Water and energy futures for Melbourne: implications of land use, water use, and water supply strategy
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ABSTRACT
This paper quantifies the effect of three policy levels on the water and energy futures of Melbourne, Australia. During a time of severe water shortages attributed to climate change, water strategies lacked consideration of energy consequences. Modeling, guided by urban metabolism theory, demonstrated that a compact urban form, reduced water consumption by 90 GL/a, compared with a sprawling city, and had greater water conservation impact than simulated demand management measures. Household water conservation, coupled with increased use of solar hot water systems, reduced grid energy use by some 30 PJ/a. Desalination, tripled water supply energy demand, growing to a total of 4.5 PJ/a, by 2045. While the increase is less than 1% of total Melbourne urban energy use, it contributes to a substantial increase in the energy bill for urban water provision. Importantly, the energy impact could be offset through demand management measures. Recommendations for the combined management of water and energy include improving energy characterization of the urban water cycle; impact-evaluation of regional plans; using total urban water and energy balances in analysis to provide context; and developing reporting mechanisms and indicators to help improve baseline data across the water and energy systems.

Key words | energy, future cities, land use, urban metabolism, water

INTRODUCTION
Between 2002 and 2009, many Australian cities faced an extended period of below average rainfall leading to critically low water storage levels. Future projections of climate change suggest exacerbated severity of dry periods (Howe et al. 2005; Jones & Durack 2005), with up to a 25% reduction in catchment inflows for some cities (WSAA 2005). Australian cities have responded to this period of water stress by developing strategic water plans that have the purpose of providing water security in the face of uncertain rainfall and inflows, and increasing demand being driven by population growth (Rijke et al. 2015). Strategic water plans were underpinned by the adoption of rainfall independent water sources, most significantly desalination of seawater by reverse osmosis, together with a focus on water efficiency measures and demand reduction (Donald & Seeger 2010).

However, the development of water plans gave relatively little consideration to the energy implications of adaption strategies. Australia had not ratified the Kyoto Protocol at the time and had no firm long-term greenhouse gas mitigation target. It was not easy, or even possible, to see how the actions of ‘solving’ one problem in the system (such as water), could lead to influences elsewhere (such as energy). The influence of longer-term processes such as land use planning or urban form were even further from the discussion, as was the energy implications of water conservation. Since 2007, the rapid anticipated growth of energy demand for urban water provision in Australia, due to adoption of rainfall independent water sources, has become increasingly clear (Kenway et al. 2008b; Chanan et al. 2009; Hall et al. 2011). It has been identified that as water and energy are intrinsically connected, there is need to develop complementary long-term strategies for water...
security and energy management (Dubreuil et al. 2013). Scott et al. (2011) made the point that considering the water-energy nexus requires more than a focus on opportunities for resource efficiency but also needs to consider the policy frameworks underlying decision-making processes.

This research aimed to improve knowledge of the interconnections of urban water and energy. In particular, the research addressed the question: how would the pattern of existing water and energy use shift under a range of policy scenarios for a major city? Critically, the research approach linked both water and energy issues to the urban footprint of Melbourne and the land use pattern. Consequently, we sought to characterize flows of water and energy influenced by water, within the total urban consumption of Melbourne. Importantly, we sought to identify how policy at the level of (i) urban form, (ii) water systems and (iii) household consumption could influence total flows. Included in our analysis was consideration of the water consumption influenced by demand for electrical energy. While there has been considerable research into the influence of urban form on energy demand (Liu & Sweeney 2012; Futcher & Mills 2013; Yin et al. 2013), there is a lack of studies that have quantified the dynamics of urban form, potential water supply sources and implications for energy demand.

This manuscript presents original work built upon a number of research projects undertaken in Australia. These include (a) construction and population of the Australian Stocks and Flows Framework Model (Turner et al. 2011) with various physical (e.g. water and energy) accounts (Turner et al. 2010; Baynes et al. 2011; Turner & West 2011) and (b) characterization of the energy intensity of Australia’s urban water systems (Kenway et al. 2008a, 2008b; Hall et al. 2011). The focus and contribution of this article is on the following:

- Identifying the relevance of the analysis in the international literature.
- Updated energy analysis of the various water supply options. For example, it includes more current energy intensity values of water supply options in scenarios.
- Provides a relatively rare example of the application of urban metabolism theory in order to gain insight into the water-energy nexus.
- Identify the implications for city-scale management and design of water and energy efficient cities.

Our intention was to help inform the design of an efficient future city; a city which drew less water and energy. Such a city would be arguably competitive in a future where water and energy (or carbon-dioxide emissions) availability are more constrained.

**BACKGROUND**

**Population and urban form**

Melbourne is home to over 3.5 million people, and is Australia’s second largest city. The city’s population is predominantly accommodated in low density separate dwellings, which has resulted in considerable urban sprawl. In response to issues associated with urban sprawl the Victorian Government released Melbourne 2030 (Department of Infrastructure 2002) and then Melbourne 2030 (Victorian Government 2008): a planning update. Both documents set strategies for the growth of the metropolitan area to accommodate an expanded population. A key direction of this strategy was the setting of urban growth boundaries to limit sprawl and encourage higher density development. Increasing the density of Melbourne’s is a very contentious issue due to perceived effects on land value inflation, over-crowding and loss of open space (Chhetri et al. 2013).

**Water system and climate**

Melbourne has historically relied upon water supplied from natural catchments, which is largely supplied by gravity from ranges to the east. Minimal water treatment is required in this system because the water catchments are largely protected and consequently deliver relatively clean water (Donald & Seeger 2010).

Projected growth in demand and possible decline in inflows to natural catchments led to Melbourne facing a projected water shortfall of over 200 GL/year by 2055 (DSE 2006). Under the assumptions of most climate change scenarios, Melbourne is projected to receive less rainfall and display higher evaporation rates. This will drive water shortages and demand for alternative water sources (Howe et al. 2005).
The Victorian government released a number of Water Strategies (Action to 2055 and Our Water Our Future) with solutions for providing water security, which included: wastewater recycling, seawater desalination, demand management and inter-basin transfers. The Office of Living Victoria has recently released an updated strategy (Melbourne’s Water Future), which places a greater emphasis on an integrated approach that considers how different parts of the urban water cycle interact such as the harvesting and reuse of stormwater to both improve drainage management, reduce mains water demand, and improve natural waterway health (Office of Living Victoria 2013). While this integration is a good step, the approach falls short of integrating energy issues into the water supply future. This appears an omission, considering the energy demand of urban water supply for Melbourne is now viewed as a substantial business risk (Victorian Water Industry Association 2011), due to its anticipated growth and cost.

**Household water use and energy use**

Melbourne is projected to grow from 3.47 million people in 2001, to 4.8 million in 2031 (DSE 2005). This population growth is a major driver of projected increases in water and energy demand. Between 2007 and 2011, household water consumption declined very gradually, from around 150 L/hh.d to around 140 (National Water Commission 2013). Melbourne’s urban form has traditionally been characterized by homes situated on large lots, meaning significant urban demand for irrigation with 55% of all residential water demand for outdoor uses (ABS 2006).

In Victoria, water heating accounts for 27% of total residential energy demand (ABS 2005). Other significant household demands for energy are heating and cooling (39%) and appliance use, including lighting (30%). Therefore, a water demand management strategy that focuses on a shift to cleaner energy sources for water heating, such as solar hot water systems (HWS), and increased efficiency of hot water appliances, could be expected to significantly reduce residential draw on energy demands from the city network. As the majority of Melbourne households use gas as an energy source for water and space heating, a focus on appliances and hot water would also address the majority of household greenhouse gas emissions.

Per capita indoor water consumption decreases with increasing household size (Birrell et al. 2005). In Melbourne, it is projected that the number of households will increase at a greater rate than population due to demographic shifts, such as an ageing population and lower fertility, which will lead to an increased proportion of single person and two person households. The projected impact of urban consolidation and demographic change on Melbourne has been explored by Birrell et al. (2005) who suggested that if Melbourne achieved a shift to medium and high density dwellings consistent with the goals of Melbourne 2030, there would be a 37% increase in domestic water consumption by 2031.

In Victoria, the adoption of rainwater tanks and solar HWS have been encouraged in new homes by requirements in the building code, while for existing homes financial incentives, such as rebates, have encouraged their adoption. The increased uptake of many demand management strategies, such as more efficient washing machines, may largely depend on government incentives or statutory requirements, as in many cases the economic payback period does not justify the investment at current water and energy prices. Rainwater tank uptake in Melbourne is estimated at 6% of households (Marsden Jacobs Associates 2007).

**Urban metabolism**

Urban metabolism is a conceptual model useful for describing flows of materials and energy within cities (e.g. Wolman 1965; Newman 1999; Decker et al. 2000). Urban metabolism was put first forward with the intent of simultaneously addressing ‘shortages of water and the pollution of water and air’ around 50 years ago (Wolman 1965). At its simplest, urban metabolism considers the mass balances of all materials (including water) and energy of urban systems (Sahely et al. 2005). The model offers benefits to studies of urban sustainability by providing a unified viewpoint encompassing all activity in a single model. The theory has been argued as having strong relevance to water, energy and urban systems (Decker et al. 2000; Kennedy et al. 2007; Kenway et al. 2011a), and potential practical applications have been suggested for standardized reporting of urban material and energy flows in cities and urban planning.
Urban metabolism models have evolved from linear input–output models, to models that include simulation of network processes such as cycling and transformation of urban resources (Zhang 2013). Recent applications of the urban metabolism model have expanded the method to consider both flows of materials and energy but also some of the causal socio-economic factors to provide a platform for integrated assessment (Kennedy et al. 2011; Pincetl et al. 2012). Because urban form influences resource efficiency, there is a need for analysis of urban development in metabolism methods (Moore et al. 2015).

This paper aimed to contribute a hierarchical analysis of policy options within this metabolism framework. Our intent was to be as systematic as possible with regard to the total water and energy flows through the city. The complexity of the urban water system inevitably meant that not all water flows could be examined. Consequently, water balance elements such as groundwater seepage and evapotranspiration loss were not quantified. However, many of these elements are not even currently dealt with even in advanced urban modeling analysis focused solely on water balance (Kenway et al. 2010). Other elements of the urban metabolism framework (such as food and materials inputs and waste and product outputs) were excluded from this study for reasons of practicality.

**METHOD**

In this section, we first describe the analytic framework used to simulate the scenarios of water-energy outcomes for Melbourne. The settings for the six scenarios are then described, followed by the assumptions common to all scenarios. A long time-frame was used in this study in order to consider significant changes to the urban form of Melbourne. Like other authors (e.g. Lundie et al. 2005; Hall et al. 2011) we considered the full water system including water supply and wastewater for centralized and decentralized options. However, the work goes further in considering the energy implications of end-use as well as the total urban system. We also additionally consider stormwater which has been frequently ignored in urban water resources planning and options analysis, yet represents a substantial potential resource (Kenway et al. 2010a).

Our analysis focused on operational rather than life cycle energy use, primarily because several authors have demonstrated this to be by far the dominant fraction of the energy impact of urban water infrastructure (Stokes & Horvath 2006, 2009). Finally, the study simultaneously addresses technological, environmental and policy dimensions of the water-energy nexus, within the ‘nested’ boundaries of (a) water utility, (b) residential and (c) total urban system. This is relatively unique in the literature because it addresses multiple systems as opposed to studying single elements of the water-energy nexus (such as energy use of desalination or rainwater tanks) (Kenway et al. 2010c). Like many other studies on the water-energy nexus (e.g. Cheng 2002; Arpke & Hutzler 2006; Kenway et al. 2010b), social and economic dimensions are not considered in this paper, nor are the industrial or agricultural sectors. This is primarily due to issues of data availability and scope.

**Analytic framework**

An analysis structure was developed to consider the water balance of Melbourne, along with energy use associated with water utilities, residential end-users and the entire city of Melbourne.

The scenarios were modeled using the Victorian Regional Stocks and Flows Framework (VRSFF) model developed by CSIRO (Baynes et al. 2009). The Stocks and Flows approach has previously been developed and applied in Australia to undertake analyses of the Australian physical economy (Turner et al. 2011). The VRSFF is a systems model comprised of linked calculators that account for many important natural resources dynamics. These include land use, demographics and water and energy accounts. Several decades of historical data have been used to calibrate the model which can be used for simulation over the next 50 to 100 years (Turner & West 2011; Baynes et al. 2011).

The VRSFF water account (Turner et al. 2010) covers, in annual time-step, the main flows of the UN System of Environmental-Economic Accounting for Water (SEEAW) framework (United Nations Statistical Division 2006). It contains the following features:
water requirements across all sectors of the Victorian economy and society (informed by other components of the VRSFF) at Local Government Area (LGA) level, including water recycling by centralized treatment plants and re-use of water (within each industry or sector);

- water availability by 29 water basins, influenced by factors, including climate and land use (informed by other components of the VRSFF);

- water stocks or flows including surface (rivers, wetlands) and major storage (dams);

- water discharge to groundwater/aquifers from all water uses, tracking water quality as unpolluted, blackwater, greywater, stormwater;

- water regions are major catchment basins and are linked in the framework according to the river networks;

- water transfers occur between water regions as well as inter-state;

- additions to and extractions from all water stocks, by centralized systems; or self-extracted means;

- energy required for potable treatment and pumping sewage; treatment and pumping; desalination; and inter-region transfers.

**Scenario settings**

Six scenarios of development to the year 2045 were designed to identify the potential influence of policy options at three levels: urban form, residential water end-use and water service provision (Table 1). The key objective was to investigate a set of factors that influence the urban water system and its interaction with the energy system.

A baseline was also considered including minimal additional demand management or uptake of solar HWS. The base case was taken as 2001, as this is the starting point for the simulation with years prior to 2002 populated with historical data.

Each scenario was created from a combination of changes to urban form, water end-use, and water supply strategies. Within the water supply strategies are also implicit assumptions about different energy types for water supply: solar hot water versus heating water with electricity or fossil fuels. Scenario sets 1 and 2 portray, respectively, a shift to more compact urban form and continued low-density development on Melbourne’s fringes.

**Scenario set 1: compact urban form**

For scenario set 1, all future urban growth was accommodated within high and medium density residential dwellings constrained within the Urban Growth Boundary defined in Melbourne 2030. High and medium density dwellings were assumed to occupy 25 and 50% of the land footprint of low density. The average residential density increased by about 33%, from the historical level of 23 persons per hectare to 31 persons per hectare by 2045. This scenario also incorporates an evolution in water end-use,
and alternative water supply options in sub-scenarios 1a and 1b as described below.

Scenario 1a considers conventional water supply, but with an increase in solar HWS, with 20% of existing dwellings and 80% of new residential dwellings moving to solar (gas boosted) HWS. Existing dwellings are assumed to move proportionally from the current energy source mix for HWS, which shows 78% of Melbourne households have gas HWS and 19% electric (ABS 2005). Scenario 1a also explores a number of residential demand management strategies such as low-flow showerheads and water efficient washing machines. The uptake was presumed to be 80% of new dwellings and 20% of existing dwellings.

Scenario 1b is consistent with 1a, with the exception that the water supply option includes increased wastewater reuse and use of rainwater tanks. Scenario 1b considers 20% of wastewater collection at centralized treatment plants is available for local non-potable use with minimal energy investment for treatment or pumping. It also assumes 20% of wastewater generated in heavy industry, such as mining and manufacturing, is treated on-site to a standard required for on-site non-potable applications with minimal energy investment for treatment or pumping. The wastewater treatment occurs close to treated wastewater reuse sites. Residential rainwater tanks are used. This option also simulates 20% of separate dwellings installing an onsite rainwater tank that is used for toilet flushing with mains back-up and with minimal energy cost where gravitational flow is not possible.

**Scenario set 2: sprawling Melbourne**

For scenario set 2, all new development was assumed to comprise low density dwellings occurring at the fringe of Melbourne. This assumes no limit to low density urban growth. Consequently the average residential density fell to 19 persons per hectare (compared with 23 p/ha).

Scenario 2a represents business as usual approach for water supply which we refer to as ‘Baseline’. There are no demand management strategies and solar HWS are not taken up beyond the existing use. This scenario assumes that new ‘conventional’ supplies can meet all new demand.

Scenario 2b is identical to Scenario 2a with the exception that desalination meets all new water demand requirements. At the time of analysis, desalination had been identified by the Victorian government as a preferred option to augment water supplies. This analysis assumed 17,753 J/L (4.9 kWh/kL) for the production of water by desalination.

Scenarios 2c and 2d have the same demand management and solar HWS adoption strategies to Scenarios 1a and 1b. Respectively they adopt the ‘conventional’ or ‘desalination’ water supply options identical to Scenarios 1a and 1b which are described above.

### Common scenario assumptions

All scenarios also assumed the following:

- By 2050 Victoria’s population grows to approximately 6.7 million of which 4.9 million live in the Melbourne statistical division (DSE 2005).
- There is 2% per capita growth in material and energy consumption – consistent with trends over the last decades (Turner & West 2011).
- Low-flow showerheads reduce water consumption by 40% over conventional systems and that water efficient washing machines use 30% less water.
- The present methods of electricity generation continue into the future.
- A ‘medium’ climate change scenario (Howe et al. 2005; Jones & Durack 2005) corresponding to an average global temperature increase of 1.5 °C by 2050, involving decreased rainfall, increased evapotranspiration and increased dam evaporation.
- Residential outdoor water use increases due to climate change impacts (Moran 2005).
- Dam levels are maintained at 2001 levels through a 50/50 combination of diversions from rivers and inter-region transfers where possible, otherwise solely from river diversions.
- Low-, medium- and high density residential development uses water at 413, 354 and 358 L/year/m² respectively (ABS 2001; Troy et al. 2005). The indoor/outdoor use in Victoria is split approximately 65/35. This was applied to the total water use per dwelling then calibrated, in proportion, to total water use. With demand management measures in place, residential water use were assumed to drop to 380, 326 and 329 L/year/m², respectively.
- Floor space area for dwelling units of these dwelling density types for business as usual are 300, 250 and 200 m² for low, medium and high density, respectively.

In this analysis, the energy embedded in the treatment, transport and consumption of water is represented but not in the production and consumption of other goods and services. The energy embedded in the construction and decommissioning phases is also not included in the options assessed. This is because several reports (e.g. Stokes & Horvath 2006, 2009) demonstrate that the operational phase accounts for the majority of total life cycle energy in most cases. Further, less significant assumptions are described in (Kenway et al. 2008a).

**RESULTS AND DISCUSSION**

Key analysis points for this project included residential water demand, energy required for water supply, total residential energy demand, total urban systems energy demand, flows in major regional rivers, water demand for electricity production, the fraction of flows by-passing storages, and urban stormwater flows.

**Overview**

A summary of the results for the baseline (i.e. 2001 situation) and six scenarios is presented in Table 2. The effect of a particular change can be determined by comparing two scenarios with all features in common other than the effect being analyzed.

Major trends evident include (i) urban form had a significant influence on water use and (ii) water demand management and solar HWS substantially influenced residential energy use. If Melbourne’s urban growth and water supply continue on without conservation efforts (Scenario 2a) then residential water use increases by 55% relative to 2001 and residential energy use increases by 200% over the same period.

Apart from energy use associated with the water system, implications of scenarios on Melbourne’s total energy consumption were not assessed. In this analysis, the additional energy for transporting desalination or treated

### Table 2 | Projected water and energy demands of six potential Scenarios for Melbourne

<table>
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<tr>
<th>Water service options</th>
<th>Water end-use options</th>
<th>Urban form</th>
<th>Water and energy outcomes</th>
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<td>Conventional water supply</td>
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<td>Fringe</td>
<td>Baseline n/a 330 1.1 95 1120</td>
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<td>Desalination demand management and solar HWS</td>
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<td>Melbourne in 2001, (population = 3.47 million) – baseline</td>
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<td>Melbourne in 2045, (population = 4.80 million) – scenarios</td>
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*Note that energy for water treatment only is considered, but transport energy is included in one scenario.*
reuse water was not able to be calculated as the energy demand would be highly site-specific. Pumping 100 GL to a height of approximately 200 m (e.g. Cardina Reservoir) could require around 0.2 PJ energy excluding pipe resistance. For rainwater tanks, the total energy required was estimated from the modeled water capture reliability of 80% and energy intensity of 5.4 MJ/kL. This results in additional energy use of 0.31 PJ in 2045.

The effect of urban form (Level 1)

Urban form has a significant impact on reducing water demand. A compact urban form (Scenario 1a) versus urban sprawl (Scenario 2c) could reduce the growth in residential water consumption by 90 GL/a. In contrast, the demand management simulation reduced water use around 40 GL/a (comparing Scenarios 2a and 2c).

The effect of urban form was primarily achieved through reduced outdoor water consumption. The garden area requiring irrigation reduces as urban density increases. Substantial high-rise development was required to accommodate population growth within the Melbourne 2030 urban growth boundary. This meant that while the total water use of low-density residential areas remained relatively static (for compact Melbourne), high density residential areas used significantly more water (Figure 1). This is because the total area of high-density residential land increases in this scenario.

Urban form also had implications for surface water flows. Our simulations indicated that a more compact city (Scenarios 1a and 1b) had reduced stormwater flows compared with the sprawling city. An expanding city increases the area of impervious surfaces and hence of stormwater flows. For the urban sprawl scenarios, the stormwater flows increase for about 20 years however they decrease after that time. The decrease is due to the expected influence of climate change.

The direct and indirect effect of water conservation (Level 2)

Water demand management (Scenario 2a versus Scenario 2c) could directly save 40 GL/year water at 2045. Indirectly, it saved a further 10 GL/year in 2050 because less water would be required to provide cooling for the generation of electricity in the nearby Latrobe Valley, which produced around 166 PJ of electrical electricity in 2001, most of
which was used by Melbourne. Additionally, the demand management and solar HWS options in Scenario 2c reduce energy use by utilities by 0.14 PJ/year for water supply, as well as about 30 PJ/year in reduced residential energy use. This is due primarily to the effect of solar HWS; it represents approximately a 12% difference in residential energy demand from the forecast baseline.

Demand management is expected to contribute even further to reduced energy associated with in-house water heating (e.g. through targeted conservation of hot water); however, it was not able to be separated in this analysis.

There is only a marginal decrease in the energy required for water supply for the demand management strategy relative to the baseline scenario. This is due in part to Melbourne’s water supply catchments being situated in the upper reaches of the Yarra Ranges, meaning the system is largely gravity fed, thus reducing reliance on energy for pumping of urban water supplies.

The effect of water supply options (Level 3)

Water supply strategies differed substantially with regard to their total impact on energy use. When all new demand is met by desalination, energy use for water supply approximately triples, growing from 1.3 to approximately 4.5 PJ/a. This is approximately 3 PJ more energy than other water options. While this increase is less than 1% of total urban energy use, it is a contributor to an anticipated six-fold increase in the energy bill for urban water provision by 2020 (from 2007 levels) (Cook et al. 2012). The ‘metabolic’ approach adopted for this project helps show that the increased energy intensity of desalination could be readily offset through a shift to end-use demand management strategies and solar HWS. In so doing, it helps open options for water service providers to find alternative solutions for providing water supply solutions and simultaneously contributing to greenhouse gas mitigation targets.

Desalination scenarios required less water to be diverted from natural rivers to storage, reducing pressures on river flow. Figure 2 shows the fraction of river flow that is bypassing dams for the Yarra, Maribyrnong and Werribee rivers under a conventional water service Scenario (2c) and a desalination Scenario (2d). Climate change impacts decrease overall river flow substantially in both scenarios. However, desalination may have other impacts of a negative nature, which were beyond the scope of the current work to analyze, such as the production of brine effluent.
and its impact on marine environments. This example underscores the need to further develop the urban metabolism model. Wastewater recycling also reduces pressure on river flows; however, the level of wastewater recycling simulated within the scenarios (20% of wastewater flows) is not of the same magnitude as simulated in scenarios where desalination is a feature, as these assume that all new demand for potable water is met by desalination plants.

A shift to decentralized water supply alternatives, such as rainwater tanks and wastewater recycling, has only a minor impact on river flow in the Thompson River, which is diverted to the Thomson Reservoir (Melbourne's major storage). The additional energy requirements are relatively minor (e.g. 0.3 PJ/a for rainwater tanks) compared with energy demand for water supply (1.3–4.8 PJ/a depending on options such as desalination). Relative to total city energy requirements, the additional energy is considerably marginal.

Most major investment in water infrastructure occurred prior to Australia's ratification of the Kyoto protocol in 2007. Now that Australia has progressed a carbon taxation system as a part of its commitments, a carbon price of $23/ton CO2 has been implemented. This makes the energy risks of the adopted high-energy water strategies much clearer (Victorian Water Industry Association 2011).

General discussion and recommendations to improve water and energy co-management

To our knowledge, this analysis represents a first simultaneous analysis of the entire water cycle, energy and land use futures of a major city. In a carbon and water-constrained future, it will be necessary to decide not only the total amount of water and energy needed to sustain urban systems, but also to agree on the acceptable associated impacts. Understanding the water-energy interface will be critical to optimize urban performance and protect the environment that sustains them.

While this analysis was based on a particular Australian city, there are broader design implications for all cities. In particular, the outputs have demonstrated there is the need for a trans-sector approach to minimize the water, energy and carbon footprint of urban areas. This trans-sector approach to strategic land use planning needs to include departments and organizations from the energy and water sectors.

We were surprised that urban form had a stronger implication on water use than the demand management strategies proposed. Likewise, it was a surprise that water conservation and solar HWS had a far greater energy impact, via end-users, than the anticipated energy impacts at water utilities.

The urban metabolism approach helped to highlight total flows of urban water and energy. Awareness and accounting of these flows is a first step towards their combined management. The metabolism method helps lead policy-makers towards options which will have more substantial influence on material flows. Such an approach is necessary if we seek to genuinely solve problems, rather than simply shift them around.

Clearly the way any particular city performs with regard to its water and energy efficiency will depend significantly on attributes specific to the city. For example, climate, urban form, building and appliance stock, natural water sources and infrastructure, energy supply options could all have significant influence on the water and energy efficiency of a city, and the suitability of any particular scenario.

This study did not involve analysis of alternative population growth levels, energy supply options, energy use, climate change or their interrelations. Consideration of these factors, along with more detailed assessment of urban form, demographics, lifestyle and technology adoption (e.g. rainwater capture or greywater systems), water demand and end-use options, could add further detail.

More detailed scenarios related to short- and long-term urban development, water and energy strategies could be considered. For example, scenarios could consider the effect that larger lot sizes, and/or new building design which allow for far greater stormwater capture and use, potentially using renewable energy sources such as wind and/or solar systems. Ideally such scenario design should include input from government, industry and the community. It would also be worthwhile considering how systems cope under extreme versus average scenarios for their energy and water systems. For example, do some options for energy work counter to water and vice versa, not only during drought, but during flooding.
Partitioning the energy effect of water conservation and solar HWS appears a worthwhile task. Similarly, exploring the energy conservation implications of other water uses (such as industrial and commercial water users) warrants attention. More detailed characterization of energy use through the centralized, and decentralized water systems, and spatially across Melbourne, would also support more detailed analysis and conclusions. Carrying the analysis through to include influences on greenhouse gas emissions is recommended. A first step in this regard would be to broaden the analysis to energy-related greenhouse gas emissions. More complex, but systematic, would be to broaden the analysis to include all fugitive greenhouse gas emissions (for example including methane releases from storage), and also the embedded greenhouse gas emissions in the components or infrastructure of each scenario. Incorporating a range of measures of environmental impacts, together with socio-economic considerations, alongside the water-energy-greenhouse gas interactions would provide further insight, as the analysis of river flows under alternative water supply options suggests.

This work focuses on the impacts of water supply options, due to the pressing need to augment depleted supplies. Inclusion of implications of the full water balance including flows to groundwater (e.g. from irrigation or pipe losses) and evapotranspiration losses could potentially improve the resolution of impacts attributed to alternative urban designs. Should an alternative focus develop (for example how could a city contribute to an 80% greenhouse gas mitigation goal), other aspects of the urban metabolism model may have greater relevance. Inclusion of material inputs and waste outputs could have high significance here as a number of international projects have recently used waste flows to simultaneously provide for electricity generation and efficient district water heating as an alternative to individual HWS.

In future, it would appear strategic for future city blueprints to simultaneously consider the implications for water and energy as well as their interactions. Water and energy issues would also ideally be considered in regional land use planning such that the energy intensity of water (and water intensity of energy), is considered in urban design. In order to advance such measures it may be necessary to first commence reporting to agreed ‘whole of system’ indicators to enable an improved baseline of information on which scenarios can be considered.

A challenge for future analysis of urban water-energy-greenhouse interactions is to bring together information and skill sets which have traditionally been managed separately. These include water and energy supply, use and conservation as well as urban and regional planning. Investigations which integrate across these boundaries will help progress our understanding of our complex urban systems. It will also help improve the environmental design and management of our future cities.

**CONCLUSIONS**

This paper clearly demonstrates how a range of quite distinct policy scenarios influence the water and energy flows of a city, sometimes in surprising ways.

Urban form (Level 1) had a major influence on water demand and stormwater flows. A compact Melbourne saved some 90 GL/a water compared to a sprawling city. This was largely due to reduced outdoor water use.

A shift to end-use demand management strategies and solar HWS (Level 2), demonstrated reduced energy use by approximately 30 PJ/a. It also reduced water consumption directly (within house) as well as water requirements for electricity generation.

Water supply strategies (Level 3) differed substantially with regard to their total impact on energy use. When all new demand is met by desalination, energy use for water supply approximately triples, growing from 1.3 to 4.5 PJ/a. When this increase is placed in context with the total energy consumption for Melbourne, the increase is less than 1% of total urban energy use, however it contributes to an anticipated six-fold increase in the energy bill for urban water provision by 2020 (from 2007 levels). The ‘metabolic’ approach adopted for this project helps show that the increased energy intensity of desalination could potentially be offset through a shift to end-use demand management strategies and solar HWS. In so doing, opens alternative solutions for water utilities to provide water supply solutions, and simultaneously contributing to greenhouse gas mitigation targets through the wider water system.
The ‘metabolism’ approach adopted for this study made transparent the interconnections and feedbacks between water and energy in different parts of the system. By quantifying the total flows through Melbourne, it helped to (a) highlight potential steps towards their combined management and (b) place the impact of these flows in context.

While further and more detailed scenarios analysis would be necessary to guide infrastructure and development-related decisions, a number of recommendations can be made to improve policy and action in the domain of urban water and energy interactions. These include: improved energy characterization of the urban water cycle; evaluation of regional plans for their impacts on and interactions between water and energy; using total urban water and energy balances in analysis to provide context; and developing reporting mechanisms and indicators to help improve baseline data across the water and energy system.

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