

The Water-Energy Nexus and Urban Metabolism - Connections in Cities

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January 2013



Urban Water Security Research Alliance
Technical Report No. 100

Urban Water Security Research Alliance Technical Report ISSN 1836-5566 (Online)
Urban Water Security Research Alliance Technical Report ISSN 1836-5558 (Print)

The Urban Water Security Research Alliance (UWSRA) is a \$50 million partnership over five years between the Queensland Government, CSIRO's Water for a Healthy Country Flagship, Griffith University and The University of Queensland. The Alliance has been formed to address South East Queensland's emerging urban water issues with a focus on water security and recycling. The program will bring new research capacity to South East Queensland tailored to tackling existing and anticipated future issues to inform the implementation of the Water Strategy.

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Kenway, S. (2012). *The Water-Energy Nexus and Urban Metabolism - Connections in Cities*. Urban Water Security Research Alliance Technical Report No. 100.

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ACKNOWLEDGEMENTS

This research was undertaken as part of the South East Queensland Urban Water Security Research Alliance, a scientific collaboration between the Queensland Government, CSIRO, The University of Queensland and Griffith University. I am indebted to their support.

A scholarship from the Australian American Fulbright Commission was fundamental to my opportunity to collaborate with Lawrence Berkeley National Laboratory and the University of California Berkeley (USA) to identify research and policy directions. The support of Eawag (The Swiss Federal Institute of Aquatic Science and Technology) enabled me to explore the detailed Material Flow Analysis methods used in household analysis.

My sincere appreciation is extended to Paul Lant, Hans-Peter Bader, Ruth Scheidegger, Tove Larsen Jurg Keller, Ted Gardner, Damien Batstone, Joe Lane, Paul Greenfield, Don Begbie, Sharon Wakem, Peter Daniels, Manfred Lenzen, Jim McMahon, Gary Wolff, Alan Gregory, Freeman Cook, Deborah Marsh, Nathan Cammerman and others.

This Technical Report summarises a thesis awarded for the degree of Doctor of Philosophy at The University of Queensland, August 2012 in the School of Chemical Engineering.

FOREWORD

Water is fundamental to our quality of life, to economic growth and to the environment. With its booming economy and growing population, Australia's South East Queensland (SEQ) region faces increasing pressure on its water resources. These pressures are compounded by the impact of climate variability and accelerating climate change.

The Urban Water Security Research Alliance, through targeted, multidisciplinary research initiatives, has been formed to address the region's emerging urban water issues.

As the largest regionally focused urban water research program in Australia, the Alliance is focused on water security and recycling, but will align research where appropriate with other water research programs such as those of other SEQ water agencies, CSIRO's Water for a Healthy Country National Research Flagship, Water Quality Research Australia, eWater CRC and the Water Services Association of Australia (WSAA).

The Alliance is a partnership between the Queensland Government, CSIRO's Water for a Healthy Country National Research Flagship, The University of Queensland and Griffith University. It brings new research capacity to SEQ, tailored to tackling existing and anticipated future risks, assumptions and uncertainties facing water supply strategy. It is a \$50 million partnership over five years.

Alliance research is examining fundamental issues necessary to deliver the region's water needs, including:

- ensuring the reliability and safety of recycled water systems.
- advising on infrastructure and technology for the recycling of wastewater and stormwater.
- building scientific knowledge into the management of health and safety risks in the water supply system.
- increasing community confidence in the future of water supply.

This report is part of a series summarising the output from the Urban Water Security Research Alliance. All reports and additional information about the Alliance can be found at <http://www.urbanwateralliance.org.au/about.html>.



Chris Davis
Chair, Urban Water Security Research Alliance

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EXECUTIVE SUMMARY

The Australian urban water sector faces a significant challenge: energy use is expected to grow to 200-250% of 2007 levels by 2030. However, Australia aims to reduce greenhouse gas (GHG) emissions 80% below 2000 levels by 2050. To contribute proportionately, the water sector would need to reduce the projected energy demand in 2030 by over 90%, or reduce the carbon-intensity of its energy by an equivalent amount.

The problem is not isolated to the water sector: our cities, their buildings, and their management are all part of the challenge. A lack of quantitative information regarding water-related energy has constrained the motivation and solutions. However, there is substantial opportunity for action. Understanding the nexus, or connection between water and energy, is the key.

The first objective of this research was to understand the current energy consumption influence of water supply and use in cities. Particular attention was given to understanding not only the direct energy consumed by water and wastewater services in cities, but also the indirect influence of water use within cities. *Indirect* water-energy links were focused on because several authors have identified that they are large, and relatively poorly studied. A conceptual model of all known links was developed and populated for an average city of one million Australian people. This demonstrated that water-related energy accounted for 13% of the total electricity and 18% of the natural gas used in Australia in 2006-2007. Collectively, this represented 9% of the primary energy use or 8% of total national GHG emissions. Water-related energy in cities is equivalent to one-third of the total energy use of all Australian industry (excluding transport); it is equal to approximately half the energy usage of the Australian residential sector; and it is over four times the direct energy use of Australian agriculture (excluding embodied energy use).

Residential water-use accounted for 45% of water-related energy in cities, with industrial and commercial water-use accounting for another 41%. The balance was comprised of utility energy use, energy related to carbon and nutrient loss, and the “water component” of the urban heat island effect.

The second objective sought to understand and quantify water-related energy in households. A detailed Mathematical Material Flow Analysis (MMFA) model was developed to generically describe household flows of water, electricity, natural gas, and related GHG emissions and costs. The model was structured so that either an individual household could be simulated, or a collection of household types (ie, a city) could be simulated in aggregate. Simulation of the current state of an existing household was validated with three years of independently monitored data from utility records. Key factors of influence and uncertainties were quantified. Water-related energy accounted for 59% of household energy use (excluding transport), and 35% of household GHG emissions. The shower, clothes-washer and bath sub-systems comprised the major share of water-related energy use. The clothes-washer, dishwasher and electric kettle comprised the bulk of water-related GHG emissions.

Detailed scenarios investigated the impact of changes to technologies and behaviours within the household. The model was populated for an individual household in Brisbane, Queensland, where good data was available for many parameters. For this household, improvements in technology, without changing to a solar hot water system, result in less than a 15% reduction in energy use and GHG emissions. In contrast, combined behavioural and technical changes have much greater potential. The simulations also demonstrated that some water-saving technologies, such as installation of energy-efficient clothes-washers, could increase GHG emissions if it shifted energy consumption from natural gas, to coal-fired electricity.

The third objective aimed to develop, apply and explore an aspect of urban metabolism theory with regard to our understanding of water flows in cities. A mass balance representing all anthropogenic and natural urban water flows was developed and populated for four Australian cities. The mass balance exposed large volumes of rainwater, stormwater and evapotranspiration, which are typically ignored and unaccounted for in current reporting. Using the mass balancing approach, quantitative

indicators of the hydrological performance of the city were derived. These highlighted large inter-city variability within Australia. The mass balance approach proved to be very valuable in terms of urban water accounting, monitoring and management. This has widespread implications for designing and managing cities to increase water harvesting within the urban system.

The fourth objective was to define research priorities for systematic management and policy formulation regarding water-related energy in cities. An international workshop was convened with diverse representation. Facilitated discussion identified a vision for successful cities as well as relevant opportunities and barriers. Themes of necessary work were identified using the World Café method - a meeting process designed to identify and elicit a degree of consensus from diverse stakeholders about complex issues. The identified themes were ranked by participants to help quantify the potential of each initiative and the anticipated effort necessary to undertake it. This enabled the author to create a roadmap articulating a staged program which could begin with the easier, higher-impact measures; the low-hanging fruit. Priority elements in the road map for improved management of water-related energy include: (i) combined standards, guidelines and funding for water and energy efficiency; (ii) development of educational programs; (iii) methods to quantify and track water-related energy and GHG emissions; and (iv) improved understanding and management of customer motivations.

This research shows how urban water management influences a sizable proportion of Australia's energy use. It demonstrates the importance of understanding households as a primary source of influence. It provides a systematic methodology to explore, understand and manage water-related energy in cities. It shows how aspects of the urban metabolism framework may be used to derive quantitative indicators of performance and drive accuracy for reporting systems.

Overall, the work provides a new way of looking at the influence of water management in cities. The results provide key insights to help water and city managers create better plans for our cities - plans that solve problems at the core, rather than shifting them from one domain to another. This is anticipated to be of great value in a future of water shortages and carbon caps.

1. INTRODUCTION

1.1. The Problem of Rising Energy Demand for Urban Water Service

In 2005, five major Australian cities faced crisis-level shortages of water. Headlines warned of “Armageddon”. We had to “Desalinate or Die” (Stolz 2007; ABC News 2007). Climate change was widely held as responsible (Howe *et al.* 2005; Bernstein *et al.* 2007; WSAA 2005).

The “Millennium” drought led to a significant surge in urban water infrastructure investment. In 2005-06, a then record AUD \$2.4 billion was invested in major cities alone for water (and wastewater) infrastructure. Most of the investment was aimed at increasing the proportion of “climate-independent” sources such as desalination or wastewater reuse (WSAA 2008). This investment grew to almost \$4 billion in 2007-08, and over \$7 billion for 2008-09. Expenditure for 2009-10 was forecast as greater than \$14 billion (WSAA 2009), but stabilised around \$7 billion, excluding the Melbourne Desalination Plant (National Water Commission 2011)¹.

Since 2008, rainfall has temporarily alleviated water shortages in eastern and southern Australia, and also reduced the pressure for investment or management action. However, a new challenge has emerged. The energy demands for water in Australian cities is anticipated to grow to 200-250% of 2007 levels by 2030 (Kenway and Lant 2011; Kenway *et al.* 2008b). In December 2007, Australia ratified the Kyoto Protocol, and in 2012 established a long-term goal to reduce GHG emissions 80% below 2000 levels by 2050 (Australian Government Department of Climate Change and Energy Efficiency 2012). This means that if the water sector was to contribute proportionately, then energy use for urban water must be reduced by more than 90% from the projected 2030 levels (Figure 1). Alternatively, an equivalent cut to the GHG emissions of the relevant energy sources needs to be achieved.

This technical report, summarises the extensive research undertaken for a thesis aimed at contributing a new perspective relevant to this challenge (Kenway 2012).

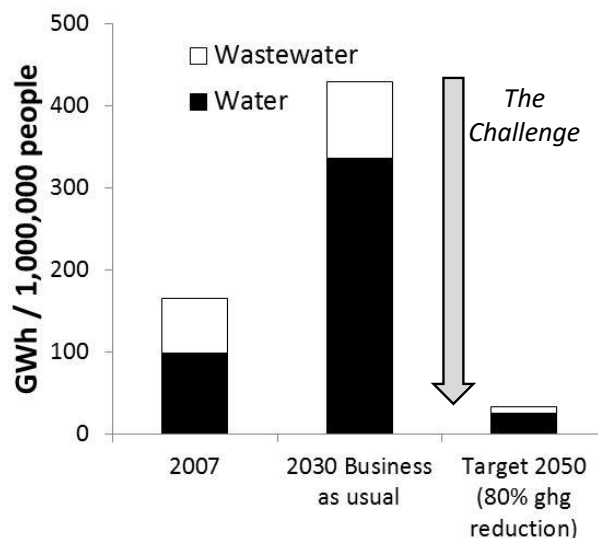


Figure 1. The challenge: reduce energy use for water and wastewater services more than 90% of the 2030 forecast*. (Source: Kenway 2012)*.

*Note: 2050 energy target assumes no change to the GHG emissions intensity of fuel used. The target arbitrarily shows water and wastewater in proportion to the 2030 forecast

¹ Estimated then at around AUD \$4 billion.

Increased energy use for urban water supplies is one problem. When this is compounded by forecast rising electricity costs, the energy demands of providing water and wastewater services represents a significant risk to the Australian water sector (Victorian Water Industry Association 2011). Ultimately, these costs of producing water have to be incorporated into water prices and passed onto consumers, indicating the risk is more one for the entire Australian economy. Consequently, it is timely to look at water-energy connections because such understanding could help find solutions which reduce water and energy consumption, rather than, for example, solving a water problem with energy or vice-versa.

1.1.1. A Problem within Other Problems

Large as the urban water energy problem appears, it is only a component of a much larger problem set: a Russian doll within many others. An arguably bigger problem than the rising energy demand of our water system is the design and operation of cities. Cities are increasingly being found at the core of problems including climate change, global ecosystem health and human well-being (Sheehan 2007).

How we think and manage could also be considered part of the larger problem set. Over the past centuries, science has focussed on narrow, tightly defined challenges, rather than consider wider, systems-related problems. For example, historically the issue of “metabolism” considered the holistic exchange of matter and energy between humans and the environment. Today the concept is applied far more to the internal workings of cells (Fischer-Kowalski 1998). This reductionism leads to a lack of adequate knowledge for us to understand the emergence of complex, and wicked problems; problems which are ever-changing and are highly interconnected with actions that could be taken.

In cities, the management of water and energy is frequently shared across three levels of government and a myriad of regulators. Little consideration is given with regard to: interaction of the components; to overall efficiency; or to how performance could be co-ordinated. For example, in Figure 2 the performance indicators are shown out of alignment because they are all managed separately. Management of the flows of water, energy and materials through cities (the metabolism) is undertaken in isolation and to inconsistent boundaries. Consequently, there is little or no recognition that in solving one problem (for example improving the water system to perform from level “B” to level “A”, another problem may be created (for example shifting the energy performance from a level “C” to a level “D”).

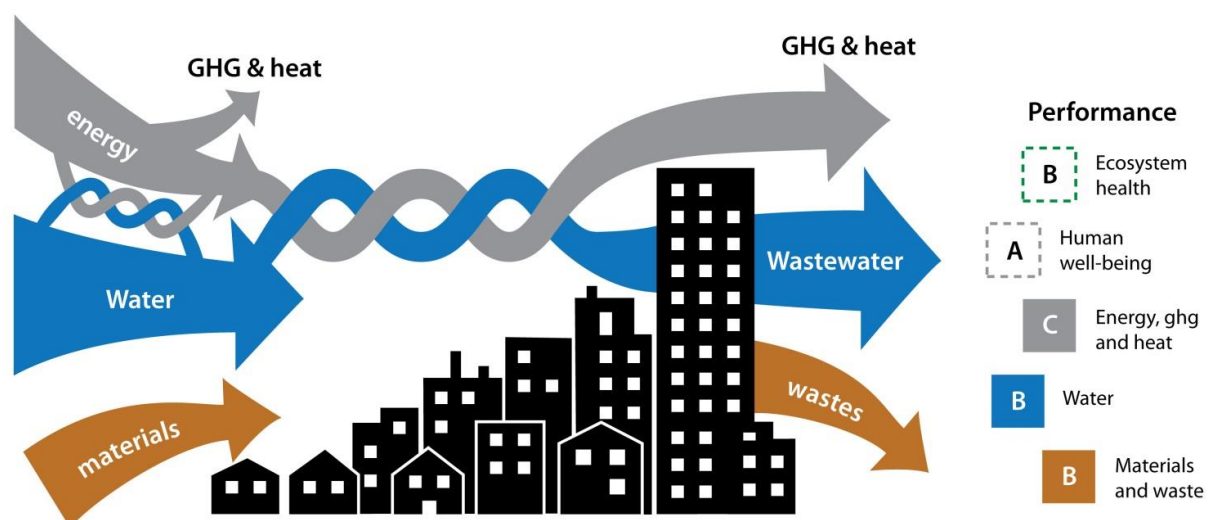


Figure 2. The current paradigm: fragmented urban performance.

Many water-energy links are not well understood or considered. Little effort has been expended to optimise the overall city for its water and energy performance. Compartmentalising the problem has meant that the performance indicators that guide decision-making in each sector are narrowly focused and no consideration is given to the overall efficiency and function of the city.

Finally, the water-energy problem is dynamic; it is changing with time. As our technologies, behaviours, infrastructures, pricing of water and energy, and our cities change, the connections between water and energy – and the available solution sets – also change. Collectively, this comprises a very big problem. However, there is much scope for action.

1.2. An Opportunity – Indirect Effects of Water in Cities

Cities offer considerable scope for solving many problems of resource-efficiency (O'Meara 1999). In part, this is because large flows of water, energy and materials pass through cities. It is also because they are centres of investment and are continually being redesigned and recreated.

To understand water-related energy in cities, it is helpful to consider both *direct* and *indirect* impacts. *Direct* energy impacts occur, for water utilities, when “mains” water or wastewater is pumped or treated. *Indirect* energy impacts (for utilities) occur when water is used, for example in water heating. Indirect impacts also occur when other water sources are used, for example through the use of rainwater tank pumps or creating and transporting bottled water. More complex indirect connections exist via flows of carbon and nitrogen in wastewater, in the urban heat island effect, in the production of food in cities, and elsewhere.

The *indirect* influences of water on energy are very substantial. For example, water-related energy accounted for 19% and 32% of California's respective electricity and natural gas usage in 2005 (Klein *et al.* 2005). Of this, water use in cities was the majority of the effect. Water policy, pricing and restrictions influence water use. So too do technology rebates. Clearly water management has a large potential to affect significant quantities of energy.

In this work, direct impacts are considered from the perspective of water utilities or water service providers. Indirect impacts are considered from the perspective of users of water. Other authors may also use the term direct and indirect, however they may do so from a different perspective (deMonsabert and Liner 1998).

A central proposition in this research is that a major opportunity to influence energy use exists in the myriad *indirect* effects that water management has in cities.

Because Australia is increasingly urban, our cities offer the possibility for solutions that simultaneously address water and energy issues. In 2006, 68% of the Australian population of 21 million people lived within major cities (ABS 2006). In 2006, around 90% of Australians lived in urban settings (PMSEIC 2010). The Australian population is anticipated to grow to 25-33 million by 2050 (ABS 2006), with most of the growth in major cities. This growth will intensify Australia's urbanism and have major implications for infrastructure and related investment decisions.

Despite the major significance of cities, the knowledge and understanding of urban performance is woeful. Satterthwaite (2008) points out that even basic statistics such as population can vary by millions of people pending the definitions adopted. For more complex attributes such as energy or GHG emissions we understand even less (Kennedy *et al.* 2007). This has flow-on effects for the design and management of our cities. Satterthwaite (2008) also notes the central role that well planned and governed cities could play in delinking high quality of life from high energy and materials consumption, and GHG emissions.

Understanding water-energy links within cities will help quantify anticipated changes in one as a result of changes in the other. With this knowledge, we can better manage the invisible trade-offs which are occurring, and thereby develop solutions that decouple growth from consumption. While such knowledge is only a part of the solution set, it will help identify options which simultaneously reduce

water and energy use. It will help our future cities achieve higher levels of water and energy efficiency.

Consequently, the first objective of this research (“Objective 1”) is to identify and quantify the links between water supply and consumption, and energy use in cities.

1.3. The Need to Understand Households

Within cities, households (groups of people living together) deserve particular attention because households are a major building block of cities. Several studies have demonstrated that the heating of water within households dominates energy use of the residential water cycle (Arpke and Hutzler 2006; Cheng 2002). In order to understand the energy influenced by water management in cities, it is important to understand households.

Water-energy links in households have received far less attention than direct energy use by utilities (Kenway *et al.* 2011c). To date, only relatively simple models of the connections between water and energy in households have been built (Cheng 2002). Of the modelling work undertaken, few results have been validated with independent measurements. Key causal factors, uncertainties and sensitivities, have not been identified. Likewise, the potential for water management in households to reduce energy use has not been quantified.

The omission of quantified, validated, sensitivity-tested studies of known uncertainty is a surprise, given the significance of such information for policy and strategy. Detailed tools and methods could help guide Federal, State, local government policy such as pricing structures or rebate initiatives aimed at influencing water use and related energy. Consequently, the second objective is to understand household water-related energy including key factors, sensitivities, and uncertainties.

Water use in the industrial, commercial and government sectors is also known to have significant energy influence and is also a major knowledge gap. This area is not addressed in detail here due to reasons of scope, however it is flagged as of high importance for the design and management of GHG smart cities. Consequently, where “cities” are described in relation to Objective 1, the focus is typically on the residential component of cities.

1.4. The Need for a Framework and Performance Indicators

Given the scale of investment in urban water and cities, we need to know if our solutions are solving problems, or if they are simply shifting them around. Assessment and management frameworks are fundamental to this knowledge. Among other things, frameworks establish performance indicators, methods, and ultimately operational tools.

Many different frameworks, such as the “triple bottom line” (TBL) accounting, “natural step” (Kenway *et al.* 2008a), and ecological footprint (Wackernagel and Rees 1996) have been used to evaluate urban water performance. Helpful as they are, many existing frameworks fall well short of quantifying resource-related impacts or efficiency of the overall system. Many, such as the ecological footprint (which ignores upstream and downstream water flow consequences), are largely irrelevant to quantifying or benchmarking flows of water, energy and materials through cities (Sahely *et al.* 2003).

Many current sustainability assessment frameworks help organisations reduce their individual impact, such as their energy use. However, relatively little is typically considered about the city or “system” of which the organisation is a component. In particular, the impacts associated with the use of products supplied by organisations, is almost never considered. Considering Figure 3, many water organisations would actively manage their own energy impacts (A) yet be unaware of wider energy use influenced indirectly by their operations or decision making (B). In some futures, it is possible, and in many cases likely, that an organisation may reduce its own energy use, yet lead to increased energy use of the system that it supports (eg Pathway (1) in Figure 3). Conversely, futures are possible where the organisational energy use grows, yet the energy use of the “system” reduces (Pathway 2). Futures also exist where utility energy use and wider water-related energy use both decrease (Pathway 3).

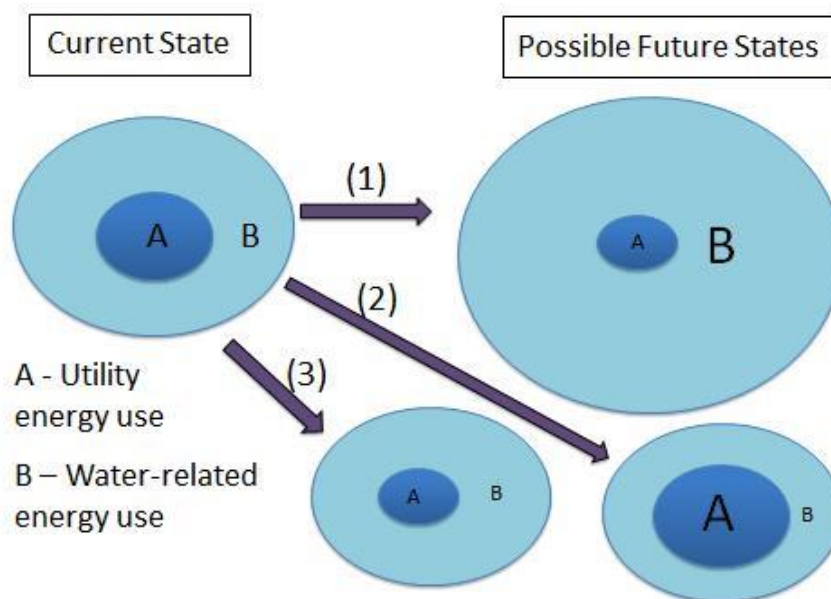


Figure 3. The influence of “boundary” on sustainability performance.

Organisations, such as governments and industry, will increasingly report, and then take responsibility for, upstream (supply-related) and downstream (product-related) impacts, in addition to their operational impacts (GRI 2005; Heemskerk *et al.* 2002). This is not only due to environmental stewardship reasons, but also to managing business risks as well. If a component of their supply chain is unsustainable, there is a likely consequence for the sustainability of their own organisation. As a result, awareness or recognition of the wider “system boundary” is likely to have increased interest and relevance within large organisations and also consumers. But what is the system? And what is its boundary?

Urban metabolism is the theoretical framework used in this research. Urban metabolism is a conceptual model which has been used to describe and analyse flows of materials, including water and energy, within cities (e.g. Newman 1999; Wolman 1965; Decker *et al.* 2000; Sahely *et al.* 2003). A challenge however, is that “metabolic” methodologies are relatively poorly developed (Daniels 2002; Daniels and Moore 2001). As a result, the concept appears poorly understood (Priestley 2012). Because water dominates the mass balance of cities (Wolman 1965), it has been suggested as a priority for metabolism research (Decker *et al.* 2000).

Consequently, the third objective (“Objective 3”) of this research is to **explore potential uses of urban water mass balance analysis in the management of urban water**. Arguably, water mass balance analysis represents a very small – but progressable – window into the potential of the overall metabolism model.

1.5. The Need for Systematic, Collaborative Research

Several authors have identified necessary elements of water-energy nexus research, both outside and within cities. However, overall research priorities have not been well established and no overall roadmap has emerged to guide progress.

Perhaps the most substantive effort to identify research and development needs for water-energy technologies was undertaken by the United States National Laboratories together with allied energy and water research agencies, utilities and regulators (Pate *et al.* 2007). Over 500 participants were involved in the process to develop the “roadmap” (Hightower 2006; Pate *et al.* 2007). Research templates for integrated planning alone indicated investment of some USD \$200-300 million over 10

years (Sandia National Laboratory 2007). This included water, energy and economic modelling, policy development and monitoring, and information collation and infrastructure trials. While the roadmap was aimed for release in 2007, it remains unavailable in early 2012, despite over 20 rewrites (Schneider 2012).

Drawing on the limited information publicly available (Hightower 2006; Pate *et al.* 2007) the roadmap appears to be highly focussed on the “supply” side, and in particular the issue of water supply for electrical energy generation. In contrast, the “consumption side”, such as the role of water and energy efficiency did not adequately feature. This is surprising given the apparent potential and cost-effectiveness of efficiency measures.

The absence of clear research and policy priorities means that policy, planning, funding, and evaluation is relatively ad hoc. The fragmentation means that it is much harder for studies to be compared and for systems to be benchmarked. It is also almost impossible for an overall picture and strategy to emerge. Arguably much more powerful analysis and solutions could be achieved by combining the efforts of those working in this area.

Consequently, Objective four of this research is to identify and describe research priorities for managing water-related energy in cities.

1.6. Goal, Structure and Significance of this Research

In summary, the research objectives included in this report are:

Objective One: Identify and quantify the links between water supply and consumption, and energy use in cities.

Objective Two: Understand household water-related energy including key factors, sensitivities, and uncertainties.

Objective Three: Explore potential uses of urban water mass balance analysis in the management of urban water.

Objective Four: Identify and describe research priorities for managing water-related energy in cities.

The relationship between the first three objectives is illustrated in Figure 4.

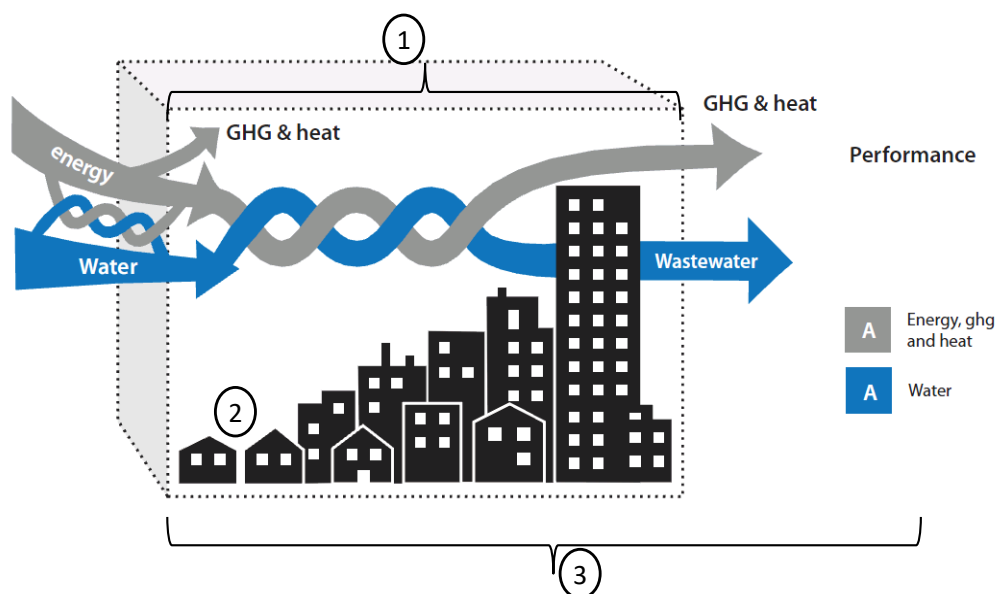


Figure 4. Inter-relationship of research objectives in this research.

The collective aim of this research is to improve the quantification of water-related energy in cities. Quantitative understanding could give water and city managers better information on the consequences of their decisions. It could contribute to better plans and strategies for reducing “water-related energy” and improve the resource efficiency of cities. This appears to be of strategic and long-term economic, social and environmental significance for Australia.

Objective three demonstrates some of the potential of the urban metabolism model with particular attention to understanding the full mass balance, and the subsequent derivation of performance indicators. This has high relevance and will ultimately shape our knowledge regarding the efficiency of urban systems. Quantified urban performance indicators could have considerable implication for the planning, governance, design, funding and many other aspects of urban management.

The structure of this report was adopted to provide the overall story, or the collective picture, of the research. Detail is provided in individual published papers: Objective One - [Kenway *et al.* 2011c](#); [Kenway *et al.* 2011b](#); Objective Two [Kenway *et al.* 2012](#); Objective Three - [Kenway *et al.* 2011a](#); and Objective Four - [Kenway *et al.* In press \(Accepted 12 December 2012\)](#) and other papers published or submitted elsewhere.

The combined picture paints a strong need for improved conceptual, analytical and ultimately management integration of our urban water and energy systems. An exciting aspect is that this work could help transform cities and their water systems. It aims to do this by providing a new way of considering the influence of urban water on energy use, and associated GHG emissions and costs.

2. LITERATURE REVIEW

This section briefly summarises the content and conclusions of a literature review undertaken to provide background context for, and explore the significance of the research area. The full review is provided in the Appendix. It considers knowledge of water-energy linkages in cities including methods of quantitatively evaluating links. It also provides background to, and possible applications of, the urban metabolism model.

2.1. Background to Quantification of the Water-Energy Nexus

There are many compelling economic and political drivers for our increased understanding and management of the water-energy nexus. There is a growing realisation that managing water, energy and carbon, and their connections, is vital to economic success of nations and cities. In 2001 19% of California's electricity, and 32% of California's natural gas use was shown to be influenced by water provision and use. Cities comprised the dominant portion of the effect accounting for 15% of electricity and 31.4% of the State's natural gas use. Despite the prominence, water strategies and policies currently largely ignore energy issues.

Even though the "water-energy nexus" is widely discussed, it is poorly defined. This research considers the water-energy nexus to represent the "interconnections" or "cause-and-effect" relationships between water and energy. A less regularly articulated connection also exists between water, energy and nutrients. The water-energy nexus in this report is considered within this wider water-energy-nutrient interconnection.

It would be an enormous challenge to research and understand the myriad of water-energy-nutrient-carbon links because the connections are vast, and many are unquantified and ever-changing. However, recognising the relevance of these interconnections with water, and developing a structure within which to identify where the boundaries of the water-energy nexus start and finish in relation to these other cycles, will help provide context for the results of research focussed on water and energy.

Understanding energy use and related emissions is relevant to urban and water planning in the context of sustainable cities. This is because urban and water system design, have major and interconnecting influences on energy use.

Diverse methods have been used to understand aspects of the water-energy nexus (see Kenway *et al.* 2011c). Three main approaches stand out as highly relevant given the goal of this research to quantify linkages in cities: (i) mechanistic modelling with or without monitoring; (ii) input-output (IO) modelling; and (iii) life cycle analysis (LCA). These are all mathematical modelling approaches.

2.2. Background to Urban Metabolism and Sustainability Frameworks

Conceptual frameworks and supporting theories and principles are important because they provide the backbone against which methodology is developed. There are weak and strong interpretations of sustainability defined in the literature. The weak interpretation usually assumes that manufactured capital can be substituted for natural capital. The strong interpretation denies this and insists that natural capital must be preserved (Priestley 2012).

Urban metabolism is a conceptual model which has long been used to analyse urban flows of water, energy, and materials (cf. Newman 1999; Wolman 1965; Decker *et al.* 2000). At simplest, it considers the mass balances of all materials (Sahely *et al.* 2003). The idea was first put forward with an aim of addressing contemporary urban resource issues by Abel Wolman in 1965 (Wolman 1965). Metabolism was defined as all the materials needed to sustain the cities inhabitants at home, at work and at play. Wolman demonstrated the dominance of water in the material needs of cities. His city relied on 625,000 tonnes (t)/day (0.6t/capita (person) per day (cap*d)) of water.

Since Wolman's article, only a limited number of metabolism studies have been conducted. Decker *et al.* (2000) assessed megacities and concluded that "analysis of urban metabolism and succession will provide critical information about energy efficiency, material cycling, waste management, and infrastructure architecture in urban systems". Because of its dominance in the urban flux, Decker *et al.* (2000) suggest it should be the prime focus of urban metabolism research. In 2007, Kennedy *et al.* drew on other published studies to benchmark urban metabolic rates (water, materials, energy and nutrient balances). Paucity of published data made trend analysis impossible, however, water and wastewater flows were typically greater (on a per-capita basis) in the 1990s than 1970s.

Many conceptual frameworks for sustainability (eg The Natural Step, Natural Capitalism and Industrial Ecology) have a high degree of connection with the concept of urban metabolism. All of these approaches aim to develop and sustain systems where the use of resources is restorative, non-harmful and efficient and which allow humans and ecosystems to thrive.

A strength of the urban metabolism framework is its clear definition of the "System Boundary" which leads to clear analytical options, and strong relevance to urban design. Several authors note the importance of the "system boundary" to research conclusions (Satterthwaite 2008; Decker *et al.* 2000; Flower *et al.* 2007; French and Geldermann 2005). System boundary definition is a critical first step in modelling analysis (Sterman 1991). Without knowing the boundary it would be impossible to know which factors should be included in, or excluded from, the analysis. The boundary unequivocally influences decisions of the apparent "best" option.

2.3. Conclusions from the Review

What is clear overall from the literature review is that the method selected needs to be strongly guided by the research objective, the research question being asked and the degree of confidence sought in the results.

Much is known about utility energy demands for water and wastewater service provision. However, many of the more distant, indirect links remain uncharacterised or unquantified. This appears a major planning and management issue given that some of the more distantly related energy consequences can be order of magnitude higher than the direct consequences.

Mechanistic modelling appears well suited to simulating components of direct and/or limited indirect impacts of urban water provision and use. Very few studies have taken the step to validation (for example, through monitoring) of modelling results. Consequently, many of the models remain theoretical, with little empirical analysis to identify how well grounded they are in reality. Detailed mechanistic modelling, including sensitivity and uncertainty analysis, is likely necessary to improve our knowledge of key factors of influence.

IO analysis captures the "bigger picture" and more remote (supply chain and trade-related) water-energy links for the entire economy. However, the approach is anticipated to be difficult to apply at city-scale given most analysis and data are at national (or at best State) level. Additionally, the approach has not yet been previously undertaken for water and energy simultaneously.

Urban metabolism theory has clear international academic interest, however, it has not yet moved substantially into applied resolution of real-world problems. The concept does not yet appear to have been applied to help understand the linkages between water and energy in cities. Likewise, it has not yet been incorporated into reporting or planning process or legislation, at least in Australia.

Attractive as the urban metabolism concept is, its full application would have enormous research implications. This suggests, in regard to the problem of growing energy consumption in the provision of water services, only a limited investigation of its extremely wide potential is possible as a component of this research.

3. METHODOLOGY ADOPTED

Methodologies for this research were necessarily matched to each objective. A broad literature review was undertaken as the first step. Literature searches were undertaken in major scientific databases with a focus on work which addressed system-level interconnections between water and energy. Emphasis was initially placed on seeking reviews and books, rather than detailed studies (refer also to (Kenway *et al.* 2011c)).

The intent of the review was to identify recurring and emerging themes and perspectives as well as strengths and weaknesses of the many relevant approaches. In the final stages, the literature was read with a pre-defined set of questions in mind. The review improved the definition of the water-energy “problem”. It also helped to formulate the four research objectives, related questions and suitable approaches.

3.1. Quantifying Water-Energy Links in Cities

Objective One of the research sought to **identify and quantify the links between water supply and consumption, and energy use in cities**. Factors influencing water-energy connections were identified in a broad literature review (refer Appendix 1 and Kenway *et al.* 2011c). These included the influence of perspective, dimension, scale and system boundary.

A targeted literature search focussed on studies which had quantified water-energy connections in cities. This review particularly considered the objective of the study with specific attention to the connections. It also considered the theoretical framework and motivation for the study, the method used, and the conclusions. A summary of this review, along with perceptions on the strength and limitations of the approach is contained in Kenway 2012.

A conceptual model was developed in order to systematise the analysis of water-energy links. This identified the main components of water-related energy in cities including: (i) water provision, (ii) water use, (iii) energy effects of related resources such as nitrogen and carbon, (iv) the urban heat island effect, and (v) other water-energy connections. To quantify the links, the mathematical relationship of water-energy connections was described using consistent nomenclature. This structure then guided development of a spreadsheet model and input parameter list (Kenway *et al.* 2011b).

A number of other water-energy links were identified including urban agriculture and food production. However, no estimates of the influence of water policy on related energy via urban agriculture could be made due to lack of data.

Guided in part by the landmark work by Wolman (Wolman 1965), a hypothetical city of one million people was used in order to populate the conceptual model. This was considered the most suitable approach because it overcame limitations of data within individual cities. By overcoming such data gaps, greater focus on methodology was possible.

Data to populate the model were primarily sourced from Australian cities. However, international data (particularly from well-studied California) were necessary to augment gaps. In order to compare water-related energy to the “total urban system” energy use, it was necessary to quantify flows of water-related electricity and natural gas. These flows were converted to the “equivalent” primary energy use following the method outlined by Gleick (Gleick and Cooley 2009). Essentially, this involves converting electrical energy to the equivalent primary (thermal) energy necessary to generate the electricity. The Australian context of approximately three units of primary energy (largely coal) to produce one unit of electrical energy was adopted.

Flows of water-related electricity and natural gas were also converted to their carbon-dioxide equivalent using standard factors (Commonwealth of Australia 2008). Electrical energy was assumed to have an intensity of 1.0 kg CO₂-e/kWh. This is approximately equal to the national full fuel cycle

value for Australia's electrical supply which is provided largely from coal-fired power plants. Natural gas was assumed to be 0.2 kg CO₂-e/kWh. Full fuel cycle values were used because they capture the quantity of emissions released per unit of energy for the entire fuel production and consumption chain (Commonwealth of Australia 2008).

Total urban systems energy used was characterised by expressing total Australian flows of electricity, natural gas, primary energy and territorial GHG emissions on a per capita basis. This broad definition includes all energy use of all sectors, even for sectors outside the city, including mining and agriculture. The broad definition was adopted because it was believed that the energy-using activities outside the city were related to the city, because these activities provide support for the cities of Australia. Australian cities would not exist in their current form without the economic activity and products generated by these activities even though not all of these products pass through Australian cities. Taking this wide, and to some extent arbitrary, urban boundary definition means that the influence of "water-related energy" as a component of the "urban system" is more likely to be under, than over-estimated. If we selected a smaller boundary (say using only the electricity and other fuels consumed actually in cities), the proportion that water-related energy would include would be substantially higher.

Importantly, the adopted approach identified the nature and approximate quantity of water-related energy components within the city. This then guided subsequent detailed analysis, with the next step comprising detailed characterisation of energy consumption associated with household water use.

A disadvantage of the "hypothetical city" approach is that it is not possible to validate the results against measured data such as actual water and energy usage records for an individual city. However, totals for "water-related" electricity and natural gas usage records do not currently exist for any of the cities studied. Rather, our accounting systems track energy use by each "sector" of management, such as "water", "wastewater", and "industry". Consequently, validation was deemed more appropriate to conduct at the household scale and in the more detailed analysis conducted for Objective Three of the research.

Full details of the method adopted and input data is provided in (Kenway *et al.* 2011b).

3.2. Quantifying Water-Energy Links in Households

Objective Two of the research was to **understand household water-related energy including key factors, sensitivities, and uncertainties**. This required the development of a detailed Mathematical Material Flow Analysis (MMFA) model including: (i) system analysis, (ii) mathematical model construction, (iii) data collection and calibration, and (iv) simulation including uncertainty analysis, sensitivity analysis and scenario calculations. The MMFA was built in strong collaboration with the Swiss Federal Institute of Aquatic Science and Technology (Eawag, Switzerland).

This approach was taken because it provided an ability to rapidly understand the system based on current knowledge, and using limited data. In contrast, a large monitoring and data collection campaign would have taken considerably longer. The approach also enabled us to systematically explore key factors of influence and the impact of future scenarios.

A custom-built MMFA was required because no existing available water-energy model, such as the Pacific Institute's "Water-to-Air" model or "Watergy" by the Alliance for Water Efficiency (both of which are in the United States), had in-built functions of sensitivity or uncertainty analysis (Conrad *et al.* 2011).

A single household was studied because it enabled us to reduce the uncertainties which would have been very large if an “average” of households was to be characterised. Selecting a specific individual house also improved the ability to compare (validate) modelled results with actual measurements. A specific household, in Milton, Brisbane, Australia (the author’s home) was selected due to good access to data. This included quarterly measurements of water, electricity and natural gas use over a three year period of relatively stable water use. Detailed survey of relevant behaviours and technologies within the household was also possible and specific measurements could be taken where relevant.

While a single household can in no way be considered representative of a city, it had a further major benefit of enabling us to focus on methodology and model development. Understanding one household was seen as a stepping stone to being able to characterise “types” of households from the perspective of water-related energy, and a basis for further more extensive research. With such information, the water-related energy in the residential component of an entire city could be simulated as a mix of various household types. This could mean that the full system knowledge could be retained at household scale, without averaging all influences across a city. Such city-scale analysis is intended as a subsequent step in this research.

3.2.1. System Analysis and Model Construction

The first step, system description, involved accurately characterising the main likely systems influencing water and energy flows in the house. The core of the system is comprised of 10 “service” sub-systems (refer to Kenway *et al.* 2012). Each sub-system provides the household with water-related services such as showering, bathing, clothes-washing and dish-washing services. The exception is the “energy” sub-system which captures all other major household energy uses. While the model focussed on factors influencing water-related energy, all major flows of water and energy were captured in order to improve validation of model results against measured data.

A “demand” approach was taken. This means that the demand of each sub-system for water was first developed, and then the corresponding energy was added based on the water balance and related “energy-relevant” characteristics and thermo-dynamic equations. For example, each individual resident requires a certain “shower service” characterised by frequency, duration, water temperature and flow-rate.

This approach is similar to (but richer in detail) to that adopted by Flower (Flower 2009). However, this study deviated from Flower in that some water use was modelled directly proportional to household occupancy numbers (eg, showering or bathing). Other water uses (such as cleaning or dish-washing) were thought to be better characterised at household level. The clothes-washer system was characterised in particular detail due to its complexity and because this was recommended by Flower (Flower 2009).

Overall, this approach was adopted because it better identified underlying drivers of the system. It also meant that detailed policy-relevant questions could be asked.

A stationary (snapshot) approach was selected because of the interest in daily flows averaged over a period (in this case three years), rather than dynamic which would consider trends over time. The model was implemented in the SIMBOX² simulation program (Baccini and Bader 1990) because it was the only available tool that had built-in functionality enabling systematic sensitivity and uncertainty analysis.

The sum of the sub-system “demands” equals the necessary supply of water and energy. Losses are added on top of this, based again on characterising parameters that were expected to be most important. The parameters described “behavioural” (such as shower duration or flow rate), “technical” (such as heat-loss coefficients), and “general” attributes (such as the temperature of cold water).

² Modelling program build by the Swiss Federal Institute of Aquatic Science and Technology.

The work aimed to build a platform which could not only characterise an individual household, but ultimately describe city-scale factors and validate results with city-scale data. Consequently, it was necessary to develop a generic structure within which (i) any individual household, or (ii) group of households, could be described.

3.2.2. Data Collection and Household Simulation

Parameters were characterised by direct measurement, householder survey or estimation from literature. Detailed parameter data was systematically recorded in a spreadsheet such that it could be subsequently read into SIMBOX for a range of conditions or scenarios.

Water and energy costs were estimated using current tariffs. GHG emissions were calculated based on the current full fuel cycles published by the Australian Greenhouse Office for Queensland (Commonwealth of Australia 2008).

The model was first used to identify the local sensitivity of water, electricity and natural gas to the various input parameters. This demonstrated, for example, how the existing system would respond to small increases in parameter values (Figure 5). In most cases, an increase in the parameters led to an increase of household GHG emissions. For example, a 10% increase to the number of adults (Parameter 1 in Figure 5) leads to an approximate 0.2 kg/hh.d CO₂-e increase. A 10% increase in the number of children (Parameter 2 in Figure 5) leads to around a 0.1 kg/hh.d CO₂-e increase.

In contrast, a small number of parameters, when individually increased, lead to a reduction in household GHG emissions. For example, increasing the temperature of cold water (Parameter 3 in Figure 5), reduced GHG emissions by approximately 0.45 kg/hh.d CO₂-e³. This (local) sensitivity analysis helped focus our analysis on those parameters of greatest influence in this system. Local sensitivity analysis was used not only to determine the key influences on household GHG emissions, but also total water use, total energy use, water-related energy use and associated costs.

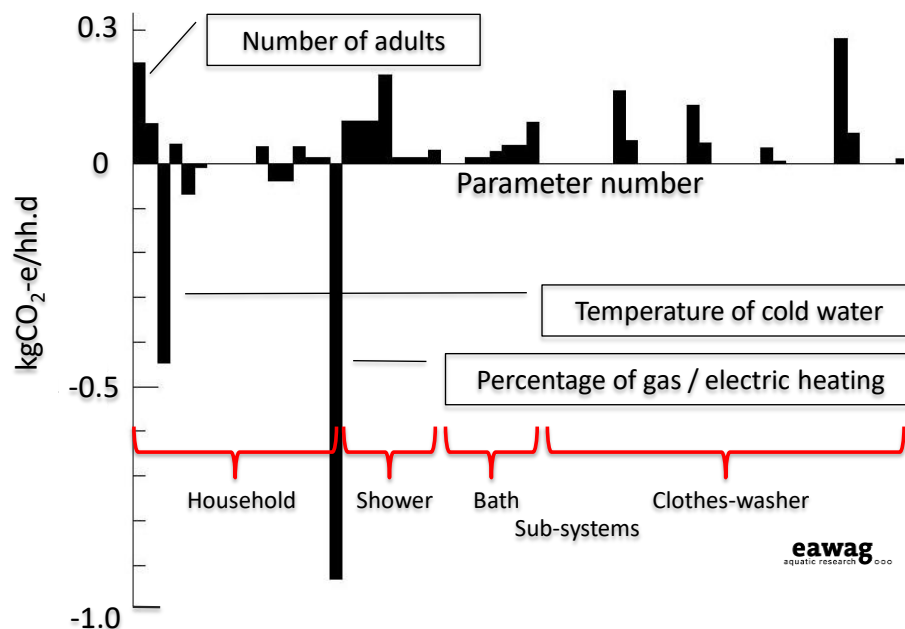


Figure 5. Change in household GHG emissions associated with a 10% in each parameter*.

*Not all parameters shown, the full parameter list for the household is in Kenway et al. 2012.

³ The system is more sensitive to the temperature of cold water than specific end-use temperatures (eg, shower water use), because the temperature of cold water influences the energy use of every sub-system where warm or hot water is required.

The uncertainty associated with an “average day” as well as a “single day” was determined for the household. Three groups of parameters were considered: (i) constants, (ii) randomly fluctuating, and (iii) seasonally fluctuating. In group 1, the standard deviation of the average parameter value was identical for the “average day” as well as the “single day”. For groups 2 and 3, however, where time-series data is available for at least a year, the standard deviation was at least $\sqrt{365}$ times smaller (19-fold) than the standard deviation of the single day. A Monte Carlo analysis was used to generate probability density distribution functions of key system variables. Parameter ranking was used to determine the contribution of each input parameter to the uncertainty of results for both the average and single day cases.

Scenario analysis considered “potential” and “realistic” changes to behaviours and technologies. Behaviour scenarios were considered as “realistic” or “potential”. Both assumed that “level of service” provided by the sub-system remains at the current level for example ensuring that clothes and bodies are still cleaned. “Realistic” assumed that there was no change in comfort level within the house. “Potential” assumed there could be a slight, but possibly tolerable, decrease in comfort to household occupants. For example, the temperature of showers for adults is currently 41°C, whereas the realistic value was seen as 38°C and the potential one as 35°C.

Collectively, the approach enabled a first probability distribution-based analysis of an individual household for water-energy interconnections. For full details refer to (Kenway *et al.* 2012).

3.3. Urban Water Mass Balance Analysis

Objective Three of the research aimed to explore potential uses of urban water mass balance analysis in the management of urban water.

The literature review identified that many urban water analysis articles ignored components of the water balance, for example, rainfall, evapo-transpiration, stormwater and groundwater flows or decentralised water. Consequently, it was necessary to develop a specific mass-balance equation for all water flows in cities. The balance needed to be sufficiently flexible to enable cross-city analysis, it was desirable to develop a water balance framework that could be applied to any city at any scale. Critically, the water balance needed to provide a systematic approach to defining all inputs, outputs and stored water in the urban environment. This needed to include “anthropogenic” (human influence) as well as “natural” flows.

Identification and definition of a clear and three-dimensional system boundary was the first and critical step in the method. Our focus was on understanding the influence of “the city” and how it performs. Consequently, “the city” needed to be separated from “the environment”, such that the exchanges of water between the two could be identified. This meant that bulk water storages supplying the city, groundwater reserves beneath the city, and watercourses running through the city were excluded. Including these elements within the balance would internalise the city-environment flows and cause them to be inconsequential for the water balance. Adopting a “tight” boundary, (one that is likely to have a low value of stored water (S)) has an additional benefit in that it will lead to increased accuracy in future water balances. This is because a small ΔS value means a small difference in Q_i (water inputs), and Q_o (water outputs) could be theoretically detected and validated.

The water-balance equation was then populated with data from four Australian cities for 2004-05, guided largely by data availability and the defined system boundary. All water inputs to and outputs from the cities were assembled from public and research reports, existing models and estimation. A small change in stored water was assumed because the boundary definition delineated a relatively small volume with the mass balance when this study was undertaken. Importantly, this enabled a powerful cross-check of the water balance. Specifically, the independently compiled elements of the (i) total water inputs should equal (ii) total water outputs, plus change of water stored within the boundary.

Indicators of the urban “hydrological performance” were developed from the water balance and used to quantitatively compare cities. One particular indicator, “water turnover rate”, was conceptualised and literally quantified the rate of water cycling through “the city”. Full details are contained in (Kenway *et al.* 2011a).

3.4. Research Priorities for Managing Water-Related Energy in Cities

Objective Four of the research sought to **identify and describe research priorities for managing water-related energy in cities**. The principle methodology was the convening of an international workshop to systematically extract converging themes from senior professionals actively working in the area. This workshop was augmented with literature review.

California was selected as the location for the workshop because it has a strong physical connection between water and energy. This has led to a high level of published information on the water-energy nexus indicating an active research community. More recently, a progressive legislative and institutional framework for conservation of both energy and water has also been developed. This has included conducting co-management trials involving water and energy utilities collaborating to understand the energy consequences of various water conservation measures (GEI and Navigant 2011b, 2011a).

To encourage diverse views at the workshop, stakeholders from both the water and energy sectors were deliberately sought. For a similar reason, representation from state, federal and local government, industry, academia and the not-for-profit sectors was also encouraged.

The “World Café” method (Dunn 2004) was used to structure the workshop to help identify emerging themes. This “organic” process helps identify and develop consensus around emerging issues. A series of short invited presentations were delivered. Subsequently, participants “self-assembled” into small sub-groups to discuss important questions. Periodically the participants, excluding the table “host”, move to other tables and take with them important ideas heard at the previous tables. Finally groups presented back, their views on the following questions: *What are the elements of success in the water-energy efficient city of the future?. What are the major opportunities for cost-effective energy efficiency via water management in cities? (Session 1). What are the major needs and barriers to progress in the most important element identified in Session 1? (Session 2).*

All sub-groups worked on the same questions simultaneously. At relatively short intervals, the groups were altered. All participants moved “organically” to other tables. The exception was the table “host” who remained to inform the re-formed group of where the table was up to. This approach enabled ideas developed at one table to be brought to other tables. Using this process, it was possible to air a diversity of issues, and strong ideas had a good opportunity to emerge.

Outcomes were summarised and discussed at the workshop, and then subsequently documented and sent to all participants. Participants were surveyed on-line in order to semi-quantify the views on “potential” as well as “level of effort” necessary to progress the elements identified.

A scatter plot was used to identify the relative “effort-to-potential” of each initiative and create a guide for potential staging of work. The on-line survey data enabled preliminary analysis of the sources of variability including institutional or sectoral perspectives. Outcomes were compared with other recent publications identifying water-energy research priorities in order to gain a more complete perspective.

An advantage of the approach was that it drew on the considerable knowledge and experience of individuals and institutions in a rapid and semi-quantitative manner. Full detail of the method adopted is described in (Kenway *et al.* In press (Accepted 12 December 2012)).

4. RESULTS AND OUTCOMES

The results and outcomes reported summarise results published in journal articles referenced at the end of this report.

4.1. The Influence of Urban Water on Energy Use (Objective 1)

In 2006-07, water-related energy associated with urban water provision and use, accounted for 6,811 GWh of (equivalent) primary energy use per one million people (Figure 6). This is equal to 13% of Australia's electricity use plus 18% of natural gas consumption. This represented 9% of the equivalent primary energy use and 8% of Australia's GHG emissions (Table 1).

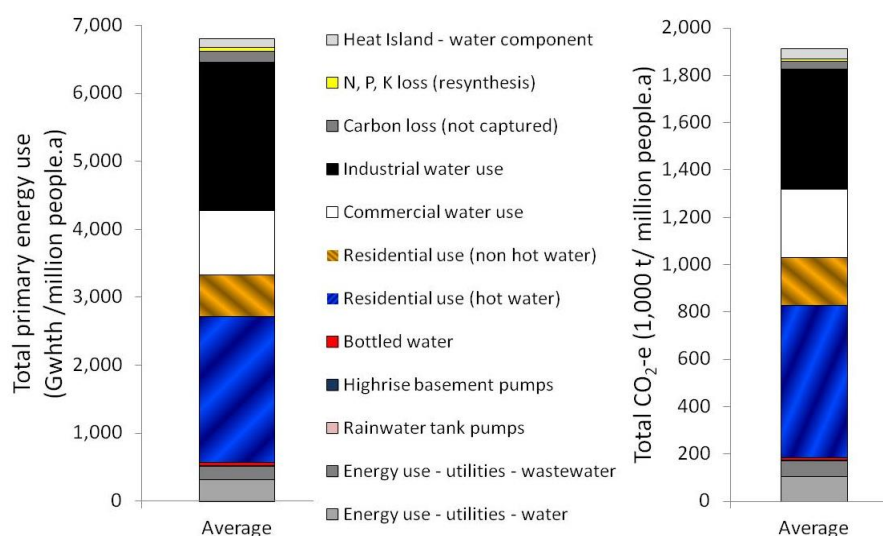


Figure 6. Water-related primary energy use (left) and GHG emissions (right) in the average Australian city*.

*Source: (Kenway *et al.* 2011b). Based on average data for major capital cities (Sydney, Melbourne, Brisbane, Adelaide and Perth). GWhth is thermal (as opposed to electrical) energy use. It is determined for this paper using 3 units of thermal energy as approximately equivalent to one unit of electrical energy. Source: (Kenway 2012).

In the average case (Figure 6), energy associated with residential water use comprised 45% of the overall GHG emissions effect of water-related energy. Water use in the commercial and industrial sectors accounted for 41%. Energy use for utilities in the provision of water and wastewater services accounted for around 10% of water-related energy. The water-component of the urban heat island and energy related to resources loss (such as Carbon, Nitrogen, Phosphorus and Potassium) accounted for the balance of energy use and emissions (4%).

Indirect (hidden) energy was nine times higher than energy used directly by utilities. Consequently, water end-use appears the dominant process influencing water-related energy in cities.

The analysis of water-related energy is underpinned by data for 100 parameters. (Kenway *et al.* 2011b) provides details on these influencing factors and related assumptions.

Table 1. Water-related and average energy use and GHG emissions per one million people (2006-07).

Comparative Area	Units	Australian Average	Water-Related in Cities	Proportion of Australian Average
Electricity use	GWhe	10,476	1,379	13%
Natural gas use	GWhth	15,154	2,675	18%
Primary energy use	GWhth	76,384	6,811	9%
GHG emissions	CO ₂ -e (1,000 t)	24,239	1,914	8%

Note: GWhe is GWh of electrical energy use. GWhth is GWh of thermal energy use noting that 3 GWh th is required to produce 1 GWhe. Data source (Kenway *et al.* 2011b).

At a carbon value of AUD \$23/tonne⁴ water-related energy represents AUD \$920m/annum in the value of emissions permits.

First-order sensitivity analysis suggests that an individual city could vary from the average by 37-238% for electricity, or 65-131% for the use of natural gas. Such a wide range of possibility suggests considerable scope exists for policy intervention and management.

4.1.1. Sectoral Comparison

Water-related energy in cities (Table 1) was compared with sector energy use. To enable this comparison, energy use accounts published by the International Energy Agency, Paris, France (IEA 2011), needed to be converted to equivalent primary energy use. This required estimating the share of primary energy (eg. coal, gas, oil) used for electricity generation was attributed to each sector, based on their proportion of final electrical energy consumed (Figure 7).

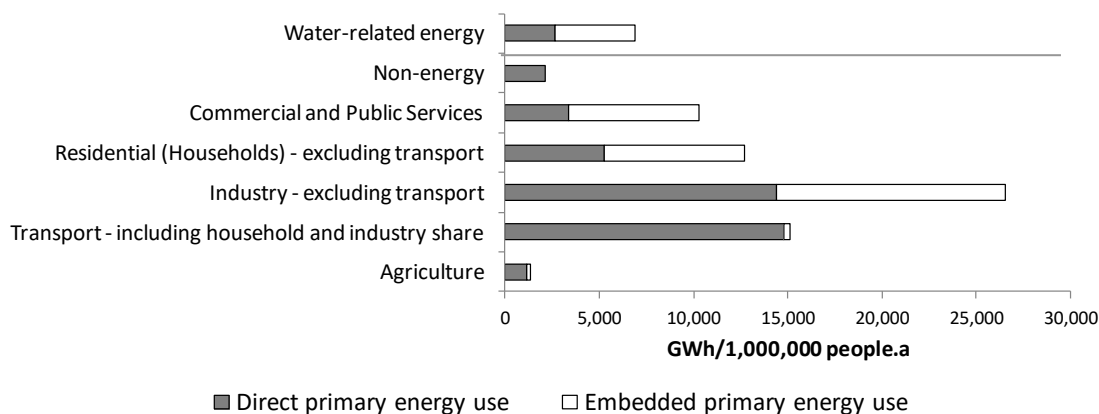


Figure 7. Water-related energy use in Australia in 2006-07 including the share of embedded electricity.*

*Data Source (IEA 2011) for all sectors in the Australian Economy (Note: these sectors total to Australia's primary energy use.) Data source for water-related energy (Kenway *et al.* 2011b).

Water-related energy use in cities is substantial. It is approximately half the energy of the Australian residential sector (excluding transport), or one-third of the total energy of the industrial sector (excluding transport). It is more than four times the energy use of Australian agriculture.

⁴ The set price for the first year of the carbon tax that commences 1 July 2012.

4.2. How Household Water Use Influences Energy (Objective 2)

This section presents the immediate results from the second objective of the research. This aimed to understand household water-related energy including key factors, sensitivities and uncertainties.

This section discusses the results immediately relevant to the single household evaluated. Wider discussion, including implications of the research, for managing the rising energy use in the urban water system, and possible next steps, are described in Section 5.2. Refer also to (Kenway *et al.* c 2012 (Accepted 15 February 2012)).

4.2.1. Quantification of Water-Related Energy

Factors influencing water-related energy in an individual household were identified in detail. The model results compared well with monitoring records taken quarterly for three years (See (Kenway *et al.* 2012), Table 3). The relative significance of each “sub-system” was established with regard to its water use, energy use, GHG emissions and costs.

For the studied single (four person) Milton household, water-related energy comprised 59% of total household energy (11.5 of 19.3 kWh/hh.d). Water-related energy use was for the shower (3.3 kWh/hh.d), clothes-washer (1.9 kWh/hh.d), bath (1.6 kWh/hh.d), taps (1.4 kWh/hh.d), dish-washer (1.0 kWh/hh.d) and electric kettle (0.9 kWh/hh.d). Losses from the electric hot water system were calculated as 1.4 kWh/hh.d.

Water-related GHG emissions accounted for 35% of total household emissions excluding emissions related to transport energy (5.4 of 15.6 kgCO₂-e/hh.d). With regard to GHG emissions, the clothes-washer, dish-washer and kettle were the most significant sub-systems. The change in sub-system priority from energy to GHG emissions is due to the proportion of electrical energy or natural gas used by each sub-system. Electricity used by the household has almost five-fold the GHG intensity of natural gas. This shows clearly that different strategies are needed to deal with either water-related (i) energy use or (ii) GHG emissions. Different strategies would also be necessary to deal with total household costs related to water use and water-related energy.

The household analysed is relatively conservative with resources use. It consumed around 80%, 50% and 60% of the Australian average (per household) for water, natural gas and electricity, respectively. This was despite the household having four persons, whereas the Australian average household was assumed to have 2.6 persons.

Water use in the household studied was similar with the “average/hypothetical” (three person) household conceptualised by Flower (Flower 2009). However, in Flowers’ analysis, the modelled use of water-related natural gas (eg, 15.5 kWh/household/day (kWh/hh.d)) natural gas for hot water system) was higher than as modelled for the Milton household (7.6 kWh/hh.d). This was largely because Flower assumed the clothes-washer relied entirely on the hot water system for energy (5.3 kWh/hh.d), rather than internal heating within the appliance. Flower’s analysis in Melbourne also assumed a temperature of 7.5 degrees lower than the Milton household, and a higher rate of shower water use.

4.2.2. Uncertainties

Probability distribution functions demonstrated the range of water, electricity, natural gas, and related carbon-dioxide equivalents and monetary flows that could be expected in a particular or average day.

Parameter ranking demonstrated that factors influencing the majority of the uncertainty of the “average” day and a “single day” vary considerably. For example, uncertainty regarding the heat-coefficient of the hot water storage and the flow-rate of showers for adults contributed 76% of the total uncertainty of water-related energy in the average day. In contrast, six parameters contributed 78% of the uncertainty in the single day results.

Parameters contributing to the uncertainty in the single day include: (i) the number of warm cycles on the (front loading) clothes-washer, (ii) number of adults in the household, (iii) temperature of cold water, (iv) heat co-efficient of the hot water storage, (v) number of showers per adult per day⁵, and (vi) flow duration per shower for adults.

Knowledge of uncertainties can guide the design of additional data acquisition or programs in order to reduce uncertainty and improve confidence. Consequently, if it was desirable to reduce the uncertainty of results in the Milton household, focussing on evaluation of the parameters described above would be strategic.

At city-scale, water service providers could have interest in designing monitoring programs to achieve a particular confidence level regarding water-related energy or GHG emissions. Such knowledge could be valuable to those seeking to confirm that they had in fact achieved target reductions in water-related GHG emissions relating to water end use. This is particularly the case if the achievement of such reductions is included as a component of strategies for carbon neutrality.

4.2.3. Scope for Reducing Flows of Water, Energy, Carbon and Costs

Scenario analysis indicated that occupant behaviour has a greater potential effect than technology changes alone. Realistic and potential behaviour changes alone⁶ reduced water-related GHG emissions 47-72% of the baseline respectively. In contrast, potential and realistic technology changes (excluding a solar hot water system) were only able to reduce water-related GHG emissions 14-15% from the baseline. With regard to water-related GHG emissions, realistic behaviour changes had a similar effect to installing a solar hot water system (Figure 8).

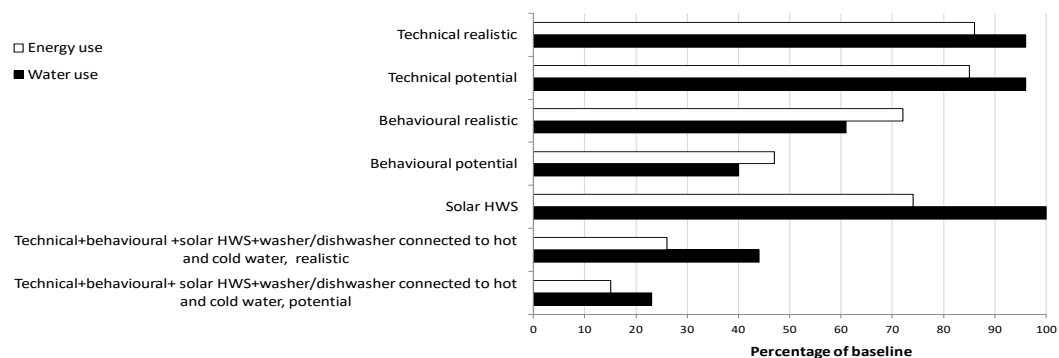


Figure 8. Scenario influence on water use and water-related GHG emissions: Milton household.
Data source: (Kenway *et al.* c 2012 (Accepted 15 February 2012)).

With all possible behavioural and technical changes (including installation of a solar hot water system and altered plumbing to maximise the use of solar water heating), water-related GHG emissions could be reduced to 12% and 7% of the baseline in the “realistic” and “potential” case respectively. For water-related energy, a reduction to 26% and 15% of baseline was achieved in the respective “realistic” and “potential” cases.

The strong influence of behaviour on the system suggests that understanding social factors motivating water-use patterns will be critical to achieve the most substantial changes. Further consideration would be required to adopt the implication of this result into appropriate water demand management strategies such as technology rebates or information provision programs.

⁵ Note the household had two children aged ~8 and 10 during the study and they used the bath far more than the shower.

⁶ Refer to (Kenway *et al.* In press (Accepted 12 December 2012)) for details.

4.2.4. Saving Water Does Not Always Reduce GHG Emissions

The modelling also demonstrated that saving water does not always reduce GHG emissions. Replacing a clothes-washer with an energy efficient model, could increase GHG emissions even if water use reduced. Increases to GHG emissions occurred if a change in technology (such as plumbing of the hot water supply), shifted the fuel source from natural gas to carbon intensive electricity. An example would be having a new clothes-washer with a cold water only connection (with an internal heating system) replacing a machine which had been plumbed to a natural gas hot water system.

While most current model clothes-washers are made solely with a single (cold water) connection point, discussions with manufacturers indicated that at least some manufacturers are shifting to enable both hot and cold water connections. Such a change could help reduce GHG emissions in systems where natural gas was common for water heating, or where other low emissions energy sources such as solar heating was used.

4.3. Use of a Water Mass Balance for Cities (Objective 3)

Application of a “metabolic” water mass balance framework revealed large flows of water that pass unaccounted for through Australian cities (Figure 9). This shows that our cities are currently not designed for, nor taking advantage of, significant flows of water, particularly wastewater and stormwater.

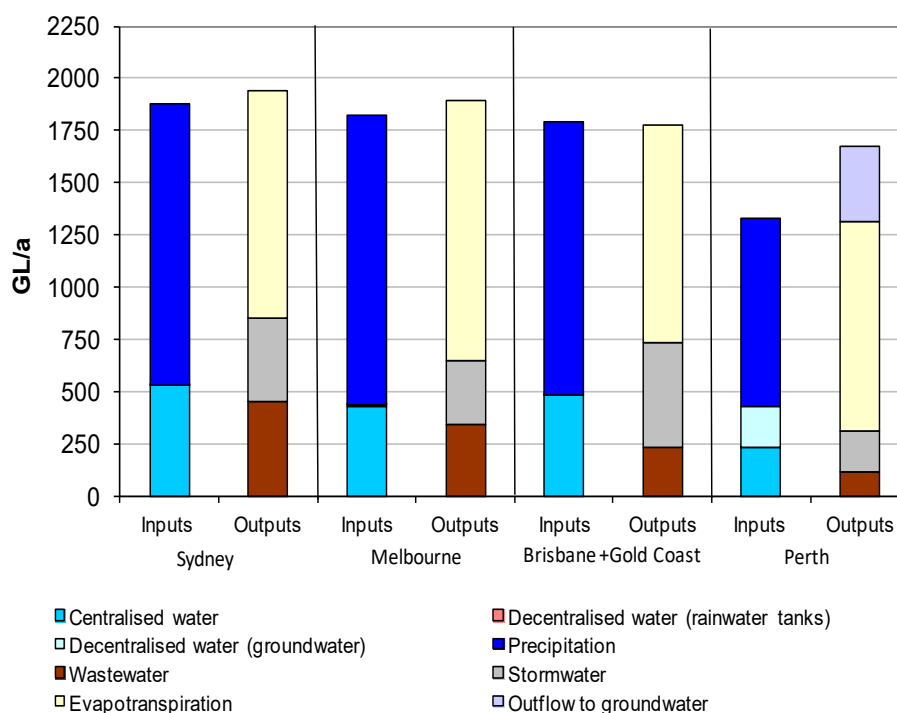


Figure 9. Water mass balances of four Australian cities/metropolitan areas in 2004-2005.
Data source: (Kenway *et al.* 2011a).

The framework quantified the hydrological performance of cities (Sydney, Melbourne, Perth and SEQ (Brisbane and Gold Coast combined)). Large inter-city variation was evident (Table 2) (see also Kenway 3). For example, in 2004-05, the cities varied from 0.1-22% in their rainfall harvesting; 257-397% in the ratio of rainfall/centralised water use; 26-86% in wastewater recycling potential; 47-104% in their stormwater recycling potential; and 1-4% in their reuse of anthropogenic input water.

Table 2. Summary water balance performance in four Australian cities (2004-05).

	Rainfall harvesting	Rainfall potential to meet supply	Wastewater proportion of water use	Stormwater proportion of water use	Reuse proportion of anthropogenic water input
Sydney	0.1%	257%	86%	76%	1%
Melbourne	0.5%	322%	79%	68%	4%
Brisbane + Gold Coast*	0.1%	273%	48%	104%	2%
Perth	22%	397%	26%	47%	1%

*The urban footprint of these two areas were considered representative of the South East Queensland (SEQ) area because they accommodate the majority of the population of SEQ. Data source: (Kenway *et al.* 2011a).

The water balance enabled a powerful independent cross-check of the many data used in the analysis. For the metropolitan areas of Sydney, Melbourne and SEQ (Brisbane + Gold Coast), total water inputs were within 4% of total outputs with the exception of Perth where inputs appeared to be 80% of outputs (Figure 9).

This result is consistent with the (tight) adopted system boundary definition. The boundary adopted means that stored water (S) in “the system” is relatively small. Consequently, the change of stored water (ΔS) would be expected to be small. This consistency was somewhat surprising given the diversity of data sources and large variability between the cities evaluated.

It was not possible to quantify the water turnover rate with confidence because water stored within the system could not be measured or accurately estimated. Consequently, the performance indicator “water turnover rate” could not be directly determined. Assuming 0.6-1.7 GL of water stored in all four cities evaluated would indicate that the anthropogenic water inputs would turnover this storage some 1,100-3,300 times per year, or three to nine times per day.

4.4. Managing Water-Related Energy in Future Cities (Objective 4)

Research for Objective 4 first used an international workshop to conceptualise a city successfully managing the water-energy nexus. Such a city was considered to be liveable, locally self-sustaining, and have diverse and affordable water and energy supply options. The city would have limited draw on the surrounding environment for inputs. Waste outputs would be small. Critically, it would operate within its local water and energy (carbon) budget. The efficiency paradigm is embraced for the “whole system”. It fosters creativity, design innovation, business and economic success. The full detail of the work is described in (Kenway *et al.* In press (Accepted 12 December 2012)).

While progress in many areas is important, four areas appeared to have a stronger case for immediate attention. The average effort-to-potential ratio for initiatives developed suggested the following to have highest priority:

Integrated standards, guidelines, funding, and planning. It is vital that the planning and development processes in cities work together to optimise the entire system. Ideally, this involves simultaneously reducing water and energy flows through the city. There is a need for greater clarity of the vision, data needs, techniques and methods, appropriate technologies, tools and development patterns in this area.

Water-energy education programs are needed at tertiary institutions, schools and within agencies and utilities. This is necessary to progress towards more inter-agency collaboration for planning and decision-making.

Methods and then targets are needed for “water-related energy” and associated GHG emissions. Methodologies are necessary to ensure that water-related energy is being accounted for consistently and accurately. Target setting would require cost-benefit analysis in order to find least-cost, system-wide implications.

Understanding, and then using, behavioural motivations to achieve urban resources efficiency. Due to the strong influence of customer behaviours, understanding motivational factors was viewed as vital to helping cities more rapidly progress towards efficiency modes.

Other areas seen as necessary to progress include: full cost charging and rate-making; understanding of the urban metabolism; aligning technology development and adoption with the need; integration with transport and waste; adaptive management; and blueprints for urban development.

Improved tools and metrics are needed, particularly regarding the economic implications of the water-energy nexus. Relationship building and trust across the myriad organisations is also important.

Barriers to progress include fragmented jurisdictional boundaries, real physical differences between water and energy (and the associated system operation implications), short-term policy-making and the wider issue of agency “entrapment”.

The work identified here complements other recently published material. However, the research roadmap developed in this paper has a distinct focus on cities. Consequently, they are arguably more relevant to urban design and the development of resource efficient cities at least from the water-energy perspective. Other publications have focussed on national policy and action priorities (AWE and ACEEE 2011; PMSEIC 2010) or specific recommendations for conserving energy via water conservation (Elkind 2011). The recent release of these diverse and multi-stakeholder reports recommending aspects of water-energy research highlights the breadth of interest in the issue.

The process used for the workshop was viewed positively by participants. The view was that it will assist them in understanding problems, identifying objectives and defining alternatives. It is possible that the approach has application potential for use in addressing other complex natural resource management issues.

5. DISCUSSION

This chapter summarises and builds on the discussion initiated in individual papers published in the thesis (Kenway 2012). It also provides a comparison across the individual research objectives, to identify a number of more immediately achievable research and implementation steps.

The chapter reconsiders the relationship between the water-energy nexus and urban metabolism in the light of the overall research findings. The future management of cities and sustainability is considered within the trajectory of our current knowledge and management systems. Potential uses and further development of the urban metabolism model are also addressed. This is followed by consideration of the veracity of the research results and conclusions within a range of possible economic and technological scenarios.

5.1. Quantifying the Water Energy Nexus in Cities

In relation to Objective 1, **identify and quantify the links between water supply and consumption, and energy use in cities**, this research has expanded the knowledge base by conceptualising a structure for the systematic identification and evaluation of all known major urban water-energy connections.

The quantum of water-related energy in each category (eg, for provision or use of water) compares well with other authors largely because the analysis was based on available literature. However, the percentage of total primary energy use influenced by urban water (9%) is far higher than previous reports regarding Australia. For example, Kenway *et al* (2008b) articulate that water service provision in cities accounts for less than 0.5% of total primary energy.

The difference in reported percentages is due to issues of (i) boundary, and (ii) energy transformation and loss. In this research, “water-related energy” includes a wide range of *indirect* effects rather than considering utilities alone, as was reported by Kenway *et al* (2008b). Notably, this includes energy related to water use, such as water heating. This research also includes the actual primary energy (largely coal) consumption necessary to create the electricity used by water utilities (or for water heating). Accounting for primary energy in this “life-cycle” way, is consistent with, and draws on, the work of several authors (eg, Klein *et al.* 2005; Wolff and Wilkinson 2011; Gleick and Cooley 2009). It is argued as more realistic than the comparison of end-use electricity with total primary energy as undertaken by Kenway *et al* (2008b). Ignoring this “embedded” fraction reduces by 66% the apparent significance of electricity use when sourced from fossil fuels.

The results presented are for an “average” or “hypothetical” case. In reality, the major cities in Australia or elsewhere could be expected to have large variability based on local conditions. Time also has considerable effect, for example comparing drought versus high rainfall years. Further analysis would be necessary before conclusions about a specific city could be made. This is particularly the case for characterisation of the industrial and commercial sectors which are scarce in data and influence almost half the overall effect. Outside Australia, the results could be expected to be approximately applicable to other western countries with similar overall socio-technological regimes, climates and water, and energy use patterns.

5.1.1. Implications for Managing Water-Related Energy

The Australian water-sector currently influences nearly nine times more energy use indirectly, than the sector itself consumes directly. Arguably, more substantial energy-related goals could be included into water planning processes.

Many steps could be taken by water businesses, urban planners, wider government and industry, which could have significant impact on water-related energy. As pointed out in section 4.2.3, water use and, water-related energy use of the residential sector could be significantly minimised with a

range of technical and behavioural changes. Such changes can be encouraged by a mixture of programs, measures or government instruments. For example, targeted information provision (eg, communicating of water use and related energy use) can influence behaviour. Creation of financial incentives and penalties for particular behaviours can also have effect. While water and energy pricing and structuring (such as stepped tariffs) are typical examples, financial incentives also can be used for installation of efficient technologies.

On a longer time-scale, standards appropriate for achieving combined savings of water and energy could be considered. It would also appear strategic to support development of technologies which simultaneously reduce water and energy use. These mechanisms could apply not only in the residential sector, but also in industrial and commercial situations. While the Australian water sector is highly active and effective in promoting water-conservation measures, it would seem a logical extension to consider the joint potential of these programs to also influence energy use and GHG emissions.

Goals for water businesses to reduce water-related energy could lead enhanced involvement of the water sector in the end-use water management. This could lead to far greater efficiencies of household water and energy use. A great difficulty, however, will relate to how to quantify indirect water-related energy. Further, because multiple-players have influence (eg, household owners, water utilities, councils, regulators), identifying who has enabled the result could be challenging.

Information alone is unlikely to fully mobilise industry to reduce the larger pool of energy indirectly influenced by water in cities. Rather, a wider, more integrated suite of programs and measures, or complementary government policy instruments, could help progress change. Consideration of the overall institutional frameworks, governance arrangements and business models for water and energy management in cities may also be necessary. Mechanisms for increasing the connection between service-provision and revenue need to be strengthened. Likewise, decoupling the revenue-dependence of utilities on volumetric sales of water and energy could be highly strategic, for example as incentives for reduced resource through-flow (Lesh 2009).

5.1.2. Reflection and Possible Next Research Steps

The broad challenges of managing and optimising water-related energy in cities are raised in Kenway *et al.* 2011b. Improved knowledge of water-related energy in cities would be highly valuable for designing and managing cities and buildings that are simultaneously “water-sensitive” and “carbon-sensitive”. The need for further methodological development and city analysis is evident. Comparison of actual data on water-related energy and trends over time, for a range of cities for would be highly instructive.

The research undertaken for Objective One has developed a method for quantifying, in overview, water-related energy in cities. The key parameters identified capture the physical cause-and-effect relationships. However, the influence of non-physical factors on these linkages has not been determined. Such factors could include behaviour/culture, economics, existing infrastructure, local conditions or decision-making processes (such as building approval or regional planning) and related standards. This is particularly important when considering the design of future systems. Further research into these non-physical drivers would help identify leverage points on water-related energy, both in the water system, and the city it supports.

Further end use and technology assessment is necessary to identify the most effective or accessible areas to target, or, effective policy interventions. Least cost analysis and the production of cost-abatement curves would be helpful. However, as Gleick *et al.* (Gleick and Cooley 2009) point out, options which conserve water will likely out-perform those which encourage continued patterns of high usage. This could be particularly expected in a future where water and energy are more expensive.

The analysis could be improved significantly using more sophisticated modelling. For example, a MMFA (Mathematical Material Flow Analysis) model could be developed and applied (see Kenway *et al.* 2012). Because of the importance of land-use patterns, a spatial component to such a model would be highly valuable. Improved definitions of the “urban footprint” would also be beneficial. This could potentially be guided by land use patterns characterised in stormwater models. Ultimately, such a model could also include economic considerations. Use of a full mass balance for water (see Kenway *et al.* 2011a) could ensure that all water flows were considered. It could also help develop quantified performance indicators.

It is anticipated that modelling water-related energy in the industrial and commercial sectors would present a challenge because of complexity and lack of available data in these sectors. A starting point could be to develop sector-by-sector estimates using water and energy consumption records. This would necessitate estimating the “degree of connection” between water and energy in each sector, as was done by Klein *et al.* (Klein *et al.* 2005). Alternatively, a “bottom-up” analysis of data for individual sectors could be undertaken, as outlined by Wolff and Wilkinson (Wolff and Wilkinson 2011). MRIO modelling and/or LCA approaches could also be used, particularly if indirect water-energy connections through the supply chain are of interest.

Finally, this research has also relied largely on “what exists” in order to understand water-related energy. It does not yet explore “what could be”. Order of magnitude improvement (reduction in water and energy use) would appear possible. This is particularly the case if the full thermal and physical properties of water (for example for heat storage and recovery, evaporative cooling, etc) are considered.

5.2. Household Water-Related Energy Use (Objective 2)

Objective 2 of this research was to **understand household water-related energy including key factors, sensitivities, and uncertainties**. Results specific to the single Milton household evaluated were discussed in Section 4.2. This section reflects on the methodology and potential next steps including city-scale analysis and management of water-related energy in households.

5.2.1. Reflection on the Methodology

The methodology developed in this research provides a first-ever assessment and simulation of the probability distribution functions of household water-related energy and associated GHG emissions and costs. It also represents the first systematic household-scale analysis of associated uncertainties.

Characterising the full water and energy balance for the household was very useful for validating the modelled results with monitoring records. This helped improve confidence in the overall conclusions.

The use of thermodynamic equations was fundamental in characterising the overall water and related energy demands including losses. Developing a model structure guided by activities within the house provides a critical understanding of scenarios, and consequently, could guide more detailed policy development. In contrast, modelling water-related energy based, say, on size (square meters) of house or typical water usage rates, would provide far less relevant information for policy development. This is because it is the pattern of water usage, and not the size of the house, that are driving water-related energy. Further, because the MMFA method does not aggregate everything into a single unit (like an overall ecological footprint) it is possible to understand the potential repercussions of individual and collective actions.

Local sensitivity analysis was highly useful during the early stages of the study. It guided the search for data towards parameters with the most leverage on the system (eg, the number of adults, the temperature of cold water). However, because local sensitivity analysis only works for continuous (not discrete) parameters, its main value was in the assessment of the baseline case, rather than in the exploration of scenarios.

Given the strong influence of behaviour, it is likely that other households would behave differently to the household studied. Comparison of a larger sample size would be necessary to make city-scale conclusions. In order to understand and manage city-wide trends, it would be necessary to either (i) aggregate results from many individual households, or more desirably (ii) aggregate results of multiple representative average household types. The developed “household water-energy” model has been structured to enable this analysis as a next step.

5.2.2. Possible Next Research Steps

There are a number of highly relevant follow-on research activities that could be undertaken regarding household water-related energy. The model developed in this research could be further improved by adding factors such as: (i) the percentage of water heated within the clothes-washer, (ii) the related energy use in clothes driers, (iii) rainwater tank pump energy use, (iv) swimming pool heating, (v) water chilling, and (vi) water-related energy in cooking. Equations and parameters characterising the exchange of energy between the water system, and building interior (eg, as cold or warm water enters a building and warms, or as warm water leaves a building), could add a further dimension to the model.

Such inclusions should be based on systems knowledge and the importance of such aspects to the area investigated. Use of probability distributions for input parameters (rather than mean, deviation and distribution “type” (such as lognormal, normal)) would help improve overall accuracy. It would also create a much more substantial demand for data. This could perhaps be best achieved at the level of representative “household type”.

It is clear from the analysis that the performance of individual technologies is highly dependent on the system into which it is placed (see clothes-washer example described in Kenway *et al.* 2012). It would also be desirable to move towards standards that determine an overall efficiency of the “system”, rather than an efficiency to be achieved from an individual technology.

City-scale analysis of water-energy connections in households is a great possibility. City-scale knowledge of water-energy connections is arguably paramount to the design and implementation of successful water strategies aimed at reducing energy consumption. City-scale analysis could underpin a benchmarking effort regarding the relative energy efficiency of the urban water system including the end-use of water and the associated technologies. There appears to be wide room to consider improved analysis of the energy, cost and GHG emissions implications of various demand management programs.

For city-scale analysis, there is a need to better understand a range of household types. For example, how is water-related energy influenced by different (i) building types (houses/apartments), (ii) socio-demographic (eg, high/low income, different occupancy rates), (iii) behaviours (eg, conservation versus non-conservation oriented), and (iv) technologies (eg, highly efficient versus not efficient). Differences in hot water system types and intra- and inter-city climatic variability also have a major influence. There is a need to better understand how individual “household types” respond to particular circumstances or configurations. Such knowledge would let policy be crafted to the applicable circumstance. This is likely to be more effective than relying on average conditions alone. If we continue to rely on average conditions, it is likely that policy could be misguided.

This research has only quantified the performance improvement potential at the level of a single household. However, there remains the possibility of significantly reducing water, and related energy demands at a range of scale including precincts and whole cities.

How connections between water and energy in households and cities change through the course of time is another major gap. For example, how do water-related GHG emissions change through a day? Or, how are socio-technological changes likely to influence the water-energy connections within individual households and cities over the coming decades? How could cities transition to minimise

water and related energy use? In order to answer such questions, it would be necessary to develop a dynamic model.

5.3. Urban Water Mass Balance Analysis (Objective 3)

Objective 3 of this research aimed to explore potential uses of urban water mass balance analysis in the management of urban water.

The urban water mass balance approach developed in this research reveals water flows through cities typically not included in the urban water “balance” (see Kenway *et al.* 2011a). This includes volumes of rainfall, stormwater, evapotranspiration and decentralised water sources. Awareness of these volumes is a first step towards designing cities that take advantage of these flows.

In future, much more water is likely to be harvested locally within cities. Drivers will include growing water use (largely due to growing populations), higher costs of distributing water, and the emergence of suitable technologies and policy frameworks encouraging use of more locally sourced water. For example, the projected water supply growth for greater Adelaide (from 2014 onwards) is dominated by planned increases in using wastewater and stormwater as well as achieving improved efficiency of water use (Government of South Australia 2009).

Changes in urban water flows and storage have energy implications. For example, it is possible that stormwater, rainwater and wastewater could be used or recycled at lower overall energy costs, than other options such as desalination or transporting water from distant sources. However, the high energy demands of some small (decentralised) systems or inefficient designs (Retamal *et al.* 2009b) means that low energy use is not necessarily always achieved. System design can be critical for reducing energy use. For example, rainwater tank systems could be designed to use less than 0.2 kWh/m³ if they utilised header tanks, low pressure pumps and reconfigured toilet valves so that they operated under low pressure (Cunio and Sproul 2009). Energy for reuse of wastewater can be reduced if land use planning enables locating industries which can use recycled water close to the point of its production. Similar scenarios are likely to exist for stormwater harvesting.

Knowledge of full urban water balances could also help quantify other energy-relevant aspects of urban design. This could include: (i) improved quantification of the urban heat island effect, (ii) potential for energy generation (eg, micro-hydro), and (iii) potential for thermal storage and recovery.

Finally, understanding the full urban water balance is vital for comparing water-related energy demands from city to city. To take one example, the mass balance revealed major inter-city differences in decentralised water use. Consequently, in cities using a large proportion of decentralised water supply, it would be essential to consider the energy-demands associated with those flows. For example, 46% of Perth’s water supply is sourced from decentralised ground water sources. This form of provision could be expected to have considerably different energy demands to alternative water supply options (such as desalination), or to cities of similar size and climate.

Consequently, future water strategies would be arguably more energy-relevant if they (i) quantified all urban water flows using a mass balance framework, and (ii) identified how the overall balance influenced energy use and generation.

The influence of detailed end use patterns on the water-balance were not investigated in this work. Water end use has considerable significance for the urban water balance because it influences both inflows and outflows of water. Where water-using appliances or technologies produce wastewater (such as toilets, showers, baths, clothes-washers, etc) reductions in water use will also reduce wastewater flows. This would have a marked influence on the overall “anthropogenic” water turnover of the city.

Given that water end use is also the critical point of influence on water-related energy (refer to Objectives One and Two of this research) further consideration of the role of end use management in the overall water and energy balance of the city is highly warranted.

5.3.1. Other Benefits and Challenges of the Mass Balance Approach

Adopting a mass balance forced a definition of the “system boundary”. This in turn enabled a powerful cross-check of the overall accuracy of all urban water inputs, outputs and storage. Importantly, the mass balance quantified performance indicators for the city. This has high relevance to the design, management and evaluation of water flows through cities.

While the results are potentially only of specific relevance to western cities of similar land and water use patterns, and/or similar climates, the methodology could well be used to evaluate any human habitation at any scale including individual households or cluster developments. Evaluation and understanding of performance is an important step in designing improved future systems.

A potential disadvantage of the water mass balance approach is that it does require prescriptive tracking of water flows across the “boundary”. And city boundaries can change with time. Understanding and managing data in accordance with the “boundary” could create challenges for existing information management programs and reporting frameworks, because many are based on other geo-political entities such as local or state government. However, as the sophistication of our knowledge management systems has grown very rapidly over the last decade or so (including Geographic Information Systems), this disadvantage would not appear insurmountable. Conceptually, a mass balance could provide a city-wide framework for reporting and management of all urban water data.

5.3.2. Reflection and Possible Next Research Steps

The mass balance analysis undertaken could be improved by development of a MMFA model (refer to Section 5.1.2 above and Kenway *et al.* 2012). Further development of the system-boundary definition appears highly warranted. Ideally, this should include more detailed description of the role of water reuse and water network losses within and outside the boundary. Similarly, techniques to estimate or measure stored water in the city could help lead to a tighter measurement of change in stored water. This could drive further accuracy into the overall urban water balance.

Trans-city analysis established the accuracy of the overall balance and gave confidence in the results. Analysis over the performance of a particular city (or set of cities) over the course of time would seem highly worthwhile. Such analysis would help capture seasonal changes as well as the influence of urban growth and development, and related water use patterns.

With a tighter definition of the system boundary it is likely that greater accuracy of urban water models would be achieved. A tighter boundary would mean a smaller change in stored water and consequently, a smaller volumetric difference between (correct) total input and output flows.

In the longer term, the mass balance approach appears highly suitable as a framework on which “water-related” urban energy, nutrient and GHG balances could be built. Undertaking such work could progressively establish the full “water-related metabolism” of the city.

From a comprehensive “metabolic” water-energy-nutrient balance, much more could be learnt about overall urban performance. By carefully constructing and tracking such a balance over time, the influence of water policy and management could likely become far clearer. Ultimately, such a balance could underpin the “efficiency labelling” of cities. While such a concept has been in place for some time at the level of technologies, and now buildings, it has yet to emerge in a quantified way for our more complete urban systems.

5.4. Research and Action Priorities (Objective 4)

Objective 4 of this research aimed to identify and describe research priorities for managing water-related energy in cities. General major knowledge gaps were identified in Objective One (refer Kenway *et al.* 2011c). These major gaps include economic, social and institutional/legal dimensions of the water-energy nexus as well as understanding the connections in the industrial and commercial sectors. Collectively, these gaps could take a decade or more to substantially progress.

Research priorities more specific to water-energy links in cities are summarised in Section 4.4 and Kenway *et al.* In press (Accepted 12 December 2012). The benefit of the overall roadmap is that it helps to identify the potential staging of relevant studies necessary for water-energy nexus research and policy development.

At this point, the roadmap identifies the necessary research themes. Considerable more work is necessary to articulate the research questions embedded within in each theme. For example, development of integrated standards to achieve efficient “buildings”, rather than “appliances” would involve considerable systems and technology-focussed research. Similarly, planning and funding processes for water and energy systems, and their cities, would first require review of the relevant legislation and processes.

5.4.1. Reflection on the Method Used

The method used to define research, policy and implementation priorities could have been improved in a number of ways. For example, wider stakeholder involvement would likely have elicited a greater diversity of issues. Involvement from regulators, local government and not-for-profit groups would have strengthened the diversity of opinions. More time for discussions would bring out richer detail. Surveys of a larger group could help refine priorities and help identify sources of variability.

A different process, a different group, or undertaking the work at a different time or location, may also have led to different results. However, what is certain is that the process teased out much more clearly the need for significant and widely collaborative effort to better define and manage water-energy interactions.

5.5. Water-Energy Nexus and Urban Metabolism

The research also considered implications of the results across a number of the research objectives. For example, as articulated in Section 5.3.2, this research explores only a very small proportion of the potential application of the urban metabolism model. Even with this limited exploration, the model has been shown to create valuable context for decision making. It clearly demonstrates the need for our city and water planners to consider all flows of water and energy when implementing water strategies. This section explores the wider potential value of the metabolism framework in two areas. Firstly, it considers the potential for performance benchmarking, followed by consideration of its use for system optimisation.

5.5.1. Performance Benchmarking

Exploring the metaphor that “cities are organisms” opens wide theoretical and also practical possibilities. As a theoretical starting point, it could enable benchmarking of the efficiency of urban performance (or their components) with organisms. This could help us understand if the city was functioning as efficiently as natural systems shaped by the local environment and evolutionary pressure. Understanding of the relative efficiency of cities could give us some idea of the quantum of improvements that could be achieved. Such knowledge could contribute to the redesign of cities and their water systems, drawing inspiration from highly efficient natural systems. Some of this benchmarking is already happening, but at the “organ” level. For example, the performance efficiency of wastewater treatment plants has been compared with kidneys (on an energetic or salt removal basis) (Leslie 2009).

Metabolism also provides critical context for benchmarking. Understanding the water-energy nexus in the absence of a metabolic framework would be like trying to understand human health solely by observing sub-systems of the body (for example the cardio-vascular system), without any knowledge of what was happening to the body in question itself. Does it have a good diet? Is it running or sleeping? Considering urban metabolism simultaneously with the water-energy nexus provides critical context to our discovery and understanding of the relevance of the connections. Put another way, if urban metabolism measured the overall performance or “speed” of the urban system, the water-energy nexus could be thought of as the gearbox or wiring.

Indicators derived from a complete water, energy and nutrient, mass balance could potentially enable quantitative benchmarking of the resource-efficiency of the city. In the first instance, comparison of cities would be possible across a range of scales. In the longer term, it may be possible to quantify indicators that are equivalent to those used in physiological assessment of organisms. For example, considering water alone, we may be able to identify the equivalent of the “dehydration status” or “thirst” of a city, eg, based on its water consumption rates or volumes of stored water. If we add energy and nutrients into the picture, we may also be able to determine indicators such as the “metabolic rate” of the city. For practitioners interested in health and efficiency of the urban system such information could be more useful than knowing a footprint alone.

While there are many possible future pathways for material flow and metabolism research, Decker *et al.* (Decker *et al.* 2000) identify some sweeping goals. They suggest that understanding the energy and materials processes of urban systems is imperative for addressing the social, environmental and energy challenges of the next century. They conclude with a wide-reaching urban research agenda. It begins with: (i) correlating input and output variables to enable; (ii) predicting material and energy fluxes for arbitrary cities in a bio-geochemically useful way. From that, he suggests; (iii) development of a gridded, regional, time-dependent model to; (iv) demonstrate urban growth and evolution; (v) determine a set of state variables; and (vi) construct a biogeochemical theory of city composition and structure. Such models and data should be used to; (vii) quantitatively consider the earth system level climax state we appear to be approaching; and (viii) draw insight from wild ecosystems to help ensure the stability and persistence of urban ecosystems.

While this is both visionary and compelling, other authors have pointed out that correlations of complex systems, by themselves, do not help understand causal factors and relationships. For example, crime rates and ice-cream sales in cities could be correlated. However, correlation will not reveal that both are triggered by elevated temperatures.

Just like organisms, the internal processes of cities govern the rate of consumption and throughput of materials and energy (Decker *et al.* 2000). As pointed out by Baccini and Brunner (Baccini and Brunner 1991), systematic, quantified, cause-and-effect analysis is necessary to manage the social material and energy flux.

5.5.2. System Optimisation and Urban Design

This research has not sought to “optimise the system”. However, this goal could become increasingly important. Optimisation studies could example how a certain goal, say accommodating one million additional people, at a certain quality of life, with minimum water and energy inputs could be achieved. Optimisation studies could be undertaken at a range of scales: water/wastewater system, city, or nation.

A mass-balance defined boundary, consistently applied, could provide a reference point against which optimisation of resource flows (converting water, energy and nutrients into human well-being) could be achieved. Without a consistent boundary, it is likely harder to fully understand the energy implications of water management or other urban strategies. It would be impossible to know which factors offer the highest potential for influencing the system. Adoption of different boundaries could lead to inclusion or exclusion of very different sets of linkages and consequently analysis could reach very different conclusions. For example, if water-related energy in the “urban water cycle” is

considered with, or without, the energy implications of end-use, approximately 90% of the implication could be missed.

If our goal is total efficiency of resource use then urban metabolism is a highly useful way of thinking and analysis framework. What underpins sustainability of our society is the ability of our populations to keep accessing resources and improving the efficiency of “the system” in converting those resources into useful forms. Urban metabolism forces planners and managers to look at the overall efficiency.

A key future research question regarding urban metabolism relates to whether the concept will help identify favourable solutions to the design of future cities (and systems), with less effort than other existing methodologies. Can it identify better outcomes, say compared with other approaches?

5.6. The Emerging Landscape

Innovative cities could reduce water and energy use and GHG emissions by an order of magnitude. They could achieve this while simultaneously maintaining or improving ecosystem health and human well-being (eg, from Figure 2 to Figure 10). Enabling this change is a major challenge for society. Such a future is likely to require increased efficiency of cities. It is likely this will require increased recycling of water, materials and heat, at local and district/city levels. Enabling this landscape would require a truly multi-disciplinary effort spanning government, industry, research and community. Some of these challenges, including planning, funding, regulation, data management, target setting and reporting requirements are summarised in Table 3.

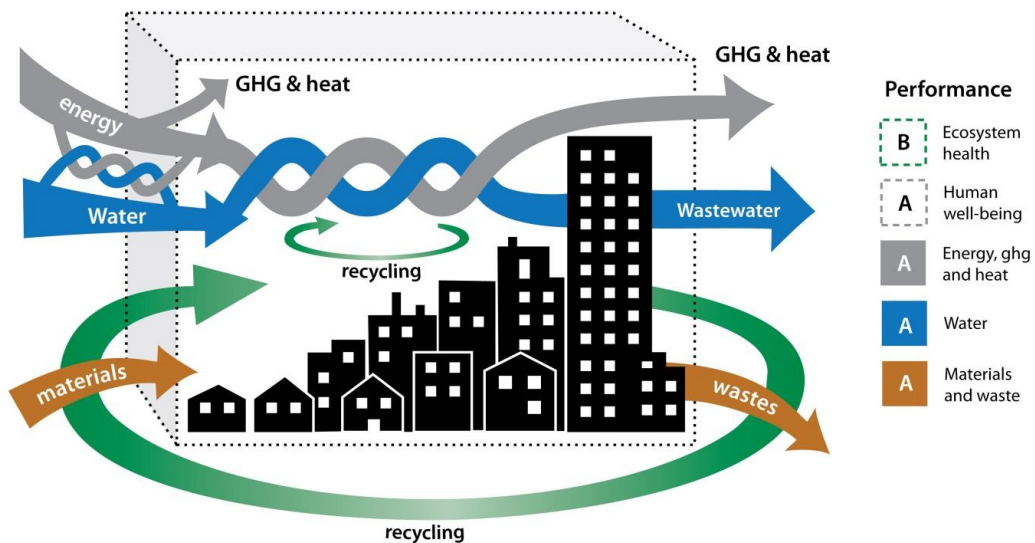


Figure 10. The future paradigm: co-ordinated performance in sustainable cities.

This research contends that the use of performance indicators to a common boundary will be important in enabling this transition. There is a need for a framework to help us understand “the city” including its flows of water, energy, GHG emissions, materials and waste. With such a framework, resultant methods and tools, we will be better able to systematically understand and manage the considerable influence of our cities.

Table 3. The emerging landscape of water-energy linkages.

Where We Are - 2010 (Figure 2)	Where We Are Going - 2030 (Figure 10)
Planning, funding, regulation and standards for water and energy are managed in isolation. Unplanned “trading” of water and energy impacts occur.	Comprehensive simultaneous consideration and management of water, energy and related cycles (including nutrients). Governance frameworks ensure “systemic efficiency” through planning and regulatory mechanisms (eg, regional planning and building approval processes).
Methodologies for assessing water and energy address only narrow component elements. The system boundary is either not considered or inconsistently applied.	Better informed decisions, enabled by comparison of options using standardised methods and boundaries will influence the total material and energy fluxes through cities.
Data sets and monitoring are scattered widely.	Coordinated and inter-locking data-sets and monitoring programs will enable diverse and powerful analysis and management of water and energy simultaneously. (This is the metabolic equivalent of a co-ordinated sensory system and single brain rather than scattered ganglia and sense-response systems.)
Unquantified indicators of urban performance or limited quantified performance indicators (such as ecological footprint) which give little policy guidance, particularly to the water sector; analysis frameworks inconsistently applied.	Quantified performance indicators which simultaneously consider water, energy and related flows underpinned by a metabolic framework and mass balances.
Optimisation analysis of the urban space for overall water and energy efficiency is totally absent.	Optimisation studies will contribute to or guide blueprints for urban futures (eg, Regional and City Plans). They will also strongly inform development assessment and building codes.
Targets for urban systems are missing or unquantified.	Quantified targets for the resource efficiency of cities. Government, industry and business function in a co-ordinated manner to achieve them.
Separate management and reporting of water and energy performance.	Co-ordinated reporting is used to evaluate the efficacy of urban design and management (including human well-being and ecosystem health).

5.7. Consideration of Future Scenarios

This section discusses some implications of various socio-economic and technological future possibilities. After considering these perspectives the conclusions of this research would remain unchanged.

5.7.1. Implications of Energy Technology Development

How would the importance of the water-energy nexus change if an emissions-free source of energy became rapidly available?

Clearly such a technology would, if connected to every water-related energy demand, reduce GHG emissions to negligible levels. However, considerable time would likely be necessary to implement such technology even if it were available today. Further, the cost of such technology could well be prohibitively expensive. Consequently, implementing available solutions now to reduce not only water use, but also related energy and GHG emissions, will at the very least buy us time to develop such technologies. Consequently, our understanding and management of the links between water and energy will be critical to optimisation of these limiting resources for considerable time to come.

5.7.2. Implications of more “Perfect” Market Forces

Could market forces solve the problem of rising energy use if all externalities (such as the impacts to local waterways due to water use or global changes associated with GHG emission) were incorporated into the price of water?

It seems possible that incorporation of all externalities into the price of water and energy would create more incentive for consumers to save water and energy. However, such a view is premised on at least two major assumptions: (i) complete and timely incorporation of all externality costs, and (ii) markets which function perfectly (that is, without distortion).

Clearly, changes in the price of water or energy will influence solutions. It could be a highly interesting economic (and behavioural) analysis to consider such changes and how they would affect the acceptability of solutions at household level and also at city-scale.

If individuals can afford to use water with wind-powered desalination to circumvent local water restrictions, then why should this not be possible?

While this question is difficult to answer in relation to a specific individual case, the collective picture offers some insight. Namely, should it be possible for the entire population to access unlimited energy to solve local water problems? Should we all be able to consume whatever amount of water or energy we choose? From a strong sustainability perspective this is clearly not possible, because there are limits to the supply of water, and we have a current energy constraint due to the implications of GHG emissions. From the collective perspective, local desalination is unlikely to represent the least-cost way of achieving a desired outcome even if it does meet the needs of individuals.

Are all forms of water interchangeable?

The trade-offs between types of water – and the associated energy penalty – raises a further issue of inter-changeability of the various forms of water (eg, centralised, decentralised and bottled). To compare the extremes of low-cost, low-energy centralised and high-cost, high-energy bottled water, perhaps many circumstances lead to individuals wanting bottled water to optimise convenience, quality and comfort. While this research makes no particular moral view on the use of bottled water, it seems likely that such behaviour would happen less often if the full implications and costs of carbon emissions were incorporated into the price of bottled water. It would also likely happen less if high quality centralised water is available and convenient to all, when and where it is needed.

5.8. Energy Accounting Inconsistencies

During the research, inconsistency was observed in national and international energy accounts. For example, major differences were observed in how transport energy was accounted for. The Australian Bureau of Statistics (ABS) (ABS 2011a) included energy for private transport as a component of “household” energy use. In contrast, the International Energy Agency (IEA 2010, 2011), and the Australian Bureau of Agriculture and Resource Economics (Commonwealth of Australia 2010) report all transport in an overall transport section.

Differences in accounting for energy transformation were also observed and embedded energy is not consistently handled. For example, the ABS energy account 2008-09 (ABS 2011a) cites a total energy use figure by directly adding primary and secondary energy consumption. In contrast, the International Energy Agency (IEA 2011, 2010) and Australian Bureau of Agriculture and Resource Economics (Commonwealth of Australia 2010) report on “total final (energy) consumption”. None of the organisations add the primary and secondary energy used by a particular sector (say industry) to identify the proportion of primary energy used by the sector (ie, by including the primary energy used to make electricity, but excluding the electricity used derived from that primary energy).

A consequence of this inconsistency is the great difficulty in deriving consistent percentages for the relative significance of sectoral or “water-related energy” as a component of total energy consumption. The ABS have acknowledged that adding primary and secondary energy is not ideal and are working towards a netted, rather than gross supply and use account, while still striving to meet international protocols for the System of Economic and Environmental Accounting (Lawson 2011).

6. CONCLUSIONS

6.1. Urban Water Management Influences Energy

This paper shows that water management significantly influences energy use and GHG emissions. It demonstrates that urban water-related management is either directly or indirectly responsible for 8% of total Australian GHG emissions. Of this, the *indirect* or “hidden” fraction of water-related energy in the urban environment is over 90%. Water end use in the residential, industrial and commercial sectors has strong influence on energy use. In contrast, the *direct* energy used by water utilities, while significant, is only a small, albeit rapidly growing, component.

If water management reduced one-ninth of the energy use *indirectly* affected by water management (for example in the conservation of hot water in households), the direct energy use of water utilities would be completely offset. Managing this indirect or “hidden” energy appears important to meeting Australia’s long-term GHG reduction goals. It could be important to finding least-cost water management solutions in cities.

This research has contributed a framework and method for quantifying water-related energy in cities. The developed method brings together disparate data to quantify water-energy linkages in an Australian urban context. It uses the framework to identify the significance of components of water-related energy.

Quantification of water-related energy in specific cities would be needed to make specific recommendations. This research will enable water and city planners, managers and regulators, to evaluate potential implications of a range of water strategies and options. A benchmarking effort comparing a range of Australian and/or international cities could be highly valuable. Analysis and comparison of cities over short or long-term time-periods could also be highly informative and help detect trends.

Further work is necessary to determine the influence of non-physical factors such as socio-economic and legal/institutional parameters in the system influencing water-related energy. The method developed here could also be further improved, and our knowledge deepened, through the development of a Mathematical Material Flow Analysis (MMFA) model. Such a model could help quantify key factors, sensitivities and uncertainties. It could also help identify key drivers and process and design scenarios targeted at city-wide reduction of water and related energy. The complex and confidential industrial and commercial sectors may present a challenge to such analysis and warrants specific attention. Scenario analysis to quantify the potential for water management to reduce energy use is also warranted.

6.2. Water Use in Households has Considerable Energy Implications

This research contributed the collaborative development and application of an MMFA model to characterise household water-related energy and associated GHG emissions and costs. The MMFA approach enabled this to be achieved without detailed monitoring and using only a relatively limited dataset. It demonstrated that 59% of energy use within a single household, was influenced by water use, even though the household was relatively water-conservative.

In the particular household evaluated, realistic and potential improvements in technology and behaviour could reduce water-related GHG emissions to less than 15% of baseline. Water use and costs of water and energy could also be substantially reduced. Identifying opportunities and overcoming constraints to implementation of solutions to reduce water and related energy use appears to be a major need in a future constrained by both water and carbon.

Some water-savings initiatives, such as installation of a water-efficient clothes-washer could increase GHG emissions, even if water use is reduced. This happened if the fuel source for heating water shifted from natural gas to coal-fired electricity within an appliance due to plumbing to a cold water intake only. Schemes which consider only saving water, may in fact exacerbate GHG emissions. Consequently, before rolling out subsidies for technologies (such as rainwater tanks or water-efficient clothes-washers) we first need to understand how the system is going to respond.

This research represents a first ever consideration of probability distribution functions, sensitivities and uncertainties of water-related energy at the scale of an individual household. It identified key parameters of influence. It also identified how uncertainties in parameters, expressed as (i) a single day, or (ii) an average day, contribute to different levels of uncertainty in the results.

A large part of the cost of individual water-using behaviours such as showering and clothes-washing is actually the energy cost in households. Consequently, cost-benefit analysis of water conservation should also include the saved energy. This may help water-efficiency programs compare more favourably other options including those focussed on supply augmentation.

The research provides a foundation for a systematic city-wide analysis based on multiple household types. The model developed in this work, has been structured to undertake such analysis. City-scale results would give managers detailed information on options available to manage water and water-related energy. Further development of the model is warranted including movement towards dynamic analysis. Ultimately, this could be used to understand and manage a range of transitioning strategies and issues such as peak energy loads.

Where this work goes further is in the understanding of factors influencing the system, including their probability distribution functions and their contribution to uncertainty in the results. Importantly, by tracking each flow, MMFA creates an ability to assess detailed alterations at sub-system level, for example including altered technologies, behaviours or environmental conditions. This information is anticipated to be critical for the design, planning and management of buildings and cities in a future, constrained simultaneously by water and energy.

6.3. Mass Balance Quantifies Flows and Performance

The third Objective involved a water mass balance (metabolic) analysis of four Australian cities in 2006-07 and demonstrated that urban water flows are not well known or accounted for. The water mass balance accounting identified a variety of unused water sources in cities, which were described as experiencing water crisis at the time.

The mass balance quantified major differences in the hydrological performance of the cities evaluated. This demonstrated major differences in: overall water balance (and data quality); water system centralisation; and rainfall, stormwater and wastewater potential to meet water supply needs. City water strategies recognise some of these flows as important future water resources and this chapter illustrates the related energy implications of their development. While it is theoretically possible that such water can be harvested using relatively low energy, schemes to date have typically not demonstrated this. Greater attention to the energy-efficient design of such systems, and cities, appears strongly warranted.

In order to undertake a mass balance calculation and a resource use comparison, a clear definition of the city “system boundary” was essential. This definition is a major difference between this work and most previous studies. Based on the (tight) adopted metropolitan boundary, mass balance enables the development of a structured equation suitable for quantifying all flows between “the environment” and “the city” in any city, at any scale. Importantly, this excluded water storages under the city, balancing storages of water outside the city, and natural flows of water (rivers and streams) running “through” cities. It shows how a powerful cross-check of all water flow data for any city is possible when a mass balance is used.

While the method of analysis highlighted major differences between the cities studied, only results from a single year are available. Further studies through time and capturing a range of climatic conditions are necessary to draw definitive conclusions. Detailed mathematical modelling – ideally with a spatial component – could be useful for identifying key factors of influence, sensitivities and uncertainties. The water mass balance appears to provide a foundation upon which other water-related balances, including water-related energy and GHG emissions, could be based.

6.4. Water-Related Energy Research and Policy Development

The fourth objective of this research contributed a roadmap to assist the systematic research, policy formulation, and management of water-related energy in cities. Broad knowledge gaps include economic, social and institutional/legal dimensions of the water-energy nexus as well as understanding of the connections in the industrial and commercial sectors.

An international workshop convened in California identified necessary action, research and policy development necessary for successful combined management of urban water and related energy. Four priorities are: (i) combined water and energy standards, guidelines, funding and efficiency planning, (ii) development of water-energy educational programs, (iii) improved methods to quantify and track water-related energy targets, and (iv) improved understanding and management of factors motivating consumers in regard to their consumption of water and related energy. Section 4.4 and Kenway *et al.* In press (Accepted 12 December 2012) contain further details. While these priorities were identified in, and hence could be California-oriented, it seems likely that they apply to cities with similar socio-technological regimes.

Collaboration across sectors and institutions is anticipated to be essential in making progress. A coordinated research effort could enable many component pieces of information to be united and help a collective picture to progressively emerge.

Because this research is focussed on cities, the research priorities identified here would seem more likely to contribute to urban design. Other efforts to characterise research priorities, identify some similar elements, however, they are typically broader and address national-scale issues. Alternatively, they are narrower and focus on water conservation efforts alone.

The method used for development of the roadmap was well supported by workshop participants. The workshop and on-line survey method used could offer a model for the development of other roadmaps relating to complex, multi-disciplinary issues.

Should a longer term water, energy, or economic (or combined) crisis emerge, having undertaken relevant research and development would help all involved respond far more quickly and effectively. Policy based on solid evidence is likely to be far more effective than decision-making on the run. The time for implementing such research is well ahead of any expected crisis.

6.5. Conclusions from the Integration of Water-Energy Approaches

This research collectively provides a number of methods capable of improving knowledge of water-related energy in cities from a macro to a micro scale.

Objective 1 has provided an overall assessment to identify major components of water-related energy in cities. It demonstrates the significance of water-related energy in Australian Cities.

Objective 2 explains a mathematical technique to detail specific areas, in this case for households. It applies this to a single household to show how 59% of the energy use of the household is influenced by water choices.

Objective 3 demonstrates how to improve our knowledge of the water balance of cities. It also shows how this could help improve understanding of water-related energy can be in future.

Finally, Objective 4 develops a future-oriented road map for management and policy development regarding water-related energy in cities.

Quantification of water-related energy is likely to support better management of both water and energy in cities. It is relevant to water and urban planners alike. Such knowledge is arguably the key for designing water- and energy-efficient cities, and buildings. Quantification of performance of the “city system” is vital if we seek to solve problems, rather than move them around.

The detailed understanding of cause-and-effect relationships enabled through MMFA provides understanding on the relevant levers of performance. While, at this stage, this has only been conducted for a single household, there is the potential to extend the MMFA approach to cover all water-related energy. It could also be extended to address all urban water flows such that the overall “water metabolism” of the city is understood, systematically monitored, and managed.

Only a small fraction of the potential of the urban metabolism model was assessed in this research. The use of a mass balance approach offered a significant analytical and practical value for understanding and managing urban water. The concept of urban metabolism appears to provide a conceptual and analytical basis against which investigation of the water-energy nexus in cities could have far greater rigour and quantification.

Wider use, understanding, and reporting of urban metabolism would be highly beneficial to the future of urban water and energy management. It could change how we think about our cities. We could view our cities as sources of water, and we could view our water as part of the solution to the energy and GHG emissions problem. Such thinking could lead to considerable changes in the physical and institutional structures. As pointed out by Abel Wolman in 1965, there is no shortage of water or energy, however, finding appropriate solutions for better management and balance requires long-term thinking.

APPENDIX - Literature Review

Background Context

This research focuses on water-energy interconnections in cities. It also considers the use of urban metabolism theory, with particular attention to the water balance. Particular effort is taken to describe existing methods, and their strengths and weaknesses.

This research does not specifically address whether we have a problem or set of problems such as climate change. This is assumed. Rather, the research addresses application of a conceptual model and its component approaches. It uses this application to identify potential research insight for cities and households.

Taking a fresh look at these areas was considered important because there appears a glaring need to improve the performance metrics of our cities, particularly with regard to water and its influence on energy. While this would appear to have significant implications for urban (and consequently national) management, these implications were not a particular focus of this research. Rather, the attention was on improved quantification. With better analysis tools, methods and data, it was hoped that the political implications would be more likely to enable appropriate responses.

Why Study the Water-Energy Nexus?

You think that because you understand “one” that you must therefore understand “two” because one and one make two. But you forget that you must also understand “and” (Sufi teaching in Meadows (2007)).

There are many compelling economic and political drivers for our increased understanding and management of the water-energy nexus. The World Business Council has declared “To find sustainable solutions (to global natural resources problems) we must ensure that we address water, energy and climate change in a wholistic way. It is not practical to look at them in isolation. When you have an energy problem, you have a water problem and vice versa” (WBCSD 2009).

There is a growing realisation that managing water, energy and carbon, and their connections, is vital to economic success. Water and energy are not only connected; they are colliding. Shortages of water are impacting on energy production potential and pricing in the USA, Asia, Europe and elsewhere (Hightower and Pierce 2008). New water supplies require more energy. Increased energy supplies will require more water.

The Sandia National Laboratories notes that “The continued security and economic health of the United States depends on a sustainable supply of both energy and water. These two critical resources are inextricably and reciprocally linked” (United States National Laboratories c2008).

The economic relevance of water-energy interconnections is taken further by Richard L. Stanley, Vice President, Engineering Division, General Electric, at the 9 July 2009 hearing of the United States Congress and the Department of Energy House Science and Technology Subcommittee on Energy and Environment: “It could be said our economy runs on water”. He went on to say that “the nexus between power generation and water usage is one of the world’s most complex and critical public policy challenges”.

Goldstein, *et al* report that the Southwest of the United States is particularly vulnerable with regard to the water-energy nexus. They observed that “if scarce water resources continue to be utilised beyond their natural recharge rates, and innovative approaches for the integrated use of water and energy are not implemented, the semi-arid regions of the United States may be economically constrained and environmentally degraded, with potentially severe impacts to the social fabric” (Goldstein *et al.* 2008).

Considerably more global political attention is being given to the issue in part because water is a major avenue for climate change impacts. The water-energy nexus appeared on agendas of the G8 Environment Ministers meetings in 2007 and 2012, and many other high level international meetings.⁷

However, despite the prominence, water strategies and policies currently largely ignore energy issues (Marsh 2008). At best, the direct implications are considered. Similarly, energy policy and strategy is typically silent on water issues. For example, the international energy outlook prepared by the United States Department of Energy (Department of Energy 2011) only very superficially addresses the associated water consequences; there is no quantification of necessary consumptive amounts, or the availability of such water. Likewise, water-related impacts are hardly mentioned.

I believe knowledge of the links between water and energy in both the production and consumption of water is necessary for us to optimise the use of, and the impacts of using, these resources. The efficiency of cities is critical in this regard, because cities are focal points of resource flows. Significant quantities of water, materials and energy pass *directly* through our cities as energy, water and materials. Even more significant quantities pass through *indirectly* embedded in food and products (eg, “virtual” water). With regard to these quantities, our performance and reporting systems have virtually no information. With no information, it is exceedingly difficult to know if our strategies and plans are improving the overall efficiency of the city.

The Water-Energy Nexus and Related Carbon and Nutrient Cycles

Even though the “water-energy nexus” is widely discussed, it is poorly defined. This research considers the water-energy nexus to represent the “interconnections” or “cause-and-effect” relationships between water and energy. When there is a connection, a change in one leads to a change in another (eg, more water requires more energy which requires more water). Alternatively, a change in a third factor causes a change in both water and energy use. For example, increased food production or consumption, means increases to both water and energy use.

Because water and energy pervade every aspect of ecosystems, human systems and economic activity, the connections between water and energy are everywhere.

There is a frequently described relationship between water, energy, carbon, and climate: the ‘WECC nexus’ (e.g. Proust *et al.* 2007). The classic example, the Australian drought situation from 2002-2007, is that a drying climate may reduce available water supplies and increase water demand. This can lead to an increase in energy required to provide the water. The additional energy use, can, if not offset, contribute to more GHG emissions and thereby accelerate climate change. The increased energy demand can also create demand for water for cooling energy plants (McMahon and Price 2011).

A less regularly articulated connection also exists between water, energy and nutrients. For example, industrial processes consume energy to manufacture nutrient fertiliser. Food production in agriculture requires water, nutrients and energy (eg, for pumping water). The influence of urban water on the nutrient cycle has been known for some time. In 1840, the pioneering German chemist Justus Liebig wrote to the British Prime Minister regarding the proposed introduction of the closet toilet. His concern was that flushing nutrients into the sea, rather than collection and reuse, would lead to soil nutrient impoverishment and consequential plant productivity decline and the need for (energy-intensive) fertiliser replacements (O'Meara 1999). Barles (2007) analysed the trend of nitrogen flows through Paris. In 1913, 40% of the nitrogen in food inflows to Paris flowed back to agriculture as valued fertiliser. Barles showed how increased residential water use, and the wider use of sewage systems, led to increased liquefaction of organic wastes rendering it too wet to economically reuse. This contributed to a subsequent rise in the dependence on synthetic fertiliser.

⁷ This includes the United Nations meeting in Bali, 2007, the World Economic Forum in Davos, 2008 and various high-level water conferences including World Water Week in Stockholm, 2008, International River Symposium in Brisbane, 2008, UNESCO Water and Energy Nexus Symposium in Paris, 2008, and the 5th World Water Forum in Istanbul, 2009, and the inaugural World Congress on Water-Energy-Carbon (Dublin 2012).

More recently, energy has also been invested to remove nutrients from wastewater in order to protect receiving environments.

Humans have tapped into the energy flows to manage water and nutrients (food) as part of the civilisation process. Herbert Spencer (1862/1880) stated in his “First Principles” that “societal progress is based on energy surplus. First, it enables social growth and thereby social differentiation. Second, it provides room for cultural activities beyond basic vital needs”.

It would be an enormous challenge to research and understand the myriad of water-energy-nutrient-carbon links because the connections are vast, and many are unquantified and ever-changing. However, recognising the relevance of these interconnections with water, and developing a structure within which to identify where the boundaries of the water-energy nexus start and finish in relation to these other cycles, will help provide context for the results of research focussed on water and energy. Approximation of the influence of the other cycles will help give confidence that the conclusions remain valid if wider linkages or an alternative perspective were also considered. It is anticipated that the urban “system boundary”, important for metabolic analysis, will provide support in this regard.

Previous Studies of Water-Energy Links

Research on various aspects of the water-energy nexus has been undertaken in several countries. In the United States, energy shortages have fostered a number of studies analysing the water-energy relationship (Gleick 1994; Gleick and Cooley 2009; Cohen *et al.* 2004; Klein *et al.* 2005; Lofman *et al.* 2002; Stokes and Horvath 2006). Research in California has been considerable, partly because significant energy is invested in moving water throughout that State, and in part due to an energy crisis which unfolded in 2001 (Marsh 2008).

Much of the work in the United States has been led by the energy sector including the Californian Energy Commission (Public Interest Energy Research (PIER) Program) and the Electric Power Research Institute (EPRI).

Australia has also been very active in water-energy nexus research (Refer (Kenway *et al.* 2011c) and Chapter 2). In contrast to the United States however, the motivator appears to be either (i) water shortages leading to energy shortages, or (ii) a desire to minimise environmental impact of water management in response to perceived climate change impacts.

Kenway *et al.* (2011c) summarises a review of international literature on the water-energy nexus taking a broader perspective. It classifies the research by objective, dimension and scale. The analysis identifies both the focus of research to date as well as the many knowledge gaps. Major gaps include our understanding of (i) energy-water connections in the industrial and commercial sectors, and (ii) the influence of economics, social and political/legal/institutional factors. These omissions are substantial considering the wide influence of the industrial and commercial sector, and the strong importance of economics, human behaviour and political/legal issues to our management of water and energy.

The review also identified a number of important recurrent and emerging themes. These include the need for water-energy sector collaboration, the potential for combined governance frameworks in water and energy, and the potential of urban metabolism as a guiding theoretical and analytical framework.

The lack of a unifying framework has meant that an enormous diversity of research approaches have been undertaken, with no particular consistency. This means that comparability across studies is virtually impossible. The quality or depth of the research also varies. Many studies are qualitative in their analysis of cause-and effect, or deal with average conditions only. Very few have made the step to understand the sensitivities of the system or the uncertainties.

The absence of studies analysing the influence of time was another surprise. Consideration of time could help establish whether the connections between water and energy are changing over decades, eg, as cities grow or water sources change. It could also help identify how changes, through a 24 hour cycle contributes to peak demands in energy loads.

Quantification of Water-Energy Interconnections

Klein, *et al* (2005) conducted a startling and well-cited analysis of the water-energy relationship: 19% of California's electricity, and 32% of California's natural gas use was related to water provision and use. In Klein's analysis, cities comprised the dominant portion of the effect accounting for 15% of electricity and 31.4% of natural gas use (see (Kenway *et al*. In press (Accepted 12 December 2012))). Agriculture accounted for 4.2% and 0.1% of the electricity and natural gas use respectively.

More recently, Wolff and Wilkinson (Wolff and Wilkinson 2011) separately estimated California's water-related energy as comprising 20% of the States' electricity use and 10% of its natural gas use. Wolff and Wilkinson indicate that the 32% cited by Klein, represented the use of natural gas for all other purposes other than electricity generation. They (Wolff and Wilkinson 2011) state that Klein's 32% is equivalent to about 18% of California's total natural gas consumption. Heede (1995), in deMonsabert (1998), noted the financial significance of water-energy connections in homes: in the United States alone, over USD \$15 billion was spent on residential water heating.

In apparent contrast to Klein's work, Kenway (2008b) identified that in Australia, urban water provision and residential water heating consumed 0.2% and 1.2% respectively of "urban systems energy". In Kenway's work, urban systems energy was measured as the pro-rata proportion of total state primary energy use including all stationary and non-stationary fuels (eg, coal, diesel, petrol, natural gas, hydropower). However, a limitation of this analysis is that it compares end-use of energy such as electricity consumption (the numerator) with total primary energy use (the denominator). This underestimates the proportion of primary energy use because thermal electricity generation requires approximately three units of primary energy (largely coal) to create and distribute one unit of electrical energy to end users (Gleick and Cooley 2009; IEA 2011). The scope of Kenway's work also covered only a fraction of the water-energy inter-linkages addressed by Klein.

Additional differences in the Californian and Australian results are likely to be attributable to differences in water use and the energy-intensity of water supply. For example, while indoor water use in Australia was estimated at around 170 litres per capita (person) per day (L/(cap*d)), the Californian estimate was approximately 230 L/(cap*d) (Klein *et al*. 2005). Similarly, total residential water use in California (372 L/(cap*d)) was higher than Australia (230 L/(cap*d)).

Water provision in California also takes more energy per unit of volume, due to longer pumping distances and elevation. Electricity use for water supply in California is 1.1-3.3⁸ kilowatt hours per cubic meter of water (kWh) /m³) for Northern and Southern California respectively. Water supply systems servicing Australian capital cities averaged around 0.8 kWh/m³ (Kenway *et al*. 2008b) in 2006-07.

Klein's residential estimate included water use for showers, taps, dish and clothes-washing, toilets, landscape irrigation, chilled water, ice making, and swimming pools and spas. Residential energy uses related to these activities included water filtering, softening, heating, hot water circulation loops, icemakers and chilled water systems, and groundwater pumping of private wells.

Commercial water-related electricity and natural gas use reported by Klein *et al* (2005), was dominated by water cooling and heating. Industrial water-related energy was largest in the publishing and broadcasting, printing, petroleum refining, non-metallic mineral product manufacturing and food production sectors. Comparable Australian data have not been identified. Kenway *et al* (2011c) identifies that a relatively sparse group of studies have undertaken research on the connections

⁸ Equal to 4,000-12,700 kWh/million gallons.

between water and energy in the industrial and commercial sectors. It also identifies this as a major gap considering the significance of the interconnections. The lack of detailed studies may be due to issues of complexity and non-uniformity of process (every industrial site is different), and also commercial sensitivities of the data.

What is clear is that considerable energy is consumed when water is provided and consumed. What is also clear is that improved methods will help with comparisons. Wolff and Wilkinson (Wolff and Wilkinson 2011) reinforce this point. They indicate that while their estimate is similar to Kleins', differences in the methodology are significant and "the apparently close match...should not be taken too seriously". In particular, Wolff and Wilkinson flag that there are numerous differences in the natural gas estimates that would move the numbers apart rather than closer.

History of the Water-Energy Nexus

The development of the water-energy nexus has a long history and is founded in our socio-economic and technological regimes. In a rare historical narrative, Marsh (Marsh 2008) evaluates the development of the water-energy nexus in the context of the Australian State of New South Wales. Adopting a focal point of water and energy infrastructure (rather than water use), she identifies how the development of the energy sector in Australia has been crucial for the development of the water sector in its current form: their histories are intertwined.

Marsh points out that Australia's adoption of technologies (steam and later electricity-driven motors) and institutional models, largely from the United Kingdom, and later the United States, have shaped the water-energy interconnection in Australia. For example, subsidies for major water and energy infrastructure projects in the mid 20th Century were not only socially and politically acceptable but considered critical to national development. Marsh notes that this infrastructure, which extends well beyond local or municipal boundaries, has shaped Australia's modern cities. Marsh (Marsh 2008) also articulates how reforms instigated by the Federal Government through the Council of Australian Governments (COAG) in the latter 20th Century brought about an interstate trade of energy and water via the National Energy and Rural Water Markets respectively. Marsh concludes with the open-ended observation that in the current era water and energy sectors are expected to make cost-effective decisions regarding infrastructure development. She observes that a current major driving force for these decisions is the market mechanism under economic rationalist theory. Little information appears to exist on historical development of the water-energy nexus in other nations, or within cities.

The Need to Focus on Energy-Related GHG Emissions

Many previous water-energy nexus studies only consider energy-related GHG emissions (e.g. Cohen *et al.* 2004; Kenway *et al.* 2008b). Diffuse or fugitive emissions are largely ignored. Knowledge of water-related energy use will help characterise a substantial portion of all water-related GHG emissions, however, other sources exist.

Focussing on energy use and related emissions is arguably more relevant to urban and water planning in the context of sustainable cities. This is because urban and water system design, have major and interconnecting influences on energy use. In Australia, electricity from coal-fired plants is the predominant source of energy (Kenway *et al.* 2008b). Consequently, reducing energy use will have a significant impact on GHG emissions.

Management of total water-related GHG emissions would also need to include fugitive emissions associated with water systems. There is a wide set of fugitive emissions. For example, diffuse emissions from methane releases from flooded vegetation in water storages (Lofman *et al.* 2002) or methane and nitrous oxide emissions from sewers and wastewater treatment plants. The physical, chemical and biological processes that drive GHG emissions in urban water are anticipated to be different to those that are driving energy use. For example, treatment plant design and management is a major factor influencing GHG emissions at treatment plants (De Haas *et al.* 2008).

Lane *et al* (2009) also noted that some decentralised systems, such as septic tanks, use low energy, but may produce significant GHG emissions. While this appears potentially a significant issue for decentralised systems, the vast majority of water supply and wastewater in Australian cities is within large centralised systems.

Consequently, this research focuses on energy-related GHG emissions. Similarly, this research is focussed on operational, rather than life-cycle energy use. This is because many studies have demonstrated that operational energy use dominates energy use through the water cycle (Stokes and Horvath 2006; Stokes and Horvath 2009). This is particularly the case for centralised water systems which dominate our current cities.

Methodologies to Quantify Water-Energy Links

Diverse methods have been used to understand aspects of the water-energy nexus (see (Kenway *et al.* 2011c)). Three main approaches stand out as highly relevant given the goal of this research to quantify linkages in cities: (i) mechanistic modelling with or without monitoring, (ii) input-output (IO) modelling, and (iii) life cycle analysis (LCA). These are all mathematical modelling approaches.

These are discussed below to clarify their existing features and uses, and to form the basis for the methodology selected for this research.

Mathematical Modelling

Mathematical models have advantages which include: (i) enabling investigators to organise their theoretical beliefs and observations, (ii) expedite the analysis, (iii) test system modifications, and (iv) analysis is generally less costly than observing the system (Fishman 1996).

In addition to quantitative methods, a range of qualitative methods have also been used to understand or describe water-energy interconnections. For example, Proust *et al* (2007) summarised the meta-policy environment surrounding the water-energy nexus. Marsh (Marsh 2008) undertook a historical survey of the nexus development in New South Wales. Structured interviews and literature review have been used by Cammerman (2009), as have case studies by Retamal (2009b). Qualitative methods may help illuminate many sources of influence including suspected physical, social, legal or economic factors affecting trends and behaviour.

In order to simulate changes, to establish performance, to determine key factors in complex systems, or to understand confidence limits, quantitative approaches are necessary. Quantified understanding of the cause-and-effect chain of water and energy is needed to identify how systems will behave into the future. Quantified understanding is essential, rather than correlation alone, particularly when non-linear responses can be triggered (Meadows 2007).

A range of quantitative tools such as elasticity analysis, and supply-based pricing have also been used to evaluate economic dimensions of the water-energy nexus. These are not reviewed here as this research focuses on quantification of physical water-energy connections. The exception is that IO modelling is considered because it has been used to study a wide range of indirect connections of physical resources within economies. Optimisation approaches were also excluded because knowledge in this area is so preliminary and the objective-functions (optimisation criteria) relevant in a system, as complex as a city, have not yet emerged.

Mechanistic Modelling

Many variations of mechanistic models have been used to quantify water-energy interrelationships. Most are deterministic, meaning that the model always produces the same output for a given input. Mechanistic modelling has been typically supported by various degrees of monitoring and data mining.

Mechanistic models express the cause-and-effect relationship for certain processes or a system as mathematical equations. The models, in principle, reflect our understanding of how the system works. They are also based on certain accounting or physical principles, or laws such as conservation of mass, energy and momentum (Aral 2010).

In 1998, deMonsabert (deMonsabert and Liner 1998) used mechanistic modelling to quantify the impact of water conservation on energy savings in United States government facilities. The WATERGY model developed used algorithms derived from published studies and appliance data. DeMonsabert's contribution was to identify key facility-scale factors affecting direct water, and a number of indirect energy, savings. For example, these included water savings from toilets and urinals, taps, showers and baths, clothes-washers and dishwashers. Energy savings in the facility⁹ were calculated including conservation of boiler water use. Utility savings were also determined. DeMonsabert noted that the complexity of each individual facility made generalisation problematic. Using a "hypothetical" facility she identified major energy savings from installing water-efficient shower heads, taps, and reduced boiler wastewater (blowdown).

In 2002, Cheng (2002) modelled energy use through the residential water cycle, including household pumps used to pressurise water for delivery in high rise buildings. Limited monitoring was also undertaken. Cheng unitised all energy use per unit of water delivered to the apartment studied. This approach identified that pumps contribute relatively little to the energy in the urban water cycle (0.14 kWh/m³ of 6.5 kWh/m³ (water supplied)). However, water heating in showers (4.74 kWh/m³ (water supplied))¹⁰ used far more energy.

Two studies led by Retamal (2009a; 2009b) identified the relatively high energy use of rainwater tank pumps (per cubic meter (m³) supply) as an emerging issue. She used mechanistic modelling together with detailed monitoring to understand likely rainwater tank pump energy use.

Flower (2009) used mechanistic modelling and data mining to characterise water-related energy in three average (hypothetical) houses with different hot water systems. Critical parameters in his analysis included the frequency and duration of various events (eg, cycles/household/day or events/persons/day) coupled with water and energy usage patterns. Flower compared baseline conditions and alternative scenarios at city-scale.

Beal *et al* (2008) undertook detailed monitoring of water and energy in six households. The work established the "metabolism" of an "ecosensitive" development in Brisbane, Queensland. Results were benchmarked with a local suburb (The Gap), the council area (Brisbane City) and the Australian average. The work gave insight into household-scale water and energy flows. However, the particular development studied could be described as "green" or "cutting edge" and is consequently not representative of mainstream households in Australia and hence not scalable to understand trends in existing cities.

Baccini and Brunner (Baccini and Brunner 1991) point out that in order to understand the material, water and energy fluxes of societies (the metabolism), it is necessary to undertake systematic and quantified analysis of the material flows around activities, goods and processes.

A range of decision-support systems have been used to understand water-energy linkages. One of the more detailed approaches is Material Flow analysis (MFA) which has been used for a number of environmental problem-solving approaches. In the 1990's MFA has been extended with modelling concepts in order to simulate flows of matter influenced by anthropogenic activities (Bader and Scheidegger 2012), resulting in Mathematical MFA (MMFA). However, to date MFA has not been used to understand water-energy interconnections within households. Similarly, no existing models

⁹ DeMonsabert considered direct savings to be at the facility and indirect savings to be at the utility. This language is a reversal of that used in this thesis, which considers the direct implications at utilities.

¹⁰ Actual energy requirements for heating water used in the shower was 26 kWh/m³, however, Cheng converted this to the equivalent energy use per unit of water delivered to the household to enable more ready benchmarking with the water supply and wastewater system energy intensity.

used for analysis of water-energy links appeared to have in-built processes to identify sensitivities (key factors) or uncertainties linkages (Conrad *et al.* 2011). As the tool SIMBOX had been used to evaluate both water and energy-related questions, and contained in-built sensitivity and uncertainty analysis capability (Baccini and Bader 1990), it appeared a highly desirable approach for this research.

Input-Output Modelling

IO analysis is an approach used to understand the overall economy, its sectors, and their interdependencies. Historically, IO has been used to assess financial data using monetary flows. Recently, many more applications have been developed including analysis of water and energy flows through the economy (Wiedmann 2009). The foundations of IO analysis stem back to the 18th Century, however its current form, including the addition of environmental and resource accounts, has been shaped by Wassily Leontief (Foran *et al.* 2005). Increasingly, IO is being used to assess multi-regions (MR), leading to development of MRIO methods. The methodology lends itself well to examining links between water, electricity and the wider economy (Marsh 2008).

Foran *et al.* (Foran *et al.* 2005; Foran *et al.* c 2004) articulate how financial IO tables can be used with the System of National Accounts (1993) (United Nations 2003) developed by the United Nations to understand the flow of resources, and environmental impacts in the economy. The materials intensity of each sector of the economy (including its supply paths) can be determined. The method reveals a diversity of impacts through the supply chain of services and products. The approach can identify indirect (embodied) water and energy used indirectly when various goods and services are consumed. IO analysis appears to have wide policy implications (Daniels *et al.* In Press Accepted November 2011).

Lenzen (2008) used IO to link Australian Water Accounts and national (financial) accounts to show direct and total (indirect plus direct) water flows through the entire Victorian economy. IO has also been used to identify the direct and indirect water (or energy) flows embedded in the products from each sector of the economy and between nations (Wiedmann 2009). For example, Lenzen (Lenzen *et al.* 2010) demonstrated that the carbon footprint of the United Kingdom has been increasing due to outsourcing of “dirty production¹¹” to China.

IO modelling overcomes two key disadvantages of most other methods. Firstly, it is scalable. IO can be used to track individual products, businesses, or entire national or even global economies (Foran *et al.* 2005). Secondly, and probably more importantly, it is flexible with regard to the system boundary through the supply chain. Consequently, analysis of indirect effects associated with the consumption of goods, or use of services, which occur through the supply chain, are readily undertaken. However, a limitation of IO computations is that the relationships developed can often not be generalised to other conditions because mechanistic relationships have not been established.

IO approaches appear philosophically consistent with the theory of urban metabolism because both are focussed on inputs and outputs to discrete entities/sectors. Consequently, it appears to have high value to the proposed research topic. However, in practice IO data is typically so high level (eg, say 30-100 sectors of a state or national economy), it may be difficult to use the approach other than an overall screening assessment and general characterisation. While IO methods appear very well suited to analysis of the water-energy nexus there has been only one study by Marsh (Marsh 2008) which used it for this purpose, and that had a focus on the state of New South Wales, rather than individual cities.

Direct and Indirect Energy and Water Flows

The preceding text shows that depending on the perspective, different linkages between water and energy are apparent. For example, energy is used by water providers (at different rates from different sources) to provide water to end users. End users consume energy at different rates when water is

¹¹ Eg, production with higher levels of waste such as carbon-dioxide emissions per unit of product.

consumed. When products move from agriculture to other sectors, or from industry and commerce to residential consumers, embedded or virtual water and energy also flows to the consumer.

Proust *et al* (2007) identify that significant energy can be embodied in the supply chain of goods and services such as food. Water and energy impacts in other “production layers” (eg, the second or third layer) can be order-of-magnitude greater than the energy or water directly consumed.

If, the goal is to reduce the consumption of water and energy in the provision of water, a particular set of links and solutions will emerge. However, if the goal is to reduce the consumption of water and energy for a region or nation, then a different set of linkages may be relevant. Adopting the perspective of the end-user or final consumer is perhaps the most complex (and powerful) because many of the linkages end up flowing to this point. Considering only the linkages in the “provision” or “production” of water and energy perspective misses much of the picture.

Life Cycle Analysis

LCA is another tool commonly used to understand the water-energy nexus in the delivery of particular products or services. LCA is an environmental management tool for identifying and comparing the “cradle to grave” environmental impacts of the creation, marketing, transport, distribution, operation and disposal of human artefacts. This wholistic approach considers direct and ideally related processes including hidden or “non-market” flows of raw materials and intermediate inputs, waste and other material, and energy outputs associated with the system (Daniels 2002 citing Guinee).

Daniels (Daniels 2002) suggests that the primary objective of LCA is to create relative comparisons of the potential environmental harm of alternative human “artefacts” and “specified services”. However, he also points out that once the overarching goal shifts to the sustainability implications of specific material (including water) or energy flows, then MFA will be required to place the results into a real regional context. The LCA procedure typically involves a comparison of a small number of substitutable products assumed to provide a similar consumption service (Stokes and Horvath 2006).

Two major forms of LCA exist: (i) process-based (eg, using the ISO14040 Standard), and (ii) IO-based. Process based LCA involves iterative steps: (i) goal and scope definition (including system boundary definition), (ii) inventory analysis, (iii) impact analysis, and (iv) improvement analysis. IO-based LCA use financial data (see also 0), often with environmental extensions, to understand flows and impacts of various activities, or developments, through the economy.

More recently, a third or hybrid LCA approach has also been used. Stokes and Horvath (2006) combined national IO data with resource consumption, emissions and waste data, to model direct and supply-chain linkages relating to alternative centralised urban water service provision options in California. Stokes and Horvath (2006) argued this minimised time and data requirements for analysis. Process based LCA was used to assess the environmental effects of system construction and operation. They are also flexible to use in common software (such as Microsoft Excel) and to undertake sensitivity analysis (Stokes and Horvath 2006). Hybrid LCA methods have not yet been standardised.

Daniels and McBean (2009) observed that LCA techniques are one of the few, if not the only, material and energy flow analysis methods governed by standards (eg, ISO14040). No current internationally recognised standard exists for related analysis approaches such as Material and Substance Flow Analysis, Water Footprint Analysis or Virtual Water Accounting.

Several LCA investigations have identified that the operational phase of water systems uses make up the vast bulk of energy when the full life cycle is considered. For example, Grant *et al* (Grant *et al*. 2006) analysed the LCA performance of rainwater tank systems (including their pumps) and compared this with the centralised water system. He noted that “capital infrastructure, while not insignificant, is much less important than operational impacts for most environmental indicators”. In an analysis of imported, desalinated and recycled water options for California, Stokes and Horvath (2009) point out that over 90% of energy consumption is in the operational phase. Flower (Flower 2009) addresses this

very issue and concludes that in water systems, “operational” issues, particularly end-use, justifies analysis rather than life cycle impacts.

Mithraratne *et al* (2006) use LCA to show that the design of a water supply system can have a big influence on the life-cycle energy consumption, particularly for small scale or decentralised systems. They demonstrated that water supply operational energy can vary from 65% (Auckland, New Zealand, reticulated supply) to 12% (plastic rainwater tank). However, as centralised water systems dominate the water system within most large cities, and as for these systems operational energy comprises the bulk of energy use (Stokes and Horvath 2009; Stokes and Horvath 2006), attention to operational energy use appears warranted.

Kenway *et al* (2008b) notes the substantial influence that site-specific conditions can have on energy use. For example, Melbourne uses very little energy for its water supply treatment and pumping (< 0.5 GJ/ML) because the supply primarily drains from elevated protected catchments. In contrast, Sydney, Perth and Adelaide used 3.0-6.0 GJ/ML (in 2006-07) primarily due to the need to pump water long distances or heights or treat more marginal quality waters. The energy consumed for water supply can range widely varying from 10-80% of the total energy to supply, treat and distribute water depending on the source (Stokes and Horvath 2009).

The dominance of operational energy and the major impact of local sources in water management appear to be significant to the relevance of LCA approaches. It means that global, or even national-level, averages have relatively little meaning. Because operational energy dominates the life-cycle impact of water systems, it would appear prudent to focus on the energy use associated with the operational phases of the system.

Urban Metabolism

Urban Metabolism is the theoretical framework used in this research. Urban metabolism is a conceptual model which has been used to describe and analyse flows of materials, including water and energy, within cities (cf. Newman 1999; Wolman 1965; Decker *et al.* 2000). At its simplest, urban metabolism considers the mass balances of all materials of urban systems (Sahely *et al.* 2003). At most complex, it draws on the rich metaphor which considers cities literally as organisms (Wolman 1965; Decker *et al.* 2000). Fischer-Kowalski *et al* (1998) argue that the concept of urban metabolism has become one of the most powerful paradigms and interdisciplinary concepts for the empirical analysis of the society-nature interaction.

History and Uses of the Metabolism Concept

Fischer-Kowalski (1998) reviewed the intellectual history and application of urban metabolism analysis to material and energetic processes within society as far back as the 1860s. She notes that it was Marx and Engels (Marx and Engels 1867/1961) who first applied the term metabolism to society within the foundations of social theory. Their work had been moulded by Moleschott (1852) who described metabolism as an exchange of matter between an organism and its environment, rather than as a cellular biochemical conversion as modern textbooks do. Fischer-Kowalski concluded that the concept assembles widely scattered approaches in biology, ecology, social theory, cultural anthropology and social geography.

Fischer-Kowalski (1998) argues that the application of the term metabolism to human society cuts across the “great divide” between the natural and social sciences. In the 1860s, when this divide was not as wide, the concept of metabolism, which then was emerging in biology, quickly found resonance in much of classic social science theory. Later, while being developed further in biology and ecology, the social science usage of this concept became more or less restricted to outsiders. Her conclusion was that metabolism is the mode in which societies organise the exchange of matter and energy with their natural environment (Fischer-Kowalski and Huttler 1998).

Fischer-Kowalski also cites several authors at that time, including Geddes (1884), who sought to find a unified calculus based on energy and material flows capable of providing a coherent framework for all economic and social activity. Many still aspire to this goal 130 years later.

The idea of urban metabolism was first put forward with a core intent of addressing contemporary urban resource issues by Abel Wolman in 1965 (Wolman 1965). He suggested it as a means of simultaneously addressing the then clear problem of “shortages of water and the pollution of water and air” as well as the call for “public economic decisions”.

Wolman defined urban metabolism as all the materials and commodities needed to sustain the cities inhabitants at home, at work and at play. This included the construction materials needed to build and rebuild the city.

In a hypothetical city of one million people, Wolman demonstrated the dominance of water in the material needs of cities. His city relied on 625,000 tonnes (t)/day (0.6t/ capita (person) per day (cap*d)) of water which entered “silently and unseen”. Water was identified as by far the dominant material flux of the city. The same city produced around 500,000 t/day (0.5 t/(cap*d)) of sewage. Total fuel consumption was approximately 9,500 t/day which included 3,000, 2,800, 2,700, 1,000 t/day of coal, oil, natural gas and motor fuel respectively. Food input was around 2,000 t/day. Wolman also commented on the complexity of the urban energy cycle. He pointed out its distinct differences to water including a lack of a centralised collection system that sewers provide.

Wolman also considered the relative price of water with other services such as communications and alcohol. He observed that “it should be clear that Americans can afford to pay for all the water they need”. In Wolman’s time, water was not seen as a scarce resource which could influence the national economy. Wolman summarised that there is plenty of water available but that supplying it requires foresight.

Since Wolman’s landmark article, only a limited number of metabolism studies have been conducted. Almost all have focussed on broad or complete inputs and outputs of individual cities (Kennedy *et al.* 2007). In most cases the research effort has been aimed at understanding the throughput of cities or how to manage cities to reduce the draw from and impact on local and global environments. More recently, the concept has been used to understand the throughput of cities for specific substances such as nitrogen flows through Paris (Barles 2007).

In one of the first systematic reviews of cities, Decker (2000) compares the metabolism of the largest 20 cities (megacities) of the world with regard to their food, fuel, water and air cycles. Decker concludes that understanding the energy and material processes of urban systems is both grossly understudied and an imperative facing the social, environment and energy challenges of the next century. He supports Wolman’s observation that water is the dominant material flux and that atmospheric (emissions) pathways surface as the most important for understanding the more recent impacts of megacities on neighbouring and global ecosystems. With regard to spatial focus, Decker notes that little effort to date has been invested in the cross-cutting comparison of the growth of megacities. He suggests that it is critical to broaden the study of individual cities into systematic cross-city comparisons. Decker concludes that “analysis of urban metabolism and succession will provide critical information about energy efficiency, material cycling, waste management, and infrastructure architecture in urban systems”. Because of its dominance in the urban flux (Decker *et al.* 2000) suggests it should be the prime focus of urban metabolism research.

Kennedy also published a review article on metabolism (Kennedy *et al.* 2007). In contrast to Decker’s work, Kennedy drew on other published studies to benchmark metabolic rates (water, materials, energy and nutrient balances) with Wolman’s pioneering work. Kennedy indicates that the paucity of published data made trend analysis impossible, however, the data did suggest that water and wastewater flows were typically greater (on a per-capita basis) in the 1990s than 1970s. He also indicated that while overall per-capita energy use is increasing, the efficiency of one city (Toronto) improved, possibly as a result of changes to industrial processes.

Kennedy pointed out that the metabolism of an ecosystem has been defined by ecologists as the production (via photosynthesis) and consumption (by respiration) of organic matter and is expressed in terms of energy (citing Odum 1971). Kennedy (2007) defined urban metabolism as the sum total of the *technical and socioeconomic processes* that occur in cities, resulting in growth, production of energy, and elimination of waste. He noted that resource accounting and management is typically undertaken at national levels and that this practice may lead to incomplete understanding of the urban processes which have wide influence on the “system” and its performance. Kennedy notes that the review by Decker (2000) made only minor reference to the metabolism concept and did not specifically ask how metabolism is changing, which was Kennedy’s focus.

In the biological world, studies on the metabolism of organisms have been carried out over an enormous range of scales for over 80 years, eg, Kleiber (1932). Recently, West and Brown (2005) show how rates of metabolism scale consistently over 27 orders of magnitude, from molecular and intracellular levels up to the largest organisms. They argue that the process of natural selection has shaped organisms to those forms of highest efficiency with particular influence on cardio-vascular design by minimising the energy needed to “democratically” distribute and remove cellular metabolic inputs and wastes within a body. There are likely to be many lessons for management of water and energy in cities from this scaling phenomenon.

It is clear that the concept of urban metabolism has had international academic interest, however, it has not yet moved substantially into applied resolution of real-world problems. The concept does not yet appear to have been applied to help understand the linkages between water and energy in cities. Likewise, it has not yet been incorporated into reporting or planning process or legislation, at least in Australia. Most metabolism studies have focussed on the macro-level inputs and outputs, without venturing within cities to identify the driving processes. No publication could be found where the concept has been used for quantifying water-energy linkages within cities or processes that lead to simultaneous conservation of water and energy.

There is hope, however, for the practical uptake of the metabolism concept. Several authors have recently pointed out its potential for urban design (Kennedy *et al.* 2011) and assessment and management (Pamminger and Kenway 2008; Novotny *et al.* 2010) of water systems.

Metabolic Analysis Approaches and Principles

In summary, there are two related, non-conflicting schools or approaches to urban metabolism assessment: one following Odum (Odum 1971) describing metabolism in terms of energy equivalents; while the second more broadly expresses a city’s flow of water, materials and nutrients as mass fluxes (Kennedy *et al.* 2011). This research focuses on the latter of these given its stronger relevance to water-energy interconnections.

Daniels *et al.* (2002) reviewed nine approaches for quantifying the metabolism of physical economies. These included techniques which consider the entire economy, such as: (i) total material requirement and output, (ii) bulk and (iii) substance flow analysis methods, (iv) physical IO tables, (v) ecological footprint, and (vi) environmental space models. He also considered (vii) LCA, (viii) material intensity per unit service, and (ix) sustainable process index methodologies. Daniels *et al.* note that the diverse array of promising but loosely assembled approaches has led to a pressing need for methodological standardisation. This is necessary to accumulate and diffuse the know-how required to successfully implement an appropriate methodological framework. Despite the noise, Daniels *et al.* (2002) identified the MFA of physical IO analysis as having ideal characteristics as a standardising environmental flow information system for future effective environmental management. While mass balance was less critical in early stages of many of the approaches used to describe metabolism, its significance is growing (Daniels 2002).

Daniels *et al* (Daniels and Moore 2002; Daniels 2002) clarified that the lack of standards for metabolic analysis is an issue of central importance for the research agenda. This absence makes repeatability problematic. It also leads to difficulty in trans-boundary or trans-study comparisons. Consequently, methodology development will be of central importance in the research agenda in this field.

Sustainability Frameworks, Urban Metabolism and Performance

Conceptual frameworks and supporting theories and principles are important because they provide the backbone against which methodology is developed.

Concepts of global sustainability arose in the 1960s and 1970s as a practical realisation of tensions between economic growth, social well-being and ecological health (Laves 2011; Priestley 2012). While there are many definitions, the most widely accepted concept of sustainable development is that it is “development that meets the needs of the present without compromising the needs of future generations to meet their own needs” (WCED 1987). This definition has a clear focus on human needs and the environment is relegated to the role of reliable service provider (Laves 2011; Priestley 2012).

Sustainability literature includes both strong and weak interpretations of the concept. The weak interpretation usually assumes that manufactured capital can be substituted for natural capital. The strong interpretation denies this and insists that natural capital must be preserved (Priestley 2012). These differences have major implications for decision-making. Among other things they have a major influence on the relative significance of various performance indicators which are used to evaluate the desirability of options.

Many conceptual frameworks have been developed for the assessment of sustainability across the full spectrum from strong to weak. Many have a high degree of connection with the concept of urban metabolism. The Natural Step (Foundation 1997) uses a systems perspective to help organisations reduce consumption of natural resources and improve technology. Natural Capitalism (Lovins *et al.* 1999) is a business approach using principles of bio-mimicry to increase natural resources productivity and invest in natural capital. Industrial Ecology aims to “incorporate the cyclical patterns of ecosystems into designs for industrial production processes that will work in unison with natural systems”.

All of these approaches aim to develop and sustain systems where the use of resources is restorative and non-harmful and which allow humans and ecosystems to thrive. These approaches set out to improve efficiencies and improve profitability. The critical difference the concept of urban metabolism provides is a framework for assessing and potentially quantifying current and projected impact and performance of cities from the perspective of resource efficiency. Priestley *et al* (Priestley 2012) notes that other elements of decision-making, including risk and resilience, would also require consideration and are not currently clearly articulated in the metabolism model.

Newman *et al* (Newman *et al.* 1996) demonstrated the relevance of urban metabolism for framing general indicators of urban performance. The commonly used “ecological footprint” (Wackernagel and Rees 1996) is an indicator derived from the metabolism model Sahely *et al* (2003). The ecological footprint is a spatial land measure of land necessary to support a city. Sahely *et al* (Sahely *et al.* 2003) point out that the ecological footprint concept does little to characterise flows through a city and to identify areas of particular concern.

While the ecological footprint concept has many strengths, its uptake by the water sector has been limited. The ecological footprint aggregates the impact of consumed products into habitat hectares of land, and water is excluded in this analysis. The concept also has great difficulty (perhaps impossibility) of converting upstream and downstream flow-related impacts (such as biodiversity influences) into a spatial measurement of necessary land. These limitations have been key motivators for the development of related concepts such virtual water and water footprints.

Another shortcoming of many existing sustainability assessment approaches relates to their inability to forecast the performance of future systems. Retrospective data is typically used as a basis for describing existing performance, however, this is not necessarily reliable for evaluating changes to the system (Priestley 2012).

More recently, Zhang (Zhang *et al.* 2010) quantifies a range of performance indicators for Beijing, China, including metabolic flux, efficiency, intensity, and density. These detailed energy-focused indicators were used to identify changes in the metabolism of Beijing over time with a hope that policy decisions would be guided by the approach.

Adopting a strong definition of sustainable cities, Newman *et al.* (Newman *et al.* 1996) articulated that a central principle of cities – and an objective of urban design and management – must be to reduce through-flow of resources, while maintaining or improving liveability, typically measured by, for example, health, employment, or income. Several authors (eg, Sahely *et al.* 2003; Tambo 2002) present similar arguments.

However it has been suggested that the definition of the problem or substantive issue is either currently inadequate, or that its framing, and resultant objectives need to be more specific. For example, what is the particular problem that it is intended to solve? In some locations, a high throughput of water, may not create a particular problem. For example if the area is water-rich and the water use is not creating significant impact. While this is possible, it is also possible that cities, systems, regions or economies which are water- and/or energy-efficient will have a competitive advantage in futures where there are water and energy shortages, or caps.

Currently, there is little research which identifies the relative merit of reducing the throughput of water versus energy or materials respectively; ie, there is nothing which demonstrates which are the most important fluxes to reduce through cities. An exception is Decker (2000), who articulates that “atmospheric processes” are the most significant environmental pathway for management of cities. Understanding the relative importance of material and energy fluxes would arguably help us identify points of trading. For example, how much energy (or carbon) is warranted to reduce the water flux of a city, say through recycling.

The Importance of System Boundary

Several authors note the importance of the “system boundary” to research conclusions (Satterthwaite 2008; Decker *et al.* 2000; Flower *et al.* 2007; French and Geldermann 2005). System boundary definition is a critical first step in modelling analysis (Sterman 1991). Without knowing the boundary it would be impossible to know which factors should be included in, or excluded from, the analysis. The boundary unequivocally influences decisions of the apparent “best” option (2005; 2007).

Satterthwaite (2008) suggests that most large cities have three or four different boundaries: (i) the core; (ii) the contiguous built up area; (iii) the metropolitan area, and (iv) extended planning region. He points out that our current loose definition of cities leads to great difficulty in comparing basic parameters. Even something as fundamental as urban population, can vary by several million persons depending on the definitions adopted.

Despite its importance, the boundary definition for cities appears absent from many discussions. It is even suggested by some as a little pedantic (eg,2008).

In a review of the contribution of cities to GHG emissions, Satterthwaite (2008) questions the assertion that *cities are responsible* for 75-80% of total global anthropogenic GHG emissions. He does not clarify if this estimate is the direct or indirect effect, and in fact does not use those terms at all. Satterthwaite (Satterthwaite 2008) concludes that the contribution of cities as a proportion of total global emissions (eg, in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report) has been over-estimated and other sectors such as agriculture, deforestation, heavy industry and fossil-fuelled power stations are underestimated. In reading example overstatements cited in

Satterthwaite's article, boundary conditions appear responsible for the discrepancy. For example, there is a loose interchange of language regarding whether GHG emissions are "emitted in" or "occur in" or are "accounted for" in cities. This highlights the need for improved accounting and, in particular, improved distinguishing of direct and indirect effects. Satterthwaite (2008) suggests that attributing emissions generally to "cities" is misleading. He suggests that emissions should be ascribed to the consumption areas that generate them. However, Daniels *et al* (2002) questions if we can separate cities from their broad economic sphere. Kenway *et al* (2008b) assumed that cities have a responsibility for total state-wide energy use including mining and agriculture. This was because much of the activity in these sectors was viewed as necessary to support the dependent urban centres.

Satterthwaite (2008) determines that accurate identification of responsibilities for GHG emissions has major implications. He also indicates that focus on both producers and consumers will be needed in the search for the best ways to reduce anthropogenic GHG emissions.

Lenzen (2004) points out that indirect emission and boundary issues become critical when comparing cities. For example, emissions could range from 14 to 102t CO₂-e (carbon dioxide equivalent) as calculated using the ICLEI-CCP method¹² for Frankston (a suburb within Greater Melbourne) and the City of Melbourne (focussed on the central business district of Melbourne), Australia. However, he also points out that people who happen to live in the central business district are largely not responsible for the large electricity use of that area in comparison to that required by business users.

The explicit definition of the system boundary (Kennedy *et al.* 2011) is a major advantage of the metabolism framework. It enables detailed mass- and energy-balance accounting in accordance with physical laws for the conservation of matter and energy, and cross-checked with the change of "stock" within the system. Consequently it can be validated independently.

Implications for Studying the Water-Energy Nexus

The concept of urban metabolism appears to provide a conceptual and theoretical basis against which investigation of the water-energy nexus in cities could have greater context and rigour. However, as the concept is so broad, the tool set and practical application of the concept so poorly developed, data sets and institutions so fragmented in their responsibilities, that metabolism research could be extremely challenging. This means that the concept of urban metabolism cannot be readily or rapidly applied to the problem of understanding of water-energy interconnections.

In the past, most metabolic analysis studies have focussed on individual cities. Decker (Decker *et al.* 2000) articulates that little effort has been invested in the cross-cutting comparisons of cities. He suggests this is critical because it would identify general, rather than locally-specific principles. He also suggests that focussing on water is warranted given its dominance of the urban mass balance. Because of its marked influence, system boundary identification and definition also warrants attention.

¹² Cities for Climate Protection Australia Program Report 1999–2000, ICLEI and the Australian Greenhouse Office.

GLOSSARY

Biogeochemical: In ecology and Earth science, a biogeochemical cycle or nutrient cycle is a pathway by which a chemical element or molecule moves through both biotic (biosphere) and abiotic (lithosphere, atmosphere, and hydrosphere) compartments of Earth. In effect, the element is recycled, although in some cycles there may be reservoirs where the element is accumulated for periods of time

Calibration: In statistics is a reverse process to regression. The calibration problem is the use of known data on the observed relationship between a dependent variable and an independent variable to make estimates of other values of the independent variable from new observations of the dependent variable. Model calibration is also used to refer to Bayesian inference about the value of a model's parameters, given some dataset.

Correlation: Often measured as a correlation coefficient which indicates the strength and direction of a linear relationship between two random variables. In general statistical usage, correlation refers to the departure of two random variables from independence. In this broad sense there are several coefficients, measuring the degree of correlation, adapted to the nature of the data.

Centralised System: Large-scale system provided by government-regulated water utilities that supplies clean water and wastewater services.

CO₂-e Carbon Dioxide Equivalent: An index that integrates various greenhouse gases associated with a system by using the global warming potential of each to weight the contributions. Approximately 300 kg CO₂-e/GJ (approximately 1 kg CO₂-e/kWh) is the recommended conversion factor for indirect emissions factors (full fuel cycle including Scope 2 and 3) for consumption of purchased electricity in most Australian States (Commonwealth of Australia 2008). Use of 100 GWh (0.36 PJ) is factored to contribute approximately 100,000 t of CO₂-e.

Decentralised System: The sourcing, treatment and provision of water services at or near the point of use. This includes on-site systems, such as rainwater tanks, owned and operated by the householder.

Embodied Energy: the energy required by all activities associated with a production process, including the relative proportions consumed in all activities upstream of the acquisition of natural resources and the share of energy used in making equipment and in other supporting functions (ie, direct energy plus indirect energy).

Energy Intensity: A measure of the energy required per volume of water, to pump or treat water or wastewater.

Full Fuel Cycle, Emission Factor: gives the quantity of emissions released per unit of energy for the entire fuel production and consumption chain (Commonwealth of Australia 2006). For fuel combustion, the full fuel cycle emission factor is the sum of the fuel's direct emission factor, and the specific 'Scope 3' emission factor for the emissions from extraction, production and transport of the fuel. For the consumption of purchased electricity, the full fuel cycle emission factor is the sum of the 'Scope 2' indirect emission factor for emissions from fuel combustion at the power station, and the specific 'Scope 3' factor for emissions from extraction, production and transport of that fuel and for emissions associated with the electricity lost in transport.

Household: A "household" is defined as a person living alone or a group of related or unrelated people who usually live in the same private dwelling (ABS 2011b).

Operational Energy: Energy used for the operation of the water supply and wastewater system (as distinct from embodied or life cycle energy requirements).

Primary Energy: Is a form of energy form that has not been subjected to any conversion or transformation process. It is energy found in nature and contained in raw fuels.

Secondary Energy: Is a form of energy generated by conversion of primary energy. For example electricity from gas, nuclear energy, coal, oil, fuel oil. Likewise, gasoline is a secondary energy created from mineral oil, coke and coke oven gas from coal

Primary Energy (thermal) equivalent: We have assumed that 1 unit of electrical energy is equal to three units of primary (thermal) energy (Gleick and Cooley 2009). In the Australian context this is largely correct because the majority of grid electricity is sourced from thermal electricity using black and brown coal.

Treatment Energy: Energy necessary to treat water or wastewater including energy to pump/pressurise water (eg, for reverse osmosis), and to move on-site water from one treatment process to another.

Transport Energy: Energy necessary to move water, wastewater or recycled water to and from particular sites (eg, to point of use, commencement of treatment, or from final treatment, disposal or release).

Urban System: The physical economy of a city that includes all the flows of energy, water and materials required to sustain the population. For this report urban system's energy use was estimated as the pro-rata proportion of total energy use for the state in which the city is located.

Validation: Is the process of checking if something satisfies a certain criterion. Examples would include checking if a statement is true (validity), if an appliance works as intended, if a computer system is secure, or if computer data are compliant with an open standard. Validation implies one is able to document that a solution or process is correct or is suited for its intended use. In computer terminology, validation refers to the process of data validation, ensuring that data inserted into an application satisfies pre-determined formats or complies with stated length and character requirements and other defined input criteria. It may also ensure that only data that is either true or real can be entered into a database.

Verification: Is usually an internal quality process of determining compliance with a regulation, standard, or specification. An easy way of recalling the difference between validation and verification is that validation is ensuring "you built the right product" and verification is ensuring "you built the product as intended".

Abbreviations and Measurements

ABS	Australian Bureau of Statistics
C, N, P, K	Respectively, Carbon, Nitrogen, Phosphorus, and Potassium
cap	Capita (person)
CO _{2-e}	Carbon Dioxide Equivalent
CSIRO	Commonwealth Scientific and Industrial Research Organisation
GHG	Greenhouse Gas(es) (GHGs common to the water industry include carbon dioxide (CO ₂), methane (CH ₄) and nitrous oxide (N ₂ O))
GJ	Gigajoule (10 ⁹ joules; 1 GJ/ML = 1 MJ/m ³ = 0.277 kWh/m ³)
GL	Gigalitre
GWh	Gigawatt hour (10 ⁶ kWh)(Note GWh-e and GWh-th are GWh electrical are units of electrical and thermal respectively)
hh	Household (on average containing approximately 2.6 people in Australia in 2008)
IO	Input-output
J	One watt second
kg	Kilogram
kL	kilolitre (1m ³)
kWh	kilowatt hour (3.6 MJ or 3.6 x 10 ⁶ J)
L/cap.a	litre per capita (person) per year (annum)
L/cap.d	litre per capita (person) per day
LCA	Life Cycle Analysis
m	metre
MFA	Material Flow Analysis
MJ	Megajoule (10 ⁶ joules)
ML	Megalitre (10 ⁶ litres)
MMFA	Mathematical Material Flow Analysis
MRIO	Multi Regional Input Output
PJ	Petajoule (10 ¹⁵ joules)
S	Stored Water
ΔS	Change in Stored Water
t	Metric tonne (1,000 kg)

REFERENCES

- ABC News. 2007. Beattie scraps water poll amid 'Armageddon' situation. Brisbane.
- ABS. 2006. Australian Social Trends 2006 Canberra: Australian Bureau of Statistics.
- ABS. 2011a. AS4604.0 Energy Account Australia 08-09. Canberra: Australian Bureau of Statistics.
- ABS. 2011b. *Housing Occupancy and Costs (4130.0)*.
- Aral, M. M. 2010. *Environmental Modelling and Health Risk Analysis*. Edited by Springer. Dordrecht: Springer.
- Arpke, A. and N. Hutzler. (2006). Domestic Water Use in the United States. A Life-Cycle Approach. *Journal of Industrial Ecology* 10(1-2): 169-183.
- Australian Government Department of Climate Change and Energy Efficiency. 2012. National Targets. In *think change*. Canberra: Australian Government.
- AWE and ACEEE. 2011. *Addressing the Energy-Water Nexus: A blueprint for action and policy agenda*. Washington: Alliance for Water Efficiency and American Council for an Energy Efficient Economy.
- Baccini, P. and H.-P. Bader. 1990. *Regionaler Stoffhausholt: Erfassung, Bwertung und Steuerung*. Heidelberg: Spektrum Akademischer Verlag.
- Baccini, P. and P. H. Brunner. 1991. *Metabolism of the anthroposphere*. Berlin: Springer Verlag.
- Bader, H.-P. and R. Scheidegger. 2012. *MMFA Framework*. Dubendorf: Swiss Federal Institute of Aquatic Science and Technology: Eawag.
- Barles, S. (2007). Urban metabolism and river systems: An historical perspective-Paris and the Seine, 1790-1970. *Hydrology and Earth System Sciences* 11(6): 13.
- Beal, C., B. Hood, T. Gardner, J. Lane, and C. Christiansen. 2008. Energy and Water Metabolism of a Sustainable Subdivision in South East Queensland: A Reality Check. In *Enviro '08*. Melbourne.
- Bernstein, L., P. Bosch, O. Canziani, Z. Chen, R. Christ, and O. Davidson. (2007). Climate change 2007: synthesis report. Summary for policymakers. *Lima; CONAM, 2006, 71 p.(Serie Indicadores Ambientales, 10)*.
- Cammerman, N. 2009. *Integrated Water Resources Management and the Water Energy Climate Change Nexus, A discussion report*. Brisbane: University of Queensland.
- Cheng, C.-L. (2002). Study of the Inter-Relationship between Water Use and Energy Conservation for a Building *Energy and Buildings* 34: 261-266.
- Cohen, R., G. Wolff, and B. Nelson. 2004. *Energy Down the Drain: The Hidden Costs of California's Water Supply*. Natural Resources Defense Council.
- Commonwealth of Australia. (2006). Australian Greenhouse Office Factors and Methods Workbook. Canberra, Australia, Australian Government Department of the Environment and Heritage, Australian Greenhouse Office.
- Commonwealth of Australia. 2008. *National Greenhouse Accounts (NGA) Factors*. Canberra, Australia: Australian Government Department of Climate Change.
- Commonwealth of Australia. 2010. *Energy in Australia 2010*. Canberra: Department of Energy, Resources and Tourism.
- Conrad, S., J. Gelsenhoff, T. Brueck, M. Volna, P. Brink, M. Hall, S. Cook, and S. Kenway. 2011. *Decision Support System for Sustainable Energy Management*. Edited by W. R. F. a. W. E. R. Foundation, *Subject Area: Management and Customer Relations*. Denver: Water Research Foundation.
- Cunio, L. N. and A. B. Sproul. 2009. Low Energy Pumping Systems for Rainwater Tanks. In *Solar09, the 47th ANZES Annual Conference*. Townsville September 29 - October 2 2009
- Daniels, P., M. Lenzen, and S. Kenway. (In Press Accepted November 2011). The Ins and Outs of Water Use – A Review of Multi-region Input-Output Analysis and Water Footprints for Regional Sustainability Analysis and Policy. *Economic Systems Research*.
- Daniels, P. L. (2002). Approaches for Quantifying the Metabolism of Physical Economies: A Comparative Survey. *Journal of Industrial Ecology* 6 (1): 24.
- Daniels, P. L. and S. Moore. (2001). Approaches for Quantifying the Metabolism of Physical Economies: Part 1 Methodological Overview. *Journal of Industrial Ecology* 5(4): 24.
- Daniels, P. L. and S. Moore. (2002). Approaches for Quantifying the Metabolism of Physical Economies: Part 1 Methodological Overview. *Journal of Industrial Ecology* 5(4): 24.
- Daniels, P. L. and K. McBean. 2009. Virtual water accounting for enhanced sustainable water management: A preliminary review of its potential and links to life cycle assessment and regional

- material accounting. In *Sixth Conference of the Australian Life Cycle Assessment Society (ALCAS Inc.) Wed Feb 18 2009*.
- De Haas, D., J. Foley, and P. Lant. 2008. Energy and Greenhouse Footprints of Wastewater Treatment Plants in South East Queensland. In *OzWater09*. Melbourne.
- Decker, E. H., S. Elliott, F. A. Smith, D. R. Blake, and F. S. Rowland. (2000). Energy and material flow through the urban ecosystem. *Annual Review of Energy and the Environment* 25: 685-740.
- deMonsabert, S. and B. Liner. (1998). Integrated water and energy conservation modelling. *Journal of Energy Engineering*(April): 2-19.
- Department of Energy. 2011. *International Energy Outlook*. Washington:
- Dunn, J. P. (2004). Making Stakeholder Engagement Work. *Water* August: 41-44.
- Elkind, E. 2011. *Drops of Energy. Conserving Urban Water in California to Reduce Greenhouse Gas Emissions*. Berkeley: UC Berkeley Centre for Law, Energy and the Environment,.
- Fischer-Kowalski, M. (1998). Society's Metabolism: The Intellectual History of Materials Flow Analysis, Part I, 1860-1970. *Journal of Industrial Ecology* 2(1): 61-78.
- Fischer-Kowalski, M. and W. Huttler. (1998). Society's Metabolism: The Intellectual History of Materials Flow Analysis, Part II, 1970-1998. *Journal of Industrial Ecology* 2(4): 30.
- Fishman, G. 1996. Monte Carlo, Concepts, Algorithms, and Applications, edited by P. Glynn. New York: Springer.
- Flower, D. J. M. 2009. An Integrated Approach to Modelling Urban Water Systemsthesis, Department of Civil Engineering, Monash University, Melbourne.
- Flower, D. J. M., V. G. Mitchell, and G. P. Codner. 2007. The potential of water demand management strategies to reduce the greenhouse gas emissions associated with urban water systems. In *1st Conference on Sustainable Urban Water Management & 9th Conference on Computing and Control in the Water Industry*. Leicester, UK.
- Foran, B., M. Lenzen, and C. Dey. 2005. *Balancing Act. A Triple Bottom Line Analysis of the Australian Economy*.
- Foran, B., M. Lenzen, C. Dey, and B. Marcela. c 2004. *A Novel TBL Initiative, Integrated Sustainability Analysis Research Paper 01-02*: CSIRO and University of Sydney.
- Foundation, J. (1997). The Natural Step to Sustainability. *Wingspread Journal*. .
- French, S. and J. Geldermann. (2005). The varied contexts of environmental decision problems and their implications for decision summport. *Environmental Science & Policy* 8: 14.
- Geddes, P. 1884. *Civics as applied sociology (cited in Fischer Kowalski 1998)*. Leicester: Leicester University Press.
- GEI and Navigant. 2011a. *Embedded Energy in Water Studies. Study 2: Water Agency and Function Component Study and Embedded Energy-Water Load Profiles*. San Francisco: California Public Utilities Commission.
- GEI and Navigant. 2011b. *Embedded Energy in Water Studies. Study 1: Statewide and Regional Water-Energy Relationship*. San Francisco: California Public Utilities Commission.
- Gleick, P. (1994). Water and Energy. *Annual Review of Energy and the Environment* 19 267-299
- Gleick, P. H. and H. S. Cooley. (2009). Energy implications of bottled water. *Environmental Research Letters* 4: 6.
- Goldstein, N. N., R. L. Newmark, C. Dunham Whitehead, E. Burton, J. McMahon, G. Girish, and D. May. (2008). The energy-water nexus and information exchange: challenges and opportunities. *International Journal of Water* 4(1/2): 6-24.
- Government of South Australia. 2009. *Water for Good: A plan to ensure our water future to 2050*. Adelaide:
- Grant, T., L. Opray, A. Grant, A. Sharma, G. Mitchell, and F. Pamminger. 2006. Life Cycle Aspects of Alternative Water and Sewage Servicing. In *7th International Conference on Urban Drainage Modelling & 4th International Conference on Water Sensitive Urban Design.*, edited by A. Deletic and T. Fletcher. Grand Hyatt, Melbourne.
- GRI. 2005. *Sector Supplement for Public Agencies: Pilot Version 1.0*. Boston: Global Reporting Initiative.
- Heede, R. 1995. *Homemade money: How to save energy and dollars in your home.*: Rocky Mountains Institute.
- Heemskerk, B., P. Pistorio, and M. Scicluna. 2002. *Sustainable Development Reporting: Striking the Balance*. Geneva: World Business Council for Sustainable Development.
- Hightower, M. 2006. Energy-Water Science and Technology Research Roadmap. Albuquerque: Sandia National Laboratory.
- Hightower, M. and S. A. Pierce. (2008). The energy challenge. *Nature* 452(20 March).

- Howe, C., R. Jones, S. Maheepala, and B. Rhodes. 2005. *Melbourne Water Climate Change Study: Implications of Potential Climate Change for Melbourne's Water Resources* Canberra CSIRO.
- IEA. 2011. Statistics and balances for OECD countries. In *Online statistics and balances*. Paris: International Energy Agency.
- IEA. 2010. *Key World Energy Statistics*. Paris: OECD and International Energy Agency.
- Kennedy, C., J. Cuddihy, and J. Engel-Yan. (2007). The changing metabolism of cities. *Journal of Industrial Ecology* 11(2): 43-59.
- Kennedy, C., S. Pincetl, and P. Bunje. (2011). The study of urban metabolism and its applications to urban planning and design. *Environmental Pollution* 159: 1965-1973.
- Kenway, S., J. McMahon, V. Elmer, S. Conrad, and J. Rosenblum. (In press (Accepted 12 December 2012)). Managing water-related energy in future cities - a research and policy roadmap. *Journal of Water and Climate Change*.
- Kenway, S. J. 2012. *The Water-Energy Nexus and Urban Metabolism - Identification, Interpretation and Quantification of the Connections in Citiesthesis*, School of Chemical Engineering, The University of Queensland, Brisbane.
- Kenway, S. J. and P. Lant. 2011. The influence of water on urban energy use. In *Water Sensitive Cities*, edited by C. Howe and C. Mitchell. Amsterdam: International Water Association and UNESCO-IHE.
- Kenway, S. J., C. Howe, and S. Maheepala. 2008a. *Triple Bottom Line Reporting of Sustainable Water Utility Performance, AwwaRF Report 91179*. Denver, Colorado: American Water Works Association Research Foundation and CSIRO.
- Kenway, S. J., A. Gregory, and J. McMahon. (2011a). Urban Water Mass Balance Analysis. *Journal of Industrial Ecology* 15(5): 693-706.
- Kenway, S. J., P. Lant, and A. Priestley. (2011b). Quantifying the links between water and energy in cities. *Journal of Water and Climate Change* 2(4): 247-259.
- Kenway, S. J., P. Lant, A. Priestley, and P. Daniels. (2011c). The connection between water and energy in cities - a review. *Water Science and Technology* 63(9): 1983-1990.
- Kenway, S. J., R. Scheidegger, H. P. Bader, T. A. Larsen, and P. Lant. (2012). Water-related energy in households: a model designed to understand the current state and simulate possible measures. *Energy and Buildings*.
- Kenway, S. J., R. Scheidegger, H. P. Bader, T. A. Larsen, and P. Lant. (c 2012 (Accepted 15 February 2012)). Water-related energy in households: a model designed to understand the current state and simulate possible measures. *Energy and Buildings*.
- Kenway, S. J., A. Priestley, S. Cook, S. Seo, M. Inman, and A. Gregory. 2008b. *Energy use in the Provision and Consumption of Urban Water in Australia and New Zealand*. 9780643096165. CSIRO and Water Services Association of Australia.
- Kleiber, M. (1932). Body Size and Metabolism. *Hilgardia* 6: 39.
- Klein, G., M. Krebs, V. Hall, T. O'Brien, and B. Blevins. 2005. *California's Water-Energy Relationship - Final Staff Report*. California Energy Commission.
- Lane, J. and T. Gardner. 2009. A life-cycle comparison of decentralised and centralised water cycle options for an SEQ Urban Development. In *Ozwater09 Conference - From Challenges to Solutions*. Melbourne Convention and Exhibition Centre, Melbourne, Victoria: Australian Water Association.
- Laves, G. 2011. *Sustainability frameworks for the water sector. Draft literature review*. Brisbane.: Griffith University.
- Lawson, S. 2011. Personal Communication with Lawson, S., Understanding Australia's Energy Accounts. 30 September 2009 2011.
- Lenzen, M. 2008. *The Virtual Water Cycle of Victoria. A report to GHD for the Victoria Water Trust*. The University of Sydney.
- Lenzen, M., C. Dey, and B. Foran. (2004). Energy requirements of Sydney households. *Ecological Economics* 49(3): 375-399.
- Lenzen, M., R. Wood, and T. Wiedmann. (2010). Uncertainty analysis for Multi-Region Input-Output Models - a case study of the UK's carbon footprint. *Economic Systems Research* 22(1): 43-63.
- Lesh, P. 2009. *Rate Impacts and Key Design Elements of Gas and Electric Utility Decoupling - A Comprehensive Review*.
- Leslie, G. 2009. Personal Communication with Leslie, G., The Search For an Urban Kidney. Brisbane 2009.
- Lofman, D., M. Petersen, and A. Bower. (2002). Water, Energy and Environment Nexus: The California Experience. *Water Resources Development* 18(1): 73-85.

- Lovins, A. B., L. H. Lovins, and P. Hawken. (1999). A road map for natural capitalism. *Harvard Business Review* 77(3): 145-+.
- Marsh, D. 2008. The water-energy nexus: A Comprehensive analysis in the context of New South Wales thesis, Faculty of Engineering and Information Technology, University of Technology, Sydney.
- Marx, K. and F. Engels. 1867/1961. *Capital I*. London.
- McMahon, J. and S. Price. (2011). Water and Energy Interactions. *Annual Review of Environment Resources* 36(17): 1-29.
- Meadows, D. 2007. *Thinking in Systems, A Primer*: Sustainability Institute.
- Mithraratne, N. and R. Vale. 2006. Life-Cycle Resource Efficiency of Conventional and Alternative Water Supply Systems. In *12th Annual International Sustainable Development Research Conference*. Hong Kong.
- Moleschott, J. 1852. *Der Kreislauf des Lebens*. Mainz Von Zabern.
- National Water Commission. 2011. *National Performance Report 2009-10 Part A - comparative analysis*. Canberra: National Water Commission.
- Newman, P., R. Birrell, D. Holmes, C. Mathers, P. Newton, G. Oakley, A. O'Connor, B. Walker, A. Spessa, and D. Trait. 1996. Human Settlements. In *State of the Environment Australia 1996*. Melbourne: State of the Environment Advisory Council, CSIRO Publishing.
- Newman, P. W. G. (1999). Sustainability and cities: extending the metabolism model. *Landscape and Urban Planning* 44(4): 219-226.
- Novotny, V., V. Elmer, H. Furumai, S. Kenway, and O. Phillips. 2010. *Water and Energy Framework and Footprints for Sustainable Communities - white paper for the IWA World Water Congress Montreal*. International Water Association.
- O'Meara, M. 1999. *Reinventing Cities for People and the Planet*. Edited by J. A. Peterson, *Worldwatch Paper* 147.
- Odum, E. P. 1971. *Fundamentals of Ecology*. Philadelphia: Saunders.
- Pamminger, F. and S. J. Kenway. (2008). Urban metabolism - improving the sustainability of urban water systems. *Water* 35(1): 28-29.
- Pate, R., M. Hightower, C. Cameron, and W. Einfeld. 2007. *Overview of energy-water interdependencies and the emerging water demands of energy resources*. 1349C. Albuquerque, New Mexico: Sandia National Laboratories.
- PMSEIC. 2010. *Challenges at Energy-Water-Carbon Intersections*. Canberra: Prime Minister's Science, Engineering and Innovation Council.
- Priestley, T. 2012. *Towards Assessment Criteria for Water Sensitive Cities*. Brisbane: Urban Water Security Research Alliance.
- Proust, K., S. Dovers, B. Foran, B. Newell, W. Steffen, and P. Troy. 2007. *Climate, Energy and Water, Accounting for the links. Discussion Paper*. Canberra: The Fenner School of Environment and Society, Australian National University,.
- Retamal, M., K. Abey Suriya, A. Turner, and S. White. 2009a. *The Water Energy Nexus: Literature Review*. Sydney: Institute for Sustainable Futures.
- Retamal, M., K. Abey Suriya, T. Turner, J. Glassmire, and S. White. 2009b. *The Water Energy Nexus: Investigation into the Energy Implications of Household Rainwater Systems*. Sydney: Institute for Sustainable Futures, University of Technology.
- Sahely, H. R., S. Dudding, and C. A. Kennedy. (2003). Estimating the urban metabolism of Canadian cities: Greater Toronto Area case study. *Canadian Journal of Civil Engineering* 30(2): 468-483.
- Sandia National Laboratory. 2007. Energy-Water, Technology Innovation Workshops, Workshop Research Area Results. Albuquerque, New Mexico: Sandia National Laboratory.
- Satterthwaite, C. (2008). Cities' contributions to global warming: notes on the allocation of greenhouse gas emissions. *Environment and Urbanization* 20(2): 539-549.
- Schneider, K. 2012. Energy Department Blocks Disclosure of Road Map to Relieve Critical U.S. Energy-Water Choke Points. In *Circle of Blue*: Circle of Blue.
- Sheehan, M. 2007. *2007 State of the World: Our Urban Future*. Washington, D.C.: Worldwatch Institute.
- Spencer, H., ed. 1862/1880. *First Principles*. Edited by A. L. Burt. New York.
- Sterman, J. 1991. A skeptic's guide to computer models. Massachusetts Institute of Technology. Original edition, In Barney, G. O. *et al.* (eds.), *Managing a Nation: The Microcomputer Software Catalog*. Boulder, CO: Westview Press, 209-229. An earlier version of this paper also appeared in *Foresight and National Decisions: The Horseman and the Bureaucrat* (Grant 1988).
- Stokes, J. and A. Horvath. (2006). Life Cycle Energy Assessment of Alternative Water Supply Systems (9 pp). *The International Journal of Life Cycle Assessment* 11(5): 335-343.

- Stokes, J. R. and A. Horvath. (2009). Energy and Air Emissions Impacts of Water Supply. *Environmental Science and Technology* 43: 8.
- Stolz, G. 2007. The Water Crisis - Its Desalinate or Die. *Courier Mail* [Brisbane], 1 February 2007, section 1.
- Tambo, N. (2002). A new water metabolic system. *Water* 21(December 2002): 67-68.
- United Nations. 2003. *Handbook of National Accounting on Integrated Environmental and Economic Accounting*, . New York:
- United States National Laboratories. c2008. The Energy-Water Nexus, a Strategy for Energy and Water Security, edited by Department of Energy. Albuquerque, New Mexico: Sandia National Laboratory.
- Victorian Water Industry Association. 2011. *Electricity issues in the Victorian Water Sector*. Melbourne: Victorian Water Industry Association,.
- Wackernagel, M. and W. Rees. 1996. *Our Ecological Footprint: Reducing Human Impact on the Earth*. Gabriola Island: New Society Publishers.
- WBCSD. 2009. *Water, Energy and Climate Change, A Contribution from the Business Community*. Geneva: World Business Council for Sustainable Development.
- WCED. 1987. *Our Common Future (The Brundtland Report)*. Oxford, United Kingdom:
- West, G. B. and J. H. Brown. (2005). The origin of allometric scaling laws in biology from genomes to ecosystems: towards a quantitative unifying theory of biological structure and organization. *The Journal of Experimental Biology* 208: 16.
- Wiedmann, T. (2009). A review of recent multi-region input–output models used for consumption-based emission and resource accounting. *Ecological Economics* 69: 211-222.
- Wolff, G. and R. Wilkinson. 2011. *Statewide Assessment of Water-Related Energy Use for the Year 2000*. California Energy Commission, PIER Energy-Related Environmental Research Program. Sacramento: Californian Energy Commission.
- Wolman, A. (1965). The Metabolism of Cities. *Scientific American* 213: 179-190.
- WSAA. 2005. *Testing the Water - Urban Water in Our Growing Cities: the Risks, Challenges, Innovation and Planning* Melbourne: Water Services Association of Australia.
- WSAA. 2008. *WSAA Report Card 2007-2008. Performance of the Australian Urban Water Industry and projections for the future*. Melbourne: Water Services Association of Australia.
- WSAA. 2009. *WSAA Report Card 2008-2009. Performance of the Australian Urban Water Industry and projections for the future*. Melbourne: Water Services Association of Australia.
- Zhang, Y., Z. Yang, and B. Fath. (2010). Ecological network analysis of an urban water metabolic system: Model development, and a case study for Beijing. *Science of the Total Environment* 408: 4702-4711.

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