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A framework for planning sustainable seawater desalination water supply

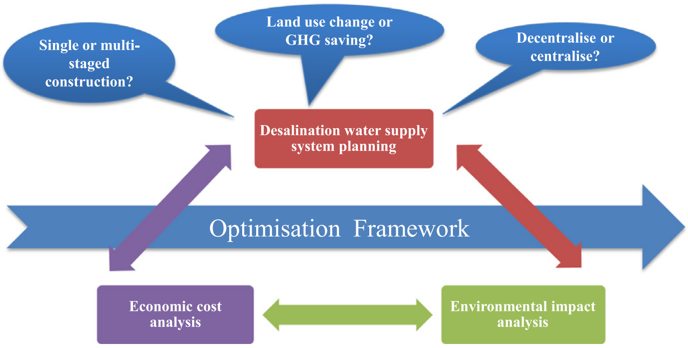
Maedeh P. Shahabi [a,*], Adam McHugh [a,b], Martin Anda [a], Goen Ho [a]

[a] School of Engineering and Information Technology, Murdoch University, Perth, Western Australia, Australia
[b] Infrastructure Advisory, Ernst & Young, Perth, Western Australia, Australia

HIGHLIGHTS

- A framework is developed for sustainability planning of desalination infrastructure.
- We integrate MILP and LCA tools for analysis of economic & environmental impacts.
- Future planning for water supply to Perth, Australia was evaluated.
- Integrating land use decisions in desalination planning relieves system impacts.

GRAPHICAL ABSTRACT



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ABSTRACT

A quantitative framework for sustainable desalination planning in metropolitan areas, which integrates the tools of mixed integer linear programming and life cycle assessment, is presented. The life cycle optimisation framework allows for optimal desalination planning by considering choices over intake type, staging and location of the infrastructure under different land-use, environmental and economic policies. Optimality is defined by the decision maker's selected objective function, being either an environmental impact or a levelised cost indicator. The framework was tested for future desalination planning scenarios in the northern metropolitan area of Perth, Western Australia. Results indicate that multi-staged construction and decentralised planning solutions may produce lower life cycle environmental impacts (58%) and at a lower levelised cost (24%) than a centralised desalination solution currently being considered by Western Australian water planners. Sensitivity analysis results suggest that the better environmental and economic performance of decentralised planning over centralised planning is highly sensitive to the proportion of land that can be made available for the siting of decentralised plants near the demand zone. Insight into land use policies is a critical factor to the initiation and success of decentralised solution in developed metropolitan areas.

1. Introduction

1.1. Planning of desalination sourced water supply

The global capacity of desalination grew by 57% between 2008 and 2013 (GWI, 2011). This trend is expected to continue in response to

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* Corresponding author.
E-mail address: m.pakzadshahabi@murdoch.edu.au (M.P. Shahabi).

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population growth, diminishing traditional water resources and advances in membrane technology. Seawater desalination contributes 59% of global desalination capacity (Burn et al., 2015). A recent global trend in metropolitan water supply system expansion planning is to commission large scale desalination plants to fulfil up to 50% of a city's long term drinking water needs (Voutchkov, 2012). For example since 2006 in the Australian cities of Perth, Melbourne and Sydney, large desalination plants have been built to contribute 25, 33 and 15% of the drinking water needs of the respective metropolitan areas during drought (Radcliffe, 2015). This trend is based on two factors: concern over water shortages in the context of increasing demand and climate change, and desalination plant economies of scale. Economies of scale refers to a lowering of the average cost (i.e. per cubic meter) of desalinated water with increasing treatment plant capacity (Greenlee et al., 2009; Karagiannis and Petros, 2008; Kurihara and Hanakawa, 2013; Wittholz et al., 2008) under an implicit assumption that there will be enough demand for desalination capacity to be utilised. The advantages of economies of scale must be balanced against the disadvantages of operating the energy intensive water distribution infrastructure, which is often required to transport desalinated water long distances from large centralised plants to demand locales (Ghaffour et al., 2013; Zhou and Tol, 2005). Previous studies have shown that, in those cases where there are sufficient savings from reduced pipe infrastructure and water pumping energy requirements, relatively small decentralised water and wastewater systems located close to demand nodes may have lower per unit metropolitan water and wastewater supply costs compared to a large centralised desalination solution (Chen and Wang, 2009; Gikas, 2009; Lee et al., 2013; Morales-Pinzón et al., 2012; Shahabi et al., 2014a; Shahabi et al., 2015a).

Policy makers and engineers need to make sure that planning decisions over metropolitan desalination supply create an overall benefit for the system rather than a burden shift between economic and environmental impact categories (e.g. private costs versus external costs)(Al-Nory et al., 2013; Saif and Almansoori, 2014) or between supply system life cycle stages (e.g. the construction phase versus the operational phase) (Loubet et al., 2014; Zhou et al., 2014). Developing desalination planning strategies for metropolitan areas requires a systems approach that covers the environmental and economic life cycles at a high level of detail.

1.2. Sustainable desalination planning

Life cycle assessment (LCA) is a systematic tool used to analyse and assess the environmental impacts of a product system throughout its life cycle (Horne et al., 2009). LCA has been employed to assess alternative strategies and planning implications for reducing the environmental impacts of desalination systems.(Zhou et al., 2014) A wide range of desalination planning options and strategies, including moving toward cleaner energy sources for treatment (Biswas, 2009; Jijakli et al., 2012; Norwood and Kammen, 2012; Raluy et al., 2005; Salcedo, 2012; Shahabi et al., 2014b; Stokes and Horvath, 2009; Zhou et al., 2011), optimising plant size and location (Shahabi et al., 2014a; Shahabi et al., 2015a), improving source water quality (Muñoz and Fernández-Alba, 2008; Shahabi et al., 2015b), and process optimisation (Al-Sarkal and Arafat, 2013; Beery and Repke, 2010; Beery et al., 2010; Hancock et al., 2012), have been assessed using LCA. In previous LCA studies, assessment of strategic options typically follows a procedure of conducting LCA for each alternative, and then comparing the environmental performances of each option. This approach has typically relied upon there being a limited number of alternative options to be compared. However, the method becomes intractable when there are large numbers of decision parameters, as extensive computational capacity is then required to solve for the optimum desalination planning solution. LCA integrated with mathematical optimisation techniques (Azapagic, 1999) could offer a novel means for determining the desired parameter settings in these more complex situations.

Since 1952 mathematical optimisation techniques have been employed as a planning tool in the water resources sector (Vaux and Howitt, 1984). Optimisation models address water allocation planning (Chung et al., 2009; Chung et al., 2008; Draper et al., 2003; Georgopoulou et al., 2001; Han et al., 2008; Joksimovic, 2008; Kondili et al., 2010; MedellÃn-Azuara, 2007; Ray, 2010; Reca et al., 2001; Vaux and Howitt, 1984), water supply infrastructure planning (Al-Nory et al., 2013; doosun, 2012; Kang and Lansey, 2012; Lim et al., 2010; Liu et al., 2011; Ray, 2010; Saif and Almansoori, 2014; Voivontas et al., 2003; Wu, 2008; Wu, 2010), regional wastewater allocation planning (Wang, 2002) and regional wastewater infrastructure planning (Cunha, 2009; Leitão et al., 2005; Ray, 2010; Zechman, 2007). Among these literatures there are decision-making methods designed for large investments in seawater desalination (Al-Nory et al., 2013; Saif and Almansoori, 2014). In 2013, Al-Nory et al. (2013) developed a mathematical optimisation model to solve for desalination plant location, intake type, capacity, operational considerations, distribution network structure and capacity. In 2014, Saif and Almansoori (2014) developed multi-period MILP modelling to optimise the retrofit of a water desalination supply system. The modelled key decision variables included new facility location and capacity expansion of water desalination supply chain infrastructure assets. In both these works Al-Nory et al. (2013) and Saif and Almansoori (2014), there is lack of detailed environmental impact data for various sizes of desalination plant and pipeline infrastructure, which could lead to burden shift between supply system life cycle stages (e.g. the construction phase versus the operational phase). In order to tackle the burden shift issue we have integrated mathematical optimisation with LCA.

To the best of our knowledge this is the first time that a life cycle optimisation framework has been employed for sustainable desalination planning in metropolitan areas. Uniquely, the framework incorporates into the planning process metropolitan land use constraints, water demand spatial and temporal patterns, and the complex relationship between desalination plant siting and infrastructure interconnections. The life cycle optimisation approach incorporates all potential decisions (e.g. optimal construction staging and location of the desalination plant and associated infrastructure) into a mathematical optimisation model that targets environmental and economic objectives (e.g. economic costs or direct and indirect environmental emissions) under case specific constraints (e.g. metropolitan land use constraints). This framework could be used to combine decision-making criteria from the distinct disciplines of engineering, economics, environment and land use planning when seawater desalination investments are contemplated for metropolitan areas.

1.3. Research scope

We integrated the tools of MILP, Geographic Information System (GIS), LCA and financial cost modelling in order to develop a framework for compatible land, environmental impacts and desalinated water supply in metropolitan areas. A multi-period MILP algorithm was used to optimise the desalinated water supply based on both life cycle costs and environmental impacts, allowing their trade-offs to be explored. The model incorporated full LCA, considering the whole life cycle of various sized of plants and pipelines, from construction to operation. The model, combined with scenario analysis, can help identify the influence of land-use, economic and environmental policies on the optimal decision.

The framework was tested for future desalination planning in the northern metropolitan area of Perth, Western Australia.

2. Materials and methods

To achieve sustainable desalination planning within existing metropolitan areas, we developed a quantitative framework by integrating

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