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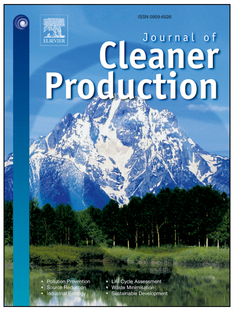

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PII: S0959-6526(16)32111-4

DOI: 10.1016/j.jclepro.2016.12.056

Reference: JCLP 8631

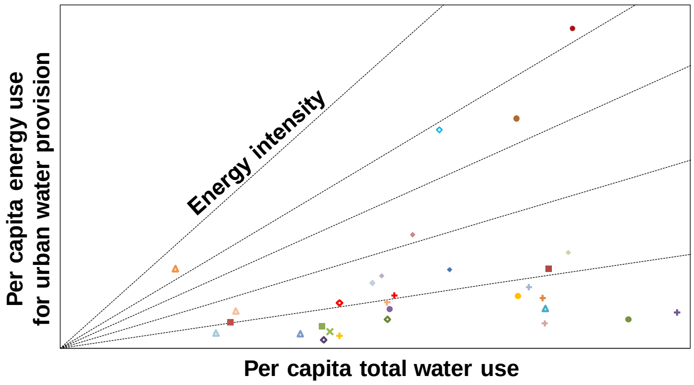
To appear in: *Journal of Cleaner Production*

Received Date: 7 March 2016

Revised Date: 5 October 2016

Accepted Date: 12 December 2016

Please cite this article as: Lam KL, Kenway SJ, Lant PA, Energy use for water provision in cities, *Journal of Cleaner Production* (2017), doi: 10.1016/j.jclepro.2016.12.056.


Energy intensity
Per capita energy use
for urban water provision
Per capita total water use

Energy use for water provision in cities

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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.

Keywords: urban water supply; water-energy nexus; energy management; water efficiency; multi-regional analysis; time-series analysis

Abbreviations

kWh/p/a	Energy use expressed as kilowatt-hour electricity use per person per year
kWh/kL	Energy intensity expressed as kilowatt-hour per kilolitre water supplied
L/p/d	Water use expressed as litre of water use per person per day
kWh	Kilowatt-hour
TWh	Terawatt-hour

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., 2011).

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.

2 Materials and Methods

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 1). 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 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 1S, 6S, 7S, 8S and 9S (Supplementary Material). All years (even if data sources are in fiscal year) are expressed as calendar year. Information on data quality control can be found in the Supplementary Material.

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 1S and Table 2S (Supplementary Material) 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.

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 2. 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 1 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		✓			○
Melbourne	Australia	2001-2015	4,377,000		✓	○		○
Perth	Australia	2002-2015	1,961,000		✓		✓	✓
Sydney	Australia	2002-2014	4,755,000		✓	○		○
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 1S (Supplementary Material) 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 1S (Supplementary Material).
[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; ○ to be operated in dry years. References can be found in Table 1S (Supplementary Material).

Table 2 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 Results

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 1). 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 4.1.2 and Table 3 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 litres per person per day (L/p/d) for Bangalore to 588 L/p/d for Bangkok (Figure 1). 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 3S, 4S and 5S (Supplementary Material).

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 2. 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 3S in Supplementary Material) show a downward trend for water use. 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 2). 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 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).

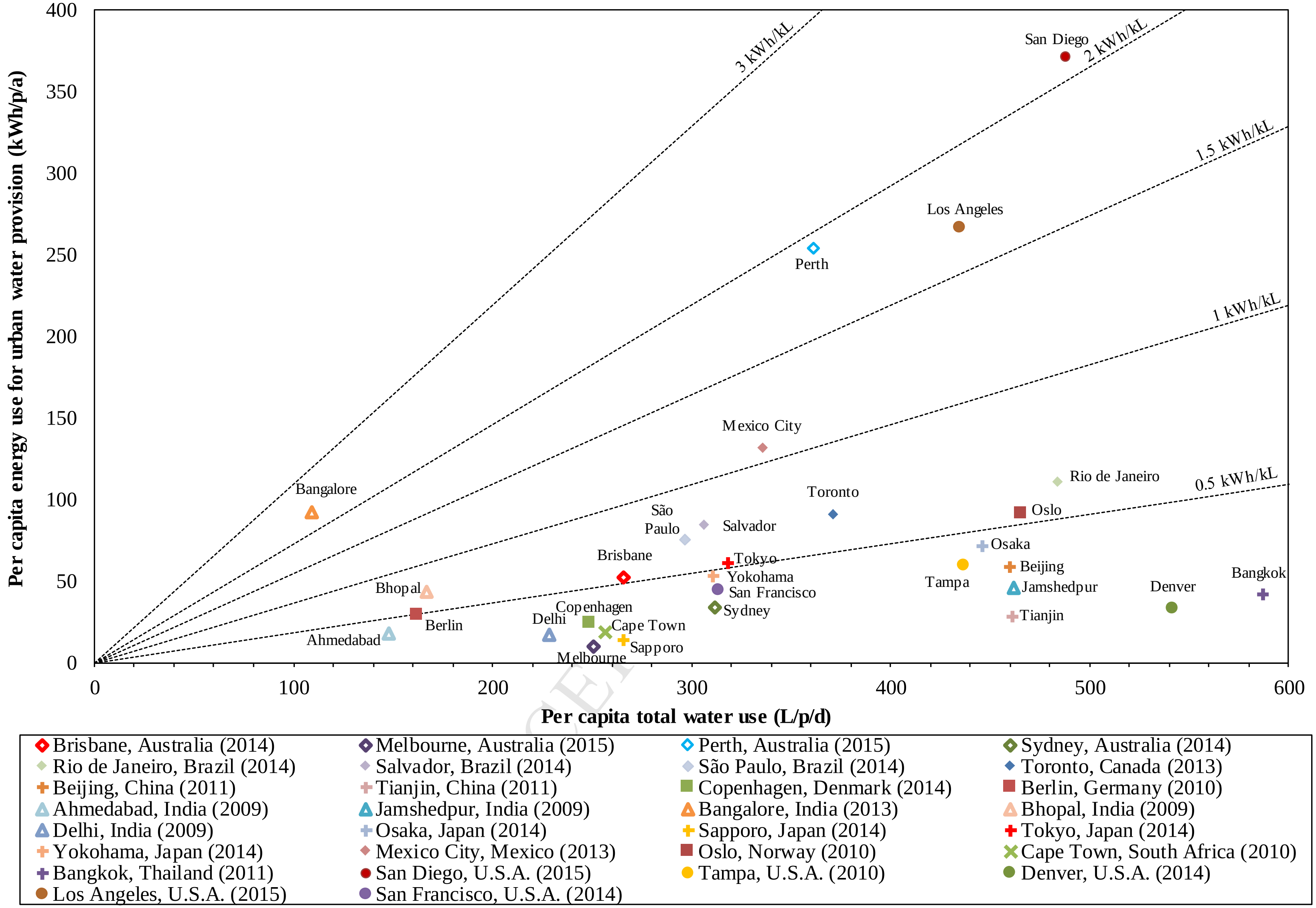

Figure 1 Water-energy profile of 30 cities, showing their per capita energy use for water provision and per capita total water use

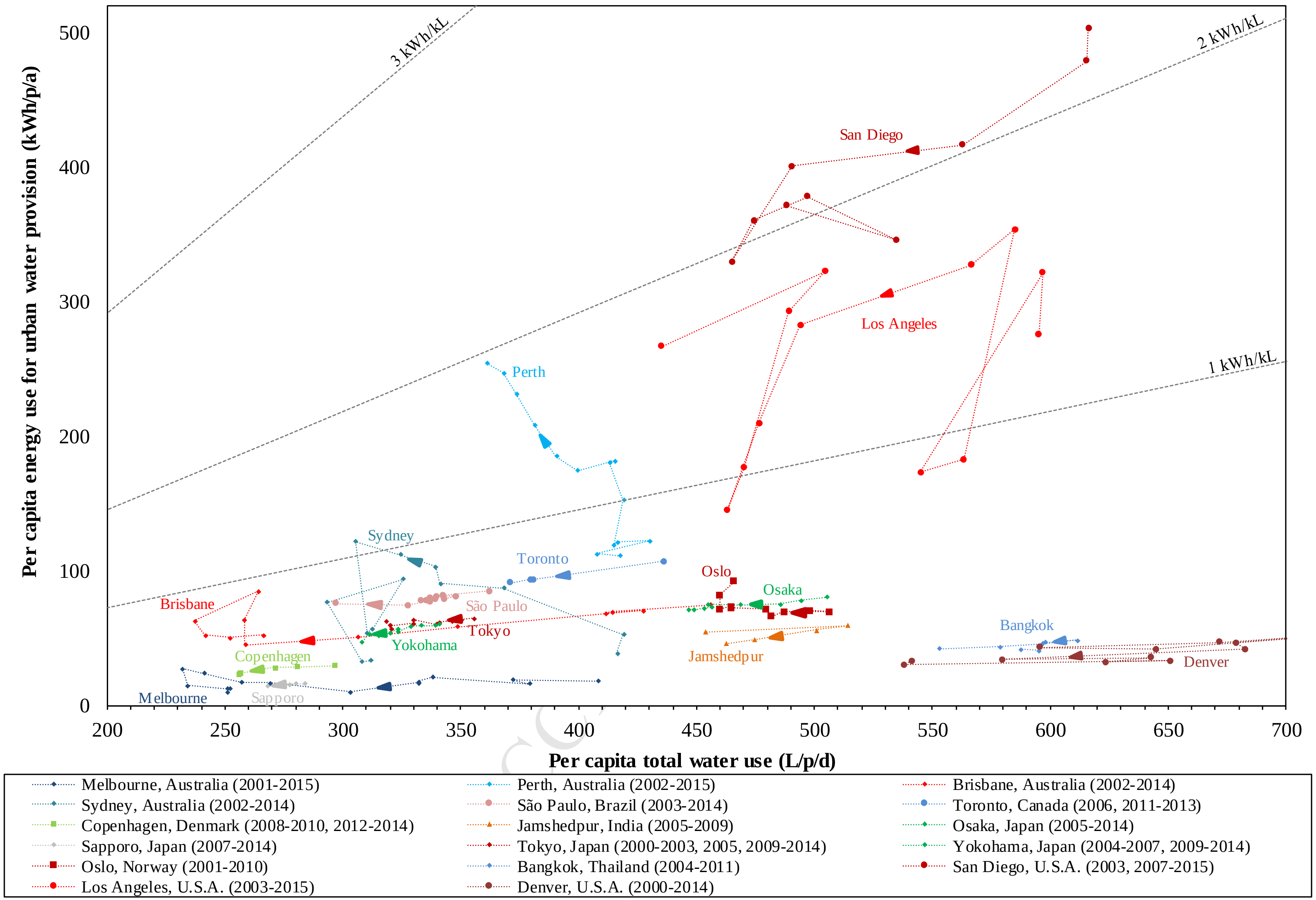

Figure 2 Water-energy profile for a sub-sample of 17 cities, showing their trajectories

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 3). 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 from 8 sources/cities), while that of water distribution ranges from 0.010 to 0.341 kWh/kL (average of 0.167 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 from 8 cities). Alternative water treatment approaches such as potable water recycling and seawater desalination are much more energy-intensive.

Table 3 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 6S in Supplementary Material
	-	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 California Aqueduct - East branch: 2.624 Colorado River Aqueduct: 1.622	0.027	0.159	
	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 hydro-power plants.

4 Discussion

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 1). It also explores how some of these influencing factors led to the time-series changes in some of the cities (as observed in Figure 2).

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 3). The long-term annual average precipitation (from 24 – 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 7S (Supplementary Material).

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 2). 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 45% 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 2).

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.* (2014) 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.

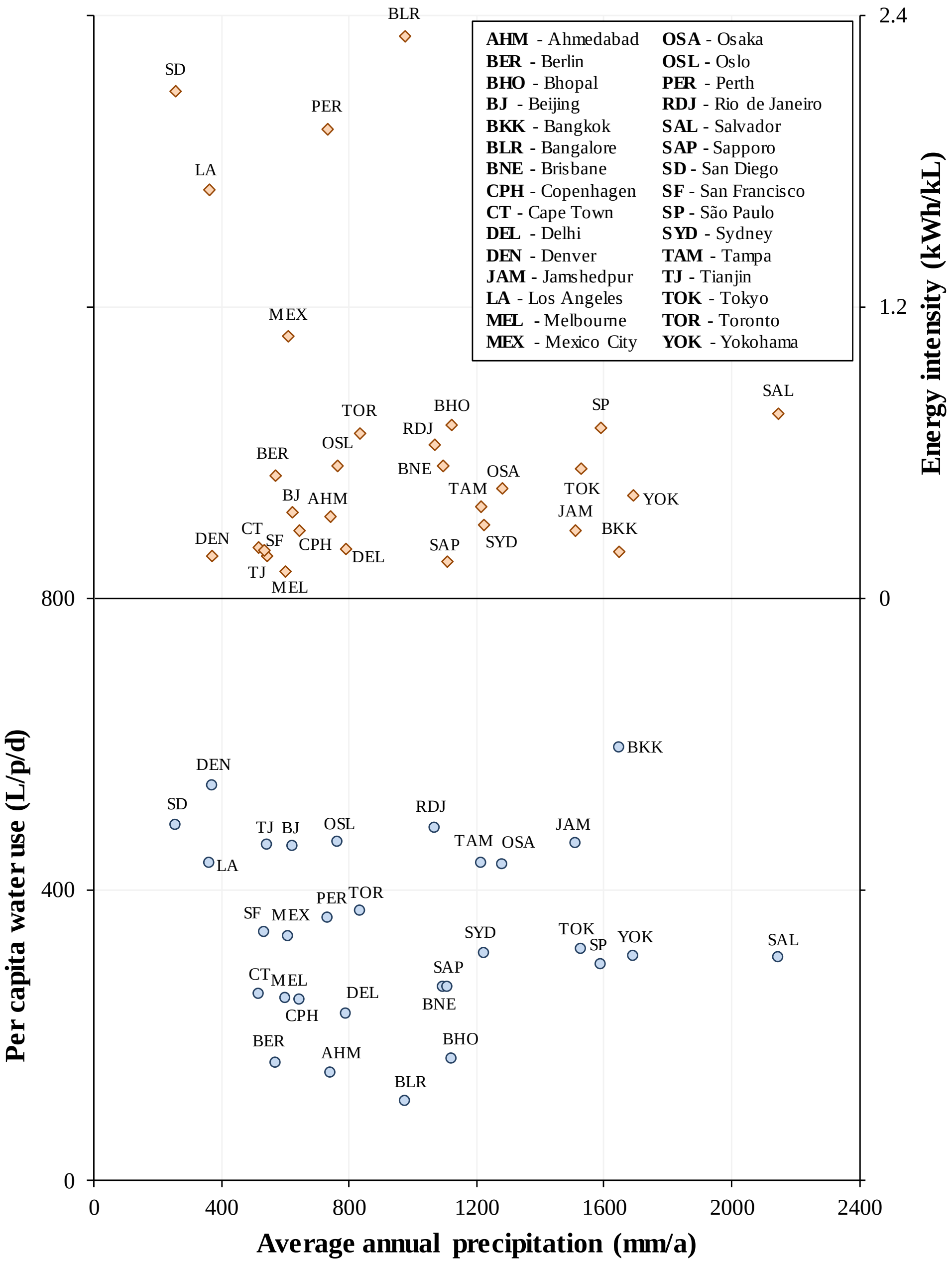

Figure 3 Average annual precipitation, per capita water use and energy intensity of water supply systems of 30 cities

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 3) has been assessed. Data sources are summarised in Table 8S (Supplementary Material).

The results clearly illustrate the nearly linear correlation between elevation difference and energy intensity for water transfer systems (Figure 4). 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 3) 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).

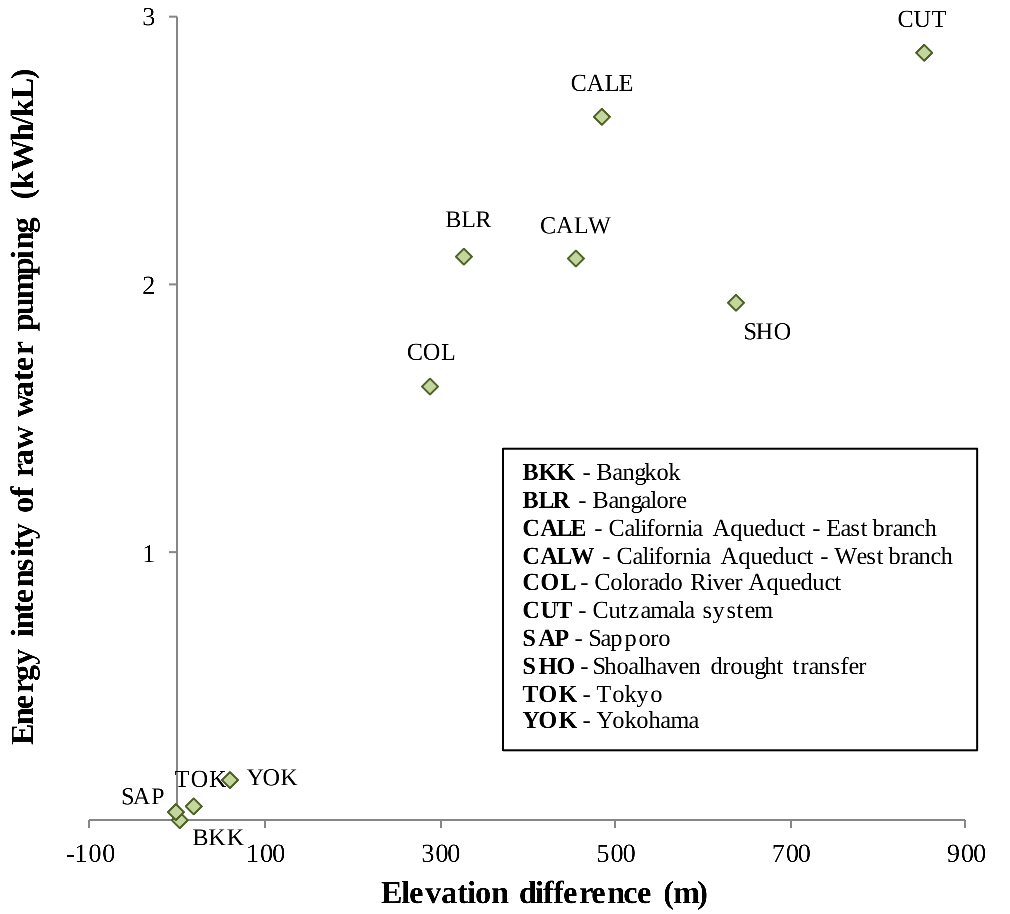

Figure 4 Energy intensity and elevation difference of different raw water transfer infrastructure

4.1.3 Water use pattern

In order to understand the results in Figure 1, 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 5). Data sources are included in Table 9S (Supplementary Material). 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.

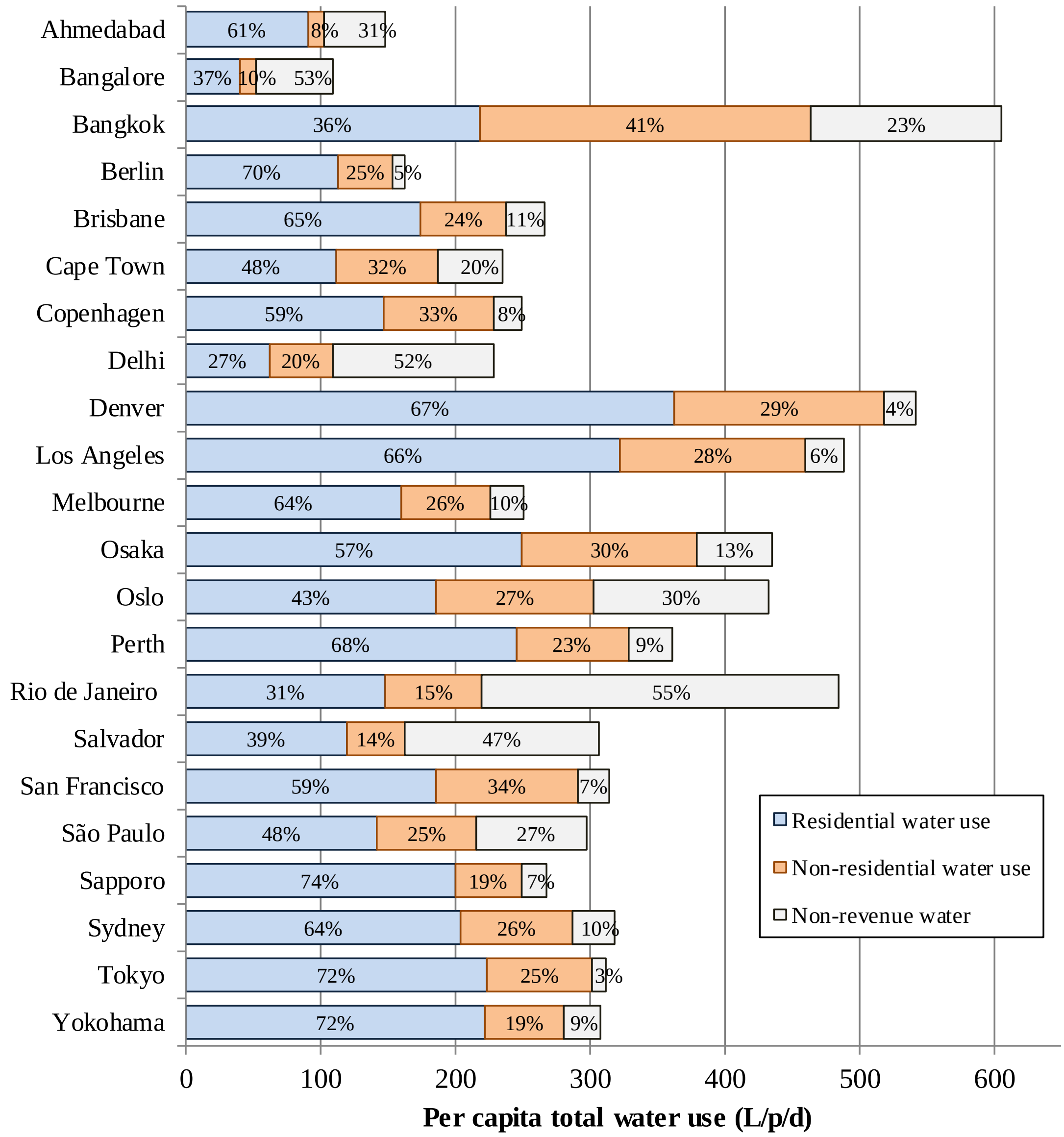

Figure 5 Breakdown of per capita total water use of 22 cities, showing the scale of residential water use and non-revenue water

In the majority of the cities in developed countries, residential water use represents over half of the total urban water use (Figure 5). 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, 2014) 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 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 5). 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 10S in Supplementary Material 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).

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 2 and Table 5S in Supplementary Material), 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.

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 3). Therefore, within water supply systems, the major opportunities for utilities to improve energy efficiency (illustrated by arrow *A* in Figure 6) 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.

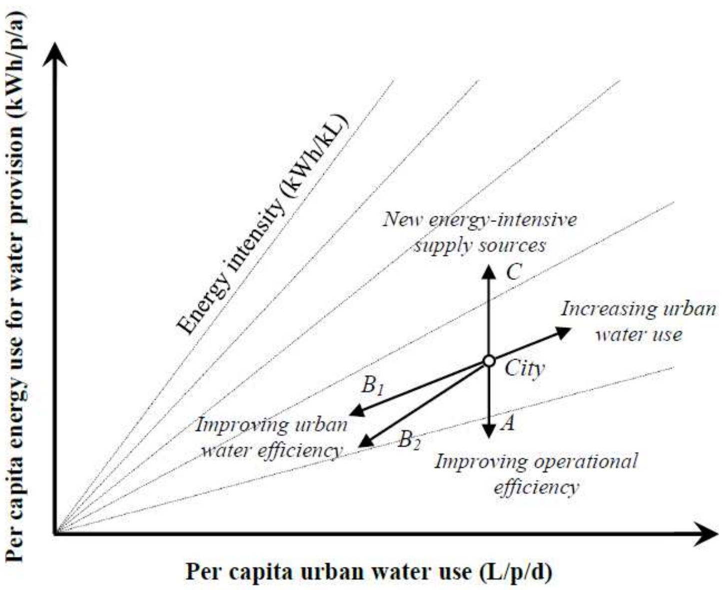

Figure 6 Illustration of where a city can transform

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, 2014)), 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.

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.

Acknowledgements

The authors would like to thank Reba Paul for providing access to the data of Bangalore, and Dr. Marguerite Renouf for review of an earlier draft of this paper. The authors also appreciate the comments from anonymous reviewers. Dr Steven Kenway acknowledges funding support from the Australian Research Council (DE160101322).

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Highlights

- A profiling approach is used to illustrate the water-energy trajectory of cities.
- Data for the direct energy use for water supply in 30 cities is compiled.
- Cities generally reduced per capita energy use for water supply in the last decade.
- Some cities provide insights into management of energy use for water provision.
- Water use reduction is needed to offset the energy impacts of system augmentations.