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Effect of domestic water use on air pollutant emissions in Abu Dhabi, United Arab Emirates

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Abstract

The members of the Cooperation Council for the Arab States of the Gulf have typically addressed water scarcity problems by building energy-intensive desalination plants. Few efforts have addressed water scarcity through metering, pricing, and other efficiency measures to reduce demand. This paper examines how decreased leakage in the water distribution system and decreased residential water use in Abu Dhabi, United Arab Emirates, could decrease air pollutant and greenhouse gas emissions from desalination plants. We developed a probabilistic model to predict the effects of water use reductions on pollutant emissions from Abu Dhabi's major independent water and power plants, which use a combination of multi-stage flash distillation and multi-effect distillation to produce fresh water from seawater drawn from the Arabian Gulf. We examine three categories of scenarios for reducing water use: increasing the price signal to residential users, instituting demand management programs among residential users, and reducing water loss in the distribution system. Our analysis suggests that water conservation price incentives could reduce air pollutant and greenhouse gas emissions by 1% to 5%, depending on assumptions about how households respond to the incentives. Demand-side management programs curbing per capita water use to levels typical of the Singapore or the UK would curb emissions by 10% or 11%, respectively. Reducing water loss during distribution from the current high level of 35% to 15% (similar to loss rates in other developed nations) could cut emissions by more than 3%. Overall, our analysis suggests that high per capita water use contributes to ambient air pollution and greenhouse gas emissions in Abu Dhabi.

Keywords: Water-energy nexus; Desalination; Air pollution; Domestic water consumption; Water scarcity

Background

The countries that make up the Cooperation Council for the Arab States of the Gulf (GCC) have the scarcest per capita renewable freshwater resources in the world, and their demand for water continues to increase [1]. Within the GCC, the United Arab Emirates (UAE) has one of the highest per capita consumption levels, at 525 to 600 liters per capita per day (l/c/day) in 2007 [2,3]. The UAE is able to maintain this high consumption level by producing fresh water through desalination plants. These plants burn fossil fuels that contribute to air pollution and greenhouse gas emissions [4]. The objective of this paper is to examine how decreases in residential water use and water loss during distribution in Abu Dhabi City (the capital of the UAE) could decrease air pollutant and greenhouse gas emissions from desalination plants. We quantify the total annual mass reductions in nitrogen oxides (NO_x), SO_2, particulate matter (PM), carbon monoxide (CO), and carbon dioxide (CO_2) emissions expected to occur as a result of plausible interventions to reduce water use.

Air quality is an increasing concern in Abu Dhabi. A recent analysis indicated that more than 545 deaths per year may be attributable to ambient air pollution in the UAE, with 208 of those in Abu Dhabi emirate [5,6]. A recent project to prioritize environmental risks in the UAE ranked air quality as the highest concern [7]. The government of Abu Dhabi is actively exploring additional options to improve air quality. As Abu Dhabi considers its options, an important question is the extent to which reducing emissions from specific pollution sources could improve air quality. The analysis presented in this paper can help to inform decisions about air quality management in Abu Dhabi City. Since the UAE has high per

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capita emissions of greenhouse gases, we also assess the extent to which water use contributes to Abu Dhabi's releases of CO_2.

Water in Abu Dhabi City is heavily subsidized. Citizens (UAE nationals) receive water for free, whereas non-nationals pay 2.2 Dhs/m^3 (US $0.60) - about 25% to 30% of the total cost to produce and supply water to consumer taps. The total annual cost of producing residential water in 2008 was US $572 million, of which the government subsidized US $423 million [8,9]. Partly as a result of this large subsidy, water consumers have little incentive to reduce their consumption. Residential water demand and related water subsidy costs are expected to increase as Abu Dhabi City's population continues its rapid growth (5.2%/year) [10].

Abu Dhabi's major independent water and power plants (IWPPs) simultaneously generate energy for electricity and produce desalinated water, using some of the waste heat from energy production to power the desalination process. However, waste heat alone is insufficient to meet all the power needs for desalination; a considerable amount of fossil fuel is burned for water production, contributing to the release of air pollutants and greenhouse gases [2]. Siddiqi and Anadon recently estimated that desalination uses 12% to 22% of the total electricity produced in the UAE [11].

We developed a probabilistic model to examine the trade-offs between domestic water consumption and emissions of air pollutants and greenhouse gases (PM_{10}, NO_x, SO_2, CO, CO_2) generated from the major IWPPs located along the coast of Abu Dhabi emirate (at Taweelah, Mirfa, Umm Al Nar, and Shuweihat). In this paper, we use the model to explore how different options for reducing residential water consumption in Abu Dhabi City could affect water demand and atmospheric pollutant emissions. Raluy et al. showed that more than 90% of the environmental loads (energy use, raw materials, emissions, and waste products) of desalination plants are associated with the operating stage of the plants, with less than 10% of the load attributed to construction and end-of-life emissions [12]. Therefore, this paper focuses on the energy requirements of the water production stage since this stage causes majority of the environmental impacts.

Desalination effects on atmospheric pollution: previous studies

Several previous life cycle assessments have examined the environmental effects (including air quality effects) of different desalination technologies. A study by Raluy et al. found that multi-stage flash distillation (MSF) technology, followed by multi-effect desalination (MED), generated the most atmospheric pollution. However, when residual heat is used to help power the thermal processes of MSF and MED, emissions can be reduced to an order comparable to that of a reverse osmosis (RO) plant [13,14].

Stokes and Horvath conducted a full life cycle assessment of water management options in California, concluding that the energy and air emission footprint in California would be 1.6 to 3.4 times larger if the state used RO desalinated seawater than if water were imported or recycled [15]. Using the California energy mix and life cycle emissions, the study determined that desalination would consume 2.3 to 2.5 times more energy and emit 2.3 to 2.4 times more carbon dioxide, 1.8 to 3.4 times more nitrogen oxides, 1.6 to 1.9 times more particulate matter, and 2.4 times more sulfur oxides than if water were imported or recycled.

A study by Alameddine and El-Fadel [16] used the Industrial Source Complex-3 model to simulate plume dispersion of SO_2 from a typical IWPP located in the Arabian Gulf. Simulation results indicated that the impact of SO_2 stack emissions in several instances can lead to concentrations exceeding international health standards for SO_2, depending on the sulfur concentration of the fuel source [16].

Rubio-Maya et al. [17] conducted a feasibility analysis of a combined cooling-heating power plant with a desalination unit to supply a tourist resort on the Mediterranean coast of Spain. They concluded that although RO consumes less energy than MED when considered in isolation from power production and heating/cooling operations, overall, the use of MED offered greater potential for reductions in greenhouse gas emissions due to the ability to link the production schedule for desalinated water to the availability of waste heat from the power generation and cooling units [17].

Although studies have shown that atmospheric emissions are a major component of the environmental impact caused by desalination plants, to our knowledge, no studies have been conducted to determine the fraction of total air pollutant and greenhouse gas emissions arising from desalination plants in energy-rich and water-scarce regions of the world. This is the first study to examine how steps to reduce water consumption through demand management and reduced water losses can benefit air quality in Abu Dhabi.

Current water tariff

According to the World Bank, nations in the Arabian Gulf region have typically dealt with water scarcity from the supply side by building desalination plants to generate fresh water to meet the growing demand. Few, if any, efforts are in place to improve demand management of urban water supplies through metering, pricing, or other efficiency-improving measures [1], despite ample evidence that people change consumption habits based on price or alternative demand-side management policies (information campaigns, retrofit subsidies, water rationing, or use restrictions) [18].

According to information from the Abu Dhabi Distribution Company (ADDC), water tariffs are 2.2 Dhs/m^3 (US $0.60) for non-nationals and free for nationals [9]. Furthermore, 35% of water entering the distribution system goes unaccounted for: 16% due to physical losses from leaky pipes and the remainder due to mismanagement (such as unbilled connections) [2]. Ironically, nationals are charged 0.05 Dhs/kW h (US $0.014) for electricity, yet pay nothing for water even though production of 1 m^3 of desalinated water uses an average of 22.4 kW h (which would cost Dhs 1.12 or US $0.31 if bought at current rates) [19].

A number of different options are available for governments to employ to try to decrease residential water demand. One option is to increase the price of water. A previous research study by Abu Qdais and Al Nassay provides an indication of how nationals and non-nationals might respond to changes in domestic water prices in Abu Dhabi in the short term [8]. Based on a short-term study of 90 households, they determined that in Abu Dhabi City, the price elasticity of water (in other words, the percent change in water quantity demanded in response to the percent change in water price) is −0.072 (standard deviation (SD) = 0.0089). This elasticity is low, which is consistent with previous research showing that residential water demand is comparatively inelastic, for three reasons: (1) there is no close substitute for water in most of its uses, (2) the amount spent on water is a relatively small fraction of the typical household budget, and (3) water is often jointly demanded with some other good or service [18]. Nonetheless, as this study and others have demonstrated, financial incentives can reduce water demand. Furthermore, over the longer term, one would expect to see a higher absolute value of elasticity - and thus further reductions in water use - in response to a financial incentive.

Water tariffs are a management tool that the UAE could examine more closely in order to create an efficient system for the residential water sector. Yet, pricing water is a complex and controversial issue for several reasons. First, policymakers often disagree about the objectives of a water pricing system; some view the primary objective as a provision of affordable water, while others view it as a sustainable management of scarce resources. Second, water managers may disagree about the effects of implementing a particular water tariff because empirical studies on customers' reactions to long-term price changes are often lacking. Third, no market test exists for different tariff structures; many tariff structures are tried simply because they are feasible and can accomplish a portion of the objective [20]. Finally, adding to these complexities in the Arabian Gulf region, water subsidies are viewed as an essential service that governments provide to citizens, and hence, reducing these subsidies is likely to be highly controversial.

Policy tools other than raising water price have also shown considerable promise in reducing water consumption. Demand-side management programs established in California and Las Vegas have been effective in conserving water. Las Vegas introduced a turf removal program, replacing turf with more water-efficient landscapes. Replacing grass with a drought-tolerant natural landscape for the desert ecosystem reduced water use by an average of 76%, saving 2,260 l/m^2 of irrigated land each year [21]. In a study in California, Renwick and Green concluded that public information campaigns and retrofit subsidies reduced household water consumption by 8% and 9%, while water rationing and water restriction dropped consumption by 19% and 29%, respectively [18].

With the population growth that Abu Dhabi is experiencing and the high costs of producing desalinated water, current water pricing policies, as well as a range of options for curtailing demand, should be examined more closely. This paper examines how such incentives could reduce air pollutant and greenhouse gas emissions from major desalination plants serving Abu Dhabi City.

Methods

The model created for this study incorporates probabilistic inputs and site-specific data to run Monte Carlo simulations (using Analytica 4.2 software, Lumina Decision Systems, Los Gatos, CA, USA). The model estimates total reductions in PM, NO_2, SO_2, CO, and greenhouse gas emissions from Abu Dhabi's IWPPs under different water consumption scenarios. We use 2008 as the base year for our estimates since it was the most recent year for which water production figures were available at the time our analysis was conducted.

The amount of water produced, along with the type of technology employed, determines the amount of energy needed to desalinate the water. This energy use, in turn, determines how much fuel is consumed in producing water. The type and amount of fuel combusted then determine how much pollution is emitted. In estimating atmospheric emissions, our model uses local water demand data along with data about specific desalination technologies and fuels employed at each IWPP. The following sections provide details on the model's components.

Current residential water demand

Residential water production in Abu Dhabi for 2008 was calculated using reports from Abu Dhabi Water and Electricity Company and ADDC. The ADDC receives 70% of desalinated water produced, and 44% of this travels to the residential sector. Of the water that ADDC distributes, 35% is lost, 16% due to physical leakage and the rest from technical and administrative losses [2].

Our model divides residential water users into two main groups, nationals and non-nationals, and then subdivides these groups by housing type. Based on information from the Regulation and Supervision Bureau (responsible for overseeing potable water quality), non-nationals living in flats consume 160 to 220 l/c/day, whereas those in villas use 270 to 730 l/c/day. This trend is also seen among UAE nationals: families in flats use around 165 l/c/day, villa households use 460 to 1,760 l/c/day, and families in shabias (a form of housing traditionally provided by the government for citizens) use 610 to 1,010 l/c/day [3]. The variation in consumption between users suggests that many different water policies will be needed to reach targeted goals. On average across all these groups, residential water demand was 544 l/c/day during the study year [9]. These current water use rates constitute the baseline scenario.

Scenarios

We examine the potential reduction in air pollutant and greenhouse gas emissions under several scenarios of decreased water use. First, we assess the potential effects of price changes. Even though increasing water prices may not be politically feasible in the UAE, quantifying the effects of price changes serves as a proxy for the potential effects of other, politically feasible demand-side management programs, such as rebates for xeriscaping or water-efficient fixtures. Our model examines how residential consumption could change as water price (or equivalent rebates offered to households that reduce water use) fluctuates near its average cost, 7.4 Dhs/m^3 (US $2.00). Then we consider air emission reductions if per capita residential water consumption levels in Abu Dhabi were reduced to those of several other developed countries (Australia, Spain, Singapore, and the UK) - all of which have lower per capita residential water use rates than Abu Dhabi - through demand-side management. We also examine how air emissions would decrease if water use were curtailed to per capita rates in the UAE in 2000. Last, we consider the effects of decreasing the volume of water lost during distribution below the current rate of 35%.

Elasticity

The scenarios in which water prices are increased (or rebates are offered) require an estimate of the price elasticity of water. As noted above, Abu Qdais and Nassay, in a study of 90 households, determined that the short-term price elasticity of water is approximately −0.07 [8]. However, for two reasons, this elasticity may not adequately represent how water demand in Abu Dhabi might respond to financial incentives. First, since Abu Dhabi's water consumers to date have paid only a very small fraction of the cost of production, Abu Qdais and Nassay's observed elasticity may not apply to the large financial incentive (whether cash rebate for decreased water use or charge for use) needed to reflect the full cost of production. It is possible that elasticity would increase (i.e., become increasingly negative) as the price increases and water consumes a larger fraction of the household budget (or offers a larger potential rebate). Second, Abu Qdais and Nassay's study estimated the short-run elasticity of water, but the long-run elasticity of demand should be used to predict long-term changes in consumption. Based on previous studies, the long-run elasticity tends to be approximately 0.2 to 0.3 points lower than the short-run elasticity of water [22]. Using this estimate, Abu Dhabi City's long-run price elasticity should be around −0.37 to −0.27. This elasticity range is closer to the average elasticity of water that Dalhuisen and Florax found in their meta-analysis of price elasticity of water demand, averaging −0.38 (range, −1.3 to +0.1) in 282 observations [23]. An Espey et al. meta-analysis showed an average elasticity of −0.51, while Nauges and Whittington showed that price elasticity for water from private connections ranges from −0.3 to −0.6 in developing countries [24,25]. Based on this information, our model examines three different scenarios of demand elasticity: (1) −0.072 (SD = 0.0089) from Abu Qdais and Al Nassay [8], (2) −0.27, and (3) −0.37.

We use the following function to estimate how water demand changes with price:

$$w = \alpha p^{\varepsilon} \tag{1}$$

where w = demand, p = price, ε = elasticity, and α = a constant determined by dividing current demand by current price raised to a power equal to the elasticity. The function is based on the assumption that elasticity is constant. The parameter alpha is estimated from current demand and price information. Elasticity does not always stay constant as price changes. Nonetheless, the assumption of constant elasticity represents a conservative estimate of water reduction due to financial incentives. In theory, water becomes more elastic as its price rises, resulting in a greater subsequent reduction because the water bill makes up a greater portion of a typical household income or because the value of the jointly demanded good or service is less desirable at the higher water price.

Energy use

The amount of energy used to produce water depends on the desalination technology that the plant employs and the plant's overall operational efficiency (considering both the fraction of fossil fuel converted to useable energy and the fraction of waste heat captured to support desalination). Three different technologies are used in the GCC to process seawater into potable water: MSF, MED, and RO. Table 1 shows information on the energy requirements of each of these technologies, as estimated from a meta-analysis of previous studies. As shown, MSF is the most energy-intensive of the three. Despite this drawback, the majority (85.3%) of the desalination units at Abu Dhabi's IWPPs are MSF systems, with 8.9% using MED and 5.8% using RO [2]. All of the major desalination facilities located within the emirate of Abu Dhabi in 2008 used MSF and MED; the use of RO occurred only in a facility in the emirate of Fujairah, which exports water to Abu Dhabi, and in small facilities serving remote communities or desalinating brackish groundwater [2]. None of the major installations included in this analysis use RO. The high reliance on MSF systems among these major installations is driven by the high salinity levels in the Arabian Gulf due to the performance limitations of the other technologies (especially RO) under high-salinity conditions [26].

Each major desalination facility in this analysis employs a different mix of MSF and MED technologies and therefore uses a different amount of energy to produce a unit volume of water. We employed data available from the Abu Dhabi Water and Electricity Company and Environment Agency-Abu Dhabi to determine the percentage of total annual produced water volume treated by each technology in each desalination unit [2]. Then for each plant, we estimated the energy needed to produce 1 m^3 of water as a weighted average of the energy requirements of each technology:

$$\text{Energy}_{\text{water}} = E_{\text{MSF}} \times W_{\text{MSF}} + E_{\text{MED}} \times W_{\text{MED}} \tag{2}$$

where $\text{Energy}_{\text{water}}$ is the amount of energy (kW h) required to produce 1 m^3 of water from the given desalination unit, E_{MSF} and E_{MED} are the energy requirements per 1 m^3 of water produced by MSF and MED systems, respectively, and W_{MSF} and W_{MED} are the percentages of water processed by the two technologies at the given desalination unit. We represent E_{MSF} and E_{MED} as triangular probability distributions with the parameters (determined from the review of previous studies) shown in Table 1.

Table 1 Energy (kW h) required per cubic meter of water produced by MSF, MED, and RO desalination plants

Technology	Number of studies[a]	Minimum[b] (kW h/m^3)	Mode[b] (kW h/m^3)	Maximum[b] (kW h/m^3)
MSF	5	10	22	38
MED	4	7.5	15	40
RO	6	2.5	4.5	7

[a]Refers to the number of previous research studies used to estimate the statistical parameters shown. The mode was estimated from central values reported in relevant previous studies [12,14,15,19,26-32]. [b]The minimum and maximum values were determined as the lowest and highest reported energy use for the particular technology in previous studies.

To calculate the total amount of energy actually used to produce 1 m^3 of water at each plant, we divided the amount of energy required to produce water ($\text{Energy}_{\text{water}}$) by an efficiency factor. The efficiency factor accounts for energy lost when converting fossil fuel to useable energy and energy gained by reusing waste heat. The efficiency factor is computed from the following equation:

$$\text{Eff} = \frac{E_{\text{Gross}}(\text{kW h}) + E_{\text{wasteheat}}(\text{kW h})}{\text{totalfuel}(\text{MMBtu}) \times 293.1\left(\frac{\text{kW h}}{\text{MMBtu}}\right)} \tag{3}$$

where E_{Gross} is the gross amount of energy produced by the plant, $E_{\text{wasteheat}}$ represents the energy content of waste heat used in water production, and totalfuel is the energy content of the fuel consumed by the plant. Therefore, the total amount of energy actually used to produce 1 m^3 of water (denoted $\text{Energy}_{\text{water,total}}$) is given by

$$\text{Energy}_{\text{water,total}} = \frac{\text{Energy}_{\text{water}}}{\text{Eff}} \tag{4}$$

Atmospheric emissions

The fuel mix at each desalter determines the mass of pollutants emitted per unit volume of fuel consumed. The calculation of emissions per unit of fuel is based on the U.S. Environmental Protection Agency (U.S. EPA) estimates for the different boiler types in use at each desalting unit [33]. Based on U.S. EPA emission factors for each boiler-fuel combination, we calculate statistical emission factors (g/MMBtu) for each plant. More than 99% of the energy mix burned at these plants is natural gas, with the remainder provided by fuel oil, crude oil, and gas oil [34]. To estimate the total emissions for each plant attributable to residential water production under each scenario, we multiply the emission rate (g/kW h) for each plant by the total energy ($\text{Energy}_{\text{water,total}}$, in kW h/$m^3$) used for water production and by the total amount of water produced to meet residential demand in Abu Dhabi City in 2008.

Results and discussion

We present results for three scenarios of decreased water use:

- financial incentives alone,
- a decrease in per capita consumption (via a package of demand-side management incentives) to levels observed in other developed countries or to those in Abu Dhabi in 2000, and

- a decrease in water loss in the distribution system.

Although we express financial incentives as a price increase, a more politically feasible option might be to offer cash rebates to households that decrease their volumetric water use from prior years or use less than some predetermined threshold volume. Table 2 summarizes atmospheric pollutant emissions from the IWPPs under the baseline scenario as well as under these alternative scenarios.

Scenario 1: financial incentives

As noted above, the actual elasticity of water in Abu Dhabi in response to a long-term price signal is unknown because of a lack of previous studies in Abu Dhabi. Thus, we consider three elasticity scenarios. First, under the most conservative assumption (i.e., assuming the smallest decrease in water use in response to a financial incentive), using projections from Abu Qdais and Al Nassay [8], per capita consumption decreases by a relatively small amount: from 544 to 500 l/c/day. These figures suggest an approximately 1% decrease in emissions of all atmospheric pollutants from IWPPs. Assuming that water is slightly less inelastic at −0.27, per capita consumption would decline to 390 l/c/day, resulting in a reduction of approximately 4% of IWPP emissions for all pollutants. When the price elasticity is −0.37, water consumption drops to 350 l/c/day, cutting emissions by approximately 5%.

Scenario 2: package of incentives

If Abu Dhabi City could establish incentives (whether price signals, information campaigns, rebate programs, water reuse programs, or other initiatives) sufficient to curtail per capita consumption to levels observed in the year 2000 (323 l/c/day), results suggest an approximately 6% reduction of atmospheric pollutant emissions. Because Australia consumes large volumes of water and has regions that suffer from physical water scarcity, it can serve as another benchmark for comparison. If Abu Dhabi City's per capita consumption levels could be decreased to match those in Australia (490 l/c/day on average), atmospheric emissions would decrease by approximately 1%. If Abu Dhabi City instead consumed water at a level matching that in Spain (320 l/c/day), where the northern region is approaching water scarcity, emissions would drop by almost 6%. Singapore also relies heavily on reclaiming wastewater and desalination due to its limited water resources. Singapore has a per capita consumption rate of 160 l/c/day, which if matched would reduce emissions from Abu Dhabi IWPPs by about 10%. If Abu Dhabi City were able to decrease consumption to levels observed in the UK (a water-rich country using only minimal water, 150 l/c/day), emissions would decrease by approximately 11%.

Scenario 3: decreased water loss

If water consumption is assumed constant but less water is lost during distribution, emissions will also decrease. Typically, in high-income countries, about 10% to 15% of water produced at a treatment plant is lost somewhere between the plant and the consumer, mostly through leaks in the water distribution system [35]. This figure increases to above 50% in low-income countries [36]. During 2008 in Abu Dhabi, 16% of desalinated water was lost through physical leakage and another 19% from mismanagement (such as illegal and unmonitored connections) [2]. If 5% more water is used (decreasing the loss rate to 30%), approximately 1% fewer atmospheric emissions from IWPPs will follow. If losses are reduced to 25%, emissions would be 2% lower. A loss rate of 20% corresponds to an approximately 3% reduction in emissions. The model shows that every 5% decrease in water loss results in a 1% emission reduction.

Comparison of options

All scenarios of reduced water consumption lead to reductions in atmospheric emissions (Table 2). Each scenario changes just one parameter (water financial signals, per capita water use, or water loss) while holding all other parameters constant. Based on these results, the effectiveness of different water management options in reducing atmospheric emissions can be compared. Also, our model can be used to estimate emission reductions achievable under combinations of scenarios.

At a long-term price elasticity of −0.07, implementing financial incentives (such as rebates or water charges) that reflect the full price of producing and distributing residential water decreases emissions by amounts comparable to emission reductions achieved by decreasing the amount of unaccounted-for water to 30% (from its current level of 35%). These expected reductions are similar to the reductions predicted to occur if water consumption is equivalent to that in Australia. If the elasticity is actually −0.37 (the lowest value assumed in this analysis), indicating a stronger response to financial signals, then financial incentives would lead to consumption levels similar to those of Spain or of the UAE in 2000.

If Abu Dhabi desires to achieve water consumption levels consistent with those in the most water-efficient developed countries, then a combination of demand-side management practices will be required. Financial incentives and the patching of leaks in the distribution system do not result in water use reductions substantial enough

Table 2 Annual pollutant emissions from IWPPs (tons/year) under the baseline and alternative residential water use scenarios

	NO_x	SO_2	CO_2	PM_{10}	CO
Baseline (current residential water use)	59,300 (26,700-94,800)	500 (310–700)	23,481,700 (23,481,600-23,481,700)	1,500 (680–2,200)	10,500 (5,500-15,500)
Scenario 1 [a]					
−0.07 [a]	750 (320–1,300)	6.1 (3.3-9.6)	295,000 (212,000-389,000)	18 (8.1-32)	130 (58–230)
	1.2% (0.9%-1.6%)	1.2% (0.8%-1.6%)	1.2% (0.9%-1.6%)	1.2% (0.9%-1.6%)	1.2% (0.9%-1.6%)
−0.27 [a]	2,500. (1,100-4,100)	20 (11–30)	974,009.9 (769,569.6-1,163,634)	61.62 (27.26-99.09)	436.4 (197.6-717.2)
	4.1% (3.2%-4.9%)	3.9% (2.8%-5.1%)	4.1% (3.2%-4.9%)	4.1% (3.2%-4.9%)	4.1% (3.2%-4.9%)
−0.37 [a]	3,100 (1,400-5,300)	26 (15–39)	1,257,000 (993,000-1,494,000)	80 (35–130)	560 (250–920)
	5.3% (4.2%-6.3%)	5.1% (3.6%-6.6%)	5.3% (4.2%-6.3%)	5.3% (4.2%-6.3%)	5.3% (4.2%-6.3%)
Scenario 2					
UAE 2000 (323 l/c/day)	3,500 (1,500-5,900)	29 (17–43)	1,407,000 (1,109,000-1,658,000)	89 (40–140)	630 (290–1,000)
	5.9% (4.7%-7.0%)	5.7% (4.0%-7.4%)	5.9% (4.7%-7.0%)	5.9% (4.7%-7.0%)	5.9% (4.7%-7.0%)
Australia (490 l/c/day)	870 (380–1,400)	7.1 (4.1-11)	344,000 (271,000-406,000)	22 (9.8-35)	150 (70–250)
	1.4% (1.1%-1.7%)	1.3% (0.9%-1.8%)	1.4% (1.1%-1.7%)	1.4% (1.1%-1.7%)	1.4% (1.1%-1.7%)
Spain (320 l/c/day)	3,600 (1,500-6,000)	29 (17–44)	1,428,000 (1,125,000-1,682,000)	90 (40–150)	640 (290–1,000)
	6.0% (4.7%-7.1%)	5.8% (4.0%-7.5%)	6.0% (4.7%-7.1%)	6.0% (4.7%-7.1%)	6.0% (4.7%-7.1%)
Singapore (160 l/c/day)	6,200 (2,700-10,000)	50 (29–75)	2,448,000 (1,929,000-2,884,000)	150 (70–250)	1,100 (500–1,800)
	10% (8.2%-12%)	10% (6.9%-13%)	10% (8.2%-12%)	10% (8.2%-12%)	10% (8.2%-12%)
UK (150 l/c/day)	6,300 (2,800-11,000)	51 (30–77)	2,512,000 (1,979,000-2,959,000)	160 (72–260)	1,100 (510–1,800)
	11% (8.4%-12%)	10% (7.1%-13%)	11% (8.4%-12%)	11% (8.4%-12%)	11% (8.4%-12%)
Scenario 3					
30% [b]	630 (280–1,000)	5.1 (2.963-7.655)	248,000 (197,000-292,000)	16 (6.9-25)	110 (51–180)
	1.1% (0.8%-1.2%)	1.0% (0.7%-1.3%)	1.1% (0.8%-1.2%)	1.1% (0.8%-1.2%)	1.1% (0.8%-1.2%)
25% [b]	1,200 (520–2,000)	9.5 (5.5-14)	462,000 (367,000-546,000)	29 (13–47)	210 (94–340)
	2% (1.6%-2.3%)	1.9% (1.3%-2.4%)	2% (1.6%-2.3%)	2% (1.6%-2.3%)	2% (1.6%-2.3%)
20% [b]	1,600 (740–2,800)	13 (7.8-20)	650,000 (516,000-767,000)	41 (18–66)	290 (130–480)
	2.8% (2.2%-3.3%)	2.7% (1.9%-3.4%)	2.8% (2.2%-3.3%)	2.8% (2.2%-3.3%)	2.8% (2.2%-3.3%)
16% [b]	2,000 (890–3,300)	16 (9.4-24)	784,000 (622,000-926,000)	50 (22–80)	350 (160–570)
	3.3% (2.7%-3.9%)	3.2% (2.3%-4.1%)	3.3% (2.7%-3.9%)	3.3% (2.7%-3.9%)	3.3% (2.7%-3.9%)
15% [b]	2,100 (920–3,400)	16 (9.8-25)	815,000 (647,000-963,000)	52 (23–83)	370 (170–600)

Table 2 Annual pollutant emissions from IWPPs (tons/year) under the baseline and alternative residential water use scenarios *(Continued)*

	3.5% (2.8%-4.1%)	3.3% (2.4%-4.3%)	3.5% (2.8%-4.1%)	3.5% (2.8%-4.1%)	3.5% (2.8%-4.1%)
10%	2,400 (1,100-4,100)	20 (12–30)	963,000 (764,000-1,140,000.)	61 (27–97)	430 (200–700)
	4.1% (3.3%-4.8%)	3.9% (2.8%-5.1%)	4.1% (3.3%-4.8%)	4.1% (3.3%-4.8%)	4.1% (3.3%-4.8%)

Numbers at the top line of each cell show annual reduction in tons of emissions (tons/year); numbers in parentheses represent 95% confidence intervals of these estimates. Numbers at the bottom line of each cell show the percentage by which total emissions from all IWPPs would be reduced under the scenario (with 95% confidence intervals in parentheses). Scenario 1, implement financial incentives equal to cost of water production (US \$2.00/m^3); Scenario 2, implement package of demand management programs to match per capita consumption in other countries; Scenario 3, reduce water loss in the distribution system (through leak reduction and improved management). [a] Assumed price elasticity of water. [b] Assumed percentage of water lost during distribution.

to decrease UAE's per capita consumption to the conservatively low levels observed in Singapore or the UK.

Limitations

Emission reductions depend on three major inputs in this model. Emissions per unit of fuel estimates are based on U.S. EPA data, which provide the most extensive estimates available on emissions associated with boiler technologies used in the UAE. In addition, our analyses may have overstated the efficiency of the IWPPs due to overweighting the value of waste heat, causing an underestimate of emissions from water production. Furthermore, our estimate of the energy used to produce water is based on a nine-study meta-analysis using triangular probability distributions to represent the possible range of energy consumption needed to produce potable water for different kinds of desalination plants. A further limitation of our analysis is that it focuses on the production of potable water and does not perform a full water-energy analysis; it does not include distribution, end use (heating water for washing, cooking, or cleaning), or wastewater treatment due to the lack of data. It also includes residential water use only, which accounts for only 44% of total desalinated water use in Abu Dhabi [2]. Including all the other water users, plus conducting a full life cycle analysis of the energy consumed through water use, would result in much greater reductions in emissions from efforts to reduce water use.

Conclusions

Despite the scarcity of water resources in the GCC, the traditional approach to address increased water demand has been to increase water supply by boosting production from desalination plants. The UAE has averaged an 11.7% annual increase in desalinated water production over the past decade [37]. This approach results in unintended consequences: increases in both amounts of energy consumed and amounts of air pollution emitted.

This analysis demonstrates that establishing incentives to reduce residential water demand can result in substantial reductions in water use and air emissions. Charging UAE households full price for water (rather than subsidizing water consumption) could reduce total emissions of particulate matter, NO_2, SO_2, CO, and greenhouse gases from Abu Dhabi's water and power plants by 1% to 5%, depending on assumptions about the price elasticity of water. Reducing water loss in the distribution system from the current high level of 35% to 15% (similar to loss rates in other developed nations) could cut emissions by more than 3%. Demand-side management programs curbing per capita water use to levels typical of Singapore or the UK would curb emissions by 10% (95% CI 8.2% to 12%) or 11% (95% CI 8.4% to 12%), respectively.

Notably, the estimates presented here consider residential water use only, accounting for only 44% of use of desalinated water produced in Abu Dhabi. Of the remaining desalinated water, 33% is used for government facilities and schools, 11% is used for commercial facilities, and 11% is used for agriculture [2]. Considering options to reduce demand by other users could yield substantial additional air quality benefits.

In order to build on this analysis, the UAE could extend the calculations to nonresidential water users. An additional step would employ air quality and risk assessment models to characterize the health benefits gained by the estimated reductions in NO_x, PM_{10}, CO, and SO_2 emissions that occur when water demand is curbed. Additional research in this area could enhance understanding on how the reduction of water consumption results in health benefits due to improved ambient air quality. Ambient air quality was recently ranked as the highest environmental health risk in the country [7], which in itself may encourage new research to understand how reducing emissions from specific sources could benefit air quality. Other important topics for future research include studies on the effects of financial incentives (rebates, retrofit subsidies, water reuse programs, public information campaigns, water rationing, and water restriction policies) on water demand.

The reduction in water demand will play a key role in the development of Abu Dhabi City over the next 20 years as it grows to over 3 million residents. Using excess resources today to produce water to meet extremely high consumption rates comes at a cost to ambient air quality. The value of improved air quality should be accounted for when setting policies associated with water consumption, especially when large portions of energy-intensive potable water are lost during distribution.

Abbreviations

ADDC: Abu Dhabi Distribution Company; CO: Carbon Monoxide; CO_2: Carbon Dioxide; GCC: Cooperation Council for the Arab States of the Gulf; IWPP: Independent water and power plant; MED: Multi-effect distillation; MSF: Multi-stage flash distillation; NO_x: Nitrogen Oxides; PM: Particulate Matter; RO: Reverse Osmosis; UAE: United Arab Emirates; U.S. EPA: U.S. Environmental Protection Agency.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

NBD developed the probabilistic model. NBD and JMG drafted the manuscript. Both authors read and approved the final manuscript.

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References
1. World Bank: A water sector assessment report on the countries of the cooperation council of the Arab States of the gulf. Report no.32539-MNA World Bank, Washington, D.C. (2005)
2. Environment Agency-Abu Dhabi: Water policy and master plan, Emirate of Abu Dhabi. Environment Agency-Abu Dhabi, Abu Dhabi (2008)
3. Regulation and Supervision Bureau: Water and electricity consumption by residential customers. Regulation and Supervision Bureau, Abu Dhabi (2008)
4. Mohamed, H, Hmaeid, B: Influence of turbulent mixing intensity on the MILD combustion and the pollutant formation. Int. J. Energy Environ. Eng. **3**, 22 (2012). doi:10.1186/2251-6832-3-22
5. Li, Y, Gibson, JM, Jat, P, Puggioni, G, Hasan, M, West, JJ, Vizuete, W, Sexton, K, Serre, M: Burden of disease attributed to anthropogenic air pollution in the United Arab Emirates: estimates based on observed air quality data. Sci. Total Environ. **408**, 5784–5793 (2010). doi:10.1016/j.scitotenv.2010.08.017
6. MacDonald Gibson, J, Brammer, A, Davidson, C, Folley, T, Launay, FJP, Thomsen, JTW: Environmental Burden of Disease Assessment: A Case Study in the United Arab Emirates. Springer, Dordrecht (2013)
7. Willis, HH, Gibson, JM, Shih, R, Geschwind, S, Olmstead, S, Hu, J, Curtright, AE, Cecchine, G, Moore, M: Prioritizing environmental health risks in the UAE. Risk Anal **30**, 1842–1856 (2010). doi:10.1111/j.1539-6924.2010.01463.x
8. Abu Qdais, HA, Al Nassay, HI: Effect of pricing policy on water conservation: a case study. Water Policy **3**, 207–214 (2001)
9. Abu Dhabi Distribution Company Financial Reports, Energy and Water, 2004 to 2008. Abu Dhabi Distribution Company, Abu Dhabi (2008)
10. Abu Dhabi Urban Planning Council: Plan Abu Dhabi 2030: urban structure framework plan. Abu Dhabi Urban Planning Council, Abu Dhabi (2007)
11. Siddiqi, A, Anadon, LD: The water-energy nexus in the Middle East and North Africa. Energy Policy **39**, 4529–4540 (2011)
12. Raluy, RG, Serra, L, Uche, J, Valero, A: Life-cycle assessment of desalination technologies integrated with energy production systems. Desalination **167**, 445–458 (2004)
13. Palazzo, P: Thermal and mechanical aspect of entropy-exergy relationship. Int. J. Energy Environ. Eng. **3**, 4 (2012)
14. Raluy, R, Serra, L, Uche, J: Life-cycle assessment of water production technologies–part 1: life-cycle assessment of different commercial desalination technologies (MSF, MED, RO). Int. J. Life Cycle Assess. **10**, 285–293 (2005)
15. Stokes, JR, Horvath, A: Energy and air emission effects of water supply. Environ. Sci. Technol. **43**, 2680–2687 (2009)
16. Alameddine, I, El-Fadel, M: Stack emissions from desalination plants: a parametric sensitivity analysis for exposure assessment. Desalination **177**, 15–29 (2005)
17. Rubio-Maya, C, Uche, J, Pacheco-Ibarra, JJ: Feasibility analysis of a combined cooling-heatingpower and desalted water plant for a non-residential building. Int. J. Energy Environ. Eng. **2**, 33–41 (2011)
18. Renwick, ME, Green, RD: Do residential water demand-side management policies measure up? An analysis of eight California water agencies. J. Environ. Econ. Manag. **40**, 37–55 (2000)
19. Darwish, M: Desalting fuel energy cost in Kuwait in view of $75/barrel oil price. Desalination **208**, 306–320 (2007)
20. Whittington, D, Boland, J, Foster, V: Water tariffs and subsidies in South Asia: understanding the basics. The World Bank, Washington, D.C. (2003)
21. Southern Nevada Water Authority (SNWA): SNWA water conservation plan 2004–2009. SNWA, Las Vegas (2004)
22. Griffin, R: Water Resource Economics: The Analysis of Scarcity, Policies, and Projects. The MIT Press, Cambridge (2006)
23. Dalhuisen, J, Florax, R: Price and income elasticities of residential water demand: a meta-analysis. Land Econ. **79**(2), 292–308 (2003)
24. Espey, M, Espey, J, Shaw, W: Price elasticity of residential demand for water: a meta-analysis. Water Resour. Res. **33**(6), 1369–1374 (1997)
25. Nauges, C, Whittington, D.: Estimation of water demand in developing countries: an overview. World Bank Res. Observer **25**(2), 263–294 (2010)
26. Hamed, O: Evolutionary developments of thermal desalination plants in the Arab Gulf region. In: 2004 Beirut Conference. (2004)
27. Darwish, M, Yousef, F, Al-Najem, N: Energy consumption and costs with a multi-stage flashing (MSF) desalting system. Desalination **109**(3), 285–302 (1997)
28. Darwish, M, Al Asfour, F, Al-Najem, N: Energy consumption in equivalent work by different desalting methods: case study for Kuwait. Desalination **152**, 83–92 (2003)
29. Zander, A, Elimelech, M, Furukawa, D, Gleick, P: Desalination: A National Perspective. National Research Council, Washington, D.C. (2008)
30. Buros, O: The ABCs of desalting. International Desalination Association, Topsfield (2000)
31. Lattemann, S, Höpner, T: Environmental impact and impact assessment of seawater desalination. Desalination **220**, 1–5 (2008)
32. Al-Shammiri, M, Safar, M: Multi-effect distillation plants: state of the art. Desalination **126**, 45–59 (1999)
33. U.S. Environmental Protection Agency: AP-42: compilation of air pollutant emissions factors, stationary point and area sources, vol. 1, 5th edn. U.S. EPA, Washington, D.C (1995). With updates in 2009
34. Environment Agency-Abu Dhabi: Waste and pollution sources in Abu Dhabi Emirate. Environment Agency-Abu Dhabi, Abu Dhabi (2006)
35. Yepes, G, Dianderas, A: Water & Wastewater Utilities: Indicators. World Bank, Washington, D.C. (1996)
36. Worthington, A, Hoffman, M: An empirical survey of residential water demand modeling. J. Econ. Surv. **22**(5), 842–871 (2008)
37. Abu Dhabi Water and Electricity Company: Statistical reports water and energy 2008. Abu Dhabi Water and Electricity Company, Abu Dhabi (2008)

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