**Chapter E5**

**Life Cycle Assessment of Alternative PFAS Treatment Solutions for Contaminated Groundwater**

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**Abstract**

We assembled life cycle models for groundwater treatment and bottled water delivery to residents of Wright-Patterson Air Force Base, Ohio where wells were recently taken out of service due to concerns related to per- and polyfluoroalkyl substance (PFAS) contamination. Two treatment methods, granular activated carbon filtration and ion-exchange columns, were modeled under a range of contaminant concentrations covering three orders of magnitude: 0.7, 7.0, and 70 µg/L PFAS. On-site infrastructure, operations, and adsorbent cycling were included in models. Impacts of bottled water production and supply were assessed using two data sets reflecting a range of production and supply chain assumptions. Uncertainty in input data was captured using Monte Carlo simulations. Results show that for contaminant concentrations below 70 µg/L the dominant contributor to life cycle impacts is electricity use at the treatment facility. Production, reactivation, and disposal of treatment media become major sources of impact only at very high PFAS concentrations. Though the life cycle impacts of bottled water are up to three orders of magnitude higher than remediated groundwater on a volumetric basis, supplementing a contaminated water supply with bottled drinking water may result in lower life cycle human health impacts when only a small proportion of the total population is vulnerable.

**1.0 Introduction**

Discovery of PFAS-contaminated groundwater at military bases has triggered water supply well shutdowns, emergency bottled water delivery, and warnings to vulnerable populations.

Several studies have identified granular activated carbon (GAC) as a promising treatment technology, particularly for longer-chained PFAS including PFOA and PFOS (Appleman et al. 2013, 2014; Dickenson and Higgins 2016a). Ion exchange (IEX) resins have also been successful at removing PFAS at various bench scale studies and pilot system tests, achieving up to 99% removal of both PFOS and PFOA (Appleman et al. 2014, Dickenson and Higgins 2016b). Concerns remain for scaling up ion exchange resins from pilot scale, such as media interactions with dissolved organic matter or other competing compounds, and the effectiveness and efficiency of media regeneration.

Some institutions have responded to the EPA health advisory limiting the combined concentration of PFOA and PFOS to 70 parts per trillion in drinking water (USEPA 2016a) by supplying bottled water to populations whose water may exceed the recommended maximum concentrations for PFOA and PFOS as either a temporary or permanent solution. Though bottled water has been shown to have relatively high life cycle impacts relative to tap water (Fantin et al. 2014), differences in the quantity of water supplied through drinking water distribution and municipal water systems could affect the net impacts of bottled water and groundwater treatment scenarios. Environmental implications of bottled water vary depending on the size of the bottle, transportation distance from the bottler to consumer, and particular processing, labeling, refrigeration and bottle disposal methods (Amec Foster Wheeler 2017). For water packaged near to the consumer, the energy requirements are dominated by the energy used to produce the plastic bottles, while bottled water requiring for long-distance shipment, energy costs for transportation can be comparable to, or even larger than energy used for plastic bottle manufacture (Gleick and Cooley 2009).

In this study we examine, using life cycle assessment (LCA), two methods of high-throughput groundwater treatment that have been shown to be effective in eliminating PFAS (GAC and IEX). LCA is a widely recognized method to evaluate “cradle-to-grave” environmental impacts from a product or a process. According to ISO 14040 series of standards, it involves: a goal and scope definition, inventory analysis, impact assessment and interpretation (Finkbeiner et al. 2006). For this study, we assessed the life-cycle impacts to climate, human health, and ecosystem health of operating these systems at PFAS concentrations representative of some contaminated sites in the United States (e.g., CDPH 2016, USEPA 2016). We compare these results to life cycle analyses of bottled water provisioning as a substitute for PFAS-contaminated drinking water. A contaminated aquifer at Wright-Patterson Air Force Base (WPAFB) (Ohio, USA) served as case study for the analysis.

## **2.0 Methods**

We assembled life cycle models for clean water supply to residents of WPAFB near Dayton, Ohio where two groundwater production wells were recently taken out of service due to concerns related to PFAS contamination. Water supply scenarios include groundwater treatment and bottled water delivery. Two treatment methods, granular activated carbon (GAC) filtration and ion-exchange columns (IEX) were examined under a range of contaminant concentrations covering three orders of magnitude. Bottled water models were based on two major data sources: a prior life cycle study of beverage production with detailed process data for bottle manufacturing (Quantis 2010) and a broader review of the scientific literature. Figure E5.1 shows the processes modeled in each scenario. Our analyses are based on a functional unit of 1 m3 of safe drinking water delivered to a residential customer at WPAFB.

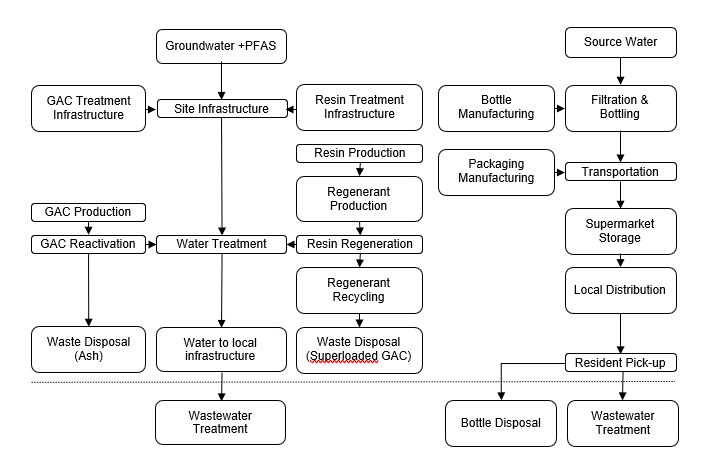


Figure E5.1. System diagram of stages included in life cycle assessment of water supply scenarios. Stages below the dashed line are not included in the analysis.

### **Site data and infrastructure**

Site data and infrastructure are based on designs for a groundwater treatment system at WPAFB. The planned facility will treat 3,800 m3 of groundwater per day from one contaminated well. Treated water enters a system supplying 1,290 permanent residents and an average weekday population of 16,550. The treatment equipment will be housed in a 280 m2 facility designed and built for this purpose. Site infrastructure for the treatment site is included based on architectural designs supplied by Legacy Building Solutions, Inc. and industry standards for construction materials. Infrastructure for the treatment system, including contactors, pipe, fittings, and corrosion-resistant coatings of internal surfaces, are included in our model. GAC use rates and IEX column regeneration frequency were calculated for treatment of groundwater at 0.7, 7.0, and 70 µg/L (micrograms per liter) combined PFOA and PFOS concentrations, reflecting the range of contaminant concentrations at several USAF installations (Anderson et al. 2016).

### **GAC-based Treatment System**

Model data GAC treatment of PFAS contaminated water is based in large part on a report of energy consumption and GAC use rates at a similar facility currently in operation (personal communication, Ryan Morrish, 11 November 2016). The model system pumps contaminated groundwater through two contactors in series each containing 9,100 kg GAC. When breakthrough is detected in the primary contactor, the used GAC is removed and replaced. Activated carbon production from bituminous coal was modeled primarily based on previous studies (Bayer and Finkel 2006, Jeswani et al. 2015) supplemented with energy use data from Calgon Carbon, Inc (personal communication, Kendra Ryan, 7 December 2016) and waste ash production estimate from Isla-Cabaraban et al. (Isla-cabaraban et al. 2016). We model GAC use rates based upon an adsorption capacity of 0.11 g PFAS per kg GAC at anticipated system operating conditions (Amec Foster Wheeler 2017).

A key component of our treatment system is the reactivation of used GAC. Used GAC is transported by truck to a central reactivation facility where application of heat and steam degrades and removes contaminants, restoring most of the treatment potential of the carbon. Our model includes complete reactivation of used carbon. Ten percent of carbon mass is lost during reactivation which is compensated by addition of fresh GAC on an equivalent mass basis. Water and energy use during reactivation are from the available literature (Hutchinson 1975, Isla-cabaraban et al. 2016, Jeswani et al. 2015) and local experts (personal communication, William Scoville). Transportation of carbon to and from the treatment site is based on distances from WPAFB to a Calgon Carbon, Inc. facility (Huntington, WV).

### **IEX-based Treatment System**

A treatment system using ion exchange columns was modeled based on pilot scale tests conducted at a DoD facility. The modeled system uses three IEX columns in series with a contact times of 2.5 minutes each and an adsorption capacity of 1.3 g combined PFOA and PFOS per kg resin (Amec Foster Wheeler 2017). Once saturated, the ion-exchange columns are regenerated by washing with solvent and brine solutions to remove PFAS and any other contaminants. Based on protocols developed at the pilot scale, we assume that washing with five bed volumes of regenerant, five bed volumes of brine, and one bed volume of water is sufficient to completely restore the column’s adsorptive capacity (Amec Foster Wheeler 2017).

The large volumes of waste produced during resin regeneration are mitigated by recycling the regenerant solutions. Used regenerant is distilled to produce a ‘clean’ methanol fraction and concentrated brine. Methanol demand in subsequent regeneration cycles is supplemented with 5% new methanol by volume. Contaminants in the concentrated brine are removed in a GAC superloader. Based on pilot scale trial data, treated brine is expected to perform equivalently to fresh brine in IEX column regeneration. Waste GAC from the superloader is assumed to be incinerated as hazardous waste (Amec Foster Wheeler 2017).

Contactors and regenerant storage tank materials were estimated based on the necessary capacity of contactors to process well water at the desired flow rate and residence times. Piping and other infrastructure requirements were conservatively assumed to be double that of the GAC system due to the increased complexity of the resin treatment and regeneration system.

### **Bottled Water Supply**

After the release of the US EPA health advisory for PFAS in May of 2016, WPAFB made bottled water available to residents of its affected areas. Data for brand 1 bottles in this analysis come primarily from a report on Nestle manufacturing and supply chain life cycle impacts, which included life cycle (upstream) energy and materials use through delivery and storage at a local supermarket (Quantis 2010). This was supplemented with distribution transportation distances from regional Nestle facilities (Greenwood, IN) to WPAFB. Data for an alternative bottled water scenario, referred to as brand 2, were sourced from the literature, supplemented by Quantis (2010) where necessary. Bottle manufacturing and spring water sourcing and facility energy use were supplemented with distribution transportation distances from regional Crystal Geyser company facilities (Benton, TN) to WPAFB. Bottles were purchased as packages of 28 0.5 L bottles and we include the additional packaging (cardboard tray and low-density polypropylene wrap) in our analysis.

We developed two scenarios for local bottled water distribution at WPAFB based on actual on-site procedures. Under both scenarios, bottled water is picked up from a local supermarket and delivered by gasoline-fueled light truck to distribution centers at WPAFB. These distribution centers include sites with potentially sensitive populations (such as a childcare center). This local distribution stage included round-trip transportation between the distribution site and supermarket, with impacts distributed among the 1 – 4 m3 of water transported per trip. The second distribution scenario included pick-up from the distribution sites by residents. Driving distances were determined from several factors, including proximity of working and living facilities to the pickup location (0.25 – 7.0 km), attributable share of the trip to water pickup (10% – 100%), and volume of water acquired per trip (1 – 4 cases, or 0.013 – 0.052 m3). This resulted in a best estimate of 29 km/m3 with a range of 0.48 – 538 km/m3.

Based on the anticipated health effects of PFAS-contaminated groundwater, we assessed two levels of bottled water supply to WPAFB. Both were based on a substitution of the drinking water fraction of total water use, assumed to be five liters per person per day (USEPA 2011). The provisioning of tap water to homes and workplaces is not included in these scenarios. The sensitive residents (SR) scenario included only bottled water delivery to locations serving EPA-designated sensitive populations to the effects of PFOA and PFOS (pregnant and nursing mothers, infants, and young children), who were assumed to make up 5% of the population. The residents and sensitive nonresidents (RSN) scenario included bottled water delivery to locations serving sensitive populations, assumed to make up 5% of the nonresident population, as well as individual bottled water pick-up by the non-sensitive full-time resident population.

Post-consumer treatment of plastic bottles was not included due to a lack of reliable data on crucial parameters such as local recycling rates, waste transportation distances, and recycling process energy use and end products. The potential influence of recycling on bottled water supply as an alternative to treatment of contaminated groundwater was examined in a sensitivity analysis based on default Ecoinvent version 3 recycling parameters for plastic and cardboard.

### **Life Cycle Impact Modeling and Monte Carlo Simulation**

SimaPro software was used to implement the life-cycle models (v. 8.3, Pré Consultants, Amersfoort, The Netherlands). Database entries designed for North America, the United States, or the region containing the study area (such as North American Electric Reliability Corporation regions) were preferred when assembling the life cycle models. However, relatively few local database entries were available. Most entries were sourced from the Ecoinvent version 3 database using global or rest-of-world (non-European) values. Impact calculations were performed using TRACI 2.1 v 1.04 US 2008 indicator methods. TRACI is widely regarded as the most accurate midpoint impact assessment model for the United States region, particularly for the categories of primary interest in this study (climate change and human health) (Hauschild et al. 2013).

Likelihood distributions were introduced for most model parameters. Where available, operations data from full-scale or pilot-scale facilities or industry reports were used to develop distributions based upon best estimates, maximum, and minimum values. For most parameters, a pedigree matrix approach was used to introduce uncertainty around a best estimate based upon the degree of confidence in the accuracy of the chosen value. The pedigree matrix implementation in SimaPro with Ecoinvent database version 3 adjusts parameter value according to a lognormal distribution parameterized based on a matrix of six data quality categories each ranked from 1 (best) to 5 (worst): data type, reliability, completeness, temporal correlation, geographical correlation, and technological correlation (Ciroth et al. 2012). Stochastic analysis was done with SimaPro using built-in Monte Carlo simulation capabilities with 5000 iterations per model.

To clarify differences between models with similar impacts, we ran additional simulations of the difference in impacts between the GAC and IEX water treatment systems at the baseline PFAS concentration of 0.7 µg/l and the maximum concentration of 70 µg/l, and between the two bottled water systems (brand 1 and brand 2). Unfortunately, because SimaPro can only conduct stochastic comparison modeling between systems on an equivalent mass basis, we could not assess a meaningful comparison of groundwater treatment systems and bottled water provisioning according to our parameters for supply of bottled water only for drinking water for sensitive individuals.

### **Aggregated Human Health Impacts**

Life-cycle human health damage due to treatment operations and bottled water provisioning were calculated by SimaPro in comparative toxic units (CTU) which indicated the expected incident rate of cancer (c) and noncancer (nc) health effects. We converted CTUs to disability-adjusted life-years (DALY) using conversion factors developed by Huijbregts et al. (2005) (11.5 DALY per cancer CTU and 2.7 DALY per non-cancer CTU). Economic endpoints were presented by using the US EPA guidelines on value of a statistical life (VSL), $10.7 million in 2017 (USEPA 2016d) and average US life expectancy of 78.8 years (USCDC 2016). The economic value of a DALY (VDALY) was estimated as $136,000 based upon the ratio of VSL to life expectancy.

## **Results**

### **3.1 Groundwater treatment**

Life-cycle impacts of groundwater treatment at the baseline concentration of 0.7 µg/L PFAS were dominated by electricity use at the treatment facility, which was responsible for 90% and 95% of GWP impacts in GAC-based and IEX-based treatment systems, respectively. Remaining sources of GWP included GAC supply and reactivation and on-site infrastructure and equipment (7% and 3% respectively, in the GAC model) and on-site IEX infrastructure and equipment (4%). Other life-cycle impacts were highly correlated with energy use; human health, ecotoxicity, smog formation, and other impacts were similar between the GAC and IEX treatment methods (Table E5.1). Ozone depletion, impacted by the production of ion-exchange resins, was higher in the IEX treatment scenarios.

Table E5.1. Deterministic model results for supply of 1 m3 treated groundwater water or bottled water

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Scenario | PFOA + PFAS Combined Concentration (µg/L) | | | | | | Local Distribution | | Resident Pickup | |
|  |  | 0.7 | | 7.0 | | 70 | |
|  |  | GAC | IEX | GAC | IEX | GAC | IEX | Brand 1 | Brand 2 | Brand 1 | Brand 2 |
| GWP | kg CO2 eq | 0.33 | 0.32 | 0.54 | 0.33 | 2.7 | 0.50 | 139 | 241 | 144 | 246 |
| Toxicity (cancer) | CTU(h,c) | 2.8E-08 | 3.1E-08 | 2.9E-08 | 3.1E-08 | 3.9E-08 | 3.6E-08 | 6.6E-06 | 8.2E-06 | 6.7E-06 | 8.3E-06 |
| Toxicity (noncancer) | CTU(h,nc) | 9.3E-08 | 9.6E-08 | 9.9E-08 | 9.7E-08 | 1.5E-07 | 1.1E-07 | 3.2E-05 | 4.4E-05 | 3.3E-05 | 4.5E-05 |
| Ozone depletion | kg CFC-11 | 2.7E-08 | 1.7E-07 | 2.8E-08 | 1.7E-07 | 3.6E-08 | 1.7E-07 | 7.3E-06 | 8.0E-06 | 7.3E-06 | 8.0E-06 |
| Smog | kg O3 eq | 8.2E-03 | 8.3E-03 | 0.011 | 8.6E-03 | 0.035 | 0.011 | 9.7 | 20 | 10 | 21 |
| Acidification | kg SO2 eq | 1.2E-03 | 1.2E-03 | 1.7E-03 | 1.3E-03 | 5.7E-03 | 2.0E-03 | 0.72 | 1.4 | 0.74 | 1.4 |
| Eutrophication | kg N eq | 2.8E-03 | 2.8E-03 | 2.8E-03 | 2.8E-03 | 3.7E-03 | 3.0E-03 | 0.38 | 0.38 | 0.38 | 0.38 |
| Respiratory effects | kg PM2.5 eq | 1.1E-03 | 1.1E-03 | 1.2E-03 | 1.1E-03 | 1.7E-03 | 1.4E-05 | 0.14 | 0.16 | 0.14 | 0.16 |
| Ecotoxicity | CTUe | 3.0 | 3.1 | 4.6 | 3.1 | 4.6 | 3.4 | 821 | 1089 | 836 | 1103 |
| Fossil fuel depletion | MJ | 0.16 | 0.16 | 0.28 | 0.18 | 1.5 | 0.38 | 345 | 629 | 356 | 640 |

At higher contaminant concentrations (7.0 and 70 µg/L PFAS), greenhouse gas impacts of GAC-based treatment increased substantially to 0.54 and 2.7 kg CO2 eq/m3 H2O. GAC production and reactivation leads GAC-based treatment impacts to outpace those from IEX-based treatment at higher contaminant concentrations (Table E5.1). At the highest contaminant concentrations, electricity consumption represented only 15% of climate change impacts from GAC-based treatment, but 63% of impacts from IEX-based treatment. Higher overall energy consumption throughout the GAC production and reactivation process leads to higher energy-related life cycle impacts across most categories, including fossil fuel depletion, respiratory effects, and smog formation (Table E5.1).

Human health effects appeared less sensitive to changes in GAC use rate. At 70 µg/L PFAS, electricity production continued to dominate human health and ecotoxicity impacts of groundwater treatment with over 75% to 90% of health and ecotoxicity impacts from both GAC and IEX systems, and approximately 50% of life cycle health and ecotoxicity impacts from coal-fired electric generation. Life cycle electricity consumption increased from 1.5 – 1.9 (GAC) and 1.5 – 1.6 (IEX) MJ/m3 remediated water from the baseline (0.7 µg/L PFAS) and 70 µg/L PFAS scenarios.

Stochastic analyses generally mirror deterministic scenario results, with average climate change and human health impacts increasing substantially only at the highest contaminant level (70 µg/L PFAS, Figure E5.2A and Figure E5.3A). Mean and median values for climate change impacts of groundwater treatment trended higher than the deterministic model results, particularly at higher contaminant concentrations and for IEX-based treatment (up to 400 – 600% of the deterministic model). Stochastic assessment of the difference between GAC and IEX treatments at the baseline PFAS concentration supports deterministic results that impacts were similar between treatment methods. Across most impact categories, GAC resulted in higher impacts in roughly 50-60% of model runs. At the highest contaminant level, stochastic assessment of the difference between treatments continued to show higher average climate change impacts of GAC treatment, though not at 95% confidence.

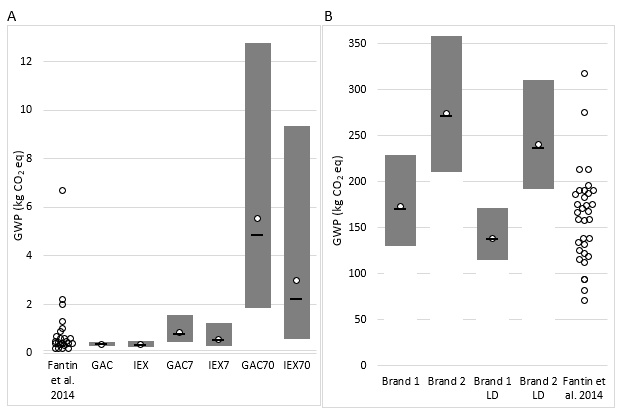


Figure E5.2. (A) Greenhouse gas impacts of GAC and IEX remediation methods from baseline (0.7 µg/L), 7.0, and 70 µg/L combined PFOA and PFOS concentrations and (B) bottled water with resident pick-up or local delivery (LD). Bars indicate 95% confidence intervals (2.5 to 97.5 percentiles). Lines and circles indicate median and mean values, respectively. Studies (n = 24 (A), n = 33 (B)) reviewed by Fantin et al. (2014) are displayed in both figures for comparison purposes.

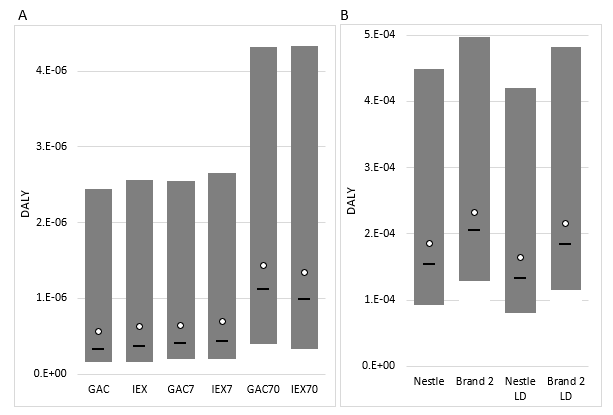


Figure E5.3. (A) Human health impacts of clean water supply via remediated groundwater from baseline (0.7 µg/L), 7.0, and 70 µg/L contaminant concentrations and (B) bottled water with resident pick-up or local delivery (LD). Bars indicate 95% confidence intervals (2.5 to 97.5 percentiles). Lines and circles indicate median and mean values, respectively.

Average human health impacts were similar in stochastic and static models (±20% of the deterministic model), except at 70 µg/L PFAS where stochastic averages were 180% – 230% of the deterministic model for GAC and IEX, respectively. Though GAC treatment generated higher average impacts than IEX-based treatment, confidence intervals for each pair of treatment scenarios largely overlapped. Uncertainty in both climate change and aggregated human health impacts for both systems cover an order of magnitude (1 – 13 kg CO2 eq, Figure E5.2; 0.5 – 4.5 ×10-6 DALY, Figure E5.3). Though a stochastic assessment of the difference between GAC and IEX treatments showed higher human health impacts of IEX in a majority of cases, differences between the two treatment methods were near zero at both baseline PFAS concentration and 70 µg/l.

### **Bottled water**

Production and delivery of bottled water generated life-cycle impacts orders of magnitude larger than remediated groundwater on a common volume basis (Table E5.1). Differences between the two model data sets (brand 1 and brand 2) stemmed primarily from the type and quantity of energy used in PET bottle manufacturing. Production of brand 1 bottles generated 75 kg CO2 eq/m3 bottled water, relative to 135 kg CO2 eq/m3 for brand 2 bottles. Life cycle GWP impacts for the brand 1 system were 18 kg CO2 eq for electricity and 9.6 kg CO2 eq for natural gas. In contrast, life cycle GWP impacts of brand 2 were 5.8 kg CO2 eq for electricity and 42 kg CO2 eq for natural gas. Regional transportation impacts from the bottling facility to a local supermarket also differed between models, contributing 29 kg CO2 eq for brand 1 and 80 kg CO2 eq for brand 2. Life cycle human health impacts were similar between both bottled water models (Table E5.1).

Local distribution and consumer pick-up of bottles were modeled identically for both models. Local distribution contributed 0.6 kg CO2 eq (0.6% and 0.4% of total GWP for brands 1 and 2, respectively), 0.2% – 0.4% of total human health impacts, and 0.2% – 0.3% of total ecotoxicity. Pick-up of bottled water by consumers from a local distribution site contributed 5.3 kg CO2 eq (4% and 2% of total GWP for brands 1 and 2, respectively), 1% – 2% of total human health impacts, and 1% – 2% of total ecotoxicity.

Stochastic simulation of bottled water production and delivery provided expected values similar to deterministic results for climate change and human toxicity impact factors with median climate change, human health, and ecotoxicity impacts within 20% of deterministic values. Ninety-five percent confidence intervals for climate change impacts ranged from 110 – 170 and 190 – 310 kg CO2 eq with local distribution to 130 – 230 and 210 – 360 kg CO2 eq with local distribution and consumer pick-up (brands 1 and 2, respectively) (Figure E5.2B). Life cycle human health impacts were similar across brands and delivery scenarios (Figure E5.3B). Stochastic assessment of the difference between bottled water brands provide evidence for higher human health impacts in the brand 2 system, though not at 95% confidence.

### **Scenario results**

Over the 20-year lifetime of a groundwater treatment system, life cycle climate change impacts may range from 6000 – 14,000 t CO2 eq at 0.7 µg/L PFAS, using GAC or IEX-based treatment methods. At higher contaminant concentrations, we estimate median lifetime system climate change impacts of 21,000 or 130,000 t CO2 eq (GAC) and 14,000 or 62,000 t CO2 eq (IEX) treating 7.0 or 70 µg/L PFAS, respectively (Figure E5.4A). Supplying bottled drinking water as a supplement to PFAS-contaminated drinking water, in lieu of a treatment system, resulted in 270 – 420 t CO2 eq (brand 1) or 810 – 1100 t CO2 eq (brand 2) when bottled water was supplied only to the sensitive fraction of permanent residents on-site. When bottled water was supplied to all residents and also to the sensitive fraction of non-residents, we estimated climate change impacts of 8100-14,000 t CO2 eq (brand 1) or 23,000-33,000 t CO2 eq (brand 2) over a 20-year period (Figure E5.4A).

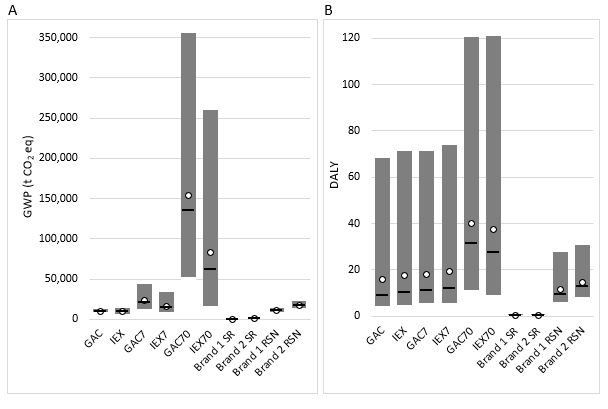


Figure E5.4. Life cycle impacts of clean water supply over 20 years to (A) human health and (B) climate change by groundwater remediation (GAC, IEX) and bottled water (Brand 1, Brand 2). Bottled water scenarios include supply only to sensitive resident populations (SR) or to all residents and sensitive non-residents (RSN). Bars indicate 95% confidence intervals (2.5 to 97.5 percentiles). Lines and circles indicate median and mean values, respectively.

Model results for system lifetime impacts on human health indicated that at low to moderate contaminant concentrations, a groundwater treatment system may result in 4 – 74 DALYs across the full system life cycle. These impacts may increase to 10 – 120 DALYs at higher contaminant concentrations due to increased cycling of the remediating material (GAC or ion exchange resin) (Figure E5.4B). Economic valuation of these health impacts resulted in likely total costs of $1.2M or $1.4M for GAC and IEX, respectively, at 0.7 µg/L PFAS, up to $4.2M or $3.7M for GAC and IEX at 70 µg/L PFAS.

Supplemental drinking water scenarios may result in 0.2 – 1.2 DALYs over 20 years when bottled water was supplied only to the sensitive fraction of permanent residents on-site. When bottled water was supplied to all residents and also to the sensitive fraction of non-residents, life cycle human health impacts may rise to 6 to 33 DALYs. Economic impacts of these losses to human health may range from $42,000 (brand 1) or $69,000 (brand 2) in the sensitive residents scenario to $1.3M (brand 1) or $2.0M (brand 2) in the residents and sensitive non-residents scenario.

## **Discussion**

GAC and IEX-based groundwater treatment methods appeared to perform similarly on a life-cycle basis. The dominance of on-site energy use, which was used primarily for pumping water through the contactors and into the distribution system, helps explain the similarities in climate change impacts between our scenarios and a review of tap water life cycle assessments (Figure E5.2A) (Fantin et al. 2014). Only when GAC use and IEX column regeneration rates increased at higher contaminant concentrations did impacts exceed the range of expected results for tap water provisioning.

Our results for climate change impacts of bottled water supply fell within the range of bottled water life cycle assessments harmonized by Fantin et al. (2014) (Figure E5.2B). The similarity between deterministic and stochastic results for our brand 1 scenarios for local delivery and resident pick-up and the majority of studies reviewed by Fantin et al. (2014) supports the validity of the Quantis (2010) data set. Unfortunately, insufficient data on the human health or ecotoxicity impacts of bottled water production was available in published life cycle assessments to make substantive comparisons with the literature.

### **4.1 Role of energy use in groundwater treatment**

The primary source of life-cycle climate change, human health, acidification, and ecotoxicity impacts from both systems was electricity use at the treatment facility. In particular, electricity generation from coal represented 78% and 82% of total life-cycle greenhouse gas emissions from GAC and IEX-based treatment methods, respectively. At higher PFAS concentrations, the recycling of treatment components made up a larger fraction of life-cycle impacts and the contributions of coal-fired power plants dropped to 49% and 13% (GAC) and 78% and 54% (IEX) for groundwater with 7 and 70 µg/L PFAS, respectively.

Electric generation offered an easy target for impact reduction. Substitution of low-impact electricity sources such as wind or solar could reduce the human health costs of groundwater treatment by 76% to 96% (Hertwich et al. 2014) and reduce global warming potential by 92% to 99% (Asdrubali et al. 2015, Hertwich et al. 2014). When treatment systems treat groundwater with higher concentrations of contaminants, the influence of GAC reactivation and IEX regenerant recycling increased, powered in large part by natural gas combustion for heat and power, as well as coal extraction in the case of GAC. At 70 µg/L PFAS, GAC reactivation and IEX regenerant recycling produced 30% to 40% and 10% to 15% of human health and ecotoxicity impacts, respectively.

### **Logistical considerations**

At higher contaminant concentrations at or above those modeled in this study, logistical considerations could outweigh environmental costs and benefits in system design decision-making. Under the current system design, at 700 µg/L, GAC may need to be replaced every 0.5 – 4 days, or IEX columns regenerated every 5 days. Even at 70 µg/L, GAC may need to be replaced every 1 – 3 weeks at the flow rate and configuration modeled in this study. Ion exchange resins could have the added benefit of greater adsorption capacity, and therefore slower column saturation cycles. On-site recycling of resin columns and regenerant solution could also provide benefits, reducing the logistical and financial burden of scheduling GAC replacement.

### **Comparing groundwater treatment and bottled water scenarios**

On a functional unit basis, life cycle impacts of bottled water far surpassed those of groundwater treatment. However, only 2% of the water supplied by the contaminated well is expected to be consumed as drinking water (the primary mode of exposure to PFAS considered by the EPA). The remaining water is used for a wide range of services, such as washing clothes, bathing, flushing toilets, watering plants, and aircraft maintenance. Though it is possible that some of these activities could result in additional exposure (wearing clothes washed with contaminated water, walking across a lawn watered with contaminated water, etc.), we expect the majority of impacts to human health to occur via direct consumption. Supplying drinking water to the subsets of the total site population considered in our scenarios reduced the fraction of contaminated water replaced by bottled water to 0.008% (sensitive residents scenario) or 0.2% (residents and sensitive nonresidents scenario). Providing these smaller quantities of bottled water to sensitive fractions of the site population could result in similar or reduced life-cycle impacts compared to full treatment of groundwater at the well pump (Figure E5.4).

Supplying bottled water to sensitive populations (infants and nursing and pregnant mothers) in lieu of implementing full-scale groundwater treatment can be examined from a risk analysis perspective on the basis of expected damage to the population exposed to contaminated groundwater. Our results show that average life cycle human health impacts are higher from GAC-based treatment than from supplying bottled water to the sensitive fraction of permanent residents at WPAFB. This accounting does not take into account the potential health impacts of consuming PFAS-contaminated water which are not fully understood and thus difficult to quantify. In our sensitive residents scenario, implementing GAC-based groundwater treatment would reduce net health impacts if the expected incidence rate of health effects from PFAS-contaminated groundwater is higher than two to three cases per 1000 people. Though the actual incidence rate of PFAS-related health impacts is unknown, current evidence suggests that at the baseline concentration in this study (0.7 µg/L), incidence of adverse health effects is far below three cases per 1000 among the non-sensitive population (USEPA 2016a).

### **Sensitivity assessments**

Alternate criteria for bottled water supply rates, or alternate demand for bottled water by the affected population, could lead to variability in the impacts associated with a bottled water supply program. Disaster preparedness documents cite a broad range of possible supply rates for clean water depending on the population affected, environmental conditions, expected uses of the water, and the duration of the supply (USEPA 2011). A plausible high-end estimate of 15 liters per person per day would roughly triple the life-cycle impacts of bottled water supply. However, with the difference between scenarios and confidence intervals for results spanning orders of magnitude, this would have limited effect on the conclusions of this study. At 15 liters per person per day, providing bottled water to sensitive residents would still have lower life cycle impacts than any groundwater treatment scenario, and impacts of bottled water supply to all residents and sensitive nonresidents would still be within the 90% confidence intervals of impacts from groundwater treatment at higher contaminant concentrations.

We find that at the rate of five liters per person per day, supplying bottled drinking water to between 8% and 16% of the total population would have equivalent human health impacts to a treatment system treating 100% of water extracted from the ground. Similarly, climate change impacts of bottled water supply and groundwater treatment are equivalent when drinking water is supplied for 7% – 12% of the population (a total of 5.5 – 10 m3 per day). As previously stated, the sensitive portion of the population is comprised of nursing mothers, pregnant females and young children. This latter segment of the sensitive population is unlikely to consume 5 L, much less 15 L, of water per day.

Though we do not consider the disposal of water bottles in our analysis, a sensitivity analysis suggests that including curbside pickup and disposal in a municipal landfill could increase the climate change impacts from bottled water by 22 kg CO2 eq/m3, or 9% – 16%. Recycling of some portion of waste bottles could mitigate that impact. Garfi et al. (2016) found that life cycle greenhouse gas emissions of bottled water, including the disposal phase, decreased from 79 kg CO2 eq/m3 to 71 kg CO2 eq/m3 when the modeled recycling rate increased from 25% to 75%. Unfortunately, like many prior life cycle assessment studies of bottled water, Garfi et al. did not report outcomes for human health impacts. Our sensitivity analysis suggests that the disposal phase could contribute up to 1.6×10-4 DALY/m3, potentially doubling the human health impacts of bottled water supply.

PFAS have been identified as potent greenhouse gases with substantial contributions to life cycle climate change impacts semiconductor manufacturing and aluminum production (Krishnan et al. 2008, USEPA 2017). However, we expect volatilization rates of PFOA and PFOS to be very low during treatment of contaminated groundwater. Even if 1% of total combined PFOA and PFOS were volatized during treatment, this would contribute only 0.3% – 1.4% of total climate change impacts of GAC-based or IEX-based treatment, respectively.

### **Economic Valuation**

The economic burden of health-related externalities were similar to, or exceeded, the costs associated with provision of potable water. Based on the actual costs of supplying bottled drinking water on an on-demand basis at WPAFB during the six months following the announcement of the EPA health advisory for PFOA and PFOS, the purchase cost of bottled water may total $140,000 over 20 years. Costs associated with treatment of PFAS-impacted water are higher; over a 20-year system lifetime, not considering infrastructure costs, a groundwater treatment facility may pay $0.35M for GAC (at 0.7 µg/L combined PFOA + PFOS) and $1.7M for electricity. These costs are comparable to the economic burden of health-related externalities from the various scenarios explored in this work (Figure E5.5). Over a 20-year system lifetime, externalized health costs range from a low of $42,000 to $59,000 (brand 1 and brand 2 bottled water, sensitive residents scenario) to a high of $3.7M to $4.2M (IEX and GAC treatment at 70 µg/L PFAS). The total cost of health externalities for other six scenarios in Figure E5.5 were between $1.2M and $1.7M. The life cycle analysis demonstrates the significant cost contribution from health-related externalities over the expected duration of the remedial decision.

Figure E5.5. Economic costs from life-cycle human health impacts of clean water supply by groundwater remediation (GAC, IEX) and bottled water (brand 1, brand 2) over 20 years. Bottled water scenarios include supply only to sensitive resident populations (SR) or to all residents and sensitive non-residents (RSN). Bars indicate 95% confidence intervals (2.5 to 97.5 percentiles). Lines and circles indicate median and mean values, respectively.

## **Conclusions**

This study examined the life-cycle impacts to climate and human health from treatment of perfluorinated alkyl substances using case studies based on approaches developed for the United States Air Force. We find that at concentrations ten times higher than the EPA health advisory for PFOA and PFOS, the climate impacts of treatment using GAC and IEX are similar to those for conventional tap water supply and human health impacts are negligible. Impacts of both treatment technologies are highly dependent on energy use at the treatment site, making renewable energy sources a key target for reducing climate, human health, and ecotoxicity impacts.

The range of likely impacts from GAC and IEX based treatment are similar across most scenarios. At PFOA and PFOS concentrations above 70 µg/L, 1000 times the US EPA health advisory, reactivation of carbon and recycling of ion-exchange regenerant become primary impacts, resulting in higher climate and human health damages.

Supplying bottled drinking water to sensitive populations could have lower life-cycle impacts than full-scale groundwater treatment. When contaminant concentrations are low enough to pose a negligible risk to the general population, supplementing tap water with bottled drinking water for up to 5% of the most sensitive individuals within a population could be a low-impact alternative both environmentally and economically. Better understanding of the health impacts of PFAS-contaminated groundwater is necessary to make informed decisions on the risk management of water contamination and treatment. Although this study used WPAFB contaminated site as a case study, the LCA presented here can apply to any study comparing treatment options for water impacted by emerging contaminants.

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