-reports (accessed 26.04.16).

WaterSecure (2009) WaterSecure Annual Report 2008-09. http://www.parliament.qld.gov.au/docs/find.aspx?id=5309T1425 (accessed 09.09.14).

Willis, R.M., Stewart, R.A., Panuwatwanich, K., Jones, S. and Kyriakides, A. (2010) Alarming visual display monitors affecting shower end use water and energy conservation in Australian residential households. *Resources, Conservation and Recycling* 54(12), 1117-1127.

Willuweit, L. and O'Sullivan, J.J. (2013) A decision support tool for sustainable planning of urban water systems: Presenting the Dynamic Urban Water Simulation Model. *Water Research*.

WSAA (2012) Cost of carbon abatement in the Australian water industry. http://www.wsaa.asn.au/sites/default/files/publication/download/Occasional%20Paper%2028%20Cost%20carbon%20abatement%20in%20the%20urban%20water%20industry%20May%202012.pdf (accessed 18.01.15).

Appendix A1 Data sources and details for energy use for water provision in cities

Lam, K.L., Kenway, S.J., Lant, P.A. (2017) Energy use for water provision in cities. *Journal of Cleaner Production* 143, 699-709.

Supplementary Material

Table A1-1 Data sources and quantification approaches

City/ region[a]	Country	Year(s) of the result	Data sources				Quantification approaches & assumptions		
			Population (P)	**Total water supplied (W_T)**	**Total energy use for water supply (E_T)**	**Energy intensity for water supply (EI)**	**Per capita water use (W_C)**	**Per capita energy use for water supply (E_C)**	**Remark**
Brisbane	Australia	2002-2014	-	-	-	-	[1]	[1]	The energy result is referenced from an earlier work that quantified the time-series energy use based on a regional water balance model of South East Queensland and energy data from the regional bulk water supplier
Melbourne	Australia	2001-2015	$P = W_{T,B} / W_C$	Retailers ($W_{T,R}$): [2-5] Bulk water ($W_{T,B}$): [6]	Retailers* ($E_{T,R}$): [7-10] Bulk water** ($E_{T,B}$): [11-18]	Retailers*: $EI_R = E_{T,R} / W_{T,R}$ [19-22] Bulk water**: $EI_B = E_{T,B} / W_{T,B}$	[6]	$E_C = (EI_R + EI_B) \times W_C$	* For the three retailers (i.e., Yarra Valley Water, City West Water and South East Water), data gaps for energy exist for some years and were estimated from interpolating or averaging the energy intensity from other years. ** Bulk water supplier (i.e., Melbourne Water) is the biggest energy consumer for the water supply system in Melbourne. The complete time-series data (2001 – 2014) are available.
Perth	Australia	2002-2015	[2-5]	[2-5]	-	[23-26] *	$W_C = W_T / P$	$E_C = EI \times W_C$	* The energy intensity for water supply of the whole state of Western Australia was used to estimate the per capita energy use in Perth (84% of the state's total population)
Sydney	Australia	2002-2014	[2-4]	[2-4]	[27-45]	-	$W_C = W_T / P$	$E_C = E_T / P$	The results include the regions of Greater Metropolitan Sydney, Illawarra and Blue Mountains served by Sydney Water.
Rio de Janeiro	Brazil	2014	[46]	[46]	[46]	-	$W_C = W_T / P$	$E_C = E_T / P$	-
Salvador	Brazil	2014	[46]	[46]	[46]	-	$W_C = W_T / P$	$E_C = E_T / P$	-
São Paulo	Brazil	2003-2014	[46-57]	[46-57]	[46-57]	-	$W_C = W_T / P$	$E_C = E_T / P$	Considering the area supplied by Companhia de Saneamento Básico do Estado de São Paulo S.A (SABESP)
Toronto	Canada	2006, 2011-2013	-	[58-61]*	[58-61]	$EI = E_T / W_T$**	[62]***	$E_C = EI \times W_C$	* Total water treated in Toronto (included for the York region) ** Energy intensity of water produced in Toronto (included for the York region) *** Per capita water use in the Toronto (not including the York region).

Table A1-1 (cont.) Data sources and quantification approaches

City/ region[1]	Country	Year(s) of the result	Data sources				Quantification approaches & assumptions		
			Population (P)	Total water supplied (W_T)	Total energy use for water supply (E_T)	Energy intensity for water supply (EI)	Per capita water use (W_C)	Per capita energy use for water supply (E_C)	Remark
Beijing	China	2011	-	-	-	[63]	[64]*	$E_C = EI \times W_C$	* Excluding the use for environmental flow
Tianjin	China	2011	-	-	-	[63]	[64]*	$E_C = EI \times W_C$	* Excluding the use for environmental flow
Copenhagen	Denmark	2008-2010, 2012-2014	[65-70]	[65-70] *	-	[65-70]	$W_C = W_T / P$	$E_C = EI \times W_C$	* Based on the amount of water sold and the percentage of water loss.
Berlin	Germany	2010	[71]	[71, 72] *	-	[73]	$W_C = W_T / P$	$E_C = EI \times W_C$	* Based on the amount of water supplied to final consumers and the percentage of water loss.
Ahmedabad	India	2009	[74]		-	-	[75]	[76]	-
Bangalore	India	2013	[74]	[77]	-	[77]	$W_C = W_T / P$	$E_C = EI \times W_C$	-
Bhopal	India	2009	[74]	[76]	-	-	$W_C = W_T / P$	[76]	-
Delhi	India	2009	[74]	-	-	-	[75]	[76]	-
Jamshedpur	India	2005-2009	[78] *	[78]	-	[78]	$W_C = W_T / P$	$E_C = EI \times W_C$	* Based on the population coverage for the lease area's population
Osaka	Japan	2005-2014	[79]	[79]	[80-82]	-	$W_C = W_T / P$	$E_C = E_T / P$	-
Sapporo	Japan	2007-2014	[83, 84]	[83, 84]	-	[85-87]	$W_C = W_T / P$	$E_C = EI \times W_C$	-
Tokyo	Japan	2000-2003, 2005, 2009-2014	[88]	[88]	[89]	[90-93]	$W_C = W_T / P$	$E_C = EI \times W_C$	-
Yokohama	Japan	2004-2007, 2009-2014	[94]	[95-100]	[95-111]	$EI= E_T / W_T$ *	[112-116]	$E_C = EI \times W_C$	* The energy intensity is aggregated based on the proportion of water supplied from Yokohama Waterworks Bureau and Kanagawa Water Supply Authority.
Mexico City	Mexico	2013	[117]	[117]	-	[117, 118] *	$W_C = W_T / P$	$E_C = EI \times W_C$	* Considering the energy intensity of Cutzamala system and SACM wells.
Oslo	Norway	2001-2010	[119]	[119]	[119, 120]	-	$W_C = W_T / P$	$E_C = E_T / P$	-

Table A1-1 (cont.) Data sources and quantification approaches

City/ region[1]	Country	Year(s) of the result	Data sources				Quantification approaches & assumptions		
			Population (P)	**Total water supplied (W_T)**	**Total energy use for water supply (E_T)**	**Energy intensity for water supply (EI)**	**Per capita water use (W_C)**	**Per capita energy use for water supply (E_C)**	**Remark**
Cape Town	South Africa	2010	-	-	-	[121, 122] *	[75]	$E_C = EI \times W_C$	* Based on the energy intensity of the water sector [122] and the percentage of energy use for water supply [121].
Bangkok	Thailand	2004-2011	[123, 124]	[123, 124]	-	[125]	$W_C = W_T / P$	$E_C = EI \times W_C$	-
Denver	U.S.A.	2000-2014	[126]	[126]	Product water distribution: [126] *	[127]	$W_C = W_T / P$	$E_C = EI \times W_C$	* Total energy use based on the energy intensity of raw water pumping and water treatment [127] and actual energy use for product water distribution [126]
Los Angeles	U.S.A.	2003-2015	[128]	[128, 129]	-	[128, 129]	$W_C = W_T / P$	$E_C = EI \times W_C$	-
San Diego	U.S.A.	2003, 2007-2015	[130-145]	[130-145]	*	Imported water: [129] Treatment and distribution: [146]	$W_C = W_T / P$	$E_C = E_T / P$	* Estimated based on the ratio of water sources (local/ imported) used by San Diego, the ratio of imported water sources (State Water Project/ Colorado River) for the San Diego County, and the energy intensities of imported water, treatment and distribution
San Francisco	U.S.A.	2014	-	-	-	[147]	[148]	$E_C = EI \times W_C$	-
Tampa	U.S.A.	2010	[149]	[149]	-	[149] *	$W_C = W_T / P$	$E_C = EI \times W_C$	* Based on the electricity primary energy factor estimation for Tampa Bay, Florida [150].

[a] Brisbane: based on the results of South East Queensland: including Greater Brisbane, Gold Coast, Sunshine Coast; São Paulo: considering greater São Paulo served by SABESP; Osaka, Tokyo, Yokohama: not considering the separated industrial water supply systems; Mexico City: considering the Federal District of Mexico City; San Diego: considering the city of San Diego instead of the whole county

Data Quality Control

This study was reliant on data-mining diverse data published by various cities and water utilities. It is inevitable that there are some uncertainties in the results. Regarding the scope and boundary of both the “city” and the “water system”, it has been noted by UN-HABITAT that there is a need for a better classification of urban areas, however, it is extremely difficult for any country to change their definition of urban areas [151]. In this work, we assume the city population is the population served by the water utilities. In addition, utility data are the primary data sources in this work. Some countries such as Australia, Brazil, Denmark and Japan have established some national indicator-based frameworks for assessing and reporting performance of water utilities. This study utilised the data reported from these sources and IBNet [75] whenever possible to improve the consistency of data for inter-city comparisons.

The characteristics of the raw energy data are summarised in Table 2S. For most of the cities, the raw energy data are originated from water utilities or government agencies in the form of electricity consumption or electricity intensity of the urban water supply systems. In cities served by a single utility, the system boundary is clearly defined by the service area and included the energy use for raw water pumping, water treatment and water distribution. In cities served by multiple utilities, this work aggregated the raw energy data from all the regional utilities (i.e., bulk water supplier, water distributors, water treatment utilities) to quantify the source-to-tap energy use.

Table A1-2 Primary data characteristics

City	Country	Number of water utility [a]	Raw energy data sources				Quantification approach of raw energy data				Boundary			Scope of electricity use [b]			Form of energy data reported					Unit(s) used in raw data source	Remark
			Water utility	National benchmarking/ government report	Academic literature	Non-utility grey literature	Measurement by utilities	Calculation based on utility data	Input-output based hybrid analysis	Modelling based on utility model and data	Data source matching the city boundary	Utilities serving a wider region than the city	Not include transboundary water transfer	Operation use (Excluding administrative)	Operation use (Including administrative)	Not specified/ other	Electricity use per unit volume of water produced	Annual electricity use by system components or whole system	Per capita electricity use for water supply	Energy use per unit volume of water produced	Not specified (if it is per unit volume of water produced or not)		
Brisbane	Australia	6	✓	✓	✓					✓		✓		✓					✓			kWh/p/a	
Melbourne	Australia	4	✓				✓				✓			✓			✓	✓		✓		MJ/yr, kWh/ML, TJ/yr	The energy reported is not primary energy unit (i.e., converted using 1kWh = 3.6MJ).
Perth	Australia	1	✓				✓					✓				✓	✓					MWh/ML	
Sydney	Australia	3	✓				✓					✓			✓		✓	✓				kWh/ML, GWh, kWh	
Rio de Janeiro	Brazil	1		✓			✓				✓				✓			✓				MWh/yr	
Salvador	Brazil	1		✓			✓				✓				✓			✓				MWh/yr	
São Paulo	Brazil	1		✓			✓				✓				✓			✓				MWh/yr	
Toronto	Canada	1		✓			✓					✓		✓				✓				kWh/yr	
Beijing	China	-			✓			✓					✓	✓			✓					kWh/kL	
Tianjin	China	-			✓			✓					✓	✓			✓					kWh/kL	
Copenhagen	Denmark	1		✓			✓				✓			✓			✓					kWh/kL	
Berlin	Germany	1	✓				✓				✓					✓	✓					kWh/kL	
Ahmedabad	India	-			✓		✓				✓			✓				✓				GWh/yr	
Bangalore	India	1	✓				✓				✓			✓			✓					kWh/kL	
Bhopal	India	-			✓		✓				✓			✓				✓				GWh/yr	
Delhi	India	-			✓		✓				✓			✓				✓				GWh/yr	
Jamshedpur	India	1	✓				✓				✓					✓	✓					kWh/kL	
Osaka	Japan	1	✓				✓				✓				✓		✓					kWh/kL	

[a] Number of water utility considered in this work; "-" implies that no information are available from the data source(s). For Brisbane, the water utilities of the South East Queensland region are considered.

[b] It refers to the direct electricity use for water provision.

Table A1-2 (cont.) Raw data characteristics

City	Country	Number of water utility [a]	Raw energy data sources				Quantification approach of raw energy data				Boundary			Scope of electricity use [b]			Form of energy data reported					Unit(s) used in raw data source	Remark
			Water utility	National benchmarking/ government report	Academic literature	Non-utility grey literature	Measurement by utilities	Calculation based on utility data	Input-output based hybrid analysis	Modelling based on utility model and data	Data source matching the city boundary	Utilities serving a wider region than the city	Not include transboundary water transfer	Operation use (Excluding administrative)	Operation use (Including administrative)	Not specified/ other	Electricity use per unit volume of water produced	Annual electricity use by system components or whole system	Per capita electricity use for water supply	Energy use per unit volume of water produced	Not specified (if it is per unit volume of water produced or not)		
Sapporo	Japan	1	✓				✓				✓				✓		✓					kWh/kL	
Tokyo	Japan	1	✓				✓				✓				✓ *		✓					kWh/kL	* In 2013, electricity use other than system operation was 1.7% of total electricity use.
Yokohama	Japan	2	✓				✓					✓		✓				✓				kWh/yr	
Mexico City	Mexico	1		✓		✓	✓	✓			✓			✓			✓				✓	GWh/yr, kWh/kL	
Oslo	Norway	1			✓		✓				✓			✓				✓				GWh/yr	
Cape Town	South Africa	-		✓				✓			✓					✓		✓				kWh/yr	
Bangkok	Thailand	1	✓				✓				✓			✓			✓					kWh/kL	
Denver	U.S.A	1	✓				✓				✓			✓			✓	✓				kWh/AF, kWh	
Los Angeles	U.S.A	1	✓				✓				✓			✓			✓					kWh/AF	
San Diego	U.S.A	1	✓			✓	✓	✓			✓			✓			✓					kWh/AF, kWh/Mgal	
San Francisco	U.S.A	-				✓		✓			✓			✓			✓					kWh/AF	
Tampa	U.S.A	1			✓				✓		✓					✓*			✓			MJ/kL	* In this work, the direct primary energy use for operation and maintenance phase is used and converted to electricity unit with a primary energy factor of 3.5 [150].

[a] Number of water utility considered in this work; "-" implies that no information are available from the data source(s).

[b] It refers to the direct electricity use for water provision.

Table A1-3 Per capita water use by city, L/p/d

City	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Brisbane, Australia		478	456	414	412	428	349	306	258	258	264	237	241	252	266	
Melbourne, Australia		408	372	379	338	332	332	303	269	257	241	232	234	252	251	251
Perth, Australia	482	539	418	408	430	416	415	419	413	415	399	390	381	374	368	361
Sydney, Australia		425	416	419	368	341	339	324	305	310	312	325	293	308	312	
Rio de Janeiro, Brazil									486	525	484	488	487	483	484	
Salvador, Brazil									310	295	316	313	316	303	306	
São Paulo, Brazil				362	339	343	348	342	337	333	335	337	339	328	297	
Toronto, Canada			480	467	447	453	436	431	405	401	389	381	380	371		
Beijing, China								547	524	506	460	460	404	399		
Tianjin, China								572	519	508	461	461	431	434		
Copenhagen, Denmark									297	281	271		256	256	249	
Berlin, Germany		167			163			153			162					
Ahmedabad, India										148						
Bangalore, India														110		
Bhopal, India										167						
Delhi, India										229						
Jamshedpur, India						454	514	501	474	462						
Osaka, Japan						505	494	485	468	455	457	453	449	446	435	
Sapporo, Japan								284	277	277	280	274	274	268	266	
Tokyo, Japan	356	350	346	341	343	340	337	334	335	330	330	320	320	318	318	
Yokohama, Japan					341	339	333	329		323	323	320	315	311	308	
Mexico City, Mexico									338					336		
Oslo, Norway		498	506	487	482	479	465	464	460	460	466	452	414	433	414	
Cape Town, South Africa							223				257	219	236	233	235	
Bangkok, Thailand					553	579	597	606	612	598	595	588	601	612	606	
Denver, U.S.A	837	802	744	645	595	672	728	679	683	580	642	624	651	538	541	
Los Angeles, U.S.A	602	591	591	595	597	545	563	585	567	494	476	463	470	489	505	435
San Diego, U.S.A		596	603	570	630	592	603	616	616	563	490	465	474	497	535	488
San Francisco, U.S.A						394	386	371	367	356	344	341	337	333	314	
Tampa, U.S.A											437					

Table A1-4 Per capita energy use for water provision by city, kWh/p/a

City	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Brisbane, Australia			74.9	69.8	68.7	70.8	58.5	51.2	45.2	63.9	85.2	63.2	52.3	50.4	52.6	
Melbourne, Australia		18.4	19.2	16.6	21.3	17.7	16.8	10.2	16.8	17.5	24.3	27.4	15.0	12.4	12.6	10.1
Perth, Australia		118.1	111.3	113.1	122.5	121.6	119.7	152.9	180.8	182.0	175.0	185.3	208.7	231.8	247.2	254.4
Sydney, Australia			39.2	53.1	87.3	90.7	103.2	112.4	122.1	54.3	56.6	94.3	77.0	32.9	33.9	
Rio de Janeiro, Brazil															111.5	
Salvador, Brazil															84.6	
São Paulo, Brazil				85.2	81.2	79.4	81.0	81.6	80.5	77.7	77.6	77.6	79.0	74.5	75.9	
Toronto, Canada							107.1	102.3				93.7	93.9	91.5		
Beijing, China												58.7				
Tianjin, China												28.6				
Copenhagen, Denmark									29.8	28.8	28.3		24.2	23.3	25.1	
Berlin, Germany											29.9					
Ahmedabad, India										18.0						
Bangalore, India														92.6		
Bhopal, India										43.4						
Delhi, India										17.0						
Jamshedpur, India						55.0	59.9	56.5	49.0	46.2						
Osaka, Japan						83.8	80.8	78.6	75.5	75.2	75.2	73.0	72.5	71.3	71.4	
Sapporo, Japan								16.6	16.2	16.2	16.4	16.0	15.0	14.7	14.6	
Tokyo, Japan	64.9	63.9	63.2	62.2		60.5				63.9	61.0	59.6	57.3	62.7	61.6	
Yokohama, Japan					60.5	59.5	59.4	58.9		54.9	57.1	53.9	52.6	53.5	47.1	
Mexico City, Mexico														132.1		
Oslo, Norway		70.9	69.6	69.5	66.4	71.6	72.5	73.6	71.9	82.3	92.3					
Cape Town, South Africa											19.2					
Bangkok, Thailand					42.4	44.0	46.4	47.7	48.5	47.1	41.2	41.9				
Denver, U.S.A	51.1	53.4	55.7	42.0	43.4	46.9	53.6	46.6	41.8	34.2	35.5	32.5	33.2	30.6	33.4	
Los Angeles, U.S.A				276.0	321.5	173.2	183.0	353.8	327.6	282.7	210.1	145.7	177.4	293.0	322.7	266.8
San Diego, U.S.A				433.6				503.7	479.0	416.8	400.7	329.9	360.4	378.2	346.1	371.7
San Francisco, U.S.A															44.8	
Tampa, U.S.A											60.1					

Less data are available for per capita energy use for water provision, compared to per capita water use (Table A1-3).

Table A1-5 Energy intensity for water provision by city, kWh/kL

City	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Brisbane, Australia			0.450	0.462	0.457	0.454	0.460	0.458	0.479	0.678	0.883	0.731	0.594	0.547	0.541	
Melbourne, Australia		0.124	0.141	0.120	0.172	0.146	0.139	0.092	0.171	0.187	0.276	0.324	0.176	0.135	0.137	0.110
Perth, Australia		0.600	0.730	0.760	0.780	0.800	0.790	1.000	1.200	1.200	1.200	1.300	1.500	1.700	1.840	1.930
Sydney, Australia			0.258	0.347	0.650	0.729	0.834	0.950	1.096	0.480	0.497	0.794	0.719	0.293	0.298	
Rio de Janeiro, Brazil															0.631	
Salvador, Brazil															0.757	
São Paulo, Brazil				0.645	0.655	0.634	0.638	0.653	0.654	0.639	0.635	0.631	0.639	0.623	0.700	
Toronto, Canada							0.673					0.674	0.677	0.675		
Beijing, China												0.350				
Tianjin, China												0.170				
Copenhagen, Denmark									0.275	0.281	0.286		0.259	0.249	0.276	
Berlin, Germany							0.536				0.505					
Ahmedabad, India										0.333						
Bangalore, India														2.310		
Bhopal, India										0.710						
Delhi, India										0.204						
Jamshedpur, India						0.332	0.319	0.309	0.283	0.274						
Osaka, Japan						0.454	0.448	0.444	0.442	0.453	0.452	0.442	0.442	0.438	0.450	
Sapporo, Japan								0.160	0.160	0.160	0.160	0.160	0.150	0.150	0.150	
Tokyo, Japan	0.500	0.500	0.500	0.500		0.488				0.531	0.507	0.510	0.490	0.540	0.530	
Yokohama, Japan					0.486	0.481	0.489	0.491		0.465	0.484	0.462	0.458	0.471	0.419	
Mexico City, Mexico														1.078		
Oslo, Norway				0.391	0.378	0.409	0.428	0.434	0.428	0.490	0.543					
Cape Town, South Africa											0.205					
Bangkok, Thailand					0.210	0.208	0.213	0.216	0.217	0.216	0.190	0.195				
Denver, U.S.A	0.167	0.182	0.205	0.179	0.200	0.191	0.202	0.188	0.168	0.162	0.151	0.143	0.140	0.156	0.169	
Los Angeles, U.S.A				1.270	1.476	0.871	0.890	1.656	1.584	1.568	1.208	0.862	1.034	1.641	1.752	1.680
San Diego, U.S.A				2.084				2.239	2.132	2.028	2.238	1.944	2.081	2.085	1.774	2.086
San Francisco, U.S.A															0.391	
Tampa, U.S.A											0.377					

Table A1-6 Data sources for energy intensity for raw water pumping, water treatment and water distribution

City	Data source	Year/ period of results	Remark
Brisbane, Australia	[1, 152]	2009-2010 (desalination, water recycling) 2011-2012 (conventional treatment, product water distribution)	
Melbourne, Australia	[15, 19, 20]	2014	
Sydney, Australia	[42, 43, 45, 153]	2003-2009 (Shoalhaven drought transfer) 2009-2012 (Desalination)	Energy intensity of the desalination was quantified as the total electricity used by the desalination plant for the whole operation period (2009-2012) over the total volume of desalinated water produced. Energy intensity of the Shoalhaven drought transfer was quantified as the total electricity used during 2003 – 2009 over the total volume of water transferred.
Toronto, Canada	[61]	2013	
Copenhagen, Denmark	[65]	2013	Energy intensities were reported in per unit volume of water sold. Therefore, they were adjusted by considering the water loss to convert to per unit volume of water supply.
Bangalore, India	[77]	2014	
Delhi, India	[76]	2009	
Sapporo, Japan	[83]	2013	Energy intensity of raw water pumping is defined as the energy use (before water treatment) per unit volume of water abstracted from the water source (instead of the volume of water treated).
Tokyo, Japan	[154]	2013	
Yokohama, Japan	[101]	2010	Energy intensity of raw water pumping is defined as the energy use before water treatment per unit volume of water abstracted from the water source by Yokohama Waterworks Bureau. Energy intensity of water distribution is defined as the energy use after water treatment per unit volume of water distributed throughout Yokohama (including both water treated by Yokohama Waterworks Bureau and Kanagawa Water Supply Authority).
Oslo, Norway	[155]	2007	
Bangkok, Thailand	[125]	2011	Energy intensity of water distribution is considered as the summation of that for product water transmission and distribution.
Denver, U.S.A.	[127]	2007	
Los Angeles, U.S.A.	[129]	2009	
San Diego, U.S.A..	[129, 146]	2009	
San Francisco, U.S.A.	[147]	2014	

Table A1-7 Annual average precipitation data (for Figure 4)

City	Annual average precipitation (mm)	Period	Data source	Energy intensity (kWh/kL)	Per capita water use (L/p/d)	Year of results
Brisbane, Australia	1093.3	1981-2004	World Meteorological Organization	0.541	266	2014
Melbourne, Australia	601.9	1981-2010	World Meteorological Organization	0.110	251	2015
Perth, Australia	733.3	1994-2010	World Meteorological Organization	1.930	361	2015
Sydney, Australia	1222.9	1981-2010	World Meteorological Organization	0.298	312	2014
Rio de Janeiro, Brazil	1069.4	1961-1990	Instituto Nacional de Meteorologia	0.631	484	2014
Salvador, Brazil	2144.0	1961-1990	Instituto Nacional de Meteorologia	0.757	306	2014
São Paulo, Brazil	1591.3	1961-1990	Instituto Nacional de Meteorologia	0.700	297	2014
Toronto, Canada	834.1	1971-2000	World Meteorological Organization	0.675	371	2013
Beijing, China	623.0	1971-2000	China Meteorological Administration	0.350	460	2011
Tianjin, China	544.3	1971-2000	China Meteorological Administration	0.170	461	2011
Copenhagen, Denmark	643.0	1961-1990	Danmarks Meteorologiske Institut	0.276	249	2014
Berlin, Germany	570.7	1971-2000	World Meteorological Organization	0.505	162	2010
Ahmedabad, India	740.6	1971-2000	India Meteorological Department	0.333	148	2009
Bangalore, India	974.5	1971-2000	India Meteorological Department	2.310	109	2013
Bhopal, India	1123.1	1949-2000	India Meteorological Department	0.710	167	2009
Delhi, India	790.0	1971-1990	National Oceanic and Atmospheric Administration	0.204	229	2009
Jamshedpur, India	1508.5	1971-2000	India Meteorological Department	0.274	462	2009
Osaka, Japan	1279.0	1981-2010	Japan Meteorological Agency	0.450	435	2014
Sapporo, Japan	1106.5	1981-2010	Japan Meteorological Agency	0.150	266	2014
Tokyo, Japan	1528.8	1981-2010	Japan Meteorological Agency	0.530	318	2014
Yokohama, Japan	1688.6	1981-2010	Japan Meteorological Agency	0.419	308	2014
Mexico City, Mexico	610.2	1971-2000	National Water Commission of Mexico	1.078	336	2013
Oslo, Norway	763.0	1961-1990	Norwegian Meteorological Institute	0.543	466	2010
Cape Town, South Africa	515.0	1961-1990	World Meteorological Organization	0.205	257	2010
Bangkok, Thailand	1648.2	1981-2010	Royal Irrigation Department	0.190	595	2010
Denver, U.S.A	371.3	1900-2014	National Weather Service	0.169	541	2014
Los Angeles, U.S.A	360.4	1900-2014	National Weather Service	1.680	435	2015
San Diego, U.S.A	257.8	1900-2014	National Weather Service	2.086	488	2015
San Francisco, U.S.A	534.9	1900-2014	National Weather Service	0.195	341	2011
Tampa, U.S.A	1212.9	1900-2014	National Weather Service	0.377	437	2010

Table A1-8 Elevation difference data (for Figure 5)

City/ infrastructure	Source [a]				End [b]				Elevation difference (m)	Energy intensity of raw water pumping (kWh/kL)
	Name	Latitude [c]	Longitude [c]	Elevation (m) [c]	Name	Latitude	Longitude	Elevation (m)		
Bangalore	Kaveri River near T K Halli Water Treatment Plant	12.40275955	77.19978404	585	Bangalore's city centre	12.9715987	77.5945627	912	327	2.100
Bangkok	Chao Phraya river (canal) near Bangkhen water treatment plant	13.87980532	100.5508704	7	Bangkhen water treatment plant	13.8795278	100.5515793	10	3	0.006
California Aqueduct - East branch	Clifton Court Forebay	37.8407652	-121.5769572	1	Lake Perris	33.8569	-117.1745	485	484	2.624
California Aqueduct - West branch	Clifton Court Forebay	37.8407652	-121.5769572	1	Castaic Lake	34.5258138	-118.6049772	454	453	2.092
Colorado River Aqueduct	Intake pump near Park Dam at Colorado River	34.29741956	-114.1394348	138	Lake Mathews	33.8383716	-117.4380189	426	288	1.622
Cutzamala system	Colorines Dam	19.40830821	-100.400671	1692	Los Berros water purification plant	19.3847029	-100.0793306	2543	851	2.862
Sapporo	白川取水場 (Water intake)	42.96478682	141.2791092	156	白川浄水場 (Shirakawa water purification plant)	42.9657996	141.2793775	153	-3	0.032
Shoalhaven drought transfer	Tallowa Dam	-34.77283244	150.3132763	41	Wingecarribee Reservoir	-34.5565767	150.4979302	677	636	1.929
Tokyo	秋ヶ瀬取水堰 (Water intake)	35.84085172	139.6036223	4	朝霞浄水場(Asaka purification plant)	35.8210674	139.5907955	22	18	0.058
Yokohama	寒川取水堰 (Water intake)	35.37583371	139.3714042	6	小雀浄水場 (Kosuzume purification plant)	35.3659537	139.5109791	66	60	0.155

[a] "Source" refers to the water body near to the water intake point.

[b] "End" refers to the pumping destination for the corresponding energy intensity.

[c] All latitude and longitude and elevation information was obtained from Google Maps.

Table A1-9 Per capita water use breakdown, L/p/d (for Figure 6)

City	Residential water use	Non-residential water use	Non-revenue water	Total water use	Year	References
Ahmedabad	91	11	46	148	2009	[75]
Bangalore	40	11	58	110	2013	[77]
Bangkok	218	246	142	606	2014	[124]
Berlin	113	41	8	162	2010	[71, 72]
Brisbane	174	64	28	266	2014	[4]
Cape Town	112	76	48	235	2014	[75]
Copenhagen	146	82	20	249	2014	[70]
Delhi	62	47	120	229	2009	[75]
Denver	363	156	22	541	2014	[126, 156]
Los Angeles	323	137	28	488	2011-2014	[128]
Melbourne	160	66	25	251	2015	[5]
Osaka	250	130	55	435	2014	[79]
Oslo	186	117	130	433	2013	[75, 157]
Perth	245	83	33	361	2015	[5]
Rio de Janeiro	148	72	264	484	2014	[46]
Salvador	119	44	143	306	2014	[46]
San Francisco	185	106	23	314	2014	[148]
São Paulo	142	74	81	297	2014	[46]
Sapporo	200	50	19	268	2013	[83]
Sydney	204	82	31	318	2014	[4]
Tokyo	224	78	11	313	2013	[88, 91]
Yokohama	222	58	27	308	2014	[116]

Table A1-10 Estimation of energy use associated with non-revenue water

City	Year	Per capita non-revenue water (L/p/d)	Per capita total water use (L/p/d)	Energy intensity (kWh/kL)	Population basis	Per capita energy use for non-revenue water (kWh/p/a) [a]	Energy use for non-revenue water (GWh) [b]
Ahmedabad	2009	46	148	0.333	5,577,940	5.59	31.2
Bangalore	2013	58	110	2.310	8,443,675	48.88	412.7
Bangkok	2014	142	606	0.195	8,000,693	10.11	80.9
Berlin	2010	8	162	0.505	3,437,590	1.49	5.1
Brisbane	2014	28	266	0.541	2,275,000	5.53	12.6
Cape Town	2014	48	235	0.205	3,655,247	3.56	13.0
Copenhagen	2014	20	249	0.276	574,871	2.03	1.2
Delhi	2009	120	229	0.204	16,787,941	8.90	149.5
Denver	2014	22	541	0.169	1,172,000	1.38	1.6
Los Angeles	2011-2014	28	488	1.322	3,987,622	13.61	54.3
Melbourne	2015	25	251	0.110	4,377,012	1.01	4.4
Osaka	2014	55	435	0.450	2,686,246	9.08	24.4
Oslo	2013	130	433	0.543	584,000	25.72	15.0
Perth	2015	33	361	1.930	1,961,000	23.13	45.4
Rio de Janeiro	2014	264	484	0.631	5,912,546	60.85	359.8
Salvador	2014	143	306	0.757	2,699,981	39.59	106.9
San Francisco	2014	23	314	0.391	837,000	3.22	2.7
São Paulo	2014	81	297	0.700	26,075,299	20.63	537.9
Sapporo	2013	19	268	0.150	1,928,460	1.03	2.0
Sydney	2014	31	318	0.298	4,755,000	3.42	16.3
Tokyo	2013	11	313	0.540	13,257,000	2.07	27.4
Yokohama	2014	27	308	0.419	3,712,122	4.19	15.6
Total energy use for non-revenue water (GWh)						1920	
Population-weighted average per capita energy use for non-revenue water (kWh/p/a) [c]						15.6	
Population-weighted average per capita energy use for water provision (kWh/p/a) [d]						62.5	

[a] Per capita energy use for non-revenue water = Per capita non-revenue water × Energy intensity

[b] Energy use for non-revenue water = Per capita energy use for non-revenue water × Population

[c] Population-weighted average per capita energy use for non-revenue water = Total energy use for non-revenue water / total population

[d] Population-weighted average per capita energy use for water provision = Total energy use for water provision / total population

References

1. Lam, K.L., Lant, P.A., O'Brien, K., Kenway, S.J., 2016. Comparison of water-energy trajectories of two major regions experiencing water shortage. Journal of Environmental Management 181, 403-412.
2. Water Services Association of Australia, 2008. National Performance Report 2006-07: Urban water utilities.
3. National Water Commission, 2011. National Performance Report 2009–10: Urban water utilities.
4. Bureau of Meteorology, 2015. National performance report 2013–14: urban water utilities, Part B.
5. Bureau of Meteorology, 2016. National performance report 2014–15: urban water utilities, Part B.
6. Melbourne Water, 2015. Water Outlook for Melbourne 1 December 2015.
7. Yarra Valley Water, 2014. Yarra Valley Water Annual Report 2013-14.
8. Kenway, S.J., Priestley, A., Cook, S., Seo, S., Inman, M., Gregory, A., Hall, M., 2008. Energy use in the provision and consumption of urban water in Australia and New Zealand.
9. Cook, S., Hall, M., Gregory, A., 2012. Energy use in the provision and consumption of urban water in Australia: an update.
10. Yarra Valley Water, 2015. Yarra Valley Water Annual Report 2014-15.
11. Melbourne Water, 2009. Melbourne Water Annual Report 2008-09.
12. Melbourne Water, 2006. Melbourne Water Sustainability Report 2005-06.
13. Melbourne Water, 2008. Melbourne Water Sustainability Report 2007-08.
14. Melbourne Water, 2009. Melbourne Water Sustainability Report 2008-09.
15. Melbourne Water, 2014. Melbourne Water Annual Report 2013-14.
16. Melbourne Water, 2013. Melbourne Water Annual Report 2010-11.
17. Melbourne Water, 2012. Melbourne Water Annual Report 2011-12.
18. Melbourne Water, 2015. Melbourne Water Annual Report 2014-15.
19. City West Water Corporation, 2014. Annual Report 2013-14.
20. South East Water, 2014. Annual Report 2013-14.
21. South East Water, 2015. Annual Report 2014-15.
22. City West Water Corporation, 2015. Annual Report 2014-15.
23. Water Corporation, 2006. Annual Report 2006.
24. Water Corporation, 2011. Annual Report 2011.
25. Water Corporation, 2014. Annual Report 2014.
26. Water Corporation, 2015. Annual Report 2015.
27. Sydney Water Corporation, 2001. Sydney Water Annual Report 2001.
28. Sydney Water Corporation, 2002. Sydney Water Annual Report 2002.
29. Sydney Water Corporation, 2003. Sydney Water Annual Report 2003.

30. Sydney Water Corporation, 2004. Sydney Water Annual Report 2004.
31. Sydney Water Corporation, 2005. Sydney Water Annual Report 2005.
32. Sydney Water Corporation, 2006. Sydney Water Annual Report 2006.
33. Sydney Water Corporation, 2007. Sydney Water Annual Report 2007.
34. Sydney Water Corporation, 2008. Sydney Water Annual Report 2008.
35. Sydney Water Corporation, 2009. Sydney Water Annual Report 2009.
36. Sydney Water Corporation, 2010. Sydney Water Annual Report 2010.
37. Sydney Water Corporation, 2011. Sydney Water Annual Report 2011.
38. Sydney Water Corporation, 2012. Sydney Water Annual Report 2012.
39. Sydney Water Corporation, 2013. Sydney Water Annual Report 2013.
40. Sydney Water Corporation, 2014. Sydney Water Annual Report 2014.
41. Sydney Catchment Authority, 2005. Sydney Catchment Authority Annual Report 2004-05.
42. Sydney Catchment Authority, 2006. Sydney Catchment Authority Annual Report 2005-06.
43. Sydney Catchment Authority, 2010. Sydney Catchment Authority Annual Report 2009-10.
44. Sydney Catchment Authority, 2014. Sydney Catchment Authority Annual Report 2013-14.
45. Sydney Water Corporation, 2012. Sydney Water Operating Licence Environment Report: Environmental Indicators Report 2011–12.
46. Sistema Nacional de Informações sobre Saneamento, 2016. Diagnóstico dos Serviços de Água e Esgotos - 2014.
47. Sistema Nacional de Informações sobre Saneamento, 2004. Diagnóstico dos Serviços de Água e Esgotos - 2003.
48. Sistema Nacional de Informações sobre Saneamento, 2005. Diagnóstico dos Serviços de Água e Esgotos - 2004.
49. Sistema Nacional de Informações sobre Saneamento, 2006. Diagnóstico dos Serviços de Água e Esgotos - 2005.
50. Sistema Nacional de Informações sobre Saneamento, 2007. Diagnóstico dos Serviços de Água e Esgotos - 2006.
51. Sistema Nacional de Informações sobre Saneamento, 2009. Diagnóstico dos Serviços de Água e Esgotos - 2007.
52. Sistema Nacional de Informações sobre Saneamento, 2010. Diagnóstico dos Serviços de Água e Esgotos - 2008.
53. Sistema Nacional de Informações sobre Saneamento, 2011. Diagnóstico dos Serviços de Água e Esgotos - 2009.
54. Sistema Nacional de Informações sobre Saneamento, 2012. Diagnóstico dos Serviços de Água e Esgotos - 2010.
55. Sistema Nacional de Informações sobre Saneamento, 2013. Diagnóstico dos Serviços de Água e Esgotos - 2011.

56. Sistema Nacional de Informações sobre Saneamento, 2014. Diagnóstico dos Serviços de Água e Esgotos - 2012.
57. Sistema Nacional de Informações sobre Saneamento, 2014. Diagnóstico dos Serviços de Água e Esgotos - 2013.
58. RiverSides, 2010. Rainwater Harvesting in Toronto – Potential Energy Conservation & Greenhouse Gas Emission Reductions.
59. City of Toronto, 2013. Annual Energy Consumption & Greenhouse Gas Emissions Report 2011.
60. City of Toronto, 2014. Annual Energy Consumption & Greenhouse Gas Emissions Report 2012.
61. City of Toronto, 2015. Annual Energy Consumption & Greenhouse Gas Emissions Report 2013.
62. Toronto City Council, 2013. Water Services 2013 Performance Measurement And Benchmarking Report.
63. Smith, K., Liu, S., Liu, Y., Savic, D., Olsson, G., Chang, T., Wu, X., 2015. Impact of urban water supply on energy use in China: a provincial and national comparison. Mitigation and Adaptation Strategies for Global Change.
64. National Bureau of Statistics of China, 2012. China Statistics Yearbook 2012.
65. Danish Water and Waste Water Association, 2014. DANVA Benchmarking 2014 – process benchmarking and statistics.
66. Danish Water and Waste Water Association, 2013. DANVA Benchmarking 2013 – process benchmarking and statistics.
67. Danish Water and Waste Water Association, 2011. DANVA Benchmarking 2011 – process benchmarking and statistics.
68. Danish Water and Waste Water Association, 2010. DANVA Benchmarking 2010 – process benchmarking and statistics.
69. Danish Water and Waste Water Association, 2009. DANVA Benchmarking 2009 – process benchmarking and statistics.
70. Danish Water and Waste Water Association, 2015. DANVA Benchmarking 2015 – process benchmarking and statistics.
71. Statistisches Bundesamt, 2015. Statistik der öffentlichen Wasserversorgung.
72. Berliner Wasserbetriebe, 2009. Water for Berlin.
73. Berliner Wasserbetriebe, 2011. Abschlussbericht zur Kooperationsvereinbarung Klimaschutz BWB 2006-2010 [Final report on the climate cooperation agreement BWB 2006-2010].
74. Government of India, 2011. The Indian Population Census 2011.
75. The International Benchmarking Network for Water and Sanitation Utilities, 2015. Utility Reports.

76. Miller, L.A., Ramaswami, A., Ranjan, R., 2013. Contribution of water and wastewater infrastructures to urban energy metabolism and greenhouse gas emissions in cities in India. Journal of Environmental Engineering (United States) 139, 738-745.
77. Paul, R., 2014. Assessment of Low Energy Water Supply Options for Bangalore and their Implementation Strategy.
78. Chiplunkar, A., Seetharam, K., Tan, C.K.T., 2012. Good Practices in urban water management: Decoding good practices for a successful future. Asian Development Bank, Mandaluyong City, Philippines.
79. Osaka Municipal Waterworks Bureau, 2015. 大阪市水道事業概要.
80. Osaka Municipal Waterworks Bureau, 2010. 平成20年度水道局事業年報.
81. Osaka Municipal Waterworks Bureau, 2011. 平成21年度水道局事業年報.
82. Osaka Municipal Waterworks Bureau, 2015. 平成25年度水道局事業年報.
83. Sapporo City Waterworks Bureau, 2015. 平成25年度水道事業年報.
84. Sapporo City Waterworks Bureau, 2016. 平成26年度水道事業年報.
85. Sapporo City Waterworks Bureau, 2013. VIII　水道事業ガイドライン（環境関係）.
86. Sapporo City Waterworks Bureau, 2015. 水道事業ガイドライン（平成25年度版） ～　業務指標で見る札幌の水道　～.
87. Sapporo City Waterworks Bureau, 2016. 水道事業ガイドライン（平成26年度版） ～　業務指標で見る札幌の水道　～.
88. Tokyo Metropolitan Government Bureau of Waterworks, 2015. Water Supply in Tokyo.
89. Tokyo Metropolitan Government Bureau of Waterworks, 2014. 東京水道エネルギー効率化10年プラン [Tokyo Water Supply Energy Efficiency 10 Year Plan].
90. Tokyo Metropolitan Government Bureau of Waterworks, 2014. 水道事業ガイドライン（業務指標）.
91. Tokyo Metropolitan Government Bureau of Waterworks, 2015. 業務指標. http://www.waterworks.metro.tokyo.jp/suidojigyo/torikumi/hyoka/pdf/guideline_result.pdf.
92. Federation of Japan Water Industries, 2010. 首都圏における低炭素化を目標とした水循環システム実証モデル事業.
93. Tokyo Metropolitan Government Bureau of Waterworks, 2016. 業務指標. http://www.waterworks.metro.tokyo.jp/suidojigyo/torikumi/hyoka/pdf/guideline_result_24-26.pdf.
94. Yokohama Waterworks Bureau, 2015. 平成27年度横浜市水道事業概要.
95. Yokohama Waterworks Bureau, 2005. 平成17年度 環境報告書.
96. Yokohama Waterworks Bureau, 2006. 平成18年度 環境報告書.
97. Yokohama Waterworks Bureau, 2007. 平成19年度 環境報告書.

98. Yokohama Waterworks Bureau, 2008. 平成20年度 環境報告書.
99. Yokohama Waterworks Bureau, 2010. 平成22年度 環境報告書.
100. Yokohama Waterworks Bureau, 2015. 平成26年度 電力年報.
101. Yokohama Waterworks Bureau, 2011. 平成23年版 環境報告書.
102. Yokohama Waterworks Bureau, 2012. 平成24年度 環境報告書.
103. Yokohama Waterworks Bureau, 2013. 平成25年度 環境報告書.
104. Kanagawa Water Supply Authority, 2012. 環境報告書2011.
105. Kanagawa Water Supply Authority, 2013. 環境報告書2012.
106. Kanagawa Water Supply Authority, 2014. 環境報告書2013.
107. Kanagawa Water Supply Authority, 2015. 環境報告書2014.
108. Kanagawa Water Supply Authority, Undated. 平成１８年度地球温暖化対策実行計画評価書.
109. Kanagawa Water Supply Authority, Undated. 第１次 神奈川県内広域水道企業団 地球温暖化対策実行計画の取組結果.
110. Kanagawa Water Supply Authority, Undated. 平成２１年度地球温暖化対策実行計画評価書.
111. Yokohama Waterworks Bureau, 2014. 平成26年度 環境報告書.
112. Yokohama Waterworks Bureau, Undated. 水道事業ガイドラインに基づく業務指標について【平成16～18年度】.
113. Yokohama Waterworks Bureau, Undated. 水道事業ガイドラインに基づく業務指標について【平成19～21年度】.
114. Yokohama Waterworks Bureau, Undated. 水道事業ガイドラインに基づく業務指標について【平成20～22年度】.
115. Yokohama Waterworks Bureau, Undated. 水道事業ガイドラインに基づく業務指標について【平成22～24年度】.
116. Yokohama Waterworks Bureau, Undated. 水道事業ガイドラインに基づく業務指標について【平成23～25年度】.
117. Comisión Nacional del Agua, 2014. Estadísticas del Agua en México edición 2014.
118. Mario Molina Center, 2011. Energy Assessment on the Current Urban Water Systems and Management Proposal for Water Resources in Mexico City.
119. Venkatesh, G., Brattebø, H., 2011. Case study: Analysis of chemicals and energy consumption in water and wastewater treatment, as cost components: Case study of Oslo, Norway. Urban Water Journal 8, 189-202.
120. Venkatesh, G., Brattebø, H., 2011. Energy consumption, costs and environmental impacts for urban water cycle services: Case study of Oslo (Norway). Energy 36, 792-800.
121. City of Cape Town, 2011. Cape Town: State of Energy and Energy Futures Report 2011.

122. Ahjum, F., Stewart, T.J., 2014. A systems approach to urban water services in the context of integrated energy and water planning: A City of Cape Town case study. Journal of Energy in Southern Africa 25.
123. Metropolitan Waterworks Authority, 2013. Metropolitan Waterworks Authority Annual Report 2013.
124. Metropolitan Waterworks Authority, 2014. Metropolitan Waterworks Authority Annual Report 2014.
125. Shrestha, S., 2015. Water-Energy-Carbon Nexus in Cities: Cases from Bangkok, New Delhi, Tokyo.
126. Denver Water, 2014. Denver Water Comprehensive Annual Financial Report 2014.
127. Western Resource Advocates, 2009. Water Conservation = Energy Conservation.
128. Los Angeles Department of Water and Power, 2016. Urban Water Management Plan 2015.
129. Los Angeles Department of Water and Power, 2011. Urban Water Management Plan 2010.
130. San Diego County Water Authority, 2001. San Diego County Water Authority Annual Report 2000.
131. San Diego County Water Authority, 2002. San Diego County Water Authority Annual Report 2001.
132. San Diego County Water Authority, 2003. San Diego County Water Authority Annual Report 2002.
133. San Diego County Water Authority, 2004. San Diego County Water Authority Annual Report 2003.
134. San Diego County Water Authority, 2005. San Diego County Water Authority Annual Report 2004.
135. San Diego County Water Authority, 2006. San Diego County Water Authority Annual Report 2005.
136. San Diego County Water Authority, 2007. San Diego County Water Authority Annual Report 2006.
137. San Diego County Water Authority, 2008. San Diego County Water Authority Annual Report 2007.
138. San Diego County Water Authority, 2009. San Diego County Water Authority Annual Report 2008.
139. San Diego County Water Authority, 2010. San Diego County Water Authority Annual Report 2009.
140. San Diego County Water Authority, 2011. San Diego County Water Authority Annual Report 2010.
141. San Diego County Water Authority, 2012. San Diego County Water Authority Annual Report 2011.

142. San Diego County Water Authority, 2013. San Diego County Water Authority Annual Report 2012.
143. San Diego County Water Authority, 2014. San Diego County Water Authority Annual Report 2013.
144. San Diego County Water Authority, 2015. San Diego County Water Authority Annual Report 2014.
145. San Diego County Water Authority, 2016. San Diego County Water Authority Annual Report 2015.
146. The City of San Diego, 2015. City of San Diego Draft Climate Action Plan July 2015 Appendices.
147. Navigant Consulting, 2015. Water/Energy Cost-Effectiveness Analysis ERRATA to the Revised Final Report.
148. San Francisco Public Utilities Commission, 2014. San Francisco Public Utilities Commission Water Resources Division Annual Report 2013-14.
149. Mo, W., Zhang, Q., Mihelcic, J.R., Hokanson, D.R., 2011. Embodied energy comparison of surface water and groundwater supply options. Water Research 45, 5577-5586.
150. Mo, W., Wang, R., Zimmerman, J.B., 2014. Energy-water nexus analysis of enhanced water supply scenarios: A regional comparison of Tampa bay, Florida, and San Diego, California. Environmental Science and Technology 48, 5883-5891.
151. WHO/UNICEF, 2011. JMP Technical Task Force Meeting on Monitoring progress in water supply and sanitation – challenges in urban settings.
152. Poussade, Y., Vince, F., Robillot, C., 2011. Energy consumption and greenhouse gases emissions from the use of alternative water sources in South East Queensland. Water Science and Technology: Water Supply 11, 281-287.
153. NSW Government, 2012. Inquiry into the Adequacy of Water Storages Answers to Questions on Notice: Sydney Catchment Authority.
154. Tokyo Metropolitan Government Bureau of Waterworks, 2015. 東京都水道局 環境５か年計画 2015-2019.
155. Venkatesh, G., Chan, A., Brattebø, H., 2014. Understanding the water-energy-carbon nexus in urban water utilities: Comparison of four city case studies and the relevant influencing factors. Energy 75, 153-166.
156. Denver Water, 2015. Key Facts. http://www.denverwater.org/AboutUs/KeyFacts/.
157. Statisitcs Norway, 2015. Municipal water supply.

Appendix A2 Case study 1: Supplementary Material

Lam, K.L., Lant, P.A., O'Brien, K.R., Kenway, S.J. (2016) Comparison of water-energy trajectories of two major regions experiencing water shortage. *Journal of Environmental Management* 181, 403-412.

Supplementary Material

SEQ: Overview

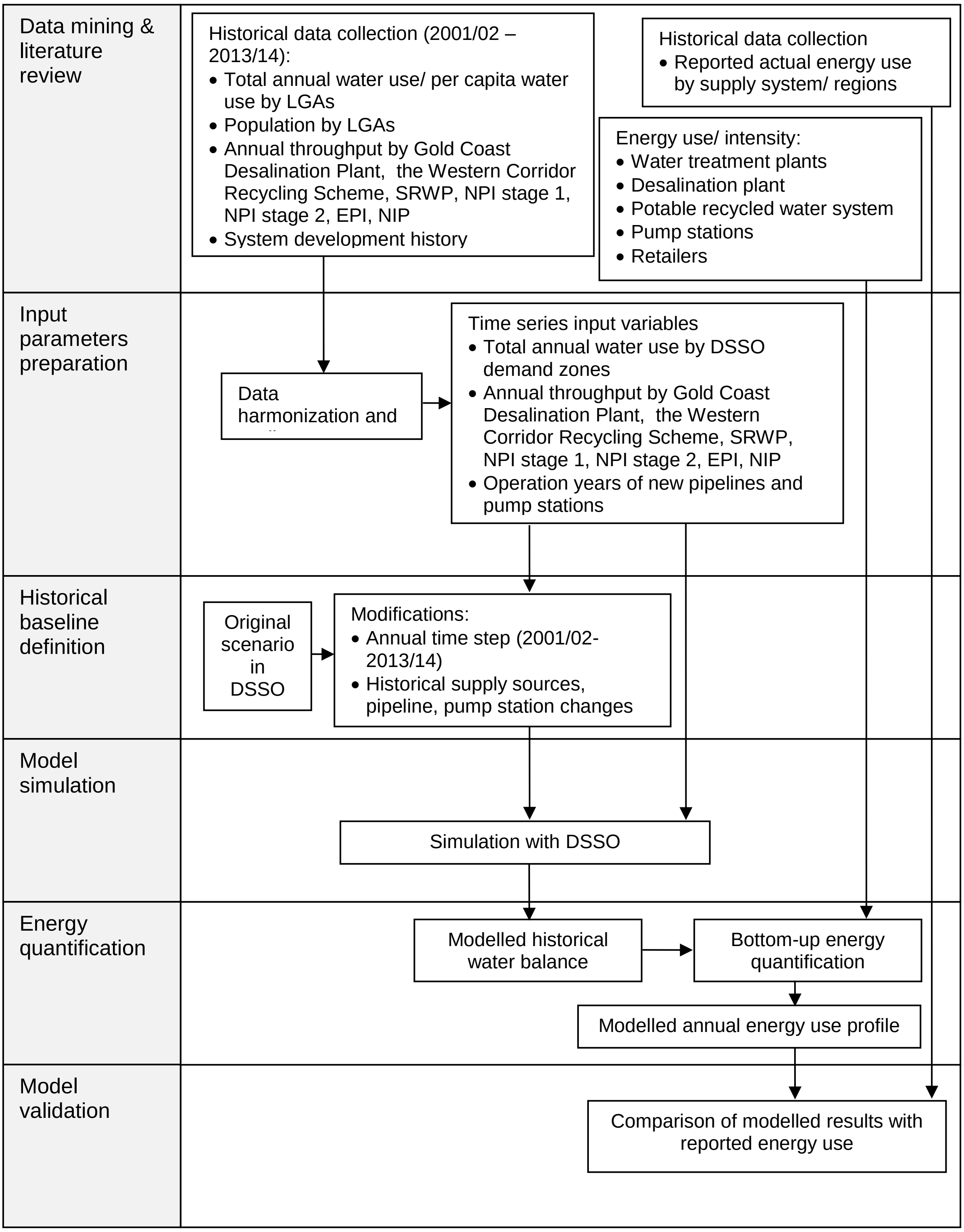

Figure A2-1 Overview of methodology to model energy use in the SEQ water supply system

SEQ: Data collection & processing

Water data

Urban water use data by local government area (LGA) or urban centre were obtained primarily from public reports such as city council annual reports, utilities annual reports and national performance reports, while some of the data were from Seqwater. The urban water use includes residential use, non-residential use and system loss. Most of the LGAs (i.e., Gold Coast, Redland, Logan, Brisbane, Ipswich) have the exact data for all the years, while Sunshine Coast and Moreton Bay do not have the total regional data for some years and require scaling from water use of some urban centres based on their populations. Water production data such as throughputs from desalination plants and regional bulk water transfer were predominantly sourced from utilities public reports.

This work does not consider the non-potable recycled water use, which is usually in a smaller scale and decentralised. For water use of power stations, this work only considers the supply of Western Corridor Recycled Water Scheme, which was built with an intention of supplying urban potable water use. In term of data screening, if there are inconsistencies between multiple data sources, figures from utility reports are preferred whenever they are concrete, available and consistent.

Energy data

Electricity use and water production data of the major water treatment plants and the desalination plant were obtained from Seqwater. A linear regression approach was then used to quantify the flow dependent (i.e., pumping related) and flow independent electricity use of each water treatment plants. The linear regression approach helps understand the flow dependent and flow independent energy use in each treatment plants. This fitting exercise forms the basis for modelling the electricity use of water treatment plants at different throughputs.

Other than electricity use in water treatment plants, Seqwater also provided the electricity use intensity of a list of key pump stations in the bulk water supply network. For pumping electricity use by distributors and retailers, it was estimated from several public reports - *Prudency and Efficiency Assessment on Price Monitoring of South East Queensland Water and Wastewater Distribution and Retail Activities 2013 -2015*.

SEQ: Data sources

Table A2-1 Sources of water consumption data by local government areas in SEQ

	2001 / 02	2002 / 03	2003 / 04	2004 / 05	2005 / 06	2006 / 07	2007 / 08	2008 / 09	2009 / 10	2010 / 11	2011 / 12	2012 / 13	2013 / 14
Gold Coast	1	1	1	1	1	1	2	2	2	4	4	3	3
Redland	5	5	5	5	5	6	6	7	8	4	4	9	10
Logan	11	1	1	1	1	1	2	2	2	4	4	3	3
Brisbane	1	1	1	1	1	1	2	2	2	4	4	4	12
Ipswich	1	1	1	1	1	1	2	2	2	4	4	4	12
Sunshine Coast	13	13	13	13	13	13	14	4	4	4	4	4	16
Moreton Bay	15	15	15	15	4	4	4	4	4	4	4	4	16

1 Water Services Association of Australia, National Performance Report 2006-07: Urban water utilities. 2008.

2 National Water Commission, National Performance Report 2009–10: Urban water utilities. 2011.

3 Bureau of Meteorology, National Performance Report 2013–14: Urban water utilities. 2015.

4 Data from Seqwater

5 Redland Shire Council, Redland Shire Council Annual Report 2005–06. 2006.

6 Redland City Council, Redland City Council Annual Report 2007–08. 2008.

7 Redland City Council, Redland City Council Annual Report 2008–09. 2009.

8 Redland City Council, Redland City Council Annual Report 2009–10. 2010.

9 Redland City Council, Redland City Council Annual Report 2012–13. 2013.

10 Redland City Council, Redland City Council Annual Report 2013–14. 2014.

11 Estimated based on the change in the per capita water use in Brisbane and Gold Coast in 2001/02 and 2002/03.

12 Estimated based on the total water supply by Queensland Urban Utilities (National Performance Report 2013–14: Urban water utilities) and the relative water consumption by Brisbane and Ipswich (Queensland Urban Utilities Water Netserv Plan).

13 Estimated based on the per capita water consumption in Maroochy (National Performance Report 2006-07) and Caloundra (Caloundra City Council Annual Report 2005-06, 2006-07) and population of Sunshine Coast (Australian Bureau of Statistics).

14 Estimated based on the change in the per capita water use in Moreton Bay in 2006/07 and 2007/08.

15 Estimated based on the per capita water consumption in Caboolture (Caboolture Annual Report 2004/05) and the population of Moreton Bay (Australian Bureau of Statistics).

16 Estimated based on the total water supply by Unity Water (National Performance Report 2013–14: Urban water utilities) and the relative water consumption by Sunshine Coast and Moreton Bay in 2012/13

Table A2-2 Sources of system operation data and energy intensity data in SEQ

System operation	• WaterSecure Annual Report 2008-09 • ABS Water Account Australia, 2011-12 • Seqwater Annual Report 2012-13 • National Performanc Report 2010-11: Urban water utilities • SEQ Water Grid Manager Annual Report 2011-12 • SEQ Water Grid Manager Annual Report 2009-10 • SEQ Water Grid Manager Annual Report 2010-11 • National Performance Report 2013–14: Urban water utilities • Data from Seqwater
Energy intensity	• Poussade, Y., Vince, F., Robillot, C., Energy consumption and greenhouse gases emissions from the use of alternative water sources in South East Queensland, in Water Science and Technology: Water Supply. 2011. p. 281-287. • Prudency and Efficiency Assessment - Gold Coast City Council • Prudency and Efficiency Assessment - Logan City Council • Prudency and Efficiency Assessment - Queensland Urban Utilities • Prudency and Efficiency Assessment – UnityWater • Data from Seqwater

SEQ: Water balance modelling with DSSO

The DSSO model was initially specified with demand forecast and inflow scenario from 2013/14 to 2033/34. In order to utilise the model to quantify the historical energy use, some model changes and assumptions were made.

Frist of all, since the DSSO model represents the seven LGAs (Brisbane, Gold Coast, Sunshine Coast, Redland, Logan, Ipswich and Moreton Bay) by 40 demand zones and the urban water use data collected/estimated are the overall water use of each LGA from 2001/02 to 2012/13, demand segregation was performed. The segregation was based on the relative demands of different DSSO's demand zones in 2013/14. Secondly, the monthly time series (2013/14 - 2033/34) was modified to annual time series (2001/02 - 2012/13). Afterwards, the segregated historical demand data were input.

The inflows scenario for all the catchments was set based on the historical dam levels. Dam level data from 2001/02 to 2012/13 are available for three major dams (i.e., Wivenhoe Dam, Somerset Dam, North Pine Dam) from Seqwater's website. The historical levels of other dams were assumed to follow the weighted average volume of those three dams during the same period. Thirdly, for any infrastructure (e.g., desalination plant, pipelines) that were built during the period, their throughput for all the years before their operation were simply set to zero.

In summary, several key assumptions were made.

1) The relative water use of different DSSO's demand zones within a LGA over the period of 2001/02 to 2012/13 follows that of 2013/14.
2) The relative operating costs between all system components including WTPs and pipelines follows that of year 2014.
3) (For the energy quantification) The energy intensities of different system components remain steady over the modelled period.

SEQ: Bottom-up approach for quantification of energy use

Only electricity use was accounted to quantify the energy use of the supply system, since electricity is the major form of energy for water supply services. A bottom-up approach was used to calculate the electricity use in the operation of the bulk water supply network (E_{bulk}) for a specific year, and the equation is simply,

$$E_{bulk} = \sum_n \left(EI_{d,n} F_n + EI_{i,n} \right) \qquad (1)$$

where *n* is the system component being considered, $EI_{d,n}$ is the flow-dependent energy intensity of system component *n* (MWh/ML), $EI_{i,n}$ is the annual flow-independent energy intensity of system component *n* (MWh) and F_n is the annual throughput of system component *n* (ML). The quantified system components include 13 key water treatment plants, the desalination plant, 19 key pump stations and the recycled water facility. For the pumping electricity uses of distributors and retailers, it was quantified using the average distribution energy intensity and the water demand by region. Based on this definition, the total energy use by the water supply system (E_{supply}) becomes

$$E_{supply} = E_{bulk} + \sum_d (EI_{r,dz} D_{T,dz}) \qquad (2)$$

where EI_r is the energy intensity for the water distribution by distributors & retailers (MWh/ML), D_T is the total annual water demand (ML) and dz is the demand zone.

The script for the energy quantification was coded in MATLAB.

SEQ: Hypothetical case

A hypothetical case considering the absence of water conservation strategies was set up. In this case, from 2005/06 onward, the demand from each demand zones were adjusted to follow the average per capita water use for the corresponding LGA from 2001/02 to 2004/05 (e.g., Brisbane: 495 L/p/d). This simulation generated a time-series energy use profile. The difference between this profile and the historical baseline is the estimated energy saving from water conservation.

SEQ supply system diagram

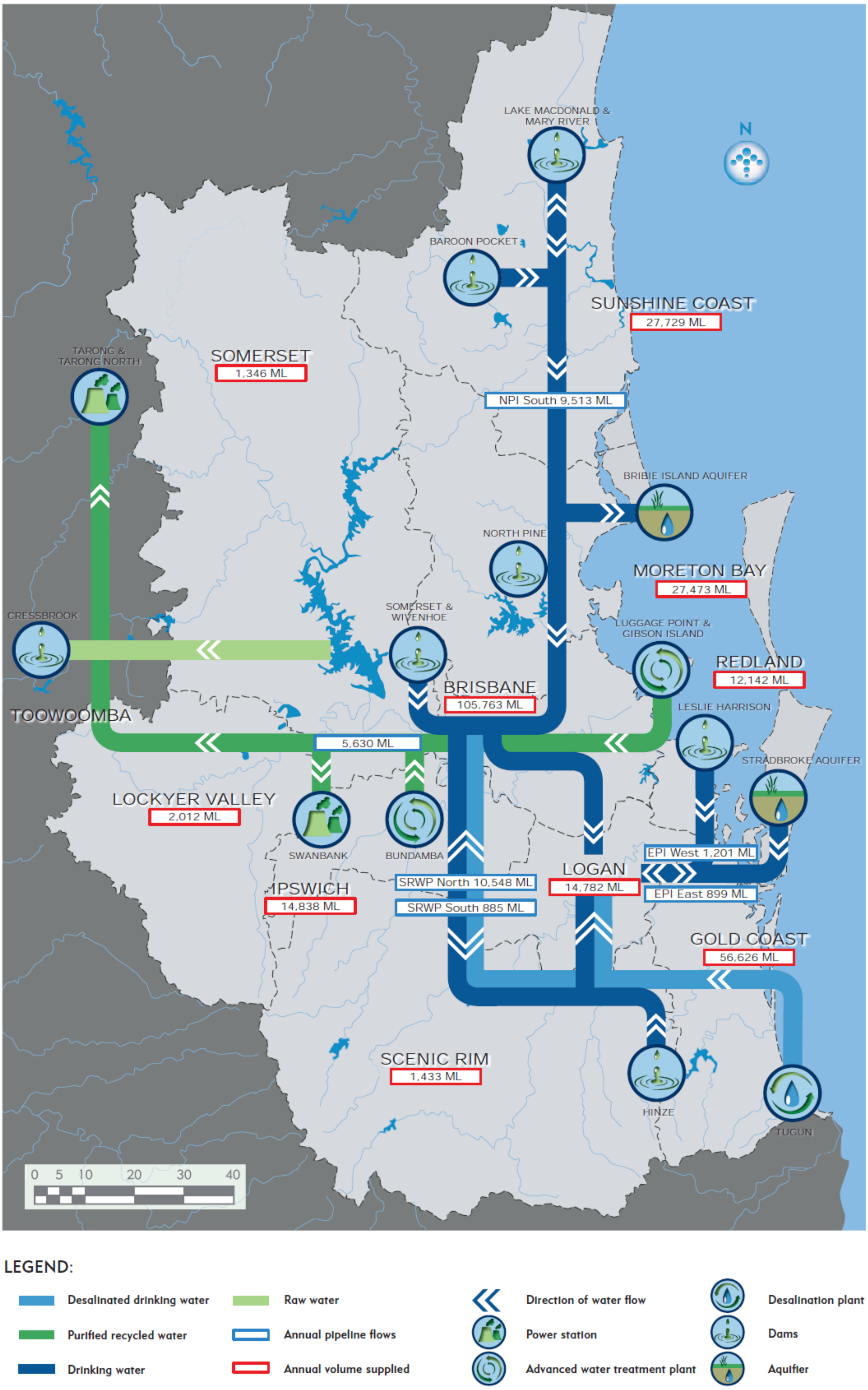

Figure A2-2 South East Queensland bulk water supply network (annual operation situation in 2011–12) (Adopted from SEQ Water Grid Manager Annual Report 2011-12)

Perth: Data collection & processing

Water Corporation (i.e., the water entity in the Australian state of Western Australia) reported the energy intensity for water supply services in Western Australia, while the National Performance Reports presented the water consumption rate in Perth. The data were used directly in this study to quantify the per capita water use and per capita energy use for water supply services in Perth. Since segregated data for the energy intensity of Perth only is not available. As the Greater Perth region had 84% of the state's total population in 2014, the per capita energy use for water supply services in Western Australia was used to represent that of Perth.

Perth: Data sources

- Water Services Association of Australia, National Performance Report 2006-07: Urban water utilities. 2008.
- National Water Commission, National Performance Report 2009–10: Urban water utilities. 2011.
- Bureau of Meteorology, National Performance Report 2013–14: Urban water utilities. 2015.
- Water Corporation Annual Report 2006
- Water Corporation Annual Report 2011
- Water Corporation Annual Report 2014

Additional results

Table A2-3 Urban water consumption and energy use for water provision in SEQ and Perth

Fiscal Year	SEQ					Perth				
	Water use (GL)	Energy use (GWh)	Energy intensity (GWh/GL)	Per capita water use (L/p/d)	Per capita energy use (kWh/p/a)	Water use (GL)	Energy use (GWh)	Energy intensity (GWh/GL)	Per capita water use (L/p/d)	Per capita energy use (kWh/p/a)
2001/02	374	169	0.45	456	75	214	156	0.73	418	111
2002/03	350	161	0.46	414	70	212	161	0.76	408	113
2003/04	357	163	0.46	412	69	228	178	0.78	430	122
2004/05	381	173	0.45	428	71	225	180	0.8	416	122
2005/06	314	144	0.46	349	59	227	180	0.79	415	120
2006/07	283	130	0.46	306	51	235	235	1	419	153
2007/08	245	117	0.48	258	45	240	288	1.2	413	181
2008/09	256	173	0.68	258	64	250	300	1.2	415	182
2009/10	269	237	0.88	264	85	250	300	1.2	399	175
2010/11	247	181	0.73	237	63	247	321	1.3	390	185
2011/12	257	153	0.59	241	52	248	372	1.5	381	209
2012/13	274	150	0.55	252	50	249	423	1.7	374	232
2013/14	294	159	0.54	266	53	260	479	1.84	368	247

The modelled energy use result and trend (i.e., low energy consumption in 2008 and high energy consumption in 2010) is comparable to reported figures from the literature and utility (Cook *et al.*, 2012; Gold Coast City Council, 2006; Kenway *et al.*, 2008) with derivations within -10% to 15%. None of the available figures capture the total energy use of the urban water supply system(s) for whole of SEQ (either before or after network integration through the building of regional network interconnectors).

Table A2-4 A comparison of the water and energy consequences of SEQ and Perth

Water and energy impacts	SEQ	Perth
Per capita water consumption	456 L/p/d (2002) 266 L/p/d (2014) ~42% per capita reduction from 2002	416 L/p/d (2002) 368 L/p/d (2014) ~12% per capita reduction from 2002
Per capita energy use for water supply services	75 kWh/p/a (2002) 53 kWh/p/a (2014) ~30% per capita reduction from 2002	111 kWh/p/a (2002) 247 kWh/p/a (2014) ~122% per capita increase from 2002
Total energy use for water supply services	169 GWh/yr (2002) 159 GWh/yr (2014) ~6% reduction from 2002	156 GWh/yr (2002) 479 GWh/yr (2014) ~207% increase from 2002
Energy intensity for water supply services	0.45 GWh/GL (2002) 0.54 GWh/GL (2014) ~20% increase from 2002	0.73 GWh/GL (2002) 1.840 GWh/GL (2014) ~152% increase from 2002

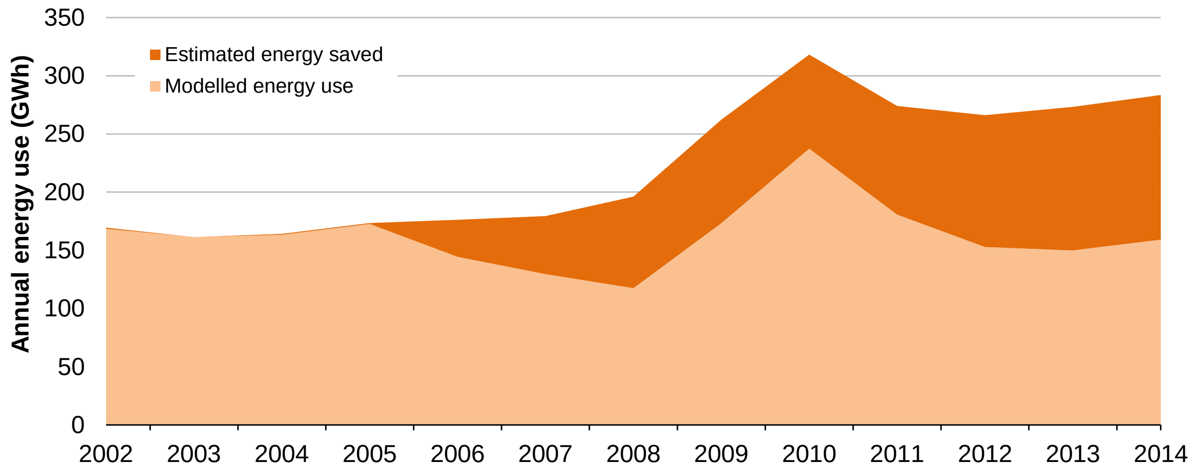

Figure A2-3 An estimate of energy saving from implementing water conservation strategies

References

1. Kenway, S.J., Priestley, A., Cook, S., Seo, S., Inman, M., Gregory, A., Hall, M., *Energy use in the provision and consumption of urban water in Australia and New Zealand*. 2008, CSIRO Water for a Healthy Country Flagship.
2. Cook, S., Hall, M., Gregory, A., *Energy use in the provision and consumption of urban water in Australia: an update*. 2012, CSIRO Water for a Healthy Country Flagship.
3. Gold Coast City Council, *Gold Coast City Council Annual report 2005-06.* 2006.

Appendix A3 Case study 3: Supplementary Material

Lam, K.L., Stokes-Draut, J.R., Horvath, A., Lane, J.L., Kenway, S.J., Lant, P.A. (To be submitted) Life-cycle energy impacts for adapting an urban water supply system to droughts.

Supplementary Material

1 Detailed inventories

This section summaries the inventories and assumptions used for the life-cycle energy assessment of the mains water supply in South East Queensland and the four alternative water supply strategies introduced during the Millennium Drought.

1.1 Water balance

The water balance of SEQ in 2014 was based on that of the 2013-14 finial year (Table A3-1). The regional water use from new rainwater tanks was estimated from various data sources (Australian Bureau of Statistics, 2013; Siems and Sahin, 2016; Walton and Holmes, 2009). The detailed of the estimation can be found in Section 1.6.

Table A3-1 Water balance of SEQ in 2013-14

	Volume (ML)	**Source**
Total urban water supplied from water mains	295,877	(Bureau of Meteorology, 2016)
Desalinated water	1,435	(Bureau of Meteorology, 2016)
Potable recycled water	1,282	(Bureau of Meteorology, 2016)
Bulk water transfer (through NPI, EPI and SRWP)	22,053	Operation data from utility
Water from new rainwater tanks	6,720	See Section 1.6

1.2 Mains water supply

This study considers the embodied energy use for the construction of water treatment plants, the construction of water supply network, the electricity used for water treatment and distribution, and the chemicals used for water treatment.

The water treatment capacity of the SEQ system was assumed to be the “Level of Service” yield (446,600 ML/yr) (Queensland Water Commission, 2010). The amount of materials used for construction of water treatment plants in SEQ were then estimated from a reference water treatment plant found in the Australasian LCI database (lifecycles, 2015) (“Water works”: a 11,000ML/yr capacity water treatment plant). The chemicals use inventories and water production rate for the top five largest water treatment plants in SEQ in 2011-12 (representing approximately 86% of the water supply) were obtained from the water utility. The raw data were used to determine a weighted-average chemical use intensity for potable water treatment in SEQ for each chemicals (tonne/ litre of chemical per megalitre of water treated) (Table A3-2). The four major chemicals being included are sodium hydroxide, aluminium sulphate, lime and sodium hypochlorite. The chemical use intensities were then applied to estimate the total amount of chemicals used for the whole SEQ system based on its urban water supplied by conventional water treatment plants. The electricity used for operating individual treatment plants and bulk water supply network were obtained directly from the utility, while the electricity used for water distribution at different regions were estimated form various utility report (Lam *et al.*, 2016). The data have been compiled and used by the authors in some previous studies (Kenway *et al.*, 2015; Lam *et al.*, 2016).

Table A3-2 Chemicals use intensity

Chemical	**Amount use per unit of water produced**	**Source**
Sodium Hydroxide 50%	3.2 L/ML	Weighted-average from raw utility data
Aluminium Sulphate	105.4 kg/ML	
Lime	19.3 kg/ML	
Sodium Hypochlorite 10%	49.4 L/ML	

A detailed distribution pipelines inventory (different pipe size and material) for the Gold Coast system in 2008-09 was obtained from a previous study (Lane *et al.*, 2015). It was then used to scale up to represent the SEQ system in 2014 based on the length of water mains of different SEQ regions reported (Table A3-3).

Table A3-3 Length of water mains by SEQ region

Region	**Length of water mains (km)**	**Source**
Gold Coast (2008-09) - reference	3170	(Lane *et al.*, 2015)
Brisbane (2013-14)	6278	(Queensland Urban Utilities, 2014)
Ipswich (2013-14)	1618	(Queensland Urban Utilities, 2014)
Logan (2013-14)	2083	(Bureau of Meteorology, 2016)
Redland (2013-14)	1254	(Redland City Council, 2014)
Sunshine Coast (2013-14)	5683	(Unitywater, 2014)
Gold Coast (2013-14)	3427	(Bureau of Meteorology, 2016)

1.3 Bulk water transfer pipelines

The three bi-directional bulk water transfer pipeline systems were built majorly with mild steel cement lining (MSCL) of two sizes (i.e., 813 mm and 1290 mm). The pipelines were supplied by Steel Mains under the brand SINTAKOTE® (Steel Mains, Undated). The pipe is a steel pipe coated with an inner cement mortar lining and an outer polyethylene protection layer. The amount of materials used (i.e., steel, cement mortar, polyethylene) can be estimated from the pipe specification equations provided by the supplier (Steel Mains, 2015). Pipe manufacturing process inventories (including pipe drawing, cement coating, welding and plastic coating processes) were based on that of Lane *et al.* (2015). The energy intensities for the operation of the three bulk water transfer systems are from the utility.

Table A3-4 Pipe size and length for the bulk water transfer pipelines

Pipeline section	Pipe size	Length	Source
Southern Regional Water Pipeline	813 mm	94.5 km	(Queensland Government Department of Infrastructure, 2007)
Northern Pipeline Interconnector	1290 mm	95 km	(Queensland Government Department of State Development, 2016a; b)
Eastern Pipeline Interconnector	813 mm	8.4 km	(Seqwater, 2014a)

1.4 Seawater desalination system

This study considered the embodied energy use for the construction of the desalination plant, the construction of the 25 km product water pipeline, the electricity used by the desalination plant, and the chemicals used by the desalination plant.

The material inventory for the construction of the 125ML/day seawater desalination plant was based on that of Lane et al. (2015), which scaled from a detailed inventory (Muñoz and Fernández-Alba, 2008). The 25 km pipeline is 1085 mm MSCL pipeline supplied by Steel Mains (Steel Mains, Undated; The Australian Pipeliner, 2016a). Its embodied energy use was quantified in the same way described in Section 1.3, only with a different pipe size.

Monthly electricity use and water production rate for the desalination plant in 2011 and 2012 were obtained from the utility. A linear regression (R2 = 0.9973) was used to obtain the flow-independent electricity use (MWh/month) and the flow-dependent electricity use (MWh/ML) for the plant. Chemicals inventory was based directly on an earlier study (Lane et al., 2015).

1.5 Indirect potable water recycling system

For the indirect potable water recycling system (Western Corridor Recycled Water Scheme), this study considered the embodied energy use for the construction of the three advanced wastewater treatment plants, the construction of over 200 km bulk water pipeline, the electricity used by the advanced wastewater treatment plants, and the chemicals used by the plants.

The system consists of three advanced wastewater treatment plants located at Bundamba (66 ML/day), Luggage Point (66 ML/day) and Gibson Island (two phases, each 50 ML/day) (Veolia Water, 2008). The material inventory for their construction was based on that of Lane et al. (2015), which estimated the inventory for the plant in Bundamba. The specifications of the bulk water pipelines used in the system are shown in Table A3-5. The MSCL pipelines were supplied by Steel Mains (Steel Mains, Undated), while the glass reinforced pipelines (GRP) were from Iplex Pipelines (Iplex Pipelines, 2013). The amount of materials used for fabricating these pipelines can be estimated from the specifications given by the suppliers (Iplex Pipelines, 2013; 2015; Steel Mains, 2015).

Table A3-5 Pipe size, type and length for the Western Corridor Recycled Water Scheme

Pipeline section	Pipe size	Length	Source
Eastern Pipelines • Luggage Point, Gibson Island AWTPs to Bundamba pump station • Exley, Oxley WWTPs to Goodna • Goodna WWTP to Bundamba AWTP	 1085 mm (MSCL) 1085 mm (MSCL) 1085 mm (MSCL)	 58.5 km 17.1 km 29.1 km	(The Australian Pipeliner, 2016b)
Western Pipelines • Bundamba AWTP to Lowood • Lowood to Caboonbah • Lowood to Coominya (Wivenhoe Dam)	 1451 mm (MSCL) 1000 mm (GRP) 1200 mm (GRP)	 32 km 48.5 km 16.4 km	(The Australian Pipeliner, 2016b)

The energy intensity of the advanced wastewater treatment process and product water distribution were based on the operation data presented by Poussade *et al.* (2011). Chemicals inventory follows that of Lane *et al.* (2015).

1.6 Rainwater tanks

Polyethylene is believed to be the major material type for these new tanks (Lane et al., 2015). In this study, it is assumed that each tank is 4,000 L in size and fabricated from 100kg of high-density polyethylene. In addition, 5 kg of PVC pipe was used for each tank for plumbing adjustment (Hallmann *et al.*, 2003). It was further assumed that 86% of these tanks were installed with a small pump (Moglia *et al.*, 2014) and all internally plumbed tanks have pumps installed. All the above described parameters together with parameters from a detailed rainwater tank study on water use and pumping energy use (Table A3-6) (Siems and Sahin, 2016) were used to estimate the regional life-cycle energy use.

Table A3-6 Water use and energy use data for rainwater tanks in SEQ

Parameter	Value
Energy intensity for outdoor water use only	1.00 kWh/m^3
Energy intensity for both indoor and outdoor water use	1.33 kWh/m^3
Water use from tank for outdoor water use only	16.3 kL/hh/yr
Water use from internally plumbed tank	58.2 kL/hh/yr

1.7 Other inventories

Some other inventories and assumptions are as follows.

- All infrastructure lifespans were assumed to be 50 years, while rainwater tank fabricated from polyethylene was assumed to last for 25 years. The life-cycle energy use for the construction phase was then annualised based on these defined lifespans.
- Unless data are available, the distance for material transportation was taken as 100 km. A distance of 1,800 km was assumed for shipping the MSCL pipe from Steel Mains' manufacturing plant in Victoria to South East Queensland.
- For construction activities, only excavation work was considered. The amount of soil excavated for each key component was estimated (Table A3-7). Both the amount of soil for the desalination plant and the advanced wastewater treatment plants were scaled from a

previous study (Muñoz and Fernández-Alba, 2008). For all the pipelines, it was assumed that a typical working corridor of 8 m^3 soil was excavated per meter of pipeline. The estimated hours and energy used for the excavation work were based on the hourly output (95.6 m^3/hr) and energy intensity of a small excavator John Deere 200C in the inventory of the Water-Energy Sustainability Tool (WEST) (Stokes and Horvath, 2010).

- Disposal phase was not considered in this study.

Table A3-7 Soil excavation work

Component	Amount of soil (m^3)
Desalination plant	150,150
Desalination system pipeline	200,000
Advanced wastewater treatment plants	328,152
Recycled water system pipelines	1,612,800
Bulk water transfer pipeline	1,583,200

2 Scenario modelling

2.1 DSSO model and energy quantification

The Decision Support System Optimiser (DSSO) can generate a water balance of the SEQ based on the defined scenario (e.g., operation rules, catchment inflow, water demand). The water balance describes the output of each treatment plant/ supply source and the flow of each bulk water pipeline. In this study, a bottom-up approach was used to quantify the energy use in the operation of the whole bulk water supply network (E_{bulk}) for a specific year, and the equation is,

$$E_{bulk} = \sum_n \left(EI_{d,n} F_n + EI_{i,n} \right) \tag{1}$$

where *n* is the system component being considered, $EI_{d,n}$ is the flow-dependent energy intensity of system component *n* (MWh/ML), $EI_{i,n}$ is the annual flow-independent energy intensity of system component *n* (MWh) and F_n is the annual throughput of system component *n* (ML). The quantified system components include 12 key water treatment plants, the desalination plant, 19 key pump stations and the recycled water facility. Their energy intensities were obtained from the infrastructure operator. For the pumping energy use of distributors and retailers, it was quantified using the average distribution energy intensity and the water demand by region (Lam *et al.*, 2016). Based on this definition, the total energy use by the water supply system (E_{supply}) becomes

$$E_{supply} = E_{bulk} + \sum_d (EI_{r,dz} D_{T,dz}) \tag{2}$$

where EI_r is the energy intensity for the water distribution by distributors & retailers (MWh/ML), D_T is the total annual water demand (ML) and dz is the demand zone.

2.2 Scenario definition

Three different scenarios were defined in the future assessment study (Table A3-8), described in the material and methods section. “Normal” scenario is the “baseline” case following the most-likely scenario defined in the DSSO model. “Dry” scenario has a 75% reduction in catchment inflow and a 8.4% reduction in water demand. “High water demand” scenario has a 20% higher water demand than the “Normal” scenario. The unsatisfied demand for an internally-plumbed rainwater tank over a 20 year period was estimated to be 23.2 m^3/yr (Siems and Sahin, 2016). In addition, 65 % outdoor demand could be satisfied. In the “Dry” scenario, it was assumed that the amount of unsatisfied demand (both indoor and outdoor) as doubled.

Table A3-8 Scenario definition

Parameter	“Normal” scenario	“Dry” scenario	“High water demand” scenario
Catchment inflow	default	75% lower	default
Average annual urban water use (ML/yr)	362,989	332,445	432,627
Annual tank water use (ML/yr)	6,578	2,997	6,578

The operation rules of the water supply network follows an early operation plan from the infrastructure operator (Seqwater, 2014b). The desalination system would be in full operation when the combined key storage level drops to below 60% its full capacity. The indirect potable water recycling system would be in full operation when the level drops to below 40%.

3 Life cycle energy assessment method

The “Cumulative Energy Demand - by energy type version 2.02” impact assessment method in the Australasian LCI database (lifecycles, 2015) was used to quantify the life-cycle energy use for material supply and electricity supply. Electricity use for all infrastructure was assumed to be high voltage electricity supply in eastern Australia (11.27 MJ/kWh), while that of the rainwater tanks was assumed to be low voltage electricity supply in eastern Australia (11.92 MJ/kWh).

References

Australian Bureau of Statistics (2013) Environmental Issues: Water use and Conservation, Mar 2013. http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/4602.0Mar%202001 (accessed 29.09.14).

Bureau of Meteorology (2016) National performance report 2014–15: urban water utilities, Part B. http://www.bom.gov.au/water/npr/docs/2014-15/National-performance-report-2014-15_part-B.xlsx (accessed 27.06.16).

Hallmann, M., Grant, T. and Alsop, N. (2003) Yarra Valley Water Life Cycle Assessment and Life Cycle Costing of Water Tanks as a Supplement to Mains Water Supply. (accessed

Iplex Pipelines (2013) Flowtite® GRP Pipe Systems Features and Case Studies. http://www.iplex.com.au/iplex.php?page=lib&lib=31&sec=230 (accessed 13.10.16).

iplex Pipelines (2015) FLOWTITE™ Nominal pipe stiffness SN10,000 Dimensions. http://www.iplex.com.au/resources/library/Flowtite/pipe%20dimensions%20sn10000.pdf (accessed 13.10.16).

Kenway, S.J., Binks, A., Lane, J., Lant, P.A., Lam, K.L. and Simms, A. (2015) A systemic framework and analysis of urban water energy. *Environmental Modelling and Software* 73, 272-285.

Lam, K.L., Lant, P.A., O'Brien, K. and Kenway, S.J. (2016) Comparison of water-energy trajectories of two major regions experiencing water shortage. *Journal of Environmental Management* 181, 403-412.

Lane, J.L., de Haas, D.W. and Lant, P.A. (2015) The diverse environmental burden of city-scale urban water systems. *Water Research* 81, 398-415.

lifecycles (2015) Australasian LCI database version 2015.02. http://www.lifecycles.com.au/australasian-database (accessed 28.09.16).

Moglia, M., Tjandraatmadja, G., Delbridge, N., Gulizia, E., Sharma, A.K., Butler, R. and Gan, K. (2014) Survey of savings and conditions of rainwater tanks. http://www.clearwater.asn.au/user-data/research-projects/swf-files/10tr4---001-rainwater-surveys-final-report.pdf (accessed 22.09.16).

Muñoz, I. and Fernández-Alba, A.R. (2008) Reducing the environmental impacts of reverse osmosis desalination by using brackish groundwater resources. *Water Research* 42(3), 801-811.

Poussade, Y., Vince, F. and Robillot, C. (2011) Energy consumption and greenhouse gases emissions from the use of alternative water sources in South East Queensland. *Water Science and Technology: Water Supply* 11, 281-287.

Queensland Government Department of Infrastructure (2007) The Coordinator-General's Change Report on the Environmental Impact Statement for the Southern Regional Water Pipeline. http://www.statedevelopment.qld.gov.au/resources/project/southern-regional-water-pipeline/mp-srwp-change-report-may-07.pdf (accessed 17.09.16).

Queensland Government Department of State Development (2016a) Northern Pipeline Inter-connector Project - Stage 1. http://www.statedevelopment.qld.gov.au/assessments-and-approvals/northern-pipeline-interconnector-stage-1.html (accessed 16.09.16).

Queensland Government Department of State Development (2016b) Northern Pipeline Inter-connector Project - Stage 2. http://www.statedevelopment.qld.gov.au/assessments-and-approvals/northern-pipeline-interconnector-stage-2.html (accessed 16.09.16).

Queensland Urban Utilities (2014) Queensland Urban Utilities Water Netserv Plan Part A. http://www.urbanutilities.com.au/development-services/help-and-advice/water-netserv-plan (accessed 17.09.14).

Queensland Water Commission (2010) South East Queensland Water Strategy. http://www.dews.qld.gov.au/__data/assets/pdf_file/0019/32734/seqws.pdf (accessed 09.12.13).

Redland City Council (2014) Redland City Council Annual Report 2013-14. http://www.redland.qld.gov.au/download/downloads/id/961/2013-2014_annual_report.pdf (accessed 21.07.15).

Seqwater (2014a) Supply network. http://www.seqwater.com.au/water-supply/supply-network (accessed 16.09.16).

Seqwater (2014b) Annual Operations Plan May 2014. http://www.seqwater.com.au/sites/default/files/PDF%20Documents/Publications/Annual%20Operations%20Plan%20May%202014.pdf (accessed 14.07.14).

Siems, R. and Sahin, O. (2016) Energy intensity of residential rainwater tank systems: Exploring the economic and environmental impacts. *Journal of Cleaner Production* 113, 251-262.

Steel Mains (2015) SINTAKOTE® Steel Pipeline Systems Product Data Version 1. http://www.steelmains.com/files/Steel%20Mains_A4%20Product%20Data_Handbook_we.pdf (accessed 12.10.16).

Steel Mains (Undated) SEQ Water Grid. http://www.steelmains.com/files/SM%20SEQ%20Water%20Grid%202008.pdf (accessed 12.10.16).

Stokes, J. and Horvath, A. (2010) Life-Cycle Assessment of Urban Water Provision: Tool and Case Study in California. *Journal of Infrastructure Systems* 17(1), 15-24.

The Australian Pipeliner (2016a) Trenchless technology proves its worth for Australian desal. http://www.pipeliner.com.au/2016/03/16/trenchless-technology-proves-its-worth-for-australian-desal/ (accessed 19.12.16).

The Australian Pipeliner (2016b) Western Corridor Recycled Water Project nears completion. http://www.pipeliner.com.au/2016/03/16/western-corridor-recycled-water-project-nears-completion/ (accessed 21.09.16).

Unitywater (2014) Unitywater Netserv Plan Part A 2014. http://www.unitywater.com.au/netserv (accessed 03.10.2014).

Veolia Water (2008) Western Corridor Recycled Water Project Australia. http://www.pecc.org/resources/infrastructure-1/1128-wastewater-policy-and-tourism-in-coastal-cities-and-islands/file (accessed 21.09.16).

Walton, C. and Holmes, K. (2009) How much water efficiency does $321 million buy?, Sydney, Australia.

Appendix A4 Details of water-related energy management options, scenario and sensitivity analysis

Lam, K.L., Kenway, S.J., Lant, P.A. (2017) City-scale analysis of water-related energy identifies more cost-effective solutions. *Water Research* 109, 287–298.

Supplementary Material

Abbreviations

$CAPEX_{City}$	Capital expenditure from water utility/government and end users ($)
$CAPEX_{Utility}$	Capital expenditure from water utility ($)
E_{EU}	Energy saving at water end use as quantified by the data source (MWh/year)
$E_{EU,t}$	Energy saving at water end use in *t* th year (MWh)
$E_{EW,t}$	Energy saving at water utility in *t* th year (MWh)
$E_{O,WU}$	Energy saving at water utility (non-water saving related) (MWh/year)
$EC_{EU,t}$	Electricity price at water end use in the *t* th year ($/MWh)
$EC_{WU,t}$	Electricity price at water utility in the *t* th year ($/MWh)
$ECS_{EU,t}$	Energy cost saving at water end use in the *t* th year ($)
$ECS_{WU,t}$	Energy cost saving at water utility in the *t* th year ($)
EI_{EU}	Energy intensity for water end use activities (MWh/ML)
$EI_{WS,t}$	Energy intensity for water supply in the *t* th year (MWh/ML)
$EI_{WW,t}$	Energy intensity for wastewater treatment in the *t* th year (MWh/ML)
EP_{City}	Energy saving potential of an option from the city perspective (MWh)
$EP_{Utility}$	Energy saving potential of an option from the water utility perspective (MWh)
$i_{EC,EU}$	Electricity price annual change rate at water end use (%)
$i_{EC,WU}$	Electricity price annual change rate at water utility (%)
$i_{EI,WS}$	Energy intensity for water supply annual change rate (%)
$i_{EI,WW}$	Energy intensity for wastewater treatment annual change rate (%)
i_{WC}	Water price annual change rate (%)
MC_{City}	Marginal cost of an option from the city perspective ($/MWh)
$MC_{Utility}$	Marginal cost of an option from the water utility perspective ($/MWh)
n	Monte Carlo run
N_{max}	Total number of Monte Carlo simulation
t	Year
t_{option}	Lifetime of option

T_{max}	Number of assessment year
TC_{City}	Net cost of an option from the city perspective ($)
$TC_{Utility}$	Net cost of an option from the water utility perspective ($)
V_w	Water saving from the mains (ML/year)
WC_t	Water price ($/ML)

Table A4-1 More details of the options

No.	**Option**	**Year of Study**	**Details** [1]
1	Active leak detection and pressure management	2012	It is based on the "*Active Leak Detection*" and "*Pressure management*" programs implemented by Sydney water in 2011-12. The option focused on reducing water leakage in the water distribution network. For household leak management, it is partly included in option 16 (Plumber visit). In Australia, leakage prevention is a favourable option to the water utilities and planners (Girard and Stewart, 2007; Sydney Water Corporation, 2012; Turner *et al.*, 2010).
2	Scrubber ventilation efficiency	2013	It is based on an option of "*Scrubber Ventilation Efficiency at Malabar Waste Water Treatment Plant*" implemented by Sydney Water.
3	Sewage pumping efficiency	2013	It is based on an option of "*Pump's VSD control optimisation at Fairfield Waste Water Treatment Plant*" evaluated by Sydney Water.
4	Minimising the use of DAF	2012	It is based on an option of "*Switch from DAF to Clarifier operation at North Richmond Water Filtration Plant*" implemented by Sydney Water.
5	Most open valve aeration strategy	2012	It is based on an option of "*Implementation of Most Open Valve (MOV) aeration strategy*" implemented by Sydney Water.
6	Inverter speed control pump for bulk water transfer	2009	It is based on an option of the use of inverter speed control pump in the Shoalhaven Scheme evaluated by Sydney Catchment Authority.
7	Aeration optimisation	2013	It is based on an option of reducing the continuous aeration of WTP's pond implemented by Melbourne Water.
8	Plant upgrade for biogas recovery and electricity generation	2012	It is based on the upgrade of Bolivar wastewater treatment plant in Adelaide.
9	Existing STP reuse and minor recycling	2002-2009	It is based on the recycled water scheme implemented by Sydney Water Corporation between 2002 and 2009.
10	Stormwater harvesting	2015	5 stormwater harvesting projects of the same scale as "*Blacktown Stormwater Harvesting and Reuse scheme*" were assumed to be implemented in the city.
11	Water-efficient clothes washer rebate	2006-2008	It is based on the result of the "*Home WaterWise Rebate*" launched in South East Queensland between 2006 and 2008. The energy saving at the end use was estimated based on a study of energy saving (i.e., electricity) from the use of water efficient devices in Brisbane (Beal *et al.*, 2012). The expenditure in the end use is assumed to be the same as the cost of the rebate scheme.
12	Water-efficient shower head rebate	2006-2008	
13	Dual flush toilet rebate	2006-2008	
14	Solar hot water system rebate	2010-2012	It is based on the "*QLD Government Solar Hot Water Rebate*" launched between 2010 and 2012. The rebate target was to replace old existing electricity hot water systems with solar hot water systems. It is assumed that the end use spent two times the cost of the rebate scheme. The energy saving was estimated based on a study of energy saving (i.e., electricity) from the use of solar hot water system in Brisbane (Beal *et al*., 2012).
15	Alarming visual display monitors for shower	2010	It is based on a water end use study that quantified the water and energy impact of the use of alarming visual display monitor for shower. It is assumed the utility is paying the cost of the devices, while the end use is paying the installation cost (though the study suggested that it can be easily installed by the end user).
16	Plumber visit	2000-2002	It is based on a large scale water demand management program launched by Sydney Water between 2000 and 2002. Under the program, the end user only needs to pay approximately 15% of the total cost. The energy saving (i.e., electricity) at the end use was estimated based on a study of energy saving from the use of water efficient devices in Brisbane (Beal *et al*., 2012).
17	Cooling towers upgrade	2012	10 cooling tower upgrade projects of the same scale as a project conducted in Melbourne were assumed to be implemented in the city. The nominal CAPEX in Table 1 includes both utility and end use cost.
18	Irrigation and landscape efficiency program	2010-2011	It is based on a water efficiency program of a part of the "*Hawkesbury-Nepean River Recovery Program*" implemented by NSW government. The end user contributed 37% of total cost of the program.

[1] References are included in Table 11.

Table A4-2 Consumer Price Index of Australia

Year	Consumer Price Index[1]
2000	71.5
2001	74.6
2002	76.9
2003	79.0
2004	80.8
2005	83.0
2006	85.9
2007	87.9
2008	91.8
2009	93.4
2010	96.1
2011	99.3
2012	101.0
2013	103.5
2014	106.1

[1] Average of the four quarters in each year

Table A4-3 Summary data and characteristics of four Australian cities and the hypothetical city

Context [1]	Brisbane	Melbourne	Sydney	Perth	Hypothetical city [2]
Population	2,274,600	4,440,300	4,840,600	2,021,200	3,394,175
Urban density					
Population density (people/ km^2)	150	450	400	320	360
Occupied private dwellings: separate house	79.0%	72.6%	60.9%	78.6%	70.4%
Climate					
Type	Humid subtropical	Oceanic	Humid subtropical	Hot summer Mediterranean	Humid subtropical [3]
Mean maximum temperature (°C)	26.5	19.8	21.7	24.8	26.5
Mean minimum temperature (°C)	16.3	9.6	13.8	12.8	16.3
Mean monthly sunshine hours (hr)	247	183	220	269	247
Energy intensity of main water supply (kWh/kL)	0.541	0.137	0.298	1.840	0.57
Energy intensity of wastewater treatment (kWh/kL)	0.733	1.359	0.492	0.790	0.83
Water consumption charge ($/kL)	2.99	2.60	2.17	1.38	2.28
Electricity price – Utility ($/MWh)	139	154	140	-	144
Electricity price – Residential ($/MWh)	245	239	233	-	239
Emission factor (full fuel cycle) (kg CO_2eq/kWh)	0.95	1.34	1.00	0.83	1.03
Total urban water demand (ML)	173,484	395,462	541,492	260,142	253,773
% of different water source [4]					
Surface water	89%	96%	93%	17%	79%
Groundwater	3%	0%	0%	42%	9%
Desalinated seawater	0%	0%	0%	38%	7%
Recycled water (non-potable)	7%	4%	7%	3%	5%
% of water end use type					
Residential [5]	61.5%	64.0%	65.5%	68.4%	65.1%
Commercial, municipal and industrial	30.0%	25.0%	23.4%	20.3%	24.1%
Other [6]	8.5%	11.0%	11.1%	11.3%	10.8%
Total wastewater collected (ML)	154,374	341,263	469,579	135,380	325,051
% of wastewater treatment level					
Primary	0.1%	0%	74.2%	5.2%	30.3%
Secondary	9.7%	51.2%	3.3%	0%	18.1%
Tertiary	90.2%	48.8%	22.5%	94.8%	51.6%
Household water use pattern [7]					
Garden and outdoor	43%	24%	27%	43%	34%
Shower and bathroom	24%	27%	15%	17%	21%
Washing machine	13%	19%	17%	14%	16%
Toilet	11%	19%	24%	11%	16%
Other	10%	11%	17%	15%	13%

[1] Some figures may not add up to the total due to rounding. This work uses the National Performance Report - Urban Water Utilities as the primary dataset (Bureau of Meteorology, 2015) and is supplemented with other data sources (Australian Bureau of Statistics, 2014; 2015; Bureau of Meteorology, 2016; Department of the Environment, 2014; Lam *et al.*, 2016a; Lam *et al.*, 2016b; Melbourne Water, 2014; Origin Energy, 2016; Queensland Government, 2008; Sydney Water Corporation, 2014; Water Corporation, 2014).

[2] Except for the climate condition, all the values in the hypothetical city are taken as either direct or population-weighted average of the four cities.

[3] The climate of the hypothetical city is based on that of Brisbane, where the end use water-related energy use studies (Beal *et al.*, 2012; Willis *et al.*, 2010) used in this work were conducted.

[4] Considering the wider South East Queensland region for Brisbane as regional water supply systems are inter-connected

[5] In the residential sector, the energy saving potential is evaluated based on electricity hot water system, which is the majority type in Brisbane.

[6] Including non-revenue water such as unbilled water use and water leakage, does not include agricultural water use

[7] Reference figures before 2007 (Queensland Government, 2008).

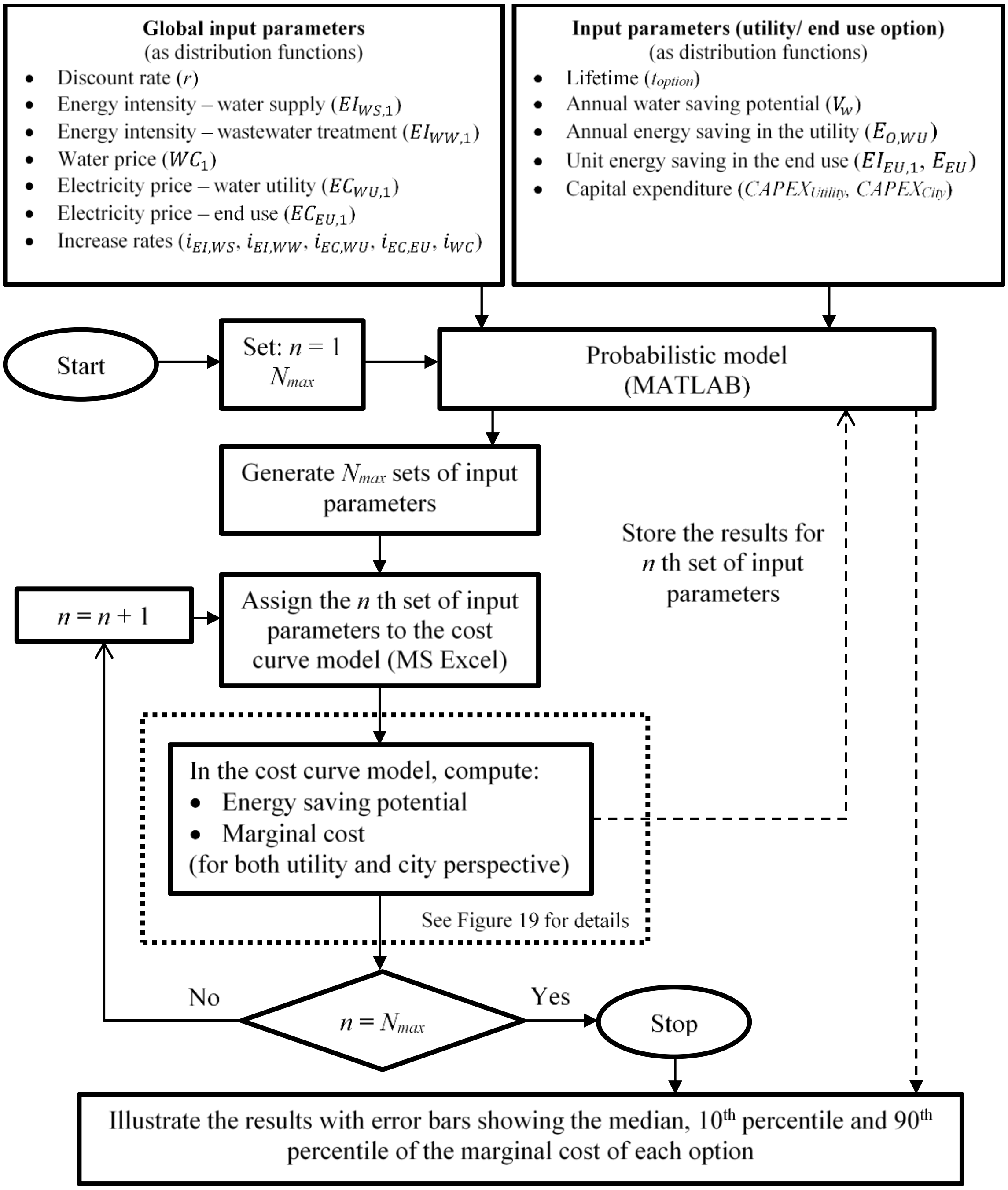

Figure A4-1 Flow diagram showing the steps of simulating with Monte Carlo approach for uncertainty analysis

Table A4-4 Distribution functions of input parameters of the city for uncertainty analysis

Context	Value	Lower bound	Upper bound	Distribution shape
Energy intensity of main water supply (kWh/kL)	0.57	0.14	1.84	Triangular
Energy intensity of wastewater treatment (kWh/kL)	0.83	0.49	1.36	Triangular
Water consumption charge ($/kL)	2.28	1.38	2.99	Triangular
Water price annual change	2%	1%	5%	Uniform
Electricity price - Utility ($/MWh)	144	139	154	Triangular
Electricity price –End use ($/MWh)	239	233	245	Triangular
Electricity price annual change	2%	1%	5%	Uniform
Energy intensity of water system annual change	1%	0%	5%	Uniform
Discount rate	5%	3%	7%	Uniform
Extra parameters for the marginal abatement cost curves for GHG emissions				
Emission factor (tCO2-eq/kWh)	1.03	0.83	1.34	Triangular
Emission factor change	0.0%	-2%	2%	Uniform

Table A4-5 Distribution functions of input parameters of all the options for uncertainty analysis

Option	Lifetime (year)				Water saving (ML/year)				Energy saving – utility (MWh/year)				Unit energy saving – end use					Capital expenditure (utility perspective, real terms in 2014)			
	V	L%	U%	S	V	L%	U%	S	V	L%	U%	S	V	Unit	L%	U%	S	V	L%	U%	S
1	20	50%	150%	Uni	30416	50%	100%	Uni	-	-	-	-	-	-	-	-	-	9989582	50%	150%	Uni
2	20	50%	150%	Uni	-	-	-	-	1044	50%	150%	Uni	-	-	-	-	-	208526	50%	150%	Uni
3	20	50%	150%	Uni	-	-	-	-	562	50%	150%	Uni	-	-	-	-	-	59955	50%	150%	Uni
4	20	50%	150%	Uni	-	-	-	-	500	50%	150%	Uni	-	-	-	-	-	82634	50%	150%	Uni
5	20	50%	150%	Uni	-	-	-	-	2000	50%	150%	Uni	-	-	-	-	-	230997	50%	150%	Uni
6	20	50%	150%	Uni	-	-	-	-	6219	50%	150%	Uni	-	-	-	-	-	1349581	50%	150%	Uni
7	20	50%	150%	Uni	-	-	-	-	4468	50%	150%	Uni	-	-	-	-	-	1190910	50%	150%	Uni
8	20	50%	150%	Uni	-	-	-	-	31450	50%	150%	Uni	-	-	-	-	-	27168430	50%	150%	Uni
9	20	50%	150%	Uni	2160	50%	150%	Uni	-	-	-	-	-	-	-	-	-	9468667	50%	150%	Uni
10	20	50%	150%	Uni	1000	50%	150%	Uni	-	-	-	-	-	-	-	-	-	31181800	50%	150%	Uni
11	10	50%	150%	Uni	1465	50%	150%	Uni	-	-	-	-	76	MWh/ML	50%	150%	Uni	56663998	50%	150%	Uni
12	10	50%	150%	Uni	475	50%	150%	Uni	-	-	-	-	42	MWh/ML	50%	150%	Uni	1047791	50%	150%	Uni
13	10	50%	150%	Uni	755	50%	150%	Uni	-	-	-	-	-	-	-	-	-	7611750	50%	150%	Uni
14	20	50%	150%	Uni	-	-	-	-	-	-	-	-	67067	MWh/year	50%	150%	Uni	28588371	50%	150%	Uni
15	10	50%	150%	Uni	1491	50%	150%	Uni	-	-	-	-	60200	MWh/year	50%	150%	Uni	8278486	50%	150%	Uni
16	10	50%	150%	Uni	3344	50%	150%	Uni	-	-	-	-	32	MWh/ML	50%	150%	Uni	29565963	50%	150%	Uni
17	20	50%	150%	Uni	220	50%	150%	Uni	-	-	-	-	4400	MWh/year	50%	150%	Uni	4651445	50%	150%	Uni
18	20	50%	150%	Uni	1090	50%	150%	Uni	-	-	-	-	-	-	-	-	-	6181270	50%	150%	Uni

V: Value; L%: Lower percentage; U%: Upper percentage; S: distribution shape; Uni: uniform distribution

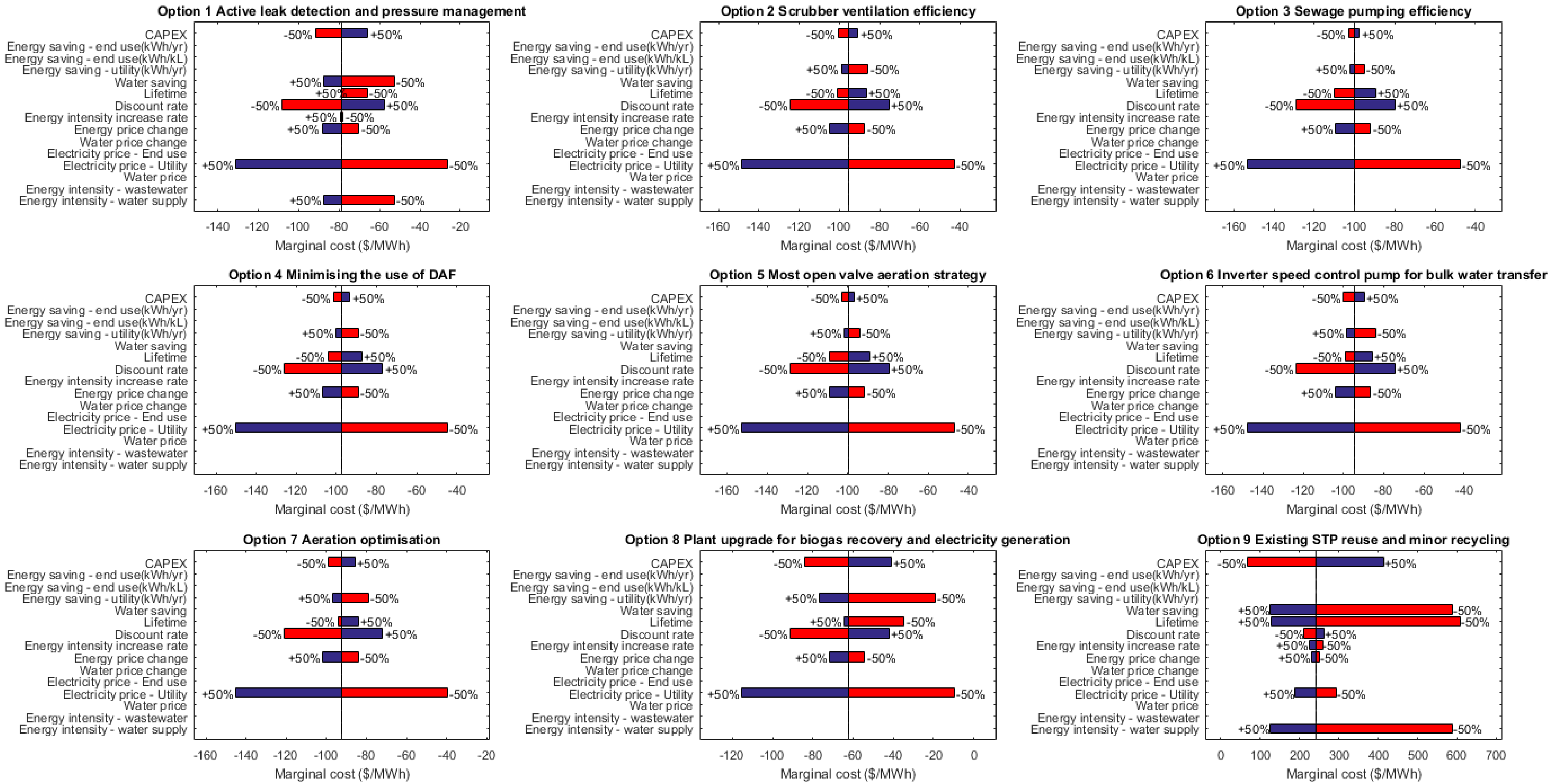

Figure A4-2 Sensitivity diagrams showing the ranges of the marginal costs of option 1 to 9 for low (-50%) and high (+50%) values of all input parameters

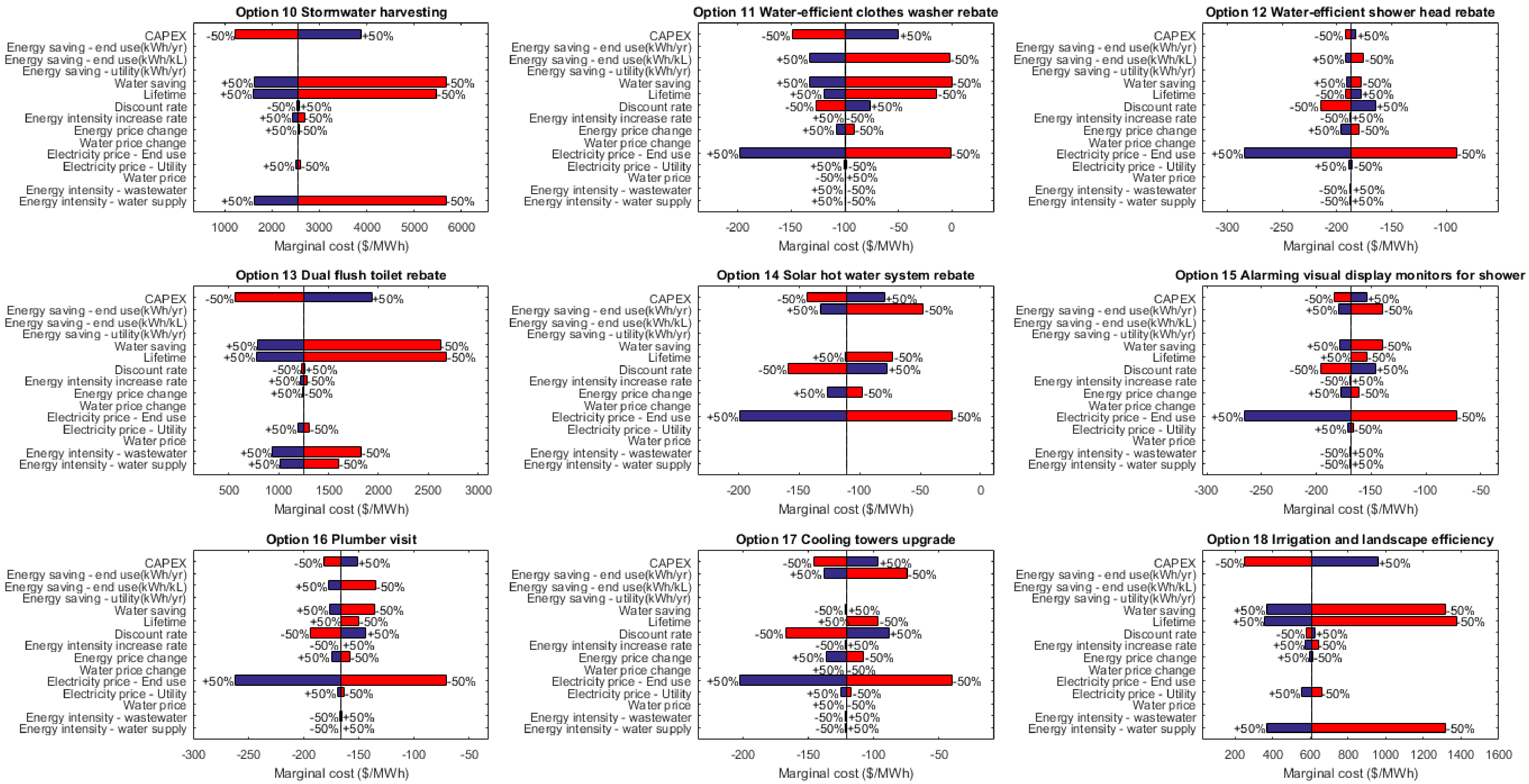

Figure A-3 Sensitivity diagrams showing the ranges of the marginal costs of option 10 to 18 for low (-50%) and high (+50%) values of all input parameters

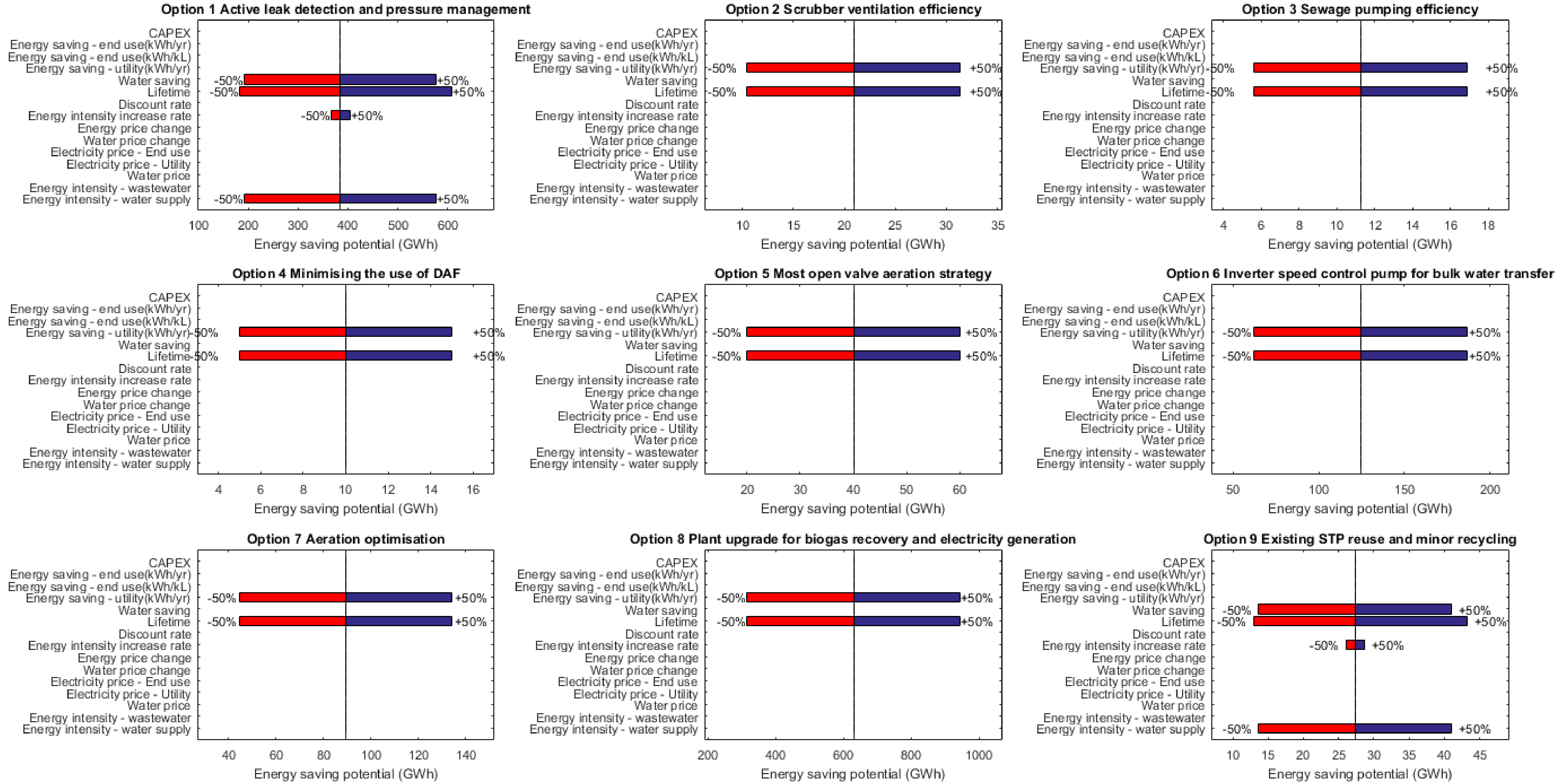

Figure A4-4 Sensitivity diagrams showing the ranges of the energy saving potential of option 1 to 9 for low (-50%) and high (+50%) values of all input parameters

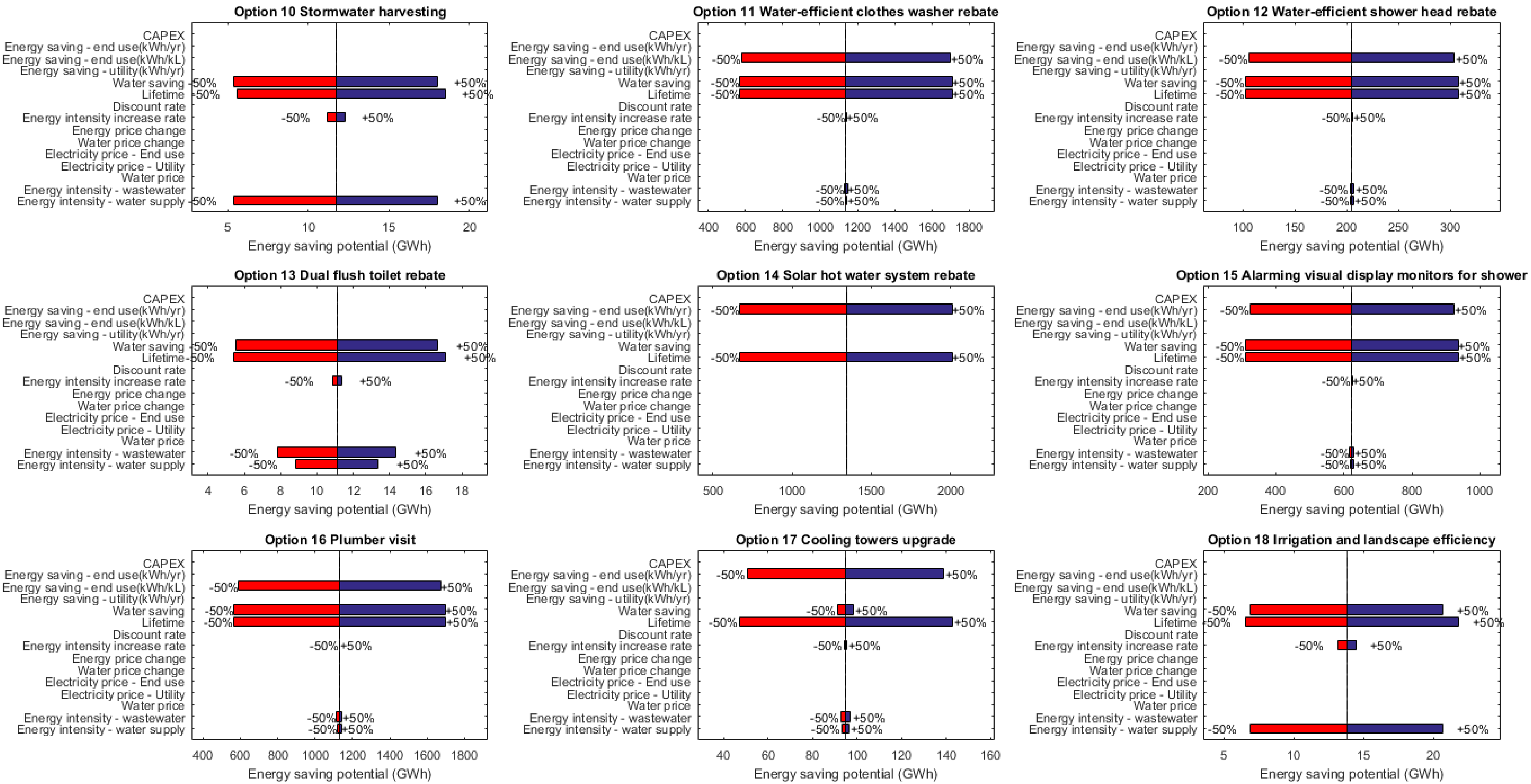

Figure A5-5 Sensitivity diagrams showing the ranges of the energy saving potential of option 10 to 18 for low (-50%) and high (+50%) values of all input parameters

References

Australian Bureau of Statistics (2014) Regional Population Growth, Australia, 2013-14. http://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/3218.0Main+Features12013-14 (accessed 29.12.15).

Australian Bureau of Statistics (2015) 2011 Census. http://www.abs.gov.au/websitedbs/censushome.nsf/home/quickstats?opendocument&navpos=220 (accessed 27.09.16).

Beal, C.D., Bertone, E. and Stewart, R.A. (2012) Evaluating the energy and carbon reductions resulting from resource-efficient household stock. *Energy and Buildings* 55, 422-432.

Bureau of Meteorology (2015) National performance report 2013–14: urban water utilities, Part B. http://www.bom.gov.au/water/npr/docs/2013-14/National_Performance_Report_2013-14_PartB.xlsx (accessed 12.07.15).

Bureau of Meteorology (2016) Climate Data Online. http://www.bom.gov.au/climate/data/index.shtml (accessed 27.09.16).

Department of the Environment (2014) National Greenhouse Account Factors July 2014. http://www.environment.gov.au/system/files/resources/b24f8db4-e55a-4deb-a0b3-32cf763a5dab/files/national-greenhouse-accounts-factors-2014.pdf (accessed 07.09.15).

Girard, M. and Stewart, R.A. (2007) Implementation of pressure and leakage management strategies on the gold coast, Australia: Case study. *Journal of Water Resources Planning and Management* 133(3), 210-217.

Lam, K.L., Kenway, S.J. and Lant, P.A. (2016a) Energy use for water provision in cities. *Manuscript submitted for publication*.

Lam, K.L., Lant, P.A., O'Brien, K. and Kenway, S.J. (2016b) Comparison of water-energy trajectories of two major regions experiencing water shortage. *Journal of Environmental Management* 181, 403-412.

Melbourne Water (2014) Melbourne Water Annual Report 2013-14. http://www.melbournewater.com.au/aboutus/reportsandpublications/annual-report/documents/4977_mel_annual_report_2014_lr.pdf (accessed 19.06.15).

Origin Energy (2016) Current Residential Electricity and Gas Tariffs. http://www.originenergy.com.au/content/dam/origin/business/Documents/elec-gas/multi-site-pricing-booklet.pdf (accessed 10.02.16).

Queensland Government (2008) State of the Environment Queensland 2007. http://www.ehp.qld.gov.au/state-of-the-environment/report-2007/pdf/soe-report-2007.pdf (accessed 15.04.15).

Sydney Water Corporation (2012) Water Efficiency Report 2011-12. http://www.sydneywater.com.au/Publications/Reports/AnnualReport/2012/assets/Operating%20Licence%20Water%20Efficiency%20Report%202011-12.pdf (accessed 10.02.16).

Sydney Water Corporation (2014) Operating Licence Environment Report. http://www.sydneywater.com.au/sw/about-us/our-publications/reports-and-publications/index.htm (accessed 19.06.15).

Turner, A., Coates, A., Fyfe, J., White, S. and Retamal, M. (2010) SEQ's One to One Water Savings Program. *Water: Journal of the Australian Water Association* 37(1), 82-84, 86, 88-91.

Water Corporation (2014) Annual Report 2014. http://www.watercorporation.com.au/-/media/files/about-us/our-performance/annual-report/annual-report-2014/water-corporation-annual-report-2014.pdf (accessed 27.03.15).

Willis, R.M., Stewart, R.A., Panuwatwanich, K., Jones, S. and Kyriakides, A. (2010) Alarming visual display monitors affecting shower end use water and energy conservation in Australian residential households. *Resources, Conservation and Recycling* 54(12), 1117-1127.