Quantifying water–energy links and related carbon emissions in cities
S. J. Kenway, P. Lant and T. Priestley

ABSTRACT

To date, key water–energy connections have not been systematically quantified. Nor has their potential for contributing to greenhouse gas mitigation been evaluated. Lack of knowledge of these links, particularly within cities, is viewed as a major limitation to energy-sensitive urban water management and integrated urban design. This paper fills part of this void. The key contribution is a new conceptual model coupled with a systematic review of the connections of influence. Drawing on Australian and international data, the results provide a structured estimate of water-related energy use and associated emissions in a hypothetical city of 1,000,000 people. This demonstrates that water-related energy use accounts for 13% of total electricity and 18% of the natural gas used by the population in the average case. This represents 9% of the total primary energy demand within Australia or 8% of total national territorial greenhouse gas emissions. Residential, industrial and commercial water-related energy use constitutes 86% of water-related greenhouse gas emissions. We conclude that urban water is a significant and overlooked lever that could significantly influence urban energy consumption.

Key words | energy, future cities, greenhouse gas, urban metabolism, water, water-sensitive city

NOTATION

GL  giga litre (1,000,000,000 l)
kWhe  1 kWh of electrical energy
kWhth  1 kWh of thermal energy. Note we assumed it takes three units of thermal (primary) energy to create one unit of electrical energy (Gleick & Cooley 2009)

INTRODUCTION

The water sector in Australia and elsewhere has recently been active in reducing energy use and associated greenhouse gas emissions (WSAA 2007). However, existing measures alone are unlikely to cope with the magnitude of forecast energy increases. Energy use by major Australian water utilities is anticipated to grow by 130–200% above 2006–07 levels by 2030 (Kenway et al. 2008). This growth could be much higher if: (i) water consumption rates increase above the drought-affected levels of 230 l per capita per day residential use; (ii) climate change alters existing low energy yields; or (iii) population growth of greater than 25% occurs. Some existing adopted greenhouse mitigation strategies such as clean-energy purchase, while commendable, arguably make the sector overly dependent on factors outside their control. A significant opportunity to diversify the approach lies in harnessing the influence of water management on energy use indirectly.

This paper contributes by systematically reviewing the diverse links between water management and energy use within cities. To date, these connections have largely been underestimated and ignored or overlooked. A possible reason is that many of the influences or ‘links’ are indirect, difficult to quantify accurately outside the typical boundary of ‘urban water’ responsibility and are constantly changing.

Early analysis in California suggests that ‘water-related energy’ in 2001 composed 19% of state-wide electricity use, and 32% of state-wide natural gas use excluding natural
gas for electricity generation (Klein et al. 2005). More recently published work (Wolff & Wilkinson 2011) evaluates the year 2000 in California. This indicates that ‘water-related energy’ accounted for 20% of the electricity use in the state and 10% of the natural gas use (including gas for electricity generation). In both studies energy use included use by water utilities, as well as energy associated with the use of water for residential, commercial, industrial and agricultural purposes.

This paper considers the connections between water and energy in the provision and consumption of water in cities, as well as in the management of wastewater. This focus excludes provision of water to, and use of water by, agriculture. Related nutrient flows are also considered. Energy use associated with water for provision and use in agriculture was excluded because this work focused on cities.

The paper aims to contribute towards development of methods to analyse water–energy–carbon links in cities. We hope this will help to inform policies and strategies which simultaneously address water and energy flows, and to move away from solutions which shift the problem from one resource domain to another.

Water and energy represent major components of the overall urban metabolism, the analysis of which has long been in need of methodological advance and consistency (Daniels & Moore 2001). Addressing resource flows through cities, while maintaining or improving human well-being and ecosystem health is a current sustainability challenge (Newman 1999).

**FOCUS, SCOPE AND METHOD**

**Focus and scope**

This paper considers water flows from centralised and decentralised urban water systems. Stormwater was not considered because most current stormwater management in Australia involves relatively low energy inputs and substantially less data exists. With regard to the energy cycle, the paper addresses both the *provision* and *consumption* of water in cities including pumping and treating water and wastewater. It does not consider links in the generation and supply of energy such as the water necessary to provide energy.

Several authors identify that the operational phase of water assets uses the vast bulk of energy, rather than pre or post-operational stages. For example, Stokes & Horvath (2009) point out that over 90% of energy consumption of California’s imported, desalinated and recycled water options is accounted for in the operational phase. Grant et al. (2006) noted that ‘capital infrastructure, while not insignificant, is much less important than operational impacts for most environmental indicators’ when considering centralised water systems and small-scale rainwater tanks. Based on these conclusions, our approach ignores life-cycle energy use including energy embedded in chemicals such as alum. Similarly, impacts of water management on fugitive emissions (e.g. at wastewater treatment plants or in water storages) were ignored partly because of the focus on direct energy consumption and partly because data and research in these areas is less advanced.

‘Direct’ links between water and energy were considered from the perspective of water utilities. ‘Indirect links’ were considered as having implications other than at water utilities. Owing to the complexity of indirect energy links, we considered only those connections already identified in the literature. More indirect connections could be expected to emerge with further analysis.

The focus on cities was adopted because they are now home to over half the world’s population (Sheehan 2007). The rapid anticipated growth of urban systems provides major opportunities to reconfigure infrastructure to more efficient forms. Understanding the links between water and energy within cities helps address the root cause of consumption, and consequently also contributes to resolving energy supply issues.

**Method**

Guided in part by the method outlined in a seminal paper by Wolman (1965), a hypothetical city of 1,000,000 people was used to provide an analysis framework. This helped overcome difficulties compiling data sets for any particular city and enabled use of data from the best international sources.
Literature and data review was central to identifying and quantifying linkages. Water-related energy connections were defined and grouped by characteristic categories. These included: (i) the provision \( P \) of water; (ii) the use of water \( U \); (iii) resources in wastewater \( R \); (iv) the urban heat island effect \( H \); and (v) other water-related energy \( O \) Equation (1).

\[
T = P + U + R + H + O
\]  

(1)

The components of \( T \) are further described as follows. All units are in GWh for all equations (i.e. the equations do not add intensities in kWh/m³).

- **Water services provision** \((P)\): This is energy related to supplying water and wastewater services Equation (2).

\[
P = P_w + P_{uw} + P_d + P_h + P_b
\]  

(2)

Here, \( P_w \) and \( P_{uw} \) include energy use for treating and transporting water and wastewater, respectively, via centrally managed facilities. This largely represents utility energy use; however, energy for transfer of raw water by private contractors operating infrastructure for utilities is also included. \( P_d \) is the energy to deliver decentralised (household and cluster-scale) supplies such as rainwater tanks. \( P_h \) is energy for additional pressure necessary to deliver water to high-rise apartments. Finally, \( P_b \) is the energy demand for bottled water provision.

- **Water use** \((U)\): This includes energy use related to the use of water Equation (3): either consumptively or non-consumptively. For example, this includes energy for heating within households \((U_{rhw})\), other energy associated with residential water use \((U_{ro})\) such as filtering or pressurising water. It also includes energy use associated with use of water in the commercial \((U_c)\) and industrial \((U_i)\) sectors.

\[
U = U_{rhw} + U_{ro} + U_c + U_i
\]  

(3)

- **Resource recovery**: This includes energy use affected by management of resources in wastewater Equation (4). For example, carbon and methane \((R_c)\) are either lost from the wastewater system, or captured and harnessed for heat or electricity at wastewater treatment plants. It also includes the energy needed to return to productive purposes, nutrients and elements lost in wastewater such as nitrogen \((R_n)\), phosphorus \((R_p)\) and potassium \((R_k)\).

\[
R = R_c + R_n + R_p + R_k
\]  

(4)

- **Heat island effect** \((H)\): The component of urban heat island influence associated with water management in cities.

- **Other** \((O)\): All other energy use influenced by water management including role of urban agriculture.

Energy use was tracked either as electrical or natural gas. Natural gas was converted from various units (therms, megajoules, BTU) into kWhth based on the energetic value (e.g. 3.6 MJth per kWhth). In order to compare total ‘water-related’ energy use with primary energy use, electrical energy \((kWh)\) was converted to thermal equivalents using 3 kWhth for each 1 kWh, based on the approximate current natural gas or coal-fired power station efficiency \((Gleick & Cooley 2009)\). For the purpose of the hypothetical city, electrical energy was assumed to have greenhouse gas emissions intensity of 1.0 kg CO₂-e/kWh. This is approximately the national full fuel cycle value for Australia’s electrical supply which is provided largely from coal-fired power plants. The greenhouse gas intensity of natural gas was similarly assumed to be 0.2 kg CO₂-e/kWh \((Australia 2008)\).

A first-order sensitivity analysis was undertaken by identifying the range of each parameter considered in the literature (Appendix, available online at http://www.iwaponline.com/jwc/002/005.pdf). Upper and lower values were input to a Microsoft Excel model structured according to the water-related energy links identified in each area and guided by Equations (1)–(4).

The literature describes both direct and indirect links between water and energy. However, what is considered direct and indirect varies with the perspective considered by the author. For example, de Monsabert & Liner \((1998)\) considers direct implications at facilities (i.e. physical sites) and indirect impacts as consequences to water utilities. In contrast, Kenway *et al.* (2008) considered direct impacts from the perspective of utilities as does this paper.
QUANTIFYING WATER-RELATED ENERGY: BACKGROUND

Water services provision (P)

Centralised water and wastewater treatment and transport (Pu)

Substantial information exists for centralised systems (e.g. Carlson & Walburger 2007; Kenway et al. 2008; Stokes & Horvath 2009). In Australian cities, the energy required to deliver water ($P_w$) varies significantly. The source and quality of raw water supplies has major impact on energy demands for water supply and treatment. In 2006–07, this ranged from a low of 0.09 kWhe/m$^3$, to a high of 1.92 kWhe/m$^3$ (Table 1). The larger relative error for water reflects a wide range of local physical conditions: from elevated and protected catchments which drain high quality water by gravity, to cities pumping significant distances. These values are generally consistent with those reported for northern California (1.1 kWhe/m$^3$ [4,000 kWhe/million gallons]; Klein et al. 2005). In contrast, southern California consumes far more energy for water supply (3.3 kWhe/m$^3$ [12,700 kWh/million gallons]) because it moves water further and higher.

Energy demands for wastewater in Australian cities ranged from 0.45 to 1.13 kWhe/m$^3$ (Table 1). The lower standard deviation is possibly because treatment and discharge standards are influenced by legislation which is relatively consistent from city to city. Energy use for wastewater appears to be more affected by treatment standards than by local physical or environmental conditions as is the case for water supply.

Carlson & Walburger (2007) used multivariate analysis to evaluate the relative importance of factors influencing total energy use by utilities. In a survey of over 100 parameters in water and wastewater systems operated by over 125 water utilities across the United States water use was by far the strongest determinant of total utility energy use. This parameter alone accounted for 75–80% of the variability of total utility energy consumption. This almost direct correlation means that total energy use could be calculated for the hypothetical city by multiplying the volume of water required by the average energy intensity (kWhe/m$^3$) for water supply.

Decentralised supplies including rainwater tanks (Pd)

In contrast to centralised systems, there has been relatively limited analysis of the energy demand of decentralised systems and alternative supply options such as rainwater tanks, bottled water provision and pumping for high rise buildings. Many forms of decentralised (household scale) water and wastewater services exist in Australia. Of these, rainwater tanks have received the most attention recently following the rapid uptake of such systems during prolonged drought. A range of energy intensities of supply have been reported and many factors have been identified influencing energy use (Table 2). Mean energy use is around 1.5 kWhe/m$^3$; however a range exists. System design and water use patterns can have a major influence on energy consumption. For example, Cunio & Sproul (2009) point out that a rainwater tank system could be designed to achieve an energy intensity as low as 0.04–0.2 kWhe/m$^3$ if the systems used low pressure head (5 m rather than 30 m) together with header tanks, low pressure valves for toilet cisterns and larger diameter supply pipes (32 mm rather than 20 mm). Rainwater tank policies (such as rebates or installation specifications) which drive towards lower energy

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**Table 1 | Energy demands of water and wastewater services for Australian Cities 2006–2007**

<table>
<thead>
<tr>
<th></th>
<th>Water pumping and treatment (kWhe/m$^3$ supplied)</th>
<th>Wastewater pumping and treatment (kWhe/m$^3$ wastewater collected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean $^b$</td>
<td>0.82</td>
<td>0.76</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.66</td>
<td>0.26</td>
</tr>
<tr>
<td>Relative error/relative variance</td>
<td>0.80</td>
<td>0.34</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.09</td>
<td>0.45</td>
</tr>
<tr>
<td>Maximum</td>
<td>1.92</td>
<td>1.13</td>
</tr>
<tr>
<td>Number of observations</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

$^a$Data from Kenway et al. (2008), for 2006–07 for Sydney, Melbourne, Brisbane, Perth, Adelaide and Gold Coast ranging from 0.492 to 4.300 million people. Minimum is the minimum of any individual city. Total is the total for the entire city (i.e. not a composite of individual cities’ minima for components of the water cycle).

$^b$Administrative use averaged an additional 9.6% across the cities.
Intensities could help reduce energy use associated with rainwater tanks.

**High rise pumps (Ph)**

Cheng (2002) identified that pressurising water for use in high-rise buildings contributes about 0.14 kWh/m³ for each six stories of lift. Cities with a larger proportion of high-rise buildings increase the amount of vertical pumping required. However sprawling cities also often require increased horizontal pumping to distribute water to suburbs which are often increasingly distant from the primary sources of water.

**Bottled water (Pb)**

Bottled water uses from 1,500 to 2,800 kWh/m³ (5.6–10.2 MJ/l) depending largely on the transport distance and bottle size (Gleick & Cooley 2009). This is around 1,000–2,000 times the energy demand per volume of centralised water supplies. Locally produced bottled water has its energy profile dominated by manufacture of the bottle (390–1,600 kWh/m³); larger bottles are more energy efficient per litre. However, long distance transport (e.g. greater than around 1,000 km) can lead to transport energy requirements being more than the bottle manufacture.

Some 516,000 m³ of bottled water was sold in Australia in 2007 (Anon 2007); around 25 l per person. Anticipated growth in bottled water use is high (around 8% per annum). Strategies which encourage greater use of the centralised water system (e.g. maintaining consumer confidence in water quality, provision of public water dispensers, discouraging bottled water use through regulation or taxation) could reduce energy use associated with bottled water.

**Water use (U)**

Several authors identify that energy consumption associated with water use is a significant, and often dominating, component of energy use in the water cycle (Cheng 2002; Cohen et al. 2004; Klein et al. 2005).

**Residential hot water use (Urhw)**

In 2007, the Australian residential sector consumed 397 PJ of energy (Commonwealth of Australia 2008). This included 197 PJ of primary energy use and 200 PJ of electrical energy. Of this, hot water systems consumed 43 PJ of the electricity and 48 PJ of the primary energy (natural gas and LPG). The dominant uses of hot water in households include showers, clothes-washers, taps and dishwashers (Flower 2009). For a household in Australia using 630 l water per day, approximately 171 l/d of use is hot water (GWA 2004); equivalent to approximately 60 l/d per person.

Traditionally, energy for heating water has been provided through an electric or natural gas hot water system. However, appliances such as washing machines and dishwashers are increasingly heating water internally and do not draw on the hot water system. For example, in 2007, appliances in Australian households consumed 112 PJ of electrical energy (Commonwealth of Australia 2008). Of this, some 16 PJ was consumed by water-using appliances including clothes-washers, dishwashers, kettles and swimming pool filters. Consequently, total water-related energy could be substantially more than the energy demand of the hot water system, particularly with regard to usage of electricity.

Water policy can substantially influence indoor water use. For example, the proportion of water-saving fixtures (e.g. water efficient shower heads), and the efficiency of appliance stock (clothes-washers, dishwashers) can all have a

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**Table 2 | Energy demands of decentralised water supplied from rainwater tanks**

<table>
<thead>
<tr>
<th>Energy Intensity (kWh/m³)</th>
<th>Mean (N)</th>
<th>Range</th>
<th>Factors influencing energy use</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 (10)</td>
<td>1.0–4.0</td>
<td>Energy use is dependent on water use volume and use pattern (events and durations), system design (head, flow, pressure vessels, rainwater switches), pump size, water treatment levels</td>
<td>Retamal et al. (2009)</td>
<td></td>
</tr>
<tr>
<td>1.8 (5)</td>
<td>Up to 5.1</td>
<td>Use of ultraviolet treatment can significantly increase energy use</td>
<td>Hood et al. (2010)</td>
<td></td>
</tr>
</tbody>
</table>

*aAssumed from the number of monitoring sites.*
major influence on the quantity of hot water use. Water utilities, or governments more broadly, often influence these patterns through setting of appliance standards, provision of rebates, customer information programs and through industry collaborations for technology development.

**Residential other water-related energy use (Uро)**

While hot water use appears to dominate residential water-related energy use, many other household activities and appliances simultaneously influence water and energy. Swimming pool filters for example consume around 2,500 kWhe per household per year (e.g. George Wilkenfeld & Associates Pty Ltd 2004). Evaporative air-conditioners use around 1.5 l/min (Roberts 2005). However, evaporative conditioners use only a fraction of the energy of non-evaporative cooling systems, which can consume 5–12 kWhe (Commonwealth of Australia 2008). Consequently, shifting to water-efficient non-evaporating air conditioning systems could substantially influence energy use.

Energy is also consumed in clothes-driers. Depending on the residual moisture remaining in clothes after washing (which depends on the spin cycle), energy demands for clothes drying can be substantial. Finally, energy is also consumed when water is used in kettles and boiling water dispensers, chilled water dispensers and ice makers in fridges. Depending on the use of such systems, the energy use per household could be very high.

**Industrial and commercial water use (Uс, Uі)**

Substantially less information exists on water-related energy use in the commercial and industrial sectors. A literature review on water–energy connections indicated that almost none addressed industry or commerce (Kenway et al. 2011b). This is a significant omission given that other authors have identified that addressing materials flow through industry is critical to addressing urban metabolism (Kennedy et al. 2007). Commercial data sensitivity and processes heterogeneity are possible reasons for the absence of this literature.

Klein et al. (2005) and Wolff & Wilkinson (2011) note that all the connections between water and energy domestically are relevant in industry and commerce, plus hundreds more. Typical uses of water that consume energy in these sectors include heating (e.g. for washing and cooking), steam production, cooling, filtering and air-conditioning. Energy for cooling towers (air-conditioning) uses substantial volumes of water and dominates the industrial water-related energy estimates of Klein et al. (2005). However, energy use is also significantly influenced by water heating and steam production as well as refrigeration. Commercial water-related energy is common in publishing and broadcasting, printing, petroleum refining and non-metallic mineral product manufacturing and food manufacturing industries (Klein et al. 2005).

The direct (facility) and indirect (utility) energy savings associated with water conservation at US Federal Facilities was assessed by deMonsabert & Liner (1998). Steam production and boiler blow-down criteria were significant. Small changes to water savings were shown to result in significant energy savings.

Energy use of water-using customers can be substantially influenced by water conservation strategies such as water-efficiency retrofits, efficient appliance rebates and improved customer information programs (Sydney Water 2006). Industry innovation in water and energy efficiency too has been supported by some utilities with ‘connectionless steamers’ (Larabee & Ashktorab 2007) and ‘waterless wok stoves’ (Waterset Pty. Ltd. in Kenway et al. 2007) which simultaneously save water and energy.

**Resource recovery (R)**

This section considers the chemical energy in wastewater as well as the energy necessary to ‘reproduce’ the nitrogen, phosphorus and potassium lost in wastewater. This has been considered because there is an energy demand of returning the equivalent nutrients and carbon to our cities in the form of food. Historically, urban waste including sewage has been more significant as an input to agricultural systems. Barles (2007) identified that 40% of the nitrogen intake of Paris in 1914 was sourced from human and animal wastes originating in the city and returned to agriculture via composting. This became much harder to do once a sewerage system was installed because of the liquid nature of the waste which was instead discharged to river.
O’Meara (1999) points out that small farms in and around cities face daunting obstacles to compete with more distant mega-farms which have more efficient economies of scale. However, she also points out that if hidden energy subsidies and direct crop subsidies supporting this distant agriculture were reduced, then local and city-based agriculture could flourish. She also points out that many cities produce significant quantities of food. For example, Hong Kong and Singapore have supported and encouraged this production. The thermal energy (heat) of the wastewater itself is not considered here because it potentially overlaps with the heating of water described in the section on use, above.

**Carbon and methane (Re)**

Substantial carbon, nitrogen, phosphorus and other elements are lost from urban systems through wastewater discharge. One million Australians produce around 100 GL of wastewater each year (WSAA 2009). Each GL of sewage contains around 5,900 GJ (1.65 kWh/m³) of energy potentially recoverable as methane (Priestley 2009).

**Nitrogen, phosphorus and potassium (Rn, Rp, Rk)**

Energy is required to manufacture or bring new nutrients back as inputs to agricultural systems. To synthesise nitrogen for agriculture using the Haber-Bosch process uses around 10,000 kWh/tonne of ammonia (Rafiqul et al. 2002; Gellings & Parmenter 2004). Clearly policies which affect the potential capture of carbon, and reuse of nutrients in wastewater, impact on the total urban system energy use.

**Urban heat island (Uhi): Water component**

In some cities, there is up to a 10° difference between the temperature in the urban core and surrounding rural areas (Kennedy et al. 2007). This is due to the combined effects of: (i) altered urban land surfaces and colours (e.g. dark roads); (ii) loss of vegetation and associated shading and evapotranspiration; together with (iii) the combustion of fuel. No work yet appears to specifically consider the influence of water on the urban heat island.

Kennedy et al. (2007) suggest that for US cities with populations greater than 100,000, peak electricity loads increase by about 1% for every degree Celsius increase in temperature. For high ambient temperatures, utility loads in Los Angeles have demonstrated a net rate of increase of 167 megawatts (MW) per °C. In Toronto, a 1 °C increase on summer days corresponds to roughly a 1.6% increase in peak electricity demand. Kurn et al. (1994) indicate that a hypothetical 10 °C boundary layer cooling would reduce peak energy loads by 3%. McPherson et al. (2005) studied five cities and suggested that energy savings of increased street trees for shading could influence 95 kWh of energy use per tree by reducing household air-conditioning use. McPherson et al. also noted that not many of the potential sources of error have been quantified or included in results. They also flag that the results from the five cities they studied cannot be generalised to other cities because inter-city variability is high.

Rosenfeld et al. (1997) indicated that planting trees and lightening the colour of roofs and pavements could lower the average summer afternoon temperature in Los Angeles by 5 °C and cut the need for air-conditioning by 18%. In their analysis, trees accounted for more than half the effect. Clearly most of the benefits of managing heat islands accrue in the summer and it is possible that processes aimed at cooling cities in summer could also cool them in winter. However, Rosenfeld et al. (1997) also point out that ‘in hot climates the summertime benefits greatly outweigh the wintertime penalty’. The challenge of quantifying the ‘water component’ of the heat island effect led to the need to adopt a wide margin of error for this aspect of water-related energy.

**Other water–energy connections (O)**

Other, more remote and less well-considered links exist between urban water and energy use. For example water policy can influence urban agriculture and food production. Displacement of food production in cities, through water use restrictions or pricing, means that an equivalent quantity of food must be imported from further afield. No data or estimates of the quantity of energy use potentially influenced by displacement of agriculture from cities were available. Consequently, no estimates were made. It is possible that the influences are very significant in some situations.
WATER-RELATED ENERGY USE IN A HYPOTHETICAL CITY

Using the studies identified above, water-related electricity, natural gas and primary energy were assembled for a hypothetical city of 1,000,000 people (Table 3). The year of analysis is around 2007; however, this cannot be attributed exactly as the data is sourced from several time periods. The city could be considered dominated by Australian characteristics with some Californian attributes to cover where data sources for Australia were missing. For example, to gauge an estimate of water-related energy use in industry, it was necessary to use a pro rata estimate per unit of the Californian population (from Klein et al. 2005), within the categories of electrical and natural gas use and apply this at a similar rate to the hypothetical city (Appendix, available online at http://www.iwaponline.com/jwc/002/005.pdf). This approach assumes a similar mix of industries between Australia and California, as well as a similar degree of connection between water and energy within each industry sector. To cater for this approximation, a large error estimate was attributed to this data set for the sensitivity analysis.

Details of parameter values used to calculate water-related energy, assumptions and references are provided in the Appendix (see http://www.iwaponline.com/jwc/002/005.pdf). Total primary energy use for the average, low and high cases is shown in Figure 1. Electricity, natural gas and primary energy used by 1,000,000 people in Australia are shown in Table 4, together with the total water-related energy from Table 3.

Total water-use related energy use for a city of 1,000,000 people was 1,379 GWh per annum electricity use and 2,675 GWh per annum natural gas use. This accounted for 13 and 18%, respectively, of total national use (Table 4). This is equivalent to 9% of the total primary energy use in Australia in 2006–07.

Water use (U) constituted 86% of average water-related greenhouse gas emissions (Table 3). Provision of water (P), accounted for 10%. This included both water and wastewater service delivery but excludes water-related fugitive emissions. A further 4% of water-related greenhouse gas emissions was attributable to influences of resource loss and the urban heat island effect.

Water-related carbon emissions in cities clearly represent a major component of total national greenhouse gas emissions even when fugitive emissions are excluded from the ‘water-related’ total as they are in this analysis. To give comparative figures, total greenhouse gas emissions from transport in Australia (per 1,000,000 people) are only double the water-related emissions as are all emissions from Australian Agriculture.

DISCUSSION

Given the magnitude of energy use and associated emissions, further analysis is warranted of residential water-related energy and associated greenhouse gas emissions. The wide range of potential energy use displayed in the sensitivity analysis suggests that policy and management could have a major impact in this area. Further analysis of industrial water-energy connections is also strongly warranted but will likely require a different methodology from that of the residential sector.

Despite the significance of water-related energy, the indirect implications of water management options are typically not considered in the current paradigm. In 2008, most Australian water strategies did not consider, or report on, energy implications of options beyond the direct impacts on utilities. This is a significant omission given water strategies are likely to have far greater indirect implications. Increased attention to ‘whole of life’ issues of products, and supply-chain responsibility is likely to be increasingly common in future according to the World Business Council for Sustainable Development (Heemskerk et al. 2002).

Many factors could constrain the water sector, policy makers or urban planners from taking wider action in targeting indirect water-related energy impacts. Fragmentation of responsibilities coupled with lack of incentives and information are high on the list. Why should businesses take responsibility for impacts outside their jurisdiction? Who gets the credit if energy is saved? Who pays? Don’t customers have the right to decide how much water and energy they each use? How do we debt-finance conservation efforts? How are lost sales revenues compensated? Because most water businesses are remunerated in accordance with the volume of water sold, strategies which reduce volume...
<table>
<thead>
<tr>
<th>Aspect</th>
<th>Electricity</th>
<th>Natural gas</th>
<th>GHG emissions (1,000 T CO₂-e)</th>
<th>Primary energy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>%</td>
<td>Low GWh</td>
<td>High GWh</td>
</tr>
<tr>
<td>Provision (P)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy use: utilities – water (Pw)</td>
<td>106</td>
<td>8</td>
<td>10</td>
<td>294</td>
</tr>
<tr>
<td>Energy use: utilities – wastewater (Pww)</td>
<td>68</td>
<td>5</td>
<td>35</td>
<td>134</td>
</tr>
<tr>
<td>Rainwater tank pumps (Pd)</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>26</td>
</tr>
<tr>
<td>High-rise basement pumps (Ph)</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Bottled water (Pb)</td>
<td>0</td>
<td>50</td>
<td>2</td>
<td>23</td>
</tr>
<tr>
<td>Subtotal</td>
<td>176</td>
<td>13</td>
<td>45</td>
<td>457</td>
</tr>
<tr>
<td>Use (U)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential use (hot water) (Urhw)</td>
<td>535</td>
<td>39</td>
<td>119</td>
<td>1,467</td>
</tr>
<tr>
<td>Residential use (non-hot water) (Uro)</td>
<td>204</td>
<td>15</td>
<td>92</td>
<td>319</td>
</tr>
<tr>
<td>Commercial water use (Uc)</td>
<td>245</td>
<td>18</td>
<td>147</td>
<td>343</td>
</tr>
<tr>
<td>Industrial water use (Ui)</td>
<td>177</td>
<td>13</td>
<td>106</td>
<td>248</td>
</tr>
<tr>
<td>Subtotal</td>
<td>1,161</td>
<td>84</td>
<td>464</td>
<td>2,377</td>
</tr>
<tr>
<td>Resources (R)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon loss (not captured) (Rc)</td>
<td>0</td>
<td>164</td>
<td>6</td>
<td>98</td>
</tr>
<tr>
<td>N, P, K loss (resynthesis) (Rn + Rp + Rk)</td>
<td>0</td>
<td>61</td>
<td>2</td>
<td>28</td>
</tr>
<tr>
<td>Subtotal</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Heat island (H): water component</td>
<td>42</td>
<td>3</td>
<td>1</td>
<td>453</td>
</tr>
<tr>
<td>Other (O)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e.g. Displaced urban agriculture</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total water-related energy</td>
<td>1,379</td>
<td>100</td>
<td>511</td>
<td>3,286</td>
</tr>
</tbody>
</table>

*Note GWh/million people is equivalent to kWh/person.
*Calculated based on 1.0 kg CO₂-e/kWh for electrical energy and 0.2 kg CO₂-e/kWh for natural gas.
*Calculated by converting 1 kWh electrical energy = 3 kWh thermal energy (Gleick & Cooley 2009), and adding this to average natural gas usage.
*Assumes 80% electrical hot water systems for the 'high' case and 80% natural gas for the 'low' case.
See Appendix for all parameters, assumptions and references (http://www.iwaponline.com/jwc/002/005.pdf).
of water sales can impact business viability. Alternative incentives need to be found. While some systems (such as incentive payments for reaching water conservation targets) can be successful, alignment of incentives through supporting policy is also anticipated to be needed in order to achieve long-lasting effects.

Part of the reason that industry and government appears to have overlooked the wide connections between water and energy is because the management of our city-systems has been reduced to its components of ‘water’, ‘energy’ and ‘transport’ rather than the goal of optimising the city as a whole for a range of objectives. A result is that the performance indicators developed for each sector are narrowly focused. An example is the relatively well-developed performance indicators reported by the Australian water sector to the National Water Commission (WSAA et al. 2007) and indicators developed by the International Water Association (IWA 2006). While they address the direct issues well, they take no consideration of how the city as a whole functions and performs with regard to energy.

While this paper has progressed the methodology of understanding water–energy and related carbon connections in cities, far more methodological development is necessary. This is particularly relevant in the industrial and commercial sectors, where one product output of one sector, is used in another ‘downstream’ sector and so on. It appears likely that the direct links considered in this report are an underestimate of the total connections and influence of water on energy.

The lack of consistent and quantitative approaches to determine the connections between water and energy in cities is viewed as a critical limitation. Different conclusions would be drawn from energy studies if different aspects of water-related energy were considered. Development of a standardised methodology would assist inter-city comparisons. One critical missing element is an overall information set on the full movement of water through cities, including rainfall, capture and use of decentralised water, stormwater flows, flows to groundwater and evapotranspiration (Kenway et al. 2011a).

Water and energy optimisation of cities

Optimisation of a system cannot be achieved by optimising one part in isolation. Optimising our city-systems for water and energy simultaneously could have major implications and lead to paradigm change in the design, management and evaluation of water and cities. How can we assess how a ‘water-sensitive’ city contributes to energy management and carbon mitigation? Such a move could shift analysis beyond our current narrow, organizationally focused definitions of ‘carbon neutrality’, into one which addressed multiple and varied energy implications of...
water. More generally, such a move would be a great step forward to managing the overall urban metabolism and reducing the total impact of the city.

Innovative new cities, buildings and industries could yield order-of-magnitude improvement in both water and energy efficiency. A major challenge lies in the formulation of appropriate designs, evaluating these from water and energy perspectives conjunctively, and then working to transition to these forms. This will require a truly multidisciplinary effort spanning government, industry and research capabilities. Establishing the necessary regulatory frameworks, reporting arrangements and overall governance to provide incentives for such future design is also a major challenge.

CONCLUSIONS

Water-related energy in a hypothetical Australian city of 1,000,000 people accounted for 1,379 GWh per annum electricity use and 2,675 GWh per annum natural gas use. This is equal to approximately 13% of national electricity use, 18% of natural gas use and 9% of primary energy use. Collectively it represents 8% of total national greenhouse gas emissions with a range of 4–16% being possible for individual cities. Numerous opportunities exist for water policy and management to influence energy use; however, there are many constraints to progress.

This paper quantifies water-related energy within meta-categories of ‘provision’, ‘use’, ‘resource recovery’ and ‘urban heat island’ influences. It provides a conceptual model and structure against which cities can be analysed. It helps identify where management of water-related energy could have the greatest impact along with critical data gaps.

Substantial further work is required to move from hypothetical (average) analysis to quantified results for specific cities. Such analysis could reveal significant differences between individual cities. Further work to develop methodologies is also required along with more detailed characterisation of key factors, sensitivities and uncertainties.

As the challenges of climate change continue to unfold, and greenhouse gas mitigation targets progressively tighten, understanding and using the connections between water and energy will provide a means to simultaneously and systematically influence energy use and carbon emissions related to water. Information on the connections between water and energy is essential if we seek to solve, rather than shift the problem. Understanding the connection will also help us transition to cities with high levels of water and energy efficiency. Such cities could be well on the way to being truly water-sensitive.

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