Energy Assessment of Seawater Toilet Flushing in Qatar

Hamish R. Mackey(✉), Saad Hafiz, and Sami G. Al Ghamdi

Division of Sustainable Development, College of Science and Engineering, Hamad Bin Khalifa University, Qatar Foundation, Doha, Qatar
hmackey@hbku.edu.qa

Abstract. Seawater toilet flushing (SWTF) is an alternative water source that has been utilised in Hong Kong for economical water supply and demonstrated using other Asian case studies. Yet how the impact of SWTF translates to other regions with different water supply sources and wastewater discharge requirements remains unexplored. In this study, we look at SWTF for the water-scarce Middle East using Doha, Qatar as a case study. We demonstrate the importance of wastewater discharge conditions on the effectiveness of this technology and the role that corresponding water conservation efforts may play. Where water reuse is a baseline condition the effectiveness of SWTF is limited.

Keywords: Water resources · Scope boundary · Desalination

1 Introduction

Water scarcity is a severe economic and social stress for many countries and is ranked the most significant global risk with respect to impact over the coming decade (WEF 2015). Such impacts will be especially severe in the Middle East which will include 14 of the 33 most water-stressed countries by 2040, including five countries with a water stress index of 5.0/5.0 (WRI 2015). For this reason, this region is also the most reliant on energy-intensive desalination for water supply. Seawater toilet flushing (SWTF) is a potential technology that could benefit the regions coastal cities as an alternative to using desalinated water, as toilet flushing water requires only minimal treatment. SWTF has been utilised widely in Hong Kong for 60 years, and economically remains a preferred water supply option for the city (Tang et al. 2006; HK-DEVB 2014). Moreover, its environmental and energy benefits have been demonstrated in life cycle studies using a number of Asian cities as case studies (Liu et al. 2016). However, water supply sources and wastewater treatment and reuse regulations strongly influence the overall boundary conditions of any assessment, making outcomes of Asian case studies possibly inapplicable for other regions.

Qatar, located on a small hyper-arid peninsula within the Arabian/Persian Gulf, is one of the five countries with a predicted 2040 water stress index of 5.0/5.0. Already the municipal supply is 99% reliant on desalination (Kahramaa 2017) and wastewater recycling is already widely implemented for landscaping and fodder crop irrigation but has limitations on further use due to social acceptance (Alhumoud and Madzikanda 2010). Paradoxically, the country has one of the highest levels of per capita water use

G. Mannina (Ed.): UDM 2018, GREEN, pp. 963–968, 2019.
https://doi.org/10.1007/978-3-319-99867-1_166

globally at roughly 550 L/cap/d (Kahramaa 2017) and intense efforts are underway to reduce this consumption. For these reasons, Qatar makes an interesting case study for seawater toilet flushing. Furthermore, Qatar, like many Gulf countries, prohibits the discharge of treated wastewater to the ocean in an effort to encourage reuse and to protect the shallow enclosed oceans, on which desalination is dependent, from eutrophication. Consequently, the increased salinity of wastewater caused by SWTF requires desalination of the resulting brackish wastewater, possibly offsetting benefits of avoiding initial desalination. This study, therefore, assesses the suitability of seawater toilet flushing for the Middle East using Doha, Qatar as a case study.

The study focuses on the reduction in energy demand and water withdrawals that could possibly be achieved with SWTF in the region. Specific objectives assessed are understanding (1) the influence of the boundary conditions, particularly enforced wastewater reuse, on the effectiveness of SWTF compared with Asian case studies where ocean disposal and alternative water supplies were available; (2) the influence of changing household water demands on the effectiveness of SWTF, since water conservation could result in increased salinity of the wastewater if non-toilet uses are most conserved and; (3) the influence of desalination method as Qatar slowly shifts from thermal desalination processes to seawater reverse osmosis (SWRO) desalination.

2 Materials and Methods

2.1 Location and System Description

In Doha, Qatar, 99% of municipal water supply is by desalination, of which 94% is thermal technology (mainly multi-stage flash, MSF) (Kahramaa 2017). This water is supplied from two desalination sites to the city where it is distributed to local neighbourhood pumping zones consisting of looped networks. Wastewater collected from the city is transported to one of three major wastewater treatment plants (WWTPs) and undergoes advanced treatment including ultrafiltration for irrigation purposes. Household water use for toilet flushing in Qatar and nearby regions is 11% due to high water usage for other activities (Al-Mohannadi 2001; RTI & EAA 2009). The system diagram and boundary of the analysis are shown in Fig. 1. As the existing wastewater treatment plant remains the same in all scenarios and data for its energy use was unavailable, it has been excluded from the analysis.

2.2 Analysis Scenarios

The study compares the existing use of MSF desalinated supply (Base-0) with the augmentation of SWTF (SWTF-0), and additionally SWTF if desalination is by SWRO (SWTF-0-RO). In all these cases toilet flushing is 11% of water demand. In the second stage of analysis, the impact of future water conservation efforts is considered under two extremes. In the first, all water savings occur for outdoor uses, denoted by "-O-X" where X is the percentage water saving. For example "SWTF-O-10" would be for the case with SWTF with a 10% water conservation based on reductions only to outdoor water use. In this case, both the salt load and volume of wastewater from the house

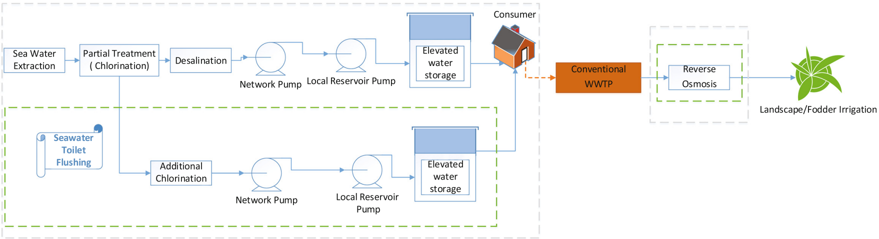

Fig. 1. Schematic of the overall process. Grey-dotted lines indicate system boundary of analysis. Green-dotted lines indicate additional components in the SWTF scenario.

remain constant assuming evaporation/infiltration of all outdoor water. In the second case, all water savings were associated with indoor usage other than the toilet, causing the wastewater salinity to increase due to decreasing volume but constant salt load. This scenario was denoted by "-I-X" where X is again the percentage of water saving. The resulting flows and salinities of each scenario are given in Table 1, based on inventory data given in Sect. 2.3.

Table 1. Relative volumes of water for each stage of abstraction, use and disposal relative to the original Base-0 household use of 1 m^3 of desalinated water.

Water supply scenario	Base-O			SWTF	SWTF-O		SWTF-I	
Conservation level	0%	10%	20%	0%	10%	20%	10%	20%
Water desalinated	1.064	0.957	0.851	0.947	0.827	0.705	0.827	0.705
Seawater abstracted	0	0	0	0.117	0.117	0.117	0.117	0.117
In-house desalinated water use	1	0.9	0.8	0.89	0.79	0.69	0.79	0.69
In-house SWTF use	0	0	0	0.11	0.11	0.11	0.11	0.11
To sewer	0.550	0.550	0.550	0.550	0.550	0.550	0.495	0.440
Wastewater salinity (g/L)	1	1	1	1.80	1.80	1.80	1.86	1.95

2.3 Data Inventory

Data used in the project was from 2016 and 2017 and were collected from Qatar's sole water utility provider and Qatar's Ministry of Development Planning and Statistics.

Desalination. Energy requirements for MSF are 4 kWh/m^3 electrical energy for mechanical equipment and 16 kWh/m^3 electrical equivalent of thermal energy capable of driving a steam turbine (Darwish et al. 2016). Energy for SWRO is 4.5 kWh/m^3 including pretreatment.

Transmission Main and Looped Network Conveyance. Desalinated water is conveyed from two locations via a connected ring transmission corridor consisting of 2 × 1600 mm DN ductile iron pipes with a total length of 168 km per pipeline. Headloss was calculated using the Darcy Weisbach and Colebrook-White method using an estimated pumping velocity of 2.1 m/s based on water demand (MDPS 2017). Velocities were adjusted according to flow reductions caused by SWTF implementation. Pumps were assumed to have an efficiency of 85% and the static pressure requirement in the system was taken as 10 m head, which had negligible influence on the specific pumping energy. Pumping energy of 0.015 kWh/m^3 was provided for by the local water utility for the looped distribution system within the city after it has been pumped to a neighbourhood reservoir. The total loss in the transmission and neighbourhood network is 6% (Kahramaa 2017). For the SWTF system, a conceptual ring main was laid around Doha with a length of 60 km and with a design velocity of 2.1 m/s. Sensitivity analysis of the SWTF ring main design (data not shown) indicated no significant influence on the analysis outcomes.

Wastewater Treatment. The current fraction of household water supply entering the sewerage network is 55%, with the remainder assumed to go to outdoor uses (MDPS 2017). No data was available for the sewerage network or treatment plant design/operation that may influence energy use. Therefore these were excluded from the boundary. The primary consideration for the WWTP is the need for RO desalination for any further increase in wastewater salinity beyond the existing baseline of 1000 mg/L TDS. Energy requirements for the WWTP RO at varying salinities was calculated using Hydranautics IMS Design software where the SWTF contribution is 42,000 mg-TDS/L-seawater based on Arabian Gulf salinity (Beltagy 1983).

3 Results and Discussion

3.1 Total Energy Comparison

All options relative to the base case provided an overall energy saving due to the significant contribution of thermal energy used in the MSF process that could otherwise be utilised for work to generate electrical energy (Fig. 2). However, when only considering mechanical energy utilised in the processes SWTF no longer became advantageous compared to the base case, showing a small increase due to the WWTP RO. Water conservation efforts towards internal use were more effective than outdoor use due to the reduction in wastewater flows, despite causing a higher water salinity to the WWTP RO (Table 1). However, these differences were minute. The results also indicate that if SWRO is used for seawater desalination, then SWTF would not be advantageous, given the higher mechanical energy requirements of SWRO. In all cases, conveyance energy requirements were negligible compared to desalination both for supply and for wastewater treatment.

3.2 Volumetric Energy Requirement

In the case of outdoor water conservation SWTF led to increasing specific mechanical energy requirements with increasing water conservation due to the increase of salinity in the wastewater without a reduction in volume. When considering total energy, a small difference was observed in specific energy requirements between the options, with the difference for SWTF between indoor and outdoor conservation almost negligible. A change in the portion of water used inside the house (i.e. going to the sewer) led to little change in the overall energy comparison but led to significantly closer specific energy requirements (data not shown).

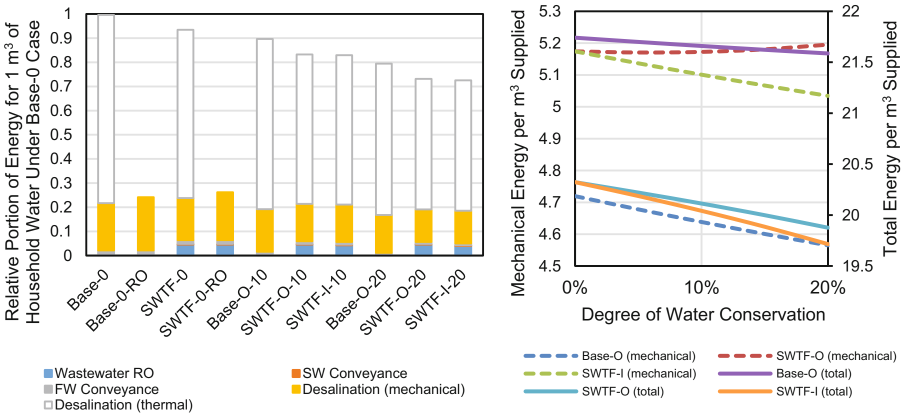

Fig. 2. Comparison of the energy requirements for the different scenarios showing relative contributions to the base case from different system components (left) and absolute specific energy requirements (right).

3.3 System Boundary Considerations

Existing studies demonstrating SWTF systems as environmentally and cost competitive have started with a base case of surface/imported water supply and ocean discharge of treated wastewater (Tang et al. 2006; Liu et al. 2016). However, for a city to consider a dual network for toilet flushing indicates high water-stress and therefore that existing desalination or water reuse is likely existing or also planned. In this study the MSF water supply system should favour SWTF, being the most energy intensive option available. Despite this, SWTF showed only minor improvements in total energy. When compared with SWRO, a more popular but still energy-intensive desalination process, it was more disadvantageous to co-implement SWTF than solely desalinate. Only in cases where water scarcity is less severe surface water or groundwater supplies may still exist, but in these scenarios SWTF is at an even higher energy penalty if water reuse is implemented. Another critical consideration of genuinely water-scarce cities is water availability which also does not favour SWTF. For instance, the water savings available through water reuse is considerably greater than that of SWTF as it makes use of all internal house water (55% vs 11% in Qatar case). Thus, for very water-scarce cities, the choice of SWTF does not seem to be advantageous, especially in light of construction costs and additional maintenance requirements (Tang et al. 2006).

4 Conclusions

This work demonstrates the importance of existing wastewater discharge conditions on the effectiveness of proposed water supply strategies, namely SWTF. In the Middle East case, despite a reliance on high-energy thermal desalination for water supply, the case for SWTF does not appear strong due to energy requirements for water reuse RO. Water conservation efforts in conjunction with SWTF and water reuse create a tradeoff between reduced treatment volume and increasing salinity resulting in reduced benefits. It is therefore recommended to only focus on water reuse and conservation within severely water-stressed cities.

References

Al-Mohannadi, H.I.: Water resources in the State of Qatar: toward holistic management. Doctoral thesis, University of Huddersfield (2001)

Aluhumoud, J.M., Madzikanda, M.: Public perceptions on water reuse options: the case of Sulaibiya Wastewater Treatment Plant in Kuwait. Int. Bus. Econ. Res. J. **9**(1), 141–158 (2010)

Beltagy, A.I.: Some oceanographic measurements in the Gulf waters around Qatar Peninsula. Qatar Univ. Sci. Bull. **3**, 329–341 (1983)

Darwish, M.A., Abdulrahim, H.K., Hassan, A.S.: Realistic power and desalted water production costs in Qatar. Desalin. Water Treat. **57**(10), 4296–4302 (2016)

HK-DEVB Examination of estimates of expenditure 2014–2015, Question No 2504, Reply DEVB(W)121. Development Bureau, Hong Kong (2014)

Kahramaa Annual statistics report 2017. General Electricity and Water Corporation, Doha, Qatar (2017)

Liu, X., Dai, J., Jiang, F., Chen, G., Chui, H.-K., van Loosdrecht, M.C.M.: Sustainable application of a novel water cycle using seawater for toilet flushing. Engineering **2**, 460–469 (2016)

Luo, T., Young, R., Reig, P.: Aqueduct projected water stress country rankings. Technical Note. Water Resources Institute, Washington DC, USA (2015)

MDPS: Water statistics in the State of Qatar 2015. Ministry of Development Planning and Statistics, Doha, Qatar (2017)

RTI & EAA: Demand-Side Management for Electricity and Water Use in Abu Dhabi, Report by RTI & Executive Affairs Authority, Abu Dhabi, UAE (2009)

Tang, S.L., Yue, D.P.T., Li, X.Z.: Comparison of engineering costs of raw freshwater, reclaimed water and seawater for toilet flushing in Hong Kong. Water Env. J. **20**, 240–247 (2006)

WEF: Global risk report 2015. World Economic Forum, Switzerland (2015)