LETTER

Water use and electricity-for-water savings trends in three representative U.S. cities

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Abstract
A life-cycle assessment approach is used to analyze the energy demand and greenhouse gas emissions associated with potable water usage trends in three major cities of the United States in different regions and climates and relying on different types of raw water sources. Between 2011 and 2016, a decreasing trend in per-person water consumption is observed despite growing populations. The per-person water consumption decreased by 10% in Tucson (Arizona) and Washington, DC, and by 16% in Denver (Colorado). Leveraging certain distinctive water and electricity supply characteristics of the case study cities can provide insights into potential interventions and cross-comparison for generalizing trends. In Tucson, potable water production is the most energy intensive and electricity is produced mainly from coal. The greenhouse gas emissions of the per-person water consumption in Tucson are about five times higher compared to Denver and Washington, DC, thus water savings in Tucson should be particularly pursued. GHG emissions decreased in the period by even higher percentages than water use: 15%, 14% and 27% between 2011 and 2016 for Tucson, Washington, DC, and Denver, respectively. In 2015, just four years’ worth of forgone GHG emissions in Tucson were somewhat higher than the total GHG emissions associated with water consumption in all of Washington, DC, a city with the same population size as Tucson. Results show that cities should prioritize promotion of water savings to decrease the average per-person water consumption because it can be achieved and can compensate for increases in population. Lower greenhouse gas emissions can be attained in tandem with the local electric power industry.

1. Introduction
Reliably providing water to a growing population while also reducing environmental impacts of water supply is a global issue that must be addressed. Previous work in this field has evaluated water treatment alternatives [1–4], energy demand and GHG emissions associated with groundwater and surface water sources [5, 6], the impact of adding recycled water infrastructure [7], the impact of importation, reclamation and desalination [8–10], how a changing power mix can affect the GHG footprint of potable water [11], and the interdependence of water and energy savings [12]. While one study compared water supply in cities of similar sizes, economies, and location [13], no study thus far has contrasted water usage, energy demand, and GHG emissions over multiple years in large cities in the United States or elsewhere that are far away from each other, are in different climates and hydrologic zones, and use different raw water sources (groundwater, large multistate river water, regional river water, and snow melt). In this paper, we answer the question: How do GHG emissions attributable to water consumption evolve compared to the population growth in major cities of the United States?

Prior to being treated, potable water can either be pumped from surface sources or from groundwater. Coastal cities may face saltwater intrusion into groundwater, which leads to further treatment step requirements. If local supply is insufficient for meeting water demand, cities may turn to water importation from other areas by pumping water over long distances. Due to the variability in water sourcing among cities, the energy demand and the GHG footprint of water differ as well [14].
Water use trends between 2011 to 2016 (the only years available) in three representative case study cities, Tucson (Arizona), Denver (Colorado), and Washington, DC, are analyzed. They were chosen due to their distinct locations (Southwest, Rocky Mountains, and East Coast, respectively), water sources, and electric power mixes compared to one another. Leveraging certain distinctive water supply characteristics of the case study cities can provide insights into potential interventions and cross-comparison for generalizing trends.

Tucson receives the least precipitation among the three cities. The water provider, Tucson Water, produced 87 million cubic meters of water in 2016 and provided potable water for 0.7 million people [15]. Denver has the highest population among the three cities with 1.2 million people. The water provider, Denver Water, treated and distributed 83 million cubic meters of potable water in 2016 [16]. DC Water produced the 39 million cubic meters of potable water needed annually to supply the 0.7 million residents of the District of Columbia. It also provides water for 2.5 million people living in Montgomery County and Prince George’s County in Maryland and in Fairfax County and Loudoun County in Virginia [17]. More information about potable water management is available in the Supplementary Information (available online at stacks.iop.org/ERL/15/084048/mmedia).

2. Methodology

2.1. Scope of the study

A life-cycle assessment approach is employed to analyze how energy demand and GHG emissions associated with potable water use have evolved in three major cities of the United States. The water consumption data have been obtained from the respective water utilities, and are courtesy of Canon Furth and Mazdak Arabi (Colorado State University) available in Supplementary Information (Part 2, tables SI.3 and SI.4).

The system boundary presented in figure 1 includes pumping raw water from the city’s water source(s) and water treatment for potable water production. The full life-cycle of electricity production is included in the analysis. The emissions associated with chemical use in the treatment processes, water distribution, and construction of treatment infrastructure facilities are not included in the analysis due to lack of data.
2.2. Estimation of energy-for-water demand

Data regarding the population of each city, the water sources, water consumption rates, and water treatment processes are presented in Table 1. A report by the Electric Power Research Institute (EPRI) [14] is used to estimate the energy intensity of potable water production. This report assesses the electricity used for potable water treatment processes in the United States. Estimates were made for different water treatment flow rates, 1, 5, 10, 20, 50, 100, and 500 megagallons per day. Details about the unit treatment processes are available in Supplementary Information (Part 1, table SI.3).

The pumping of raw water from groundwater and surface water sources is an energy-intensive process. Tucson’s water is pumped from groundwater sources under the requirement of recharge and recovery from a sustainable source [15]. Therefore, Tucson’s facilities must pump water twice: once from the groundwater source and once from the Colorado River to replenish the underground source [18]. Denver’s water is sourced from the Rocky Mountains through three different collection systems: South Platte, Roberts, and Moffat [16]. Washington, DC’s water is pumped from the Potomac River [17]. As water treatment facilities can have different sets of treatment processes, Table 1 lists the common water treatment processes over the three cities and the treatment processes specific to each treatment facility. The energy intensity of water treatment stayed the same in the analysis period as no technological changes were put in place.

2.3. GHG emissions estimation

The GHG inventory includes the emissions from energy use as defined by the system boundary shown in Figure 1. The energy providers are Tucson Electric Power Co., Xcel Energy in Denver, and Pepco Inc. in Washington, DC. The power mix is provided by Tucson Electric Power Co. and Xcel annually and by Pepco every other year.

The required data for establishing the GHG footprint of energy generated from fossil fuels are sourced from eGRID reports from 2011 to 2016 [20–23] for onsite emissions. Data from a California Energy Commission report [24] were used for the life-cycle phases preceding the power plant. eGRID releases data every other year, thus emissions for the missing years were estimated through linear interpolation.

2.4. Forgone energy and GHG emissions

The forgone water reflects the amount of water saved each year due to the average per-person water consumption reduction. Equations 1–3 show how the forgone water, energy, and GHG emissions were calculated. For each year, the forgone water amount is based on the population and average per-person water consumption, as well as the average per-person water consumption relative to 2011. The forgone energy is based on the forgone water and the amount of energy per cubic meter of water delivered to the water treatment plant and treated. The forgone GHG emissions are calculated from the forgone energy and the GHG emissions per kWh.

\[
\text{Forgone Water} (i) = \frac{\text{Water (2011)}}{\text{Population (2011)}} \cdot \text{Population (i)} - \frac{\text{Water (i)}}{\text{Population (i)}} \cdot \text{Population (i)}
\]

\[
\text{Forgone Energy} (i) = \text{Forgone Water} (i) \cdot \text{Energy per m}^3 \text{ of water (i)}
\]
2.5. Uncertainty assessment

We have analyzed three sources of uncertainty associated with the water and electricity systems in the three cities: Electricity demand for pumping water from raw source, electricity demand for water treatment processes, and the life-cycle emission factors of electricity generation (excluding combustion). Electricity for pumping and treatment are the main sources of uncertainty because they depend on pump efficiency, that can vary from 55% to 75% [14]. This variability was tested with Monte Carlo analysis for the electricity demand and GHG emissions in all three cities. For each result, 10 000 iterations were conducted. Details about the entry data and results of the Monte Carlo analysis are presented in the Supplementary Information. The expected uncertainties are shown as error bars in the figures presenting energy demand and GHG emissions in the next section.

3. Results

Figure 2 shows the average per-person water consumption in Tucson, Denver, and Washington, DC for 2011–2016. A decreasing trend is observed, which, given the high quality of data, is significant. Between 2011 and 2016, the average per-person water consumption decreased by 10% in Tucson and Washington, DC and by 16% in Denver. The average per-person water consumption in Tucson is two times higher than in Denver or Washington, DC. The data we have worked with did not come with an explanation why the drop in water usage had occurred.

As shown in figure 3, Tucson’s potable water production is the most energy intensive since water is first pumped from a ground source and then from the Colorado River to replenish the groundwater.

The energy use attributable to potable water consumption depends on the average per-person water consumption and the energy intensity of water production. Figure 4 shows that Tucson had
the highest per-person energy demand for water consumption due to high average per-person water consumption and high energy intensity of water production. Following the decreasing trend in water consumption per person shown in figure 2, a decreasing trend in the annual energy demand per person associated with water consumption is observed.

Figure 5 shows the energy use in Tucson (5A), Denver (5B), and Washington, DC (5C), for potable water production disaggregated by energy source. In all three cities, coal-powered electricity generation has dropped since 2011 and has been replaced by natural gas, wind, and solar sources.

Figure 6 shows the GHG emissions trends. The emissions in Tucson were about five times higher compared to Denver and Washington, DC. This can be explained by the high proportion of coal in Tucson’s power mix. GHG emissions also decreased between 2011 and 2016, and by even higher percentages than water use: 15%, 14% and 27% for Tucson, Washington, DC, and Denver, respectively. This decreasing trend reflects the decrease in water consumption and the decarbonization of the power mix in all three cities.

Figure 4. Annual energy consumption per person associated with water consumption in Tucson, Denver, and Washington, DC. The error bars show the expected uncertainties.

Figure 5. Energy consumption for water production disaggregated by energy source for Tucson (A), Denver (B) and Washington, DC (C).
Figure 6 shows the GHG emissions associated with annual potable water consumption per person for Tucson, Denver, and Washington, DC. The error bars show the expected uncertainties.

Figure 7 shows the total annual potable water consumption (markers) and forgone water (bar graph) in the three cities. Since 2011, no major changes have been observed in total, but the average per-person water consumption has been decreasing, offsetting the observed population growth in all three cities. (The blue marker shows that water consumption in Denver in 2012 was higher than in 2011. It explains the negative forgone water of 2012.) The population evolution is presented in supplementary information (figure SI.1).

Figure 8 shows the total energy consumption (markers) and the forgone energy (bar graph) from 2011 to 2016. For 2015 and 2016, although forgone water for Denver is larger compared to Tucson and Washington, DC, Tucson’s forgone energy is the greatest due to the high energy intensity of Tucson’s water.

Figure 9 shows the varying effects of water consumption reduction and a cleaner energy mix on the total GHG emissions among the three cities. In 2015, just four years’ worth of forgone GHG emissions in...
Figure 8. Total annual energy consumption associated with water production for Tucson (green markers), Denver (blue markers), and Washington, DC (red markers), and forgone energy using energy consumption in 2011 as a baseline for Tucson (green bar), Denver (blue bar), and Washington, DC (red bar). The error bars show the expected uncertainties.

Figure 9. GHG emissions associated with water production for Tucson (green markers), Denver (blue markers) and Washington, DC (red markers) and forgone GHG emissions, using GHG emissions consumption in 2011 as a baseline, in Tucson (green bar), Denver (blue bar), and Washington, DC (red bar). The error bars show the expected uncertainties.

Tucson were somewhat higher than the total GHG emissions associated with water consumption in all of Washington, DC, a city with the same population size as Tucson. This shows that the GHG savings of water consumption reduction can differ between cities. Therefore, technological investments and customer incentives leading to water savings and a cleaner electricity mix implemented in Tucson will lead to higher emissions savings compared to Denver and Washington, DC.

4. Discussion

The GHG emissions associated with water consumption vary across the three cities. Per-person they are about five times higher in Tucson com-
pared to Denver and Washington, DC, depending on several parameters which differ from one city to another: the average per-person water consumption, the emission factors of electricity generation, and the energy intensity of water production (pumping and treatment of raw water). The energy intensity of water production is largely affected by the raw water source and the pumping requirements, and is rather insensitive to the water treatment processes. Tucson’s high GHG footprint is determined by its high water-consumption levels. The average per-person water consumption in Tucson is twice as high as in Denver or Washington, DC, with Tucson’s arid climatic conditions possibly being a contributing factor. Additionally, the coal-based power mix in Tucson leads to high emission factors for electricity generation. The energy intensity of water production is also significantly higher in Tucson compared to Denver and Washington, DC due to Tucson’s double pumping requirements. The GHG footprint of water consumption across the three cities scales with the forgone GHG emissions due to water savings.

Cities can reduce the GHG footprint of their water usage in several ways, e.g. by reducing water consumption, using alternative sources of raw water (requiring less pumping and treatment energy), lowering the GHG emissions of electricity generation, and enhancing the energy efficiency of water treatment systems. Nevertheless, population growth imposes additional challenges due to increased water demand. Results show (figure 7) that cities could rely on decreasing the average per-person water usage to compensate for the increase in population. Although raw water sources are restricted by availability and benefit the cities that can pump raw water directly from a nearby river (such as Washington, DC), the use of alternative sources of water, such as recycled water for irrigation, has high water- and greenhouse gas-saving potentials. Reducing the energy intensity of the water production system is also an opportunity to reduce the GHG emissions associated with water consumption. GHG emissions from electricity generation can be reduced by decarbonizing the power mix, such as by integrating renewables, getting rid of fossil fuels, and generating hydroelectric power in the process of water sourcing when possible (such as in the case of Denver), as seen in the three cities. The GHG emissions per person are proportional to the GHG emission per kWh, to the energy per ton of water and to the consumption. For example, a reduction of 5% of the energy need per ton of water will result in a 5% reduction of GHG emission per person. The same principle applies to the water consumption per person and the GHG emissions per kWh. Strategies to decrease the GHG footprint should be location specific. The suggested pathways could result in GHG savings which could significantly differ from one city to another. More research is required to explore GHG saving potentials.

This paper shows that water usage reductions lead to forgone energy and emissions in all three cities, albeit at different scales. In Tucson, 8000 MWh of electricity were forgone over the 5 years of the study period, enough to power about 160 average U.S. residential homes in the period [25]. In Denver, the savings were 3000 MWh, and in Washington, DC, 1800 MWh. The forgone GHG emissions in Tucson amounted to 10000 metric tons of CO₂ equivalents over 5 years, similar to the emissions from combusting 5000 metric tons of coal [26].

In the future, more studies are needed to compare these results with other cities. An assessment over a longer period would be helpful to know if this decreasing trend is recent or perhaps the end of a longer trend. As well, it would be valuable to see if the water savings continued in 2017–2019 as well. Different water saving technologies (e.g. low-flow toilets and showers, water-efficient appliances, xeriscaping) and water saving behavior by consumers can influence the trends shown in this study but were not identified. The suggested strategies need to be quantified and compared among the cities, using location-specific data [27, 28], to identify the cities with the largest energy and GHG savings potential. Finally, reducing water consumption could lead to wastewater reduction, thus further energy use and GHG emissions reductions in urban water systems.

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**Data availability statement**

Any data that support the findings of this study are included within the article or in the supplementary information.

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