Environmental Modelling & Software 73 (2015) 272–285

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

A systemic framework and analysis of urban water energy

S.J. Kenway [a], [*], A. Binks [a], J. Lane [a], P.A. Lant [a], K.L. Lam [a], A. Simms [b]

[a] *The School of Chemical Engineering, The University of Queensland, Brisbane, Australia*
[b] *Seqwater, Australia*

ARTICLE INFO

Article history:
Received 6 January 2015
Received in revised form
9 August 2015
Accepted 10 August 2015
Available online 5 September 2015

Keywords:
Integrated
Infrastructure
Metabolism
Decision support
Business case

ABSTRACT

Energy impacts of urban water systems are substantial, but not typically analysed systemically. We develop a new system boundary framework including a utility, the ‘bulk water supply authority’ (SB1); the ‘urban water system’ including water use (SB2); and the ‘regional water system’ (SB3). We use the framework to review existing models and show that most address only one boundary. We apply the framework to quantify thermal equivalents of water-related energy in SB1 and SB2, and identify that over 96% of water-related energy in South East Queensland (SEQ) is outside SB1 and within SB2. Consideration of energy influenced by water use is paramount to systemic energy efficiency and optimisation in the urban water system. Clear articulation of system boundaries will improve modelling and management of the energy impact of urban water. Systemic modelling will help decision makers answer increasingly integrated and cross-system and sector questions regarding water and energy interactions.

1. Introduction

The influence of urban water supply, water use and wastewater services is significant. It accounts for 13–18% of State electricity use, and 18–32% of state natural gas consumption in Australia and the United States (Kenway et al., 2011a,b,c; Klein et al., 2005). The energy use of water utilities for pumping and treatment typically accounts for 10% of water-related energy. Energy use related to water use within households, industry and commerce typically accounts for more than 80% of the energy use in the “urban water cycle” for example, for water heating (Arpke and Hutzler, 2006; Cheng, 2002; Stokes and Horvath, 2009). Water-related energy is energy use which is directly or indirectly influenced by changes to water (Klein et al., 2005).

Energy use for water is a growing business risk in many nations, both to water utilities and the populations they support (Goldstein et al., 2008; Hightower and Pierce, 2008; Victorian Water Industry Association, 2011; WBCSD, 2009). In Australia, for example, the energy demand for urban water is anticipated to increase by approximately 200% of 2007 levels by 2030 (Cook et al., 2012; Kenway et al., 2008). Most of the influence is due to increased dependence on energy-intensive water supply sources such as desalination and recycling. Population growth, spreading cities, and tightening water and wastewater regulatory standards also contribute to growing energy demands. In combination with rising electricity costs, the total energy bill paid by water utilities is anticipated to grow in Australia to around 500% of 2007 levels by 2030 (Cook et al., 2012).

Most analysis of the water-energy nexus ignores discussion of “the system boundary”. In the relatively few papers observed where boundary issues are mentioned, the observations are brief. For example, in a thorough review of integrated modelling, (Bach et al., 2014), system boundary delineation is described as selecting the “level of integration”. Clear articulation of boundary, and acknowledgement on the significant influence on results, is an important issue because the “selected” boundary can have a major influence on decisions connected to the aim of the study. For example, Paton et al. (2014), propose an integrated framework to assess “urban water supply security of systems with non-traditional sources of water under climate change”. The issue of system boundary is not discussed in the method which aims to identify preferred solutions. The authors conclude that “should minimising greenhouse gas emissions [of new water sources] be an objective, the high-energy of desalination plants would render these alternatives as less favourable than indicated by this study”.

Boundary definition is a critical first step in modelling analysis (Decker et al., 2000; French and Geldermann, 2005; Satterthwaite, 2008; Sterman, 1991) inextricably interconnected with the study aims. Without a clear boundary description, it is impossible to know which factors should be included in, or excluded from, analyses (Sterman, 1991). The boundary unequivocally influences

---

[*] Corresponding author.

http://dx.doi.org/10.1016/j.envsoft.2015.08.009
1364-8152/

decisions of the apparent best option (2007; French and Geldermann, 2005; Parnell et al., 2011). Consequently, clear boundaries are paramount to good decision-making. But how should we define these boundaries given the highly interconnected nature of urban water and energy systems?

Given this, the research question and modelling objective of this work focusses on understanding how boundaries of the urban water system can be defined to quantify their wide energy impacts. This information contributes internationally to a new structure, method, and language relevant for water (or energy) analysts wishing to systematically evaluate the energy effect of water within cities. It is also relevant to those wishing to compare and prioritise options across those boundaries. It is particularly relevant when comparisons are needed across options water supply and demand solutions which is increasingly needed in urban water management (Rozos and Makropoulos, 2013).

A hypothesis driving our work is that most current analysis of energy influences in urban water deal only with parts of the "water system". An outcome of this is that it is difficult for decision-makers to identify true least-energy (or ultimately least-cost) solutions in the design and operation of urban water systems. Our rationale is that consideration of wider boundaries than individual water utilities is necessary in order to identify solutions which address water-energy problems, rather than moving them around.

2. Background and context

This paper addresses the first stage of a wider project exploring the extent to which a bulk water supply authority (Seqwater) can improve energy efficiency (and related costs and greenhouse gas emissions) directly through their operations, as well as influencing systemic change. The research objective is to evaluate energy efficiency, and improve systemic decision-support in urban water. Systemic efficiency is encouraged by the Statement of Obligations under which Seqwater operates (Queensland Government, 2013).

Seqwater manages more than $10 billion (AUD) of assets for almost three million people (Seqwater, 2013). In 2013, these assets included major water catchments, 26 dams, 46 water treatment plants, 47 weirs, a desalination facility, a major recycled water asset (currently non-operational), a 600 km bulk water supply network, and hydro-power schemes at some dams. Seqwater is responsible for water security and the regional supply-demand balance and efficiency, and also provides irrigation services to more than 1000 rural customers in five schemes.

Like Seqwater, many water managers have actively considered the *direct* energy impacts of their operations for some time (Kenway et al., 2007a,b). However, they are typically unaware of the wider, and often substantially larger, *indirect* energy use influenced by their policy. For example, most water utilities are not aware of how much their water pricing or policy influence the energy use of their customers. These changes can be significant because changes in water use, particularly hot water use, can have a large effect on household (Kenway et al., 2013a,b,c), industrial and commercial energy use. Consequently, water utilities influence energy use both *directly* and *indirectly*. The *direct* and *indirect* scopes of influence are shown as System Boundaries 1 and 2 in Fig. 1.

As many water suppliers, retail distributors, and wastewater treatment utilities are evaluating, planning, and investing in options to reduce energy use (Rothhausen and Conway, 2011), it is important to consider both *direct* and *indirect* energy impacts (Kenway et al., 2011a,b,c). Without such consideration it is possible *direct* energy use by utilities may reduce, but that the wider pool of water-related energy may increase. This is shown as pathway a' in Fig. 1. This could occur for example where utilities invest to provide more energy-efficient assets, or improve efficiency, but inadvertently allow, or even encourage *indirect* energy consumption to increase. For example "water-related energy" in SB2 could increase if water use increases, particularly for high-energy applications such as showering and clothes-washing in households. Pathway (a) is observed relatively regularly because most water businesses need to generate revenue from water sales, in order to pay for energy efficiency measures or other asset improvements.

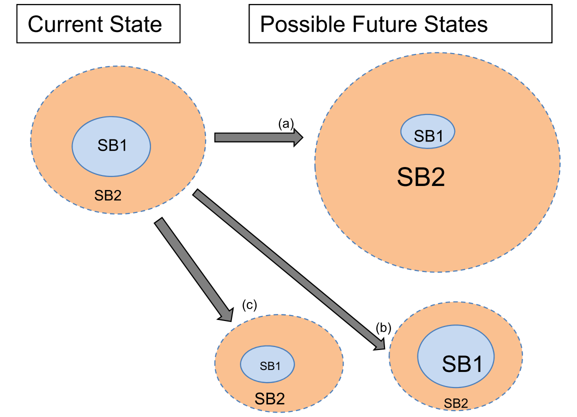

Fig. 1. Energy impact of future urban water systems could have widely different patterns. Direct energy use by individual water utility is represented by System Boundary 1 (SB1). Wider indirect energy impact of the "urban water system", (including SB1) is represented by System Boundary 2, (SB2). A range of possible future states exist, with (a), (b) and (c) being examples. These are explained in Section 2, and involve energy use within SB1 and SB2 increasing or decreasing in various combinations.

Future states are also possible where energy use by utilities (SB1) grows, yet indirect water-related energy (SB2) reduces. This is shown as 'pathway b'. 'Pathway c' shows a future where both utility energy use and indirect water-related energy use could decrease.

Further consideration is needed to determine how strategies cost-effectively guide investment in these two systems to achieve the greatest outcome. This is part of the challenge of finding the most appropriate scale to act at: centralised (typically large asset) or decentralised (typically household or site-based). It forces planners to ask is it possible to view efficient household appliances, as part of "urban water infrastructure"? Or, "Can centralised systems overcome the need for household systems". While this may seem far-fetched to some, the concept of "source-to-tap, and back again" analysis of water options is gaining traction. Similarly, district heating systems, (which capture waste heat from power generation to provide hot water services), make household-level water heating redundant. However, to-date, very little research or industry analysis has compared the efficiency of urban water supply-demand options across centralised and decentralised scales. We argue here that such an approach will be increasingly important in identifying least-cost options for energy-efficient urban water provision. For example, such an approach could compare the energy costs and benefits of alternatives such as (a) additional sources of water (dams, desalination as well as stormwater) and (b) additional water conservation effort such as reducing non-revenue water (reducing loss) or demand-side water options including within-household or within-industry efficiency measures.

3. Material and methods

This research had three principle methods: (i) identification of energy questions relevant to water stakeholders; (ii) definition of system boundary, and (iii) use of the boundary to quantify water-related energy throughout the system.