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Comparative economic and environmental assessments of centralised and decentralised seawater desalination options

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HIGHLIGHTS

- Comparative life cycle assessment of decentralised and centralised desalinated water supply
- Integration of spatial case study scenarios with LCA and levelised cost analyses
- Using the case of Perth, Australia, future planning of desalination was evaluated.
- Decentralisation is a potential strategy to reduce environmental impacts of desalination.

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ABSTRACT

This study presents comparative life cycle assessments (LCAs) and levelised cost (LC) analyses of desalination supply systems, integrated with a spatial–temporal model at three geographical scales: a *centralised scenario* and two alternative *decentralised scenarios*. For the *centralised scenario* we focused on a proposed 320,000 m^3/day SWRO desalination plant to support future urban expansion in the northern corridor of Perth, Western Australia. The alternative, *decentralised scenarios* each integrate several medium sized plants into the same geographical water demand area as the *centralised scenario* and also produce 320,000 m^3/day in total. Results indicate that environmental impacts would be ~20% lower and LC 7% to 18% lower for the *decentralised scenarios* than for the *centralised scenario*. Contribution analysis revealed that, for the *centralised scenario*, although economies of scale resulted in lower environmental impacts from the desalination plant construction and operation phases, these savings were outweighed by the environmental impacts associated with the construction and operation of the water transfer mains required to connect the large plant to the network. Perth water stakeholders and policy makers can use our results to inform development decisions, and the proposed LCA method can be implemented in other metropolitan areas for desalination planning.

1. Introduction

1.1. Background

Desalination has a long history of supplying clean water in arid environments such as the Middle East, the Caribbean and the Mediterranean. However, recent climate change, combined with population growth and limited availability of terrestrial water sources, has hastened the widespread expansion of the technology. Freshwater resources are scarce, whereas desalinated seawater is climate independent and only limited by the capital and energy required to produce it. Moreover, approximately three billion people — about half of the world's population — live within 200 km of a coastline [1], so seawater is an accessible resource.

A recent trend in seawater desalination is the construction of large capacity plants, and this has significantly contributed to freshwater supply for coastal cities around the globe. Large desalination plants built between 2000 and 2005 were typically designed to supply 5 to 10% of the drinking water of coastal cities. More recently, regional or national seawater desalination projects in countries such as Spain, Australia, Israel, Algeria and Singapore have been planned to fulfil 20 to 50% of a city's long term drinking water needs [2]. Desalination plants enjoy economies of scale in treatment facility construction. However, potential sites for large plants need to meet specified criteria such as proximity to the ocean, access to a power source and minimal impact on environmentally sensitive areas [2]. Obtaining land planning and environmental regulatory approvals for large plants and maintaining ongoing compliance can be challenging in developed countries with effective environmental legislation and governance. Identifying sites that meet all of these criteria — while having enough acreage to accommodate a large-scale plant, its various components and the necessary buffers — is generally not possible in established

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urban areas. These regulatory barriers result in large desalination plants being constructed far from the location of water demand and consequently long water transportation distances, compared to those that would apply if plants were instead located within the distribution network. Long distance water transportation has environmental and economic burdens that should be considered in the planning stage.

Currently, reverse osmosis (RO) is the leading technology for seawater desalination [3]. When compared with conventional sources such as dams, seawater reverse osmosis (SWRO) plants are a more desirable option for decentralisation because SWRO has a scalable, modular design whereas conventional water sources such as dams lack design and scale flexibility. Dam sites are also highly restricted by natural factors such as site topography, catchment conditions, salt levels and soil materials while the only naturally restricting factor for desalination plants is proximity to treatable water.

This paper argues for the need to identify the optimum geographical scale of a desalination system and thus resist the default mindset of "big is better" [4] in the water sector. A framework for investigating the optimum geographical scale for water planning using spatial and temporal case study data (e.g. land availability, water demand, and existing pipeline network) coupled with hybrid life cycle assessment (LCA) and levelised cost (LC) analyses is proposed. Comparative LCA and LC are demonstrated for three geographical scale desalination supply systems, these being one centralised scenario and two decentralised scenarios. For the centralised scenario we focus on a new 320,000 m^3/day SWRO desalination plant. The decentralised scenarios — where several smaller plants also produce, 320,000 m^3/day in total — are proposed as alternative water supply options for the same area of demand. Centralised planning of desalination supply system often leads to economies of scale in the construction phase. However, engineers and decision makers need to make sure that centralisation generates overall system benefits rather than only shifting environmental and economic burdens from the treatment facility's construction to other sub-systems such as distribution network construction and/or the operational phase. Understanding which planning strategies may be most beneficial in the long run requires a system approach that not only covers all life cycle stages of the supply system at a high level of detail, but also considers a range of environmental impacts to avoid burden shifting between different environmental impact categories.

1.2. Perth case study

Perth, Western Australia (WA) has been chosen as a case study due to the availability of comprehensive site-specific data and the appropriateness of its geography, geology, climate and urban form to the employment of the desalination technologies under examination. The metropolitan area of Perth has a low-density urban form spread along the coast of the south west of Western Australia and is built predominantly upon ancient sand dunes. Since about 1975, south west Australia has experienced a significant reduction in rainfall which, combined with population growth, has led to an increased dependence upon desalination to secure its water supply [5]. Perth is currently the largest user of seawater desalination among Australian cities [6]. Half of the water supply for Perth and surrounding areas is sourced from two large seawater reverse osmosis (SWRO) plants; the Southern Seawater Desalination Plant (SSDP) and the Perth Seawater Desalination Plant (PSDP) contribute 320,000 m^3/day and 145,000 m^3/day respectively. A new 320,000 m^3/day SWRO desalination plant, the Northern Seawater Desalination Plant (NSDP), was proposed to support future urban expansion in the northern corridor of Perth and to replace a loss of capacity in the groundwater water supply system resulting from a persistent trend in reduced rainfall in its catchment area [7]. The SSDP and PSDP are located 130 and 30 km south from Perth city centre, respectively. The NSDP would be located 90 km north of Perth's city centre.

The water supply infrastructure in Perth is operated by the government-owned enterprise, Water Corporation. Water Corporation purchases electricity for its two large desalination plants (total design capacity of 465,000 m^3/day desalinated water) from three wind and solar farms annually and consumes the equal amount of electricity from WA's electricity grid [8]. The pairing of desalination plant with wind and solar farms can reduce supply chain GHG emissions by 90% per unit of water [9] provided the pairing results in renewable energy production that is additional to any mandated portfolio standard. However, the purchase of renewable energy may come at a price premium and is susceptible to changes in government policy. The current study evaluates the decentralisation of SWRO desalination plants as a possible strategy to reduce the life cycle impacts of desalinated supply systems, independently of the energy supply choice.

1.3. Literature review

Geographical scale assessment of water supply can be tracked back to the cost modelling of water supply systems by Clark and Stevie in 1981 [10]. Technical, economic, environmental and social performance of different scales of water and sanitation supply options such as stormwater recycling, grey water recycling, truck distribution [11], wastewater treatment [11–14], desalination [11,15–18] and rainwater tank [19] were investigated in the literature employing a range of different quantitative and qualitative methods. Methods included mathematical optimisation [15–17], multi-criteria decision analysis [11,13], sustainability analysis [12], specific net present value [14], and statistical analysis [19]. These quantitative and qualitative methods were applied to different case studies in developing and developed countries. While these studies have acknowledged the significance of decentralisation as a planning strategy for improving water supply economic and environmental performance, there is a lack of application of full LCA perspective in the assessments. A few studies have considered the carbon footprint of a supply option's operational phase in their geographical scale assessment rather than a holistic environmental appraisal [16–18]. Moreover in these works, there is a lack of detailed environmental impact data for various sizes of treatment plant and pipeline infrastructure. Life cycle assessment, standardised by the International Organisation for Standardisation (ISO) [20] is a powerful tool for environmental impact assessment of the systems that produce goods or services. Full LCA can be used to identify cases of burden shifting, i.e. between different environmental impact categories (e.g. climate change versus ozone layer depletion) or between supply system life cycle stages (e.g. construction phase versus operational phase). Developing desalination planning strategies for metropolitan areas requires a system approach that covers the environmental and economic life cycles at a high level of detail. To the best of our knowledge, previous studies have not considered the geographical scale of a supply system when evaluating the supply chain contributions to the life cycle environmental impacts and economic costs of desalination. The objective of this study is to conduct the full LCA of the proposed NSDP using a hybrid Economic Input–Output (EIO) environmental LCA approach coupled with temporal and spatial modelling of the case study scenarios, and then to use these estimates to complete a comparative LCA and LC of the centralised and decentralised desalination systems modelled. The method has the potential to be used in geographical scale assessments of proposed water supply systems more generally.

2. Methodology

2.1. Overview

We created a spatial–temporal database of forecast desalinated water demand from 2015 to 2035, vacant land for accommodating plants and water storage facilities, and existing pipeline infrastructure,