Final Report

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Appendix J: Technology Analysis for Project 1007 Non-Drinking Water Treatment Alternatives

Project 1007 Feasibility Study
Minnesota Pollution Control Agency

MINNESOTA POLLUTION CONTROL AGENCY

Prepared for:

Minnesota Pollution Control Agency
520 Lafayette Rd
Saint Paul, MN 55155

Prepared by:

AECOM
800 LaSalle Avenue
Minneapolis, MN 55402
(612) 376-2000
aecom.com

Minnesota Pollution Control Agency
520 Lafayette Road North | Saint Paul, MN 55155-4194 |
651-296-6300 | 800-657-3864 | Or use your preferred relay service. | Info.pca@state.mn.us
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Acronyms and Abbreviations

AOC	Area of Concern
BV	Bed Volume
CAPEX	Capital Expenditure
CCRO	Closed Circuit Reverse Osmosis
CIP	Clean in Place
EBCT	Empty Bed Contact Time
EPA	United States Environmental Protection Agency
EPL	Eagle Point Lake
FS	Feasibility Study
ft	Feet
ft2	Square Feet
ft3	Cubic Feet
GAC	Granular Activated Carbon
gpm	Gallons per Minute
gpm/ft2	gallons per minute per square foot
HALT	Hydrothermal Alkaline Treatment
HDD	Horizontal Directional Drilling
hp	Horsepower
hr	hour
IX	Ion Exchange
lbs	pounds
MCL	Maximum Contaminant Levels
MGD	Million Gallons per Day
mg/L	milligram per liter
NCP	National Contingency Plan
NF	Nanofiltration
NOM	Natural Organic Matter
O&M	Operations and Maintenance
PFAS	Per- and Polyfluoroalkyl Substances
PFBA	Perfluorobutanoic acid
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctanesulfonic acid
RO	Reverse Osmosis
RSSCT	Rapid Small-Scale Column Test
SAFF®	Surface Active Foam Fractionation
SCWO	Supercritical Water Oxidation
SLR	Surface Loading Rate
UF	Ultrafiltration
UV	Ultraviolet
WCL	Washington County Landfill
WLL	West Lakeland Township

J1 Introduction

Project 1007 is a flood mitigation system constructed to address flooding of Lakes De Montreville, Olson, and Jane, which are also known as the Tri-Lakes area. It utilizes both natural surface water bodies and constructed water conveyance structures to lower the water levels in the Tri-Lakes area, ultimately discharging that water to the St. Croix River. Per- and polyfluoroalkyl substances (PFAS) were historically disposed of in the Washington County Landfill (WCL) and the Oakdale Disposal Site (ODS), both of which historically discharged to the Project 1007 conveyance system. Impacts from ODS continue to be discharged to Project 1007 via Raleigh Creek. WCL and ODS are shown in Figure 2 of Appendix A and further described in Section 3 of the Feasibility Study (FS). Leaching from both WCL and ODS, and infiltration from contaminated surface water has created PFAS-impacted groundwater plumes, which are migrating across the East Metro of the Twin Cities. More details on Site impacts can be found in Section 3 of the FS with a conceptual site model in Section 5 of the FS. This Site has been divided into Areas of Concern (AOCs) to better describe which areas of the Site would be receiving treatment and are described in Section 7 of the FS.

This FS has proposed eight remedial alternatives to manage per- and polyfluoroalkyl substances (PFAS) impacts and protect human health across the Project 1007 Site ('Site'). These are described in Section 11 of the FS and evaluated in Sections 12 and 13 of the FS. The remedial alternatives do include proposed treatment around the WCL as the impacted shallow groundwater onsite and immediately downgradient is included as an AOC. Remedial alternatives for ODS are not discussed in this FS as development of remedial alternatives for that source area will be considered as part of the superfund process at the site, as ODS is currently managed under the MPCA Superfund Program. Site investigation and development of remedial alternatives at ODS was not within the scope of this FS. The remedial alternatives proposed for AOCs included in this FS largely differ in where treatment is occurring, and subsequently, which areas of the plume are being treated and the end use of the water. The water can either be treated and injected back into the aquifer, discharged elsewhere, or distributed for municipal drinking water demand. Pump and treat systems are included for various AOCs in multiple remedial alternatives proposed for the Site to reduce the PFAS concentrations within the current plume extent and reduce downgradient migration of PFAS within drinking water aquifers to protect the current and future use as a drinking water resource. The treated water would ideally be injected back into the aquifer to create areas of groundwater mounding which inhibits contaminant migration. To improve the efficiency, costs, and implementability of a treatment system, a treatment train approach will be required to treat the PFAS in groundwater at the Site. Typical treatment trains include pretreatment to remove natural organic matter (NOM) and metals, a PFAS separation and concentration step, followed by destruction or disposal of the PFAS concentrate. The separation and concentration step may include multiple technologies to increase removal efficiency of the different PFAS found at the Site and to reduce overall treatment costs. Similarly, the extent of pretreatment required is dependent on the subsequent treatment technologies chosen.

The purpose of this appendix is to describe and evaluate the different treatment trains being considered for the Site-wide alternatives that do not involve the distribution of the treated water for municipal supply as are discussed in detail in Appendix K (Multi-Benefit Well Array Technology Analysis). This appendix will evaluate the potential treatment trains based off the technologies discussed and retained in Section 9 (Remedial Technology and Action Screening) and Appendix D (Remedial Technology and Action Screening: Detailed Descriptions and Analysis).

J1.1 Remedial Alternatives Involving Pump and Treatment

A pump and treatment approach is proposed for several AOCs and multiple proposed remedial alternatives. AOC 1 (Washington County Landfill [WCL] Surface Water and Shallow Groundwater) is proposed to be treated with a pump and treatment system in Alternatives 2 – 8. AOC 2 (WCL Bedrock Aquifers) and AOC 7 (Raleigh Creek [RC] + Eagle Point Lake [EPL] Groundwater) are proposed to be treated with pump and treatment in Alternative 4. AOC 10 (West Lakeland Township [WLL] Groundwater) would be treated in Alternatives 4, 6, and 7. These remedial alternatives are summarized in Table J.1 and discussed in detail in Section 11 of the FS.

Potential extraction and injection well arrays were developed for this evaluation. These well arrays were developed based on the conceptual site model and knowledge of municipal pumping plans as of Fall 2024. As the conceptual site model and plans change for the municipality, the well arrays are also expected to change. The goal of these pump and treat systems is to work with municipal supply wells, specifically those in Lake Elmo and Oakdale, to provide capture of the PFAS plume. Particle tracking was completed, as shown in Section 12 of the FS. For costing estimates, assumptions were made for the required size of treatment plants based on the results of these pumping rates. Water extracted from AOCs 2 and 7 is expected to be extracted at approximately 2,000 gallons per minute (gpm) combined, as is water extracted from AOC 10. Proposed wells in AOCs 2 and 7 are sufficiently close to each other that a treatment plant would be built to treat water from both AOCs. Extraction wells in AOC 10 (located in WLL) are geographically further from AOCs 2 and 7 (located in Lake Elmo) and could thus be treated with a separate treatment plant or be piped to the proposed treatment location for AOCs 2 and 7. Cost estimates were prepared for both individual plants (2,000 gpm) and a combined plant (5,000 gpm). A combined plant was sized larger to provide more flexibility in long-term operation. Final decision making will depend on a cost comparison of building two smaller treatment plants as opposed to one larger treatment plant, the cost of piping, and the expected cost to operate one larger facility versus two smaller facilities. Potential treatment plant locations are shown in Figure J.1.

Table J.1. Summary of Proposed Treatment Systems by Remedial Alternative and AOC.

Remedial Alternative	AOC(s) Treated	Expected Treatment System Size
Alternative 1 [(1)]	-	-
Alternative 2	AOC 1	500 gpm
Alternative 3	AOC 1	500 gpm
Alternative 4 [(2)]	AOC 1	500 gpm
	AOCs 2 & 7	2,000 gpm
	AOC 10	2,000 gpm
	AOCs 2, 7, & 10	5,000 gpm
Alternative 5	AOC 1	500 gpm
Alternative 6	AOC 1	500 gpm
	AOC 10	2,000 gpm
Alternative 7	AOC 1	500 gpm
	AOC 10	2,000 gpm
Alternative 8	AOC 1	500 gpm

(1) Alternative 1 is the no further action alternative. No additional treatment would occur besides what is required to supply safe drinking water to the public.

(2) For Alternative 4, either 2 plants could be built to separately treat AOCs 2 & 7 and AOC 10, or a treatment plant could be built to treat the combined flow of AOCs 2, 7, and 10.

All pump and treat systems are expected to include an extraction and injection well network. Potential extraction and injection well placement along with proposed treatment plant locations are shown in Figure J.2 (WCL), Figure J.3 (RC + EPL), Figure J.4 (WLL), and Figure J.5 (RC + EPL & WLL). The exception to this is the WCL, which may or may not utilize an injection well network. Surface discharge or an infiltration array may also be potential discharge options at WCL; further work is needed to identify the best discharge option.

J1.2 Summary of Proposed Treatment Trains

Technologies retained in Section 9 of the FS were evaluated for their potential application in the treatment of groundwater and surface water at the Site. As the effluent from this treatment system would not be used for drinking water, additional technologies are viable for this application that are not currently approved for the use in the treatment of drinking water. Treatment trains being considered for pump and treatment are as follows:

- Treatment Train 1: Reactivated Granular Activated Carbon (GAC) would be used to remove all target PFAS from the pumped water. PFAS destruction would occur when GAC is reactivated offsite.
- Treatment Train 2: Single-use ion exchange (IX) resin would be used to remove short- and long-chain PFAS from the pumped water. The IX resin would be disposed of or destroyed.
- Treatment Train 3: Reactivated GAC would be used to remove long-chain PFAS like perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) from the pumped water. This would be followed by single-use ion exchange to target short-chain PFAS like perfluorobutanoic acid (PFBA). PFAS removed by the GAC would be destroyed during GAC offsite reactivation while a separate destruction or disposal alternative would be implemented for the ion exchange resin.
- Treatment Train 4: Nanofiltration (NF) or reverse osmosis (RO) would be used to separate PFAS from the bulk of the pumped water. The PFAS concentrated in the rejected water would be treated with reactivated GAC to remove long-chain PFAS like PFOS and PFOA. This would be followed by single-use ion exchange resin to target short-chain PFAS like PFBA. PFAS removed by the GAC would subsequently be destroyed during offsite GAC reactivation while a separate destruction or disposal alternative would be implemented for the ion exchange resin.
- Treatment Train 5: Regenerable IX resin would be used to remove long- and short-chain PFAS from the pumped water. Regeneration would be performed using a solvent regenerant, and subsequent distillation of the PFAS-containing spent regenerant would occur on site to recover the solvent for reuse and to concentrate the aqueous PFAS-containing portion for disposal. The PFAS concentrate would be disposed of or destroyed. A preconcentration step of NF/RO would likely be used to decrease the size of the regeneration system.
- Treatment Train 6: Foam Fractionation would be used to predominantly remove long-chain PFAS from the pumped water. Short-chain PFAS such as PFBA may be removed if a cationic surfactant is utilized. The concentrate from the foam fractionation would be disposed of or destroyed. Polishing media (reactivated GAC or single-use IX resin) would then be used to remove residual PFAS to achieve the required concentrations for re-injection. The PFAS removed by GAC would be destroyed during offsite reactivation. IX resin would be managed with a separate destruction or disposal step.
- Treatment Train 7: NF/RO would be used to separate PFAS from the bulk of the pumped water. The PFAS concentrated in the rejected water would be treated with foam fractionation to remove the bulk of the PFAS. Use of a cationic surfactant would promote the removal of short-chain PFAS.

The foam fractionation concentrate would be disposed of or destroyed. If needed, treated foam fractionation effluent would be treated by single-use IX resin to meet treatment targets. IX resin would be disposed or destroyed.

For Treatment Trains 6 and 7, it must be noted that evaluation of foam fractionation in this appendix is focused on Surface Active Foam Fractionation (SAFF®). As part of this FS, the MPCA purchased a SAFF® treatment unit from EPOC Enviro (EPOC) in 2021, and AECOM began operating the system as a pilot test in November 2022. SAFF® was selected as a foam fractionation technology as EPOC was the only vendor to respond to the Request for Proposals posted by the State. Since the commencement of pilot testing, additional vendors have brought technologies to market that could be applicable for this Site, especially with the removal of short chain PFAS. Additionally, the SAFF® technology has improved and is in the process of being scaled up to larger vessel sizes and noncontainerized units. For the purposes of this appendix, SAFF® technology is the basis of cost estimates and treatment system designs as data was available from pilot testing on Site-specific water. Availability of data relevant to Site-specific water increases the confidence of cost estimates and initial system design parameters over purely theoretical calculations. However, should either Treatment Train 6 or 7 be selected as a remedial alternative, a careful evaluation of all foam fractionation vendors is recommended prior to selection of a foam fractionation system. Finally, for the purposes of this report, 'foam fractionation' indicates a reference to foam fractionation as a general technology, while 'SAFF®' refers to the commercially available technology produced by EPOC.

Additional treatment alternatives were evaluated as part of this report and were ruled out after initial analysis. Regenerable GAC was initially evaluated as a treatment alternative, which would utilize an outside vendor to truck in a regenerant solution to regenerate GAC onsite. However, it was quickly ruled out because the technology is still at the pilot scale, adsorptive capacity is lost with every regeneration, and expected costs (up to $2.50/lb of GAC) are greater than costs of new GAC ($1.10/lb for off-site reactivated GAC and $2.25/lb for virgin GAC). Additionally, GAC was initially considered as a polishing media for Treatment Train 7; however, after initial concentration with NF/RO and treatment with foam fractionation, short-chain PFAS would be dominant, making IX resin the superior alternative to GAC. Finally, novel adsorbents such as modified clays or DEXSORB® (a beta-cyclodextrin-based sorbent) were not included as treatment alternatives as they are not widely used technologies at the writing of this report, unlike GAC and IX resin. Use of a novel media with only a single supplier with limited full-scale implementation increases risk of higher-than-expected costs or worse than expected performance. Novel media should be reconsidered if additional, peer-reviewed information consistently demonstrates superior performance compared to GAC and IX resin, including when operating at scale, these technologies could be reconsidered depending on the final remedy selected for implementation and after further discussions with stakeholders. Evaluating alternative media would also require additional treatability studies such as the rapid small-scale column tests (RSSCTs) described in Section 10 of the FS.

J1.3 General Operating Assumptions

This section describes assumptions how the treatment trains would be operated and requirements for specific technologies. Treatment of the PFAS-impacted groundwater plume is intended to meet remedial action objectives (RAOs), defined by AOC in Section 8 of the FS. Generally, RAOs are to decrease mass flux of PFAS into the drinking water aquifers from primary and secondary source zones, reduce PFAS concentrations in the current groundwater plume extent, and to slow the downgradient migration of PFAS into unimpacted drinking aquifers.

Treatment plants would be designed to target the treatment goals defined in Section 9 of the FS. Treatment targets are generally set to the lowest applicable regulatory standards. The exceptions to this are PFOA and PFOS, as the lowest standards are below current detection limits. Thus, the treatment target for PFOA and PFOS is non-detect. It is assumed the effluent from a remediation plant would be regulated to drinking water standards, though actual permit limits are unknown for these hypothetical plants. Other criteria, such as Site-Specific Surface Water Quality Criteria could apply as well. See Section 9 of the FS for more details.

Three sizes of treatment plants were considered for evaluation: small (500 gpm), medium (2,000 gpm), and large (5,000 gpm). A small plant could be used to treat source zone pollution at AOC 1 (WCL Surface Water and Shallow Groundwater). A medium sized plant could be used for plume control in AOC 7 (RC + EPL Groundwater) or AOC 10 (WLL Groundwater), while a large plant could be used to treat water from multiple AOCs piped to the same location. Flow rates are estimates based on current particle capture modeling results and may require further study/validation prior to implementation and construction of a treatment plant. Specifically, flow rates in AOC 1 would require additional pumping tests to confirm particle capture model results, due to the highly fractured nature of the bedrock.

Pre-treatment is assumed to be needed for all treatment options. Foam fractionation requires the least amount of pretreatment and can be accomplished with bag filters to remove particulates that may harm pumps within the system. All other treatment trains require more extensive pretreatment. Naturally occurring iron and manganese in groundwater can cause fouling in GAC and IX vessels, as can natural organic matter (NOM). While NOM is expected to be low in groundwater, iron and manganese are elevated across the Site and municipal supply plants have found pre-treatment is typically required. Municipalities have also discontinued pumping of specific municipal supply wells with high levels of NOM or iron/manganese to limit the need for pretreatment. Pre-treatment options include oxidation of iron and manganese with chlorine, filtration with rapid sand filters and/or greensand, cartridge filters, or other pre-filtration options. Treatability testing as part of this FS indicated good results with greensand filters for iron and manganese removal, thus, greensand media was selected for use in cost estimates. See Section 10 of the FS and Appendix H (Groundwater Treatability Study for PFAS Treatment for Project 1007 Bench-Scale Study Report) for additional details on treatability testing.

This study assumed vertical pressure vessels for the 500-gpm plant and horizontal pressure vessels for the 2,000- and 5,000-gpm plants. All vessels are assumed to operate with a loading rate of 4 gallons per minute per square foot (gpm/ft^2). The design criteria for the greensand filters are included in Table J.2.

Table J.2. Greensand Pre-Filter Preliminary Design Criteria.

Parameter	Unit	Small Plant	Medium Plant	Large Plant
Flow Rate	gpm	500	2,000	5,000
Pressure Vessel Style	-	Vertical	Horizontal	Horizontal
Process Trains	-	2	2	4
Flow Rate per Train	gpm	500	2,000	1,667
Vessel Diameter	ft	12	12	12
Vessel Length	ft	-	40	36
Surface Loading Rate (SLR)	gpm/ft^2	4.4	4.1	4.1
Chlorine Dose	mg/L	6	6	6
Backwash Frequency	hr	23	23	23

Legend: ft = foot or feet; gpm/ft^2 = gallons per minute per square foot; hr = hour; mg/L = milligrams per liter.

GAC and IX vessels would be operated in lead/lag configuration. In this configuration, the lead, or primary, bed serves to remove the majority of the contaminant from the water and the lag, or polishing, bed acts as a safeguard and removes any contaminants that breakthrough the lead bed. Upon exhaustion of the lead vessel, the media is replaced in the lead vessel, and the vessel is placed back in service as the new lag vessel. The old lag vessel is switched into the lead position, where it runs as the lead until it reaches the end of its life, and the process repeats. Breakthrough and exhaustion can be defined multiple ways and depends on the treatment goals and risk tolerance of a project (i.e. if end use is drinking water use vs. re-injection). In some drinking water applications, breakthrough is considered to occur when the concentration in effluent of the lead bed (before going through treatment of the lag bed) is above the analytical detection limit of the compound. In other drinking water applications, breakthrough may be defined as the effluent of the lead bed reaching 50% of an applicable Maximum Contaminant Level (MCL) or exceeding the MCL. In non-drinking water applications, breakthrough may be considered when the effluent of the polishing bed is above the relevant detection limit of a compound or when a permit limit is approached. Total exhaustion occurs when the effluent concentration is equal to the influent concentration. For the purposes of this analysis, breakthrough and thus, the trigger for media changeouts, was considered to occur when the effluent from the primary (lead) vessel exceeded the applicable MCL.

Reactivated GAC, as opposed to virgin or single-use, GAC is used for initial cost estimates. Removal efficiencies and required empty bed contact time (1) (EBCT) of long-chain PFAS are typically similar between virgin and reactivated GAC, but breakthrough of reactivated GAC is typically seen before virgin GAC. At the time of writing this report, reactivated GAC was quoted at $1.10/pound (lb) (freight and reactivation not included) while virgin GAC was approximately $2.25/lb (freight and reactivation not included). Freight and reactivation costs are expected to be similar for both types of GAC, at approximately $0.25-$0.55/lb. Reactivated GAC cannot be used in drinking water applications, but in a non-drinking water application, it offers substantial cost savings over virgin GAC, provided the bed life of reactivated GAC is greater than 50% of the bed life of virgin GAC. Final selection between reactivated and virgin GAC would require completion of RSSCTs for an in-depth cost comparison.

Operating equipment would be designed with N+1 redundancy to increase system uptime and reliability. N+1 redundancy design allows for maintenance and repairs to occur on a piece of equipment or entire operating unit while still operating at maximum design flow. One additional piece of (redundant) equipment is installed beyond the minimum number 'N' required to achieve a design flow (e.g. if five GAC vessel pairs are needed to achieve design flow, six pairs of vessels will be included in the design/cost estimate). Cost assumptions are built on this N+1 redundancy. This approach is standard practice as outlined in the 10 States Standard for wastewater treatment (Health Research, 2014)

Several waste streams would be generated during the treatment process that would require further treatment with process equipment beyond the process equipment used to remove PFAS (e.g. clarifier to remove solids from a waste stream). Due to the infrequent nature (e.g. GAC changeout water) or small volume (e.g. sanitary toilet/sink discharges), construction of separate wastewater treatment equipment to treat these flows is unlikely to be cost effective compared to sanitary sewer discharge rates. Thus, a connection to the city sewer system (likely the Metropolitan Council's Metro wastewater plant) is also assumed to be available for each system for the following discharges:

- Restroom facilities are assumed to be required for all treatment plants, necessitating a city sewer connection for sanitary discharges.
- Proposed pre-treatment options will require backflushing to remove accumulated solids. This waste stream should not be recirculated, as recirculating it to the plant headworks would create a recirculation loop for solids. Solids-containing backwash water would be discharged to the sanitary sewer for further treatment. Treated effluent water would be used to minimize the potential of sending PFAS to the sanitary sewer.

(1) Empty Bed Contact Time is calculated by dividing the volume of a treatment vessel by the flow rate through the vessel, giving a theoretical treatment time for liquid that passes through the vessel. It assumes all liquid moves at the same velocity. EBCT provides a comparison between media types for the relative amount of time a liquid must be in contact with a treatment media to reach treatment objectives. A longer EBCT requires a larger vessel. Adsorptive media that requires a shorter EBCT is preferable, as smaller vessels can be purchased, and less building footprint is needed, reducing the cost of projects.

- During media (GAC and IX) changeouts, the media is slurried with excess water as it is loaded into the vessels. This water would contain residual solids and should not be recirculated to the plant headworks, to avoid the risk of plugging instrumentation and pre-treatment or GAC/IX media. Additionally, GAC requires a fines backwash after initial loading, which also could cause plugging issues. Discharge of media changeout water to the sanitary sewer would prevent operational issues with high solids loading in these streams; treated effluent water would be used to minimize the potential of sending PFAS to the sanitary sewer.
- GAC, and potentially IX, may require periodic backwashing; this water should not be recirculated to the plant headworks to prevent a recirculation loop for solids and to prevent potential operational issues due to high solids loading in the waste stream. Treated effluent water would be used to minimize the potential of sending PFAS to the sanitary sewer.

These waste streams will likely require approval from the Metropolitan Council prior to discharge; to limit impacts to the Metro Plant, backwash waste streams should first be sent to a waste buffer tank prior to discharge to sanitary sewer to decrease the instantaneous flow. Backwashes and changeouts should also use treated water to decrease the risk of PFAS being discharged to the wastewater plant. To facilitate this, it is assumed a storage tank with a discharge overflow will be used to maintain a suitable volume of treated water for plant usage. If backwashes cannot be discharged to a city sewer, additional infrastructure, such as a lamella clarifier or other type of solids removal process equipment, would be required to handle the onsite waste streams.

Finally, buildings are assumed to need a control room, locker rooms/restroom facilities, and a laboratory/testing area. Detailed building design was not performed for the cost estimating at this point in the FS; instead, sufficient contingency was assumed for incorporation of these building amenities.

J1.4 Phased Implementation

Phased implementation of the pump and treat systems could be considered if costs needed to be spread over a period of time. In remedial alternatives where separate pump and treatment systems are proposed for the Site-wide remediation, source area control should be implemented first with hydraulic control of the bedrock aquifers implemented after to reduce the continued migration of the high PFAS impacts located at the source areas. Phasing of an individual pump and treatment system could also be implemented. In most cases, this would entail construction of the treatment plant and a subset of the extraction and injection wells. Additional extraction and injection wells could be installed at a later date. The potential phasing of the pump and treatment systems is discussed in Section J5.3 of this appendix and phasing of the components of the recommended alternatives is discussed in Section 14 of the FS. Costs would increase in a phased approach because of inflation over the construction time period.

J1.5 Cost Estimates

Treatment plant capital costs, operations and maintenance costs, and piping costs were estimated for the seven treatment trains considered in this appendix. Unit cost estimates reflect the opinion of AECOM of probable construction costs utilizing information available at the time the document was prepared.

AECOM has no control over future costs of construction labor, materials, equipment, nor of contractors' methods of determining prices, nor of competitive construction industry market conditions. The accuracy of the estimates is not guaranteed, and they are not intended to predict the outcome of the construction bidding.

AECOM has based the unit costs on AACE Class V estimating guidance. This opinion of probable costs is based on conceptual design and the basis of estimate summarized in this report. All costs were developed in September 2024 dollars based on the ENR Building Cost Index for Minneapolis. All project descriptions and cost estimates in this report represent planning-level accuracy and opinions of costs (-50%, +100%).

The unit costs have been developed based on cost estimating resources including:

- Local vendor estimates for specialized materials and equipment;
- Construction and installation costs from similar AECOM projects;
- Historical data and prices for similar facilities designed and/or constructed by AECOM;
- Where applicable, historic costs have been inflated based on Engineering News Record construction indices.

The estimated unit cost includes the sum of materials, labor, and equipment of reasonably identified features of a project. The estimated total project cost is the sum of construction costs with additional allowances for direct and indirect costs and contingencies. The engineering costs include design and surveying.

The following additional direct and indirect costs and contingencies were included while developing costs:

Direct:

- Mobilization and Site Setup (5%)
- Bonding and Insurance (3%)

Indirect:

- Contractor Overhead and Profit (15%)
- Engineering and Construction Contingencies (45%)

J1.5.1 Capital Expenditure Estimates

CAPEX estimates are based on preliminary design criteria for all treatment trains. Design parameters such as EBCT and surface loading rate (SLR) are selected based on standard design ranges and expected PFAS influent conditions. Equipment sizing is considered preliminary and subject to change after completion of additional pilot and treatability testing.

CAPEX cost estimates include the following major categories:

- Pretreatment process equipment (Greensand filters, chlorine feed)
- PFAS separation and removal process equipment by treatment technology
    - GAC process equipment
    - IX process equipment
    - Membrane process equipment, including chemical dosing
    - Foam fractionation process equipment (based on SAFF® process equipment)
- Tanks and pumps
- Piping (process piping, valves, check valves, flow meters)
- Electrical (building/process electrical, instrumentation & controls, generator)
- Building and Foundation (building, concrete, fire protection, HVAC)

Additional administrative space is not provided in treatment buildings and is assumed to be available in other city buildings. Administrative space, or other beneficial uses, could be added to any treatment building design at additional cost, pending site location and land availability.

J1.5.2 Treatment Plant Operations & Maintenance Estimates

OPEX estimates are based on estimates of adsorptive media usage, chemical usage, process testing, labor costs, electrical use, and replacement parts/operational equipment. Assumptions made regarding each category of costs are detailed in Table J.3. Cost estimates in this report represent planning-level accuracy and opinions of costs (-50%, +100%). OPEX estimates were developed for the 500 gpm, 2,000 gpm, and 5,000 gpm plant sizes; OPEX is assumed to be the same for both AOCs that would utilize a 2,000-gpm plant if separate treatment plants were selected.

Table J.3. Operating Expenditure (OPEX) Cost Estimating General Assumptions.

Parameter	Assumptions
PFAS Testing	• $700/sample for rapid testing • Weekly influent and effluent testing for all treatment trains • Mid-bed and post samples for adsorptive media (GAC/IX)
Process / NPDES Testing	• $1000 per week
Electrical Costs	• $0.10 / kWh • 24/7 operations @ 90% uptime (7884 hours per year) • 80% efficiency for pumps
Labor Costs	• $57.50 / hour for operators • $150 / hour for engineer or supervisor
Replacement Parts & Operations Equipment	• 2% of total process equipment CAPEX cost
Sewer Cost	• Discharge to sanitary sewer • Yearly permit at $10,325 from the Metropolitan Council • Cost of $2.31 per 1000 gal of discharge
GAC and GAC Reactivation Costs	• Reactivated GAC quoted at $1.10 per pound • Delivery of $0.15 per pound • Reactivation of $0.30 per pound • Total cost of $1.75 per pound with contingency
IX and IX Disposal Costs	• IX quoted at $439 per cubic foot • Assumed 20% for delivery and labor to load media • All IX media would be landfilled • Landfilling cost of $10,000 per trip and $0.10 per pound IX media
Chemical Dosing	• Chlorine dose of 6 mg/L assumed for removal of iron and manganese

Results from RSSCTs performed during treatability studies conducted for this FS were used to estimate media life. One sample of water from the WCL (AOC 1), a sample from both the Jordan and Shakopee aquifers (relevant for AOCs 2, 7, and 10), and one SAFF®-treated sample were tested with virgin GAC and single-use IX media. Specific throughputs [2] for this appendix were derived from these results, though not all treatment trains were directly tested. Tables J.1 (WCL) and J.2 (AOC 2, 7, and 10) provide specific throughputs used to calculate media life. Estimated yearly changeouts based on these calculated media

[2] Specific Throughput is the expected amount of water that can pass through (be treated by) a unit of adsorptive media prior to media breakthrough occurring in units of volume of water per mass of media (i.e. gallons of water per pound of media). Specific throughput in this FS utilized applicable State and Federal drinking water limits to determine media breakthrough. Generally, at WCL PFBA determined specific throughput while either the Hazard Index or PFOA determined breakthrough for samples representative of AOCs 2, 7, and 10.

lives are provided in Table J.4. There is uncertainty in the PFBA removal efficiency by foam fractionation and NF/RO. High media usages were incorporated into the 500-gpm plant as this is the size that would need to be utilized at WCL to capture this uncertainty. Additional details on treatability studies can be found in Section 10 of the FS and Appendix H.

Table J.4. Estimated Yearly Media Changeouts for Treatment Trains.

Treatment Train	Media	Yearly Changeouts		
		500 GPM	2,000 GPM	5,000 GPM
Treatment Train 1	GAC	439	25	25
Treatment Train 2	IX	283	1.5	1.5
Treatment Train 3 [(1)]	GAC	44	2	2
	GAC	142	1	1
Treatment Train 4 [(1,2)]	GAC	140	7	6
	IX	181	3	2
Treatment Train 5 [(3)]	GAC (Sacrificial)	4	N/A	N/A
	GAC (PFOA Removal)	55	N/A	N/A
Treatment Train 6 [(4)]	GAC (High Usage)	439	-	-
	GAC	44	4	4
	IX (High Usage)	71	-	-
	IX	7	1.5	1.5
Treatment Train 7 [(2)]	IX (High Usage)	57	-	-
	IX	3	3	3

(1) Treatment Trains 3 and 4 utilize both GAC and IX.
(2) Treatment Trains 4 and 7 would utilize NF/RO, thus the concentrate stream would approximately 25% of the overall flow. The size of media pressure vessels would thus be smaller, and require more frequent changeout, but of a smaller volume of media.
(3) Regeneration of IX resin may not sufficiently remove long-chain PFAS from the resin. If insufficient removal is observed, GAC ahead of the IX would be required to maintain resin performance.
(4) Treatment Train 6 would utilize either GAC or IX individually.

All IX media is assumed to be landfilled for the purposes of this FS; disposal costs and thus yearly OPEX costs would increase for Treatment Trains 2, 3, 4, 6, and 7 if spent IX media were to be incinerated instead of landfilled. Novel methods such as destruction by supercritical water oxidation (SCWO) or offsite regeneration by a third party were not considered as they are not currently available at the scale needed for any of these treatment plants. Landfilling costs were estimated from a similar project within the Midwest at approximately $10,000 per load and $0.10 per kWh, or approximately $12,000 per 15 tons of material. As PFAS disposal regulations change, this cost is likely to increase in the future.

Vendor budgetary estimates were used for reactivated GAC and IX resin. Reactivated GAC was quoted at $1.25 per pound delivered to Lake Elmo, MN, with reactivation costs estimated at $0.10 to $0.40 per pound. A budgetary estimate of $1.75 per pound was used for OPEX estimates to account for other costs that could occur while changing out GAC. IX resin was quoted at $439 per cubic foot. A 20% cost adder was used to account for resin changeout costs.

The labor rate for treatment plant operators was estimated at $57.50/hr, based on a rate of $50/hr used by the Minnesota Pollution Control Agency's (MPCA) Conceptual Drinking Water Supply Plan (CDWSP) in August 2021, accounting for inflation since the publishing of the CDWSP. This rate assumes direct hire of treatment plant operators. Labor rates for an engineer/supervisor were estimated at $150/hr, which assumes oversight of the treatment plant was outsourced to a third party. Direct hire of an engineer or supervisor or outsourcing of treatment plant operators would likely result in a change to the yearly salary estimates.

Sewer costs were estimated based on discharge rates published by the Metropolitan Council of $2.31 per 1000 gal for industrial users (MCES, 2024). A $10,325 permit for quarterly reporting industrial users with a discharge of less than 50 million gallons per year was also assumed to be needed and included for all treatment plants. Actual permit costs may vary depending on the final plant design. Total volume of water discharged to sewer was estimated using preliminary design criteria for greensand pre-treatment for iron and manganese removal, which would require backwashing every 18 hours. Lead GAC vessels were assumed to be backwashed twice per week while lag vessels were assumed to be backwashed once per week. A safety factor of two was applied to GAC backwash volumes to account for GAC changeout water, sanitary waste, or other uses of water.

Electrical costs were estimated at $0.10 per kWh. Electrical rates will fluctuate seasonally, with higher rates typically observed during the summer months. An average rate was used for calculation of OPEX estimates.

J1.5.3 Piping Capital Cost Estimates

Treatment plants would require piping from extraction wells to the treatment plant as well as piping from the treatment plant to injection wells. Details of proposed extraction and injection well arrays and pipe networks shown in Figure J.2 (WCL), Figure J.3 (RC + EPL), Figure J.4 (WLL), and Figure J.5 (RC + EPL & WLL). Treatment plants, regardless of treatment train, would require piping and well installation. Thus, these costs are applicable to all treatment trains evaluated in this appendix. The placement of wells, and subsequently the piping, is dependent on land availability. The well locations to maximize PFAS capture are also dependent on the locations of planned municipal supply wells in Oakdale and Lake Elmo.

The estimated unit cost includes the sum of materials, labor, and equipment of reasonably identified features of a project. The estimated total project cost is the sum of construction costs with additional allowances for direct and indirect costs and contingencies. The engineering costs include design and surveying. This appendix presents the opinion of probable costs for the following major elements:

- Pipelines
- Injection and Extraction Pumps
- Injection and Extraction Well Sites
- Additional Costs: Direct Cost, Indirect Costs, and Contingencies

Both open-cut and horizontal directional drilling (HDD) were considered. Piping costs are summarized in Table J.5. Detailed open-cut pricing is given in Table J.6, and HDD costs are given in Table J.7. Final selection would be dependent, in part, on city and county roadwork plans, as open-cut cost estimates assume removal and reinstallation of roadways. If road replacement is already planned, the costs to install piping with an open-cut may be competitive with HDD. Final selection may include a combination of both installation methods if either HDD or open-cut cannot be used in certain areas. Thus, the costs presented here offer the probable range of costs for piping networks.

Table J.5. Potential Piping Network Installation Costs.

Flow Rate	500 GPM	2,000 GPM	2,000 GPM	5,000 GPM
Location	AOC 1	AOCs 2 & 7	AOC 10	AOCs 2, 7, & 10
Open Cut	$21,127,000	$48,879,000	$30,152,000	$113,146,000
HDD	$8,871,000	$24,791,000	$14,239,000	$47,604,000

Table J.6. Open-Cut Pipe Installation Cost Estimates.

Flow Rate	500 GPM	2,000 GPM	2,000 GPM	5,000 GPM
Location	AOC 1	AOCs 2 & 7	AOC 10	AOCs 2, 7, & 10
Extraction Wells	$ 2,025,000	$ 3,150,000	$ 1,800,000	$ 3,150,000
Extraction Booster Station (1)	-	$ 776,000	$ 576,000	$ 1,352,000
Extraction Piping – Open Cut	$ 2,391,000	$ 11,830,000	$ 8,154,000	$ 27,024,000
Injection Piping – Open Cut	$ 7,288,000	$ 11,291,000	$ 5,744,000	$ 32,095,000
Injection Booster Station (2)	$ 200,000	$ 776,000	$ 200,000	$ 1,352,000
Injection Wells	$ 900,000	$ 1,800,000	$ 1,800,000	$ 3,600,000
SUBTOTAL – Open Cut	$ 12,804,000	$ 29,624,000	$ 18,274,000	$ 68,573,00
Mobilization & Site Setup (5%)	*$640,000*	*$1,481,000*	*$914,000*	*$3,427,000*
Contractor Overhead and Profit (15%)	*$1,921,000*	*$4,444,000*	*$2,741,000*	*$10,286,000*
Engineering & Construction Contingency (45%)	*$5,762,000*	*$13,331,000*	*$8,223,000*	*$30,858,000*
TOTAL (2024) – Open Cut	$21,127,000	$48,879,000	$30,152,000	$113,146,000

(1) Assumes RC/EPL would need 2 total booster stations for extraction wells, WLL would need 1 booster station, and the RC/EPL + WLL would need 3 total booster stations.

(2) Assumes 1 injection booster station for WCL, 2 for RC/EPL, 1 booster station for WLL, and 3 booster stations for RC/EPL + WLL.

Table J.7. Horizontal Direction Drilling (HDD) Pipe Installation Cost Estimates.

Flow Rate	500 GPM	2,000 GPM	2,000 GPM	5,000 GPM
Location	AOC 1	AOCs 2 & 7	AOC 10	AOCs 2, 7, & 10
Extraction Wells	$ 2,025,000	$ 3,150,000	$ 1,800,000	$ 3,150,000
Extraction Booster Station (1)	-	$ 776,000	$ 576,000	$ 1,352,000
Extraction Piping – HDD	$ 632,000	$ 3,220,000	$ 2,548,000	$ 7,936,000
Injection Piping – HDD	$ 1,620,000	$ 5,303,000	$ 1,706,000	$ 11,461,000
Injection Booster Station (2)	$ 200,000	$ 776,000	$ 200,000	$ 1,352,000
Injection Wells	$ 900,000	$ 1,800,000	$ 1,800,000	$ 3,600,000
SUBTOTAL – HDD	$ 5,377,000	$ 15,025,000	$ 8,630,000	$ 28,851,000
Mobilization & Site Setup (5%)	*$269,000*	*$751,000*	*$431,000*	*$1,443,000*
Contractor Overhead and Profit (15%)	*$806,000*	*$2,254,000*	*$1,294,000*	*$4,326,000*
Engineering & Construction Contingency (45%)	*$2,419,000*	*$6,761,000*	*$3,883,000*	*$12,983,000*
TOTAL (2024) – HDD	$8,871,000	$24,791,000	$14,239,000	$47,604,000

(1) Assumes RC/EPL would need 2 total booster stations for extraction wells, WLL would need 1 booster station, and the RC/EPL + WLL would need 3 total booster stations.

(2) Assumes 1 injection booster station for WCL, 2 for RC/EPL, 1 booster station for WLL, and 3 booster stations for RC/EPL + WLL.

J2 Evaluated Treatment Trains

Treatment trains considered for groundwater remediation are described in the following section. Additional information on specific technologies can be found in Section 9 of the FS and Appendix D.

J2.1 Treatment Train 1 (Reactivated GAC)

Treatment Train 1 would use reactivated GAC to remove PFAS from pumped groundwater. A conceptual process flow diagram is given in Figure J.6. GAC is a widely used PFAS treatment technology and is currently used by multiple treatment plants in the East Metro. Once breakthrough occurred in a GAC vessel, GAC would be sent back to the vendor for reactivation. As part of the reactivation process, PFAS is stripped from the GAC using high temperature steam and is then incinerated at high temperatures, resulting in destruction of PFAS (DiStefano, 2022). For more information on GAC reactivation, see Section 9 of the FS and Appendix D.

Pros and cons for Treatment Train 1 are summarized in Table J.8. GAC is effective at removing long-chain PFAS, with high removal of PFOA and PFOS widely reported (AWWA, 2019; ITRC, 2023). GAC reactivation results in the destruction of PFAS and allows for reuse of exhausted media, dramatically decreasing the volume of waste sent to the landfill. Short-chain PFAS removal, however, is significantly lower than long-chain PFAS removal, and breakthrough is observed for short-chain species much earlier than long-chain species. This would limit the ability of a GAC-only treatment system to meet future standards, should short-chain PFAS species be further regulated.

Table J.8. Pros and Cons of Treatment Train 1 (Reactivated GAC) for PFAS Removal.

Pros	Cons
• Proven technology that is widely used and available from multiple vendors • PFOA and PFOS removal to below treatment targets achievable • Can be backwashed to reduce pressure drop across the GAC bed • GAC reactivation destroys PFAS and significantly reduces solid waste generation • Can remove other contaminants like NOM • Reactivated GAC is a cheaper alternative to virgin/single use GAC	• Poor short-chain PFAS removal efficiencies and faster breakthrough of short-chain PFAS • Limited ability to adapt to future regulations should regulatory framework change in the future • Requires long residence time for effective treatment • Longer EBCT requires larger vessels and larger footprint than other alternatives • Backwash generates a wastewater stream that must be processed • Requires more frequent changeouts than other types of media • High pH and arsenic can be a concern during initial startup • Bio-growth can occur if vessel is idle/stagnant for extended periods of time • Removal of other contaminants can reduce GAC capacity for PFAS • Pooled reactivated GAC generally cannot be used for drinking water treatment • Reactivated GAC will have a shorter bed life than virgin/single use GAC

The preliminary design criteria for Treatment Train 1 are summarized in Table J.9. All design criteria, particularly surface loading rate (SLR) and EBCT, must be validated by RSSCTs and/or pilot testing and should be viewed as preliminary only. Vessels would be operated in lead/lag configuration and N+1 redundancy is assumed for operations.

Table J.9. Treatment Train 1 (Reactivated GAC) Preliminary Design Criteria.

Parameter	Unit	Small Plant	Medium Plant	Large Plant
	Example AOC	WCL - Source Zone	RC + EPL, or WLL Plume Control	WLL, WCL, RC + EPL Combined Treatment Plant
Flow Rate	gpm	500	2,000	5,000
	MGD	0.72	2.9	7.2
Process Trains Installed/In- service (1)	-	3/2	5/4	6/5
Filters Per Train	-	2	2	2
GAC per Filter	lbs	20,000	20,000	40,000
Vessel Diameter	ft	10	10	12
Surface Area per Filter	ft^2	78.5	78.5	113.1
Total In-Service Surface Area	ft^2	157.1	314.2	565.5
Filter Surface Loading Rate (SLR) (2)	gpm/ft^2	3.18	6.37	8.84
EBCT per Process Train (2)	min	20	10	10

(1) Assumes N+1 redundancy for all operations.
(2) Loading rate and EBCT to be evaluated during RSSCTs and future pilot testing.
Legend: MGD = million gallons per day.

A reactivated GAC treatment plant to treat 500 gpm from AOC 1 is estimated to have a CAPEX cost of $13.3 million. A 2,000-gpm plant to treat water from either AOCs 2 & 7 or AOC 10 is estimated to have a CAPEX cost of $24.3 million, while a 5,000-gpm plant to treat water from AOCs 2, 7 & 10 is estimated to have a CAPEX cost of $39.1 million. Expected treatment plant CAPEX is summarized in Table J.10; detailed cost estimates are available in Table J.51.

Table J.10. Treatment Train 1 (Reactivated GAC) CAPEX Estimate.

Equipment & Estimated Installation Costs	500 GPM	2,000 GPM	5,000 GPM
Greensand Process Equipment	$1,075,000	$3,368,000	$6,625,000
GAC Process Equipment	$1,935,000	$3,225,000	$5,115,000
Tanks and Pumps	$820,000	$950,000	$1,120,000
Piping	$344,000	$582,000	$803,000
Electrical	$400,000	$700,000	$1,200,000
Building and Foundation	$3,325,000	$5,625,000	$8,425,000
SUBTOTAL	$7,899,000	$14,450,000	$23,288,000
Mobilization & Site Setup (5%)	*$395,000*	*$723,000*	*$1,164,000*
Bonding & Insurance (3%)	*$237,000*	*$434,000*	*$699,000*
Contractor Overhead and Profit (15%)	*$1,185,000*	*$2,168,000*	*$3,493,000*
Engineering & Construction Contingency (45%)	*$3,555,000*	*$6,503,000*	*$10,480,000*
TOTAL (2024)	$13,300,000	$24,300,000	$39,100,000

Yearly OPEX costs for treatment plants were calculated with estimated GAC usage rates, given in Table J.11. Yearly OPEX is estimated to cost $31.3 million for a 500-gpm plant to treat AOC 1, $4.6

million for a 2,000-gpm plant to treat AOCs 2&7 or AOC 10, and $10.6 million for a 5,000-gpm plant to treat AOCs 2, 7 &10.

Table J.11. Treatment Train 1 (Reactivated GAC) OPEX Estimates.

Parameter	500 GPM	2,000 GPM	5,000 GPM
GAC Changeouts	$30,730,000	$3,500,000	$8,795,000
Chemical	$30,000	$118,000	$296,000
Process/NPDES Testing (non-PFAS)	$52,000	$52,000	$52,000
PFAS Testing	$182,000	$255,000	$291,000
Electrical	$18,000	$73,000	$184,000
Labor Costs	$168,000	$276,000	$395,000
Replacement Parts & Operations Equipment	$104,000	$192,000	$306,000
Sewer Cost	$68,000	$151,000	$284,000
Yearly Estimate	$31,400,000	$4,600,000	$10,600,000

J2.2 Treatment Train 2 (Single-Use IX)

Treatment Train 2 would use IX resin to remove short and long-chain PFAS species. A conceptual process flow diagram is given in Figure J.7. IX resin has been shown to remove both short and long chain species effectively (AWWA, 2019); different resins could be selected for different treatment areas to optimize the removal depending on the influent PFAS conditions. If this treatment train was selected, additional RSSCTs could be completed to determine the optimal IX resin. Once breakthrough occurs in an IX vessel, the media would be replaced and exhausted media sent to a landfill or incinerated. Other disposal options may become available for IX resin in the future, but at the time of this report (September 2024), other disposal options are not widely available at the scale needed for these treatment systems.

Pros and cons of Treatment Train 2 are given in Table J.12. IX resin generally outperforms GAC for service life and provides more efficient removal of short-chain PFAS species compared to GAC. The required EBCT is also significantly shorter than is required for GAC, which allows for smaller vessels and a smaller building footprint to be used. Lower short-chain PFAS limits could be reasonably met with IX resin by changing out the media sooner than would currently be necessary, allowing for system adaptability should the regulatory framework change in the future. IX resin, however, is more susceptible than GAC to fouling from NOM, manganese, and iron, and competing anions (e.g. nitrate, sulfate) can reduce removal efficiency and resin life. Backwashing can damage IX resin beads, potentially limiting options if an unacceptably high pressure differential builds across a resin bed. Media costs are also higher compared to GAC, increasing O&M costs if resin life is shorter than expected.

The preliminary design criteria for Treatment Train 2 are summarized in Table J.13. All design criteria, particularly SLR and EBCT, must be validated by RSSCTs and/or pilot testing and should be viewed as preliminary only. Vessels would be operated in lead/lag configuration and N+1 redundancy is assumed for operations.

Table J.12. Pros and Cons of Treatment Train 2 (Single-Use IX) for PFAS Removal.

Pros	Cons
• Smaller footprint • No backwash required • Longer run times • Less waste handling with more efficient media performance • Better performance over wider range of PFAS (both short- and long-chain) should regulatory framework change in the future • Accepted for drinking water use	• Targeted treatment for PFAS and effectiveness could be impacted by presence of other anions (e.g. nitrate) • More susceptible to fouling from NOM, manganese, and iron • Single-use resin disposal options are currently incineration or landfilling • Higher head loss than GAC and requires pre-filters to protect media • Not tolerant of oxidants such as Cl_2 in water • Need ability to waste initial bed volumes while resin stabilizes • Flow turn-down considerations to prevent channeling through media • Backwashing can damage the resin beads and shorten resin life which increases reliance on effective pre-filtration • Higher media costs

Table J.13. Treatment Train 2 (Single-Use IX) Preliminary Design Criteria.

Parameter	Unit	Small Plant	Medium Plant	Large Plant
	Example AOC	WCL – Source Zone	RC + EPL, or WLL Plume Control	WLL, WCL, RC + EPL Combined Treatment Plant
Flow Rate	gpm	500	2,000	5,000
	MGD	0.72	2.9	7.2
Process Trains Installed/In-service (1)	-	2/1	3/2	6/5
Filters Per Train	-	2	2	2
IX per Filter	ft^3	282.4	423.6	423.6
Vessel Diameter	ft	8	10	10
Surface Area per Filter	ft^2	50.3	78.5	78.5
Total In-Service Surface Area	ft^2	50.3	157.1	392.7
IX Filter SLR (2)	gpm/ft^2	9.95	12.73	12.73
EBCT per Process Train (2)	min	4.2	3.2	3.2

(1) Assumes N+1 redundancy for all operations.
(2) Loading rate and EBCT to be evaluated during RSSCTs and future pilot testing.

A single-use IX treatment plant to treat 500 gpm from AOC 1 is estimated to have a CAPEX cost of $12.4 million. A 2,000-gpm plant to treat water from either AOCs 2 & 7 or AOC 10 is estimated to have a CAPEX cost of $24.1 million, while a 5,000-gpm plant to treat water from AOCs 2, 7 & 10 is estimated to have a CAPEX cost of $41.1 million. Expected treatment plant CAPEX is summarized in Table J.14; detailed cost estimates are available in Table J.52.

Table J.14. Treatment Train 2 (Single-Use IX) CAPEX Estimate.

Equipment & Estimated Installation Costs	500 GPM	2,000 GPM	5,000 GPM
Greensand Process Equipment	$1,075,000	$3,368,000	$6,625,000
IX Process Equipment	$1,469,000	$3,206,000	$6,418,000
Tanks and Pumps	$810,000	$960,000	$1,100,000
Piping	$299,000	$477,000	$681,000
Electrical	$400,000	$700,000	$1,200,000
Building and Foundation	$3,325,000	$5,625,000	$8,425,000
SUBTOTAL	$7,378,000	$14,336,000	$24,449,000
Mobilization & Site Setup (5%)	*$369,000*	*$717,000*	*$1,222,000*
Bonding & Insurance (3%)	*$221,000*	*$430,000*	*$733,000*
Contractor Overhead and Profit (15%)	*$1,107,000*	*$2,150,000*	*$3,667,000*
Engineering & Construction Contingency (45%)	*$3,320,000*	*$6,451,000*	*$11,002,000*
TOTAL (2024)	$12,400,000	$24,100,000	$41,100,000

Yearly OPEX costs for treatment plants calculated with estimated IX usage rates, given in Table J.15. Yearly OPEX is estimated to cost $49.4 million for a 500-gpm plant to treat AOC 1, $1.9 million for a 2,000-gpm plant to treat AOCs 2&7 or AOC 10, and $3.8 million for a 5,000-gpm plant to treat AOCs 2, 7 &10.

Table J.15. Treatment Train 2 (Single-Use IX) OPEX Estimates.

Parameter	500 GPM	2,000 GPM	5,000 GPM
IX Resin	$42,101,000	$669,000	$1,674,000
Resin Disposal	$1,672,000	$35,000	$83,000
Chemical	$30,000	$118,000	$296,000
Process/NPDES Testing (Non-PFAS)	$52,000	$52,000	$52,000
PFAS Testing	$182,000	$255,000	$291,000
Electrical	$18,000	$73,000	$184,000
Labor Costs	$168,000	$276,000	$395,200
Replacement Parts & Operations Equipment	$112,000	$208,000	$341,000
Cartridge Filters	$10,000	$40,000	$100,000
Sewer Cost	$48,000	$128,000	$244,000
Yearly Estimate	$44,400,000	$1,850,000	$3,660,000

J2.3 Treatment Train 3 (Reactivated GAC & Single-Use IX)

Treatment Train 3 would utilize a two-stage treatment approach to remove PFAS from pumped water. Water would first be treated with GAC, which would be used to target long-chain PFAS. GAC effluent would then be treated with IX resin to remove short-chain PFAS. GAC preferentially removes long chain species, which would allow for selection of a resin to optimize removal of short chain species (e.g. PFBA at the WCL). A conceptual process flow diagram is given in Figure J.8.

Once breakthrough occurred in a GAC vessel, GAC would be sent back to the vendor for reactivation at high temperatures. Once breakthrough occurred in an IX vessel, the media would be replaced and exhausted media sent to a landfill or incinerated. Other disposal options may become available for IX resin in the future, but at the time of writing this report, they are not widely available at the scale needed for these treatment systems. For AOC's where short chain species are not above current limits, use of a single media may be applicable (e.g. AOC 10, WLL Groundwater).

Pros and cons for Treatment Train 3 are given in Table J.16. Use of GAC ahead of IX would likely extend the life of IX resin by acting as an additional pre-treatment step, removing NOM and other foulants present in the water. Long-chain PFAS would largely be removed by the GAC, reducing the load on the IX resin, and allowing for an IX resin that best removes short-chain PFAS to be selected. Inclusion of IX will also facilitate compliance with future PFAS regulations should PFBA regulatory limits be lowered or if additional short-chain PFAS become regulated. Use of both GAC and IX would increase capital cost, as a larger building footprint would be required as compared to a GAC- or IX-only treatment system. This alternative would likely use the highest volume of media, potentially increasing disposal costs.

Table J.16. Pros and Cons of Alternative 3 (Reactivated GAC & Single-Use IX) for PFAS Removal.

Pros	Cons
• GAC removal of long-chain PFAS would allow for IX resin to be selected that is best for short-chain PFAS removal • GAC would provide effective pre-filtration for IX resin (NOM removal) and may extend IX resin life • Would give ability to meet lower PFAS limits should regulatory framework change in the future	• Larger footprint required than a GAC-only or IX-only treatment plant • Increased media usage • Higher initial costs than a system with just GAC or IX resin

The preliminary design criteria for Treatment Train 3 are summarized in Table J.17. All design criteria, particularly SLR and EBCT, must be validated by RSSCTs and/or pilot testing and should be viewed as preliminary only. Vessels would be operated in lead/lag configuration and N+1 redundancy is assumed for operations.

Table J.17. Alternative 3 (Reactivated GAC & Single-Use IX) Preliminary Design Criteria.

Parameter	Unit	Small Plant	Medium Plant	Large Plant
	Example AOC	WCL – Source Zone	RC + EPL, or WLL Plume Control	WLL, WCL, RC + EPL Combined Treatment Plant
Flow Rate	gpm	500	2,000	5,000
	MGD	0.72	2.9	7.2
GAC				
Process Trains Installed/In-service [(1)]	-	3/2	5/4	6/5
Filters Per Train	-	2	2	2
GAC per Filter	lbs	20,000	20,000	40,000
Vessel Diameter	ft	10	10	12
Surface Area per Filter	ft^2	78.5	78.5	113.1
Total In-Service Surface Area	ft^2	157.1	314.2	565.5
GAC Filter SLR [(2)]	gpm/ft^2	3.18	6.37	8.84
EBCT per Process Train [(2)]	min	20	10	10
IX				
Process Trains Installed/In-service[1]	-	2/1	3/2	6/5
Filters Per Train	-	2	2	2
IX per Filter	ft^3	282.4	423.6	423.6
Vessel Diameter	ft	8	10	10
Surface Area per Filter	ft^2	50.3	78.5	78.5
Total In-Service Surface Area	ft^2	50.3	157.1	392.7
IX Filter SLR [(2)]	gpm/ft^2	9.95	12.7	12.7
EBCT per Process Train [(2)]	min	4.2	3.2	3.2

[(1)] Assumes N+1 redundancy for all operations.
[(2)] Loading rate and EBCT to be evaluated during RSSCTs and future pilot testing.

A reactivated GAC and single-use IX treatment plant to treat 500 gpm from AOC 1 is estimated to have a CAPEX cost of $19.5 million. A 2,000-gpm plant to treat water from either AOCs 2 & 7 or AOC 10 is estimated to have a CAPEX cost of $33.6 million, while a 5,000-gpm plant to treat water from AOCs 2, 7 & 10 is estimated to have a CAPEX cost of $54.3 million. Expected treatment plant CAPEX is summarized in Table J.18; detailed cost estimates are available in Table J.53.

Table J.18. Treatment Train 3 (Reactivated GAC and Single-Use IX) CAPEX Estimate.

Equipment & Estimated Installation Costs	500 GPM	2,000 GPM	5,000 GPM
Greensand Process Equipment	$1,075,000	$3,368,000	$6,625,000
GAC Process Equipment	$1,935,000	$3,225,000	$5,115,000
IX Process Equipment	$1,436,000	$3,125,000	$6,249,000
Tanks and Pumps	$820,000	$950,000	$1,120,000
Piping	$362,000	$631,000	$858,000
Electrical	$500,000	$800,000	$1,300,000
Building and Foundation	$5,475,000	$7,900,000	$11,075,000
SUBTOTAL	$11,603,000	$19,999,000	$32,342,000
Mobilization & Site Setup (5%)	*$580,000*	*$1,000,000*	*$1,617,000*
Bonding & Insurance (3%)	*$348,000*	*$600,000*	*$970,000*
Contractor Overhead and Profit (15%)	*$1,740,000*	*$3,000,000*	*$4,851,000*
Engineering & Construction Contingency (45%)	*$5,221,000*	*$9,000,000*	*$14,554,000*
TOTAL (2024)	$19,500,000	$33,600,000	$54,300,000

Yearly OPEX costs for treatment plants were calculated with usage rates derived from RSSCTs, given in Table J.19. Yearly OPEX is estimated to cost $25.8 million for a 500-gpm plant to treat AOC 1, $2.4 million for a 2,000-gpm plant to treat AOCs 2&7 or AOC 10, and $4.4 million for a 5,000-gpm plant to treat AOCs 2, 7 &10.

Table J.19. Treatment Train 3 (Reactivated GAC & Single-Use IX) OPEX Estimates.

Parameter	500 GPM	2,000 GPM	5,000 GPM
GAC Changeouts	$3,080,000	$350,000	$840,000
IX Changeouts	$21,125,000	$669,000	$1,339,000
IX Resin Disposal	$842,000	$38,000	$76,000
Chemical	$30,000	$118,000	$296,000
Process/NPDES Testing (Non-PFAS)	$52,000	$52,000	$52,000
PFAS Testing	$255,000	$364,000	$510,000
Electrical	$18,000	$73,000	$184,000
Labor Costs	$168,800	$276,000	$395,000
Replacement Parts & Operations Equipment	$180,000	$295,000	$455,000
Sewer Cost	$55,000	$151,000	$284,000
Yearly Estimate	$25,800,000	$2,390,000	$4,430,000

J2.4 Treatment Train 4 (NF/RO to Reactivated GAC & Single-Use IX)

Treatment Train 4 would use NF or RO membranes to provide an initial separation step, which would generate permeate (treated, PFAS-free water) and a concentrated waste stream (reject) that contains more highly concentrated PFAS. The permeate would require no further treatment for PFAS. The concentrate would be treated using reactivated GAC and single-use IX resin. The GAC would capture the long-chain PFAS and serve to protect the IX vessels, while the IX resin would be used to capture short-chain PFAS. A conceptual process flow diagram is given in Figure J.9. Once breakthrough occurred in a GAC vessel, GAC would be sent back to the vendor for reactivation at high temperatures. Once breakthrough occurred in an IX vessel, the media would be replaced and exhausted media sent to a landfill or incinerated. Other disposal options may become available for IX resin in the future, but at the time of this report, other disposal options are not widely available at the scale needed for these treatment systems. For AOCs where short chain species are not above current limits, use of a single medium may be applicable (e.g. AOC 10, WLL groundwater).

Pros and cons for Treatment Train 4 are listed in Table J.20. Use of NF/RO to pre-concentrate PFAS prior to treatment with adsorptive media would decrease the volume of water that requires further treatment. NF/RO would provide the widest range on contaminant removal and would remove a wide range of PFAS species. Concentration of PFAS into the membrane reject may also improve GAC and IX performance by increasing the initial concentration sent to the media. A membrane treatment system may require more extensive pre-treatment (e.g. greensand or ultrafiltration (UF) membranes and cartridge filters), though due to the high levels of iron and manganese in the groundwater present at the Site, all Treatment Trains may require greensand or other pre-treatment to improve media life. High-pressure pumping is required, which increases energy consumptions/cost, and membrane systems generally require additional chemical feeds, potentially including sulfuric acid for pH control, antiscalant, and high/low pH cleaners. Site sampling results for hardness indicate scaling could be a concern for the concentrate, as sparingly soluble salts naturally present in the water are also removed from the permeate and concentrated in the reject stream along with the PFAS. These salts could precipitate out of solution, if their concentrations get too high, causing scale to form and potentially damaging equipment or media. This would likely limit the recovery, or percentage of water that becomes permeate, a membrane system could achieve.

Table J.20. Pros and Cons of Treatment Train 4 (NF/RO to Reactivated GAC & Single-Use IX) for PFAS Removal.

Pros	Cons
• NF/RO separate PFAS from the bulk water stream, reducing downstream treatment GAC/IX equipment size • Provides widest range of contaminant removal • Increased concentration of PFAS in concentrate may improve GAC/IX performance • Best performance over wider range of PFAS (both short- and long-chain) should regulatory framework change in the future (for separation of PFAS from the permeate) • NF/RO permeate would result in the lowest effluent PFAS concentrations out of any Treatment Trains	• Requires additional high-pressure pumping (increased energy costs) • Requires additional chemical feeds (antiscalant, pH control, reducing agent) • CIP waste streams must be properly neutralized/disposed • Periodic RO/NF membrane replacement will be required, increasing the cost (every 5-7 years is typical) • System requires cartridge filters ahead of NF/RO, which require replacement • Sparingly soluble salts in the NF/RO concentrate can precipitate out of solution and cause scaling, limiting the amount of time concentrate can be handled • Membrane system requires more operator/engineer oversight than a GAC or IX system

There are several waste streams unique to membrane operations that do not exist for other potential treatment trains. Membranes require cleaning, called Clean in Place (CIP), to remove accumulated foulants and decrease transmembrane pressure, which increases as foulants accumulate on the membranes. Typically, high and low pH cleans are performed; these would both require a discharge location, and potentially onsite neutralization prior to discharge. Ideally, CIPs are performed semi-annually or less frequently, but quarterly cleaning may be necessary depending on influent conditions. While greensand is proposed as a pre-treatment for membrane system, UF membranes may be required to provide greater protection to the NF/RO membranes. If a UF membrane system was required, daily chlorine CIPs would likely be required for the UF system. Membranes would also need to be disposed of at the end of their life, either via incineration or landfilling. Finally, UF membranes typically operate as a deadheaded system, where water passes through the UF membrane, leaving solids behind. This requires a backwash, which typically would be UF permeate. However, to reduce PFAS loading to the sanitary sewer the RO permeate would likely require treatment or an additional treatment technology would be required to remove solids from the UF backwash water prior to recirculation to the plant headworks.

The preliminary membrane design criteria for Treatment Train 4 are summarized in Table J.21. A 75% recovery was assumed, though RO recoveries can range from 70-85% and NF recoveries can range from 85-95%. For a more detailed discussion of RO and NF membranes, see Section 9 of the FS and Appendix D. Further evaluation (bench and/or pilot scale testing) of NF and RO membranes would be required prior to full-scale system design. For initial comparison of different treatment plants, a 500-gpm skid using a 2-pass arrangement of pressure vessel (10:5, 6 elements per pressure vessel) was used. Further analysis of a pilot test would be needed to optimize the membrane system design for a specific flow rate.

Table J.21. Treatment Train 4 (NF/RO to Reactivated GAC & Single-Use IX) Preliminary Membrane Design Criteria.

Parameter	Unit	Small Plant	Medium Plant	Large Plant
	Example AOC	WCL – Source Zone	RC + EPL, or WLL Plume Control	WLL, WCL, RC + EPL Combined Treatment Plant
Influent Flow Rate	gpm	500	2,000	5,000
Permeate Flow Rate	gpm	375	1,500	3,750
Concentrate Flow Rate	gpm	125	500	1,250
Membrane Model (1)	-	TM720D-400	TM720D-400	TM720D-400
Trains Installed / Duty Trains (2)	-	2/1	5/4	11/10
Total Number of Pressure Vessels	-	30	90	165
Active Membrane Area per Train	ft^2	36,000	36,000	36,000
Recovery Rate (3)	%	75	75	75
Flux	gal / ft^2 / d	20	20	20
Feed Pump Power	HP	125	125	125

(1) Toray RO membranes were used for budgetary estimates; however, bench- and pilot-scale studies should be performed to identify the optimal membrane.
(2) For comparison of different sized treatment plants, a 500-gpm skid with 15 pressure vessels was priced out. Further analysis would be needed to determine the optimal skid size and arrangement for a specific treatment plant.
(3) Recovery rate is assumed to be 75% to decrease scaling risk in GAC and IX pressure vessels. Optimal recovery rate should be further analyzed with bench- and pilot-scale studies to determine the optimal recovery rate.

Preliminary media design criteria are given in Table J.22. Similar EBCTs to a GAC-only or IX-only system were assumed for GAC and IX vessels for treating membrane reject; RSSCTs are required to evaluate IX and GAC performance prior to full scale design and may result in longer EBCTs. Additionally, vessel sizing and configuration would depend on required SLRs, which also requires benchtop or pilot testing for analysis.

Table J.22. Treatment Train 4 (NF/RO to Reactivated GAC & Single Use IX) Preliminary Media Design Criteria.

Parameter	Unit	Small Plant	Medium Plant	Large Plant
	Example AOC	WCL – Source Zone	RC + EPL, or WLL Plume Control	WLL, WCL, RC + EPL Combined Treatment Plant
Flow Rate	gpm	125	500	1250
	MGD	0.18	0.72	1.8
GAC				
Process Trains Installed/In-service (1)	-	2/1	2/1	4/3
Filters Per Train	-	2	2	2
GAC per Filter	lbs	10,000	20,000	20,000
Vessel Diameter	ft	8	10	10
Surface Area per Filter	ft^2	50.3	78.5	78.5
Total In-Service Surface Area	ft^2	50.3	78.5	235.6
GAC Filter (SLR) (2)	gpm/ft^2	2.49	6.37	5.31
EBCT per Process Train (2)	min	20	10	12
IX				
Process Trains Installed/In-service1	-	2/1	2/1	4/3
Filters Per Train	-	2	2	2
IX per Filter	ft^3	177.0	282.4	282.4
Vessel Diameter	ft	6	8	8
Surface Area per Filter	ft^2	28.3	50.3	50.3
Total In-Service Surface Area	ft^2	28.3	50.3	150.8
IX Filter SLR (2)	gpm/ft^2	4.42	9.95	8.29
EBCT per Process Train (2)	min	10.6	4.2	5.1

(1) Assumes N+1 redundancy for all operations.
(2) Loading rate and EBCT to be evaluated during RSSCTs and future pilot testing.

An NF/RO to reactivated GAC & single-use IX treatment plant to treat 500 gpm from AOC 1 is estimated to have a CAPEX cost of $19.1 million. A 2,000-gpm plant to treat water from either AOCs 2 & 7 or AOC 10 is estimated to have a CAPEX cost of $36.4 million, while a 5,000-gpm plant to treat water from AOCs 2, 7 & 10 is estimated to have a CAPEX cost of $67.0 million. Expected treatment plant CAPEX is summarized in Table J.23; detailed cost estimates are available in Table J.54.

Table J.23. Treatment Train 4 (NF/RO to Reactivated GAC and Single-Use IX) CAPEX Estimates.

Equipment & Estimated Installation Costs	500 GPM	2,000 GPM	5,000 GPM
Greensand Process Equipment	$1,075,000	$3,368,000	$6,625,000
Membrane Process Equipment	$2,659,000	$6,667,000	$14,615,000
GAC & IX Process Equipment	$2,034,000	$2,726,000	$5,451,000
Tanks and Pumps	$899,000	$1,094,500	$1,330,000
Piping	$562,000	$935,000	$1,548,000
Electrical	$800,000	$1,200,000	$1,850,000
Building and Foundation	$3,350,000	$5,650,000	$8,450,000
SUBTOTAL	$11,379,000	$21,640,500	$39,869,000
Mobilization & Site Setup (5%)	*$569,000*	*$1,082,000*	*$1,993,000*
Bonding & Insurance (3%)	*$341,000*	*$649,000*	*$1,196,000*
Contractor Overhead and Profit (15%)	*$1,707,000*	*$3,246,000*	*$5,980,000*
Engineering & Construction Contingency (45%)	*$5,121,000*	*$9,738,000*	*$17,941,000*
TOTAL (2024)	$19,100,000	$36,400,000	$67,000,000

Yearly OPEX costs for treatment plants were calculated based on treatability study RSSCTs and are given in Table J.24. Yearly OPEX is estimated to cost $21.9 million for a 500-gpm plant to treat AOC 1, $3.1 million for a 2,000-gpm plant to treat AOCs 2&7 or AOC 10, and $6.1 million for a 5,000-gpm plant to treat AOCs 2, 7 &10.

Table J.24. Treatment Train 4 (NF/RO to Reactivated GAC & Single-Use IX) OPEX Estimates.

Parameter	500 GPM	2,000 GPM	5,000 GPM
GAC Changeouts	$3,150,000	$315,000	$810,000
IX Changeouts	$16,877,000	$446,000	$893,000
IX Resin Disposal	$671,000	$22,000	$45,000
Chemical [(1)]	$111,000	$431,000	$1,070,000
Process/NPDES Testing (Non-PFAS)	$52,000	$52,000	$52,000
PFAS Testing	$237,000	$237,000	$382,000
Electrical	$103,000	$397,000	$992,000
Labor Costs	$395,000	$671,000	$790,000
Membrane Replacement [(2)]	$27,000	$68,000	$149,000
Cartridge Filter Replacement	$2,000	$8,000	$20,000
Replacement Parts & Operations Equipment	$174,000	$332,000	$593,000
Sewer Cost	$70,000	$146,000	$281,000
Yearly Estimate	$21,900,000	$3,120,000	$6,080,000

(1) Chemical usage for NF/RO includes chlorine, sodium bisulfite, low & high pH cleaners, antiscalant, sulfuric acid, and sodium hydroxide.
(2) Membrane replacement assumes 6-year membrane life, 1/6th of membranes are replaced per year, at $750/membrane element, plus 20% for installation.

J2.5 Treatment Train 5 (Regenerative IX)

Regenerative IX is currently only available as an on-site technology where the end user operates equipment to regenerate IX resin themselves. Regenerative IX is generally considered as a viable treatment option only when total PFAS levels are > 10,000 ng/L due to the high capital costs associated with regeneration systems. Thus, regenerative was only considered for AOC 1, as the total PFAS levels at AOC's 2, 7, and 10 are not high enough to consider use of regenerative IX. IX venders have expressed interest in establishing off-site centralized regeneration facilities, where IX resin is regenerated by a vender or a third-party and then returned to the end user. Should a facility like this be built within a reasonable trucking distance of the Twin Cities, regenerative IX could be a viable treatment option for AOCs with lower total PFAS concentrations. However, at this time, off-site regeneration is not available, thus AOC's 2, 7, and 10 are not discussed in this section further.

Treatment Train 5 would utilize regenerable IX resin to remove short and long chain PFAS. NF/RO would likely be used as an initial concentration step, reducing the volume of water requiring further treatment. GAC would likely be used ahead of IX resin vessels to protect the IX resin and extend the life of the resin. Multiple IX trains would be required to provide adequate redundancy to allow operations to continue while a regeneration was occurring. A conceptual process flow diagram is given in Figure J.10.

Once breakthrough of IX resin occurred, the vessel or train to be regenerated would be taken out of service and regenerated using a regenerant stored and processed on site. A typical regenerant solution would be a solution of solvent, sodium chloride (salt), and water, which would strip PFAS from the resin and replace the anionic PFAS species with a chloride ion. Typically, a regenerant is flowed in the reverse direction (or counter current) of the forward flow (or normal treatment path); this initially exposes the strongest regenerant concentration to the resin with the lowest concentrations of PFAS, increasing regeneration efficiency. Additionally, it prevents high concentrations of PFAS from the lead vessels being re-sorbed by the lag vessel, which will have lower concentrations of PFAS prior to regeneration. The general sequence of a regeneration would be a clean water flush followed by the regenerant solution, followed by clean water flushes. A brine soak could be used prior to introduction of the regenerant to better desorb PFAS, and the regenerant would likely soak the resin for some period of time. Recirculation of the regenerant would not be recommended. Flush water would be used to push out the regenerant solution and continue until the salt and solvent levels were acceptable for discharge to the environment. The vessel would then be placed back into service.

The spent regenerant and flush water would be captured in tanks and processed on site with a distillation column. Distillation of the spent regenerant and flush water would separate the solvent (distillate) from the salt and PFAS (still bottoms). The distillate would go to stocking tanks where it would be reblended with salt and any make up water needed to hit the target recipe before being reused for additional regenerations. The still bottoms would contain concentrated PFAS, salt, and water. This waste stream could be incinerated (if the salt concentration is not prohibitively high, as high salt concentrations have negative impacts to incinerators), mixed with a stabilizing agent and landfilled, sent through 'superloader' IX vessels to concentrate the PFAS onto a smaller volume of resin that would be incinerated or landfilled, or sent through a destruction technology. Process steps such as closed-circuit RO (CCRO) or high-pressure batch RO, or a thin film evaporator could remove water from the still bottoms, decreasing the volume of the waste that needed disposal. These steps would correspondingly increase the salt and PFAS concentration in the still bottoms waste stream.

Vessel trains in a regenerable system could operate in pairs (lead/lag), or in trios (lead/lag/polish). In a lead/lag/polish configuration, different resins could be used to target different species. For example, if a regenerable resins showed a higher selectivity to short chain species but did not desorb long chain PFAS species during regeneration, it could be used as a polishing resin after a resin that did desorb long-chain PFAS better was used as a lead vessel. In a lead/lag/polish configuration, the first vessel (or first 2 vessels) could also be a sacrificial vessel designed to remove long chain species to allow the final two vessels (or vessel) to remove short chain species. In some cases, GAC ahead of IX vessels could also be used to further remove long chain species prior to the IX resin.

For a regenerable IX system, the regeneration trigger would depend on the configuration of the system and the treatment goals. Regenerations could be triggered when effluent concentrations begin to approach regulatory limits (e.g. PFBA target effluent concentration of 3500 ng/L), when a specific species begins to breakthrough a lead bed (e.g. PFOA/PFOS are observed after the lead bed and are desired to be kept off the lag or polishing resin beds), or other criteria. Initially, laboratory studies would be performed to estimate the number of bed volumes (BV) that could be processed before a regeneration would need to be performed. Upon initial operation, a safety factor would be applied; for example, if lab testing showed 1000 BVs before breakthrough, only 750-900 BVs would be run through the vessels. Samples would be collected to determine PFAS breakthrough, and based on those results, future runs would increase or decrease in length.

Pros and cons of Treatment Train 5 are given in Table J.25. A regenerative IX system could greatly reduce the volume of resin sent to landfill or incineration and greatly reduce media costs by allowing IX media to be used for many years. This is particularly advantageous for short- chain PFAS species that breakthrough resin faster than long-chain PFAS species. This would amplify IX resin's advantage over a GAC-only system, as the higher media capacity and more effective removal of short chain species can be further increased by regenerating the media and extending media life. A regenerative system would also facilitate compliance with future PFAS regulations. Increasing the frequency of regeneration would decrease the effluent concentration of short-chain PFAS species, which would allow for significantly lower short-chain limits to be achieved without increasing media usage. This treatment train would represent the lowest media usage of any proposed treatment trains, based on current performance.

Table J.25. Pros and Cons of Treatment Train 5 (Regenerable IX) for PFAS Removal.

Pros	Cons
• IX media can be regenerated on site when breakthrough occurs • Life of IX media is significantly extended • Reduction in volume of IX resin sent to landfill/incineration • Greater ability to remove short-chain PFAS species • Flexibility in meeting future limits should regulatory framework change	• Regenerable IX for PFAS removal is not widely used; few full-scale plants exist • Regenerant would not remove NOM or metal foulants, likely requiring GAC as a pre-filtration step • GAC may be required to remove long-chain PFAS if insufficient desorption of long-chain PFAS is observed during regeneration • Still bottoms waste must be further processed of disposed of properly • High complexity of operation requires more operator and engineer oversight • High sodium chloride usage to run regeneration sequences • Solvent containing flush water must be processed on site or disposed of properly • Solvent use would require electrically classified areas • NF/RO likely required to decrease size and cost of the regeneration equipment • Long lead times on specialty regeneration equipment parts

The CAPEX associated with a regeneration system would be high, and NF/RO would likely be needed to reduce the volume of water requiring treatment with IX resin to prevent the cost of the regeneration system from being prohibitively high. Costly specialty alloys would likely be required for regeneration equipment to handle the high solvent and high salt concentrations, and the presence of a solvent would require at least some portion of the treatment area to be electrically classified/intrinsically safe rated. More spare parts would need to be purchased prior to the start of operations compared to other treatment trains, as the specialty alloys often have long lead times that would be prohibitive to operations if not kept as a shelf spare. Additional PFAS testing would likely be required to monitor vessel breakthrough and regeneration efficiency.

An additional uncertainty is the performance of the regenerant to remove long-chain PFAS during a regeneration. Long-chain PFAS may not be desorbed during regeneration, which would result in a loss of resin active sites. Resin capacity would decrease with each regeneration if more and more long-chain PFAS accumulated on the resin. Resin regeneration would then have to increase in frequency until the resin had to be replaced prematurely. If this were found to occur, either GAC usage ahead of the IX would be required to remove long-chain PFAS, or resin life would be significantly shorter than expected. In both scenarios, OPEX costs would increase significantly. Sufficient bench- and pilot-scale testing would be required to ensure the system was properly designed to prevent this from occurring, or to demonstrate sufficient desorption of long-chain PFAS.

Final disposal of the still bottoms waste stream also presents a major challenge. It is possible a still bottoms waste stream could be sent directly to a destruction technology such as Hydrothermal Alkaline Treatment (HALT), electrochemical oxidation, or SCWO, but this would be highly dependent on the volumetric flowrate of the still bottoms. Destruction technologies are not yet available at scales large enough to process large volumes of waste, potentially limiting the use of destruction. Attempts to landfill the still bottoms would likely be quite costly, as the liquid waste stream would have to be stabilized. Similarly, attempts to incinerate a still bottoms waste stream could be quite costly, as the high salt levels would pose a corrosion risk to incinerator equipment. These same corrosion risks could also be an issue with some of the destruction technologies. A CCRO, thin film evaporator, or other means of reducing the final disposal volume of the still bottoms stream could be pursued; however, any additional concentration step of the still bottoms would increase the salt and PFAS concentrations, potentially further complicating disposal or destruction. It should be noted, if a destruction technology was available to fully mineralize all PFAS species in the still bottoms waste stream, salt could potentially be reused for regenerations if sufficiently re-concentrated. Otherwise, even with complete destruction, the still bottoms waste stream would still be a 1-23% salt waste stream that likely could not be discharged into surface or groundwater.

Currently, regenerable IX systems are not widely used with a limited number of systems installed or under construction worldwide. Similar to other new technologies, there will likely be unexpected challenges and obstacles to operations, complicating start up and operation. This type of system is also significantly more complex than other proposed treatment trains and will require a higher number of operators and significantly more operator and engineer oversight of the facility. For these reasons, regenerable IX was only further evaluated for AOC 1 (WCL Surface Water and Shallow Groundwater), as this AOC is the AOC with the highest concentrations of short-chain PFAS.

Design criteria for Treatment Train 5 was identical to Treatment Train 4 for the forward flow portion of the treatment process. See Table J.21 and Table J.22 for additional details. Preliminary design criteria for the regeneration system provided by the regeneration vendor contacted for this FS are given in Table J.26. Pilot testing would be required to finalize forward flow and regen system design.

A regenerable IX treatment plant to treat 500 gpm from AOC 1 is estimated to have a CAPEX cost of $41.2 million, and an OPEX cost of $3.3 million per year. Expected treatment plant CAPEX is summarized in Table J.27; detailed cost estimates are available in Table J.55. Expected OPEX is summarized in Table J.28; note that due to the uncertainty about the ability of IX to remove long-chain PFAS from resin, two GAC usage rates are given. Further testing would be required to evaluate actual GAC usage.

Table J.26. Treatment Train 5 (Regenerable IX) Preliminary Regeneration Design Criteria.

Parameter	WCL – Source Zone
Brine Tank	2,500 gal
Distillate Stocking Tanks	3 x 2,000 L
Regen Supply Tank	10,000 gal
Rinse Supply Tank	25,000 gal
Spent Regen Tank	10,000 gal
Distillation System	3 x HR1200
Distillate Purifiers	3 x 12 ft^3
Rinse Return Tank	25,000 gal
Still Bottoms Tank	5,000 gal
Superloaders	3 x 30 ft^3

Table J.27. Treatment Train 5 (Regenerable IX) CAPEX Estimate.

Equipment & Estimated Installation Costs	500 GPM
Greensand Process Equipment	$1,075,000
Membrane Process Equipment	$2,659,000
GAC & IX Process Equipment	$2,007,000
Regen Process Equipment	$10,000,000
Tanks and Pumps	$879,000
Piping	$625,000
Electrical	$1,000,000
Building and Foundation	$6,286,000
SUBTOTAL	$24,531,000
Mobilization & Site Setup (5%)	*$1,227,000*
Bonding & Insurance (3%)	*$736,000*
Contractor Overhead and Profit (15%)	*$3,680,000*
Engineering & Construction Contingency (45%)	*$11,039,000*
TOTAL (2024)	$41,200,000

Table J.28. Treatment Train 5 (Regenerable IX) OPEX Estimates.

Parameter	500 GPM (Sacrificial GAC)	500 GPM (GAC for PFOA Removal)
GAC Changeouts	$140,000	$962,000
IX Changeout (1)	$29,000	$29,000
Regen Costs (Ethanol, Salt, other)	$750,000	$750,000
Still Bottoms Disposal (2)	$627,000	$627,000
Chemical (3)	$110,000	$110,000
Process/NPDES Testing (Non-PFAS)	$52,000	$52,000
PFAS Testing	$309,000	$309,000
Electrical	$103,000	$103,000
Labor Costs	$671,000	$671,000
Membrane Replacement (4)	$27,000	$27,000
Cartridge Filter Replacement	$2,000	$2,000
Replacement Parts & Operations Equipment	$426,000	$426,000
Sewer Cost	$45,000	$45,000
Yearly Estimate	$3,290,000	$4,110,000

(1) Resin life assumed to be 5 years with 1/5th of the resin changed out yearly.
(2) Still bottoms are assumed to be landfilled at a cost of $0.10 per pound with a load charge of $5,000 per load.
(3) Chemical usage for NF/RO includes chlorine, sodium bisulfite, low & high pH cleaners, antiscalant, sulfuric acid, and sodium hydroxide.
(4) Membrane replacement assumes 6-year membrane life, 1/6th of membranes are replaced per year, at $750/membrane element, plus 20% for installation.

J2.6 Treatment Train 6 (Foam Fractionation + Polishing)

Treatment Train 6 would first treat water with foam fractionation for bulk removal of long-chain PFAS and potentially short-chain PFAS, then GAC or IX would serve as a polishing step to treat foam fractionation effluent to treatment targets. A conceptual process flow diagram is given in Figure J.11.

Foam fractionation uses air bubbles to create an air-water interface to which long-chain PFAS species preferentially migrate. Foam fractionation systems can operate in batch or continuous flow, depending on the vendor. Treatment time is dependent on the system and foaming properties of the water. As was found in the SAFF® pilot study (Appendix E), water that does not foam can also have a high percentage of PFAS removal with SAFF®. Alternatively, surfactants or "boosters" can be added to the water to increase the foaming properties and subsequent PFAS removal. Cationic surfactants can promote the removal of short-chain PFAS although the efficiency needs to be evaluated at least on the bench-scale but preferably at the pilot-scale. The foam is captured, removing the PFAS from the bulk solution. This PFAS is further treated to concentrate the PFAS into a smaller waste stream to reduce disposal or destruction costs. As the treated water would likely still have PFAS above the treatment targets, the treated water would be polished with GAC or IX prior to discharge or injection.

Multiple foam fractionation vendors could be used, but a SAFF® system was piloted for this feasibility study and, for that reason, was used for cost and design principles. The SAFF® system utilizes a two-stage batch system. Primary fractionation is the first process which removes PFAS from the bulk water by flowing the foam over a top cone. Secondary fractionation further concentrates the PFAS. The effluent from secondary fractionation is cycled back to the primary fractionation vessels to ensure the PFAS is removed.

Pilot testing by AECOM at Tablyn Park using a SAFF® system has shown over 99% removal of PFOA and PFOS from contaminated groundwater, and a concentration factor of 10,000-20,000x achieved by secondary fractionation; see Section 10 of the FS and Appendix E for more details. While PFOA and PFOS removal was significant, removal below the instrument detection limits was not always achieved, and limited short-chain removal was observed, indicating treatment targets would be unlikely to be met with foam fractionation alone. While surfactant usage may improve removal, especially of short-chain PFAS, a polishing step of either GAC or IX would be required to achieve treatment targets. Additionally, while not incorporated into the AECOM pilot, a tertiary fractionation step can be run to provide further volume reduction, with the manufacturer reporting a concentration factor of 1,500,000 to 2,000,000 (EPOC, 2024).

Pros and cons of Treatment Train 6 are given in Table J.29. The primary advantage of foam fractionation is the large volume reduction of the PFAS concentrate with lower energy inputs than NF/RO. For example, the PFAS concentrate of a 500-gpm (0.72 MGD) stream could be reduced to 36 gallons per day with a concentration factor of 20,000, similar to what was observed during pilot testing. This would make new PFAS destruction technologies much more feasible, as a current challenge with PFAS destruction technologies is the scale at which it can be operated.

Table J.29. Pros and Cons of Treatment Train 6 (Foam Fractionation with Polishing) for PFAS Removal.

Pros	Cons
• Requires low energy input compared to other treatment options • Secondary concentrate provides volume reduction needed to utilize new PFAS destruction technologies • Sparingly soluble salts are not concentrated like NF/RO • NOM is concentrated by foam fractionation, which could improve polishing media performance • Bulk removal of PFAS, especially long-chain, will decrease PFAS mass loading to polishing media • Media polishing will also remove a surfactant if used in the foam fractionation, reducing this concern	• Full flow would have to be treated by polishing media • Current foam fractionation installations have not been scaled to larger treatment plants which may result in more variable PFAS removal • Novel designs required for larger plants may have unforeseen design, implementation, and operational challenges • Short-chain PFAS may have a lower removal efficiency by foam fractionation

There are several limitations to foam fractionation which could limit its effectiveness in a final treatment plant. Foam fractionation is still an emerging technology and is not widely used, especially at the proposed treatment capacities. As designs for larger plants have yet to be implemented, the novel designs would bring all the challenges of scaling a new technology. Additionally, the likely requirement of GAC or IX to polish the entire effluent volume of foam fractionation to meet the treatment objectives increases CAPEX costs.

Preliminary media design criteria are given in Table J.30; note that at full scale design, it is assumed only one type of polishing media would be utilized. As previously discussed, SAFF® was used for the preliminary design in this appendix due to the availability of data from the pilot test conducted as part of this FS. For more details on pros and cons of GAC versus IX, see Table J.8 (GAC) and Table J.12 (IX).

Table J.30. Treatment Train 6 (Foam Fractionation with Polishing) Preliminary Design Criteria Using SAFF® as the Foam Fractionation Technology.

Parameter	Unit	Small Plant	Medium Plant	Large Plant
	Example AOC	WCL – Source Zone	RC + EPL, or WLL Plume Control	WLL, WCL, RC + EPL Combined Treatment Plant
Flow Rate	gpm	500	2,000	5,000
	MGD	0.72	2.9	7.2
SAFF®				
SAFF®40 Capacity	MGD	0.25	N/A (3)	N/A (3)
Process Units Installed/Required	-	4/3	N/A (3)	N/A (3)
GAC Polishing Option				
Process Trains Installed/In- service (1)	-	3/2	5/4	6/5
Filters Per Train	-	2	2	2
GAC per Filter	lbs	20,000	20,000	40,000
Vessel Diameter	ft	10	10	12
Surface Area per Filter	ft^2	78.5	78.5	113.1
Total In-Service Surface Area	ft^2	157.1	314.2	565.5
Filter Surface Loading Rate (SLR) (2)	gpm/ft^2	3.18	6.37	8.84
EBCT per Process Train (2)	min	20	10.0	10.0
IX Polishing Option				
Process Trains Installed/In- service (1)	-	2/1	3/2	6/5
Filters Per Train	-	2	2	2
IX per Filter	ft^3	282.4	423.6	423.6
Vessel Diameter	ft	8	10	10
Surface Area per Filter	ft^2	50.3	78.5	78.5
Total In-Service Surface Area	ft^2	50.3	157.1	392.7
Filter Surface Loading Rate (SLR) (2)	gpm/ft^2	9.95	12.73	12.73
EBCT per Process Train (2)	min	4.2	3.2	3.2

(1) Assumes N+1 redundancy for all operations.
(2) Loading rate and EBCT to be evaluated during RSSCTs and future pilot testing.
(3) Not Applicable: SAFF®40's treatment capacity are too small to be practically applied to a larger treatment plant, as the 5,000-gpm plant would require installation of 30 units to meet treatment demands. Instead, a Mega-SAFF® treatment plant would be considered for the 2,000- and 5,000-gpm treatment plant. Specific design criteria were not provided by the vendor; instead, high level cost estimates were provided.

A foam fractionation + polishing treatment plant to treat 500 gpm from AOC 1 is estimated to have a CAPEX cost of $32.3 million for GAC polishing and $31.3 million for IX polishing. A 2,000-gpm plant to treat water from either AOCs 2 & 7 or AOC 10 is estimated to have a CAPEX cost of $62.8 million for GAC polishing and $62.4 million for IX polishing, while a 5,000-gpm plant to treat water from AOCs 2, 7 & 10 is estimated to have a CAPEX cost of $118 million for GAC polishing and $119 million for IX polishing. Expected treatment plant CAPEX is summarized in Table J.31 (GAC) and Table J.32 (IX). Detailed cost estimates are available in Table J.56 (GAC) and Table J.57 (IX).

Table J.31. Treatment Train 6 (Foam Fractionation with Reactivated GAC Polishing) CAPEX Estimate Using SAFF® as the Foam Fractionation Technology.

Equipment & Estimated Installation Costs	500 GPM	2,000 GPM	5,000 GPM
Greensand Process Equipment	$1,075,000	$3,368,000	$6,625,000
SAFF® Process Equipment	$9,000,000	$20,415,000	$43,836,000
GAC Process Equipment	$1,935,000	$3,225,000	$5,115,000
Tanks and Pumps	$710,000	$800,000	$910,000
Piping	$400,000	$704,000	$1,091,000
Electrical	$650,000	$950,000	$1,450,000
Building and Foundation	$5,475,000	$7,900,000	$11,075,000
SUBTOTAL	$19,245,000	$37,362,000	$70,102,000
Mobilization & Site Setup (5%)	*$962,000*	*$1,868,000*	*$3,505,000*
Bonding & Insurance (3%)	*$577,000*	*$1,121,000*	*$2,103,000*
Contractor Overhead and Profit (15%)	*$2,887,000*	*$5,604,000*	*$10,515,000*
Engineering & Construction Contingency (45%)	*$8,660,000*	*$16,813,000*	*$31,546,000*
TOTAL (2024)	$32,300,000	$62,800,000	$117,800,000

Table J.32. Treatment Train 6 (Foam Fractionation with IX Polishing) CAPEX Estimate Using SAFF® as the Foam Fractionation Technology.

Equipment & Estimated Installation Costs	500 GPM	2,000 GPM	5,000 GPM
Greensand Process Equipment	$1,075,000	$3,368,000	$6,625,000
SAFF® Process Equipment	$9,000,000	$20,415,000	$43,836,000
IX Process Equipment	$1,436,000	$3,125,000	$6,249,000
Tanks and Pumps	$610,000	$700,000	$790,000
Piping	$400,000	$704,000	$1,091,000
Electrical	$650,000	$950,000	$1,450,000
Building and Foundation	$5,475,000	$7,900,000	$11,075,000
SUBTOTAL	$18,646,000	$37,162,000	$71,116,000
Mobilization & Site Setup (5%)	*$932,000*	*$1,858,000*	*$3,556,000*
Bonding & Insurance (3%)	*$559,000*	*$1,115,000*	*$2,133,000*
Contractor Overhead and Profit (15%)	*$2,797,000*	*$5,574,000*	*$10,667,000*
Engineering & Construction Contingency (45%)	*$8,391,000*	*$16,723,000*	*$32,002,000*
TOTAL (2024)	$31,300,000	$62,400,000	$119,500,000

Yearly OPEX costs for treatment plants were calculated with estimated media usage rates based on RSSCTs and are given in Table J.33. Yearly OPEX for GAC polishing is estimated to cost between $4.2 and $31.9 million for a 500-gpm plant to treat AOC 1, $3.0 million for a 2,000-gpm plant to treat AOCs 2&7 or AOC 10, and $5.5 million for a 5,000-gpm plant to treat AOCs 2, 7, & 10.

Table J.33. Treatment Train 6 (Foam Fractionation with Reactivated GAC Polishing) OPEX Estimates Using SAFF® as the Foam Fractionation Technology.

Parameter	500 GPM	2,000 GPM	5,000 GPM
GAC Media Cost	$3,080,000	$700,000	$1,680,000
GAC Media Cost (High Use)	$30,730,000	-	-
Chemical	$30,000	$118,000	$296,000
Process/NPDES Testing (Non-PFAS)	$52,000	$52,000	$52,000
PFAS Testing	$218,000	$291,000	$328,000
Electrical (GAC)	$18,000	$73,000	$184,000
Electrical (SAFF®)	$59,000	$237,000	$591,000
Labor Costs	$395,000	$671,000	$790,000
Replacement Parts & Operations Equipment	$314,000	$617,000	$1,149,000
Incineration Costs (1)	$11,000	$44,000	$110,000
Sewer Cost	$55,000	$151,000	$284,000
Yearly Estimate	$4,240,000	$2,950,000	$5,460,000
Yearly Estimate (High GAC Use)	$31,900,000	-	-

(1) Assumed SAFF® concentration factor is 200,000x with tertiary fractionation, $1 per pound for incineration.

Yearly OPEX for IX polishing is summarized in Error! Not a valid bookmark self-reference. and is estimated to cost between $2.3 and $12.1 million for a 500-gpm plant to treat AOC 1, $2.6 million for a 2,000-gpm plant to treat AOCs 2&7 or AOC 10, and $4.6 million for a 5,000-gpm plant to treat AOCs 2, 7, & 10. The large range of treatment costs for AOC 1 are due to the high concentrations of PFBA present at WCL and uncertainty over the ability of foam fractionation to remove PFBA. High end treatment costs assume minimal removal of PFBA with foam fractionation, while low end treatment costs assume foam fractionation is able to remove PFBA. Bench-scale and pilot-scale testing is recommended to determine optimal foam fractionation treatment technology.

Table J.34. Treatment Train 6 (Foam Fractionation with Single-Use IX Polishing) OPEX Estimates Using SAFF® as the Foam Fractionation Technology.

Parameter	500 GPM	2,000 GPM	5,000 GPM
IX Media Cost	$1,041,000	$335,000	$669,000
IX Disposal Costs	$52,000	$58,000	$106,000
IX Media Cost (High Use)	$10,563,000	-	-
IX Disposal Costs (High Use)	$422,000	-	-
Chemical	$30,000	$118,000	$296,000
Process/NPDES Testing (Non-PFAS)	$52,000	$52,000	$52,000
PFAS Testing	$218,000	$291,000	$328,000
Electrical (IX)	$18,000	$73,000	$184,000
Electrical (SAFF®)	$59,000	$237,000	$591,000
Labor Costs	$395,000	$671,000	$790,000
Replacement Parts & Operations Equipment	$314,000	$617,000	$1,149,000
Incineration Costs (1)	$11,000	$44,000	$110,000
Sewer Cost	$55,000	$151,000	$284,000
Yearly Estimate	$2,260,000	$2,650,000	$4,560,000
Yearly Estimate (High IX Use)	$12,100,000	-	-

(1) Assumed SAFF® concentration factor is 200,000x with tertiary fractionation, $1 per pound for incineration.

J2.7 Treatment Train 7 (NF/RO to Foam Fractionation & Single-Use IX)

Treatment Train 7 would use NF/RO membranes to reduce the volume of water requiring treatment by foam fractionation, with IX polishing of the treated foam fractionation effluent. NF or RO membranes would be used as an initial separate step, which would generate permeate (clean water) and a concentrate, or reject, stream that contains PFAS. The membrane permeate would require no further treatment for PFAS. The concentrate would then be treated through foam fractionation, which would provide bulk removal of PFAS. Treated foam fractionation effluent would likely require polishing with IX but if higher short-chain PFAS removal is achieved by foam fractionation, IX media changeouts would be infrequent. The foam fractionation concentrate would be disposed of via a PFAS destruction technology or incineration. A conceptual process flow diagram is given in Figure J.12. GAC was initially considered for this alternative, however, after bulk removal of long-chain PFAS by foam fractionation, it would predominantly be short-chain PFAS remaining in the reject stream, making IX the more suitable media. Bench- and pilot-scale testing would be required to validate this assumption and to validate that RO reject can be treated using foam fractionation. Pros and con of Treatment Train 7 are given in Table J.35. Use of a membrane system prior to foam fractionation and IX polishing would reduce the volume of water that required foam fractionation and IX treatment. This would decrease flow rates to ranges available for treatment with current foam fractionation (SAFF®) installations. As discussed with Treatment Train 6, use of foam fractionation would result in a concentrated PFAS stream that could be destroyed with a destruction technology.

Table J.35. Pros and Cons of Treatment Train 7 (RO/NF to Foam Fractionation with IX Polishing) for PFAS Removal.

Pros	Cons
• NF/RO would reduce volume requiring foam fractionation treatment to levels in line with current treatment installations • Pre-concentration by NF/RO may improve foam fractionation PFAS performance • NOM is removed by foam fractionation, which could help IX performance • Bulk removal of PFAS will decrease PFAS mass loading to polishing media • Surfactant usage in foam fractionation may reduce the need for IX polishing if it can enhance the removal of short-chain PFAS • IX is effective at removing short-chain PFAS • IX requires smaller footprint than GAC • Ability to meet lower effluent limits should regulatory framework change in the future	• NF/RO reject contains sparingly soluble salts, which may cause scaling in foam fractionation tanks and IX vessels, and limit processing time of the reject • NF/RO require high energy input • Treated foam fractionation effluent anticipated to still require treatment with IX to meet treatment targets • Limited options for disposal of IX resin (landfilling or incineration)

Preconcentration with membranes will significantly decrease the number of IX vessel required compared to other alternatives. Additionally, if future regulatory limits decrease for short-chain PFAS species, IX polishing would be well positioned to meet lowered limit due to the ability of IX to remove short-chain PFAS, though media use would likely increase if lower effluent limits are required.

While foam fractionation itself is a lower energy operation, membranes rely on high-pressure pumps to separate clean water from the reject stream, which would increase the overall OPEX cost. There are other disadvantages distinct to membrane systems. NF and RO membranes are susceptible to fouling if pre-treatment is not sufficient. Membranes should have a service life of 5-7+ years with proper care and pre-treatment; however, improper pre-treatment can shorten membrane life and lead to significant replacement costs earlier than expected. Yearly operating costs will be higher as well, as significant expense will come from antiscalant, chemical cleaners, and high energy use of NF/RO booster pumps. Building footprints savings may be limited by the footprint required for the membrane systems and more extensive pre-treatment. Due to the higher complexity of the system, a membrane plant will require significantly more operator and engineer oversight and require operations staff with membrane experience to operate efficiently and cost effectively.

Finally, the concentrate stream poses the largest risk to foam fractionation operations. Membranes would not only concentrate PFAS, but also hardness and dissolved salts. By concentrating the dissolved salts, the risk of precipitation of sparingly soluble salts increases. When precipitation occurs, scaling could form in piping and vessels, which could decrease foam fractionation performance, increase equipment downtime, foul IX resin and force early media changeouts, and may require citric acid (or other weak acid) cleanings to remove scale. Piloting would be essential to prove that the foam fractionation technology selected could be operated using a membrane concentrate stream.

The preliminary membrane design criteria for Treatment Train 7 are summarized in Table J.36. A 75% recovery was assumed, though RO recoveries can range from 70-85% and NF recoveries can range from 85-95%. For a more detailed discussion of RO and NF membranes, see Section 9 of the FS and Appendix D. Further evaluation (bench- and pilot-scale testing) of NF and RO membranes would be required prior to full-scale system design. For initial comparison of different treatment plants, a 500-gpm skid using a 2-pass arrangement of pressure vessel (10:5, 6 elements per pressure vessel) was used. Further analysis would be needed to optimize membrane system design for a specific flow rate.

Table J.36. Alternative 7 (NF/RO to Foam Fractionation with IX Polishing) Preliminary Membrane Design Criteria.

Parameter	Unit	Small Plant	Medium Plant	Large Plant
	Example AOC	WCL – Source Zone	RC + EPL, or WLL Plume Control	WLL, WCL, RC + EPL Combined Treatment Plant
Influent Flow Rate	gpm	500	2,000	5,000
Permeate Flow Rate	gpm	375	1,500	3,750
Concentrate Flow Rate	gpm	125	500	1,250
Model (1)	-	TM720D-400	TM720D-400	TM720D-400
Trains Installed / Duty Trains (2)	-	2/1	5/4	11/10
Total Number of Pressure Vessels	-	30	90	165
Active Membrane Area per Train	ft^2	36,000	36,000	36,000
Recovery Rate (3)	%	75	75	75
Flux	gal / ft^2 / d	20	20	20
Feed Pump Power	hp	125	125	125

(1) Toray RO membranes were used for budgetary estimates; however, bench- and pilot-scale studies should be performed to identify the optimal membrane.
(2) For comparison of different sized treatment plants, a 500-gpm skid with 15 pressure vessels was priced out. Further analysis would be needed to determine the optimal skid size and arrangement for a specific treatment plant.
(3) Recovery rate is assumed to be 75% to decrease scaling risk in GAC and IX pressure vessels. Optimal recovery rate should be further analyzed with bench- and pilot-scale studies to determine the optimal recovery rate.

Preliminary SAFF® and IX design criteria for Treatment Train 7 are summarized in Table J.37. All design criteria, particularly SLR and EBCT, must be validated by RSSCTs and/or pilot testing and should be viewed as preliminary only. Vessels would be operated in lead/lag configuration and N+1 redundancy is assumed for operations.

Table J.37. Treatment Train 7 (NF/RO to Foam Fractionation with IX Polishing) Preliminary Foam Fractionation Design Criteria Using SAFF® as the Foam Fractionation Technology.

Parameter	Unit	Small Plant	Medium Plant	Large Plant
	Example AOC	WCL – Source Zone	RC + EPL, or WLL Plume Control	WLL, WCL, RC + EPL Combined Treatment Plant
Membrane Reject Flow Rate @ 75% Recovery	gpm	125	500	1250
	MGD	0.18	0.72	1.8
SAFF®				
SAFF®40 Capacity	MGD	0.25	0.25	0.25
Process Units Installed/Required	-	2/1	4/3	9/8
IX				
Process Trains Installed/In- service (1)	-	2/1	2/1	4/3
Filters Per Train	-	2	2	2
IX per Filter	ft^3	177	282.4	282.4
Vessel Diameter	ft	6	8	8
Surface Area per Filter	ft^2	28.3	50.3	50.3
Total In-Service Surface Area	ft^2	28.3	50.3	150.8
Filter Surface Loading Rate (SLR) (2)	gpm/ft^2	4.42	9.95	8.29
EBCT per Process Train (2)	min	10.6	4.2	5.1

(1) Assumes N+1 redundancy for all operations.
(2) Loading rate and EBCT to be evaluated during RSSCTs and future pilot testing.

An NF/RO to foam fractionation and single-use IX treatment plant to treat 500 gpm from AOC 1 is estimated to have a CAPEX cost of $25.1 million. A 2,000-gpm plant to treat water from either AOCs 2 & 7 or AOC 10 is estimated to have a CAPEX cost of $49.0 million, while a 5,000-gpm plant to treat water from AOCs 2, 7 & 10 is estimated to have a CAPEX cost of $86.4 million. Expected treatment plant CAPEX is summarized in Table J.38; detailed cost estimates are available in Table J.58.

Table J.38. Treatment Train 7 (NF/RO to Foam Fractionation + IX Polishing) CAPEX Estimate Using SAFF® as the Foam Fractionation Technology.

Equipment & Estimated Installation Costs	500 GPM	2,000 GPM	5,000 GPM
Greensand Process Equipment	$1,075,000	$3,368,000	$6,625,000
Membrane Process Equipment	$2,659,000	$6,667,000	$14,615,000
SAFF® Process Equipment	$4,500,000	$9,000,000	$14,559,000
IX Process Equipment	$1,144,000	$1,436,000	$2,871,000
Tanks and Pumps	$905,000	$1,106,750	$1,330,000
Piping	$504,000	$755,000	$1,137,000
Electrical	$800,000	$1,200,000	$1,850,000
Building and Foundation	$3,350,000	$5,650,000	$8,450,000
SUBTOTAL	$14,937,000	$29,182,750	$51,437,000
Mobilization & Site Setup (5%)	*$747,000*	*$1,459,000*	*$2,572,000*
Bonding & Insurance (3%)	*$448,000*	*$875,000*	*$1,543,000*
Contractor Overhead and Profit (15%)	*$2,241,000*	*$4,377,000*	*$7,716,000*
Engineering & Construction Contingency (45%)	*$6,722,000*	*$13,132,000*	*$23,147,000*
TOTAL (2024)	$25,100,000	$49,000,000	$86,400,000

Yearly OPEX costs for treatment plants were derived from RSSCT data and are given in Table J.39. Yearly OPEX is estimated to cost between $1.5 and $6.7 million for a 500-gpm plant to treat AOC 1, $2.9 million for a 2,000-gpm plant to treat AOCs 2&7 or AOC 10, and $5.8 million for a 5,000-gpm plant to treat AOCs 2, 7 & 10. Large ranges in OPEX for AOC 1 are due to uncertainty over the ability of foam fractionation to remove PFBA. The low range cost estimate assumes significant removal of PFBA with foam fractionation, while the high end assumes minimal removal of PFBA by foam fractionation. Additional bench- and pilot-scale testing is recommended to optimize the foam fractionation technology selected.

Table J.39. Treatment Train 7 (NF/RO to SAFF® with Single-Use IX Polishing) OPEX Estimates using SAFF® as the Foam Fractionation Technology.

Parameter	500 GPM	2,000 GPM	5,000 GPM
IX Media	$280,000	$446,000	$1,339,000
IX Media Disposal	$21,000	$22,000	$65,000
IX Media (High Use)	$5,315,000	-	-
IX Media Disposal (High Use)	$211,000	-	-
Chemical [1]	$111,000	$431,000	$1,070,000
Process/NPDES Testing (Non-PFAS)	$52,000	$52,000	$52,000
PFAS Testing	$200,000	$200,000	$273,000
Electrical (RO)	$103,000	$397,000	$992,000
Electrical (SAFF®)	$15,000	$59,000	$148,000
Labor Costs	$395,000	$671,000	$790,000
Membrane Replacement [2]	$27,000	$68,000	$149,000
Cartridge Filter Replacement	$2,000	$8,000	$20,000
Replacement Parts & Operations Equipment	$214,000	$392,000	$649,000
Incineration Cost [3]	$3,000	$11,000	$27,000
Sewer Cost	$43,000	$127,000	$244,000
Yearly Estimate	$1,460,000	$2,880,000	$5,820,000
Yearly Estimate (High Use)	$6,690,000	-	-

[1] Chemical usage for NF/RO includes chlorine, sodium bisulfite, low & high pH cleaners, antiscalant, sulfuric acid, and sodium hydroxide.
[2] Membrane replacement assumes 6-year membrane life, 1/6th of membranes are replaced per year, at $750/membrane element, plus 20% for installation.
[3] Assumed SAFF® concentration factor is 200,000x with tertiary fractionation, $1 per pound for incineration.

J3 Analysis of Treatment Trains

The United States Environmental Protection Agency's (EPA) National Contingency Plan (NCP) lays out nine criteria for use in evaluating remedial alternatives. The EPA's nine criteria are: Overall protection of human health and the environment; Compliance with applicable or relevant and appropriate standards; Long-term effectiveness and permanence; Reduction of toxicity; mobility or volume; Short-term effectiveness; Implementability; Cost; State acceptance; and Community acceptance.

These NCP criteria were used to evaluate Site-wide alternatives and were used as a basis for the criteria used to evaluate the proposed treatment trains. Criteria for pump and treatment were selected to be more specific to the PFAS treatment trains being considered. Criteria, and how they were applied, are below.

Short-Term Effectiveness: Short-term effectiveness considers the ability of a treatment train to meet current regulatory PFAS standards. Current standards include EPA maximum contaminant levels and Minnesota Department of Health Health-Based Values and Health Risk limits; these regulations are discussed in Section 9 of the FS.

Long-Term Effectiveness: Long-term effectiveness considers the ability of a treatment train to meet future regulatory PFAS standards, should regulatory standards be dropped for species that are already regulated, or should additional species be regulated. Specific consideration is given to the ability of a treatment train to remove short-chain PFAS, as short-chain species are generally more difficult to remove than long-chain species.

Cost: Capital expenditure (CAPEX) and operating expenditure (OPEX) are both considered for this criterion. Evaluation was completed using initial CAPEX and OPEX estimates; these estimates and the assumptions made are detailed at the end of this document. Total cost must be considered, as a treatment train with a low initial (CAPEX) cost may have significantly higher yearly (OPEX) costs and cost more over the life of the plant than a treatment train with a higher CAPEX cost but lower OPEX costs.

Sustainability – Media Consumption: Expected media usage is evaluated by this criterion. Media usage is based on estimates derived by RSSCTs completed as part of treatability testing for this FS. See Section 10 of the FS and Appendix H for additional details on RSSCTs. Additional treatability testing is needed to verify assumptions on membrane system, foam fractionation, and adsorptive media performance for treatment trains not directly tested in this FS.

Sustainability – Energy Use: Relative amount of energy use is compared by this criterion. This criterion focuses on process equipment, as building size and heating/cooling requirements are not expected to impact relative energy usage as much as pumping and other process equipment.

Operations and Maintenance Requirements: This criterion evaluates the number of operators/technical staff required to operate and maintain a facility, the relative ease/difficulty of operating a facility, and the expected relative difficulty of maintenance. For example, membranes require more oversight than GAC. Plants would be built to required code, minimizing risk to nearby homes, thus safety to nearby homes is not considered further.

Technology Readiness: Technology readiness is evaluated by how widely used a technology is currently, relative amount of time a technology has been used for full-scale PFAS treatment, ease of access to spare parts or replacement media, and technical feasibility of construction and operation.

Portion of PFAS Destroyed vs. Landfilled: This criterion compares the relative mass of PFAS that is ultimately destroyed by a given treatment train or landfilled. Destruction could occur from incineration, reactivation of GAC, or through a novel destruction technology. Further details on PFAS destruction can be found in Section 9 of the FS and Appendix G (PFAS Destruction Technology Bench-Scale Study Summary and Analysis).

Due to relative cost of landfilling versus incineration, it is assumed all single-use ion exchange media will be landfilled. Landfilling is considered to be less desirable, as PFAS is sequestered in a landfill and not ultimately destroyed. Treatment trains that consume less IX media may be candidates for incineration of IX media to destroy PFAS as the volume of media to be incinerated would be lower.

Additional technologies are in development for disposal/re-use of GAC and IX media; however, they are not discussed here as they are not ready for full-scale use. As research and development of PFAS destruction continues, options should be evaluated periodically to reevaluate future options for disposal and destruction of PFAS and adsorptive media.

It must also be noted that at this time, no destruction or disposal facility exists in the State of Minnesota for destruction of PFAS-impacted waste. Any destruction or disposal of spent media would require transport out of state.

Individual treatment train rankings are summarized in Table J.40 (AOC 1 – WCL) and Table J.41 (AOCs 2, 7, and 10) with descriptions of rankings in Table J.59 (AOC 1) and Table J.60 (AOCs 2, 7, and 10).

Table J.40. Summary of Individual Treatment Train Rankings - AOC 1 (WCL).

Treatment Train	Treatment Technology	Short-Term Effectiveness	Long-Term Effectiveness	Cost [1,2]	Sustainability - Media Consumption [2]	Sustainability - Energy Use	O&M	Technology Readiness	Portion of PFAS Destroyed vs. Landfilled [3]
Treatment Train 1	Reactivated GAC	Low	Low	CAPEX: $13 M OPEX: $31 M	High	Low	Low	High	High
Treatment Train 2	Single-Use IX	Low	Low	CAPEX: $12 M OPEX: $44 M	High	Low	Low	High	Low
Treatment Train 3	Reactivated GAC + Single-Use IX	Low	Low	CAPEX: $19 M OPEX: $26 M	High	Low	Low	High	Moderate
Treatment Train 4	NF/RO to Reactivated GAC +Single-Use IX	Low	Low	CAPEX: $19 M OPEX: $22 M	High	High	High	High	Moderate
Treatment Train 5	Regenerable IX [4]	High	High	CAPEX: $41 M OPEX: $3.3	Low	High	High	Low	High
Treatment Train 6	SAFF® [5] + Reactivated GAC	Low to Moderate	Low	CAPEX: $32 M OPEX: $4.2 M to $32 M	Moderate to High	Moderate	Moderate	Moderate	High
	SAFF® [5] + Single-Use IX	Moderate to High	Moderate to High	CAPEX: $31 M OPEX: $2.2 M to $12 M	Low to Moderate	Moderate	Moderate	Moderate	Moderate to High
Treatment Train 7	NF/RO to SAFF® [5] + Single-Use IX	Moderate to High	Moderate to High	CAPEX: $25 M OPEX: $1.5 M to $6.7 M	Low to Moderate	High	High	Moderate	Moderate to High

(1) Based on preliminary cost estimates. RSSCTs and pilot testing required to confirm preliminary design assumptions and to validate media usage estimates.
(2) Significant uncertainty exists around how much PFBA would be removed by foam fractionation. Lower scores represent minimal PFBA removal while higher scores represent higher PFBA removal.
(3) Assumes IX media is landfilled as opposed to incinerated due to cost.
(4) Assumes long-chain PFAS can be removed from IX during reactivation. If GAC is required to remove long-chain PFAS, media use and OPEX costs would increase significantly.
(5) For the purposes of this report, SAFF® was used as the foam fractionation technology for cost estimates and preliminary design due to its use in an on-site pilot study conducted as part of this FS. Since the commencement of the pilot study, additional vendors now offer foam fractionation treatment technology; it is recommended that multiple vendors be evaluated if foam fractionation is selected as a remedial technology.

Table J.41. Summary of Individual Treatment Train Rankings - AOCs 2, 7, and 10.

Treatment Train	Treatment Technology	Short-Term Effectiveness	Long-Term Effectiveness	Cost (1)		Sustainability - Media Consumption (2)	Sustainability - Energy Use	O&M	Technology Readiness	Portion of PFAS Destroyed vs. Landfilled (3)
				2,000 gpm	5,000 gpm					
Treatment Train 1	Reactivated GAC	Moderate	Low	CAPEX: $24 M OPEX: $4.6 M	CAPEX: $39 M OPEX: $11 M	High	Low	Low	High	High
Treatment Train 2	Single-Use IX	High	Moderate to High	CAPEX: $24 M OPEX: $1.9 M	CAPEX: $41 M OPEX: $3.7 M	Moderate	Low	Low	High	Low
Treatment Train 3	Reactivated GAC + Single-Use IX	High	Moderate to High	CAPEX: $34 M OPEX: $2.4 M	CAPEX: $54 M OPEX: $4.4 M	Moderate	Low	Low	High	Moderate
Treatment Train 4	NF/RO to Reactivated GAC + Single-Use IX	High	Moderate to High	CAPEX: $36 M OPEX: $3.1 M	CAPEX: $67 M OPEX: $6.1 M	Moderate	High	High	High	Moderate
Treatment Train 5	Regenerable IX	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Treatment Train 6	SAFF® (4) + Reactivated GAC	High	Low to Moderate	CAPEX: $63 M OPEX: $3.0 M	CAPEX: $120 M OPEX: $5.5 M	Moderate	Moderate	Moderate	Moderate	High
	SAFF® (4) + Single-Use IX	High	High	CAPEX: $62 M OPEX: $2.6 M	CAPEX: $120 M OPEX: $4.6 M	Low	Moderate	Moderate	Moderate	Moderate
Treatment Train 7	NF/RO to SAFF® (4) + Single-Use IX	High	High	CAPEX: $49 M OPEX: $2.9 M	CAPEX: $86 M OPEX: $5.8 M	Low	High	High	Moderate	High

(1) Based on preliminary cost estimates. RSSCTs and pilot testing required to confirm preliminary design assumptions and to validate media usage estimates.
(2) PFBA is below drinking water standards in AOCs 2, 7, and 10; it is assumed treatment targeting PFBA is not required at this time.
(3) Assumes IX media is landfilled as opposed to incinerated due to cost.
(4) For the purposes of this report, SAFF® was used as the foam fractionation technology for cost estimates and preliminary design due to its use in an on-site pilot study conducted as part of this FS. Since the commencement of the pilot study, additional vendors now offer foam fractionation treatment technology; it is recommended that multiple vendors be evaluated if foam fractionation is selected as a remedial technology.

Next, treatment trains were compared against one another with respect to criteria previously discussed. The comparative approach highlights the key advantages, disadvantages, and tradeoffs that are considered as part of the selection process. Comparative analysis is separated out into AOC 1 and AOCs 2, 7, and 10 due to the relative similarities of PFAS concentrations expected in AOCs 2, 7, and 10. The comparative analysis results described below are summarized in Table J.42 (AOC 1) and Table J.43 (AOCs 2, 7, and 10).

Table J.42. Comparative Rankings of Evaluated Treatment Trains - AOC 1 (WCL).

Criteria	**Alternative Ranking** (1)
Short -Term Effectiveness	Most able to meet current regulatory PFAS limits to least able 5 > 7 > 6 (IX) > 6 (GAC) > 4 > 2 = 3 > 1
Long-Term Effectiveness	Most able to meet potential future regulatory PFAS limits (e.g. lower short-chain PFAS limits) to least able 5 > 7 > 6 (IX) > 4 > 2 = 3 > 6 (GAC) > 1
Cost (2)	Lowest expected CAPEX to highest expected CAPEX 2 < 1 < 4 < 3 < 7 < 6 (IX) < 6 (GAC) < 5 Lowest expected OPEX to highest expected OPEX 7 < 6 (IX) < 5 < 6 (GAC) < 4 < 3 < 1 < 2
Sustainability - Media Consumption (2)	Least adsorptive media use to highest adsorptive media use 5 < 7 < 6 (IX) < 4 < 3 < 2 < 6 (GAC) < 1
Sustainability - Energy Use	Lowest energy use to highest energy use 1 = 2 < 3 < 6 (GAC) = 6 (IX) < 4 < 7 < 5
Operations and Maintenance Requirements	Least demanding O&M to most demanding 1 < 2 = 3 < 6 (GAC) = 6 (IX) < 4 < 7 < 5
Technology Readiness	Most widely used/developed technology to least 1 = 2 = 3 > 4 > 6 (GAC) = 6 (IX) > 7 = 5
Portion of PFAS Destroyed vs. Landfilled (3)	Highest percentage to PFAS destroyed to lowest percentage of PFAS destroyed 1= 5 = 6 (GAC) > 7 > 6 (IX) > 3 = 4 > 2

Legend: =: equal to; <: less than; >: greater than.

(1) Foam Fractionation alternatives are ranked assuming moderate to high removal of PFBA can be achieved with foam fractionation through use of a surfactant.

(2) CAPEX and OPEX costs are based on media usage estimates derived from initial RSSCTs and assumed design parameters. Media usage estimates must be validated by RSSCTs, particularly for treatment trains including RO or foam fractionation.

(3) IX media is assumed to be landfilled instead of incinerated, which would result in no PFAS destruction.

Table J.43. Comparative Rankings of Evaluated Treatment Trains - AOCs 2, 7, and 10.

Criteria	Alternative Ranking (1)
Short -Term Effectiveness	Most able to meet current regulatory PFAS limits to least able 2 = 3 = 4 = 6 (GAC) = 6 (IX) = 7 > 1
Long-Term Effectiveness	Most able to meet potential future regulatory PFAS limits (e.g. lower short-chain PFAS limits) to least able 7 > 6 (IX) > 4 > 2 = 3 > 6 (GAC) > 1
Cost (2)	Lowest expected CAPEX to highest expected CAPEX 1 = 2 < 3 < 4 < 7 < 6 (GAC) = 6 (IX) Lowest expected OPEX to highest expected OPEX 2 < 3 < 6 (IX) < 6 (GAC) < 7 < 4 < 1
Sustainability - Media Consumption (2)	Least adsorptive media use to highest adsorptive media use 7 < 6 (IX) < 6 (GAC) < 4 < 3 < 2 < 1
Sustainability - Energy Use	Lowest energy use to highest energy use 1 = 2 < 3 < 6 (GAC) = 6 (IX) < 4 < 7
Operations and Maintenance Requirements	Least demanding O&M to most demanding 1 < 2 < 3 < 6 (GAC) = 6 (IX) < 4 < 7
Technology Readiness	Most widely used/developed technology to least 1 = 2 = 3 > 4 > 6 (GAC) = 6 (IX) > 7
Portion of PFAS Destroyed vs. Landfilled (3)	Highest percentage to PFAS destroyed to lowest percentage of PFAS destroyed 1 = 6 (GAC) > 7 > 6 (IX) > 3 = 4 > 2

Legend: =: equal to; <: less than; >: greater than.

(1) Foam Fractionation alternatives are ranked assuming short chain removal (e.g. PFBA) is not required as current concentrations in AOCs 2, 7, and 10 are below the 7,000 ng/L regulatory standard for PFBA.

(2) CAPEX and OPEX costs are based on media usage estimates derived from initial RSSCTs and assumed design parameters. Media usage estimates must be recommended to be validated by additional RSSCTs, particularly if a different foam fractionation vendor is selected.

(3) IX media is assumed to be landfilled instead of incinerated, which would result in no PFAS destruction.

J3.1 Short-Term Effectiveness

Short-term effectiveness is based on ability of a treatment train to meet current regulatory limits. As they relate to the AOCs considered in this appendix, this analysis generally focuses on the ability of a treatment train to reach non-detect (or < 1 ng/L) of PFOA and PFOS and to reduce PFBA effluent concentrations to < 7,000 ng/L. More information on current regulatory limits can be found in Section 9 of the FS.

J3.1.1 AOC 1

For AOC 1, treatment trains must be able to remove high concentrations of PFOA (potentially > 15,000 ng/L) and PFBA (potentially > 140,00 ng/L). Treatment Train 5 is expected to be able to have the highest ability to meet current regulatory limits. However, it is unknown if long-chain PFAS could be desorbed off the IX resin during regeneration or if GAC would be required to remove long-chain PFAS. If GAC is required, this would decrease the effectiveness of the treatment train.

Next, generally, are the foam fractionation treatment trains. While the SAFF® pilot test performed during this FS showed limited PFBA removal, use of a surfactant or other vendors may improve this. Treatment Train 7, with preconcentration via RO, is expected to have the next highest ability to meet current standards, followed by Treatment Train 6 (IX) and Treatment Train 6 (GAC). It must be noted that if foam fractionation does not remove significant amounts of PFBA and polishing media is relied upon to remove PFBA, effectiveness would only be moderately better than the adsorptive media-based treatment trains.

Treatment Trains 1, 2, 3, and 4 are the adsorptive media-based treatment trains. Due to results in the RSSCTs, they are not expected to be able to meet effluent standards without an unrealistically high number of media changeouts per year. While ranked 4 > 2 = 3 > 1, this ranking is not meaningful, as none of these four treatment trains are expected to meet current regulatory standards.

J3.1.2 AOCs 2, 7, and 10

Generally, all treatment trains evaluated would be able to meet required effluent standards in AOCs 2, 7, and 10. This is in contrast with AOC 1 and is due primarily to the lower overall concentration of PFAS in the groundwater in these AOCs as well as the significantly lower concentrations of PFBA. While some samples indicate PFBA concentrations into the 2,000 to 3,000 ng/L range, these are still well below the current regulatory standard of 7,000 ng/L. Thus, all treatment trains could meet current regulatory standards. The notable caveat here though, is Treatment Train 1. Results from the initial RSSCTs indicate as many as 25 GAC changeouts per year could be required; while biweekly GAC changeouts are possible, the effectiveness of Treatment Train 1 is demonstrably lower than the other treatment trains evaluated, thus it is ranked lower than the others.

J3.2 Long-Term Effectiveness

Long-term effectiveness is based on ability of a treatment train to meet lower PFAS effluent limits, should regulatory limits be decreased. This analysis is focused on short-chain PFAS, as these species are generally harder to remove than long-chain PFAS. Additionally, short-chain PFAS either currently do not have regulatory standards or have high regulatory limits (e.g. PFBA – 7,000 ng/L) compared to PFOA and PFOS. Further reduction of long-chain PFAS regulatory limits would not meaningfully impact treatment trains, as current Minnesota Department of Health targets are significantly lower than current analytical detection limits. However, a decrease in the PFBA limit or limits on additional short-chain PFAS would likely have a large impact on treatment trains.

J3.2.1 AOC 1

Treatment Train 5 would be the most able to meet lower effluent limits, as regeneration of IX resin frequency could be increased to meet lower effluent limits. There are, however, two important caveats. First, as previously mentioned, the ability of PFOA to be removed from the IX resin is unknown. This impacts the amount of GAC usage as well as the lifetime and performance of the resin. If active sites on the IX resin are increasingly lost to long-chain PFAS that cannot be desorbed off the resin, resin capacity would decrease rapidly and would not be able to achieve as low of effluent standards. Second, increasing regeneration frequency to meet lower effluent standards would be limited by the regeneration equipment size, from the regenerant supply through the distillation of spent regenerant. Oversizing a system is likely to result in a system that runs inefficiently under current regulatory limits, thus detailed analysis would be required to properly size the system. Overall, though, a regenerable IX treatment train is most likely to be able to achieve the lowest effluent standards for short-chain PFAS.

Treatment Train 7 would be expected to have the next highest ability to meet lower effluent limits, as bulk removal of long-chain PFAS would occur with foam fractionation after pre-concentration with NF/RO, and an IX resin selective of short-chain PFAS could be used for polishing. Similarly, Treatment Train 6 would be expected to be the next most capable, though decreased foam fractionation performance would likely be expected due to the lack of pre-concentration with NF/RO prior to foam fractionation. It must be mentioned, though, that it is unknown how efficient of removal could be achieved by foam fractionation for short-chain PFAS. Currently, foam fractionation is primarily used to remove long-chain PFAS, thus future performance and ability to decrease short-chain PFAS in effluents would be dependent on improved short-chain performance.

Treatment Trains 1 through 4, which do not utilize foam fractionation, would be the least able to meet lower short-chain effluent limits. While Treatment Train 4 does incorporate NF/RO and would produce a clean permeate stream, treatment of the concentrate which contained PFAS would still be required. As proposed, using GAC and IX to treat the concentrate would likely be a little more efficient than Treatment Trains 2 and 3 due to potential improvements in the adsorption isotherms, but the difference is not expected to be meaningful in practice. Treatment Train 6 (GAC), which does incorporate foam fractionation, would be expected to have a worse ability than Treatment Trains 2-4 to meet lower effluent standards due to the use of GAC polishing and lack of use of IX. Finally, Treatment Train 1, which would only use GAC, would not be able to meet current regulatory limits and would similarly have no ability to meet even lower future effluent limits.

J3.2.2 AOCs 2, 7, and 10

For AOCs 2, 7, and 10, foam fractionation systems that incorporate IX polishing are expected to have the highest ability to be meet lower effluent standards. Treatment Train 7 is expected to have the best ability to meet future limits, as use of NF/RO ahead of foam fractionation is expected to improve foam fractionation performance. Next, Treatment Train 6 (IX) would be expected to have the next best performance. It must be noted that complete short-chain removal using foam fractionation is not expected; removal would rely on IX resin for polishing. Use of a surfactant or other operational changes may be required to improve short-chain removal for both treatment trains.

Treatment Train 4 is expected to have the next best ability to meet lower effluent concentrations, followed by Treatment Trains 2 and 3. As proposed, using GAC and IX to treat the NF/RO concentrate in Treatment Train 4 would likely be more efficient than Treatment Trains 2 and 3 due to potential improvements in the adsorption isotherms, though the impact this has on media life/usage (and therefore cost) is unknown. Finally, Treatment Train 6 (GAC) followed by Treatment Train 1 would be the least able to meet future limits. While Treatment Train 6 (GAC) would remove a majority of long-chain PFAS with foam fractionation, use of GAC as a polishing media would result in high rates of GAC use as GAC does not remove short-chain PFAS effectively. Similarly, Treatment Train 1 would be ineffective at removing short-chain PFAS and would have the lowest ability of evaluated treatment trains to meet future regulatory limits.

J3.3 Cost

A summary of estimated CAPEX (Table J.44) and OPEX (Table J.45) costs are given below. Media usage rates are based off initial RSSCTs, though not all treatment trains were tested in treatability studies. Table J.4 gives assumed media usage rates by treatment train, and Table J.49 (AOC 1) and Table J.50 (AOCs 2, 7, and 10) provide more details on how the RSSCTs were applied to each treatment train. This cost does not include any destruction technology costs nor associated well or piping costs for treatment plants.

For AOC 1, Treatment Train 2 would have the lowest CAPEX, followed closely by Treatment Train 1. These would be followed by Treatment Train 4, then Treatment Train 3, with Treatment Trains 7, 6, and 5 having the highest CAPEX. OPEX estimates for AOC 1 are less certain, as the removal of PFBA by foam fractionation is unknown and could drastically change media usage. Assuming a foam fractionation system can be set up to remove high levels of PFBA, the OPEX estimates would be ranked 7 < 6 (IX) < 5 < 6 (GAC) < 4 < 3 < 1 < 2. Both GAC and IX variations of Treatment Train 6 and Treatment Train 7 would have significantly higher OPEX costs if minimal PFBA removal is observed. Similarly, as discussed previously, if GAC is required for Treatment Train 5 to remove long-chain PFAS prior to the regenerable IX resin, OPEX would increase significantly for Treatment Train 5. Additional bench- and pilot-scale testing is recommended to reduce cost uncertainty.

Table J.44. Summary of Estimated CAPEX Costs for Evaluated Treatment Trains.

Treatment Train	500 GPM	2,000 GPM – RC/EPL	2,000 GPM - WLL	5,000 GPM
Treatment Train 1	$13,300,000	$24,300,000	$24,300,000	$39,100,000
Treatment Train 2	$12,400,000	$24,100,000	$24,100,000	$41,100,000
Treatment Train 3	$19,500,000	$33,600,000	$33,600,000	$54,300,000
Treatment Train 4	$19,100,000	$36,400,000	$36,400,000	$67,000,000
Treatment Train 5	$41,200,000	-	-	-
Treatment Train 6 (GAC)	$32,300,000	$62,800,000	$62,800,000	$117,800,000
Treatment Train 6 (IX)	$31,300,000	$62,400,000	$62,400,000	$119,500,000
Treatment Train 7	$25,100,000	$49,000,000	$49,000,000	$86,400,000

For AOCs 2, 7, and 10, Treatment Trains 1 and 2 are expected to have the lowest and similar CAPEX costs, followed by Treatment Train 3 < 4 < 7 < 6 (GAC) = 6 (IX). OPEX estimates for AOCs 2, 7, and 10 would be Treatment Train 2 < 3 < 6 (IX) < 6 (GAC) < 7 < 4 < 1.

Table J.45. Summary of Estimated OPEX Costs for Evaluated Treatment Trains.

Treatment Train	Technology Used	500 GPM	2,000 GPM	5,000 GPM
Treatment Train 1	GAC	$31,400,000	$4,620,000	$10,600,000
Treatment Train 2	IX	$44,400,000	$1,850,000	$3,660,000
Treatment Train 3	GAC + IX	$25,800,000	$2,390,000	$4,430,000
Treatment Train 4	NF/RO to GAC + IX	$21,900,000	$3,120,000	$6,080,000
Treatment Train 5 (1)	Regenerable IX	$3,290,000	-	-
	Regenerable IX (High GAC)	$4,110,000	-	-
Treatment Train 6 (2)	SAFF® (3) + GAC	$4,250,000	$2,950,000	$5,460,000
	SAFF® (3) + GAC (High)	$31,900,000	-	-
	SAFF® (3) + IX	$2,260,000	$2,650,000	$4,560,000
	SAFF® (3) + IX (High	$12,100,000	-	-
Treatment Train 7	NF/RO to SAFF® (3) + IX	$1,460,000	$2,880,000	$5,820,000
	NF/RO to SAFF® (3) + IX (High)	$6,690,000	-	-

(1) Regenerable IX was only considered for the 500 gpm plant size; costs were not developed for the 2,000 gpm or 5,000 gpm plant sizes. Lower OPEX cost assumes GAC is only used as a sacrificial vessel ahead of IX, while the higher OEPX cost (High GAC) assumes GAC is needed to reduce long-chain PFAS loading to the resin.

(2) While GAC and IX were both costed for Treatment Train 6, it is assumed only one medium would be used if this treatment train were selected as a remedial option.

(3) SAFF® was used as the foam fractionation technology for developing cost estimates as previously discussed. Evaluation of other foam fractionation vendors is recommended prior to selection of a treatment technology.

A present-worth analysis, which allows for comparison of total expected OPEX and CAPEX costs over a period of operational plant time, was not conducted for these treatment trains due to high uncertainty over the ability of foam fractionation to remove short-chain PFAS. Additional testing is recommended to provide more insight on the ability of foam fractionation to remove PFBA and to reduce the uncertainty in treatment costs.

Potential 25-year operational costs, calculated without accounting for inflation or interest, for adsorbent media and non-adsorbent media-based treatment trains are summarized for WCL in Figure J.13. Costs for each AOC 1 (WCL) treatment train over time are given in end Figure J.14 (adsorbent media based) and Figure J.15 (WCL, non-adsorbent media based). Costs for a pump and treat plant in AOCs 2, 7, and 10 are shown in Figure J.16 (2,000-gpm plant) and Figure J.17 (5,000-gpm plant).

Piping and well costs must also be considered when evaluating the total cost of a potential project. For comparison, potential total project costs were calculated for Alternative 4, which would include a WCL pump and treat system in AOC 1 and either separate or combined pump and treat systems for AOCs 2/7 and AOC 10. Total potential project costs are given in Table J.46. Note that this table assumes the same treatment train is selected for each AOC; in reality, different treatment trains would likely be selected for source zone control (AOC 1) and plume control (AOCs 2, 7, and 10). This table serves to illustrate potential total project costs.

J3.4 Sustainability – Media Consumption

Media usage rates are based off initial RSSCTs and are based on current regulatory standards, though not all treatment trains were tested in treatability studies. Table J.4 gives assumed media usage rates by treatment train, and Table J.49 (AOC 1) and Table J.50 (AOCs 2, 7, and 10) provide more details on how the RSSCTs were applied to each treatment train.

J3.4.1 AOC 1

For AOC 1, Treatment Train 5 would offer the lowest media consumption, as IX media could be reused. As currently designed, it is assumed long-chain PFAS could be removed from IX resin during regenerations. However, if sufficient removal of long-chain PFAS does not occur during regeneration, GAC would be required ahead of IX resin, which would significantly increase the media consumption of the treatment train.

Treatment Train 5 would be followed by two of the foam fractionation treatment trains which use IX, specifically Treatment Trains 7 and 6 (IX). Media consumption would be reduced relative to other treatment trains by using foam fractionation to remove PFAS prior to the adsorptive media polishing. The amount of media required is uncertain though, as the removal of PFBA with foam fractionation is not proven out. Evaluation of multiple foam fractionation vendors is recommended to optimize PFBA removal and decrease adsorptive media usage.

Treatment Train 4, 3, and 2 are expected to have the next highest levels of adsorptive media consumption. As Treatment Train 4 would provide a preconcentration step prior to use of adsorptive media, overall media usage may be lower than in Treatment Trains 2 or 3. All three of these treatment trains are expected to have very high media usage though. Next, Treatment Train 6 (GAC) is expected to have the next highest usage of media. Though bulk removal of long-chain PFAS would be achieved with foam fractionation, GAC polishing of PFBA in the effluent would be inefficient and lead to very high volumes of GAC consumed. Should PFBA be removed effectively by foam fractionation, Treatment Train 6 (GAC) would likely have less media usage than Treatment Trains 2, 3, and 4. Finally, Treatment Train 1 would use the most adsorptive media, as a GAC-only system would require very high changeout frequency to meet PFBA limits. While Treatment Trains 1, 2, 3, 4, and 6 (GAC) are ranked in this section, in reality, these five treatment trains are likely to have media usage one to two orders of magnitude more than is practical.

Table J.46. Alternative 4 Potential Total Treatment Train and Piping CAPEX Costs.

Treatment Train	AOC 1: WCL – Surface Water & Shallow Groundwater			AOC 2: WCL – Bedrock Aquifers & AOC 7: Raleigh Creek + EPL - Groundwater			AOC 10: West Lakeland - Groundwater			AOCs 2, 7, 10 Combined Treatment Plant			Total CAPEX Cost
	Treatment Plant	Piping (Open Cut)	Piping (HDD)	Treatment Plant	Piping (Open Cut)	Piping (HDD)	Treatment Plant	Piping (Open Cut)	Piping (HDD)	Treatment Plant	Piping (Open Cut)	Piping (HDD)	
Treatment Train 1	$13,270,000	$7,419,000	-	$24,276,000	$48,879,000	-	$24,276,000	$30,152,000	-	-	-	-	$148,272,000
	$13,270,000	-	$4,463,000	$24,276,000	-	$24,791,000	$24,276,000	-	$14,239,000	-	-	-	$105,315,000
	$13,270,000	$7,419,000	-	-	-	-	-	-	-	$39,124,000	$113,146,000	-	$172,959,000
	$13,270,000	-	$4,463,000	-	-	-	-	-	-	$39,124,000	-	$47,604,000	$104,461,000
Treatment Train 2	$12,395,000	$7,419,000	-	$24,084,000	$48,879,000	-	$24,084,000	$30,152,067	-	-	-	-	$147,013,067
	$12,395,000	-	$4,463,000	$24,084,000	-	$24,791,000	$24,084,000	-	$14,239,000	-	-	-	$104,056,000
	$12,395,000	$7,419,000	-	-	-	-	-	-	-	$41,074,000	$113,146,000	-	$174,034,000
	$12,395,000	-	$4,463,000	-	-	-	-	-	-	$41,074,000	-	$47,604,000	$105,536,000
Treatment Train 3	$19,493,000	$7,419,000	-	$33,598,000	$48,879,000	-	$33,598,000	$30,152,067	-	-	-	-	$173,139,067
	$19,493,000	-	$4,463,000	$33,598,000	-	$24,791,000	$33,598,000	-	$14,239,000	-	-	-	$130,182,000
	$19,493,000	$7,419,000	-	-	-	-	-	-	-	$54,335,000	$113,146,000	-	$194,393,000
	$19,493,000	-	$4,463,000	-	-	-	-	-	-	$54,335,000	-	$47,604,000	$125,895,000
Treatment Train 4	$19,117,000	$7,419,000	-	$36,356,000	$48,879,000	-	$36,356,000	$30,152,067	-	-	-	-	$178,279,067
	$19,117,000	-	$4,463,000	$36,356,000	-	$24,791,000	$36,356,000	-	$14,239,000	-	-	-	$135,322,000
	$19,117,000	$7,419,000	-	-	-	-	-	-	-	$66,980,000	$113,146,000	-	$206,662,000
	$19,117,000	-	$4,463,000	-	-	-	-	-	-	$66,980,000	-	$47,604,000	$138,164,000
Treatment Train 5 (1)	$41,212,000	$7,419,000	-	-	-	-	-	-	-	-	-	-	*$48,631,000*
	$41,212,000	-	$4,463,000	-	-	-	-	-	-	-	-	-	*$45,675,000*
	$41,212,000	$7,419,000	-	-	-	-	-	-	-	-	-	-	*$48,631,000*
	$41,212,000	-	$4,463,000	-	-	-	-	-	-	-	-	-	*$45,675,000*
Treatment Train 6 (GAC)	$32,332,000	$7,419,000	-	$62,768,000	$48,879,000	-	$62,768,000	$30,152,067	-	-	-	-	$244,318,067
	$32,332,000	-	$4,463,000	$62,768,000	-	$24,791,000	$62,768,000	-	$14,239,000	-	-	-	$201,361,000
	$32,332,000	$7,419,000	-	-	-	-	-	-	-	$117,771,000	$113,146,000	-	$270,668,000
	$32,332,000	-	$4,463,000	-	-	-	-	-	-	$117,771,000	-	$47,604,000	$202,170,000
Treatment Train 6 (IX)	$31,325,000	$7,419,000	-	$62,432,000	$48,879,000	-	$62,432,000	$30,152,067	-	-	-	-	$242,639,067
	$31,325,000	-	$4,463,000	$62,432,000	-	$24,791,000	$62,432,000	-	$14,239,000	-	-	-	$199,682,000
	$31,325,000	$7,419,000	-	-	-	-	-	-	-	$119,475,000	$113,146,000	-	$271,365,000
	$31,325,000	-	$4,463,000	-	-	-	-	-	-	$119,475,000	-	$47,604,000	$202,867,000
Treatment Train 7	$25,094,000	$7,419,000	-	$49,027,000	$48,879,000	-	$49,027,000	$30,152,067	-	-	-	-	$209,598,067
	$25,094,000	-	$4,463,000	$49,027,000	-	$24,791,000	$49,027,000	-	$14,239,000	-	-	-	$166,641,000
	$25,094,000	$7,419,000	-	-	-	-	-	-	-	$86,414,000	$113,146,000	-	$232,073,000
	$25,094,000	-	$4,463,000	-	-	-	-	-	-	$86,414,000	-	$47,604,000	$163,575,000

(1) Regenerable IX is only considered for source zone control (AOC 1). Total project cost can be calculated by selecting a different treatment train for plume control (AOCs 2, 7, and 10).

J3.4.2 AOCs 2, 7, and 10

For AOCs 2, 7, and 10, similar rankings are expected, though with significantly less overall media usage due to the lower PFAS concentrations. Treatment Train 7 would be expected to have the least adsorptive media use, followed by Treatment Train 6 (IX). Treatment Train 6 (GAC) would likely be the next lowest user of adsorptive media, as lower levels of short-chain PFAS in AOCs 2, 7, and 10 would decrease the amount of GAC media used. Similar to AOC 1, Treatment Trains 4, 3, 2, and 1 would follow in order of increasing media usage.

J3.5 Sustainability – Energy Use

No difference is expected in relative levels of energy use between AOCs 1, 2, 7, and 10 for the different treatment trains, thus all are compared together. Treatment Trains 1, 2, and 3, which only use adsorptive media to treat water, are expected to have the lowest plant energy usage. These options use relatively little energy, as pumping is mainly required to overcome head loss through pressure vessels. Treatment Trains 1 and 2 are expected to have slightly lower energy use than Treatment Train 3, as Treatment Train 3 would require pumping through both GAC and IX vessels, though this difference would be marginal.

After media only treatment trains, the next tier of energy use would be Treatment Train 6. Foam fractionation would require more energy use than adsorptive media treatment trains. Similar energy use would be expected for both the reactivated GAC and single-use IX polishing variations of Treatment Train 6.

Treatment Trains with the highest energy use would be those which incorporate NF/RO. Membrane systems require high-pressure pumping to operate, which requires high energy input. Treatment Trains 4, 5, and 7, which all incorporate NF/RO membranes, would be in the highest tier of plant energy use. Treatment Train 4 would be the lowest energy user of the NF/RO treatment trains, as the process would rely on adsorptive media, a relatively low energy process step, to treat NF/RO concentrate. The highest energy users would be Treatment Train 5 and 7, as they utilize addition treatment steps that would require higher energy input (foam fractionation for Treatment Train 7, IX regeneration for Treatment Train 5). Note that Treatment Train 5 is only considered for AOC 1 and is not considered for treatment of AOCs 2, 7, and 10.

Comparison of plant energy use does not account for the energy required to transport and dispose or reactivate the filtration media. It only accounts for energy usage at the treatment plant. While it is outside the scope of this appendix to do a full life-cycle assessment, disposal of media should be considered when selecting a treatment train. GAC production and reactivation requires large amounts of trucking and energy, thus treatment trains using higher amount of GAC will have large energy footprints from that use. Similarly, manufacture and transport of IX resin also has a large energy use footprint. Thus, it is important to consider more than just plant energy use when selecting a treatment train.

J3.6 Operations and Maintenance Requirements

Operations and Maintenance requirements are expected to be similar between AOCs 1, 2, 7, and 10. Treatment Trains 1, 2, and 3, which only rely on adsorptive media for PFAS removal and contain no pre-concentration or treatment steps, would require the least operations and maintenance and have the lowest oversight required. Of these three, Treatment Train 1 would require the least, followed by Treatment Train 2 as IX is expected to have slightly higher maintenance requirements than GAC, followed by Treatment Train 3 which utilizes both GAC and IX and would have more pressure vessels which require maintenance. The differences in these treatment trains, however, are significantly smaller than the remainder of the treatment trains under consideration.

Treatment Train 6 (GAC) and 6 (IX) would have moderate operations and maintenance requirements. While foam fractionation operates as a fully automated batch system that requires relatively little operator oversight during normal operations, these treatment plants are more complex than an adsorptive media treatment plant and would require higher levels of operations and maintenance support.

Treatment trains which utilize NF/RO would require the highest levels of operations and maintenance and oversight. Membrane systems require near constant over-site, periodic membrane cleanings, and careful review of operating data to protect membrane integrity and extend membrane lifetime. For AOCs 1, 2, 7, and 10, Treatment Trains 4 and 7 would require the most oversight, with Treatment Train 7 requiring more than Treatment Train 4 due to the inclusion of foam fractionation in the treatment train.

Treatment Train 5, specific to AOC 1, would be expected to have the highest operations and maintenance requirements. Treatment Train 5 would utilize NF/RO prior to regenerable IX along with a regeneration and spent regenerant recovery/distillation process steps. Treatment Train 5 would be the most complex of any treatment train and require the most maintenance and oversight, as well as the most specific operator and maintenance mechanic knowledge. Finding a qualified operator to oversee the system may not be easy as there are few regenerative IX systems in the world. Use of specialty alloys may also cause challenges, as parts have long lead times. Maintaining all critical spares as well as non-critical spare parts list would be essential to keeping the system running.

J3.7 Technology Readiness

Technology readiness considered how widely used a technology is currently, relative amount of time a technology has been used for full-scale PFAS treatment, ease of access to spare parts or replacement media, and technical feasibility of construction and operation. As technology readiness is generally the same for treatment plants for all AOCs, they are discussed together.

Reactivated GAC and single-use IX are widely used technologies to treat PFAS. While GAC use is historically more common than IX, both are widely used and available from multiple vendors. Treatment Trains 1, 2, and 3, which use either GAC, IX, or a combination thereof, are considered to have the highest technology readiness of all treatment trains, for all AOCs. Treatment Train 4, which would use NF/RO membranes prior to reactivated GAC and single-use IX would have the next highest technology readiness. Though use of NF/RO for PFAS treatment is a more recent application of the technology, membranes have been widely used for many years and there are multiple vendors of both membranes and membrane specific chemicals. Treatment Trains 1, 2, 3, and 4 all have high technology readiness.

The next tier of treatment trains would require scale-up and/or more significant testing prior to implementation. Treatment Train 6, which would utilize foam fractionation with either GAC or IX polishing, has generally not been implemented at the scale required to treat AOCs 2, 7, and 10. Use of foam fractionation to treat higher volumes of water may require novel design and implementation of the technology. For AOC's 2, 7, and 10, use of NF/RO ahead of SAFF® would reduce the volume of water requiring treatment by foam fractionation but could increase the risk of fouling or mineral precipitation in foam fractionation units, making Treatment Train 7 potentially less implementable than Treatment Train 6.

Treatment Train 5, which is only applicable for AOC 1, has the lowest technological readiness. Regenerative IX is not widely used, and many challenges still exist to implement regenerative IX due to limited installations and case studies available.

J3.8 Portion of PFAS Destroyed vs. Landfilled

Portion of PFAS destroyed versus landfilled is based on the assumption that IX resin is landfilled as opposed to incinerated due to high costs of incineration. These relative rankings would change, should

IX resin be incinerated or be destroyed through a destruction method like SCWO. These rankings also assume all GAC is reactivated, as the reactivation process strips PFAS from GAC and subsequently destroys PFAS in off-gas emissions treatment. IX still bottoms and foam fractionation concentrate are also assumed to be destroyed as opposed to landfilled. It should also be noted; this criterion is relevant to the mass of PFAS removed from water and is not estimated based on total starting mass. For example, Treatment Train 1 has a high ratio of destruction as all GAC would be reactivated and no waste streams are planned to be landfilled. However, Treatment Train 1 would not remove as much PFBA as a treatment train which utilized IX, so while almost all PFAS removed would be destroyed, not all PFAS would be removed.

All AOCs are discussed together, as appreciable differences are not expected between the AOCs. Treatment Trains 1, 5 (AOC 1 only), and 6 (GAC) would have the highest portion of PFAS destroyed. All PFAS removed would be removed by GAC in Treatment Train 1 and would be destroyed during reactivation. Some PFAS in Treatment Train 5 would be removed by GAC which would be utilized as a pre-filter ahead of the regenerable IX, which would undergo reactivation and subsequently the PFAS would be destroyed. The majority of the PFAS would be concentrated into the IX Still Bottoms waste stream, which could then undergo destruction. Treatment Train 6 would produce SAFF® concentrate, which could be sent to a destructive technology, and GAC used as polishing would be sent for reactivation, destroying PFAS. These three treatment trains would all have high ratio of PFAS destroyed.

Treatment Trains 7 and 6 (IX) would have the next highest ratios of PFAS destroyed vs. landfilled. Both treatment trains operate similarly, with production of a SAFF® concentrate stream that would be destroyed and polishing with IX resin that would be landfilled. Treatment Train 7 is expected to have superior SAFF® performance due to pre-concentration with NF/RO, increasing the portion of PFAS removed by SAFF® and decreasing the IX usage. Note that this assumption should be piloted prior to final treatment train selection.

The treatment trains with the lowest portion of PFAS destroyed would be Treatment Trains 4, 3, and 2. Treatment Trains 3 and 4 would be expected to have similar ratios, with the portion of PFAS removed by GAC destroyed during reactivation and the remainder of the PFAS that is removed by IX landfilled. Changeout frequency of GAC would determine how much is landfilled vs. incinerated, as more frequent GAC changeouts would result in less IX use and a higher portion of PFAS being destroyed. The lowest ratio would be with Treatment Train 2, which would see no destruction of PFAS as all PFAS would be removed by IX.

It should be noted; as additional work and investigation is performed on new ways to reuse GAC and IX media, there may be reuse or destruction options for IX resin that would destroy PFAS sorbed on IX resin that are cost competitive with landfilling. New technological developments should be monitored and evaluated for potential applicability. At this time though, landfilling is significantly cheaper than incineration, which is the only destruction option available at scale for IX resin.

J4 Applicable PFAS Destruction Technologies

Treatment technologies discussed in detail thus far in this appendix remove PFAS from water or concentrate it into a smaller volume. These technologies would produce treated water but generally do not destroy the removed PFAS. The ultimate goal of PFAS treatment is to destroy PFAS as opposed to simply moving it to a landfill or utilizing hazardous waste incinerations to destroy PFAS at high temperatures. A significant amount of work over the last few years has been focused on destruction technologies specific to PFAS, with multiple vendors and technologies close to providing full-scale solutions as of the writing of this report. Several destruction technologies were studied as part of this FS via a Request for Proposal, which utilized SAFF® concentrate from the SAFF® pilot testing performed as part of this FS. Results of the destruction testing are discussed in Appendix G.

J4.1 Description of Possible Destructive Technologies

PFAS destruction technologies that were evaluated in this FS were electrochemical oxidation, ultraviolet (UV) oxidation, reductive defluorination, plasma and SCWO. Landfilling and incineration, while disposal/destruction options, were not separately evaluated as they are currently in use and well understood. Table J.47 summarizes applicability and issues or considerations of destruction and disposal technologies.

Electrochemical oxidation destruction is accomplished using electrode (anode-cathode) pairs. Treatment is accomplished via direct oxidation at the anode surface and via radical species (e.g., hydroxyl). UV oxidation uses UV light to produce radical species that can break carbon-fluorine bonds and degrade PFAS. SCWO uses supercritical water (a state of matter that exists between liquid water and water vapor at a temperature of > 374°C and pressure of 3,200 pounds per square inch) to produce oxidative radicals that can break carbon-fluorine bonds and destroy PFAS. Plasma technology utilizes a high-voltage electrical discharge to produce radical species that can break carbon-fluorine bonds. Reductive defluorination utilizes photoactivated chemistry to reduce the PFAS (as opposed to oxidize). Further discussion of these technologies can be found in Appendix G. Destruction results varied, though all technologies demonstrated good removal of PFOA and PFOS. Reaction times varied considerably, and technologies are at various stages of development.

An additional technology that is recommended for consideration for full-scale treatment is HALT. HALT is a thermochemical process that operates at temperatures of 150 °C to 350°C, subcritical pressures, and an elevated pH typically > 13 (Pinkard, 2024). Recent work has demonstrated pilot-scale (1 gallon per hour) destruction of PFAS, including destruction of PFBA (Pinkard, 2024). Additional destruction technologies are in development but, at the time of preparation of this FS, are not far enough in development to be considered. Depending on when design and implementation occur, additional technologies may be considered at that time.

J4.2 Applicable Treatment Trains and Waste Streams

Current destruction technology is best suited for small volume, highly concentrated waste streams, as capacity and the required energy use are the biggest limiting factors for scale-up of destructive technologies. Various waste streams would be produced by the treatment trains that could utilize destruction technologies. Foam fractionation concentrate and still bottoms waste streams would be the most applicable, as they are both small volume, highly concentrated waste streams. While use of destructive technologies for GAC, IX, and NF/RO concentrate has been investigated, the scale of these technologies would not currently allow implementation of any onsite destructive technology for GAC, IX, or NF/RO concentrate.

Foam fractionation concentrate would be generated for Treatment Trains 6 (GAC & IX) and 7. Destruction of PFAS in SAFF® concentrate could be achieved with incineration, electrochemical oxidation, SCWO, HALT, reductive defluorination, or plasma. Testing with AOC specific concentrate would be needed to identify the best destructive option. IX still bottoms would be generated for Treatment Train 5 and would be specific to AOC 1. HALT has been shown to be effective for IX still bottoms (Pinkard, 2024), though other technologies should be tested as well if Treatment Train 5 were selected for further analysis.

Table J.47. Applicability and Issues or Considerations of Currently Available Destruction and Disposal Technologies.

Technology	Potential Waste Streams	Treatment Trains	Issues/Considerations
Landfill	IX Still Bottoms	5	Liquid waste stream, would require stabilization
	SAFF® Concentrate	6, 7	Liquid waste stream, would require stabilization
	GAC	1, 3, 4, 6 (GAC)	Reactivation preferable (destroys PFAS)
	IX Resin	2, 3, 4, 6 (IX), 7	
Incineration	IX Still Bottoms	5	High salt concentration may pose incineration issues
	SAFF® Concentrate	6, 7	
	GAC	1, 3, 4, 6 (GAC)	Reactivation preferable and less expensive
	IX Resin	2, 3, 4, 6 (IX), 7	Landfilling significantly cheaper but does not destroy PFAS
SCWO	IX Still Bottoms	5	High total dissolved solids may reduce treatment efficiency and cause operational issues
	SAFF® Concentrate	6, 7	
HALT	IX Still Bottoms	5	
	SAFF® Concentrate	6, 7	
Electrochemical Oxidation	IX Still Bottoms	5	High chloride levels could cause excessive perchlorate formation and may reduce treatment efficiency
	SAFF® Concentrate	6, 7	Better application to long chain destruction compared to short chain
Reductive Defluorination (UV)	IX Still Bottoms	5	Unsure if this technology has been tested with this concentrate and if the high total dissolved solids would reduce treatment efficiency
	SAFF® Concentrate	6, 7	NOM may reduce efficiency of treatment, and better application to long chain destruction compared to short chain
Plasma	IX Still Bottoms	5	Some plasma technologies use RO and the high salt concentrations could cause scaling on the RO membranes
	SAFF® Concentrate	6, 7	Better application to long chain destruction compared to short chain
UV Oxidation	IX Still Bottoms	5	
	SAFF® Concentrate	6, 7	High NOM concentrations may inhibit light penetration, decreasing effectiveness

J5 Recommendations

J5.1 AOC 1 (WCL)

After initial analysis of the treatment trains, Treatment Train 6 (IX) is recommended for additional analysis. This treatment train could offer the lowest cost option to remove PFAS from groundwater around WCL. However, there is uncertainty over the performance of foam fractionation specific to PFBA. Removal of long-chain PFAS is expected to be high, but a wide range of potential removal efficiencies have been suggested by different vendors. Further analysis of different vendors is needed prior to finalization of a recommended treatment train due to this uncertainty.

Treatment Trains 5 and 7 are also recommended for further consideration for AOC 1 should Treatment Train 6 (IX) be found to have limited PFBA removal. Treatment Train 5 would be recommended for the potential to decrease adsorptive media usage through re-use of IX media, though implementation challenges currently exist for this technology. Treatment Train 7 would be recommended as NF/RO may help to improve foam fractionation performance.

Treatment trains that are absorbent media based (Treatment Trains 1, 2, 3, and 4) are not recommended for further consideration due to extremely high media usage from high concentrations of PFBA in AOC 1. Treatment Train 6 (GAC) is similarly not recommended due to the high GAC usage expected in order to polish PFBA remaining in foam fractionation effluent. Final selection of a treatment train will likely hinge on the ability of a particular treatment train to remove PFBA. Table J.48 summarizes treatment train recommendations by AOC

Table J.48: Summary of Treatment Train Recommendations by AOC.

Treatment Train	Technology	Recommended?	
		AOC 1	AOCs 2, 7, &10
Treatment Train 1	GAC	N	N
Treatment Train 2	IX	N	N*
Treatment Train 3	GAC + IX	N	Y
Treatment Train 4	NF/RO to GAC + IX	N	N*
Treatment Train 5	Regenerable IX	Y	N/A
Treatment Train 6	FF to GAC	N	N
	FF to IX	Y	Y
Treatment Train 7	NF/RO to FF + IX	Y	N*

Legend: N = not recommended; N* = not recommended at this time but may be recommended in the future; N/A = not applicable; Y = yes recommended.

J5.2 AOCs 2, 7, and 10

For AOCs 2, 7, and 10, a modified Treatment Train 3 and Treatment Train 6 (IX) are recommended for further consideration.

A modified Treatment Train 3 would include a single sacrificial GAC vessel with lead/lag IX vessels as opposed to lead/lag GAC followed by lead/lag IX. Use of a sacrificial GAC vessel would protect the IX resin by removing non-PFAS contaminants from groundwater that can foul IX resin, extending the IX resin life. A sacrificial GAC vessel could also utilize higher loading rates, decreasing the size of vessel needed for treatment. In this arrangement, a GAC change out would not occur when PFAS breakthrough is observed but would instead occur when the pressure drop across the vessel became too high or when removal of total organic carbon was no longer sufficient. This treatment train would have the least operational demands and would require the least amount of operational oversight.

Treatment Train 6 (IX) is recommended due to the potential for significantly reduced adsorptive media usage. As short-chain PFAS are not expected to be triggers for media changeouts in AOCs 2, 7, and 10, foam fractionation is expected to remove a majority of the PFAS of concern. This is expected to drastically reduce the use of IX media. Additionally, foam fractionation would generate a PFAS concentrate stream that would be ideal for destruction with technologies including but not limited to SCWO and HALT. This would create an opportunity to destroy PFAS as opposed to transferring it to a different media which requires further destruction or disposal. While the CAPEX estimates for Treatment Train 6 (IX) in this analysis are high, additional foam fractionation technologies are now available which may reduce the costs from those estimated for SAFF®. Further analysis from additional vendors may result in lower CAPEX estimates.

Due to higher complexity of operations and higher energy inputs, NF/RO treatment trains (Treatment Train 4 and Treatment Train 7) are not recommended for further analysis at this time. However, should the scale of foam fractionation equipment required in Alternative 6 (IX) become cost prohibitive, use of NF/RO ahead of foam fractionation should be reevaluated. Similarly, should foam fractionation performance be worse than expected, NF/RO ahead of foam fractionation should be reconsidered to increase PFAS concentration and potentially improve foam fractionation performance. Additionally, should bench-testing indicate GAC is not required ahead of IX to extend IX lifetime, Treatment Train 2 would then be recommended.

Treatment Train 1 is not recommended for further consideration due to the much shorter GAC specific throughputs observed in treatability testing. Treatment Train 5 was not considered for AOCs 2, 7, and 10 due to comparatively low levels of PFAS and would not be expected to be economically feasible. Treatment Train 6 (GAC) was screened out due to the size of plant required to treat these AOCs and the performance of GAC observed in the treatability testing. Table J.48 summarizes recommended and not recommended treatment trains.

J5.3 Phased Implementation

As discussed in the introduction, a phased implementation schedule could be pursued with any of the Remedial Alternatives considered in the FS. Section 14 of the FS discusses phasing in greater detail, particularly with regard to phasing implementation of multiple remedies (e.g. if multiple remedies including access restrictions, source zone control, in-stream permeable adsorptive barriers, pump and treat systems across the Site, and/or a Multi-Benefit Well Array were pursued). Specific to pump and treat systems, there are several options for how treatment system construction and implementation could be phased.

For AOC 1 (shallow WCL groundwater impacts), a pump and treat system is expected to need nine or more wells to capture contaminated shallow groundwater. Treatment at WCL could be phased to target the most contaminated areas first, along with construction of a treatment plant with smaller capacity. Additional wells along with increased treatment capacity could then be installed at a later date. However, it must be noted that a phased implementation at WCL would lead to less source zone control initially and would be expected to increase overall project costs.

For AOCs 2, 7, and 10, a phased approach could be taken to separate out treatment at different areas of the groundwater plume. The most straightforward way to phase in treatment would be to install a pump and treat system in one area (either AOCs 2 & 7 or AOC 10), and then later install wells and potentially a treatment system in the other area. This could be pursued regardless of whether a single, larger treatment plant was selected, or whether two separate treatment plants were installed.

J6 Next Steps

J6.1 AOC 1 (WCL)

Before a final treatment train can be selected for implementation at the WCL, additional remedial investigations and treatability studies are needed. Recommended further investigation includes delineation of soil impacts, vertical and horizontal delineation of the groundwater plume, and pumping tests. These are discussed more in Section 14 of the FS. Additional treatability studies are also recommended, as described below, to evaluate the ability of specific technologies to treat the significantly higher levels of PFAS, specifically PFOA and PFBA, that are present in the groundwater. The findings of these studies and a technology recommendation could be completed in a proposed focused feasibility study on the WCL to resolve outstanding questions surrounding treatment at the landfill.

Foam fractionation is recommended based on the pilot study conducted as part of this FS and improvements made to the technology that have shown improved short-chain PFAS removal at other sites. Additionally, other foam fractionation vendors have brought technologies to market since the initial Request for Proposal for the foam fractionation work performed as part of this FS that may also have improved PFBA removal efficiencies compared to the SAFF®. To evaluate other foam fractionation vendors, bench scale studies can be performed as a low-cost way to evaluate other foam fractionation vendors with groundwater from the WCL to determine which vendors and surfactants could enhance PFBA removal. Vendors typically offer bench-scale testing as an initial evaluation of their technology at a price substantially cheaper than an on-site pilot (generally on the order of $20,000 for a bench test). However, limiting the evaluation to bench-scale studies does limit the understanding of operations and maintenance and evaluating removal at a larger scale. Moving the SAFF® to the WCL would allow for this evaluation. Operational changes are proposed as well, including improved air injection and addition of surfactants to increase short-chain PFAS removal.

As it is likely that any foam fractionation system will require adsorbent media polishing, additional RSSCTs are recommended, whether or not the bench- or pilot-scale testing are completed, to evaluate the IX media usage and determine the optimal media for removing the PFBA dominant PFAS mixture. This will aid in the costing and overall evaluation of this treatment train.

Should foam fractionation prove to be insufficient to remove PFBA, an RO pilot would be recommended. RO could either be used to pre-concentrate ahead of a foam fractionation step (i.e. Treatment Train 7) or could potentially be used as a polishing step after foam fractionation. Use of RO to polish foam fractionation effluent would reduce the size of the treatment stream requiring further treatment. Additionally, should foam fractionation be unsuccessful, regenerative IX should be further evaluated. While there are operational concerns over a regenerative IX facility, regenerative IX would likely reduce media consumption and remove PFBA to required effluent limits.

Piloting will be critical for testing performance of treatment trains prior to full-scale design and implementation. Piloting will provide valuable insight into system performance and lead to improved costs estimates. Additionally, piloting would also generate waste streams that require disposal (WCL-specific SAFF® effluent, spent IX resin, potentially spent GAC or RO concentrate), allowing for evaluation of destruction technologies and improved cost estimates for waste disposal.

J6.2 AOCs 2, 7, and 10

Should a Remedial Alternative with a pump and treat system in AOCs 2, 7, and/or 10 be pursued, further evaluation would be needed for selecting a remedial alternative. Similar to AOC 1, a focused feasibility study is recommended to better evaluate the pump and treat technology for treatment in AOCs 2, 7, and 10. Evaluation of the following is recommended:

- Additional IX RSSCTs to test to media breakthrough from more areas of the Site as IX did not breakthrough in all RSSCTs. Only groundwater from AOC 7 was evaluated in the RSSCTs completed to-date.
- Evaluation of pre-treatment during RSSCTs to determine if GAC is required ahead of IX to extend media life or if GAC can be removed from the design.
- Search for available land to determine potential plant locations and the size of treatment plant that could be built at each location.
- Determination of number of treatment plants to be built (i.e. one larger plant or two smaller plants)
- Reevaluate the well network and pumping rates, especially in AOC 2, based on updates to the conceptual site model in this area to ensure maximum PFAS capture and optimization of the pipe network to minimize overall project costs.
- Work with foam fractionation vendors to understand the potential issues, limitations, and costs with constructing and operating larger treatment plants. This is needed because these proposed treatment plant capacities are above the capacities of foam fractionation systems currently in operation.

Use of a focused FS would help to optimize the remedial treatment system installed for treated groundwater from AOCs 2, 7, and 10.

J7 References

American Water Works Association (AWWA), 2019. Per- and Polyfluoroalkyl Substances (PFAS) Treatment. August 12, 2019. Available: https://www.awwa.org/Portals/0/AWWA/ETS/Resources/Per-andPolyfluoroalkylSubstances(PFAS)-Treatment.pdf?ver=2019-08-14-090249-580.

DiStefano, R., Feliciano, T., Mimna, R.A., Redding, A.M., Matthis, J., 2022. Thermal destruction of PFAS during full-scale reactivation of PFAS-laden granular activated carbon. Remediation. 32, 213-238.

EPOC Enviro (EPOC), 2024. SAFF® Applications: Groundwater. Available: https://epocenviro.com/applications/groundwater/.

Health Research, Inc. Recommended Standards for Wastewater Facilities. Policies for the Design, Review, and Approval of Plans and Specifications for Wastewater Collection and Treatment Facilities 2014 Edition. Available: 10 States Standards - Recommended Standards for Wastewater Facilities.

Interstate Technology Regulatory Council (ITRC), 2023. PFAS Technical and Regulatory Guidance Document. September 2023. Available: https://pfas-1.itrcweb.org/.

Metropolitan Council Environmental Services (MCES), 2024. MCES Industrial User Rates and Fees: 2024 Rates and Fees. Available: https://metrocouncil.org/getattachment/Wastewater-Water/Services/Industrial-Waste/Industrial-Waste-Rates-Fees/2024-Final-IndustrialUserRatesandFees.pdf.aspx?lang=en-US.

Pinkard, B., Smith, S.M., Vorarath, P., Smrz, T., Schmick, S., Dressel, L., Bryan, C., Czerski, M., de Marne, A., Halevi, A., Thomsen, C., Woodruff, C., 2024. Degradation and Defluorination of Ultra Short-, Short-, and Long-Chain PFASs in High Total Dissolved Solids Solutions by Hydrothermal Alkaline Treatment - Closing the Fluorine Mass Balance. ACS EST Engg, https://doi.org/10.1021/acsestengg.4c00378.

J8 Figures

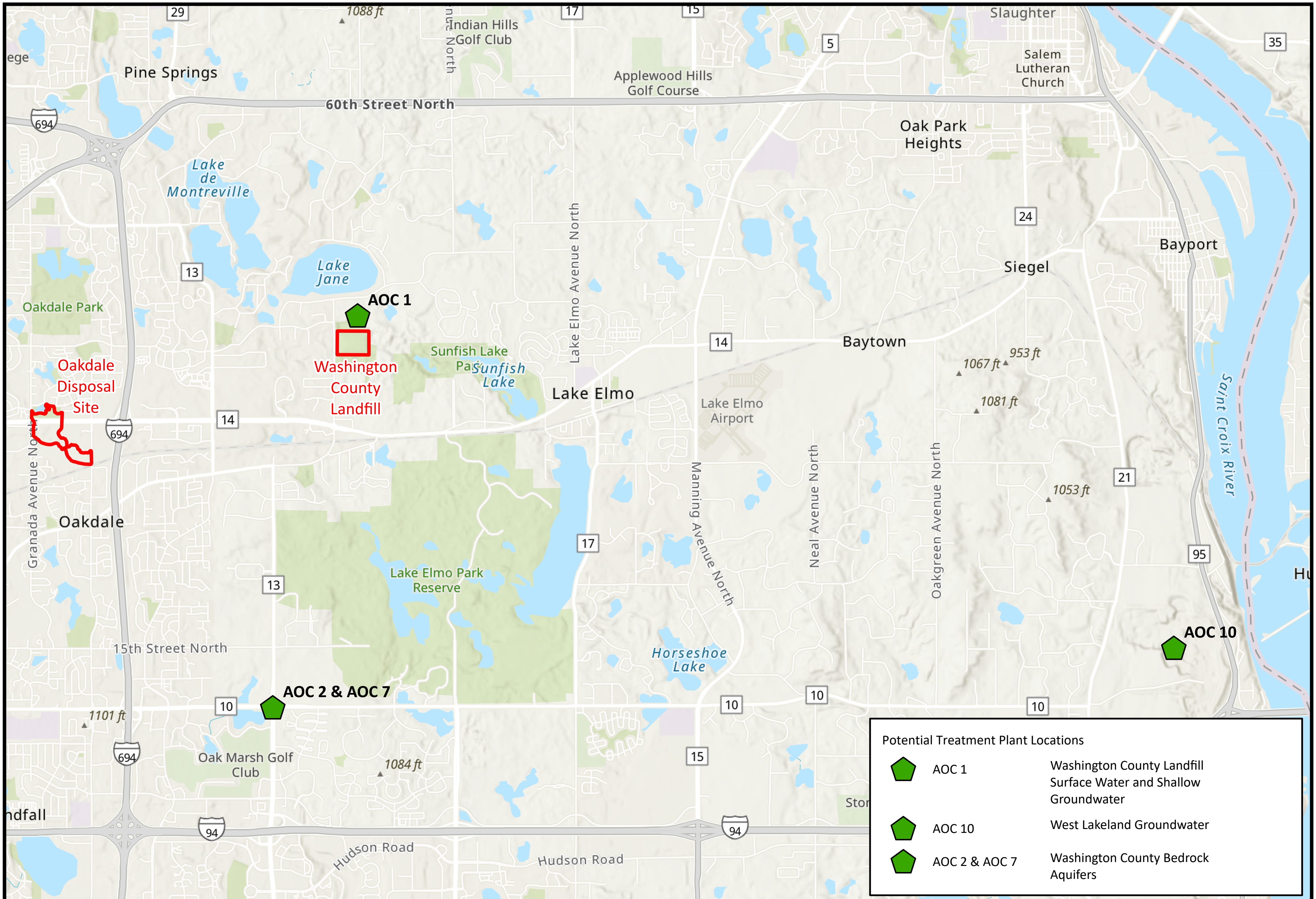

Figure J.1: Pump & Treat Potential Treatment Plant Locations
Project 1007 Feasibility Study

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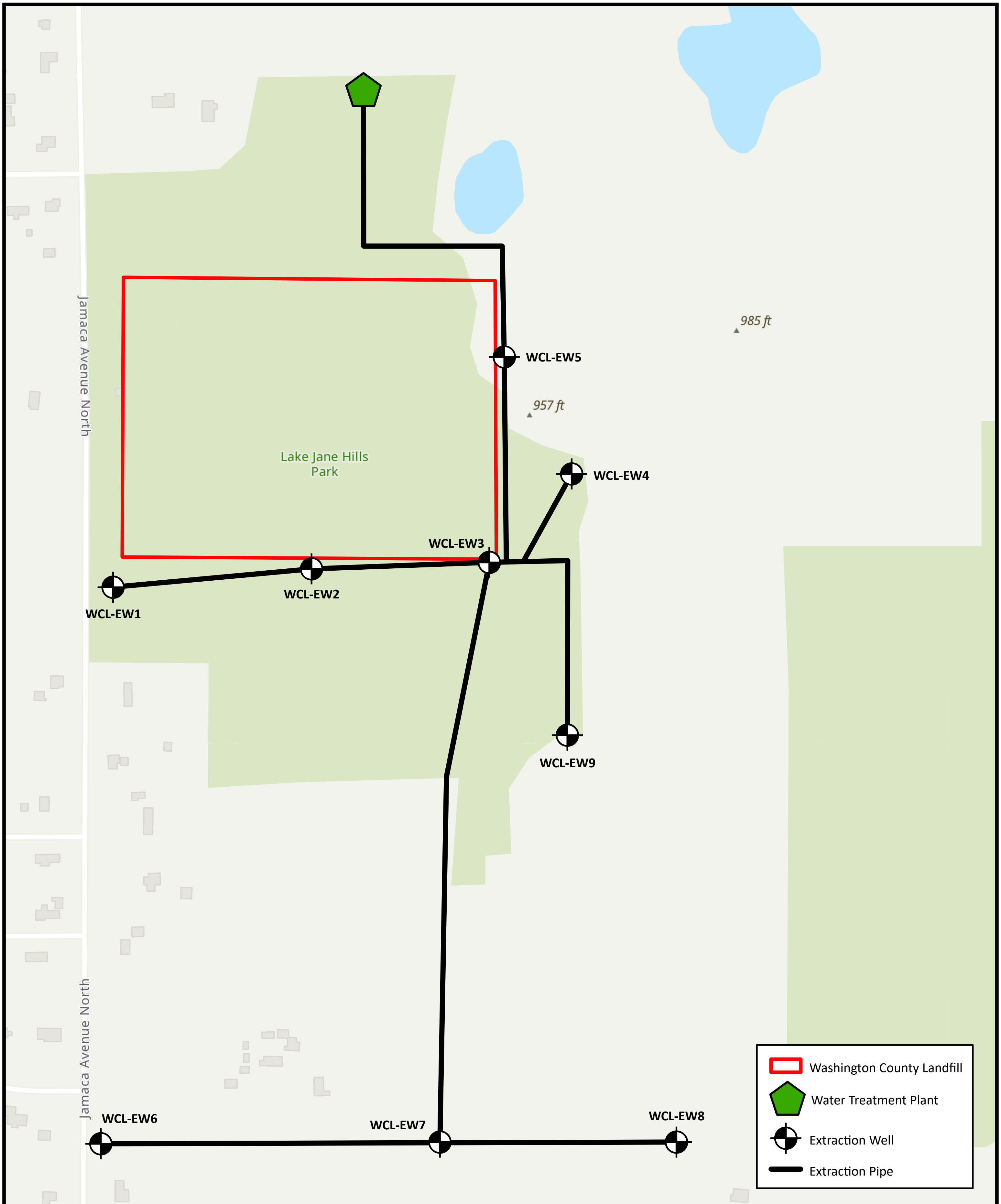

Figure J.2: 500 gpm - Washington County Landfill Extraction Well Network
Project 1007 Feasibility Study

0 0.1 0.2 Miles

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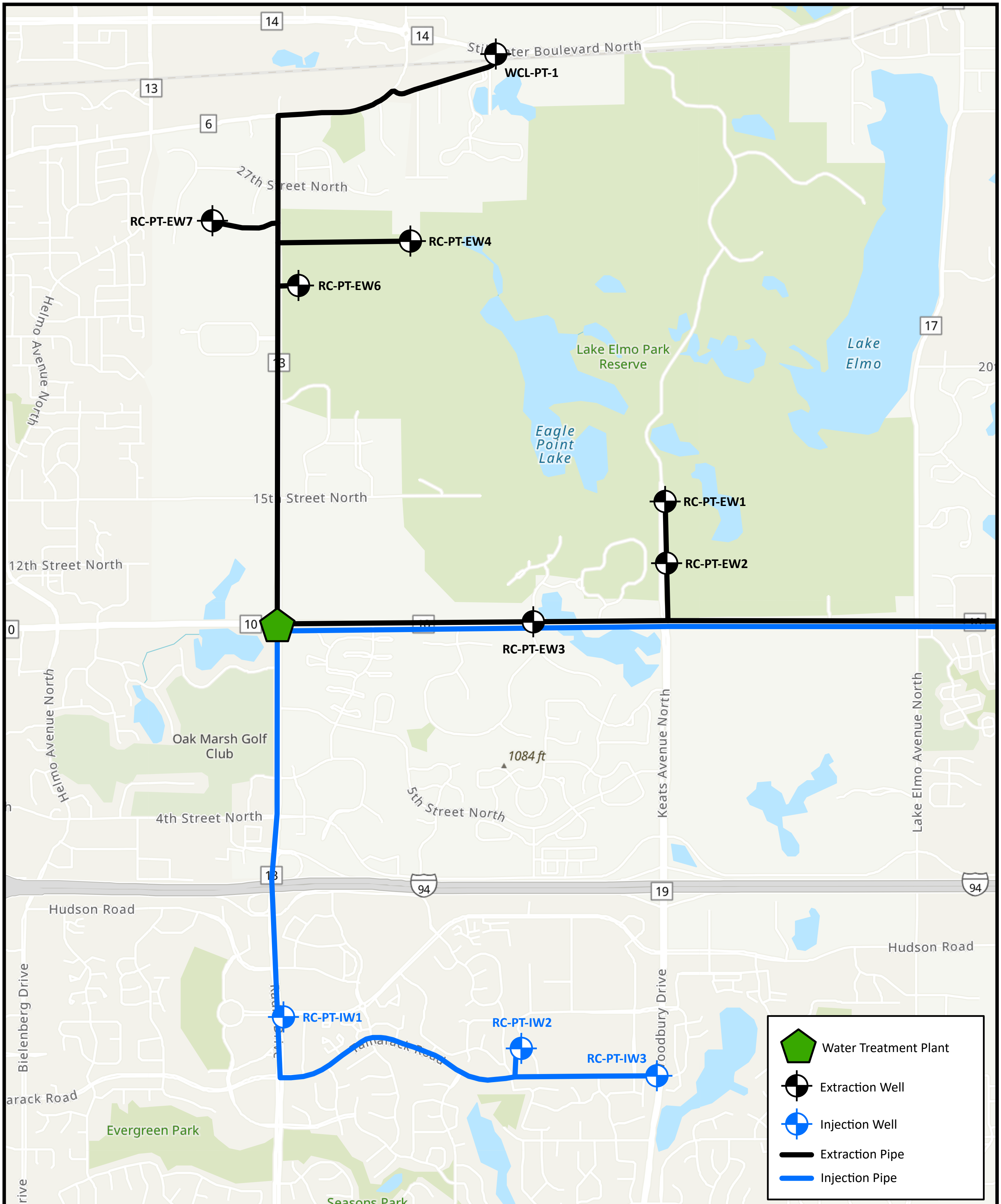

Figure J.3: 2,000 gpm - Raleigh Creek & Eagle Point Lake Extraction & Injection Well Network

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0 0.5 1 Miles

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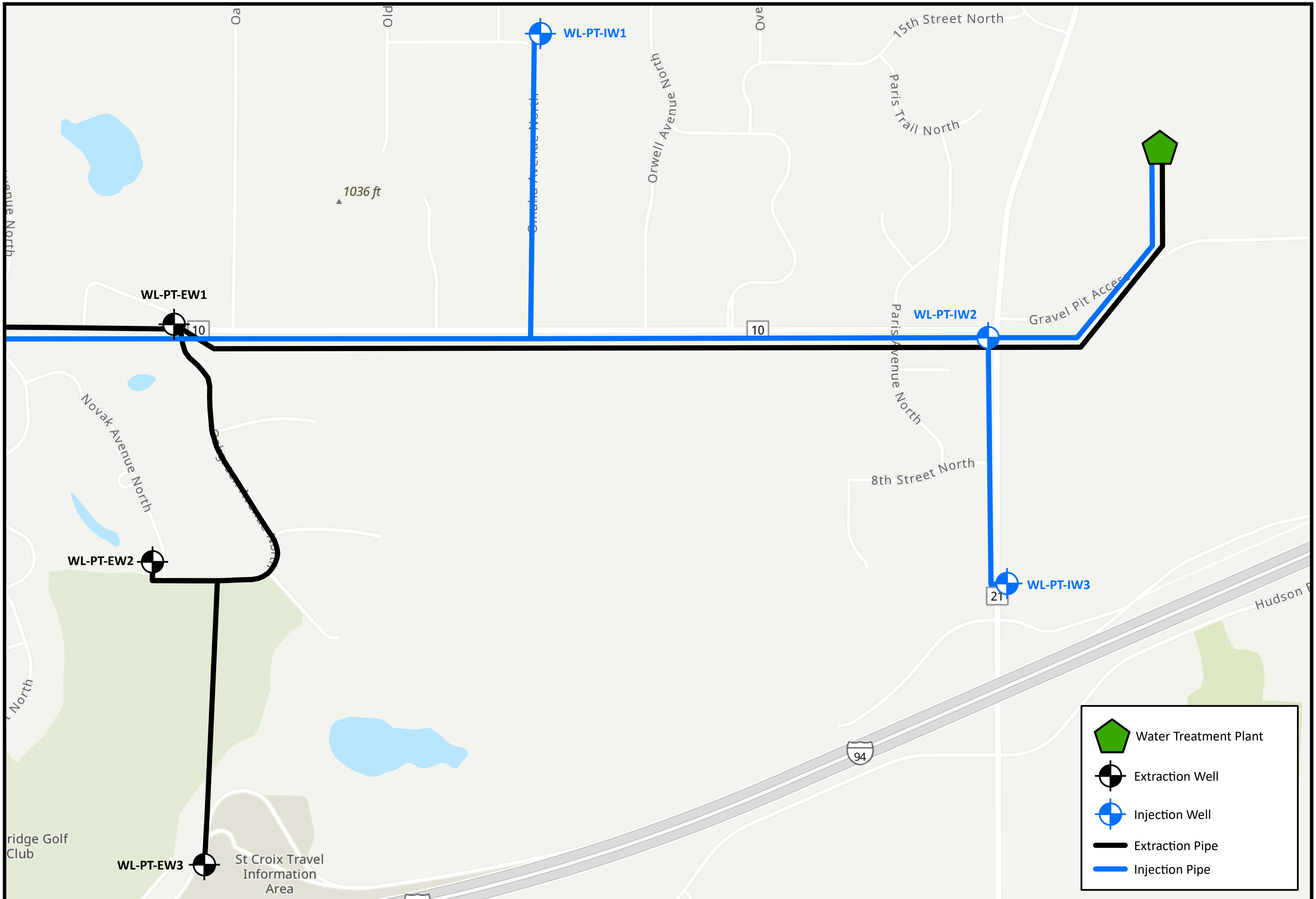

Figure J.4: 2,000 gpm - West Lakeland Extraction & Injection Well Network

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0 0.25 0.5 Miles

N

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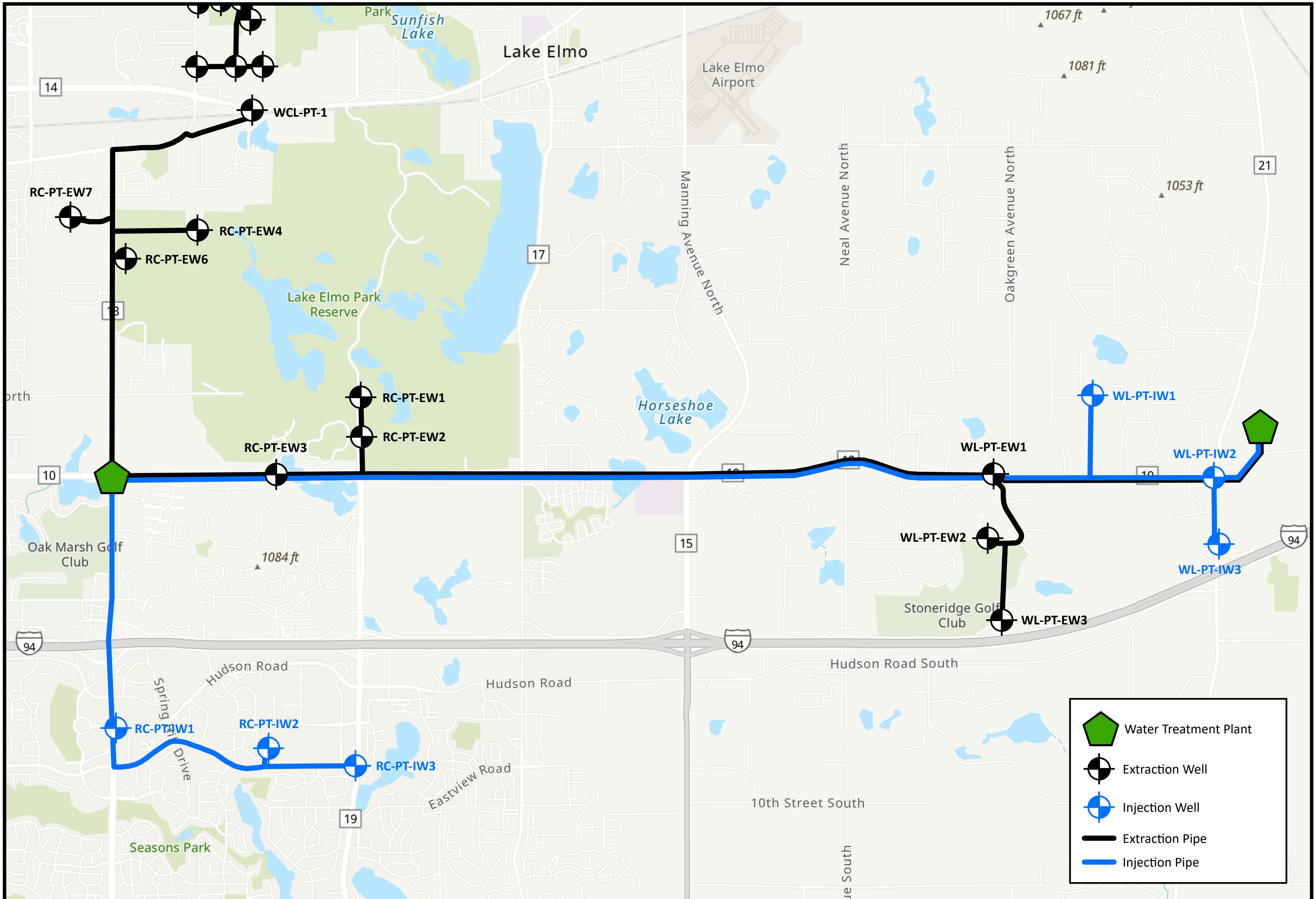

Figure J.5: 5,000 gpm - Raleigh Creek, Eagle Point Lake, & West Lakeland Extraction & Injection Well Network

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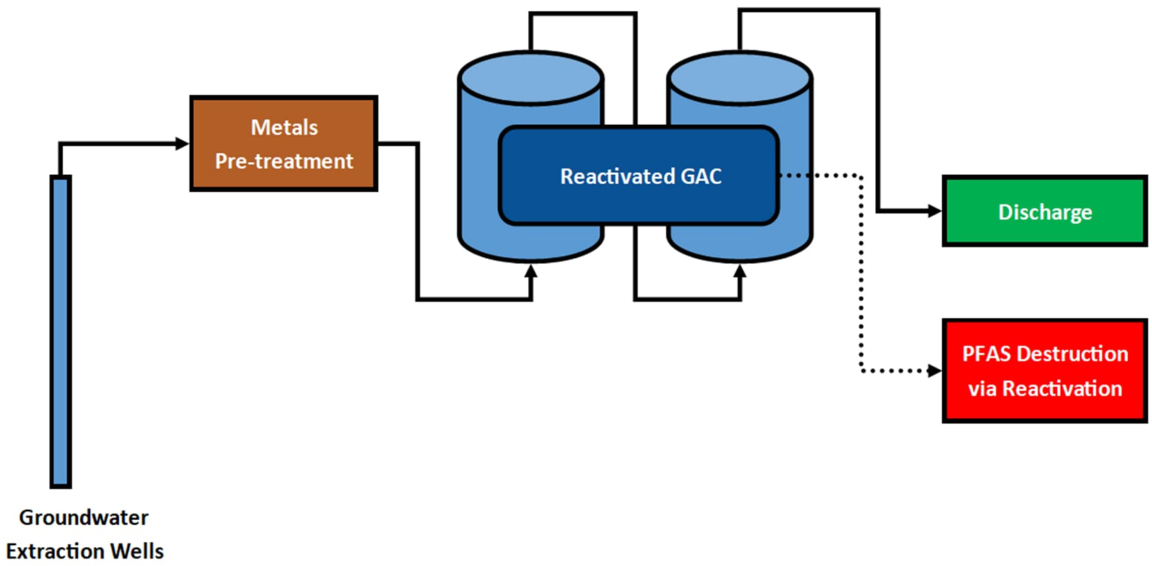

Figure J.6: Treatment Train 1 Conceptual Process Flow Diagram.

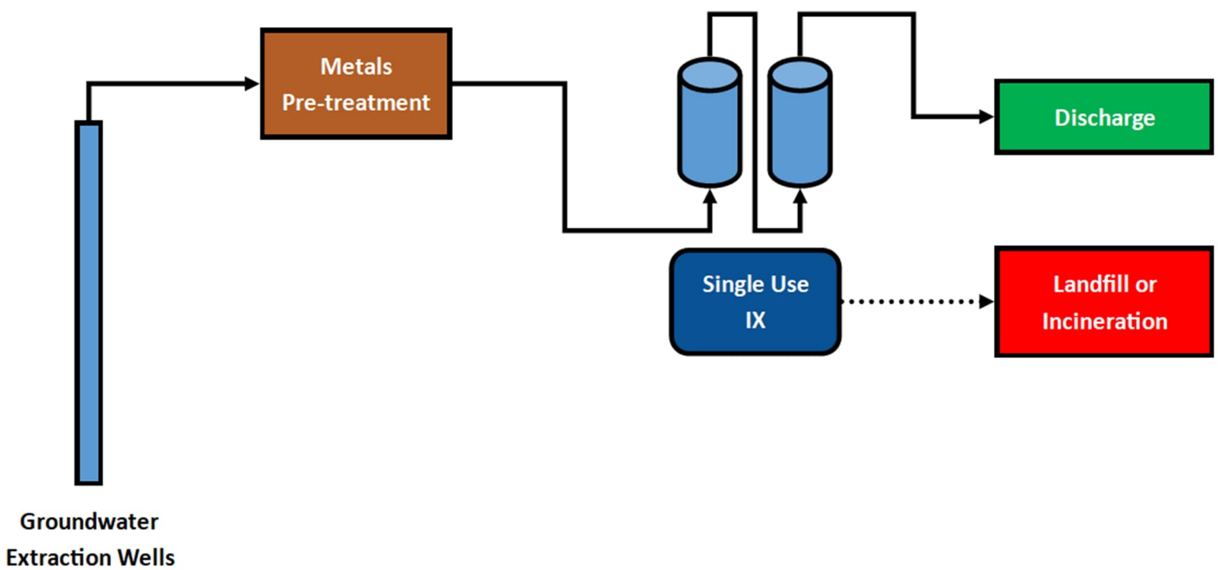

Figure J.7: Treatment Train 2 Conceptual Process Flow Diagram.

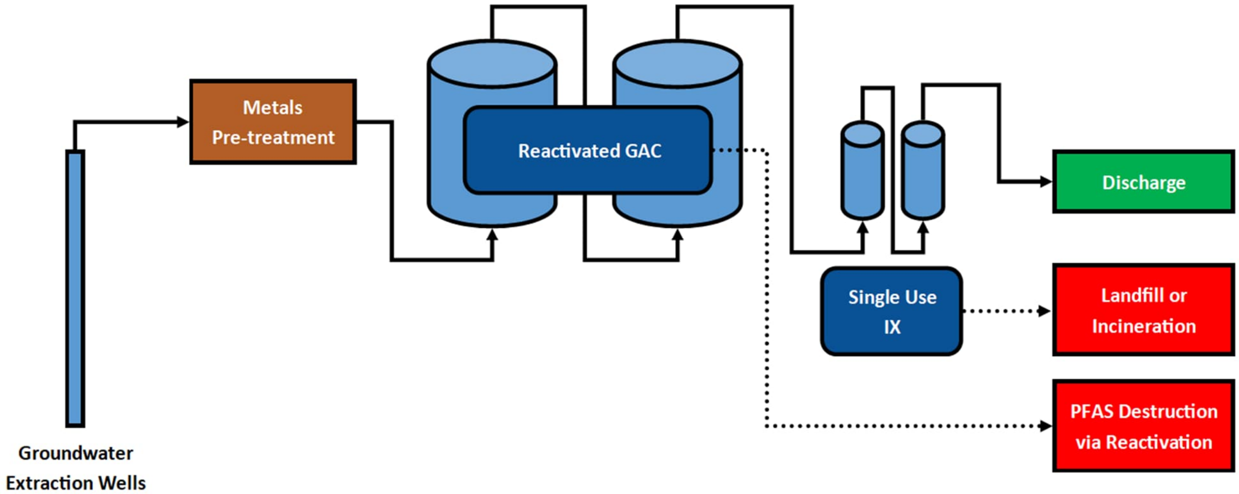

Figure J.8: Treatment Train 3 Conceptual Process Flow Diagram.

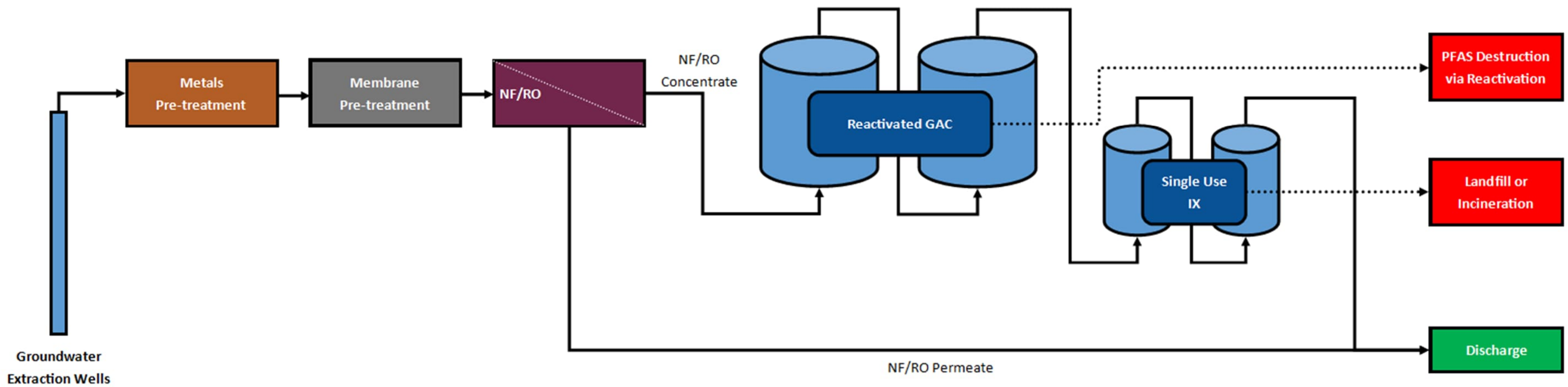

Figure J.9: Treatment Train 4 Conceptual Process Flow Diagram.

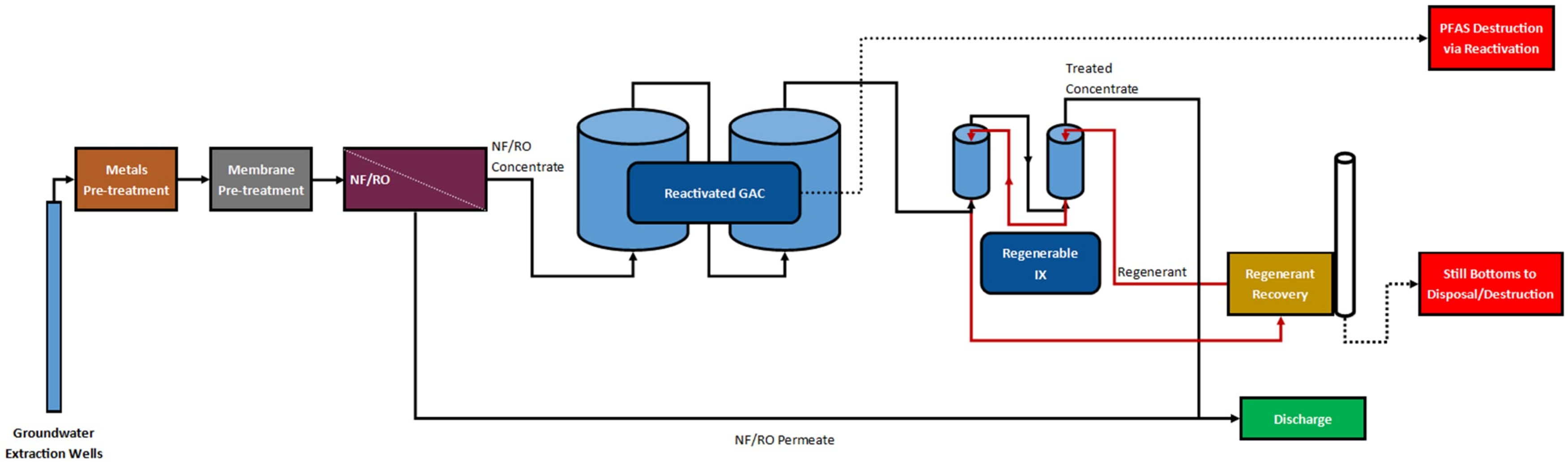

Figure J.10: Treatment Train 5 Conceptual Process Flow Diagram.

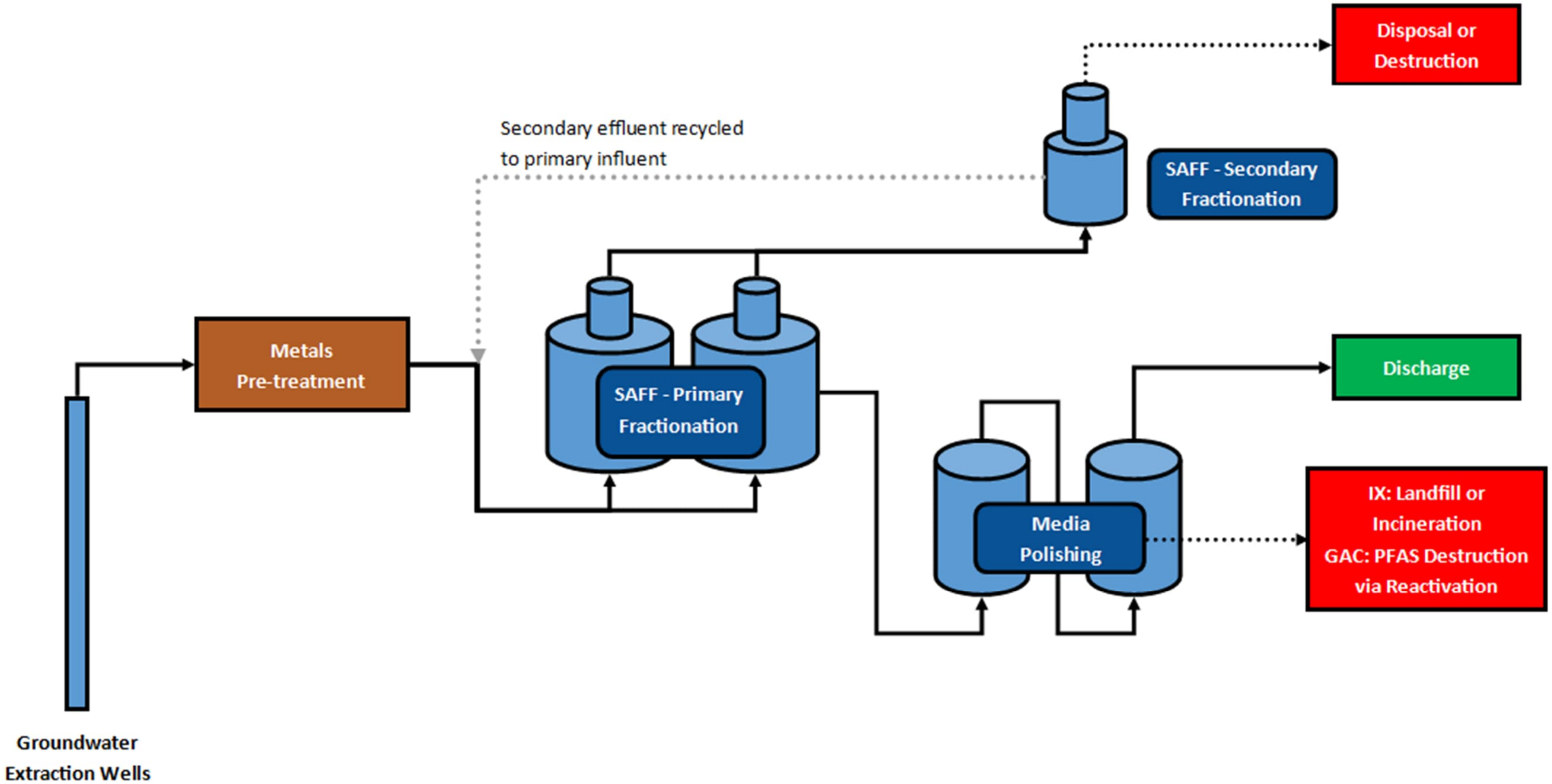

Figure J.11: Treatment Train 6 Conceptual Process Flow Diagram Using SAFF® as the Foam Fractionation Technology.

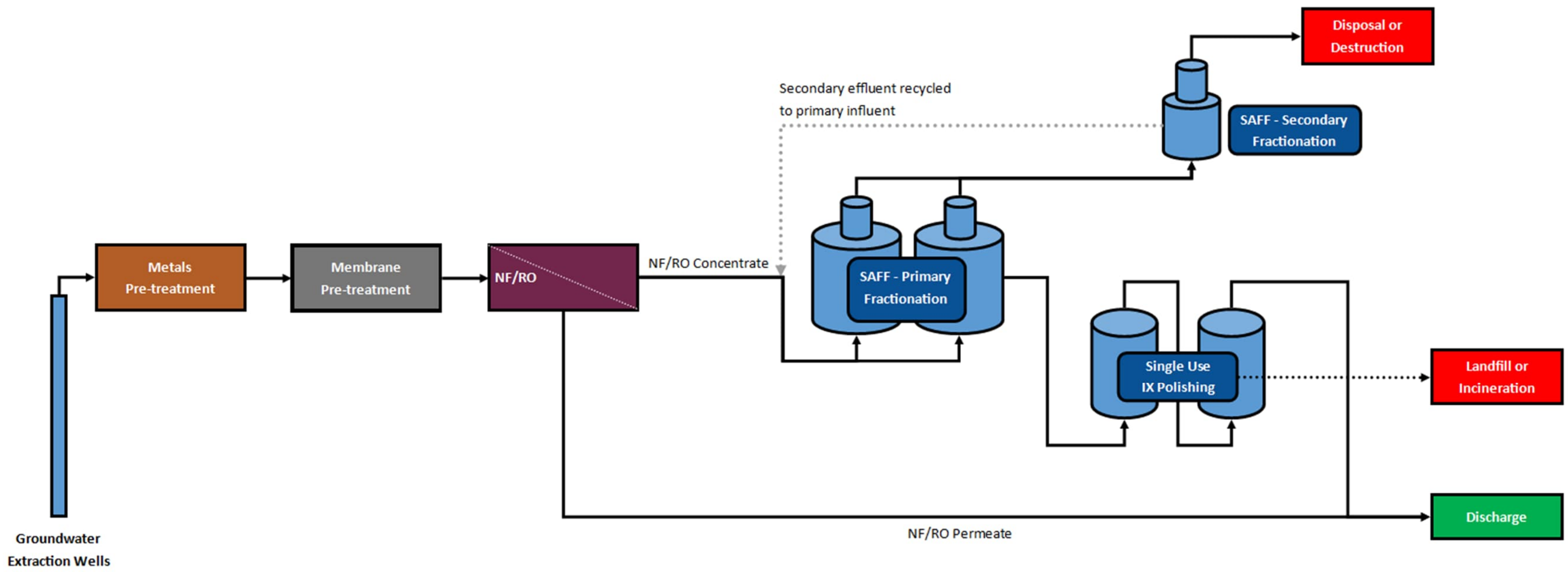

Figure J.12: Treatment train 7 Conceptual Process Flow Diagram Using SAFF® as the Foam Fractionation Technology.

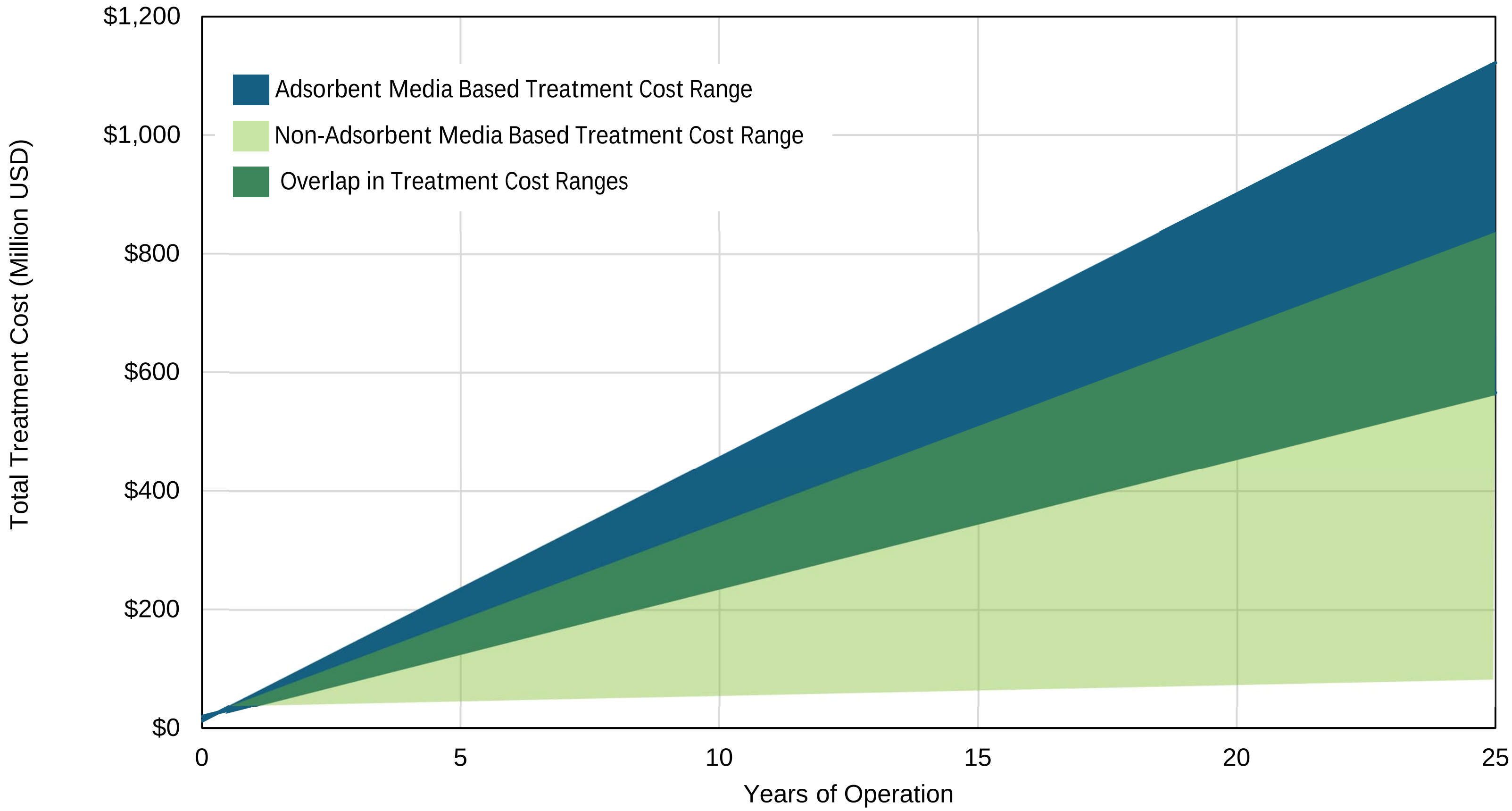

Figure J.13: Adsorbent and Non-Adsorbent Based Treatment Cost Ranges for AOC 1 (WCL).

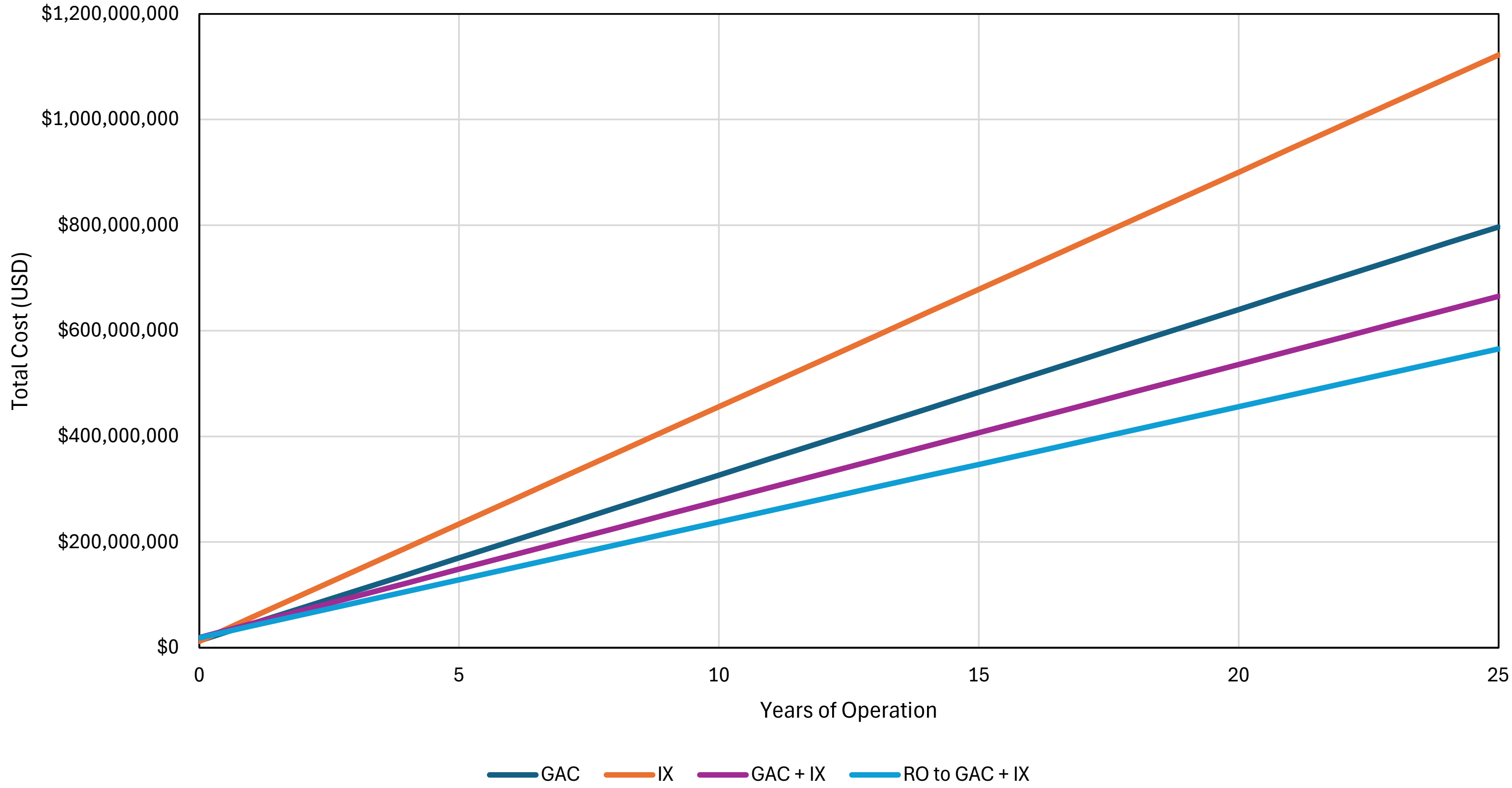

Figure J.14: 25 Year Operating Costs of AOC 1 (WCL) Absorbent Media Based Treatment Trains.

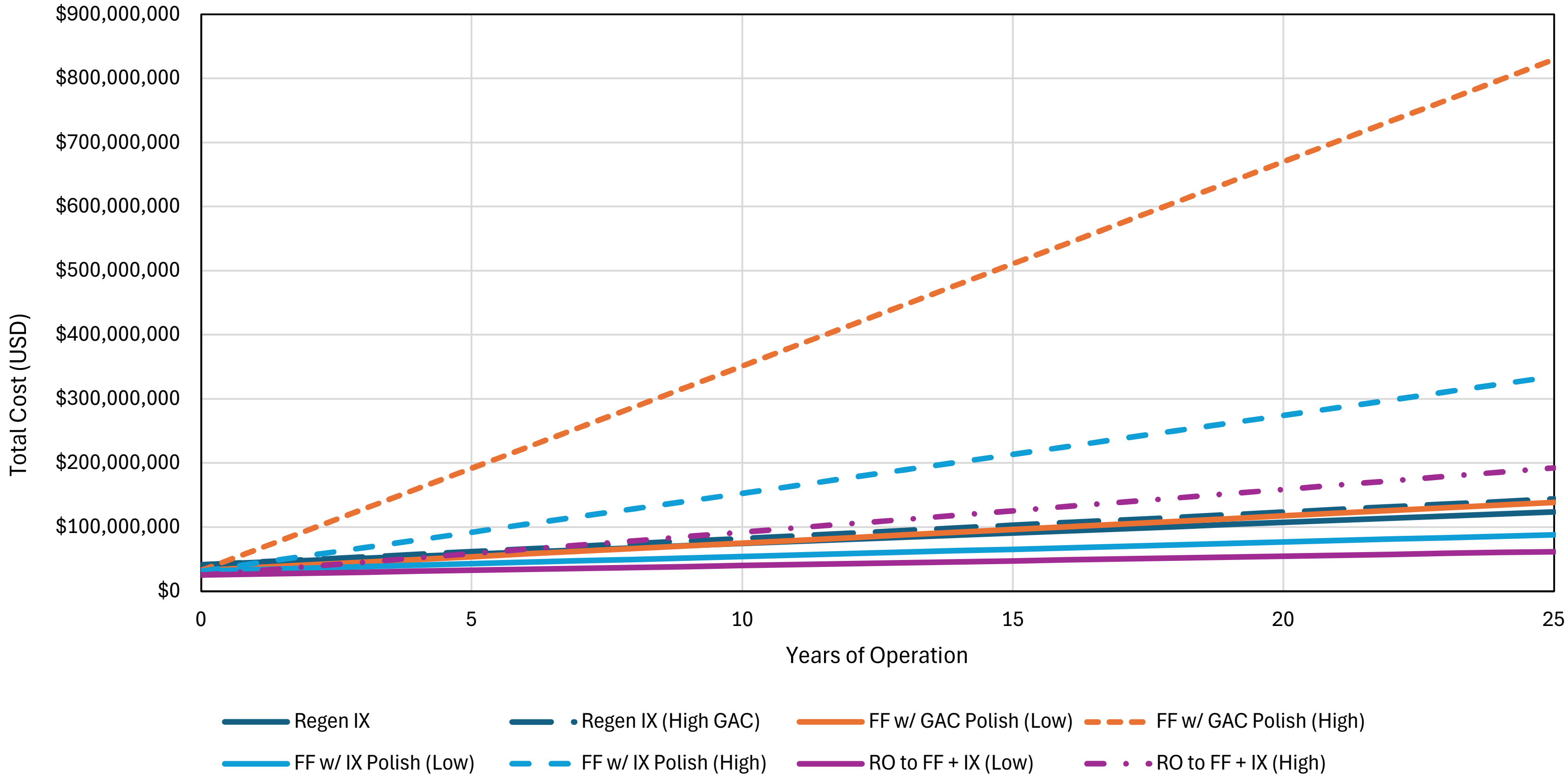

Figure J.15: 25 Year Operating Costs of AOC 1 (WCL) Non-Absorbent Media Based Treatment Trains. (1)

(1) Cost uncertainty shown as a range for non-adsorbent media treatment trains due to uncertainty in technology performance.

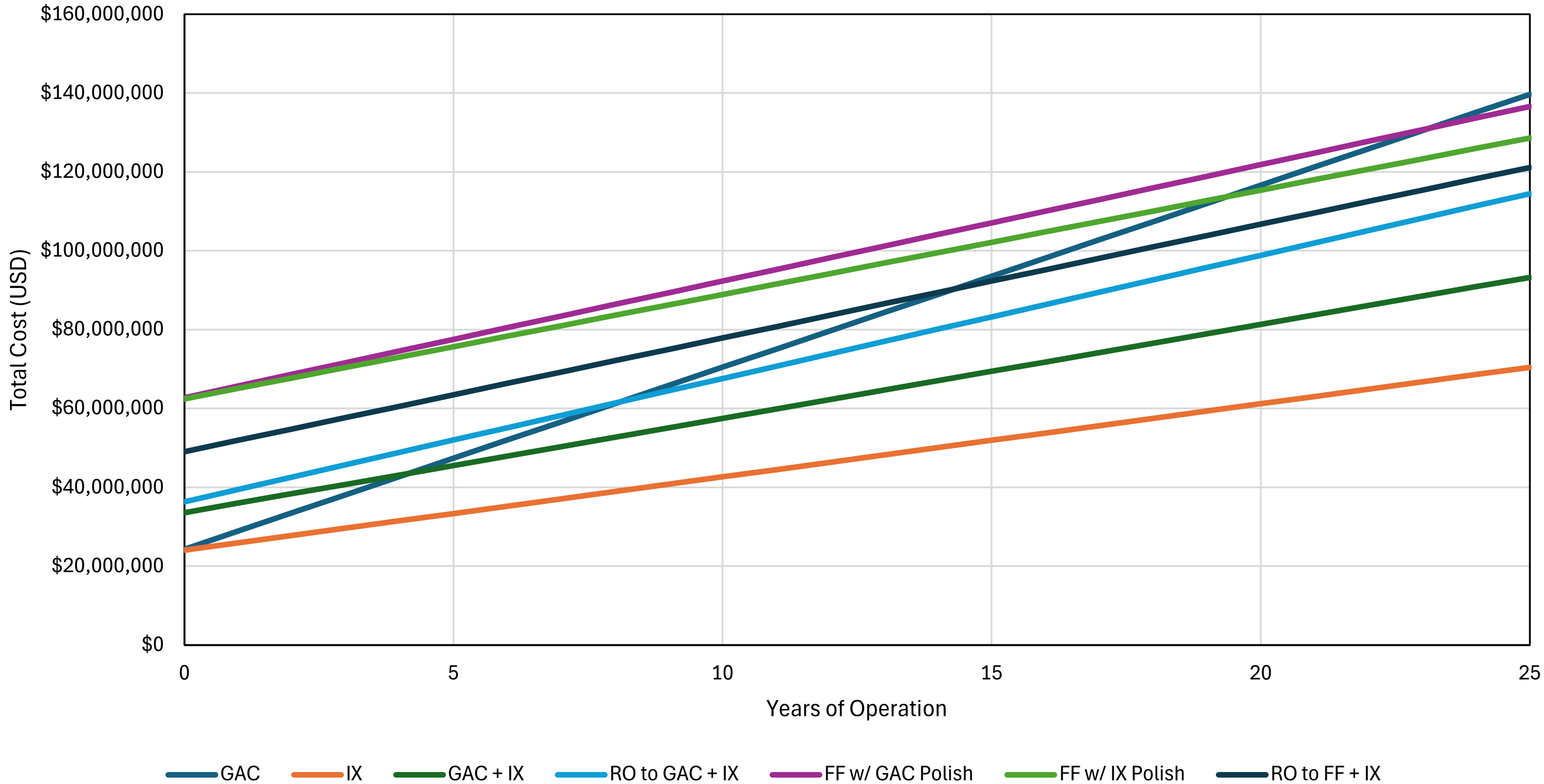

Figure J.16: 25 Year Operating Costs of a 2,000-gpm (AOCs 2 and 7 or AOC 10) Treatment Plant.

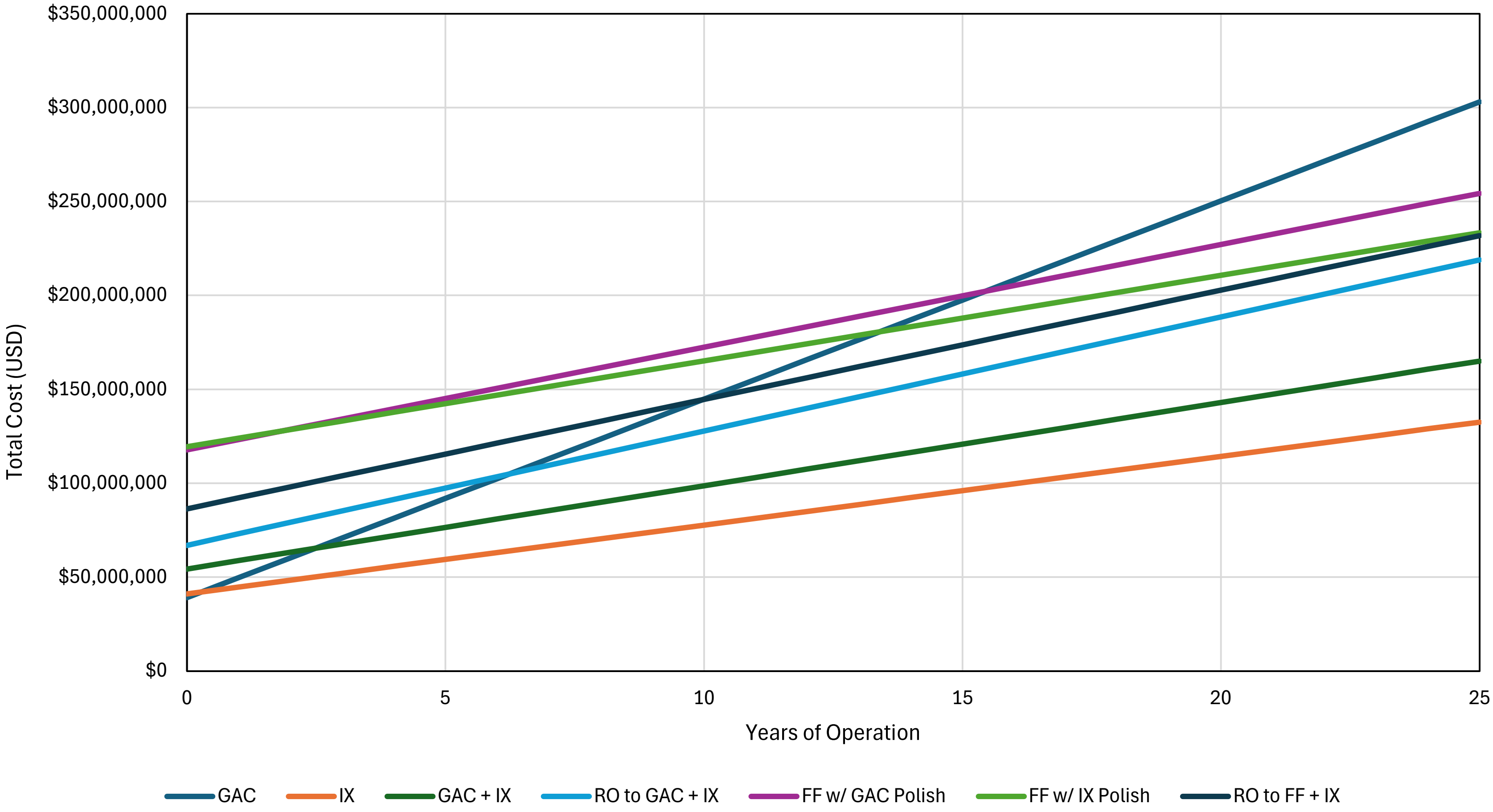

Figure J.17: 25 Year Operating Costs of a 5,000-gpm (AOCs 2, 7, and 10) Treatment Plant.

J9 Additional Tables

Table J.49: Washington County Landfill (AOC 1) Specific Throughput Estimates by Treatment Train.

Treatment Train	Media	Specific Throughput	Specific Throughput Assumptions
Treatment Train 1	GAC	15 gal/lb	Assumes GAC life of 1/5 IX resin based on other RSSCTs.
Treatment Train 2	IX	75 gal/lb	Breakthrough of PFBA at 7,000 ng/L back calculated directly from RSSCT results.
Treatment Train 3	GAC	150 gal/lb	GAC changeouts based on PFOA breakthrough in RSSCT.
	IX	151 gal/lb	Assumes IX resin life in TT2 doubled by initial treatment with GAC.
Treatment Train 4	GAC	47 gal/lb	At 75% recovery, PFAS concentration is 4x initial. Assume 25% increase in specific throughput from improved sorption isotherms and ¼ media life due to increased PFAS concentration compared to TT3.
	IX	47 gal/lb	
Treatment Train 5	GAC	N/A	Assumes GAC is only required as a sacrificial pretreatment (i.e. only there to protect IX resin from other foulants).
	High GAC [(1)]	120 gal/lb	Assumes 1000 L/kg specific throughput, but this may be an overestimate as breakthrough was too rapid during RSSCTs to calculate an accurate media life. RSSCTs/further testing would be required.
Treatment Train 6	High GAC	30 gal/lb	Assumes minimal PFBA removal, GAC throughput doubled compared to TT1.
	Low GAC	300 gal/lb	Assumes substantial PFBA removal; 10x throughput compared to TT6 High GAC.
	High IX	302 gal/lb	Assumes minimal PFBA removal, 4x media life compared to TT2.
	Low IX	3,020 gal/lb	Assumes substantial PFBA removal, 10x media life compared to TT6 High IX.
Treatment Train 7	Low IX	189 gal/lb	Assumes minimal PFBA removal, 4x media life compared to TT4.
	High IX	1,887 gal/lb	Assumes substantial PFBA removal, 10x media life compared to TT7 High IX.

(1) Treatment Train 5 may require GAC ahead of regenerable IX resin to protect the IX resin from long-chain PFAS, should long-chain PFAS desorption not be observed during regeneration.

Table J.50: Raleigh Creek/Eagle Point Lake Bedrock Aquifers and West Lakeland (AOCs 2, 7, and 10) Specific Throughput Estimates by Treatment Train.

Treatment Train	Media	Specific Throughput	**Specific Throughput Assumptions** (1)
Treatment Train 1	GAC	523 gal/lb	Shorter RSSCT life of two aquifers tested used as reactivated GAC will breakthrough faster than virgin GAC.
Treatment Train 2	IX	18,342 gal/lb	Resin life based on longer RSSCT results (153,068 L/kg) – assumes bed life optimized. (2)
Treatment Train 3	GAC	5,991 gal/lb	GAC mainly used to protect IX, changeout at 50,000 L/kg (close total bed exhaustion in RSSCT).
	IX	23,966 gal/lb	Assume IX resin life is increased to 200,000 L/kg with use of GAC.
Treatment Train 4	GAC	1,872 gal/lb	At 75% recovery, PFAS concentration is 4x initial. Assume 25% increase in specific throughput from improved sorption isotherms and ¼ media life due to increased PFAS concentration compared to TT3.
	IX	7,489 gal/lb	
Treatment Train 6	GAC	3107 gal/lb	From SAFF® treated RSSCT; breakthrough of PFOA used.
	IX	18,254 gal/lb	From SAFF® treated RSSCT (did not observe breakthrough, actual media life would likely be longer).
Treatment Train 7	IX	6,845 gal/lb	Assumes 50% increase compared to TT6 IX, and scaled to 4x concentration due to RO. Note that TT6 IX did not breakthrough. Media life would likely be longer.

(1) The same specific throughput assumptions are used for 2,000-gpm and 5,000-gpm treatment plants.

(2) Optimizing bed life assumes breakthrough is allowed in the lead bed as long as effluent from lag bed is still non-detect. This is not recommended for drinking water, but in a non-drinking water application, it allows for maximum utilization of media by pushing the lead bed closer to total exhaustion as opposed to changing out at initial breakthrough.

Table J.51: Treatment Train 1 (Reactivated GAC) Detailed Capital Expenditure Estimate.

Equipment	500 GPM	2,000 GPM	5,000 GPM
Feed Equalization Tank	$80,000	$140,000	$200,000
GAC Effluent/Backwash Tank	$150,000	$150,000	$150,000
Waste Buffer Tank	$150,000	$150,000	$150,000
Tank Finishing	$180,000	$210,000	$250,000
Chemical Tank & Feed Skid	$20,000	$60,000	$145,000
Greensand Filters	$703,000	$2,205,000	$4,320,000
Greensand Filter Install	$352,000	$1,103,000	$2,160,000
Pre-treatment Backwash Pumps	$80,000	$100,000	$100,000
GAC/Pretreatment Feed Pumps	$80,000	$100,000	$150,000
GAC Skids	$1,020,000	$1,700,000	$2,580,000
GAC Skids Install cost	$765,000	$1,275,000	$1,935,000
Initial Media	$150,000	$250,000	$600,000
GAC Backwash Pumps	$100,000	$100,000	$120,000
Generator	$100,000	$200,000	$400,000
Valves	$112,000	$160,000	$264,000
Check Valves	$72,000	$112,000	$144,000
Flow Meters	$40,000	$60,000	$75,000
Instrumentation & Controls	$150,000	$250,000	$400,000
Building	$2,000,000	$3,000,000	$4,000,000
Concrete	$1,000,000	$2,000,000	$3,000,000
Fire Protection	$75,000	$125,000	$175,000
HVAC	$250,000	$500,000	$1,250,000
Piping	$120,000	$250,000	$320,000
Electrical	$150,000	$250,000	$400,000
SUBTOTAL	$7,899,000	$14,450,000	$23,288,000
Mobilization & Site Setup (5%)	*$395,000*	*$723,000*	*$1,164,000*
Bonding & Insurance (3%)	*$237,000*	*$434,000*	*$699,000*
Contractor Overhead and Profit (15%)	*$1,185,000*	*$2,168,000*	*$3,493,000*
Engineering & Construction Contingency (45%)	*$3,555,000*	*$6,503,000*	*$10,480,000*
TOTAL (2024)	$13,270,000	$24,276,000	$39,124,000

Table J.52: Treatment Train 2 (Single-Use IX) Detailed Capital Expenditure Estimate.

Equipment	500 GPM	2,000 GPM	5,000 GPM
Feed Equalization Tank	$80,000	$140,000	$200,000
IX Effluent/Backwash Tank	$150,000	$150,000	$150,000
Waste Buffer Tank	$150,000	$150,000	$150,000
Tank Finishing	$190,000	$220,000	$250,000
Chemical Tank & Feed Skid	$20,000	$60,000	$145,000
Greensand Filters	$703,000	$2,205,000	$4,320,000
Greensand Filter Install	$352,000	$1,103,000	$2,160,000
Pre-treatment Backwash Pumps	$80,000	$100,000	$100,000
IX/Pretreatment Feed Pumps	$80,000	$100,000	$150,000
Cartridge Filters	$33,000	$81,000	$169,000
IX Skids	$480,000	$1,020,000	$2,040,000
IX Skids Install cost	$360,000	$765,000	$1,530,000
Initial Media	$496,000	$1,116,000	$2,232,000
Media Installation	$100,000	$224,000	$447,000
IX Backwash Pumps	$80,000	$100,000	$100,000
Generator	$100,000	$200,000	$400,000
Valves	$112,000	$160,000	$264,000
Check Valves	$72,000	$100,000	$126,000
Flow Meters	$40,000	$60,000	$75,000
Instrumentation & Controls	$150,000	$250,000	$400,000
Building	$2,000,000	$3,000,000	$4,000,000
Concrete	$1,000,000	$2,000,000	$3,000,000
Fire Protection	$75,000	$125,000	$175,000
HVAC	$250,000	$500,000	$1,250,000
Piping	$75,000	$157,000	$216,000
Electrical	$150,000	$250,000	$400,000
SUBTOTAL	$7,378,000	$14,336,000	$24,449,000
Mobilization & Site Setup (5%)	*$369,000*	*$717,000*	*$1,222,000*
Bonding & Insurance (3%)	*$221,000*	*$430,000*	*$733,000*
Contractor Overhead and Profit (15%)	*$1,107,000*	*$2,150,000*	*$3,667,000*
Engineering & Construction Contingency (45%)	*$3,320,000*	*$6,451,000*	*$11,002,000*
TOTAL (2024)	$12,395,000	$24,084,000	$41,074,000

Table J.53: Treatment Train 3 (Reactivated GAC + Single-Use IX) Detailed Capital Expenditure Estimate.

Equipment	500 GPM	2,000 GPM	5,000 GPM
Feed Equalization Tank	$80,000	$140,000	$200,000
GAC Effluent/Backwash Tank	$150,000	$150,000	$150,000
Waste Buffer Tank	$150,000	$150,000	$150,000
Tank Finishing	$180,000	$210,000	$250,000
Chemical Tank & Feed Skid	$20,000	$60,000	$145,000
Greensand Filters	$703,000	$2,205,000	$4,320,000
Greensand Filter Install	$352,000	$1,103,000	$2,160,000
Pre-treatment Backwash Pumps	$80,000	$100,000	$100,000
GAC/Pretreatment Feed Pumps	$80,000	$100,000	$150,000
GAC Skids	$1,020,000	$1,700,000	$2,580,000
GAC Skids Install cost	$765,000	$1,275,000	$1,935,000
Initial Media	$150,000	$250,000	$600,000
GAC Backwash Pumps	$100,000	$100,000	$120,000
IX Skids	$480,000	$1,020,000	$2,040,000
IX Skids Install cost	$360,000	$765,000	$1,530,000
Initial Media	$496,000	$1,116,000	$2,232,000
Media Installation	$100,000	$224,000	$447,000
Generator	$100,000	$200,000	$400,000
Valves	$112,000	$160,000	$264,000
Check Valves	$88,000	$152,000	$174,000
Flow Meters	$50,000	$75,000	$100,000
Instrumentation & Controls	$200,000	$300,000	$450,000
Building	$3,000,000	$4,000,000	$5,000,000
Concrete	$2,000,000	$3,000,000	$4,000,000
Fire Protection	$100,000	$150,000	$200,000
HVAC	$375,000	$750,000	$1,875,000
Piping	$112,000	$244,000	$320,000
Electrical	$200,000	$300,000	$450,000
SUBTOTAL	$11,603,000	$19,999,000	$32,342,000
Mobilization and Site Preparation (5%)	*$580,000*	*$1,000,000*	*$1,617,000*
Bonding & Insurance (3%)	*$348,000*	*$600,000*	*$970,000*
Contractor Overhead and Profit (20%)	*$1,740,000*	*$3,000,000*	*$4,851,000*
Final Design Elements (30%)	*$5,221,000*	*$9,000,000*	*$14,554,000*
TOTAL (2024)	$19,493,000	$33,598,000	$54,335,000

Table J.54: Treatment Train 4 (NF/RO to Reactivated GAC + Single-Use IX) Detailed Capital Expenditure Estimate.

Equipment	500 GPM	2,000 GPM	5,000 GPM
Feed Equalization Tank	$80,000	$140,000	$200,000
RO Permeate Tank/Backwash Supply Tank	$150,000	$150,000	$150,000
Waste Buffer Tank	$150,000	$150,000	$150,000
RO Reject Tank	$6,000	$22,500	$60,000
Tank Finishing	$193,000	$232,000	$280,000
Sulfuric Acid & Caustic Tank & Feed Skids	$40,000	$120,000	$290,000
Chlorine Chemical Tank & Feed Skid	$20,000	$60,000	$145,000
Greensand Filters	$703,000	$2,205,000	$4,320,000
Greensand Filter Install	$352,000	$1,103,000	$2,160,000
RO Skids	$1,451,000	$3,626,000	$7,978,000
RO Skid Shipping	$146,000	$363,000	$798,000
RO Shop Drawings/Design Review	$218,000	$544,000	$1,197,000
RO Installation Cost	$726,000	$1,813,000	$3,989,000
Cartridge Filters	$78,000	$201,000	$363,000
Low pressure Pretreatment Feed Pumps	$80,000	$100,000	$150,000
GAC/IX Feed Pumps	$80,000	$100,000	$140,000
GAC Skids	$480,000	$680,000	$1,360,000
IX Skids	$440,000	$480,000	$960,000
IX/GAC Install cost	$690,000	$870,000	$1,740,000
Initial GAC	$50,000	$100,000	$200,000
Initial IX	$311,000	$496,000	$992,000
IX Loading Costs	$63,000	$100,000	$199,000
GAC Backwash Pumps	$80,000	$100,000	$100,000
Pre-treatment Backwash Pumps	$80,000	$100,000	$100,000
Generator	$200,000	$300,000	$500,000
Valves	$256,000	$352,000	$576,000
Check Valves	$96,000	$108,000	$162,000
Flow Meters	$50,000	$75,000	$100,000
Instrumentation & Controls	$300,000	$400,000	$550,000
Building	$2,000,000	$3,000,000	$4,000,000
Concrete	$1,000,000	$2,000,000	$3,000,000
Fire Protection	$100,000	$150,000	$200,000
HVAC	$250,000	$500,000	$1,250,000
Piping	$160,000	$400,000	$710,000
Electrical	$300,000	$500,000	$800,000
SUBTOTAL	$11,379,000	$21,640,500	$39,869,000
Mobilization & Site Setup (5%)	*$569,000*	*$1,082,000*	*$1,993,000*

Equipment	500 GPM	2,000 GPM	5,000 GPM
Bonding & Insurance (3%)	*$341,000*	*$649,000*	*$1,196,000*
Contractor Overhead and Profit (15%)	*$1,707,000*	*$3,246,000*	*$5,980,000*
Engineering & Construction Contingency (45%)	*$5,121,000*	*$9,738,000*	*$17,941,000*
TOTAL (2024)	$19,117,000	$36,356,000	$66,980,000

Table J.55: Treatment Train 5 (Regenerable IX) Detailed Capital Expenditure Estimate.

Equipment	500 GPM
Feed Equalization Tank	$80,000
IX Effluent/GAC Backwash Tank	$150,000
Waste Buffer Tank	$150,000
RO Reject Tank	$6,000
Tank Finishing	$193,000
Cl Chemical Tank & Feed Skid	$20,000
Greensand Filters	$703,000
Greensand Filter Install	$352,000
Pre-treatment Backwash Pumps	$80,000
Sulfuric Acid Tank & Feed Skid, Caustic Tank & Feed Skid	$40,000
RO Skids	$1,451,000
RO Skid Shipping	$146,000
RO Shop Drawings/Design Review	$218,000
RO Installation Cost	$726,000
Cartridge Filters	$78,000
Low pressure Pretreatment Feed Pumps	$80,000
GAC/IX Feed Pumps	$60,000
GAC Skids	$480,000
GAC Skids Install cost	$360,000
Initial GAC	$50,000
IX Skids	$440,000
IX Skids Install Cost	$330,000
Initial IX Resin	$231,000
IX Resin Loading Costs	$116,000
GAC Backwash Pumps	$80,000
Generator	$200,000
Valves	$256,000
Check Valves	$96,000
Flow Meters	$50,000
Instrumentation & Controls	$300,000
Building	$4,000,000
Concrete	$2,000,000
Fire Protection	$250,000
HVAC	$36,000
Piping	$223,000
Electrical	$500,000
Regen Equipment	$10,000,000

Equipment	500 GPM
SUBTOTAL	$24,531,000
Mobilization & Site Setup (5%)	*$1,227,000*
Bonding & Insurance (3%)	*$736,000*
Contractor Overhead and Profit (15%)	*$3,680,000*
Engineering & Construction Contingency (45%)	*$11,039,000*
TOTAL (2024)	$41,212,000

Table J.56: Treatment Train 6 (SAFF® + GAC Polishing) Detailed Capital Expenditure Estimate Using SAFF® as the Foam Fractionation Technology.

Equipment	500 GPM	2,000 GPM	5,000 GPM
GAC Effluent/Backwash Tank	$150,000	$150,000	$150,000
Waste Buffer Tank	$150,000	$150,000	$150,000
Tank Finishing	$150,000	$150,000	$150,000
Chemical Tank & Feed Skid	$20,000	$60,000	$145,000
Greensand Filters	$703,000	$2,205,000	$4,320,000
Greensand Filter Install	$352,000	$1,103,000	$2,160,000
Pre-treatment Backwash Pumps	$80,000	$100,000	$100,000
SAFF®40	$7,200,000	-	-
SAFF®40 Install Cost	$1,800,000	-	-
MegaSAFF®	-	$17,012,000	$36,530,000
MegaSAFF® Contingency (20%)	-	$3,402,400	$7,306,000
GAC Feed Pumps	$80,000	$150,000	$240,000
GAC Skids	$1,020,000	$1,700,000	$2,580,000
GAC Skids Install cost	$765,000	$1,275,000	$1,935,000
Initial Media (GAC)	$150,000	$250,000	$600,000
GAC Backwash Pumps	$100,000	$100,000	$120,000
Generator	$100,000	$200,000	$400,000
Valves	$176,000	$288,000	$552,000
Check Valves	$72,000	$112,000	$144,000
Flow Meters	$40,000	$60,000	$75,000
Instrumentation & Controls	$300,000	$400,000	$550,000
Building	$3,000,000	$4,000,000	$5,000,000
Concrete	$2,000,000	$3,000,000	$4,000,000
Fire Protection	$100,000	$150,000	$200,000
HVAC	$375,000	$750,000	$1,875,000
Piping	$112,000	$244,000	$320,000
Electrical	$250,000	$350,000	$500,000
SUBTOTAL (GAC)	$19,245,000	$37,362,000	$70,102,000
Mobilization & Site Setup (5%)	*$962,000*	*$1,868,000*	*$3,505,000*
Bonding & Insurance (3%)	*$577,000*	*$1,121,000*	*$2,103,000*
Contractor Overhead and Profit (15%)	*$2,887,000*	*$5,604,000*	*$10,515,000*
Engineering & Construction Contingency (45%)	*$8,660,000*	*$16,813,000*	*$31,546,000*
TOTAL GAC (2024)	$32,332,000	$62,768,000	$117,771,000

Table J.57: Treatment Train 6 (SAFF® + IX Polishing) Detailed Capital Expenditure Estimate Using SAFF® as the Foam Fractionation Technology.

Equipment	500 GPM	2,000 GPM	5,000 GPM
IX Effluent/Backwash Tank	$150,000	$150,000	$150,000
Waste Buffer Tank	$150,000	$150,000	$150,000
Tank Finishing	$150,000	$150,000	$150,000
Chemical Tank & Feed Skid	$20,000	$60,000	$145,000
Greensand Filters	$703,000	$2,205,000	$4,320,000
Greensand Filter Install	$352,000	$1,103,000	$2,160,000
Pre-treatment Backwash Pumps	$80,000	$100,000	$100,000
SAFF®40	$7,200,000	-	-
SAFF®40 Install Cost	$1,800,000	-	-
MegaSAFF®	-	$17,012,000	$36,530,000
MegaSAFF® Contingency (20%)	-	$3,402,400	$7,306,000
IX Feed Pumps	$80,000	$150,000	$240,000
IX Skids	$480,000	$1,020,000	$2,040,000
IX Skids Install cost	$360,000	$765,000	$1,530,000
Initial Media (IX)	$496,000	$1,116,000	$2,232,000
IX Installation	$100,000	$224,000	$447,000
Generator	$100,000	$200,000	$400,000
Valves	$176,000	$288,000	$552,000
Check Valves	$72,000	$112,000	$144,000
Flow Meters	$40,000	$60,000	$75,000
Instrumentation & Controls	$300,000	$400,000	$550,000
Building	$3,000,000	$4,000,000	$5,000,000
Concrete	$2,000,000	$3,000,000	$4,000,000
Fire Protection	$100,000	$150,000	$200,000
HVAC	$75,000	$750,000	$1,875,000
Piping	$112,000	$244,000	$320,000
Electrical	250,000	$350,000	$500,000
SUBTOTAL (IX)	$18,646,000	$37,162,000	$71,116,000
Mobilization & Site Setup (5%)	*$932,000*	*$1,858,000*	*$3,556,000*
Bonding & Insurance (3%)	*$559,000*	*$1,115,000*	*$2,133,000*
Contractor Overhead and Profit (15%)	*$2,797,000*	*$5,574,000*	*$10,667,000*
Engineering & Construction Contingency (45%)	*$8,391,000*	*$16,723,000*	*$32,002,000*
TOTAL IX (2024)	$31,325,000	$62,432,000	$119,475,000

Table J.58: Treatment Train 7 (NF/RO to SAFF® + IX Polishing) Detailed Capital Expenditure Estimate Using SAFF® as the Foam Fractionation Technology.

Equipment	500 GPM	2,000 GPM	5,000 GPM
Feed Equalization Tank	$80,000	$140,000	$200,000
RO Permeate Tank/Backwash Supply Tank	$150,000	$150,000	$150,000
Waste Buffer Tank	$150,000	$150,000	$150,000
RO Reject Tank	$6,000	$22,500	$60,000
Tank Finishing	$193,000	$231,250	$280,000
Chlorine Chemical Tank & Feed Skid	$20,000	$60,000	$145,000
Greensand Filters	$703,000	$2,205,000	$4,320,000
Greensand Filter Install	$352,000	$1,103,000	$2,160,000
Sulfuric Acid & Caustic Tank & Feed Skids	$40,000	$120,000	$290,000
RO Skids	$1,451,000	$3,626,000	$7,978,000
RO Skid Shipping	$146,000	$363,000	$798,000
RO Shop Drawings/Design Review	$218,000	$544,000	$1,197,000
RO Installation Cost	$726,000	$1,813,000	$3,989,000
Cartridge Filters	$78,000	$201,000	$363,000
Low pressure Pretreatment Feed Pumps	$80,000	$100,000	$150,000
SAFF®40	$3,600,000	$7,200,000	-
SAFF®40 Install Cost	$900,000	$1,800,000	-
MegaSAFF®	-	-	$12,132,500
MegaSAFF® Contingency (20%)	-	-	$2,426,500
Treated SAFF® Effluent Tank	$6,000	$13,000	-
IX Feed Pumps	$80,000	$100,000	$140,000
IX Skids	$440,000	$480,000	$960,000
IX Install cost	$330,000	$360,000	$720,000
Initial IX	$311,000	$496,000	$992,000
IX Loading Costs	$63,000	$100,000	$199,000
IX Backwash Pumps	$80,000	$100,000	$100,000
Pre-treatment Backwash Pumps	$80,000	$100,000	$100,000
Generator	$200,000	$300,000	$500,000
Valves, Check Valves, & Flow Meters	$392,000	$520,000	$813,000
Instrumentation & Controls	$300,000	$400,000	$550,000
Building	$2,000,000	$3,000,000	$4,000,000
Concrete	$1,000,000	$2,000,000	$3,000,000
Fire Protection	$100,000	$150,000	$200,000
HVAC	$250,000	$500,000	$1,250,000
Piping	$112,000	$235,000	$324,000
Electrical	$300,000	$500,000	$800,000

Equipment	500 GPM	2,000 GPM	5,000 GPM
SUBTOTAL	$14,937,000	$29,182,750	$51,437,000
Mobilization & Site Setup (5%)	*$747,000*	*$1,459,000*	*$2,572,000*
Bonding & Insurance (3%)	*$448,000*	*$875,000*	*$1,543,000*
Contractor Overhead and Profit (15%)	*$2,241,000*	*$4,377,000*	*$7,716,000*
Engineering & Construction Contingency (45%)	*$6,722,000*	*$13,132,000*	*$23,147,000*
TOTAL (2024)	$25,094,000	$49,027,000	$86,414,000

Table J.59: Individual Treatment Train Evaluation Criteria Scoring Descriptions, AOC 1 (WCL).

Treatment Train	Treatment Technology	Evaluation Criteria							
		Short -Term Effectiveness	Long-Term Effectiveness	Cost [1]	Sustainability - Media Consumption [2]	Sustainability - Energy Use	Operations and Maintenance Requirements	Technology Readiness	Portion of PFAS Destroyed vs. Landfilled [3]
Treatment Train 1	Reactivated GAC	Low - PFBA is expected to breakthrough GAC almost immediately, with potential media life of less than 1 day. GAC would not be able to meet current regulatory standards.	Low - GAC could not meet current regulatory standards; decreased short-chain concentrations in the effluent would be unachievable.	CAPEX: $13 M OPEX: $31 M	High - A GAC-only system will use an impractically high amount of media.	Low - A GAC-only system does not require high pressure pumping like membrane systems.	Low - A GAC-only system requires comparatively little oversight or maintenance, as most processes can be automated.	High - GAC is widely used for PFAS treatment.	High - PFAS captured by GAC would be destroyed during reactivation.
Treatment Train 2	Single-Use IX	Low - RSSCTs indicated a media life of less than 2 days. IX could meet regulatory standards, but it would require more IX resin than is practical.	Low - Decreased effluent standards for short-chain PFAS would further decrease IX media life and are not expected to be attainable.	CAPEX: $12 M OPEX: $44 M	High - An IX-only system will use an impractically large amount of media.	Low - An IX-only system does not require high pressure pumping like membrane systems.	Low - An IX-only system requires comparatively little oversight or maintenance, as most processes can be automated. IX is more prone to fouling than GAC though, which increases the importance of pre-treatment systems.	High - IX is widely used for PFAS treatment.	Low - All PFAS removed from water would stay on IX media. If IX media is landfilled instead of incinerated, no PFAS would be destroyed.
Treatment Train 3	Reactivated GAC + Single-Use IX	Low - In theory, GAC would remove long-chain PFAS, allowing IX to be targeted for short-chain PFAS removal. In practice, breakthrough times are expected to be marginally longer than a GAC -or IX-only system and still impractical for full-scale implementation.	Low - GAC would remove long-chain PFAS, allowing IX to be targeted for short-chain PFAS removal.	CAPEX: $19 M OPEX: $26 M	High - A GAC/IX tandem system would likely decrease media usage compared to a GAC- or IX-only system, but would not be expected to substantially reduce media usage.	Low - A GAC/IX system would require more pumping pressure head due to the operation of GAC and IX vessels in series, but still significantly less than membrane systems.	Low - A GAC/IX system would require more oversight than a GAC- or IX-only system due to increased sampling requirements, but would not require as much maintenance or oversight as membrane or SAFF® treatment trains. GAC ahead of IX would decrease risk of IX fouling.	High - GAC and IX are widely used for PFAS treatment.	Moderate - PFAS captured by GAC would be destroyed during reactivation while PFAS captured by IX would be landfilled.
Treatment Train 4	NF/RO to Reactivated GAC + Single-Use IX	Low - While NF/RO effectively removes all PFAS from permeate, GAC and IX would struggle to remove PFAS from the concentrate stream.	Low - While NF/RO effectively removes all PFAS from permeate, GAC and IX would struggle to remove PFAS from the concentrate stream.	CAPEX: $19 M OPEX: $22 M	High - Use of NF/RO as a pre-concentration step would likely increase GAC and IX removal efficiencies, reducing the total volume of media needed. Overall media use would still be very high though.	High - NF/RO require high pressure pumping to force water through semi-permeable membranes. RO operates at higher pressure than NF and thus would use more energy.	High - NF/RO membranes require much more attention than GAC or IX pressure vessels. Membranes systems will require increased operator and engineer/supervisor oversight.	High - GAC and IX are widely used for PFAS treatment. Use of NF/RO membranes to treat PFAS has grown in the last decade as well and is increasingly common.	Moderate - PFAS captured by GAC would be destroyed during reactivation while PFAS captured by IX would be landfilled.
Treatment Train 5	Regenerable IX (Includes NF/RO and Reactivated GAC ahead of IX) [4]	High - Long-chain PFAS and currently regulated short-chains (e.g. PFBA) would be effectively removed by media.	High - Lower effluent standards could be achieved by increasing regeneration rates.	CAPEX: $41 M OPEX: $3.3 M	Low - Regenerative IX would allow IX resin to be reused. This option would likely have lowest media usage. Note that this assumes long-chain PFAS can be removed from IX resin during regeneration. If long-chain PFAS must be removed by GAC, media consumption would increase significantly.	High - NF/RO require high pressure pumping to force water through semi-permeable membranes. RO operates at higher pressure than NF and thus would use more energy. The regeneration system also requires substantial energy input to operate the distillation equipment.	High - Regenerable IX would require the most oversight and maintenance as it combines NF/RO membranes, GAC and IX vessels, and a regeneration system which is relatively unproven.	Low - Regenerative IX is relatively new with limited full-scale systems in operation. Technology is not yet mature.	High - PFAS captured by GAC (pre-filters to protect IX vessels) would be destroyed during reactivation, while PFAS captured by IX would be concentrated into the still-bottoms waste stream and destroyed.

Treatment Train	Treatment Technology	Evaluation Criteria							
		Short -Term Effectiveness	Long-Term Effectiveness	Cost [1]	Sustainability - Media Consumption [2]	Sustainability - Energy Use	Operations and Maintenance Requirements	Technology Readiness	Portion of PFAS Destroyed vs. Landfilled [3]
Treatment Train 6	SAFF® [5] + Reactivated GAC	Low to Moderate - Foam fractionation is generally not used of short-chain PFAS removal, thus if limited PFBA is removed, significant amounts of GAC would be required to meet current regulatory standards. If foam fractionation can remove PFBA, polishing with GAC would only be moderate in effectiveness due to the rapid breakthrough of PFBA.	Low - Foam fractionation, even with an increased ability to remove short-chain PFAS, would require a polish. Use of GAC as a polishing media would be ineffective due to the limited ability of GAC to remove short-chain PFAS.	CAPEX: $32 M OPEX: $4.2 M to $32 M	Moderate to High- Foam fractionation would provide bulk removal of long-chain PFAS, and GAC would serve as a polish to meet regulatory standards. However, if PFBA is not removed by foam fractionation, GAC usage would be similarly high to a GAC-only system.	Moderate - Foam fractionation requires more energy than just GAC or IX vessels, but the total energy required of foam fractionation and GAC polishing would be less than membrane systems.	Moderate - Foam fractionation is expected to require less maintenance than membrane systems, however more maintenance than on a GAC or IX system is expected.	Moderate - Foam fractionation is becoming more common to treat PFAS, though targeting PFBA is not a common application of the technology. Addition of GAC would not substantially increase complexity of scale-up or operations.	High - PFAS in SAFF® concentrate would be destroyed by incineration or other destruction method; PFAS on GAC would be destroyed during reactivation.
	SAFF® [5] + Single-Use IX	Moderate to High - Foam fractionation is generally not used for short-chain PFAS removal, thus if limited PFBA is removed, larger amounts of IX would be required to meet current regulatory standards. If foam fractionation can remove PFBA, polishing with IX would have high effectiveness.	Moderate to High - Ability of this treatment to target lower effluent short-chain standards would depend on the removal efficiencies achieved by foam fractionation. If foam fractionation can be tuned to remove short-chain PFAS, lower effluent standards can be achieved with an IX polish.	CAPEX: $31 M OPEX: $2.2 M to $12 M	Low to Moderate - Foam fractionation would provide bulk removal of long chains, and IX would serve as a polish to meet regulatory standards. Media usage will depend on the ability of foam fractionation to also remove short-chain PFAS.	Moderate - Foam fractionation requires more energy than just GAC or IX vessels, but the total energy required of foam fractionation and IX polishing would be less than membrane systems.	Moderate - Foam fractionation is expected to require less maintenance than membrane systems, however more maintenance than on a GAC or IX system is expected.	Moderate - Foam fractionation is becoming more common, though targeting PFBA is not a common application of the technology. Addition of IX would not substantially increase complexity of scale-up or operations.	Moderate to High - PFAS in foam fractionation concentrate would be destroyed by incineration or other destruction method; PFAS captured by IX would be landfilled. The ratio of PFAS destroyed vs. landfilled would depend on removal efficiency of foam fractionation and relative IX usage.
Treatment Train 7	NF/RO to SAFF® [5] + Single-Use IX	Moderate to High - Foam fractionation is generally not used for short-chain PFAS removal, thus if limited PFBA is removed, larger amounts of IX would be required to meet current regulatory standards. If NF/RO coupled with foam fractionation can remove PFBA, polishing with IX would have high effectiveness.	Moderate to High - Ability of this treatment to target lower effluent short-chain standards would depend on the removal efficiencies achieved by foam fractionation. If foam fractionation can be tuned to remove short-chain PFAS, lower effluent standards can be achieved with an IX polish.	CAPEX: $25 M OPEX: $1.5 M to $6.7 M	Low to Moderate - Foam fractionation would provide bulk removal of long chains, and IX would serve as a polish to meet regulatory standards. Media usage will depend on the ability of foam fractionation to also remove short-chain PFAS.	High - NF/RO require high pressure pumping to force water through semi-permeable membranes. RO operates at higher pressure than NF and thus would use more energy. Foam fractionation and IX polishing on the reject would also require additional energy.	High - NF/RO membranes require much more attention than GAC or IX pressure vessels. Membranes systems will require increased operator and engineer/supervisor oversight. Foam fractionation is expected to require less maintenance than membrane systems, though treatment of membrane concentrate may increase maintenance requirements.	Moderate - Foam fractionation is becoming more common, though treatment of RO concentrate is less common. Additionally, use of foam fractionation to target PFBA removal is not common. Addition of IX would not substantially increase complexity of scale-up or operations.	Moderate to High - PFAS in foam fractionation concentrate would be destroyed by incineration or other destruction method; PFAS captured by IX would be landfilled. The ratio of PFAS destroyed vs. landfilled would depend on removal efficiency of foam fractionation and relative IX usage.

(1) Based on preliminary cost estimates. RSSCTs and pilot testing required to confirm preliminary design assumptions and to validate media usage estimates.
(2) Significant uncertainty exists around how much PFBA would be removed by foam fractionation. Lower scores represent minimal PFBA removal while higher scores represent higher PFBA removal.
(3) Assumes IX media is landfilled as opposed to incinerated due to cost.
(4) Assumes long-chain PFAS can be removed from IX during reactivation. If GAC is required to remove long-chain PFAS, media use and OPEX costs would increase significantly.
(5) For the purposes of this report, SAFF® was used as the foam fractionation technology for cost estimates and preliminary design due to its use in an on-site pilot study conducted as part of this FS. Since the commencement of the pilot study, additional vendors now offer foam fractionation treatment technology; it is recommended that multiple vendors be evaluated if foam fractionation is selected as a remedial technology.

Table J.60: Individual Treatment Train Evaluation Criteria Scoring Descriptions, AOCs 2, 7, and 10.

Treatment Train	Treatment Technology	Evaluation Criteria							
		Short-Term Effectiveness	**Long-Term Effectiveness**	**Cost (1)**	**Sustainability - Media Consumption (2)**	**Sustainability - Energy Use**	**Operations and Maintenance Requirements**	**Technology Readiness**	**Portion of PFAS Destroyed vs. Landfilled (3)**
Treatment Train 1	Reactivated GAC	Moderate - GAC would be able to meet current effluent standards, but RSSCTs indicated GAC media would require relatively frequent replacement to meet standards.	Low - GAC is largely ineffective at removing short-chain PFAS and would struggle to meet low regulatory limits for short chains, should new regulatory standards limit short-chain PFAS.	2,000-gpm Plant CAPEX: $24 M OPEX: $4.6 M 5,000-gpm Plant CAPEX: $39 M OPEX: $11 M	High - A GAC-only system will use a large volume of media, as RSSCTs demonstrate shorter media life for GAC. Should short-chain PFAS need to be targeted in the future, media use would increase significantly.	Low - A GAC-only system does not require high pressure pumping like membrane systems.	Low - A GAC-only system requires comparatively little oversight or maintenance, as most processes can be automated.	High - GAC is widely used for PFAS treatment.	High - PFAS captured by GAC would be destroyed during reactivation.
Treatment Train 2	Single-Use IX	High - IX will efficiently remove all currently regulated PFAS compounds.	Moderate to High - IX will remove both short-chain and long-chain PFAS effectively, though targeting lower effluent short-chain PFAS concentrations will increase media usage.	2,000-gpm Plant CAPEX: $24 M OPEX: $1.9 M 5,000-gpm Plant CAPEX: $41 M OPEX: $3.7 M	Moderate – An IX-only system will use a moderate volume of media. IX can remove more media per mass but is also the only process step removing PFAS.	Low - An IX-only system does not require high pressure pumping like membrane systems.	Low - An IX-only system requires comparatively little oversight or maintenance, as most processes can be automated. IX is more prone to fouling than GAC though, which increases the importance of pre-treatment systems.	High - IX is widely used for PFAS treatment.	Low - All PFAS removed from water would stay on IX media. If IX media is landfilled instead of incinerated, no PFAS would be destroyed.
Treatment Train 3	Reactivated GAC + Single-Use IX	High - GAC would remove long-chain PFAS like PFOA and PFOS, increasing IX media life to remove shorter-chain PFAS like PhDs and PFBS.	Moderate to High - GAC would remove long-chain PFAS, allowing IX to be targeted for short-chain PFAS removal. Targeting lower effluent short-chain PFAS concentrations will increase media usage.	2,000-gpm Plant CAPEX: $34 M OPEX: $2.4 M 5,000-gpm Plant CAPEX: $54 M OPEX: $4.4 M	Moderate - A GAC/IX tandem system would likely decrease media usage compared to a GAC- or IX-only system but would not be expected to substantially reduce media usage.	Low - A GAC/IX system would require more pumping pressure head due to the operation of GAC and IX vessels in series, but still significantly less than membrane systems.	Low - A GAC/IX system would require more oversight than a GAC- or IX-only system due to increased sampling requirements but would not require as much maintenance or oversight as membrane or SAFF® treatment trains. GAC ahead of IX would decrease risk of IX fouling.	High - GAC and IX are widely used for PFAS treatment.	Moderate - PFAS captured by GAC would be destroyed during reactivation while PFAS captured by IX would be landfilled.
Treatment Train 4	NF/RO to Reactivated GAC + Single-Use IX	High - NF/RO effectively removes all PFAS from permeate. GAC would remove long-chain PFAS like PFOA and PFOS, increasing IX media life to remove shorter-chain PFAS like PhDs and PFBS in the concentrate.	Moderate to High - NF/RO effectively removes all PFAS from permeate. GAC would remove long-chain PFAS in the concentrate, allowing IX to be targeted for short-chain PFAS removal in the concentrate. Targeting lower effluent short-chain PFAS concentrations will increase media usage.	2,000-gpm Plant CAPEX: $36 M OPEX: $3.1M 5,000-gpm Plant CAPEX: $67 M OPEX: $6.1 M	Moderate - Use of NF/RO as a pre-concentration step would likely increase GAC and IX removal efficiencies, reducing the total volume of media needed.	High - NF/RO require high pressure pumping to force water through semi-permeable membranes. RO operates at higher pressure than NF and thus would use more energy.	High - NF/RO membranes require much more attention than GAC or IX pressure vessels. Membranes systems will require increased operator and engineer/supervisor oversight.	High - GAC and IX are widely used for PFAS treatment. Use of NF/RO membranes to treat PFAS has grown in the last decade as well and is increasingly common.	Moderate - PFAS captured by GAC would be destroyed during reactivation while PFAS captured by IX would be landfilled.
Treatment Train 5	Regenerable IX	Not Applicable to AOCs 2, 7, and 10	Not Applicable to AOCs 2, 7, and 10	Not Applicable to AOCs 2, 7, and 10	Not Applicable to AOCs 2, 7, and 10	Not Applicable to AOCs 2, 7, and 10	Not Applicable to AOCs 2, 7, and 10	Not Applicable to AOCs 2, 7, and 10	Not Applicable to AOCs 2, 7, and 10

Treatment Train	Treatment Technology	Evaluation Criteria							
		Short-Term Effectiveness	**Long-Term Effectiveness**	**Cost [1]**	**Sustainability - Media Consumption [2]**	**Sustainability - Energy Use**	**Operations and Maintenance Requirements**	**Technology Readiness**	**Portion of PFAS Destroyed vs. Landfilled [3]**
Treatment Train 6	SAFF® [4] + Reactivated GAC	Moderate - Foam fractionation effectively removes bulk of long-chain PFAS, GAC can polish effluent to current regulatory standards.	Low to Moderate - Foam fractionation may not be able to remove short-chain PFAS. GAC is largely ineffective at removing short-chain PFAS and would struggle to meet low regulatory limits for short chains, should new regulatory standards limit short-chain PFAS.	2,000-gpm Plant CAPEX: $63 M OPEX: $3.0M 5,000-gpm Plant CAPEX: $118 M OPEX: $5.5 M	Moderate - Foam fractionation would provide bulk removal of long-chain PFAS, and GAC would remove the remaining long chains to meet regulatory standards. Media use would increase significantly if short-chain PFAS are targeted for removal.	Moderate - Foam fractionation requires more energy than just GAC or IX vessels, but the total energy required of foam fractionation and GAC polishing would be less than membrane systems.	Moderate - Foam fractionation is expected to require less maintenance than membrane systems. More maintenance is required than in a GAC or IX system though.	Moderate - Foam fractionation is becoming more common, though a full-scale implementation at 2,000 or 5,000 gpm may exceed the largest current installations. Addition of GAC would not substantially increase complexity of scale-up or operations.	High - PFAS in foam fractionation concentrate would be destroyed by incineration or other destruction method; PFAS on GAC would be destroyed during reactivation.
	SAFF® [4] + Single-Use IX	High - Foam fractionation effectively removes bulk of long-chain PFAS and IX can polish effluent to regulatory standards for all currently regulated species.	High - Foam fractionation removal of bulk of long-chain PFAS would allow an IX resin to be selected that could target short-chain PFAS.	2,000-gpm Plant CAPEX: $62 M OPEX: $2.6 M 5,000-gpm Plant CAPEX: $119 M OPEX: $4.6 M	Low - Foam fractionation would provide bulk removal of long chains, and IX would serve as a polish. Use of foam fractionation would decrease media usage overall, and use of IX would decrease media usage compared to GAC polishing.	Moderate - Foam fractionation requires more energy than just GAC or IX vessels, but the total energy required of foam fractionation and IX polishing would be less than membrane systems.	Moderate - Foam fractionation is expected to require less maintenance than membrane systems. More maintenance is required than in a GAC or IX system though.	Moderate - Foam fractionation is becoming more common, though a full-scale implementation at 2,000 or 5,000 gpm may exceed the largest current installations. Addition of IX would not substantially increase complexity of scale-up or operations.	Moderate - PFAS in foam fractionation concentrate would be destroyed by incineration or other destruction method; PFAS captured by IX would be landfilled.
Treatment Train 7	NF/RO to SAFF® [4] + Single-Use IX	High - NF/RO effectively removes all PFAS from permeate. Foam fractionation would remove majority of long-chain PFAS in the concentrate, and IX can polish effluent to regulatory standards for all currently regulated species.	High - NF/RO effectively removes all PFAS from permeate. Foam fractionation would remove majority of long-chain PFAS in the concentrate, allowing IX to be targeted for short-chain PFAS removal in the concentrate.	2,000-gpm Plant CAPEX: $49 M OPEX: $2.9 M 5,000-gpm Plant CAPEX: $86 M OPEX: $5.8 M	Low - Use of NF/RO ahead of foam fractionation would likely improve foam fractionation removal efficiency. IX would be used to remove residual long-chain and short-chain PFAS.	High - NF/RO require high pressure pumping to force water through semi-permeable membranes. RO operates at higher pressure than NF and thus would use more energy. Foam fractionation and IX polishing on the reject would also require additional energy.	High - NF/RO membranes require much more attention than GAC or IX pressure vessels. Membranes systems will require increased operator and engineer/supervisor oversight. Foam fractionation is expected to require less maintenance than membrane systems, though treatment of membrane concentrate may increase maintenance requirements.	Moderate - Foam fractionation is becoming more common, though treatment of RO concentrate is less common. Addition of IX would not substantially increase complexity of scale-up or operations.	High - PFAS in foam fractionation concentrate would be destroyed by incineration or other destruction method; PFAS captured by IX would be landfilled. The majority of PFAS removed is expected to be in the foam fractionation concentrate.

(1) Based on preliminary cost estimates. RSSCTs and pilot testing required to confirm preliminary design assumptions and to validate media usage estimates.
(2) PFBA is below drinking water standards in AOCs 2, 7, and 10; it is assumed treatment targeting PFBA is not required at this time.
(3) Assumes IX media is landfilled as opposed to incinerated due to cost.
(4) For the purposes of this report, SAFF® was used as the foam fractionation technology for cost estimates and preliminary design due to its use in an on-site pilot study conducted as part of this FS. Since the commencement of the pilot study, additional vendors now offer foam fractionation treatment technology; it is recommended that multiple vendors be evaluated if foam fractionation is selected as a remedial technology.