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Influence of site-specific parameters on environmental impacts of desalination

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ABSTRACT

Many metropolitan areas have a high dependency on Seawater Reverse Osmosis (SWRO) desalination plants for bulk water supply. Location and scale decisions are important for SWRO desalination plants owing to the significant environmental costs associated with long distance water pumping. The aim of this study is to introduce a Geographical Information System (GIS)-based method to assist such site-specific decisions. The method has 3 stages. Stage 1 uses GIS to identify feasible plant locations and water demand areas. Stage 2 develops a range of scenarios that balance plant size and number with water demand. In stage 3, the preferred scenario is selected based on environmental life cycle assessment. The method's applicability was tested using data for the northern corridor of Perth, Western Australia (WA). Spatial water demand and suitable vacant land for accommodating SWRO plants in the case study are obtained in Stage 1. Based on these spatial data, two water planning options are designed in order to supply desalinated water to the demand area. The first option consists of a large SWRO desalination plant and its connected trunk main which supplies water into the demand centrally (centralized scenario). Second option consists of five medium-sized SWRO desalination plants integrated within the demand area (distributed scenario). The best scenario for environmental performance was found to be the distributed scenario which has 18% less GHG emission compared to centralized scenario. This method is adaptable to other case studies for identifying optimal SWRO plant sizes and locations based on environmental criteria.

Keywords: Distributed water supply; GIS; Life cycle assessment; Perth; Reverse osmosis; Plant size

1. Introduction

Over the past decade, population growth and climate change necessitated a shift from relying on conventional water sources to a diversified climate change independent water resource such as seawater and wastewater. Moreover, seawater desalination allows access to unlimited source of ocean. However, high energy intensity and subsequently high environmental impacts of desalinated seawater gives rise to concerns on its sustainability.

Since the 1990s, life cycle assessment (LCA) has been used as a tool to account and improve environ-

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mental performance of seawater desalination [1]. LCA studies of different seawater desalination technologies showed that Reverse Osmosis (RO) process has lower environmental load in comparison with thermal technologies of Multi Effect Desalination and Multi Stage Flash due to lower primary energy use and higher energy efficiency [2]. Due to significant role of energy use in total life cycle environmental impacts of seawater reverse osmosis (SWRO), previous studies investigated the effect of different electricity production models on the life cycle airborne emissions associated with desalination technologies and concluded that the electricity production models with a higher share of renewable energy decreased the environmental impact of desalination [2–4].

Although life cycle environmental impacts of SWRO have been accounted in previous work [2–5], no investigation of the influence of site-specific parameters such as size and location of SWRO desalination plants on their environmental impacts has been made. In order to capture the influence of these parameters on their environmental performance, a Geographical Information System (GIS)-based methodology was developed to aid in such decision makings. Another contribution of this study is through comparing centralized and distributed desalinated water supply system for a case study of Perth, Western Australia (WA).

2. Materials and method

2.1. Case study—Perth, WA

The methodology as will be described in Section 2.2 is applied to a case study in the northern Perth metropolitan area, WA. Perth is currently the largest user of seawater desalination [6] among Australian cities. Half of the water supply for the Perth and surrounding area is sourced from two large SWRO plants. The Southern Seawater Desalination Plant and the Perth Seawater Desalination Plant contribute 100 and 45 GL per year, respectively. A new SWRO desalination plant is proposed to support future urban expansion in the northern corridor of Perth and to replace a loss of capacity in the groundwater system [7]. In this study five desalinated water demand areas are considered in northern corridor of Perth as illustrated in Fig. 1(A).

2.2. GIS-based model

A three-stage methodology to identify location and scale decisions for SWRO desalination plants is proposed. The three stages are (1) identify the demand areas and feasible plant locations (Stage 1), (2) develop a range of scenarios that balance plant size and number with water demand (Stage 2), and (3) selection of preferred scenario based on their environmental performance (Stage 3). All spatial related tasks are performed using ArcGIS version 10.

2.2.1. Stage 1

2.2.1.1. Site selection. Site selection for a desalination plant is most often based on land availability near the water demand and on the location of the delivery points of this water to the distribution system. Moreover, potential alternative sites must be selected that meet the following requirements [8]:

- Accessibility from existing main roads, highways, etc.
- Proximity to the points of delivery of the desalinated water to the local distribution system (usually less than 8 km)
- Proximity to power supply for the plant
- Relatively short distance from the source of saline water and the points of concentrate discharge (usually less than 1 km)
- Compatibility with local land planning and zoning requirements
- Location outside of environmentally sensitive areas
- Adequate distance from residential dwellings, hotels, hospitals and other developments whose inhabitants could be sensitive to increased level of noise and traffic during plant construction and operation (at least 30 m)

Based on these requirements, input data into the GIS was collected for the case study (Table 1). Potential locations for SWRO desalination plants were selected in order to meet all of these requirements except local land planning and zoning requirements due to the fact that investigation of land use and possibility of land use change is out of the scope of this study.

2.2.1.2. Water demand. The most common method of allocating baseline water demands is a simple unit loading method [12]. This method involves counting the number of customers that contribute to the demand at a certain point, and then multiplying that number by the unit demand. The boundaries of desalinated water demand are also often influenced by the ability of the alternative water source to supply lower cost water to the same area of demand in order to balance water demand and supply.

In the current study, within the area boundaries water demand is fully supplied by desalinated water.

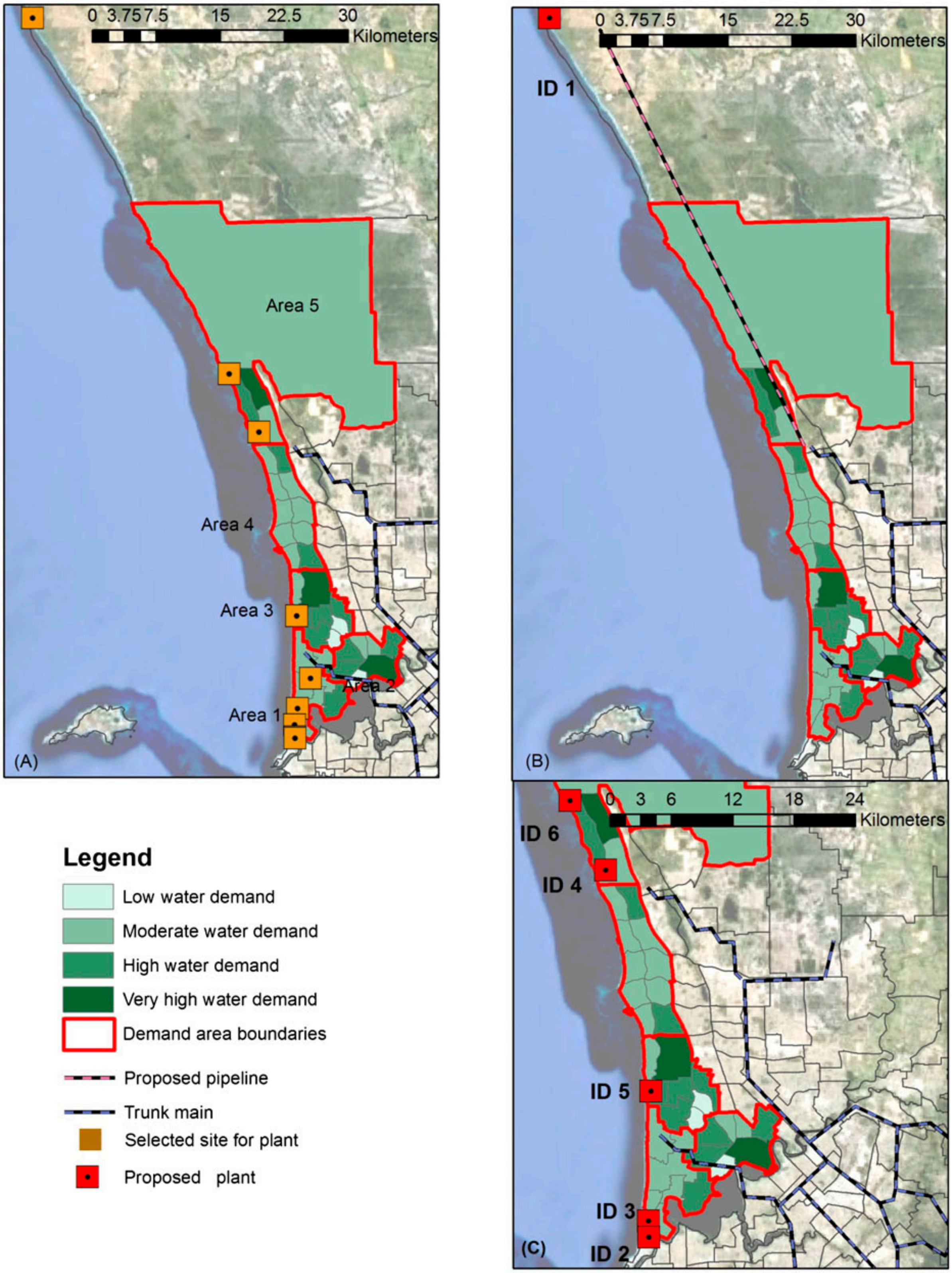

Fig. 1. Geographical illustration for (A) Potential plant sites and demand areas (B) Centralized scenario supply system (C) Distributed scenario supply system.

Table 1
Input data for GIS model

Data group	Individual layers	Source of spatial data (case study)	Notes
Potential site	Water distribution system	[7]	Relevant data were extracted from the original spatial data-sets and modification were made
	Vacant land	[9]	–
	Population	Own data gathering and processing	Spatial data were obtained by combining two sets of data-sets; Population Estimates by Statistical Area Level 2 [10] and Statistical Area Level 2 Digital Boundaries [11]
Water demand	Water demand	Own data gathering and processing	Spatial data were obtained by multiplying spatial population by annual water demand of 145 m^3 [7]
	Current and potential future water sources in the area	[7]	Relevant data were extracted from the original spatial data-sets and modifications were made

The spatial demand of desalinated water was determined by multiplying the number of customers in year 2015 by the annual demand of 145 m^3 [7]. Desalinated water demand was assumed to be constant during the 30-year system lifetime. Input data to the GIS model for building spatial demand of desalinated water is illustrated in Table 1.

2.2.2. Stage 2

The candidate sites and spatial demand of desalinated water identified in Stage 1 served as an input for Stage 2 of the analysis. Water planning scenarios with different size and location for desalination plants are designed in order to satisfy the total desalinated water requirement at the end of the 30-year planning period.

2.3. Stage 3: comparative LCA

The method applied ISO14040 [13], with LCA conducted in four stages: goal and scope, inventory analysis, impact assessment, and interpretation.

2.3.1. Goal and scope

The goal of this LCA is to compare life cycle GHG emissions of the scenarios designed in Stage 2. The functional unit for the study is one cubic meter of water supplied to the demand area in the 30-year lifetime. The scope of this study is primarily cradle to gate. More specifically, each life cycle inventory (LCI) covers the construction phase and the operational phase for SWRO plants, with some coverage of the disposal phase for high impact inputs. The main input flow analyzed were chemical use, materials consumed for membrane replacement, and electricity consumption associated with seawater extraction, water treatment, and the transportation of desalinated water to final users. Disposed waste of membranes to landfill at the end of their assumed service life was also included in each LCI. Discharged streams to sewer due to "clean in place" and chemically enhanced backwash, as well as discharged brine to sea were also covered. The decommissioning of the system was not considered. The assumptions for designing the systems are listed in Table 2.

Table 2
System assumptions and description

Assumptions	Description
Water transfer main	
Water transportation head loss	3 meters per kilometer[14]
Motor efficiency	94%
Pump efficiency	82%
SWRO plant	
Treatment process electricity use	Calculated by Rosa software for different sizes[15]
Membrane material	Obtained from [16]
Chemical use, waste disposal, material transportation	Obtained from [4]
Infrastructure capital cost	Calculated by SWRO cost estimator tool[17]

Table 3
Life cycle GHG emissions per functional unit

	Distributed scenario						Centralized scenario					
				GHG emissions (kg CO_2 eq./m^3)						GHG emissions (kg CO_2 eq./m^3)		
Service area	Plant ID	Plant size (m^3/d)	Water transportation distance (km)	Treatment	Water transportation	Total	Plant ID	Plant size (m^3/d)	Water transportation distance (km)	Treatment	Water transportation	Total
Area 1	2	50,000	–	3.29	–	3.29	1	260,000	95	3.16	1.03	4.19
Area 2	3	50,000	–	3.29	–	3.29	1	260,000	95	3.16	1.03	4.19
Area 3	4	60,000	–	3.28	–	3.28	1	260,000	65	3.16	0.81	3.97
Area 4	5	65,000	–	3.28	–	3.28	1	260,000	75	3.16	0.70	3.86
Area 5	6	35,000	–	3.30	–	3.30	1	260,000	55	3.16	0.59	3.75
Total	–	–	–	–	–	3.28	1	260,000	95	–	–	4.00

2.3.2. LCI analysis method

A LCI is the phase of LCA aimed at compiling all output emissions and wastes and also input resources as environmental flows[18]. In this study, LCI for construction phase was defined by economic input–output based (IO-based) LCI method. For operational phase, LCI was obtained by process based LCI method. Using economic input–output for construction phase was due to the process data limitation. The foreground data for the construction phase and operational phase are in monetary and physical units, respectively. Operational phase background data was mostly selected from an Australian database [19] and the grid electricity and transportation were selected for WA. For material and processes, which were not available in the Australian database, Ecoinvent library was used as a supplement database[20]. Construction phase background data are selected from GHG Input–Output LCI for Australia [21].

2.3.3. Life cycle impact assessment (LCIA) method

LCIA is the final phase of LCA in which inventory data are converted into impact results through the use of appropriate algorithms or indicators, to simplify understanding and assessing the environmental impact of a product system [18]. GHG emissions in kg CO_2 equivalent was calculated based on the Intergovernmental Panel on Climate Change 2007 method for the timeframe of 100 years with Simapro software [22].

3. Results and discussion

By implementing the GIS modeling as outlined in Section 2, desalinated water demand and most suitable locations for medium-scale desalination plants were identified in the case study area as illustrated in Fig. 1(A). In Stage 1, 8 suitable locations were identified for medium and small-sized SWRO desalination plants. In Stage 2, based on spatial desalinated water demand and potential sites, two water planning scenarios (centralized scenario and distributed scenario) were designed to supply the demand as illustrated in Fig. 1(B) and (C). In the centralized scenario, desalinated water was supplied to the demand area through a large centralized plant located nearly 95 km from demand area. In the distributed scenario, desalinated water was supplied locally by five decentralized plants located in the demand areas.

Table 3 presents the life cycle GHG emissions of two scenarios. The life cycle GHG emissions have been validated through comparison with other studies [4,5]. Results indicate that the distributed scenario has 20% lower life cycle emissions than the centralized scenario. Reducing the water transportation pumping in the distributed system plays a positive role in reducing GHG emissions in distributed water planning. In the distributed scenario, the highest GHG emissions per functional unit belong to Area 5. This is due to the fact that desalinated water is supplied to this area through an onsite desalination plant with a capacity of 35,000 m^3/d. The treatment process electricity use is slightly higher in the smaller plants due to the lower efficiency in centrifuge pumps in lower flow rates and consequently higher GHG emissions. Moreover, higher GHG emissions arise from construction of the water treatment plant buildings due to the diseconomy of scale for construction phase in small plants. In contrast, lowest GHG emissions per functional unit belong to Area 5 in centralized planning. This is due to the low water transportation distance between large SWRO plant and this demand area.

Generally, the results show that site-specific parameters of plant location and size could significantly affect the environmental impact of SWRO desalination plants. For this case study of the Perth northern metropolitan area, distributed water planning has lower GHG emissions than centralized water planning.

4. Conclusion

In this study a three-stage methodology was developed to assist in SWRO desalination plant location and size decision-making considering the environmental performance of the systems. Stage 1 used a GIS-based approach to identify potential sites and spatial desalinated water demand in the area under study. Stage 2 used input data from Stage 1 to develop water supply scenarios. Stage 3 compares the scenarios to obtain the optimum water supply scenario considering environmental impact of the system. To illustrate the model, a case study was applied. Two common scenarios of centralized and distributed water planning were compared in Perth, WA. Generally, results showed that site-specific parameters of plant location and size could significantly affect the environmental impact of SWRO desalination plants. For the case study of Perth northern metropolitan area, distributed water planning has better environmental performance than centralized water planning.

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