WITAF 56 TECHNICAL MEMORANDUM

PFAS National Cost Model Report

B&V PROJECT NO. 409850

PREPARED FOR

American Water Works Association

American Water Works Association

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BLACK & VEATCH

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Abbreviations

AACE	Association for the Advancement of Cost Engineering
AWWA	American Water Works Association
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFPUA	Cape Fear Public Utility Authority
CIP	Clean-In-Place
CWS	Community Water System
DBP	Disinfection Byproducts
EBCT	Empty Bed Contact Time
EPA	U.S. Environmental Protection Agency
EPTDS	Entry Point to the Distribution System
FRP	Fiberglass Reinforced Plastic
ft	Feet
GAC	Granular Activated Carbon
g/cc	Grams per Cubic Centimeter
gpm	Gallons per Minute
gpm/sf	Gallons per Minute per Square Feet
HRT	Hydraulic Retention Time
IX	Ion Exchange
kWh	Kilowatt-hour
lb/gal	Pounds per Gallon
LHHCWD	La Habra Heights County Water District
MCL	Maximum Contaminant Level
mgd	Million Gallons per Day
mg/L	Milligrams per Liter
NF	Nanofiltration
NTNCWS	Non-Transient Non-Community Water System
NPDWR	National Primary Drinking Water Regulation
PFAS	Per- And Polyfluoroalkyl Substances
PFBS	Perfluorobutane Sulfonic Acid
PFHpA	Perfluoroheptanoic Acid
PFHxS	Perfluorohexane Sulfonate
PFNA	Perfluorononanoic Acid
PFOA	Perfluorooctanoic Acid
PFOS	Perfluorooctane Sulfonic Acid
ppt	Parts Per Trillion
PWS	Public Water System
RO	Reverse Osmosis
SDWIS	Safe Drinking Water Information System
sf	Square Feet
SLR	Surface Loading Rate
T&O	Taste and Odor

TDH	Total Dynamic Head
TDS	Total Dissolved Solids
TOC	Total Organic Carbon
UCMR	Unregulated Contaminant Monitoring Rule
WITAF	Water Industry Technical Action Fund

1.0 Acknowledgement

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Partner Utilities:

- Cape Fear Public Utility Authority (CFPUA)
- City of Ann Arbor
- Greater Cincinnati Water Works
- Plainfield Charter Township
- City of North Miami Beach
- Miami-Dade County Water and Sewer Department
- Tucson Water

Steering Committee Members:

- Amy Stoffer – Northern Kentucky Water District
- Cynthia Lane – Platte Canyon
- Carel Vandermeyden – CFPUA
- Robert Cheng – Coachella Valley Water District
- Zaid Chowdhury – Garver USA
- Chuck Hertz – Retired

2.0 Introduction

Known as “forever chemicals” because they do not easily biodegrade, per- and polyfluoroalkyl substances (PFAS) are drawing increased scrutiny from health agencies, water utilities, and the public for their presence in drinking water and their effects on human and environmental health. They have quickly become contaminants of great concern in drinking water.

Six PFAS compounds were monitored in finished drinking water as part of the Third Unregulated Contaminant Monitoring Rule (UCMR 3) between 2013 and 2015 to quantify their prevalence across the United States. The UCMR program provides the U.S. Environmental Protection Agency (EPA) with nationally representative occurrence data to inform drinking water regulations. Using the results from UCMR 3, in February 2021, the EPA published a final determination to regulate perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS) and signaled an interest in considering the regulation of additional PFAS. The EPA is expected to promulgate the first national primary drinking water regulation for PFAS in the United States in September of 2024 as a result of this regulatory determination.

U.S. federal laws and executive orders stipulate that the U.S. EPA estimate the cost of compliance for this new primary drinking water regulation. Black & Veatch was selected by the American Water Works Association (AWWA) to develop a national cost estimate for water systems to remove PFAS from drinking water to better understand the financial impacts to communities and the costs to comply with a national primary drinking water regulation (NPDWR), a policy that could impact each of the more than 66,500 public water systems.

The project was funded by the Water Industry Technical Action Fund (WITAF), which is managed by the AWWA’s Water Utility Council to support projects, studies, analyses, reports, and presentations in support of the organization’s legislative and regulatory agenda. The national cost estimate and its cost models, developed under WITAF 056, are intended to support to AWWA’s engagement with the U.S. EPA and Congress on the differences in financial impacts of treating drinking water to various PFAS regulatory limits. WITAF funded a separate project (WITAF 057) to generate a national PFAS occurrence database using data from state monitoring and UCMR3. This national database was used as an input for the WITAF 057 project.

The national cost modeling tool programmatically evaluates each public water system (PWS) with occurrence data from WITAF 057 to generate a dataset of the most probable capital and operating costs. Those costs are then scaled up nationally to account for the PWSs without data captured in WITAF 057 to quantify the national cost of compliance of a proposed regulation, bringing flexibility for data-driven responses to EPA cost assessments. This project brought together occurrence data, cost data, and best practice design methodology to help ensure the U.S. EPA’s proposed national primary drinking water regulations for PFAS accurately reflect cost estimates for drinking water treatment.

3.0 PFAS Treatment Technologies

Treatment strategies for PFAS in drinking water include proven, commercially available technologies as well as emerging technologies. Many of these developing technologies have been demonstrated on the bench scale but have not yet been proven at the full scale or are not yet commercially available. Commercially available technologies that have been demonstrated at full scale in the field to reduce concentrations of PFAS in drinking water are limited to the following:

- Granular activated carbon (GAC).
- Ion exchange (IX).
- Nanofiltration (NF) and reverse osmosis (RO).

Treatment considerations for the application of each of these technologies are described in the following subsections.

3.1 Granular Activated Carbon

GAC media is a well-known adsorbent for organics and has been widely applied in water treatment. GAC is produced from carbon-based materials such as coal, coconut shells, peat, or wood that has been "activated" to produce a highly porous media with adsorptive properties. The pores contain sites on which organic compounds become attached and are adsorbed onto the activated carbon matrix.

GAC treatment applications include removal of organics, such as color, disinfection byproducts (DBP) and their precursors, taste and odor (T&O) causing compounds, industrial chemicals, and emerging contaminants such as PFAS, endocrine disrupting compounds, and pharmaceuticals and personal care products. Each of these contaminants compete for adsorption sites on GAC media with targeted PFAS if present. In some cases, co-adsorption can be viewed as a benefit for using GAC as the co-contaminants are simultaneously removed. Cost analyses and removal performance models must balance competitive adsorption of co-contaminants and its associated detrimental performance impact on PFAS removal.

GAC has a finite capacity for adsorbing compounds. High concentrations of organics or high flow rates will lead to more frequent media replacement. In general, short-chained PFAS are less readily adsorbed and less strongly bound than long chain compounds. The overall efficacy of GAC removal of PFAS highly dependent on the water matrix, the water treatment goals, and the design of the system. One of the most important design parameters is the empty bed contact time (EBCT), or the time during which the water is in contact with the media bed (also the duration at which adsorption can occur), assuming the water flows through the entire bed at a constant velocity. A desired EBCT will result in breakthrough when the adsorptive capacity of the media has been exhausted. The media must be either replaced or reactivated at that time.

3.1.1 Implementation and Operational Considerations

GAC applied for PFAS removal is most effective when used solely as an adsorbent. Conventional granular media filters containing GAC are typically designed for short EBCTs and must be frequently backwashed for removal of particulate material that is retained in the media. Such backwashing disrupts the adsorption front. Short EBCTs and backwashing lead to fast breakthrough of contaminants and underutilization of GAC media. If a water treatment facility contains conventional filters, contactors for GAC adsorption are typically located downstream.

Process selection (including GAC media selection) is typically confirmed through demonstration testing (bench-, pilot- or full-scale studies) to account for the unique characteristics of the source water.

GAC adsorption treatment systems installed for PFAS removal typically provide a 10 to 20 minute EBCT and a surface loading rate of 4 to10 gallon per minute (gpm) per square foot of media (gpm/sf). PFAS adsorbers are applied in two main configurations: pressure vessels or gravity basins.

- Pressure vessel configurations are more common in small systems (less than approximately 10 million gallons per day [mgd]). Pre-engineered pressure-vessel type GAC treatment systems are widely available. Vessels are typically carbon steel or fiberglass reinforced plastic (FRP). Pressure vessels may be installed in single (parallel) or dual stage (series/lead-lag) arrangements.
    - The single stage arrangement allows for columns to be operated in various stages of breakthrough or exhaustion, resulting in an overall effluent below the treatment target. This arrangement can result in better media utilization, produce a more consistent product water quality, and lessen impact of potential overruns on individual vessels. Single stage systems typically include N+1 redundancy.
    - The dual stage arrangement allows for simultaneous production during media replacement, and sampling between vessels ensures that lag vessel effluent always meets treatment targets. The lead vessel can be in service until the media is completely exhausted, leading to higher utilization of the adsorbent media. The dual stage arrangement includes built-in redundancy as either the lead or lag vessel can be removed from service without reducing the treatment flow rate. Thus, no dedicated redundant vessels are typically provided.
- To avoid an excessive number of pressure vessels, gravity basin configurations are typically applied by large systems with design flows greater than approximately 10 mgd. Gravity basins are typically single stage and operated at various stages of breakthrough, similar to a single stage pressure vessel arrangement. The basins themselves are typically constructed of concrete with an N+1 redundancy because of the single stage arrangement.

Exhausted GAC filter media will be saturated with PFAS. Bulk GAC can be reactivated by the media supplier through thermal treatment at high temperatures (up to 1800˚ F) to remove and destroy adsorbed contaminants (Rebecca DiStefano, 2022). This reactivation process restores the media's adsorptive capacity, allowing the media to be returned for reuse. GAC is sometimes regenerated by heating the media to temperatures typically less than 400˚ F to remove a portion of the adsorbed contaminants. However, this process will not remove all the compounds and will not destroy the PFAS compounds; therefore, it is not appropriate for GAC utilized for PFAS removal. Media suppliers may not accept the low volumes of GAC required by small systems for reactivation, forcing them to dispose of spent GAC and replace it with new (virgin) material.

Disposal alternatives for exhausted GAC that will not be reactivated for municipal reuse include disposal by reactivation for industrial reuse, incineration, and landfilling. The cost of each disposal method depends on proximity to disposal sites, hazardous waste classification, and volume of material. Disposal costs can be a significant operational cost for GAC treatment systems.

The EPA proposed to designate PFOS and PFOA as hazardous substances under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) in August of 2022. This designation is expected to limit the disposal sites willing to accept spent GAC media. Additionally, the practice of reactivating GAC media contaminated with PFAS is expected to be more limited in drinking water applications.

3.1.2 Assumptions for Cost Estimation

The cost model includes capital costs, annual operating and maintenance costs, life-cycle costs, and annualized costs. The assumptions that drove the results of those cost estimates are summarized in this section.

The costs for GAC contactors depend on the contactor type, size, number, and ancillary processes such as backwash pumps/recovery basins and contactor influent pumps/wet wells. The primary process design assumptions for each of these factors are summarized in Table 3-1.

Table 3-1 GAC Design Process Assumptions

Contactor Type	Parameter		Assumption/Input
Pressure Vessel	Treatment Plant Capacity		1-12 mgd
	Surface Loading Rate (Note 1)		4-10 gpm/sf (most likely 6 gpm/sf)
	Empty Bed Contact Time (Note 1)		10-20 min (most likely 18 min)
	Vessel Diameter		6-12 ft
	Arrangement		Dual Stage
	Redundancy		None
	Influent Pump Station	TDH (total dynamic head)	45 ft
		Design HRT (hydraulic retention time)	15 min
Gravity Basin	Treatment Plant Capacity		> 12 mgd
	Surface Loading Rate (Note 1)		4-10 gpm/sf (most likely 4 gpm/sf)
	Empty Bed Contact Time (Note 1)		10-20 min (most likely 18 min)
	Filter Dimensions		8-20 ft cell width, 2:1 length to width ratio
	Arrangement		Single Stage
	Redundancy		N+1
	Influent Pump Station TDH, design HRT		30 ft, 15 min

Contactor Type	Parameter		Assumption/Input
Common	Backwash(Note 2)	Loading Rate	13 gpm/sf
		Duration	30 min
		Frequency	30 days
		Pump Design TDH	60 ft
	Influent Pump Station(Note 3)	Pump Efficiency	70%
		Motor Efficiency	85%
	Backwash Water Recovery Basin(Note 4)	Water Depth	20 ft
		Backwash Cycles Held	1.0
	GAC Media	Apparent Density	0.5 gram per cubic centimeter (g/cc)
	Contactor Area Factor (for pipe gallery and appurtenances)		2.0

Notes:

1. For adsorptive media, the major specified process design inputs are the surface loading rate (SLR) and the EBCT. For each of these factors, a minimum, maximum, and most likely number was assumed using feedback from existing treatment systems. The minimum, maximum, and most likely numbers for the published model outputs are summarized herein. National variability in SLR and EBCT is included in the model using a Monte Carlo simulation. The details of how this statistical method was employed within the cost modeling tool is described in Section 5.3.
2. Backwash pumps are required for periodic backwashing of the media.
3. An influent pump station is presumed to be required to accommodate the additional headloss necessary to an existing process train.
4. Backwash recovery basin omitted from systems for size category 1 and 2.

3.2 Ion Exchange

IX is an adsorptive water treatment process that involves the selective exchange of ions in solution with ions bound to a resin matrix. IX has a long history in water treatment, and resins are manufactured for a variety of contaminants, including PFAS. Several manufacturers provide specific IX resins designed to be selective for PFAS as the market has expanded for their use. Some resins originally intended for removal of other contaminants (such as perchlorate) have shown a high degree of selectivity and capacity for PFAS as well.

IX resins, like GAC, have a limited capacity for adsorption. The adsorptive capacity of IX resins is affected by contaminant concentrations and flow rates in the same manner as GAC. However, the IX resins surveyed have proven to be highly selective toward PFAS removal, exhibiting minimal removal of other contaminants. This may result in a greater adsorptive capacity for PFAS compared to GAC, without, however, the co-contaminant removal benefits of other technologies. In general, short-chained PFAS are less readily adsorbed and less strongly bound than long chain compounds. The overall efficacy of IX for PFAS removal is highly individual to the water matrix, the water treatment goals, and the design of the system.

An IX treatment process does not result in a fixed percentage removal of a contaminant over time, as there is a variable degree of contaminant removal and gradual or sharp contaminant breakthrough. Although it is selective to certain contaminant groups, the resin can experience interference from other compounds in the water matrix. The most preferred compound will tend to exhibit long runs and sharp breakthroughs; less preferred compounds will have earlier, more gradual breakthroughs.

Exhaustion of the media is determined (in a fashion similar to that for GAC) through the measure of the contaminant in the effluent (breakthrough). When the adsorptive capacity has been exhausted, the resins require replacement or regeneration. Because of the proposed CERCLA hazardous substance designations for PFOA and PFOS as discussed in Subsection 3.1.1, single use (fixed-bed) systems are currently being considered for IX, requiring disposal of spent media and replacement with new resin when exhausted. PFAS destruction technologies are currently in research and development that may be able to destroy PFAS in the brine stream, although that technology is not yet matured enough for full-scale implementation.

Fixed-bed IX has been demonstrated at full scale in the field as a proven PFAS removal technology. Fixed-bed ion exchangers applied for PFAS removal consist of carbon steel or FRP pressure vessels and typically 1.5 to 3 minutes of EBCT (as compared to 10 to 20 minutes for GAC). IX can be favorable because of the smaller footprint required.

3.2.1 Implementation and Operational Considerations

The efficacy of an IX treatment system will likely be improved by a pretreatment step to remove interferences such as suspended solids, particulate natural organic matter, and colloidal compounds. Commercially available filters can be selected depending on the pretreatment needs to improve the treatment capacity of the IX system. This prefiltration step can prevent deposition of fine particles on the resin, reduce pressure drop across a column, and increase run time.

Process selection (including resin selection) is typically confirmed through demonstration testing (bench-, pilot- or full-scale studies) to account for the unique characteristics of the source water.

Ion exchange treatment systems are conventionally installed in pressure filters in lieu of gravity basins. As with GAC, the pressure vessels can be implemented in single or dual stage arrangements. Considerations for the single or dual stage arrangements are summarized in Subsection 3.1.1.

Exhausted IX resin will be saturated with PFAS. Disposal alternatives for exhausted IX resins include incineration and landfilling. The cost of each disposal method depends on proximity to disposal sites, hazardous waste classification, and volume of material. Disposal costs can be a significant operational cost for IX treatment systems.

3.2.2 Assumptions for Cost Estimation

The costs for IX Contactors depend on the contactor type, size, number, and ancillary processes such as backwash pumps/recovery basins and contactor influent pumps/wetwells. The primary process design assumptions for each of these factors are summarized in Table 3-2.

Table 3-2 IX Design Process Assumptions

Parameter		Assumption/Input
Surface Loading Rate (Note 1)		5-12 gpm/sf (most likely 8 gpm/sf)
Empty Bed Contact Time (Note 1)		1.5-3.0 min (most likely 2.0 min)
Vessel Diameter		4-12 ft
Contact Mode		Lead-Lag
Redundancy		None
Influent Pump Station (Note 2)	Pump Efficiency	70%
	Motor Efficiency	85%
	TDH	60 ft
	Design HRT	15 min
Backwash (Note 3)	Loading Rate	5 gpm/sf
	Duration	30 min
	Frequency	30 days
	Pump Design TDH	60 ft
Backwash Water Recovery Basin (Note 4)	Water Depth	20 ft
	Backwash Cycles Held	1.0
IX Resin	Apparent Density	1.05 g/cc
Contactor Area Factor (for pipe gallery and appurtenances)		2.0

Notes:

1. For adsorptive media, the major specified process design inputs are the SLR and the EBCT. For each of these factors, a minimum, maximum, and most likely number was assumed using feedback from existing systems. The minimum, maximum, and most likely numbers used for the published model outputs are summarized herein. National variability in SLR and EBCT is included in the model using a Monte Carlo simulation. The details of how this statistical method was employed within the cost modeling tool is described in Section 5.3.
2. An influent pump station is presumed to be required to accommodate the additional headloss necessary to an existing process train.
3. Backwash pumps are required for periodic backwashing of the media.
4. Backwash recovery basin omitted from systems for size category 1 and 2.

3.3 Reverse Osmosis and Nanofiltration

RO and NF are membrane-based water treatment processes in which a semi-permeable barrier removes dissolved contaminants from water. This capability is attractive when considering the need to remove total dissolved solids (TDS), specific ions such as calcium, magnesium, sodium, chloride, sulfate, and hardness; DBP precursors; and T&O causing compounds as well as high levels of PFAS. RO/NF processes are commonly applied in water treatment plants and have applications ranging from desalination of brackish water, softening, and the removal of nitrate, agricultural chemicals (e.g., atrazine), color, total organic carbon (TOC), DBP precursors, and PFAS. Both RO and NF processes are capable of a high rejection of PFAS. While RO/NF systems are more expensive than GAC or IX systems, they are most viable when the GAC/IX replacement frequency requirements are cost-prohibitive because of high concentrations of influent PFAS.

The key differences between RO and NF are salt passage and feed pressure. RO membranes reject a higher percentage of dissolved ions in the feed water and require a greater feed pressure than NF membranes. NF membranes preferentially remove larger divalent ions or molecules compared to monovalent ions. Thus, NF systems generally exhibit lower energy use and lower operating cost than RO systems. The lower feed pressure required for NF generally translates to a slightly favorable capital cost in relation to RO systems treating the same flow rate. However, the benefits of higher salt rejection and flexibility of systems designed for RO to utilize either NF or RO membranes typically results in utilities favoring RO over marginally lower cost NF systems.

For a typical RO/NF system, membrane elements are mounted into pressure vessels that are arranged in stages, banks, or arrays. The number of stages required depends on specified recovery. Two stages are typically used for recovery less than 80 percent, and three stages are required for higher recovery. RO/NF is a cross flow filtration method, in which only a portion of the feedwater becomes permeate (finished water). The remainder leaves the system as concentrate (brine) that carries away the concentrated material before precipitation or scaling forms on the membrane surface or in the device. Antiscalant is used to control the precipitation of sparingly soluble salts such as calcium carbonate, calcium sulphate, barium sulfate, calcium fluoride, silicon dioxide, etc.

3.3.1 Implementation and Operational Considerations

The recovery of the RO/NF treatment systems depends on the concentrations of the sparingly soluble salts and typically ranges from 75 to 85 percent. Pretreatment requirements include pH depression, antiscalant chemical products to reduce scaling, and cartridge filters to protect the RO/NF membranes from particulates.

The combination of pH depression in the feedwater and the removal of alkalinity through the process results in a low pH (acidic) finished water. Gases pass through NF/RO membranes, resulting in the potential need for removal of hydrogen sulfide and carbon dioxide from the treated water. Post-treatment generally consists of gas stripping through a decarbonation tower and chemical conditioning by addition of a base such as lime or sodium hydroxide (caustic) to raise pH, alkalinity, and hardness to render the water less corrosive. Sometimes a corrosion inhibitor is also added to prevent distribution system corrosion.

A major challenge to implementing centralized NF/RO treatment for PFAS removal is in dealing with the concentrated waste stream generated by the treatment process. Contaminants are rejected into a waste brine stream that is typically around 15 percent by volume of the feedwater (for low salinity feed waters) and 4 to 7 times more concentrated than the raw water fed to the membranes. As a result, additional raw water is required to achieve the desired finished water capacity, and the waste stream requires disposal. Traditional alternatives for disposal include sending the stream to a downstream water reclamation facility, discharging to surface water, or injection into underground deep wells. However, because of the CERCLA regulations for PFOA and PFOS as discussed in Subsection 3.1.1 and pending effluent limit goals for PFAS, concentrate treatment may be required before disposal using these methods.

3.3.2 Assumptions for Cost Estimation

The costs for RO systems depend on the number of trains, permeate flow, and ancillary processes such as the RO feed tank, low-pressure feed pump, high-pressure feed pump, chemical pretreatment, chemical post-treatment, flush pump/tank, clean-in-place (CIP) system, decarbonation system, building requirements, and brine disposal. The primary process design assumptions for each of these factors are summarized in Table 3-3.

Table 3-3 RO Design Process Assumptions

Sub-System	Parameter	Assumption/Input
RO System Design	Recovery(Note 1)	70-85%
	PFAS Rejection	95%
	RO Element Membrane Area	400 ft^2
	Design Flux	15 gallons per foot-squared per day (gfd)
	Redundancy	N+1
	Concentrate Recycle	0%
	Number of Elements per Pressure Vessel	6
	First Stage Pressure Vessel Ratio	4
	Second Stage Pressure Vessel Ratio	2
	Third Stage Pressure Vessel Ratio	1
RO Feed Tank	Hydraulic Detention Time	30 min
RO Low Pressure Feed Pump Sizing	Pump Design TDH	30 ft
RO High Pressure Feed Pump Sizing	Pump Design TDH	350 ft
Chemical Pretreatment(Note 2) Antiscalant Chemical	Density	10.01 pounds per gallon (lb/gal)
	Design Dose	3 mg/L
	Storage	30 days

Sub-System	Parameter	Assumption/Input
Chemical Pretreatment[Note 2] Sulfuric Acid (98%)	Density	15.26 lb/gal
	Design Dose	30 milligrams per liter (mg/L)
	Storage	30 days
Chemical Post-Treatment[Note 2] Caustic (50%) or Liquid Lime	Density	12.78 lb/gal
	Design Dose	45 mg/L
	Storage	30 days
RO Flush Pump Sizing	Flow Rate per Pressure Vessel	30 gpm/1st stage pressure vessel
	Pump Design TDH	140 ft
	Flush Frequency	12 hrs/yr/train
RO Flush Tank Sizing	Volume per Pressure Vessel	7 cubic feet (ft^3)
	Number of Flushes in Tank	2
	Safety Factor	50%
CIP System Sizing	Flush Flow	50 gpm/1st stage pressure vessel
	Time/skid	4 minutes
	CIP Pump TDH	140 ft
	CIP Interval	90 days
	Time/CIP	6 hrs
	CIP Temperature Increase	65 °F
	Heater Losses	10%
Forced Draft Degasifier (decarbonation)	Loading Rate	30 gallons per minute per square foot ($gal/min/ft^2$)
Building Calculations	RO Equipment Area Factor	2.0
	Unit Area	880 ft^2/mgd

Sub-System	Parameter	Assumption/Input
Brine Disposal		Deep Well Injection
Deep Well Injection	Flow per well	1 mgd

Notes:

1. For RO, the critical design input is percent recovery. A minimum and maximum recovery, but no most likely number, is specified. The minimum and maximum recovery used for the published model outputs are summarized herein. National variability in recovery is included in the model using a Monte Carlo simulation. The details of how this statistical method was employed within the cost modeling tool is described in Section 5.3.
2. Chemical systems include pumps, bulk storage, piping, and containment. No day tanks were included in the estimate.

4.0 Estimating National Occurrence

To estimate the costs of removing PFAS from drinking water nationally, national occurrence must be characterized. In parallel to this project, AWWA funded WITAF 057 to compile an occurrence database for PFAS in drinking water. In addition to data available for UCMR 3, WITAF 057 facilitated the collection of PFAS monitoring data from state databases and integrated these sources into a single data set. PWSs in this database included only active Community Water Systems (CWSs) and active Non-Transient Non-Community Water Systems (NTNCWSs). The inactive and transient non community water systems were eliminated from the dataset. Consecutive systems receiving all water from treated water wholesaler systems were not excluded from the database or from representation in the national cost estimation.

The WITAF 057 dataset consisted of 7,842 PWSs within these categories as compared to the 49,424 PWSs in the Safe Drinking Water Information System (SDWIS). To account for this incomplete occurrence data, the percent of systems impacted by a potential PFAS regulation within each system size category was multiplied by the active number of CWSs or NTNCWSs in EPA's SDWIS system at each size category to estimate the anticipated number of total water systems impacted in each size category. This methodology therefore assumed that existing occurrence data is representative of national occurrence. This assumption is considered conservative given a significant fraction of existing occurrence data came from UCMR 3, where the reporting limits of 20 parts per trillion (ppt) and 40 ppt for PFOA and PFOS, respectively, likely bias existing occurrence data to underrepresent true national occurrence that would be measured using the current reporting limits.

Monitoring data for PFAS compounds in the WITAF 057 database included more than 30 individual compounds but for this work was limited to the six PFAS covered by UCMR 3: PFOS, perfluoroheptanoic acid (PFHpA), perfluorohexane sulfonate (PFHxS), perfluorononanoic acid (PFNA), and perfluorobutane sulfonic acid (PFBS). As compiled, the WITAF 057 database includes all monitoring results under UCMR 3 and various state monitoring programs, which at times includes multiple sample results-specific PFAS at PWS. Reported data were reviewed to ensure correct translation of reporting units; fields were included for PWS identification number, state, number of people served, source type, and system type. These data were analyzed to determine the maximum and average sample results for each PFAS at each PWS in the database.

5.0 Individual Treatment Facility Cost Methodology

The next step in estimating the national costs to remove PFAS from drinking water is to use the occurrence database to estimate the costs associated with treatment for individual PWSs. The following subsections summarize how capital, operating, and life-cycle costs are calculated for each system and for each technology.

The spreadsheet tool developed to perform this task accepts inputs for individual or combined target effluent levels for the six PFAS compounds represented in the database. After both occurrence data and potential regulatory levels are input, Visual Basic scripts within Excel may be initiated by a user to run a Monte Carlo analysis and generate a 10th percentile, 90th percentile, and most probable costs for the capital, operations and maintenance (O&M), and life-cycle costs for a typical entry point to the distribution system (EPTDS) for each PWS in the database. For each system, the tool selects the treatment technology with the lowest life-cycle cost.

This methodology assumes installation of a treatment system at each EPTDS associated with PWSIDs where the maximum PFAS concentration is greater than the potential regulatory level for the corresponding PFAS. The details of individual system and EPTDS cost methodology are described in the following subsections. A list of output fields generated by the cost modeling tool for each PWS with occurrence data is shown in Table 5-1.

Table 5-1 Model Outputs for Individual PWS with Occurrence Data

Model Outputs for Each PWS with Occurrence Data
Design Flow (mgd)
Average Flow (mgd)
Capital Expenditure for GAC Vessels
Annual Operations and Maintenance Costs for GAC Vessels
Life-Cycle Costs for GAC Vessels
Capital Expenditure for GAC Basins
Annual Operations and Maintenance Costs for GAC Basins
Life-Cycle Costs for GAC Basins
Capital Expenditure for Ion Exchange Vessels
Annual Operations and Maintenance Costs for Ion Exchange Vessels
Life-Cycle Costs for Ion Exchange Vessels
Capital Expenditure for Reverse Osmosis
Annual Operations and Maintenance Costs for Reverse Osmosis
Life-Cycle Costs for Reverse Osmosis
Capital Expenditure for Lowest Life-Cycle Cost Technology
Annual Operations and Maintenance Costs for Lowest Life-Cycle Cost Technology

Model Outputs for Each PWS with Occurrence Data
Life-Cycle Costs for Lowest Life-Cycle Cost Technology
10th Percentile Capital Expenditure for Lowest Life-Cycle Cost Technology
10th Percentile Operations and Maintenance Cost for Lowest Life-Cycle Cost Technology
10th Percentile Life-Cycle Cost for Lowest Life-Cycle Cost Technology
90th Percentile Capital Expenditure for Lowest Life-Cycle Cost Technology
90th Percentile Operations and Maintenance Cost for Lowest Life-Cycle Cost Technology
90th Percentile Life-Cycle Cost for Lowest Life-Cycle Cost Technology
Capital Expenditure for Manganese Pretreatment
Annual Operations and Maintenance Costs for Manganese Pretreatment
Life-Cycle Cost for Manganese Pretreatment
Lowest Life-Cycle Cost Treatment Technology

5.1 Determining Design Parameters

5.1.1 Treatment Design Flow Determination

PWS data available in SDWIS do not include water usage data for each PWS and EPTDS. Instead, service population data from SDWIS was used and the average flow for each PWS was assumed based on a per capita per day usage of 150 gallons. While not reflective of each state's dynamics with respect to water usage, this was considered a reasonable number from a national perspective. Peaking factors for different size systems from the EPA's "Cost and Technology Document for Final Groundwater Rule" were used and are shown in Table 5-2. The trend of this dataset was best fit to a power equation to calculate peaking factor as a function of average daily flow as shown on Figure 5-1.

Table 5-2- EPA Peaking Factor for Various Average System Flows

Design Flow (MGD)	Average Flow (MGD)	Peaking Factor	Design Flow (MGD)	Average Flow (MGD)	Peaking Factor
0.007	0.0015	4.7	2	0.77	2.6
0.022	0.0054	4.1	3.5	1.4	2.5
0.037	0.0095	3.9	7	3	2.3
0.091	0.025	3.6	17	7.8	2.2
0.18	0.054	3.3	22	11	2
0.27	0.084	3.2	76	38	2
0.36	0.11	3.3	210	120	1.8
0.68	0.23	3	430	270	1.6
1	0.3	3.3	520	350	1.5

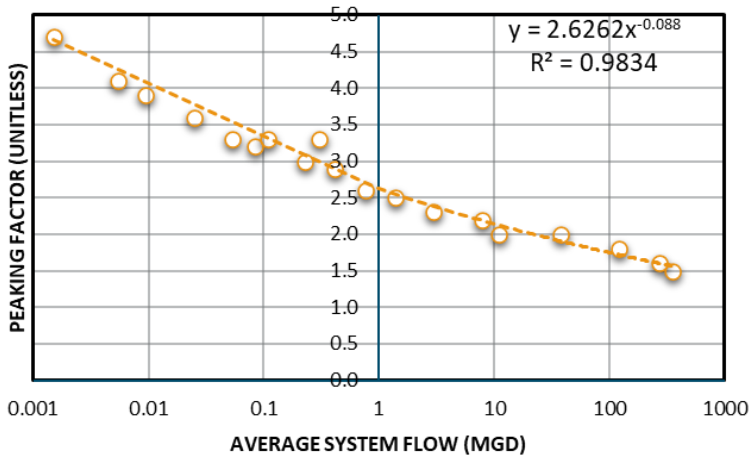

Figure 5-1 Peaking Factor as a Function of Average System Flow

The treatment design flow per EPTDS was determined by Equation 1:

$$Design\ Flow\ per\ EPTDS = \frac{(number\ of\ customers\ per\ PWS)(150\ gpdc)(peaking\ factor)}{EPTDSs\ per\ PWS\ size\ category} \quad (1)$$

Where:

$$Peaking\ factor = 2.6262(PWS\ Average\ Flow)^{-0.088}$$

The estimated number of EPTDS per system size bin is taken from the AWWA Letter to Congressional Budget Office Re: S.1507 - PFAS Release Disclosure Act, dated August 8, 2019, which incorporated updates to information originally collected by EPA's Community Water System Survey. The estimated number of EPTDS by system size bin is summarized in Table 5-3.

Table 5-3 Number of EPTDS as a Function of System Size

Size Category	Population Range	Entry Points/System
1	0-100	2.4
2	101-500	2.0
3	501-1,000	2.1
4	1,001-3,300	1.9
5	3,301-10,000	2.2

Size Category	Population Range	Entry Points/System
6	10,001-50,000	3.1
7	50,001-100,000	4.1
8	100,001-1,000,000	6.6
9	>1,000,001	14.5

5.1.2 Water Quality Considerations Incorporated

5.1.2.1 Influent and Effluent PFAS Levels

For each PWS in the occurrence database, any single PFAS monitoring result above either existing state or potential regulatory limit was assumed to incur a capital expenditure for treatment. Data down to the resolution of each individual source was not considered for this modeling effort; instead, the number of projected water treatment facilities per system was based on the EPTDS factors as summarized in the previous section. Maximum PFAS monitoring data were assumed to compel treatment for the PWS as a whole and, thus, all the projected water treatment facilities. The average PFAS monitoring data were used to estimate long-term costs of removal (annual O&M costs).

The target effluent PFAS levels for treatment was determined as an input percentage of a potential regulatory limit. For example, treatment could be triggered at 80, 90, or 100 percent of the potential regulatory level. For this work, a threshold of 80 percent was used in alignment with previous practice for estimating costs of potential regulations for drinking water, since water systems will target and operate below this threshold to ensure that the limit is not exceeded if the water quality suddenly increases.

5.1.2.2 Other Water Quality Considerations

Other water quality contaminants may impact PFAS treatment performance (and therefore costs), such as TOC and manganese. The longevity of GAC media, IX resin, and membrane operations are significantly affected by the quality of the source. Differences in source water quality parameters not specifically included (e.g., TOC, sulfate, pH, alkalinity, etc.) with pertinence to design or performance were reflected in cost by varying design parameters and treatment system performance according to probability functions using Monte Carlo analysis. This is primarily controlled through variation of the treatment performance factors (e.g., EBCT, surface area loading rate) to reflect less or more challenging water quality characteristics. The methodology for the Monte Carlo Simulation is covered in Section 5.2. Work is in progress to estimate costs associated with removing manganese and will be made available at a later date.

5.2 Monte Carlo Simulation for Design and Performance Variability

Water treatment system design is a practice that evolves non-uniformly across the country. Decisions in the design process are driven in some cases by rigorous engineering standards and in others by regional and geographic considerations, or owner and operator preferences. The result is a landscape of treatment systems across the United States that cannot be effectively modeled by clear and simple rules and frameworks. Additionally, water quality characteristics vary both regionally and locally, and these variations cannot be fully captured in the model with distinct data. These water quality characteristics may improve or hinder performance as well as increase costs to ensure water quality downstream is not altered and complies with other regulations.

To compensate for this uncertainty, Monte Carlo methods were applied to simulate variation and to account for unknowns in major factors influencing design, operation, and, ultimately, cost for PFAS reduction systems. The @RISK Probabilistic Risk Analysis Software by Lumivero, which functions through an Excel add-in, was utilized for the Monte Carlo analysis.

Monte Carlo methods consist of randomizing inputs (e.g., loading rate, GAC media life, RO recovery) according to a defined distribution and number of iterations while calculating the impact to the outputs (e.g., number of vessels, media replacement frequency, cost). As the number of variables undergoing Monte Carlo analysis increases, computer processing power and the time to simulate one scenario both increase exponentially. Thus, Monte Carlo analysis was limited to only major factors considered to exert significant influence on design, performance, and cost of the individual systems. The major factors subjected to Monte Carlo are shown in Table 5-4.

Table 5-4 Major Factors for Monte Carlo Analysis

Parameter	Value
GAC - Pressure	
Surface Loading Rate	
Distribution Type	Triangular
Minimum Value	4 gpm/sf
Maximum Value	10 gpm/sf
Most Likely Value	6 gpm/sf
EBCT	
Distribution Type	Triangular
Minimum Value	10 min
Maximum Value	20 min
Most Likely Value	18 min
GAC - Basins	
Surface Loading Rate	
Distribution Type	Triangular
Minimum Value	4 gpm/sf
Maximum Value	10 gpm/sf
Most Likely Value	4 gpm/sf
EBCT	
Distribution Type	Triangular
Minimum Value	10 min

Parameter	Value
Maximum Value	20 min
Most Likely Value	18 min
GAC Bed Volumes to Breakthrough (Note 1)	
Distribution Type	Triangular
Minimum Value	75 percent of prediction
Maximum Value	175 percent of prediction
Most Likely Value	Prediction
IX - Vessels	
Surface Loading Rate	
Distribution Type	Triangular
Minimum Value	5 gpm/sf
Maximum Value	12 gpm/sf
Most Likely Value	8 gpm/sf
EBCT	
Distribution Type	Triangular
Minimum Value	1.5 min
Maximum Value	3 min
Most Likely Value	2 min
IX Bed Volumes to Breakthrough (Note 1)	
Distribution Type	Triangular
Minimum Value	75 percent of prediction
Maximum Value	175 percent of prediction
Most Likely Value	Prediction
Reverse Osmosis/Nanofiltration	
Surface Loading Rate	
Distribution Type	Uniform
Minimum Value	70 percent
Maximum Value	85 percent

Notes:

1. GAC and IX Performance (i.e. determination of media life) is described in Section 5.4.1. Predicted value is determined using the generalized logistic function of the Clark model.

With the exception of RO recovery, all Monte Carlo inputs were assigned a triangular distribution. A triangular distribution is a probability distribution where the probability decreases linearly on either side of the most likely value (highest probability) to the minimum and maximum, at which point the probability is zero. Triangular distributions were used where typical industry design values exist. RO recovery was modeled using a uniform distribution where each value between the minimum and maximum have an equivalent probability of occurrence.

The result of the Monte Carlo analysis is a distribution of possible costs for each technology (i.e., low [10th percentile], high [90th percentile], and most probable). For each modeled scenario, each of these costs was stored as a modeled output for each system represented in the occurrence database for use in determining the overall national cost of compliance with the modeled limit.

5.3 Capital Cost Calculation

Capital costs were calculated for each EPTDS of a PWS based on the design flow per EPTDS (refer to Equation 1). The design flow was used for capital costs estimates since equipment should be sized for peak treatment flow rates. Costs were independently calculated for IX, GAC vessels, GAC basins, and RO as described in the following subsections. Capital costs generated for individual systems represent a Class 5 Association for the Advancement of Cost Engineering (AACE) estimate, at approximately 1 to 2 percent maturity level of deliverable definition.

5.3.1 Major Hardware Components

5.3.1.1 GAC Gravity Basins

The major cost components incorporated into the capital cost estimate for this option are the concrete basins themselves, an influent pump station, media for the initial fill, and a building to house the system. The design assumptions for each element are summarized in Subsection 3.1.2.

The concrete basin includes costs for influent and effluent piping, isolation valves, and monitoring instruments. Using the design flow rate and the SLR, a required surface area for filtration is calculated and used to determine the appropriate number of basin cells and anticipated basin dimensions for costing.

Once number and size of basins are calculated, the design flow and specified EBCT is used to determine the volume of media needed. Cost of media was determined by converting volume to mass using an average GAC density of 0.5 g/cc and an average cost per pound of $1.40. It should be noted that cost changes were not projected into the cost model resulting from increased demand for adsorbent media.

The pump station includes costs for influent pumps, backwash pumps, an influent wetwell, and a backwash recovery basin. The independent design inputs for the influent pumps are total dynamic head (TDH) and total number of pumps. The independent design parameters for backwash pump and backwash recovery basin calculations are backwash loading rate, backwash duration, backwash frequency, and backwash pump TDH. Costs for backwash pumping include a single duty pump and a single standby pump.

The sum of the square footage required for the contactor basins was multiplied by a sizing factor of two to account for the ancillary equipment and space for access and maintenance. Pump station square footage, including all pumps and the wet well, was estimated by benchmarking design flow against previous designs. Building area was assumed to be the sum of contactor facility area (including sizing factor), pump station area, and backwash recovery basin area (assumed to be indoors). The building cost was assumed to be $200/sf.

Black & Veatch utilized empirically derived cost curves as a function of size from several decades of infrastructure project design and delivery to estimate cost for these major components. A curve for concrete basins provides cost as a function of square footage. A curve for steel tanks provides costs as a function of volume in gallons, and a curve for pumps provides cost as a function of horsepower.

Installation fees were included at 20 percent for all major equipment components, as summarized in Table 5-5. These cost factors are identical to those for GAC and IX pressure vessels.

Table 5-5 GAC and IX Equipment Installation Cost Factors

Component	Percent Multiplier of Unit Cost
Basins/Pressure Vessels	20%
Influent Pumps	20%
Backwash Pumps	20%
Influent Wetwell	20%
Backwash Recovery Basin	20%

5.3.1.2 GAC, IX and Manganese Pretreatment Pressure Vessels

Capital equipment costs were calculated using the total contactor footprint, contactor building footprint, and media volume required. Capital costs were calculated for the ancillary pump stations using the building footprint, number and size of influent pumps, backwash pumps, influent wetwell, and backwash recovery basin. The model incorporated a building cost of $200/ft^2$. The installation fees for the various components are the same as those summarized in Table 5-6.

Calculated capital cost for manganese pretreatment for each system was considered a stand-alone output and was not included in the capital, operational, or life-cycle cost outputs for PFAS treatment.

5.3.1.3 Reverse Osmosis

Capital costs were calculated for the RO system and building, low- and high-pressure feed pumps and their associated building, storage tanks, cartridge filters, chemical treatment system, decarbonation system, and brine disposal. The model incorporated a building cost of $200/ft^2$. The installation fees for the various components are summarized in Table 5-6.

Table 5-6 RO Equipment Installation Cost Factors

System	Component	Percent Multiplier of Unit Cost
Storage Tanks	RO Feed Tank	15%
	CIP Tank	15%
	CIP Neutralization Tank	15%
	Flush Tank	15%
Pump Stations	RO Low Pressure Feed Pumps	25%
	RO High Pressure Feed Pumps	25%
	CIP Pumps	20%
	Flush Pumps	20%
Cartridge Filter	RO Feed Cartridge Filter	20%
	CIP Cartridge Filter	20%
Chemical Feed Systems	Antiscalant	20%
	Sulfuric Acid	20%
	Caustic/Liquid Lime	20%
Decarbonation System	All related equipment	20%

5.3.1.4 Additional Capital Costs

In addition to equipment costs, the capital costs for GAC, IX, RO, and manganese pretreatment included additional project costs (site work, yard piping, electrical, and instrumentation and controls), contractor markup costs, and non-construction costs. The multipliers used for each of these factors are summarized in Table 5-7.

Table 5-7 Additional Capital Cost Assumptions

Additional Capital Costs	Description	Percent Multiplier of Total Equipment Costs
Additional Project Costs	Site Work	8.0%
	Yard Piping	9.0%
	Electrical	10.0%
	Instrumentation & Controls	2.5%

Additional Capital Costs	Description	Percent Multiplier of Total Equipment Costs
Contractor Markup Costs	Overhead	7.0%
	Profit	10.0%
	Mobilization/Bonds/Insurance	3.0%
	Contingency	4.0%
Non-Construction Costs	Permitting	1.0%
	Engineering	8.0%
	Legal/Administration	0.5%
	Construction Services	7.0%
	Commissioning/Startup	3.0%
	Contingency	30.0%

5.4 Operating Cost Calculation

The operational costs for GAC, IX, and RO were calculated using the average flow rate for each EPTDS, as represented by the average flow per water system divided by the number of EPTDS. Whereas capital costs were driven by maximum PFAS levels, the operating costs incurred were driven by the average influent PFAS concentrations to reflect long-term operating conditions. The tool allows entry of a treatment goal expressed as a percent of the potential regulatory limit, and the resulting target concentration serves as the effluent concentration trigger for replacement of media. This target may be expressed either as a concentration of a single PFAS compound or as a combination of compounds.

Operating costs that were considered for this work included replacement costs (using the calculated bed volumes to breakthrough or media replacement frequency), power consumption in the pumps and buildings, maintenance costs, waste disposal, and labor costs. Analytical monitoring costs were not included in the life-cycle cost calculations. Table 5-8 provides an overview of the O&M cost assumptions.

Table 5-8 O&M Cost Assumptions

O&M Category	Description	Value
Media Replacement	GAC Virgin Media (Note 1)	$1.40/lb
	GAC Reactivated Media	$1.20/lb
	IX Resin	$240/ft^3 ($3.70/lb @ apparent density of 1.05 g/cc)
Membrane Replacement	Membrane Cost	$600/element

O&M Category	Description	Value
Power	Unit Cost	$0.10/kilowatt-hour (kWh)
	Unit Building Power Usage	19.5 kWh/ft^2/yr
	Building Utilization Factor	365 days/year
Maintenance	Installed Equipment	1.5% Percent Multiplier of Capital Costs
	Structures and Facilities	1.0% Percent Multiplier of Capital Costs
Waste Disposal	Incineration (Note 2)	$720/ton
	GAC Density	0.5 g/cc
	IX Density	1.05 g/cc
	Mn Adsorptive Media Density	1.8 g/cc
Chemical Consumption Costs	Antiscalant	$15.00/gal
	Sulfuric Acid	$2.50/gal
	Caustic	$4.50/gal
Labor	Operator Rate	$30/hr
	Admin Rate	$25/hr
	Number of Valves	3 per vessel/basin, 2 per pump (additional requirements for RO system include 2 per cartridge filter, 3 per decarbonation system, and 2 per tank)
	Number of Instruments	2 per vessel/basin, 1 per pump (additional requirements for RO system include 2 per cartridge filter, 2 per decarbonation system, and 1 per tank)
	Record Keeping and Sampling	5 minutes per day per instrument
	Pump Operation (adjustments)	5 minutes per day per pump
	Valve Adjustments	5 minutes per week per valve
	GAC Contactor Maintenance	1 hour per week per vessel/basin
	IX Replacement	16 hours per bed volume
	Cartridge Filters	12 hours per year per cartridge filter
	RO Membrane Process Labor	120 hours per week

Notes:

1. Life-cycle cost factors were chosen to match the EPA's standard practice for estimating life-cycle cost
2. Spent GAC media and IX resin was assumed to be incinerated because of the unknown viability of GAC media reactivation under CERCLA. Replacement costs were therefore assumed to be virgin media.

5.4.1 Estimation of Media Life and Disposal

The generalized logistic function of the Clark model (Clark, 1987), represented in Equation 2, was the basis for calculations for estimation of media life for both GAC and IX. While more rigorous techniques exist for modeling adsorption, Clark's model was utilized for its relative simplicity and accuracy.

$$C = \frac{{C_o}^{n-1}}{1 + Be^{-r\prime t}} \qquad (2)$$

Where:

C_o is the influent contaminant concentration, C is the concentration of a given contaminant at time t, n is the inverse of the slope of the Freundlich isotherm, and r' and B are constants. Rearranging the equation above to:

$$\ln\left[\left(\frac{C_o}{C}\right)^{n-1} - 1\right] = -r't + ln\,B$$

r' and B can be solved for from the slope and intercept of the plot of $\ln[(C_o/C)^{1/n}-1]$ versus time. If a constant flow is assumed, the number of bed volumes becomes directly proportional to time, allowing these relationships to be expressed as a function of bed volumes treated rather than time. B, n, and r' values utilized for GAC and IX are expressed in Table 5-9. The values utilized for GAC were derived from data collected during a Black & Veatch GAC pilot study for CFPUA. The values utilized for IX were derived partially from data collected during a Black & Veatch IX pilot study for CFPUA and partially from data collected during an IX pilot study for La Habra Height County Water District (LHHCWD).

Table 5-9 Values Variables in Modeled Bed Life

Media	Constant	PFOA	PFOS	PFHxS	PFNA	PFHpA	PFBS
IX(Note 1)	*n*	1.25	1.25	1.25	1.25	1.25	1.25
	B	4.8	1.8	1.4	6.0	3.6	3.2
	-r'	-2.55E-05	-3.33E-06	-3.40E-06	-1.70E-05	-2.62E-05	-6.23E-06
GAC	*n*	1.49	1.54	3.23	1.79	1.67	1.56
	B	141.7	15.8	666.0	49.1	49.1	11.3
	-r'	-6.21E-04	-2.07E-04	-3.77E-04	-3.46E-04	-4.81E-04	-3.28E-04

Notes:

1. Parameters for PFOA and PFHpA were derived from the CFPUA data set. Parameters for PFBS, PFHxS, and PFOS were derived from the LHHCWD data set. Parameters for PFNA were estimated by extrapolating data for PFOA and PFHpA because insufficient pilot data were available to support a curve fit determination.

For each system with occurrence data, *C* was calculated for each PFAS compound at a specified bed volume increment. Increments of 250 bed volumes up to a maximum of 40,000 were calculated for GAC. Increments of 5,000 bed volumes up to a maximum of 800,000 were calculated for IX. The number of bed volumes at which *C* exceeded the specified target replacement concentration was determined, and the number of bed volumes for the first contaminant to breach its target concentration was used to calculate media replacement frequency. The number of bed volumes treated before the first contaminant exceeded the target concentration was subjected to Monte Carlo variability as described in Section 5.2.

5.5 Life-Cycle Costs

The model determines 20-year life-cycle costs, which combines the capital costs and annual operating and maintenance costs. Life-cycle costs provide a means of comparing the costs of alternative technologies over the life cycle of the equipment. The life-cycle costs were calculated assuming a 20-year lifespan and a discount rate of 7 percent. While typical practice to determine life-cycle costs may incorporate other factors, such as the inflation and loan interest, the discount rate was used to match the approach that is standard practice for the EPA in promulgating national primary drinking water regulations.

6.0 National Cost Assessment Methodology

The conceptual framework for assessing the national costs is as follows:

- Assess capital, annual O&M, and life-cycle costs for EPTDSs in every water system for which potential regulatory limits for PFAS may require treatment.
- Average the costs by system size category.
- Multiply those average costs by the total anticipated number of systems impacted in each system size category based on the percentage of systems in the database impacted by a proposed regulatory limit for PFAS.

The following subsections summarize the process and details associated with the national cost estimation methodology.

6.1 Estimating National Costs Using Model Outputs

Using the treatment facility costs for systems from the occurrence database, the costs were binned by system size, and average EPTDS costs per system size bin were calculated. Using the occurrence database, the number of impacted systems per size category was calculated, and the corresponding percent of the systems in the database was determined. To estimate the number of impacted systems nationally, the percentage of impacted systems was multiplied by the total number of systems in SDWIS for each size category.

The estimated number of impacted systems per size category multiplied by the average cost per EPTDS and the assumed number of entry points yields the total cost per size category. The sum of all costs per size category yields the estimated national cost of removing PFAS to a potential regulatory limit. A summary output is included in Table 6-1 which displays the costs associated with a potential regulatory maximum contaminant level (MCL) of 4 ppt for PFOA and 4 ppt for PFOS.

Table 6-1 Example Summary Cost Table for Potential Regulatory MCL of 4 ppt PFOA and PFOS

Size Category	PWSs In Database (Note 1)	Impacted PWSs in Database	% Impacted in Database	Active PWSs in SDWIS (Note 1)	Nationally Impacted PWSs	EPTDSs per PWS	Nationally Impacted EPTDSs	Average Capital Cost per EPTDS	National Cost
1	1298	242	19%	11,622	2,167	2.4	5201	$ 800,000	$ 4,160,640,000
2	1080	177	16%	15,064	2,469	2	4938	$ 1,700,000	$ 8,394,600,000
3	341	39	11%	5,324	609	2.1	1279	$ 2,200,000	$ 2,813,580,000
4	427	46	11%	7,964	858	1.9	1630	$ 2,900,000	$ 4,727,580,000
5	660	103	16%	5,002	781	2.2	1718	$ 4,800,000	$ 8,247,360,000
6	3007	224	7%	3,419	255	3.1	791	$ 7,900,000	$ 6,244,950,000
7	579	64	11%	582	64	4.1	262	$ 11,100,000	$ 2,912,640,000
8	425	72	17%	422	71	6.6	469	$ 16,800,000	$ 7,872,480,000
9	25	4	16%	25	4	14.5	58	$ 35,000,000	$ 2,030,000,000
Total	7,842	971	12%	49,424	7,278	N/A	N/A	N/A	$47,403,830,000

Note 1: The current analysis accounts for only those costs associated with community water systems (CWSs), which are PWSs that serve more than 25 people for more than 6 months of the year.

6.2 Accounting for State Level Regulatory Costs

The model includes consideration of state regulatory actions that may have driven PWSs to remove PFAS already. Consideration of state regulatory actions is necessary to characterize the compliance costs of a potential NPDWR for PFAS. All state regulations incorporated into modeled cost output are shown in Table 6-2

Table 6-2 State Maximum Contaminant Levels Modeled for State Regulatory Cost Estimate

States	Type	PFOA	PFOS	PFHxS	PFNA	PFHpA	PFBS
Connecticut	Individual		10				
Delaware	Individual	14	21				
Delaware	Combined	17	17				
Massachusetts	Combined	20	20	20	20	20	
Michigan	Individual	8	16	51	6		
New Hampshire	Individual	12	15	18	11		
New Jersey	Individual	14	13		13		
New York	Individual	10	10				
Ohio	Combined	70	70				
Ohio	Individual			140	21		140,000
Vermont	Individual	20	20	20	20	20	
Wisconsin	Combined	70	70				

To differentiate federal regulatory costs from costs incurred because of existing state regulations, the cost tool includes an input sheet for all existing state MCLs as either individual limits or group totals. The Visual Basic Script references both the state MCLs and the projected federal MCLs. In the absence of a federal regulation (or if the state MCL is more stringent than the federal MCL), the cost tool generates costs for treatment to comply with existing state MCLs. An example of this is shown in Table 6-3, which displays treatment costs incurred as a result of state regulations.

Table 6-3 Summary of Estimated Costs Associated with State PFAS MCLs

PWS Size Category	Population Range	% Impacted	Average CAPEX/PWS	Average O&M/PWS	Annualized PWS Cost	Estimated Number of Impacted PWSs	Annualized Total Cost	Present Value of Lifecycle Cost
1	<100	7%	$1,920,000	$48,000	$229,000	761	$174,269,000	$1,846,200,000
2	101-500	5%	$3,400,000	$60,000	$381,000	809	$308,229,000	$3,265,400,000
3	501-1,100	5%	$4,620,000	$63,000	$499,000	250	$124,750,000	$1,321,600,000
4	1,001-3,300	1%	$5,510,000	$76,000	$596,000	112	$66,752,000	$707,200,000
5	3,301-10,000	5%	$10,560,000	$132,000	$1,129,000	243	$274,347,000	$2,906,400,000
6	10,001-50,000	3%	$24,180,000	$310,000	$2,592,000	99	$256,608,000	$2,718,500,000
7	50,001-100,000	1%	$43,050,000	$594,500	$4,658,000	6	$27,948,000	$296,100,000
8	100,001-1,000,000	3%	$98,340,000	$1,848,000	$11,131,000	11	$122,441,000	$1,297,100,000
9	>1,000,000	4%	$407,450,000	$8,555,000	$47,015,000	1	$47,015,000	$498,100,000
All Systems		4%				2292	$1,402,359,000	$14,856,600,000

Note: National costs for various potential MCLs are summarized in Section 7.1. The differentials between state costs in this table and various total national costs represent the cost associated with any modeled NPDWR.

7.0 Summary of Results

A summary of the cost model results for various potential federal MCL alternatives on the national and household level is presented in this section.

7.1 National Cost Estimates

The national cost modeling tool was used to evaluate both the national financial burdens on communities from PFAS drinking water contamination (the National Burden) and the costs for water systems to comply with a potential NPDWR for PFAS (NPDWR Compliance Costs).

The National Burden is reflective of the total, cumulative impact to water systems and communities across the United States from PFAS contamination of drinking water. It is calculated by estimating the drinking water PFAS treatment costs associated with the number of systems with PFAS occurrence data above the target limit. The National Burden assumes the same target limit for water systems across all states and includes systems in states with existing drinking water regulations for PFAS. The NPDWR Compliance Costs are determined by estimating the national financial burden and excluding costs for systems already triggered into treatment by existing drinking water regulations at the state level. The difference between the National Burden and the NPDWR Compliance Costs is therefore calculated using the data presented in Table 6-3.

The National Burden and NPDWR Compliance Costs were estimated for three different scenarios. The first scenario is based on a target PFOA and PFOS level of 4 ppt each. The second scenario is based on target concentrations for PFOA, PFOS, PFHxS, PFHpA, and PFNA (collectively referred to as "long-chain PFAS") of 4 ppt each. The third scenario is based on target concentrations for the same long-chain PFAS compounds of 10 ppt each.

An overview of the present value of the life-cycle cost for the National Burden and NPDWR compliance cost for each of these scenarios is displayed on Figure 7-1.

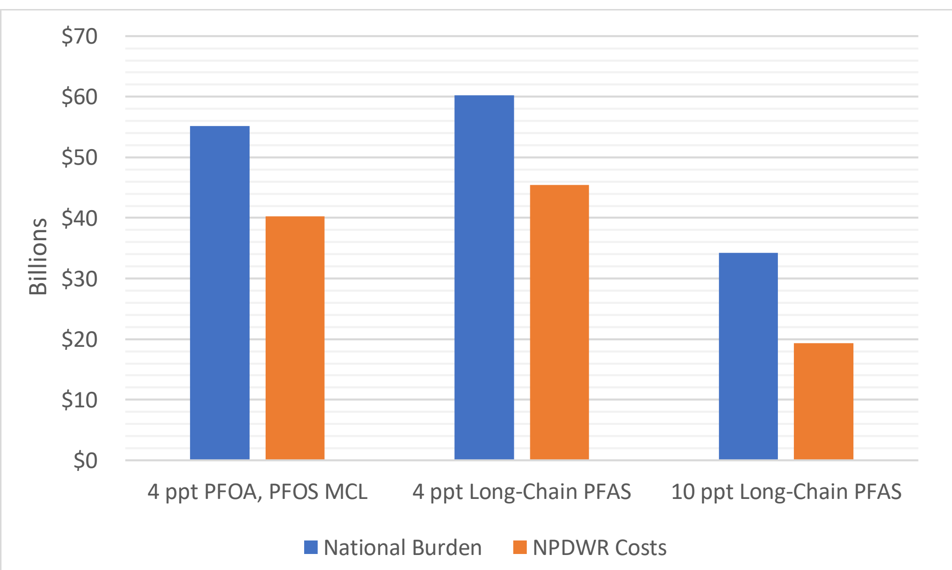

Figure 7-1 Summary of Present Value of Life-Cycle Costs for National Burdens and NPDWR Compliance Costs for Each Scenario

Annualized costs were also calculated using Formula 3. An overview of the National Burden and NPDWR Compliance Annualized Cost for each of these scenarios is presented on Figure 7-2.

$$Annualized\ Costs = \frac{(Capital\ Costs)(Discount\ Rate)}{1-(1+Discount\ Rate)^{-n}} + Annual\ Operating\ Costs \qquad (3)$$

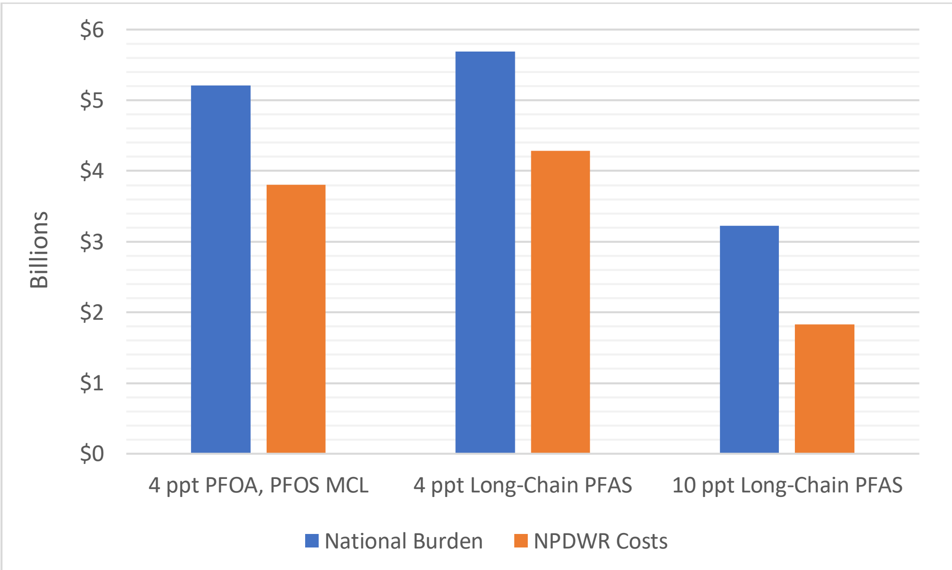

Figure 7-2 Summary of Annualized Costs for National Burdens and NPDWR Compliance for Each Scenario

A more detailed breakdown of these costs by system size is presented in Appendix A.

7.2 Household Financial Impacts

As part of this analysis, the annual financial impacts to individual households from costs associated with the installation and operation of drinking water treatment facilities for PFAS were determined. The financial impacts to individual households will vary by specific PFAS levels, system size, and other factors. Additionally, the impacts to individual households arising from a potential NPDWR will differ depending on whether there is an existing state regulation for PFAS in drinking water. Table 7-1 shows the individual household impacts as a function of system size for each of the three scenarios discussed in Section 7.1. These household level cost impacts are based on the annualized costs for each system size and an average of 2.6 persons per household and incorporate estimated average service populations for each size category based on SDWIS data. The range of household level costs in the table is reflective of communities where new treatment facilities will need to be installed and operated.

Table 7-1 Annual Costs to Household for Removing PFAS from Drinking Water

PWS Size Category	Population Range	Average Service Population	Approximate Range of Costs per Household
1	<100	59	$10,090 - $11,150
2	101-500	245	$4,045 - $4,245
3	501-1,100	736	$1,765 - $1,910
4	1,001-3,300	1,939	$765 - $800
5	3,301-10,000	5,696	$525 - $545
6	10,001-50,000	20,613	$335 - $340
7	50,001-100,000	67,417	$185 - $195
8	100,001-1,000,000	204, 194	$145 - $160
9	>1,000,000	1,700,000	$80 - $105

Appendix A. Modeled Cost Comparison Tables

Table A-1 National Cost Burden by System Size for 4 ppt PFOA, PFOS

4 ppt PFOA, PFOS MCL						
PWS Size Category	Population Range	Average CAPEX/PWS	Average O&M/PWS	Annualized PWS Cost	Estimated Number of Impacted PWSs	Annualized National Cost
1	<100	$1,920,000	$72,000	$253,000	2167	$548,251,000
2	101-500	$3,400,000	$60,000	$381,000	2469	$940,689,000
3	501-1,100	$4,620,000	$63,000	$499,000	609	$303,891,000
4	1,001-3,300	$5,510,000	$57,000	$577,000	858	$495,066,000
5	3,301-10,000	$10,560,000	$176,000	$1,173,000	781	$916,113,000
6	10,001-50,000	$24,490,000	$372,000	$2,684,000	255	$684,420,000
7	50,001-100,000	$45,510,000	$512,500	$4,808,000	64	$307,712,000
8	100,001-1,000,000	$110,880,000	$891,000	$11,357,000	71	$806,347,000
9	>1,000,000	$507,500,000	$3,045,000	$50,949,000	4	$203,796,000
	All Systems				7278	$5,206,285,000

Table A-2 National Burden Costs per System Size for 4 ppt Long-Chain PFAS

4 ppt Long-Chain PFAS						
PWS Size Category	Population Range	Average CAPEX/PWS	Average O&M/PWS	Annualized PWS Cost	Estimated Number of Impacted PWSs	Annualized National Cost
1	<100	$1,920,000	$48,000	$229,000	2265	$518,685,000
2	101-500	$3,400,000	$60,000	$381,000	2553	$972,693,000
3	501-1,100	$4,830,000	$84,000	$540,000	640	$345,600,000
4	1,001-3,300	$5,510,000	$76,000	$596,000	933	$556,068,000
5	3,301-10,000	$11,000,000	$154,000	$1,192,000	811	$966,712,000
6	10,001-50,000	$24,800,000	$372,000	$2,713,000	282	$765,066,000
7	50,001-100,000	$45,100,000	$779,000	$5,036,000	68	$342,448,000
8	100,001-1,000,000	$110,880,000	$2,277,000	$12,743,000	75	$955,725,000
9	>1,000,000	$508,950,000	$18,487,500	$66,529,000	4	$266,116,000
	All Systems				7631	$5,689,113,000

Table A-3 National Burden Costs by System Size for 10 ppt Long-Chain PFAS

10 ppt Long-Chain PFAS						
PWS Size Category	Population Range	Average CAPEX/PWS	Average O&M/PWS	Annualized PWS Cost	Estimated Number of Impacted PWSs	Annualized National Cost
1	<100	$1,920,000	$48,000	$229,000	1039	$237,931,000
2	101-500	$3,600,000	$60,000	$400,000	1032	$412,800,000
3	501-1,100	$4,620,000	$84,000	$520,000	328	$170,560,000
4	1,001-3,300	$5,320,000	$66,500	$569,000	261	$148,509,000
5	3,301-10,000	$10,560,000	$154,000	$1,151,000	455	$523,705,000
6	10,001-50,000	$24,490,000	$341,000	$2,653,000	205	$543,865,000
7	50,001-100,000	$44,690,000	$656,000	$4,874,000	47	$229,078,000
8	100,001-1,000,000	$112,200,000	$1,848,000	$12,439,000	61	$758,779,000
9	>1,000,000	$545,200,000	$15,950,000	$67,413,000	3	$202,239,000
	All Systems				3431	$3,227,466,000