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Appendix D: Remedial Technology and Action Screening: Detailed Descriptions and Analysis

Project 1007 Feasibility Study
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Acronyms and Abbreviations

µg	microgram
AFFF	Aqueous Film-Forming Foam
AOC	Area of Concern
AWWA	American Water Works Association
CDWSP	Conceptual Drinking Water Supply Plan
EBCT	Empty Bed Contact Time
EC	engineering control
EPA	United States Environmental Protection Agency
FS	Feasibility Study
GAC	granular activated carbon
gal	gallon
gfd	gallons per square foot per day
gpd	gallons per day
gph	gallons per hour
GRA	General Response Action
HALT	hydrothermal alkaline treatment
HBV	Health-Based Value
HF	hydrofluoric acid
HRL	Health Risk Limit
IC	institutional control
ITRC	Interstate Technology and Regulatory Council
IX	ion exchange
kg	kilogram
kWh	kilowatt hour
LPM	liters per minute
LTM	Long-Term Monitoring
m ³	cubic meter
MBWA	Multi-Benefit Well Array
MCL	maximum contaminant level
MDH	Minnesota Department of Health
mg	milligram
MPCA	Minnesota Pollution Control Agency
NCP	National Contingency Plan
NF	nanofiltration
NFA	No Further Action
NOM	natural organic matter
O&M	operation and maintenance
ODS	Oakdale Disposal Site
PAB	permeable absorptive barrier

PFAS	per- and polyfluoroalkyl substances
PFBA	perfluorobutanoic acid
PFBS	perfluorobutanesulfonic acid
PFOA	perfluorooctanoic acid
PFOS	perfluorooctanesulfonic acid
PFPeA	perfluoropentanoic acid
POETS	Point of Entry Treatment System
PSI	pounds per square inch
RAO	Remedial Action Objective
RO	reverse osmosis
RSSCT	rapid small-scale column test
SAFF®	Surface Active Foam Fractionation
SCWO	super critical water oxidation
SDCV	Site-Specific Sediment Cleanup Value
SDSV	Site-Specific Sediment Screening Value
SSC	MPCA Site-Specific Water Quality Criteria
SWP	soil washing plant
TOF	total organic fluorine
TRL	Technology Readiness Level
UV	ultraviolet
VOC	volatile organic compound
WCL	Washington County Landfill
WTP	Water Treatment Plant

Appendix D Remedial Technology and Action Screening: Detailed Descriptions and Analysis

Remedial technologies and actions capable of reducing per- and polyfluoroalkyl substances (PFAS) concentrations in groundwater, surface water, and sediment, limiting the continued migration of PFAS, or reducing public exposure to PFAS in these environmental media were screened to determine if these actions should be further considered in the development of remedial alternatives to address PFAS impacts throughout the Project 1007 Corridor (“Site”). The specific response actions were organized into General Response Actions (GRAs), as described in Section 9 of the Project 1007 Feasibility Study (FS), and listed below.

- No Further Action (NFA)
- Access Restrictions
- Long-Term Monitoring (LTM)
- Surface Water Hydrology Modifications (surface water only)
- In-situ Treatment
- Ex-situ Treatment

The purpose of this appendix is to describe specific remedial technologies and actions that fall into each GRA, how they could be applied at the Site, and rationale on whether they should be retained for further consideration in the development of remedial alternatives. To uniformly evaluate the specific response actions, they were screened based on effectiveness, implementability, relative cost, and technology readiness. Details on each of these criteria are included in Section 9. In-situ and ex-situ technologies receiving “poor” scores in the effectiveness, implementability, or technology readiness categories were not retained for further evaluation. Cost was discussed in narrative terms but not used to screen out technologies. The evaluation was completed separately for groundwater, surface water, and sediment except for technologies within the ex-situ GRA, which is similar for surface water and groundwater and therefore combined. Scoring, and the resulting decision to retain a remedial action or technology may differ between Areas of Concern (AOCs) based on PFAS concentrations, site-specific conditions, and the volume of sediment or water to be treated. The AOCs as defined by Section 7 are listed in Table D.1.

The research, development, and commercialization of PFAS remedial technologies is rapidly evolving, and the selection of technologies discussed within this appendix is, therefore, not representative of all technologies being developed to address environmental PFAS impacts. The technologies presented within this appendix include those that either have been commercialized for PFAS treatment, are in the process of being commercialized, or have undergone pilot studies at the time of the preparation of this FS. Methods for treatment that have only been evaluated at the laboratory scale were not considered. The US Department of Energy’s Technology Readiness Level (TRL) system has been applied to quantitatively evaluate each technology’s degree of commercialization. Treatment technologies with a TRL below 6 were not included in this screening.

Table D.1: Project 1007 Site Areas of Concern.

AOC	AOC Description	AOC Classification
AOC 1	WCL Surface Water and Shallow Groundwater	Groundwater
AOC 2	WCL Bedrock Aquifers	Groundwater
AOC 3	ODS Surface Water	Surface Water
AOC 4	Downgradient ODS Bedrock Aquifers	Groundwater
AOC 5	Raleigh Creek Surface Water	Surface Water
AOC 6	Eagle Point Lake Surface Water	Surface Water
AOC 7	Raleigh Creek + Eagle Point Lake Groundwater	Groundwater
AOC 8	Lake Elmo Surface Water	Surface Water
AOC 9	Horseshoe Lake/West Lakeland Surface Water	Surface Water
AOC 10	West Lakeland Groundwater	Groundwater
AOC 11	Upper Raleigh Creek Wetland Complexes Sediment	Sediment
AOC 12	Anna's Grove Wetland Complex Sediment	Sediment
AOC 13	Eagle Point Lake Sediment	Sediment

The effectiveness of a remedial measure or technology in treating specific PFAS is variable because of each compound's unique chemical properties. The main contributing factors are the head group and carbon-fluorine chain length. The primary head groups present at this Site are carboxylic acids such as perfluorooctanoic acid (PFOA) and sulfonic acids such as perfluorooctanesulfonic acid (PFOS). PFAS are also subdivided into short-chain and long-chain compounds, with long-chain PFAS defined as carboxylic acids with six or more carbons and sulfonic acids with eight or more carbons. Short-chain PFAS therefore include compounds below those thresholds. PFOS and PFOA are considered long-chain PFAS while perfluorobutanoic acid (PFBA) and perfluorobutanesulfonic acid (PFBS) are considered short-chains. Ultra-short chain PFAS are defined as PFAS with three carbons or less. Short-chain PFAS generally exhibit a higher degree of mobility and a lower degree of hydrophobicity when compared to long-chain PFAS.

D1 No Further Action

The NFA response generally indicates that no additional remedial actions, including interim remedial actions and sampling, will be conducted at a site. There are traditionally no costs associated with this action. While this is a possible remedial alternative for the surface water and sediment AOCs, a traditional NFA is not acceptable for the groundwater AOCs as the impacted aquifers are currently being used for drinking water and must therefore be treated for the protection of human health. The Conceptual Drinking Water Supply Plan (CDWSP) analyzed alternatives to provide safe drinking water to affected East Metro communities (Minnesota Pollution Control Agency [MPCA], 2021). The costs developed for the CDWSP are used as the cost for NFA of the applicable groundwater AOCs. Of the communities included in the CDWSP, only Oakdale, Lake Elmo, and West Lakeland Township are within the AOCs included in the FS; however, additional communities including Woodbury, Afton, Lakeland, Bayport, and Baytown Township are located downgradient of the impacts resulting from the Site. The actions required to provide safe drinking water to the communities within the AOCs are summarized in Table D.2 based on 2024 updated costs. Updated cost estimates were provided by the MPCA and the City of Lake Elmo (Stantec, March 2024; Stantec, April 2024). Additional costs are also expected to be incurred by 2040 based on plume migration and the additional homes that will be impacted. These costs

also assume that Lake Elmo can extract enough water to meet their 2040 needs without adversely impacting White Bear Lake.

Table D.2: Estimated Drinking Water Supply Costs.

Municipality	Infrastructure Needs	Capital Cost	Yearly Operating Cost
Oakdale	Expansion of current water treatment plant, potential installation of new wells.	\$37,950,000 to \$51,050,000	\$1,744,000 to \$3,488,000
Lake Elmo	Expanded groundwater extraction and treatment to accommodate future growth, install new POETSS where needed, connect additional homes to city water.	\$105,008,000 to \$130,270,000	\$964,000 to \$1,928,000
West Lakeland	O&M for currently installed POETSS and additional installation of POETSS as PFAS impacts spread.	\$5,463,000	\$1,450,000 to \$2,900,000

These costs were developed based on the Minnesota Department of Health’s (MDH) Health-Based Values (HBVs) and Health Risk Limits (HRLs) in 2020. These values have been lowered, which will increase the number of homes requiring Point of Entry Treatment Systems (POETSS) and increase the operation and maintenance (O&M) costs of the Water Treatment Plants (WTPs) as more granular activated carbon (GAC) will be required to meet the new standards.

The southern extent of the PFAS plume that is summarized by AOC 7 (Raleigh Creek + Eagle Point Lake – Groundwater) also enters Woodbury and contributes to the impacts observed at the Tamarack well field. This well field will be treated with a new WTP that will also treat other municipal supply wells impacted by sources outside of the project area. These costs were not included in the NFA remedial alternative as these are outside of the AOC, but the O&M costs could be decreased by reducing upgradient groundwater PFAS concentrations.

The CDWSP does not address surface water impacts; therefore, NFA indicates that no additional sampling or remedial actions would be completed for the AOCs except for AOC 3 (Oakdale Disposal Site [ODS] - Surface Water). AOC 3 is part of the broader ODS site that is managed through the MPCA Superfund program; remedial alternatives for AOC 3 are outside the scope of this FS and will not be discussed in this appendix.

D1.1 Groundwater

The effectiveness is scored as poor as the Remedial Action Objectives (RAOs) will not be achieved. PFAS concentrations within the drinking water aquifers will not be reduced and downgradient receptors will not be protected.

The implementability is scored as moderate as multiple POETSS and municipal WTP are required to provide safe drinking water to the municipalities.

The relative cost is moderate compared to other groundwater treatment GRAs as the only water that will be treated in an NFA response will be that with POETSS and municipal WTP.

The technology readiness score is good because the drinking water treatment plan proposed in the CDWSP uses GAC which is a widely used technology.

In accordance with the National Contingency Plan (NCP), NFA was retained for consideration for all groundwater AOCs to provide a baseline against which other technologies can be compared.

D1.2 Surface Water

The effectiveness of no further action is scored as poor as no RAOs would be met.

The implementability is scored as good as no action would be completed.

The relative cost is low because there would be no cost associated with implementation.

The technology readiness is scored as good as no technology is required.

In accordance with the NCP, NFA was retained for consideration for all surface water AOCs besides AOC 3 (ODS – Surface Water) to provide a baseline against which other technologies can be compared.

D1.3 Sediment

The effectiveness score is scored as poor as no action would be performed to reduce sediment PFAS concentrations that are above the 2-days/week and 5-days/week Site-Specific Sediment Screening Values (SDSVs), putting the public who may come into contact with this sediment at risk.

The implementability is scored as good as no action would be completed.

The relative cost is low as no additional work would be completed.

The technology readiness score is good as no remedial technologies are required.

In accordance with the NCP, a NFA was retained for consideration for all sediment AOCs to provide a baseline against which other technologies can be compared.

D2 Access Restrictions

Access restrictions include both institutional controls (ICs) and engineering controls (ECs). ICs are administrative controls or legal restrictions placed on the surface water, groundwater, or sediment to protect the public against inadvertent exposure to PFAS and/or to protect the integrity of a functioning or completed remedy. ECs are put in place to physically prevent the public from being exposed to PFAS.

Applicable access restrictions for surface water include signage, fencing, and fish consumption advisories. Access restrictions for groundwater include groundwater use restriction or management areas, property deed notices, and declaration of environmental restrictions. Sediment access restrictions include signage and fencing to prevent the public from being exposed to sediment exceeding the SDSVs.

D2.1 Groundwater

Scoring for access restrictions applied to groundwater is summarized as follows:

- The effectiveness is scored as poor as no reduction in groundwater concentrations would be achieved to meet the RAOs.
- The implementability is scored as good because applicable access restrictions could be easily implemented at the Site.
- The relative cost is low as minimal action would be taken.
- The technology readiness is scored as good as no remedial technologies would be required.
- Access restrictions are retained for consideration as a component of remedial alternatives for all groundwater AOCs to aid in the prevention of incidental public exposure to PFAS.

D2.2 Surface Water

Scoring for access restrictions applied to surface water is summarized as follows:

- The effectiveness is scored as poor as no reduction in surface water concentrations would be achieved to meet the RAOs.
- The implementability is scored as good because applicable access restrictions could be easily implemented on the Site.
- The relative cost is low as minimal actions would be taken.
- The technology readiness is scored as good as no remedial technologies would be required.
- Access restrictions are retained for consideration as a component of remedial alternatives for all surface water AOCs to aid in the prevention of incidental public exposure to PFAS.

D2.3 Sediment

Scoring for access restrictions applied to sediment is summarized as follows:

- The effectiveness is scored as poor as no reduction in sediment concentrations would be achieved to meet the RAOs.
- The implementability is scored as good because applicable access restrictions could be easily implemented on the Site.
- The relative cost is low as minimal actions would be taken.
- The technology readiness is scored as good a no remedial technologies would be required.
- Access restrictions are retained for consideration as a component of remedial alternatives for all sediment AOCs to aid in the prevention of incidental public exposure to PFAS.

D3 Long-Term Monitoring

LTM evaluates the extent to which contaminant concentrations change over time across a site. When applied to this Site, LTM would involve periodic sampling of groundwater, surface water, and/or sediment to evaluate whether changes in PFAS concentrations occur across various media as a result of either upstream/upgradient treatment or as a result of naturally occurring processes. Naturally occurring processes may include partitioning and subsequent retention by different media, matrix diffusion, biodegradation of precursor compounds, and dispersion. While precursor compounds may have been originally disposed of at the Site, at the time of this investigation, there was no evidence of a large concentration of precursor compounds, including at locations immediately downgradient of the two disposal areas. Partitioning of PFAS from surface water to sediment and subsequent partitioning back into surface water or groundwater may impact PFAS concentration fluctuations within a specific AOC. The dominant direction of this partitioning may change as surface water concentrations decrease as a result of remedial actions. While other PFAS-impacted sites have also found partitioning to the air-water interface within the vadose zone, soil and shallow groundwater sampling results show that this is most likely not impacting the distribution of PFAS within the groundwater and would not apply to the bedrock aquifers. Dispersion is occurring in groundwater as PFAS migrate downgradient and may impact the concentrations and location of PFAS within specific AOCs.

As the Site is composed of several interconnected AOCs, remedial actions in one targeted AOC may result in reduced PFAS concentrations entering downgradient/downstream AOCs. Subsequent concentration fluctuations within AOCs downgradient/downstream of the remedial action could result

in decreases in PFAS concentrations. This is most likely the process by which LTM would observe a reduction in PFAS concentrations within a specific AOC.

D3.1 Groundwater

The effectiveness is scored as poor for all groundwater AOCs as there is a high degree of uncertainty associated with the extent to which reducing concentrations in upgradient/upstream AOCs, many of which are surface water AOCs that infiltrate to groundwater, would result in decreasing groundwater concentrations. A large mass of PFAS is already present in the groundwater and would continue to migrate downgradient which would not achieve the RAOs. Additionally, the length of time required to observe decreasing trends from a reduction in PFAS inputs to an AOC is unknown and it is unlikely that the reduction would be sufficient to achieve statistically significant concentration reductions as outlined by the RAOs.

The implementability is scored as good because monitoring a specific AOC could easily be implemented. This scoring does not account for remedial efforts upgradient/upstream.

The relative cost is low as minimal actions would be taken.

The technology readiness is scored as good as no remedial technologies would be required.

While LTM is not expected to be effective at achieving the RAOs, LTM was retained as it may be incorporated into a Site-wide remedial approach for specific AOCs and also provides a comparison for other active remediation alternatives.

D3.2 Surface Water

The effectiveness of LTM without upgradient/upstream remedial action is scored as poor because any reductions in surface water concentrations resulting from LTM are most likely resulting from the adsorption of PFAS to sediment which could desorb back into surface water. If remedial actions were applied to an upgradient/upstream AOC, the effectiveness score would be dependent on the targeted AOC and where the treatment occurred. Preventing PFAS from being discharged from ODS would have a moderate to high effect on the Raleigh Creek AOC. These same actions would have a moderate effect on reducing impacts in AOC 6 (Eagle Point Lake), but it would likely take more time for the reduction to be observed. For similar reasons, preventing PFAS impacts from migrating from ODS via Raleigh Creek would have a poor to moderate effect on the West Lakeland Surface Water AOC as this AOC is further downstream and would require additional time for PFAS to migrate out of the system. Alternatively, treatment immediately upstream of the West Lakeland Surface Water AOC would have increased effectiveness, scored as moderate, as reductions in surface water PFAS concentrations within the West Lakeland Surface Water AOC are expected to occur more rapidly. As Lake Elmo is predominantly groundwater fed and receives minimal surface water flow from AOC 6 (Eagle Point Lake), upstream surface water treatment would not achieve the RAOs at Lake Elmo. Treatment of groundwater AOCs upgradient of Lake Elmo could result in a decrease in PFAS concentrations over a long period of time but there is uncertainty about the extent of the decrease because of the existing large mass of PFAS already within the groundwater. For this reason, LTM of AOC 8 (Lake Elmo) is scored as poor to moderate.

The implementability is scored as good because monitoring a specific AOC can easily be implemented. This scoring does not account for remedial efforts upgradient.

The relative cost is low as minimal actions will be taken.

The technology readiness is scored as good a no remedial technologies are required.

While LTM by itself would not result in reductions of surface water concentrations to achieve the RAOs, this remedial action could result in reductions in surface water PFAS concentrations and it may be utilized in a Site-wide remedial approach.

D3.3 Sediment

The effectiveness is scored as poor to moderate as there is a high level of uncertainty in the extent that sediment concentrations would decrease if surface water PFAS concentrations were reduced. Sediment concentrations can decrease as a result of desorption when the PFAS concentrations in the overlying water are reduced (Balgooyen, 2022). In theory, desorption would continue until equilibrium is achieved; however, it is uncertain how long it would take to achieve equilibrium, what the equilibrium sediment concentration would be, and if they would be below the SDSVs. Bench-scale studies would be needed to further study sediment desorption.

The implementability is scored as good because monitoring a specific AOC can easily be implemented. This scoring does not account for remedial efforts upgradient/upstream.

The relative cost is low as minimal actions will be taken.

The technology readiness is scored as good as no remedial technologies are required.

Reliance on LTM in upgradient/upstream AOCs was retained for further consideration treatment of all sediment AOCs. While this approach will most likely not achieve SDSVs in a short period of time, it may be utilized in a Site-wide remedial approach.

D4 Surface Water Hydrology Modifications

This GRA includes response actions to change the surface water hydrology in an effort to reduce PFAS migration through the Site by limiting or stopping downstream migration of PFAS through a specific pathway. None of the specific response actions will result in a reduction of the total mass of PFAS at the Site; however, they have the potential to reduce the migration of PFAS into a specific AOC and may meet the RAOs focused on reducing the spread of PFAS.

D4.1 Reroute Stream Channel

Sediment in wetlands along Raleigh Creek and in Eagle Point Lake contain high PFAS concentrations which can act as a PFAS source to surface water as it flows downstream and to groundwater as surface water infiltrates. Currently, increases in PFAS concentrations have not been observed in surface water or groundwater downstream/downgradient of these areas; however, if surface water is treated upstream of these areas, such as at the outfall of ODS, then desorption from these sediments could result in elevated downstream concentrations and subsequent migration of PFAS. Rerouting the stream channel away from these impacted sediments prevents this migration pathway from occurring. A consideration in the evaluation of this response action is the loss of water storage within these wetlands that could impact the flooding potential within the watershed. For this reason, routing around Eagle Point Lake is not feasible because of its role in the storage of water and prevention of flooding and this response action is only being considered for the reroute of Raleigh Creek around the Upper Raleigh Creek Wetland Sediment AOC and Anna's Grove Wetland Complex Sediment AOC. Laboratory column studies should be performed to better evaluate the long-term PFAS source potential of native sediment to surface and groundwater.

D4.1.1 Groundwater

The extent to which impacted sediment leaches to groundwater is unclear. As there is already a large PFAS mass within the Raleigh Creek + Eagle Point Lake Groundwater AOC, which receives PFAS-contaminated water from Raleigh Creek, preventing the continued migration of the PFAS from the sediment is unlikely to greatly decrease PFAS concentrations observed within this AOC. The effectiveness is therefore scored as poor.

The implementability of rerouting Raleigh Creek is poor as determining a new flow path and adequate storage to prevent flooding could be difficult, especially if the channel were to remain largely unlined. There would also be regulatory issues with disrupting the hydrology of wetland areas.

The relative cost is low to moderate as the initial cost would be high, but this would not require ongoing operation and maintenance costs.

The technology readiness is good as no additional technology is required.

Rerouting the stream would reduce the PFAS mass entering groundwater through infiltration; however, as substantial PFAS mass is already present within the Raleigh Creek + Eagle Point Lake Groundwater AOC, it is not expected that this approach would greatly decrease the groundwater concentrations. For this reason, this action is not retained for further consideration at this time. If PFAS are prevented from entering Raleigh Creek at ODS, yet long-term monitoring data demonstrate PFAS mass transfer to Raleigh Creek with groundwater infiltration is occurring, then this response action could be reconsidered.

D4.1.2 Surface Water

Once PFAS impacts in Raleigh Creek have been reduced at the outlet of ODS, the extent to which PFAS will continue to leach into surface water, resulting in downstream impacts within Raleigh Creek for an extended period of time, is uncertain. If monitoring shows sediment leaching is likely contributing to continued high PFAS concentrations downstream of the wetlands, then rerouting Raleigh Creek around these areas with high PFAS concentrations would have a moderately high effectiveness within the Raleigh Creek surface water AOC.

The implementability of rerouting Raleigh Creek is poor as determining a new flow path and adequate storage to prevent flooding could be difficult especially if the channel were to remain largely unlined. There would also be regulatory issues with disrupting the hydrology of wetland areas.

The relative cost is low to moderate. The initial cost would be high but ongoing maintenance costs would be low, similar to those already required to maintain the current stream channel.

The technology readiness is good as no additional technology is required.

This technology is not retained for further consideration in this FS; however, that may be reconsidered if the following are found to apply: sediment leaching is found to be a considerable and long-term PFAS source based on column leaching studies, and if monitoring determines ODS is no longer releasing PFAS through Raleigh Creek.

D4.1.3 Sediment

The effectiveness of rerouting Raleigh Creek around the wetland areas has an effectiveness score of poor for addressing sediment PFAS impacts as the sediment concentrations would remain above the Site-Specific Sediment Cleanup Values (SDCVs).

As the remedial action would be applied to the surface water AOC, the implementability, relative cost, and technology readiness are described previously.

While rerouting the stream will not result in a decrease in PFAS impacts to the sediment, this remedial action will prevent the sediment impacts from continuing to migrate downgradient. As the extent to which PFAS will leach from the sediment is unknown, this remedial action was not retained for further consideration at this time. After PFAS is prevented from entering Raleigh Creek from ODS, and if monitoring shows that the sediment is contributing a substantial amount of PFAS and will continue to do so for an extended period of time, then this action may be considered at that time.

D4.2 Piping Stream Channel

Piping a section of the Project 1007 conveyance can serve two purposes depending on the concentration of PFAS within the surface water. If the surface water is impacted with PFAS, it can prevent the infiltration and subsequent migration of this PFAS to groundwater. Alternatively, if unimpacted surface water is flowing through an area with impacted sediment, piping the surface water prevents the interaction of the water with the water and subsequent mobilization of PFAS from the sediment. This remedial alternative is only being considered for AOC 5 (Raleigh Creek Surface Water) as AOCs further downstream have larger volumes of water and piping around areas of higher infiltration such as Eagle Point Lake and the West Lakeland Storage Ponds would greatly reduce the storage of water within the Conveyance System, potentially resulting in upstream flooding.

D4.2.1 Groundwater

Preventing infiltration of PFAS impacted water from the Raleigh Creek Surface Water AOC would reduce the migration of PFAS into the Raleigh Creek + Eagle Point Lake Groundwater AOC. As there is already a large PFAS mass within AOC 7 (Raleigh Creek + Eagle Point Lake Groundwater), preventing the continued migration of the PFAS within the sediment will most likely not greatly decrease PFAS concentrations observed within this AOC or prevent the continued migration of PFAS within the drinking water aquifers. The effectiveness in achieving the RAOs is therefore scored as poor.

As the remedial action would be applied to the surface water AOC, the implementability, relative cost, and technology readiness are as described previously.

As a result of the limited effectiveness piping would have in addressing the RAOs of AOC 7 (Raleigh Creek + Eagle Point Lake Groundwater), piping was not retained for further consideration. If monitoring after PFAS is no longer entering Raleigh Creek at ODS shows a substantial mass of PFAS is entering the groundwater via leaching during infiltration, then this response action could be reconsidered at that time.

D4.2.2 Surface Water

Once PFAS impacts in Raleigh Creek have been reduced at the outlet of ODS, the extent to which PFAS will leach into surface water and cause downstream impacts within Raleigh Creek for an extended period of time is uncertain. If this the sediment is found to contribute to high PFAS concentrations downstream of the wetlands at that time, then piping Raleigh Creek would have a moderately high effectiveness within AOC 5 (Raleigh Creek Surface Water).

The implementability is scored as moderate because it could be implemented at the Site and the current flow path could be utilized. Piping could have negative implications on the hydrology of the wetlands within AOC 5 (Raleigh Creek Surface Water). Piping would also reduce the water storage capabilities within the watershed. The effect this would have on potential flooding would have to be investigated.

The relative cost is low to moderate. Implementation costs would be high but ongoing maintenance costs would be similar to that of the current channel.

The technology readiness is scored as good a no remedial technologies are required.

This technology is not retained for AOC 5 (Raleigh Creek Surface Wate) at this time. If considerable leaching is expected from sediment to surface water for an extended period of time after concentrations in Raleigh Creek are reduced, then this remedial approach will be reevaluated.

D4.2.3 Sediment

This remedial approach is not applicable to the sediment AOCs.

D4.3 Flow Reduction

Throughout the Project 1007 Corridor, primarily at the outlet of lakes, flow control structures regulate discharge from the waterbodies. These water control structures have stop logs which can be adjusted by inserting or removing stop logs to raise or lower the elevation of the flow control structure and decrease or increase flow, respectively, from the lake. Flow control structures within the Project 1007 flow path are located at the discharge of the Tri-Lakes, Eagle Point Lake Dam, Lake Elmo, and Horseshoe Lake. Of particular interest is the control structure at the outlet of the Eagle Point Lake Dam to control the flow of water from Eagle Point Lake, through the pipe at the bottom of Lake Elmo, to the discharge east of Lake Elmo where the water flows into AOC 9 (West Lakeland Surface Water). The elevation of this control structure has been maintained at 894 ft above mean sea level since the construction of the dam. Increasing the elevation of this control structure would reduce the flow of water from Eagle Point Lake to West Lakeland and store more water in Eagle Point Lake which would then be discharged via infiltration or evaporation. Modeling would be conducted prior to changing the flow control structure elevation to ensure upstream flooding would not occur. If this remedial approach was utilized, the elevation control structure may also have to be adjusted in the event of flooding or to preemptively mitigate the potential for flooding, depending on precipitation.

D4.3.1 Groundwater

This remedial approach is not applicable to the groundwater AOCs.

D4.3.2 Surface Water

This remedial action will only affect AOC 9 (Horseshoe Lake/West Lakeland Surface Water) and, potentially, AOC 8 (Lake Elmo Surface Water). The effectiveness is scored as moderate for AOC 9. Although the flow, and therefore the movement of PFAS, would cease, downstream migration would be greatly reduced, resulting in a decrease in surface water concentrations in AOC 9. This remedial action could have negative implications for AOC 8 in the event of high rainfall or snowmelt. The water level in Eagle Point Lake would be maintained at a higher level and could result in additional discharge events through the secondary control structure to Lake Elmo. This could be prevented, however, by preemptively lowering the flow control structure and allowing more water to pass through the pipe if higher water levels are expected based on rainfall or snow melt.

The implementability is scored as good as adding a stop log to the control structures and subsequent monitoring could easily be conducted. Modeling would have to be completed to evaluate the risk of upstream flooding.

The relative cost is scored as low.

The technology readiness is scored as good.

While adjusting the flow control structures will not reduce the surface water concentrations and AOC 9 would most likely still be above the MPCA Site-Specific Water Quality Criteria (SSC), this action could reduce the movement of PFAS into the West Lakeland Surface Water AOC and could be included in a Site-wide remedial alternative to reduce the migration of PFAS impacts. Reduction of PFAS loading AOC 9 could also decrease subsequent migration of PFAS into the AOC 10 (West Lakeland Groundwater), though there is already a large mass of PFAS within groundwater that would continue to migrate downgradient.

D4.3.3 Sediment

This response action is not applicable for the sediment AOCs.

D5 In-Situ Treatment

In-situ treatment is conducted without removing impacted media from a site. As PFAS do not degrade under conditions that can easily be applied in the field, relevant in-situ technologies at this time are limited and rely on the transfer of PFAS to a different phase. The options include sorption onto solid media installed as a barrier, desorption into a wash solution, aerosolization for above-ground capture during thermal treatment, and transfer into plant matter. In-situ treatment is limited to surface water, sediment, and shallow groundwater impacts. In-situ treatment was not considered for the bedrock aquifer AOCs (Washington County Landfill [WCL] – Bedrock Aquifers, Onsite and Downgradient ODS – Groundwater, Raleigh Creek + Eagle Point Lake Groundwater, West Lakeland – Groundwater) because of the depth and widespread nature of impacts in the bedrock aquifers.

The effectiveness of a surface water or groundwater in-situ treatment technology was primarily scored on its ability to reduce or prevent PFAS mass transport downstream and downgradient via PFAS sequestration in place. In addition to this, each sediment in-situ technology was scored on its ability to reduce concentrations in sediment and to prevent public exposure to sediments in exposure of the relevant SDSVs. It is unlikely that any of the in-situ treatment technologies at their current state of development can yield concentrations below the relevant SDSVs; however, they may provide more implementable and lower cost alternatives than ex-situ treatment alternatives.

D5.1 Permeable Adsorptive Barrier

Permeable adsorptive barriers (PABs) as applied for PFAS remediation are sorbent-amended materials that are installed perpendicular to the flow direction of water and remove contaminants as water freely passes through the barrier. They do not remove PFAS from the environment but rather contain it within a particular AOC. PABs have applications for groundwater, surface water, and sediment treatment and typically comprise sands, gravels, or geotextiles amended with sorbents such as colloidal activated carbon or modified clay that are specifically developed to bind to PFAS (AquaBlok, 2024; CETCO, 2022a). Important considerations when designing and placing PABs include contact time with the impacted water, PFAS loading capacity of the material, and sorbent longevity in the environment. Prior to the selection of a specific material, bench- or pilot-scale testing would be completed with materials available at the time.

For the treatment of channelized surface water, the adsorptive media can be placed in gabions and installed in stream channels; PFAS is then removed as water flows through each adsorptive gabion (AquaBlok, 2024). The required barrier size is dependent on the flow rate, PFAS concentrations, and water chemistry in the surface water body. Pretreatment filters are often installed to prevent sand or organic material from clogging the PAB (AquaBlok, 2024). Once the media is spent, the adsorptive media can be replaced or removed; the used media must be disposed of properly. While there are more examples of non-PFAS focused installations for stream channel PABs, this technology may offer an interim solution for decreasing PFAS in stream channels while additional upstream remediation occurs. Adsorptive media can also be installed at the bottom of surface water bodies to reduce PFAS infiltration to groundwater.

When applied for groundwater treatment, the barrier can be injected or trenched in depending on the required depth of treatment (AquaBlok, 2024). When injected, a colloidal material coats the targeted aquifer's pore structure so that as groundwater flows downgradient, PFAS sorbs to the barrier, resulting in reduced concentrations downgradient. The distance between injections and volume of material depends on subsurface permeability and PFAS concentrations in the groundwater. Bench-scale testing with an Aqueous Film-Forming Foam (AFFF) impacted groundwater has demonstrated 95-99% removal efficiency for long-chain PFAS species and reduced removal efficiencies for, with perfluoropentanoic

acid (PFPeA) only showing 31% removal (Yan, 2020). Applicability will depend on depth to groundwater; PABs are not applicable to deep aquifers with widespread contamination.

For treatment of sediment, PABs can be installed in the form of reactive core mats or loose aggregate installed above or below impacted sediment, often referred to as pond liners or sediment caps (CETCO, 2022a; McDonough, 2022a). For the purposes of this report, applications which mix adsorptive amendments into native sediment will be categorized as "Soil Mixing/Stabilization", as discussed in the following section, to account for the more invasive nature of installation and for their ability to address sediment leaching impacts into both groundwater and surface water. PABs installed above or below impacted sediments can only address leaching in one direction. Installation may use GAC, clays (e.g. ORGANOCLAY), apatite, or other modified sorbents (e.g. FLUORO-SORB to bind PFAS (CETCO, 2022a). Use of sediment caps may reduce the leaching of impacted sediment to surface water (CETCO, 2022b). A field demonstration of Fluoro-Sorb (a proprietary modified organo-clay) and RemBind (a proprietary material made of activated carbon, aluminum hydroxide (amorphous), and natural kaolinite clay) observed a >99% decrease in total PFAS leachability after a 1-year trial period (McDonough, 2022a) when amendments were mixed into sediment. Applicability will depend on the ability to install reactive core mats over large areas of an AOC, which could disturb the local ecosystem.

While sediment caps would not prevent leaching of the sediment to groundwater as surface water infiltrates, they would prevent impacted groundwater from discharging to surface water. Surface water liners would prevent leaching of sediment to groundwater as surface water infiltrates, but they would not prevent sediment from leaching to the surface water body. Liners for the treatment of sediment AOCs are not considered at this time due to the invasive nature of installation. For sediment treatment in channelized surface water bodies, the length of the barrier is dependent on the stream velocity to achieve sufficient contact time, or the length of time that water is in contact with the filter. To decrease the length of the barrier, the width of the stream channel could be increased to decrease flow velocity, though bench-scale testing would be required to determine required contact time.

D5.1.1 Groundwater

The only AOC where a groundwater-targeted PAB could be installed is within AOC 1 (WCL Surface Water and Shallow Groundwater). This treatment option was not considered for other groundwater AOCs because of their aquifer depths and the PFAS plume extent. While a PAB could be placed in the Quaternary or shallow bedrock units to prevent PFAS migration from ODS, treatment at ODS is outside the scope of this FS.

The effectiveness of PABs treating groundwater within AOC 1 is scored as poor to moderate. Effectiveness for this treatment option is scored based on its ability to prevent PFAS mass from migrating through the shallow groundwater to either surface water or deeper bedrock aquifers. There is already considerable PFAS mass that has spread beyond the boundary of the landfill, but a PAB could prevent additional mass from migrating downgradient. High PFAS concentrations have been observed in WCL monitoring wells, indicating that a significant amount of PFAS mass is still contained within groundwater and soil beneath and immediately downgradient of WCL. While evidence supports the ability of aquifer PABs to reduce horizontal migration, their capacity for reducing vertical aquifer migration is more uncertain, particularly in highly fractured bedrock. The longevity of the barrier and its response to changes in groundwater chemistry are uncertain. If downstream concentrations are observed to rebound, additional material may need to be injected.

The implementability is scored as moderate to good. While a large PAB would be necessary, colloidal materials could easily be injected at this Site. The distance between injections depends on Site-specific geology and would need to be determined by a pilot-scale study. Additional investigation closer to WCL would be required to optimize barrier placement.

The cost is low to moderate. Although a PAB is expected to span a large area and demand a significant amount of material to address this AOC, compared to other response actions, the costs associated with this treatment option are expected to be low. Unless downgradient sampling determines that additional material needs to be injected, no additional costs related to operations and maintenance are expected.

The technology readiness is good. Several commercial barrier products are available. Bench-scale studies and further geological characterization in the proposed injection area would aid in product selection.

PAB was not retained for further consideration for AOC 1 due to uncertainty around long-term performance and limited capacity to reduce vertical aquifer migration.

D5.1.2 Surface Water

The placement of a barrier within a stream channel could be effective at decreasing the continued migration of PFAS downstream. The effectiveness is largely dependent on the size of the PAB and what can be feasibly installed at the Site. There is insufficient evidence in the literature to suggest a barrier can achieve reductions in surface water concentrations to below the relevant standards; however, PABs could remove a large mass of PFAS and significantly decrease the total amount of PFAS that migrates downstream. For this reason, the effectiveness score for PABs is moderate to good, particularly as an interim solution.

The implementability of PABs in channelized surface water bodies is scored as moderate to good, although this will be dependent on the AOC and its surface water flow rate. Larger flow rates would require a larger barrier. Care must be taken to prevent a disruption to flow or cause upstream flooding, requiring a built-in bypass for high-flow events. The filter media, whose lifespan depends on surface water chemistry and PFAS loading, would be removed and disposed of once PFAS breakthrough occurs downstream.

The cost is low to moderate for a channelized PAB compared to other response actions. Operations and maintenance are expected to be minimal.

The technology readiness is moderate to good. While their application for PFAS remediation in surface water bodies is not common, PABs have been widely used for the treatment of other contaminants.

PAB was retained for further consideration for the Raleigh Creek, Eagle Point Lake, and West Lakeland Surface Water AOCs because these have defined stream channels in which a PAB could be installed. PABs in the form of surface water liners to target surface water infiltration were not retained due to invasiveness, high anticipated costs, and the limited anticipated effectiveness at removing PFAS.

D5.1.3 Sediment

PABs could be used to line impacted sediment at the bottom of surface water bodies to prevent leaching to surface water if sediment is found to be a long-term PFAS source. This is likely not applicable to the surficial sediments and bank areas of the sediment AOCs because sediment caps for this application would require removal of existing plant species to make way for the barrier and would also inhibit the future growth of plants. The application of PABs in the form of sediment capping at the Site can therefore address the leaching of impacted sediments at the bottom of surface water bodies, but not public exposure to surficial sediments. In the case of Anna's Grove Wetland Complex and the Upper Raleigh Creek Wetland Complexes, sediment caps that would become exposed during seasonally dry periods might prevent public exposure to impacted sediments, but the health effects of exposure to PFAS-containing caps are unknown. The extent to which leaching will be prevented once ODS is no longer contributing PFAS to Raleigh Creek is unclear. If ODS is contributing PFAS to Raleigh Creek, the effectiveness of a PAB is scored as moderate as it would prevent leaching to surface water but not to groundwater, as surface water infiltrates through impacted sediment.

The implementability is scored as poor to moderate. The majority of the sediment AOCs, including along the shoreline of Eagle Point Lake, are characterized as wetlands and a PAB, either as a mat or aggregate, may be difficult to install without impairing the wetland ecosystem.

The relative cost is scored as low to moderate relative to other response actions. If, however, the installed sorptive material is required to be removed in the future, costs could increase significantly.

The technology readiness is scored as moderate. Several products are commercially available, but their application to PFAS-impacted sites is limited.

This technology was not retained for use at the sediment AOCs at this time because of anticipated impairments to the wetland environments. If sediment leaching is found to contribute a large mass of PFAS to surface water in the future, sediment PABs be reconsidered at that time.

D5.2 Soil Mixing/Stabilization

Once soil or sediment is contaminated with PFAS, mobilization of PFAS and transport from the contaminated soil or sediment can occur, and often lasts for many years (McDonough, 2022a). Mobilization of PFAS can be reduced by adding amendments to the soil, which bind the PFAS in place and reduce the mass of PFAS that is transported from the sediment (Interstate Technology and Regulatory Council [ITRC], 2023). Materials such as activated carbon, modified clays (e.g. ORGANOCLAY), apatite, other modified sorbents (e.g. FLUORO-SORB, and biochar can be delivered to impacted areas without soil extraction via injection or in-situ mixing (ITRC, 2023; Askeland, 2020; CETCO, 2022a). Many of these materials are also used in permeable adsorptive barriers for groundwater and surface water applications.

Use of stabilization amendments may reduce the leaching of PFAS from impacted soil (CETCO, 2022b). A field demonstration of FLUORO-SORB® (a proprietary modified organo-clay) and RemBind® (a proprietary material made of activated carbon, aluminum hydroxide (amorphous), and natural kaolinite clay) observed a >99% decrease in total PFAS leachability after a 1-year trial period (McDonough, 2022a) when amendments were mixed into soil. Additional work has shown decrease of PFAS concentration in leachate after amendments are added to soil (Sörengård, 2022).

Effectiveness is impacted by soil chemistry, PFAS charge, and mineral components of the soil (ITRC, 2023), thus pilot-scale testing would be required to identify the most effective amendment for a particular AOC. This treatment option may limit effectiveness of future soil treatments, and the ITRC recommends not employing this in flood-prone areas because of the potential for PFAS-containing, amendment-stabilized soils to erode and be transported downstream or offsite. Long-term project goals must be considered prior to implementation of soil mixing/stabilization for sediment AOCs. Introduction of stabilization amendments to sediment may decrease the efficiency of future separation and destruction technologies.

D5.2.1 Groundwater

This technology is not applicable to the treatment of groundwater AOCs.

D5.2.2 Surface Water

This technology is not applicable to the treatment of surface water AOCs.

D5.2.3 Sediment

The effectiveness of soil mixing is scored as poor. This technology does not remove PFAS and therefore cannot address concerns around public exposure to impacted sediment, though it potentially could address leaching. While significant reductions in PFAS leachability from sediments have been achieved

with a variety of amendments, it is unknown the extent to which the high organic content in the sediment AOCs may impact the PFAS sorption capacity of these amendments. Additionally, sediment with high organic carbon content may sequester PFAS and limit opportunity for adsorption to the amendment. Because the sediment AOCs are in flood-prone wetland areas, it is possible for PFAS-containing, stabilized sediments to be transported downstream. Furthermore, the longevity of this technology is unclear, and the degree to which changing Site conditions might impact PFAS leachability is unknown. Bench-scale studies may clarify the compatibility of various amendments with Site sediment. This technology could be applied to any dry or seasonally dry portion of the sediment AOCs to address leaching concerns, but permanently submerged sediments would require more invasive dewatering activities prior to installation.

The implementability is poor. Most methods of mixing would be highly disruptive to the wetland environments of each sediment AOC.

The relative cost is moderate to high due to the labor required to mix amendments into the large AOCs areas.

The technology readiness is moderate. Several amendments are commercially available and have been applied as soil stabilization agents at the field level.

This technology is not retained due to uncertainty around the longevity of this technology. There are also concerns around transport of PFAS-stabilized sediment from flood-prone AOCs. This technology should be reconsidered, however, if specific areas around WCL are found to have high PFAS concentrations and found to be leaching a significant mass of PFAS, as this could be an interim measure for reducing PFAS migration offsite at WCL.

D5.3 Thermal Treatment

Thermal treatment can be applied in-situ or ex-situ to soil that has been removed from a site. Ex-situ thermal treatment is covered in Section D9.2. In-situ thermal treatment of PFAS heats impacted sediment to temperatures ranging from 350°C to 400°C to desorb and volatilize PFAS (Crownover, 2019). The vapors are captured and treated to remove the PFAS using destruction and disposal methods described in Section D9. Field studies have achieved greater than 99.9 percent removal of PFAS from impacted sediments, with heating times of 10 to 14 days (Crownover, 2019). To ensure high temperatures are applied over the treatment area, heaters must be closely spaced. This response action is typically applied in small areas with high PFAS concentrations.

D5.3.1 Groundwater

This technology is not applicable for the treatment of groundwater AOCs.

D5.3.2 Surface Water

This technology is not applicable for the treatment of surface water AOCs.

D5.3.3 Sediment

The effectiveness of in-situ thermal treatment for impacted sediment is scored as moderate. While total PFAS removal of greater 99.9 percent has been demonstrated in bench-scale analysis (Crownover, 2019), it is unclear whether concentrations could be reduced to the extent needed to prevent future leaching or downgradient migration from occurring or for full-scale treatment targets. It is also unclear the extent to which the organic- and clay-rich sediments within the sediment AOCs may impair desorption, nor were applicable depths of treatment given in the Crownover publication. This treatment

option is only applicable to the surficial portions of the sediment AOCs and cannot address submerged impacts.

The implementability is scored as poor because the sediment AOCs are located in wetland areas, and thermal treatment would significantly impair the wetland environments. The large surface area of the wetland AOCs would require extensive heating infrastructure, further hindering implementability.

The relative cost is high because of the large area that would have to be treated and the associated electrical costs.

The technology readiness is moderate. While in-situ thermal treatment is not widely used for the remediation of PFAS, it is commonly applied for other environmental contaminants.

Thermal treatment was not retained for the treatment of sediment due to poor implementability. If, however, further investigation around WCL identifies pockets of highly contaminated sediment, thermal treatment should be reconsidered.

D5.4 Soil Washing

In-situ soil washing is a process where an area of contaminated soil is saturated with a wash solution that transfers sediment-sorbed PFAS to a liquid stream for recapture and further treatment (EPA, 2020a). The wash solution mobilizes the contaminants and is collected and brought back to the surface, where it can be recirculated or sent for further treatment (EPA, 2020a). Treatment of wash water would use an ex-situ technology discussed for surface water or groundwater and is not discussed here; see Section D8.3.1 for more details.

After wash water is percolated through contaminated sediment, a pumping well would capture it below the point of contamination and route it through appropriate secondary treatment to remove PFAS (EPA, 2020a). The cleaned wash water can then be recycled through the contaminated sediment to continue the process of desorption. There is limited information in the literature about in-situ soil washing, though one field application achieved 73 percent removal of PFOS within 120 days of treatment of medium sand soils with a maximum organic matter content of 1.2 percent (Høisæter, 2021). It was projected that soil could be remediated down to 50 micrograms (μg) per kilogram (kg) PFOS (from starting concentrations of 751 to 2743 $\mu\text{g}/\text{kg}$) if treatment continued to somewhere between 587 and 1063 days (Høisæter, 2021). The same study compared in-situ and ex-situ soil washing and found higher removal rates in-situ, likely because preferential flow paths that form in ex-situ soil beds reduce contact between wash water and PFAS impacts (Høisæter, 2021).

The applicability of this technology is highly dependent on site-specific conditions such as soil permeability, organic content, and distance to groundwater (EPA, 2020a). At sites with a shallow distance to groundwater, the groundwater should be pumped and treated along with the wash solution to prevent contamination from spreading into groundwater, potentially limiting applicability to sites with shallow groundwater (EPA, 2020a). Effectiveness may decrease for clay-rich sediments and those with high organic content because of the high affinity of PFAS for organics and fine soil fractions. Bench-scale sediment leaching tests would be needed to evaluate leaching potential prior to any field implementation. Further hydraulic characterization may also be necessary to determine the conditions needed to recapture percolated water.

D5.4.1 Groundwater

This technology is not applicable for the treatment of groundwater.

D5.4.2 Surface Water

This technology is not applicable for the treatment of surface water.

D5.4.3 Sediment

The effectiveness of in-situ soil washing is scored as poor to moderate. Although the highly permeable soils within AOCs 12 (Anna's Grove Wetland Complex Sediment) and 11 (Upper Raleigh Creek Wetland Complexes Sediment) may facilitate wash water infiltration, it is unknown the degree to which the high organic content and clay-rich soils may decrease desorption efficiency of the wash water. It is also unknown whether soil washing could achieve a reduction in PFAS concentrations to a point at which leaching does not occur. This treatment option has the potential to address both public exposure to impacted sediments and sediment leaching potential. It can also address both surficial and submerged sediments.

The implementability is scored as moderate. Additional pumping and monitoring wells would need to be installed. Further characterization of Site hydrology and soil characteristics would need to be carried out. One of the separation technologies discussed in Section D7 would need to be selected to process the PFAS-containing wash water. Treatment could span several years, depending on remedial goals. This treatment option would be significantly less invasive than its ex-situ soil washing counterpart.

The relative cost is moderate. The largest portion of the cost would likely come from the PFAS separation technology selected for treatment of the wash water. The less invasive aspects of this in-situ treatment option, which avoid excavation and transportation of large volumes of waste, likely translate to reduced costs.

The technology readiness is poor. Only one in-situ study has been implemented at the field level for PFAS treatment.

In-situ soil washing was not retained for the treatment of sediment due to its limited field demonstration and the likelihood of the Site's clay- and organic-rich soils to impair the wash water's desorption efficiency.

D5.5 Phytoremediation

Phytoremediation relies on plant species to uptake, degrade, or stabilize contaminants in soil (Nason, 2024). No plant species have been identified which are capable of degrading PFAS, but several are capable of the uptake (phytoextraction) and immobilization (phytostabilization) of PFAS within soil (Nason, 2024). Phytoextraction typically involves repeated cropping and disposal of PFAS-rich biomass. If cropping occurs on a routine basis, both methods could reduce the movement and leaching of PFAS from sediment.

Phytoremediation can be carried out with existing plants or by introducing new plant species to a site that are effective at the phytoextraction or phytostabilization of PFAS. PFAS-containing biomass such as leaves, sap, or the whole plant can be regularly harvested for removal from site. Harvested biomass can be treated via a destruction technology such as incineration. Field studies exploring PFAS uptake by hemp and cattails have demonstrated during one growth season removal or stabilization between 0.2 and 2% total PFAS, or 0.09 milligrams (mg) per cubic meter (m³) to 0.21 mg/m³, for heavily contaminated sites (Nason, 2024). Another study estimated that at heavily contaminated sites, 1.4 g of PFAS can be removed per year per hectare through the regular harvest of plant matter (Gobelius, 2017). Depth of contamination and the PFAS species present must be considered when selecting plant species, as short-chain PFAS may be removed more favorably than long-chain PFAS (Nason, 2024).

D5.5.1 Groundwater

This technology is not applicable for the treatment of groundwater.

D5.5.2 Surface Water

This technology is not applicable for the treatment of surface water.

D5.5.3 Sediment

Phytoremediation could be applied to the surficial sediment AOCs 11 and 12 in Anna's Grove Wetland Complex and the Upper Raleigh Creek wetland complexes, as well as in the wetland buffers around Eagle Point Lake. The effectiveness of phytoremediation is poor due to its minimal capacity to reduce PFAS concentrations or PFAS migration.

The implementability is good. Planting, growing, and harvesting plants for phytoremediation is easily implementable. The most difficult aspects of phytoremediation would be associated with the disposal or destruction of harvested biomass.

The relative cost is low. The highest cost component would be associated with the disposal or destruction of harvested biomass.

The technology readiness is moderate. Several plant species have been demonstrated to remove some PFAS species, but removal is not cost effective or efficient.

Given its low removal efficiency and time required for treatment, phytoremediation was not retained.

D6 Ex-Situ Treatment

Ex-situ treatment removes impacted media prior to treatment. The method of removal is dependent on the media, the volume being treated, and site conditions in the target area. Groundwater is extracted via a network of pumping wells which remove impacted water prior to treatment. This could be completed at a smaller scale to target a specific AOC or migration pathway, or it could be completed on a regional scale and include the distribution to public drinking water supply and injection of treated water as is discussed for the Multi-Benefit Well Array (MBWA). For more information on the MBWA, see Appendix K (Multi-Benefit Well Array Technology Analysis). Similarly, ex-situ treatment of surface water would require pumping from the waterbody being treated, followed by discharge of effluent downstream of the extraction point. Ex-situ treatment of sediment is commonly accomplished by excavation or dredging. This screening focuses on the ability of a technology to treat the media once it is removed, with the exception of excavation and dredging for sediment removal, which are screened as independent treatment technologies.

A treatment train model is expected to be required to remove and either dispose of or destroy PFAS from the large volumes of impacted water and sediment at the Site as well as meet applicable regulatory limits that are protective of human health. A treatment train model would incorporate multiple technologies to increase overall effectiveness of treatment. Following media extraction from Site, PFAS must first be separated from the bulk media, yielding a concentrated PFAS waste stream and treated water or sediment with concentrations below the applicable criteria. The treated media can then be returned to a site or recycled. For aqueous matrices, the separated PFAS can undergo further concentration for more efficient disposal or destruction. For example, reverse osmosis reject water could undergo further concentration by surface-active foam fractionation, or ion exchange still bottoms could undergo superloading. Each of these two steps, separation followed by disposal or destruction, may contain sub-steps such as pretreatment or polishing to meet the required standards. The sections below subdivide technologies based on their potential role within the treatment train as either Target-Achieving or Non-Target-Achieving based on understanding of removal capacity relative to FS treatment targets at the time of writing this report. Categorization may change as technologies develop. Figure D.1 illustrates the general treatment train concept.

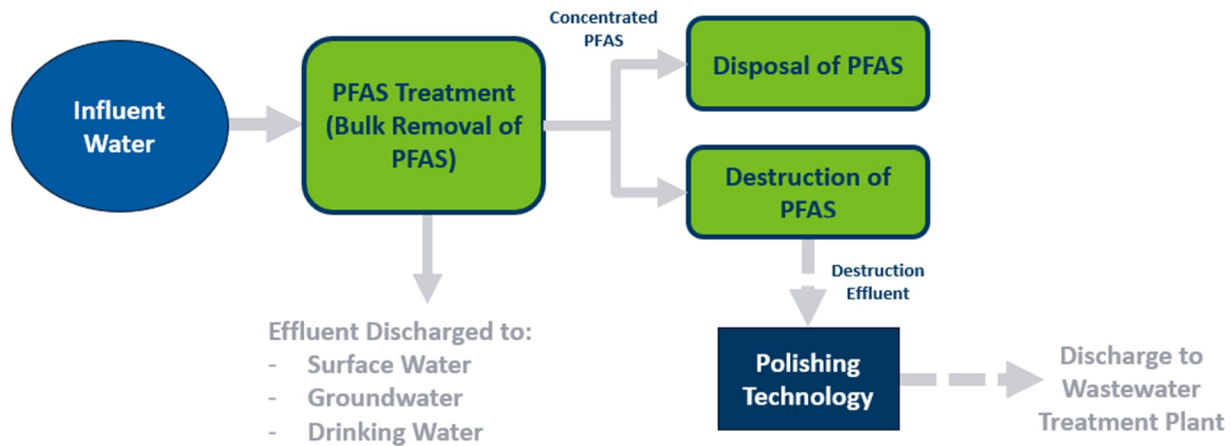


Figure D.1: Example Ex-Situ Treatment Train for PFAS Treatment of Groundwater or Surface Water.

The effectiveness scoring in the following section differs from previous GRAs as the effluent of an ex-situ treatment train will likely be required to meet specific regulatory criteria. For example, extracted and treated groundwater will likely be used as a public drinking water supply or be reinjected and be required to meet the proposed United States Environmental Protection Agency (EPA) maximum contaminant levels (MCLs) or the MDH HBVs/HRLs. Treated water discharged to a surface water body will be subject to the MDH WQV. The effectiveness of the technologies will be scored based on their ability to fulfill a specific role within a treatment train and will be justified for each specific technology below.

The scoring for implementability and relative cost of a specific technology does not account for its associated extraction system, such as an extraction well array. Approximate volumes of water or sediment required for treatment within each AOC were considered for assessing the treatment capacity of each technology. For example, treatment within the Raleigh Creek Surface Water AOC has a smaller volume than the West Lakeland Surface Water AOC.

Ex-situ treatment technologies are subdivided into the following categories:

- Water Separation
 - Target-Achieving Separation
 - Non-Target-Achieving Separation
- Sediment Treatment
- Disposal and Destruction

Standard-Achieving and Non-Standard-Achieving Separation both apply to water treatment. As these technologies would be applied similarly to surface water and groundwater, they are evaluated together. The Disposal and Destruction section (Section D9) discusses applicability to waste streams resulting from both ex-situ water and ex-situ sediment treatment.

D7 Ex-Situ Treatment: Groundwater and Surface Water Separation

Separation technologies transfer PFAS from a large volume of solid or aqueous media to a smaller volume of solid or aqueous media. This process can either transfer PFAS out of one bulk phase and into another (e.g. GAC removing PFAS from water) or reduce the volume of the initial stream (e.g. nanofiltration [NF] membrane that retains PFAS in the concentrate stream). The process yields effluent with reduced PFAS concentrations, which can then be discharged as treated effluent (e.g. returned to aquifer or distributed for drinking water) or can undergo further treatment to achieve lower effluent standards, depending on separation efficiencies and treatment targets. The reduced-volume media with high PFAS concentrations generated by the separation process can be disposed of or destroyed using a variety of methods as outlined in Section D9. Additional concentration or stabilization methods can be applied to this high-PFAS media effluent prior to disposal or destruction to improve energy efficiency, reduce waste production, and minimize future environmental releases during the following disposal and destruction steps.

While Standard-Achieving Separation technologies can be applied as the sole treatment technology, a treatment train approach which places a Non-Standard-Achieving Separation technology before the terminal Standard-Achieving-Separation stage is expected to reduce costs, energy consumption, and waste production. Each of the sorption technologies described below could be used either to separate PFAS from bulk influent streams or as a polishing step following other treatment technologies.

Liquid-Solid Separation transfers PFAS from a large volume of either groundwater or surface water to a solid media, resulting in a treated liquid waste stream with reduced PFAS concentrations and solid media containing high PFAS concentrations. The solid media must then be disposed of by landfilling or further treated via reactivation, regeneration, or destruction. Reactivation, which restores the sorption capacity of solid media and destroys PFAS in the process, occurs thermally at an offsite facility. Regeneration can occur either onsite or offsite and restores some of the media's sorption capacity, often by transferring PFAS to a liquid, gas, or steam which requires disposal or additional treatment. Destruction for bulk media has historically relied on high temperature incineration but other novel methods of destruction are in development.

GAC and ion exchange (IX) resin are the most widely used media for liquid-solid separation, however, modified clays and other novel adsorbents are an active area of research and have demonstrated success in lab settings. Most media, like GAC and modified clay, relies on adsorption to remove PFAS from the bulk liquid phase, while IX resin uses adsorption and ion-exchange to remove PFAS, by exchanging a chloride ion for a negatively charged PFAS anion. GAC and IX resin are often installed in a fixed bed pressure vessel, where media is loaded into a typically cylindrical vessel and water is pumped through the vessel to overcome the pressure head loss observed in the vessel. Fixed bed pressure vessels often utilized pre-treatment to protect the media from fouling, extending media life and decreasing pressure drop across the bed. In a fixed bed pressure vessel, Empty Bed Contact Time (EBCT) is calculated by dividing the volume of the empty vessel by the flow rate through the vessel. For example, a 1000 cubic foot vessel that had a flow rate of 100 cubic feet per minute through the vessel would have an EBCT of 10 minutes. In reality, not all liquid will flow through the vessel at this rate nor will liquid flow through the vessel at a uniform rate, but EBCT provides a standardized way to correlate time to breakthrough for different types of media and pressure vessels.

Breakthrough occurs when the contaminant of concern is detected in the effluent, and the time to breakthrough can be measured in terms of number of bed volumes. For all filtration media, removal efficiency is a function of EBCT, with longer EBCT increasing removal efficiency, though upper limits exist to removal efficiencies. Vessel geometry and flow rate through pressure vessels are therefore

determined according to effluent standards and typically require bench-scale or pilot-scale testing to determine required EBCT to treat a waste stream.

Filtration media often operate in series with two filters in a “lead-lag” arrangement. 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 depend on the treatment goals and risk tolerance of a system. In some cases, like drinking water, 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 detection limit of the compound. In other cases, breakthrough may be defined as the effluent of the lead bed reaching 50% of an applicable 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 an MCL is exceeded.

D7.1 Target-Achieving Separation

Effluent from ex-situ water treatment systems distributed for drinking water supply or injected into an aquifer will be subject to the 2024 EPA MCLs and MDH Groundwater HBVs/HRLs. These values are further discussed in Section 9.2.1 of the FS and given in Table 9.1 (EPA MCLs) and Table 9.2 (MDH HRLs and HBVs). Effluent from ex-situ water treatment systems discharged to a surface water body will be subject to the MPCA SSCs; see Section 9.2.1 of the FS for additional discussion of SSCs and Table 9.2 for SSC values. The FS treatment targets which are based on these standards, further discussed in Section 9.2.1 of the FS and given in Table 9.4 (groundwater treatment targets) and Table 9.5 (surface water treatment targets), provide the framework for scoring in the following sections; technologies which have demonstrated consistent ability to reach FS treatment targets will be categorized as “Target-Achieving”. PFOS and PFOA targets have been set to “non-detect” for drinking water supply and aquifer injection. Technologies which achieve PFOS and PFOA concentrations below current laboratory detection limits (1 to 2 ng/L) will therefore be considered Target-Achieving for those compounds.

Separation technologies that are incapable of yielding effluent to below the FS target criteria for any regulated PFAS compound are categorized as Non-Target-Achieving. These are discussed in greater detail in the next section.

D7.1.1 Single-Use Granular Activated Carbon

Single-use, or virgin GAC is a widely used and proven water treatment technology that removes PFAS and other contaminants from impacted waters. Current GAC PFAS treatment applications range from military and industrial sites to municipal drinking water facilities. Single-use GAC is approved for drinking water treatment. GAC is commonly made from bituminous coal, lignite coal, wood, peat, and coconut shells that are activated under high pressure and heat to increase the pore size and adsorptive capacity (ITRC, 2023), though bituminous coal is the most common parent material. GAC media can be housed in either a gravity filter system or pressurized vessels with the design largely dependent on the volume of water treated. GAC filter size is scaled based on treatment volumes. Treatment reliability is largely dependent on EBCT, as sufficient contact time with the media is needed to effectively remove PFAS from the bulk liquid phase (WQA, 2013).

The high surface area to volume ratio of GAC provides binding locations for PFAS; as water is filtered through GAC, PFAS adsorbs to those binding locations (WQA, 2013). Adsorption continues until the filter media binding spots are filled and breakthrough, or the detection of PFAS in the effluent, occurs. The optimal GAC for a site is determined through pilot-scale testing, as GAC will have different properties

depending on its parent material and manufacturing process (WQA, 2013). Breakthrough, measured in bed volumes, will depend on GAC type, influent PFAS concentration, specific PFAS present, and flow rate through the GAC vessel among other water quality parameters. Number of bed volumes until breakthrough may range from less than 10,000 bed volumes to greater than 80,000 bed volumes (Pannu, 2023). Once breakthrough occurs, single-use GAC is removed from the filter bed and can be sent back to the manufacturer for reactivation or disposed of via landfilling or destroyed via incineration. The effectiveness of destruction with other technologies like super critical water oxidation (SCWO) discussed in the Section D9 of this appendix, is currently being tested as well.

GAC treatment can achieve 99% or greater removal of long-chain species such as PFOS and PFOA, while short-chain PFAS may have lower removal efficiencies, though removal over 90% for many species can be expected (American Water Works Association [AWWA], 2019). Studies have shown that GAC treatment can reduce PFAS concentrations to below analytical detection limits before breakthrough occurs (ITRC, 2023). While short-chain PFAS removal is achievable, breakthrough of short-chain PFAS occurs more rapidly than with long-chain PFAS, particularly with species such as PFBA (McCleaf, 2017). Therefore, additional treatment may be required to remove short-chain PFAS following long-chain PFAS removal in primary GAC vessels. The frequency of media change out is dependent on the required effluent concentrations. Within a treatment train, filtration with GAC could be used as either the primary PFAS removal technology or a polishing step to achieve low effluent concentrations. The polishing step occurs after use of a technology capable of removing a large percentage of the PFAS but not to regulatory limits. Using GAC to remove high concentrations of PFAS from water will result in frequent GAC changeouts and increased operations and maintenance costs. Alternatively, using GAC as a polishing step after a different technology removes the majority of the PFAS, can decrease the rate of GAC usage.

Removal efficiency can be inhibited by high concentrations of natural organic matter (NOM) or other contaminants that compete with PFAS to adsorb to GAC (Darlington, 2018). Metals such as iron and manganese can also cause fouling of GAC vessels, as can excess suspended solids in the influent (AWWA, 2019). The presence of these influent co-contaminants translates to more frequent GAC replacement and less efficient removal of PFAS. Depending on the composition of the impacted waters a specific pretreatment technology may be necessary to maintain effective PFAS removal and decrease the frequency that the GAC is replaced.

D7.1.1.1 Surface Water and Groundwater

The effectiveness of single-use GAC for the treatment of surface water and groundwater is rated as good because the water could be treated to meet the applicable effluent targets. Short-chain PFAS, including PFBA, which is present in surface water at the Site, are also effectively removed with GAC, though PFBA has been demonstrated to have a shorter time to break through, relative to PFOA and PFOS. PFBA treatment targets would likely determine changeout intervals for areas with PFBA concentrations above treatment targets. NOM is present in surface water and has been shown to compete with PFAS for GAC adsorption sites. A pretreatment step to remove NOM would be recommended to maintain efficiency. Pretreatment is also recommended for groundwater to remove iron and manganese which can precipitate and foul the filters, reducing PFAS adsorption capacity. Additionally, radon can naturally occur in groundwater and be removed by GAC; if levels are high enough, this can require airing out the GAC for a period of time prior to disposal to decrease the radioactivity.

The implementability of single-use GAC is moderate depending on the AOC being targeted and the volume of water being treated. GAC filters in comparison to other filtration media require more media and therefore a larger system footprint. Additionally, pretreatment for both surface water and groundwater could increase the complexity of the treatment plant, depending on how extensive pretreatments needs prove to be. In addition to reactivation, treatment or disposal options for spent single-use GAC could include landfilling, incineration, and possibly SCWO. However, the future of

regulations regarding offsite disposal is uncertain, and the availability of facilities accepting PFAS-containing waste may become more limited.

The relative cost is scored as high. While operations costs are generally lower for GAC filtration compared to other media, the costs associated with GAC replacement and disposal are high. Frequent replacement of GAC to remove short-chain PFAS would increase costs further.

The technology readiness is good as this technology is widely implemented at the capacity required to treat all the AOCs.

This technology was retained for further consideration for the treatment of groundwater and surface water. GAC is a reliable way to treat water to meet the applicable targets. If this technology is selected, however, the ability to use reactivated or regenerated GAC should be routinely reanalyzed to determine if either of these options is more cost effective than single-use GAC.

D7.1.2 Reactivated Granular Activated Carbon

Reactivated GAC uses the same removal mechanisms as single-use GAC except that instead of disposing or destroying the spent GAC, it is treated with steam at high temperatures without oxygen to strip PFAS and other contaminants from the active sites on the GAC, restoring the capacity of the GAC to adsorb more PFAS (DiStefano, 2022). The off-gas is then treated to destroy PFAS and other contaminants through high temperature incineration (DiStefano, 2022). The reactivated GAC has adsorptive properties comparable to single-use GAC and can achieve SSC. There are no reactivation facilities in the state of Minnesota resulting in potentially higher transportation costs to bring the GAC to a reactivation facility. Reactivated GAC can come from bulk GAC that has been mixed at the reactivation facility and from multiple customers, including both virgin GAC and GAC that has previously undergone reactivation (WQA, 2013).

When GAC changeouts occur, a site does typically not retain its own GAC and would receive a mix of reactivated GAC. Alternatively, if a user's demand is large enough, virgin GAC can be purchased by a facility and can be reactivated without the mixing in of multiple customers' GAC. This requires a large volume of GAC, typically >80,000 lbs per changeout event, (Barr, 2023), to be reactivated at the same time. Once the GAC is reactivated, the same GAC would be returned to the Site for use, though storage of the reactivated GAC and logistics of the material handling increase the complexity of maintaining a GAC unique to a single facility. Bulk reactivated GAC cannot be used for drinking water treatment, though it is possible that GAC kept specific to a site and reactivated in a food grade facility could be used for drinking water treatment (WQA, 2013). NOM, iron, and manganese can shorten GAC media life, potentially requiring a pretreatment step. Additionally, radon can naturally occur in groundwater and be removed by GAC; if levels are high enough, this can require airing out the GAC for a period of time prior to disposal to decrease the radioactivity (WQA, 2013).

Due to the increased complexities of maintaining control of the same GAC through reactivation as well as the relative scale needed, it is not recommended at this time. Only bulk reactivated GAC is considered going forward. This should be re-evaluated, though, if the decision is made to use treated water as a drinking water source.

D7.1.2.1 Scoring

The effectiveness of reactivated GAC is scored as good, as treatment targets could be met with reactivated GAC. As with virgin GAC, reactivated GAC can meet the applicable targets for surface water and groundwater, though media usage would likely be increased significantly at WCL due to higher levels of PFBA present. A pretreatment step would be required for the treatment of surface water to maintain high efficiency due to higher concentrations relative to groundwater of NOM competing with the PFAS for adsorption sites. Pretreatment is also recommended for groundwater to remove iron and manganese which can precipitate and foul the filters, reducing PFAS adsorption capacity.

The implementability is good, as reactivated GAC is widely used for PFAS treatment. If desired for drinking water use, however, implementability would depend on the treatment plant's ability to manage large amounts of GAC that require reactivation.

The relative cost is scored as moderate to high. Costs provided by Calgon Carbon indicate reactivation is typically cheaper than virgin GAC by up to 50%. Disposal costs may also be decreased by reactivation, though the degree of cost savings may be dependent on the transportation costs and distance to the nearest reactivation facility. Outside of costs associated with the GAC, operation and maintenance costs are generally low. As with single-use GAC and other filtration media, the need for pretreatment would add to material and operation and maintenance costs.

The technology readiness is good as this technology is already implemented at the treatment capacities required at all of the AOCs.

Reactivated GAC is retained as a treatment technology for surface water and groundwater as it can meet treatment targets and offer cost savings compared to virgin GAC.

D7.1.3 Regenerated Granular Activated Carbon

Regenerated GAC uses the same removal mechanisms as single-use GAC except that instead of reactivation, disposing or destroying the spent GAC, it is treated onsite with a solvent or steam under lower temperature conditions than reactivation to remove contaminants (Márquez, 2022). Thermal regeneration heats GAC to 200°C with steam or nitrogen, as opposed to the higher temperatures required by reactivation (Márquez, 2022). Historically this has been used for regeneration of GAC vessels targeting non-PFAS contaminants, though efforts are being made to apply the same principles to removal of PFAS from exhausted GAC vessels (Baghirzade, 2021). High temperature desorbs PFAS and transfers it into a condensed aqueous waste stream for destruction or disposal (Baghirzade, 2021). Solvent regeneration, which can occur onsite, desorbs PFAS using a chemical solution such as ethanol and ammonium hydroxide. The PFAS is concentrated into a liquid waste stream for disposal or destruction (Revive, 2023). The regenerated GAC is typically not as efficient as single-use or reactivated GAC (Baghirzade, 2021) and may require regenerations at a higher frequency than media changeouts; however, it could still achieve the treatment targets.

Desorption efficiencies at the commercial level have been demonstrated up to 93% for PFOA and 65% for PFOS, resulting in similar adsorption isotherms for virgin and treated GAC (Battelle, 2024). The regenerant solution can be further distilled and concentrated for disposal or destruction. This technology is commercially available (Revive, 2023), though is currently not yet available at a scale needed to treat the vessel sizes that would be used for large scale treatment (e.g. 20,000 pound GAC vessels), nor is it approved for drinking water treatment at the time of writing this FS.

Alternatively, another regeneration method is in development which destroys PFAS rather than transferring it to an aqueous waste stream. Hydrothermal alkaline treatment (HALT), which is discussed in more detail in Section D9.4, uses high temperature, pressure, and pH to destroy PFAS compounds and convert them to inert salts. While scale-up efforts have been focused on liquid waste, bench-scale work with HALT regeneration has demonstrated up to 99% destruction of PFOS (Soker, 2023). Based on bench-scale work, it may be more energy efficient to regenerate spent GAC using HALT rather than thermal regeneration (Soker, 2023). However, significant scale-up efforts are required before implementation of HALT regeneration of GAC.

D7.1.3.1 Scoring

The effectiveness of regenerated GAC is moderate, with PFAS removal performance often comparable to virgin GAC and capable of meeting the applicable treatment targets although more frequent GAC changeouts may be required. A site-specific study would be required to evaluate both ability of the GAC to be regenerated and to assess the time to breakthrough and EBCT required with the regenerated GAC.

The implementability is moderate. The size and complexity of the treatment plant would depend on the AOC being treated and the required treatment plant capacity. The addition of regeneration does increase the complexity of the system as does pretreatment for NOM (surface water) and iron and manganese (groundwater). Regeneration would not remove NOM or metal fouling from the GAC, increasing the importance of pre-treatment to extend the life of regenerated GAC vessels.

The relative cost is high. The capital cost of onsite regeneration equipment is higher than for a single use GAC system, but the cost to regenerate GAC may be lower than the cost of new GAC over the lifespan of the system.

The technology readiness of GAC regeneration is poor to moderate, depending on the method of regeneration. Not all onsite regeneration technologies may currently be scalable to treat the volume of GAC required depending on the target AOC(s).

Regenerable GAC was retained for surface water and groundwater as it is capable of meeting the treatment targets and would be an option for decreasing media use.

D7.1.4 Single-Use Ion Exchange

PFAS removal by IX resin is typically comprised of positively charged polystyrene beads that contain a neutral hydrophobic backbone and positively charged exchange sites (Dixit, 2021). PFAS are adsorbed to the surface through electrostatic interactions of the negatively charged PFAS head groups and the negatively charged IX and through hydrophobic interactions between the fluorinated alkyl chain and polymer backbone of the IX (Woodard, 2017). When PFAS-containing water passes through a bed of IX, PFAS are removed from the bulk liquid as their hydrophobic “tails” adsorb to the resin’s hydrophobic backbone and crosslinks and as their negatively charged anionic “heads” fix to resin exchange sites (Woodard, 2017). This continues until the binding sites have been filled and breakthrough occurs. At that point, spent single-use resin can currently be landfilled or incinerated. Single-use IX is certified for potable water use through NSF 61 (ITRC, 2023).

Different types of IX resin are commercially available, namely “weak-base” and “strong-base” resins (Dixit, 2021). Weak-base resins typically have a primary, secondary, tertiary, or mixed amine functional group, are more resistant to organic fouling, and may be re-used through regeneration (note: regeneration is covered in more detail in Section D9.7.1.5), but typically must be operated below neutral pH (Dixit, 2021). Strong-base resins typically utilize a quaternary ammonium functional group and are characterized by their stability and ability to exchange with many anions across a wider pH range (Dixit, 2021). Rapid small-scale column test (RSSCTs) and/or pilot-scale testing would be required to determine the optimal IX based on the PFAS mixture and water chemistry.

IX has demonstrated PFAS removal efficiency of up to 97-99.99 percent for both short- and long-chain PFAS (Ellis, 2022; ITRC, 2023; Riegel, 2023; Tamanna, 2023). IX can be used for influent streams containing PFAS at concentration ranges from hundreds of parts per billion total PFAS to treat below detection limits in field applications (ITRC, 2023; Woodard, 2017). Removal efficiency is dependent upon resin type and sufficient EBCT, though IX requires much shorter EBCTs relative to GAC (AWWA, 2019; Woodard, 2017). Though ion exchange resin will remove long-chain PFAS more efficiently than short-chain PFAS and has a longer time to breakthrough time for long-chain PFAS compared to short-chain PFAS for the same functional group, ion exchange resin will significantly outperform GAC for short-chain PFAS removal (AWWA, 2019).

Time to breakthrough can range from 1,000 to 100,000 bed volumes depending on resin type, EBCT, the PFAS compounds present, and influent concentrations of PFAS, total dissolved solids (TDS), and organic material (Boyer, 2021). Anions and organics present in the influent water can compete with PFAS for binding locations and therefore decrease the lifespan of a resin (AWWA, 2019; Dixit, 2021).

Pretreatment may be required to extend the life span of the IX, and pH can impact resin properties and,

in turn, removal efficiency (Purolite, 2024). To prevent scaling and fouling and optimize performance, pretreatment needs to be considered in the design and may include pH adjustments and a reduction of TOC and TSS levels (AWWA, 2019; Purolite, 2024).

The cost per cubic foot of new resin can be \$450, based on budgetary pricing provided by a vendor for this FS. The operating expenses of single-use resin range from \$0.15 to \$0.40 per 1000 gallons (gal) (Purolite, 2018). Bench-scale or pilot-scale studies would be required to better estimate resin consumption and costs. IX media selection and system design are highly site-specific and must be selected after completion of RSSCTs for optimal performance.

D7.1.4.1 Scoring

The effectiveness of treating PFAS-containing surface water or groundwater via single-use ion exchange resin is scored as good because of its potential to remove up to 99.99 percent of PFAS and achieve applicable treatment targets. Its effectiveness is dependent upon resin selection, vessel design, and EBCT. Pretreatment may be required for both groundwater and surface water to prevent fouling of the IX.

The implementability of single-use IX is moderate depending on the AOC being targeted and the volume of water being treated. IX does require a smaller footprint compared to GAC treatment, increasing the implementability. The required pretreatment for both surface water and groundwater increase the complexity of a treatment plant compared to a GAC treatment plant. Treatment or disposal options for spent single-use IX are currently limited to landfilling and incineration, although the future of regulations regarding offsite disposal is uncertain, and the availability of facilities accepting PFAS-containing waste may become more limited.

The relative cost of single-use IX is scored as high. The size and cost of a treatment plant would be dependent on the required treatment volume. Pretreatment may also significantly increase costs. Operations and maintenance costs are also high as resin management, including disposal, can be expensive (AWWA, 2019). RSSCTs comparing various IX and GAC media are necessary to predict the optimal type and quantity of media, which helps to reduce operating costs.

The technology readiness of single-use IX is scored as good. Ion exchange resins are widely commercially available. New resins are being developed to improve the treatment of PFAS and these could be used, depending on pilot-scale study results and commercial availability.

This technology was retained for further consideration for the treatment of groundwater and surface water. Ion exchange is a reliable way to treat water to meet the applicable standards. If this technology is selected, however, the ability to use regenerated IX should be routinely reanalyzed to determine if it is more cost effective than single-use IX.

D7.1.5 Regenerable Use Ion Exchange

Regenerable IX relies on the same mechanisms for PFAS removal described in the Single-Use Ion Exchange section above; however, it extends the lifespan of resins by desorbing PFAS from spent resin to allow the resins to be reused, thereby reducing solid waste from IX resin. The solution required for regeneration is dependent on PFAS composition and concentration in the raw water (ITRC, 2023). The solution is typically a mixture of a salt or base to desorb the anionic head group and an organic solvent to desorb the hydrophobic fluorinated tail (Dixit, 2021; ITRC, 2023; Woodard, 2017). Regeneration could occur onsite or offsite at a regional facility, though offsite regeneration is not widely available at the time of this report. Distillation then removes and reclaims the solvent from the regenerant solution, producing the final concentrated, high-salinity waste stream, referred to as the “still bottoms” (Wang, 2021b). The still bottoms can also contain high concentrations of anions that get sorbed by the media (e.g. nitrates or sulfates) and high concentrations of organics, depending on the influent waste stream. Regenerable IX is not yet approved for potable water treatment per NSF 61 (ITRC, 2023).

The still bottoms must be further processed, and several approaches currently exist. If the volume is small enough, the still bottoms can be sent to a destruction technology system suited for high total dissolved solids, which is discussed below. Alternatively, the concentrated still bottom can be sent through a small volume of adsorption media at a low flow rate (long EBCT) to “superload” the media (Woodard, 2017). Recovered solution can then be recycled, and the spent media transported offsite for disposal at a landfill or incineration facility (Woodard, 2017). An alternate approach is to further concentrate the still bottoms by dewatering the waste stream. This can be accomplished using technologies such as a closed-circuit RO membrane (also known as batch RO) or thermal evaporation, among others. The further concentrated still bottoms would then be sent for destruction or disposal.

Desorption efficiency of regenerant solutions can reach up to 90 percent or more (Boyer, 2021; Woodard, 2017). Although some resin regeneration has demonstrated success returning sorptive capacity to near-virgin conditions, regenerable resins typically have lower sorptive capacity of single-use resins, which may result in longer EBCTs when compared to single-use resins (ITRC, 2023). The number of bed volumes a regenerated can treat will be less than a single-use resin, and the number of bed volumes that can be treated will decrease as more regeneration cycles have been performed. Regeneration frequency is highly variable and site-specific. The cost to regenerate spent resin has been estimated to range from \$5-\$100 per cubic foot of resin (Barr, 2023). IX resin beads can start to degrade over time, causing resin fines to form, which may lead to plugging issues in IX beds. Biological growth can also be an issue, as can loss of capacity due to competing anions (nitrates/sulfates) out competing PFAS molecules for active sites on the resin (Purolite, 2024; ITRC, 2023).

D7.1.5.1 Scoring

The effectiveness of treating PFAS-containing surface water and groundwater with regenerable IX is scored as good because of its potential to remove up to 99.99% of PFAS. Applicable treatment targets could be achieved using regenerable IX.

The implementability of regenerable IX is moderate. Unlike single-use resin, regenerable resin can be regenerated as soon as breakthrough is observed. For treatment plants with onsite regeneration capabilities, the regeneration step could occur more quickly than a media changeout. Regenerable resin furthermore reduces the volume of solid waste and reduces the uncertainty related to landfilling disposal regulations when compared to single-use resin, as resin will not need to be disposed of as frequently. These added benefits, however, come with increased WTP size and operations and maintenance and regulatory (air permitting, etc.) requirements because a regeneration facility would also be required. The rationale for the lower score is because regenerable ion exchange is not currently approved for drinking water treatment and could not be used to treat groundwater intended for use as drinking water. If regenerable ion exchange was approved for drinking water treatment or if it was allowed for treatment prior to groundwater injection, then the scoring would improve.

The relative cost of regenerable IX is scored as high. Capital costs for an onsite regeneration system would significantly increase initial cost, as specialty metals and components will be required for the combination of high salt and solvent conditions. Capital costs for onsite regeneration equipment would also be dependent on the required treatment capacity, and pretreatment would be required for both groundwater and surface water. The operating cost of regenerating spent resin is lower than the cost of new resin, though the costs of running a solvent recovery system (distillation column/hot oil heater) could negate these cost savings if resin does not have to be regenerated as frequently as expected. Regenerated resin has reduced sorptive capacity when compared to single-use resin. This will eventually translate to more frequent regeneration cycles and ultimately a higher maintenance demand and cost (ITRC, 2023). The process of regeneration necessitates higher energy consumption, but also decreases the energy demand of a downstream destruction technology by decreasing the volume of waste. A possible option to reduce overall costs is to have a regional regeneration facility that could be used by all communities utilizing IX to address PFAS impacted drinking water.

The technology readiness is moderate. Regenerable ion exchange resins are commercially available and have been demonstrated in pilot-scale and limited full-scale applications, but they are not as widely used as single-use IX, nor are offsite resin regeneration services widely available.

Regenerable IX is retained for the treatment of groundwater and surface water if the water will not be used for public distribution.

D7.1.6 Novel Adsorbents

Novel adsorbents, an alternative to GAC and IX, have been developed with improved PFAS adsorption capacity to reduce the rate of media changeouts. Of these, modified clay adsorbents are the most common and have been used in pilot-scale and full-scale treatment systems. Modified clays have high surface areas and are typically made of smectite clays treated with a surfactant. As with ion exchange resin, modified clays in fixed bed pressure vessels rely on the dual mechanisms of adsorption and ion exchange to remove PFAS from aqueous media. They have also demonstrated success as soil amendments for reducing leaching of PFAS from impacted soils (Wang, 2021a). Spent clays could be landfilled or incinerated. While solvent regeneration of modified clay has been proven in some laboratory settings, research is limited, and the surfactant “modifiers” can be lost with each regeneration process (Dong, 2021). Modified clay’s capacity for reuse is therefore unlikely.

Modified clay can achieve up to 95 to 99 percent removal of all PFAS compounds from aqueous waste streams, encompassing both short- and long-chain PFAS, down to below detection limits (Yan, 2020). As with other adsorption-based filtration technologies, the mobility and solubility of short-chain PFAS makes them more challenging to remove, but modified clays have demonstrated longer bed life for short-chain PFAS compared to GAC (Mukhopadhyay, 2021), with one study demonstrating greater than 100,000 bed volumes before breakthrough occurred on water also tested with GAC (Pannu, 2023). Removal can be impacted by pH, NOM, competing ions, ionic strength, and temperature (Mukhopadhyay, 2021). Although evidence suggests that the removal efficiency of modified clays is less impacted by organic matter than GAC and IX, pre-treatment is recommended to reduce fouling and competition of ions (Barr, 2023). The number of bed volumes prior to breakthrough could be higher with modified clay; however, a Site-specific study would be required to confirm this.

Other novel adsorbents are also in development and while these are not currently used at full-scale, they could be evaluated for future use. They include materials such as polymer-coated sand, modified cyclodextrin, gel polymers, cellulose, and metal-organic frameworks. Materials are often modified to increase surface area or with a surfactant (Mukhopadhyay, 2021). Novel adsorbents may also have the advantage of improved regeneration. DEXSORB®, for example, is made from corn and claims to be effective even after multiple cycles of regeneration (Cyclopure, 2024). Bench-scale testing of DEXSORB® demonstrated >62% average removal for all PFAS tested, with higher removal for PFOS, PFOA, PFBS, and PFBA (Ching, 2020), though removals would not meet targeted treatment levels for this Site.

D7.1.6.1 Scoring

The effectiveness of treating PFAS-containing surface water or groundwater via novel adsorbents is scored as moderate to good because of their potential to remove up to 99 percent of PFAS and in some cases reach treatment targets. The effectiveness is expected to be variable based on the adsorbent and its ability to remove PFAS from the Site-specific water. A bench-scale study would be required to better evaluate effectiveness and adsorption capacity.

The implementability of novel adsorbents is moderate. Though modified clay in the right application may have an extended bed life in comparison to other sorption media, and thus a reduced volume of solid waste due to less frequent changeouts, disposal options are likely limited to landfilling or incineration. Regeneration is not currently feasible, though future ability to regenerate would decrease solid waste but introduce additional complexity to the treatment process. The capacity of the treatment

plant and volume of media would be dependent on the targeted AOC and volume of water being treated. Novel adsorbents are not approved for drinking water treatment so they would likely not be implementable for groundwater treatment in cases where the groundwater would be distributed as drinking water or injected into groundwater.

The relative cost of modified clay adsorbents is scored as high. Pretreatment would likely be required for both the treatment of surface water and groundwater to extend media life.

The technology readiness of modified clay is scored as poor to moderate. Modified clays are commercially available; however, they are not approved for the use of drinking water in the state of Minnesota. Other novel adsorbents are not yet commercially available or are only being implemented at the pilot-scale. These novel adsorbents, however, could potentially replace GAC or IX after implementation at a later date if it was determined that they were highly effective.

Novel adsorbents, specifically modified clay, are not retained for the treatment of groundwater because they are not approved for drinking water treatment and have limited full-scale use compared to GAC and IX. Novel adsorbents, however, should be further investigated in the future, particularly if short-chain PFAS removal is demonstrated to be superior to GAC or IX.

D7.1.7 Nanofiltration and Reverse Osmosis

Nanofiltration (NF) and reverse osmosis (RO) membranes are widely used separation technologies that are approved for drinking water treatment for a variety of contaminants. NF and RO membranes used for PFAS rejection are typically constructed from thin-film composite polyamide membranes. Pore size for commercial NF membranes was found to be 0.3-2.1 nm, while RO membranes are typically ~0.1 nm (Liu, 2022). NF and RO both operate by forcing water through semi-permeable membranes at pressures ranging from 70 to 600 pounds per square inch (psi) (AWWA, 2020). PFAS is rejected by the membrane and remains in the concentrate while the majority of the water passes through the membrane to become clean permeate. The primary difference between RO and NF is the pore sizes in the membrane, where RO has a smaller pore size than NF, resulting in the rejection of smaller molecular weight molecules. NF membranes can reject divalent ions like calcium (Ca^{2+}) at high efficiencies, but rejection of monovalent ions like sodium (Na^{+}) will be significantly lower. RO, however, will reject both monovalent and divalent ions at high efficiencies.

Both RO and NF membranes rely on size exclusion for filtration, although adsorption and electrostatic interactions can also increase removal. The surface of membranes is typically negatively charged, which can lead to electrostatic repulsion of anionic PFAS and other dissolved contaminants, which can improve rejection. This may be particularly important in NF applications, as size exclusion alone may not reject all PFAS of concern, particularly short-chain PFAS. Water chemistry, membrane properties, and contaminant properties also impact the removal efficiency, as high levels of NOM or cations (e.g. Ca^{2+}) can reduce the importance of electrostatic repulsion (Verliefde, 2008). The smaller pore sizes of RO membranes result in the rejection of smaller molecular weight species, but this does result in a lower flux, or rate of water moving through the membrane, and a larger volume of concentrate that must be disposed of or further treated. A typical recovery, or percentage of feed water that passes through a membrane) will be 85% to 95% for NF membranes, while recoveries of 70% to 85% are observed for RO membranes. The tighter pores of RO membranes will also require a higher feed pressure (150 to 600 psi) to force water through the RO membrane; NF membranes can operate at lower feed pressure of 70 to 150 psi (AWWA, 2020).

Both RO and NF can remove short- and long-chain PFAS, though RO membranes have generally been observed to have higher removal efficiency as a result of the smaller pore size (Liu, 2022). RO has been found to remove PFAS to below the detection limit, with rejections over 99% for all PFAS species tested (Liu, 2021). Studies have also demonstrated over 99% removal for PFOA and PFOS for NF membranes (Zhao, 2013; Boo, 2018), though the removal efficiency of short-chain PFAS like PFBA is significantly

more varied, with one review finding most studies reported rejections less than 80% for PFBA (Liu, 2022). Rejection of PFAS and membrane recovery will depend on variables including water quality parameters, pore size, charge of membrane, and PFAS concentrations. Pilot-scale testing would be required to evaluate if RO and NF are capable of meeting the applicable standards with Site-specific water, specifically the PFOA, PFOS, and PFBA limits.

Pre-treatment will be required for NF and RO as the membranes are susceptible to scaling and fouling by inorganic salts, organic matter, and microbial growth (ITRC, 2023). Conventional water treatment technologies such as sand filtration, greensand pre-filtration for iron and manganese removal, low-pressure membranes like ultrafiltration (UF), cartridge filters, and GAC filters can be used as pre-treatment options to reduce the potential for scaling and fouling of the membranes. The specific method of pre-treatment used should be selected based on source water chemistry in order to achieve the most efficient use of the membranes. With pretreatment and proper maintenance, membranes can last up to 10 years without observed decreases in removal efficiency (AWWA, 2020).

After separation, the permeate and concentrate streams may be discharged separately. If discharged separately, permeate would likely require remineralization to decrease the corrosiveness of the permeate, which is caused by the relative lack of dissolved minerals in the permeate. A post-membrane unit operation which restores alkalinity and stabilizes pH in the permeate is often accomplished by sending the permeate through a calcium carbonate bed or adding lime/carbon dioxide. The concentrate stream would require further treatment, which could include treatment with GAC or IX, destruction, or incineration.

Alternatively, the permeate and concentrate streams may be re-blended before final discharge. The membrane concentrate would first undergo treatment with GAC, IX, or other separation technology to remove PFAS. Remineralization of the permeate stream occurs by adding the concentrate stream, which contains the dissolved ions removed by the membranes, back into the permeate stream.

Treatment of the concentrate stream will require less media vessels than a GAC- or IX-only treatment system. The volume of the concentrate typically will be up to 15% the initial volume for NF and up to 30% of the initial volume for RO membranes, though pilot-scale testing is required to determine appropriate recoveries for each AOC. The reduction in the volume of the concentrate will reduce the number of vessel pairs required for GAC or IX treatment. This can help reduce the building footprint that is required, reduces the capital costs of media pressure vessels, and may improve GAC and IX performance by concentrating the PFAS prior to treatment.

The footprint for a NF or RO treatment plant by itself would be relatively small, however, the necessary pre-treatment and post-treatment systems can add significantly to that footprint. NF installations will be smaller than RO installations, as the flux through each membrane is higher for NF membranes. The permeate flux in an NF system ranges from 14 to 20 gallons per square foot per day (gfd), while the expected flux of an RO system would be 7 to 15 gfd (AWWA, 2020), necessitating more membranes and a slightly larger system for the same volume of water treated.

D7.1.7.1 Scoring

The effectiveness of treating PFAS-containing surface water or groundwater with RO is scored as good because it is expected to achieve the applicable treatment targets. The effectiveness of NF is also scored as good as applicable targets would likely be achieved; though pilot-scale testing would be required to optimize PFBA rejection.

The implementability of RO and NF is scored as moderate. The size of the treatment plant is smaller than required for other treatment technologies although the required pretreatment and potential destruction technologies would add to the size and complexity of the treatment plan.

The relative cost of RO and NF is scored as high. The capital costs for NF and RO will be high. Operation and maintenance costs will also be high with an NF or RO system due to the high head pressure that is required of the pumps and maintenance of the membrane modules (AWWA, 2020). Additional costs will include pre-treatment and post-treatment infrastructure, operation and maintenance costs, and disposal of concentrated waste if post-treatment is not capable of treating the concentrate.

The technology readiness is scored as good. RO and NF are used in large-scale drinking water applications and membranes are commercially available and approved by NSF for drinking water treatment.

RO and NF are retained as a technology capable of removing PFAS from groundwater as this technology could likely achieve the drinking water standards and provides an alternative to the use of solid filtration media. RO and NF are not, however, retained for surface water because of the costs and complex treatment plant required for pre-treatment. At this time, these two technologies are considered together and, if selected, the type of membrane would be selected after bench-scale or pilot-scale tests.

D7.2 Non-Target-Achieving Separation

Separation technologies that are incapable of yielding effluent concentrations below the applicable treatment targets as previously discussed are categorized as Non-Target-Achieving. A treatment train approach which places a Non-Target-Achieving Separation technology before the terminal Target-Achieving-Separation stage is expected to reduce costs, energy consumption, and waste production. Effectiveness is therefore scored against the ability to achieve high PFAS mass removal for Non-Target-Achieving Technologies. Not all “non-target-achieving” separation technologies are discussed here; only those that are well demonstrated and highly effective have been included.

D7.2.1 Chemical Coagulation and Flocculation

Coagulation followed by flocculation is commonly used as pretreatment at municipal WTPs to remove particulates as well as some dissolved constituents. A coagulant is added to the raw water to destabilize suspended particles and decrease required settling time. This process improves water quality by removing suspended solids from water and can protect downstream filters by reducing the rate at which they clog. The coagulant is initially mixed quickly followed by a period of slow mixing to promote the formation of flocs or larger clumps of particles that more easily settle. Alum, ferric salts, and polyaluminum chlorides are commonly used in water treatment; however, for the treatment of PFAS, these have been shown to have limited success and would require additional polishing to achieve low effluent concentrations (ITRC, 2023). A 99% removal efficiency of PFOA has been observed with polyaluminum chlorides, but other studies have shown a removal rate of 1-25% which is more typical of studies with alum (1-20%) and ferric salts (1-50%), with the removal efficiency dependent on the coagulant dose (ITRC, 2023). A specialty biodegradable polymer, PerfluorAd[®], has been shown to remove over 99% of PFOS and to reduce total PFAS by 99.6% (Cornelson, 2021). This coagulant, however, is typically used for rinse water of firefighting foam tanks and not for drinking water, and the initial concentration of total PFAS was 1.7 mg/L, which is generally several order of magnitude more concentrated than AOCs in this Site. Additionally, the remaining concentration of PerfluorAd[®] in the water post flocculation and its effect on downstream treatment is unknown.

D7.2.1.1 Scoring

Coagulation and flocculation could potentially be used as a pretreatment option prior to filtration to address particulates, especially to remove particulates found in surface water; however, the effectiveness for PFAS removal is poor. In areas with higher initial PFAS concentrations, PerfluorAd[®] may perform well as a method to remove the bulk of PFAS in a sample. With the more dilute concentrations

that are observed in the AOCs on this Site, however, its effectiveness is unknown, and PerfluorAd® is scored as poor. Bench-scale or pilot-scale studies could change this scoring in the future.

The implementability of a coagulation and flocculation system is poor. PerfluorAd®, which is the most effective, could not be used with either groundwater or surface water as the concentration of the polymer remaining in the water is unknown, as are the potential human and environmental health effects. Other coagulants already used with drinking water treatment could be implemented with a treatment train approach, but limited PFAS removal would be expected. The accumulated sludge would require disposal or destruction.

The relative cost is moderate as the required infrastructure is potentially smaller in comparison to a larger treatment facility.

Technology readiness is moderate as this technology is commonly used in water treatment for solids removal but demonstrate use for PFAS removal is limited.

Chemical coagulation and flocculation was not retained as a PFAS treatment technology for surface water or groundwater. If future work demonstrates effective PFAS removal from more dilute samples by PerfluorAd® or similar products, coagulation and flocculation could be used a pretreatment prior to an additional PFAS treatment technology for groundwater or surface water, but the technology is not ready at this time.

D7.2.2 Electrocoagulation and Flocculation

Electrocoagulation followed by flocculation is similar to traditional coagulation; however, instead of destabilizing the suspended particles with chemical addition, the particles are destabilized with an electrical current, causing them to form flocs, which are more easily removed through sedimentation or filtration (Ryan, 2021). An electrocoagulation unit consists of multiple sacrificial metal plates that are placed in a reaction chamber. Metal cations are formed when the electrical current is applied, resulting in the destabilization of the colloidal particles by the formation of metal hydroxyl complex species. These complexes are highly adsorptive of organic contaminants including PFAS (Ryan, 2021). The efficiency has been found to be variable depending on the current density and electrode type. PFOS and PFOA removal in leachate was demonstrated to be greater than 80% with this increasing to greater than 99% with the addition of hydrogen peroxide (Powell Water, 2023). Additional studies have also observed similar high removal rates with the removal efficiency generally increasing with chain length (Chiang, 2021). Higher electrical currents may result in the formation of foam depending on the PFAS concentration and other water quality parameters, which could also be removed separately to improve removal efficiency. A pilot-scale study would be required to determine operational parameters including current density, electrode type, and treatment time.

These systems have been used in a variety of different applications including drinking water, wastewater, and groundwater remediation, and may reduce concentrations of other contaminants in addition to PFAS (Ryan, 2021). While the sludge volume is lower than what results from traditional coagulation, it would still need to be disposed of or destroyed separately. The effect of metal hydroxides formed during electrocoagulation on different destruction technologies would need to be evaluated. Single reactors are currently scaled up to 500 gallons per minute, but multiple reactors can be operated in parallel to increase the capacity (Powell Water, 2023).

D7.2.2.1 Scoring

This technology was scored as moderate to good for effectiveness because large reductions in PFAS concentrations have been observed. Electrocoagulation could be used for pretreatment to remove NOM from surface water and iron from groundwater in addition to PFAS prior to a filtration technology such as GAC and IX. This technology has typically been studied with and applied to water with higher PFAS

concentrations than are observed in the groundwater and surface water at the Site. A pilot-scale study would need to be conducted to evaluate the effectiveness with Site-specific water.

The implementability of this technology is moderate because electrocoagulation is commercially available but multiple treatment reactors would be required for the treatment volume within each of the AOCs.

Both the capital and annual costs are high. Annual electrical requirements are high for this technology.

Technology readiness is poor to moderate because although electrocoagulation units are commercially available, they are not widely used or tested. Current installations have been focused on landfill leachate and may not be as applicable for lower influent concentrations or for drinking water applications.

This technology was not retained for future consideration in the development of alternatives as part of a treatment train for the treatment of surface water and drinking water. The applicability to drinking water is uncertain, and while it could reduce PFAS concentrations prior to a polishing step, the relative cost is high, and full-scale demonstrations for influent concentrations comparable to Site-specific water are limited. Should further advancements occur, electrocoagulation and flocculation could be re-evaluated in the future.

D7.2.3 Foam Fractionation

Foam fractionation utilizes air injection into vessels containing the impacted water, causing the PFAS to concentrate into a foam which can be removed for further treatment. This is often a multistage approach where the first stage, or primary fractionation, focuses on removing PFAS from the bulk water and the subsequent stages (secondary or tertiary fractionation) focus on further concentrating the PFAS concentrate into a smaller volume (EPOC, 2022). The condensed foam from the final stage can then be treated with a destruction technology. Long-chain PFAS can be removed with just the addition of air which eliminates concerns raised by other technologies whose chemical additives must be managed.

Foam fractionation was piloted as part of this FS, evaluating both surface water and groundwater utilizing a Surface Active Foam Fractionation (SAFF®) system. Removal efficiencies of over 99% PFOS and PFOA were observed for both surface and groundwater. Short-chain PFAS compounds like PFBA were not removed by the SAFF® but these are generally below the current applicable standards in each AOC. The effluent concentrations were observed to be as low as 3.73 ng/L and <1.84 ng/L for PFOS and PFOA, respectively for the treatment of surface water and 1.07 ng/L and <1.77 ng/L for PFOS and PFOA, respectively, for the treatment of groundwater. For further details, see Appendix E (SAFF® Pilot Study Report) for the full SAFF® pilot test report. Additional treatment would be required to achieve the applicable standards and treatment targets; however, the large percentage of PFAS removal would greatly decrease the PFAS loading to GAC or IX. Additives could also be used to increase removal efficiencies, particularly those of short-chain PFAS. SAFF® was evaluated without the use of additives in this FS as there is uncertainty if they could be used in a drinking water application. Further pilot testing would be needed to evaluate the viability of additives, with a focus on short-chain PFAS removal as well as analysis of additive removal. Polishing with GAC or IX may also remove residual additives which further piloting could assess.

The containerized pilot-scale unit purchased by the MPCA and manufactured by EPOC is capable of processing approximately 50,000 gallons per day (gpd). EPOC also has commercially available units capable of treating 100,000 gpd. Other manufacturers offer similar capacity systems, which would require several units to achieve the treatment required for the surface water and groundwater AOCs. Manufacturers are working to expand system throughput to increase the amount of water that can be treated by a system per day; further analysis of vendor offerings would be needed if foam fractionation was selected as a remedial technology.

D7.2.3.1 Scoring

The effectiveness is scored as moderate to good because although foam fractionation is not expected to achieve all applicable standards for surface water and groundwater, it can remove over 99% of PFOS and PFOA from surface water and groundwater. PFBA and PFBS removal efficiencies are currently low using this technology, but these compounds are not in exceedance within the majority of surface water or groundwater at the Site. Foam fractionation could be effectively used as a pretreatment to GAC or IX to reduce PFAS loading to the filter.

The implementability is moderate to good. The size of the treatment plant does present challenges, as it would be the largest implementation to date and may require more engineering design work than other options.

The cost of this technology is high although annual O&M costs are lower than for other ex-situ technologies, as the energy costs are relatively low for foam fractionation.

The technology readiness is moderate to good. Foam fractionation is available from multiple manufacturers but is not currently at the scale required for treatment at this Site. As this is an area of rapid technological development, further conversations with manufacturers to understand updated equipment throughput are recommended if foam fractionation is pursued as a remedial alternative.

Foam fractionation was retained for the treatment of surface water and groundwater.

D7.2.4 Ozofractionation

Ozofractionation is a variation of foam fractionation that injects ozone into the impacted water instead of air to improve PFAS removal efficiency. The observed foam is more stable when produced with ozone. Removal of short-chain PFAS compounds such as PFBA and PFBS, which traditional foam fractionation treatment with air injection does not remove, is also achieved. In one case study, over 99.9% removal of the sum of all PFAS compounds has been observed, and individual PFAS compounds were all detected at less than 2 ug/L in the effluent (PFAS Cleaning & Treatment Solutions, 2024; Evocra, 2017). The PFAS is concentrated into a volume that is approximately 1% of the treated volume (Evocra, 2024). High organic load in the influent does not appear to inhibit the system and the oxidation capacity of ozone also helps break down organic matter (PFAS Cleaning & Treatment Solutions, 2024). Ozofractionation treatment plants also include an ozone generator. This system is commercially produced by Evocra and the system capacity can be increased by operating multiple systems in parallel. The system has successfully separated PFAS from water at multiple sites.

D7.2.4.1 Scoring

The effectiveness is scored as moderate. Based on pilot-scale test results on other sites, ozofractionation is not capable of achieving the applicable standards and treatment targets for surface water and groundwater, though it could be effectively used as a pretreatment to GAC or IX to reduce PFAS loading to a polishing media.

The implementability is moderate as the technology is available but not widely used.

This technical readiness is scored as moderate as ozofractionation pilot-scale tests have been completed but it is not yet been shown to operate at the treatment capacity required for the Site.

The relative cost is scored as high as both capital and O&M costs would be high.

Ozofractionation was not retained for further consideration as it would not provide substantial improvements in the treatment train over using foam fractionation with air instead of ozone. This technology, however, should be reconsidered for AOCs with higher concentrations of short-chain PFAS (e.g. WCL) if future studies demonstrate improved removal of short-chain PFAS by ozofractionation.

D8 Ex-Situ Treatment: Sediment

All ex-situ treatment technologies for sediment rely first on the physical removal of the contaminated material. In the case of a dry or dewatered AOC, physical removal can be achieved with excavation. For sediment AOCs within surface water bodies, removal could be achieved via dredging. Excavated or dredged sediment can be handled with several of the disposal or destruction technologies discussed in this appendix, or it can first undergo a separation technology that transfers PFAS from a solid to an aqueous waste stream or a stabilization technology that limits future leaching. The two separation technologies included in this section, soil-washing and thermal desorption, transfer PFAS from solid to either liquid or gas media and result in a treated solid matrix with reduced PFAS concentrations and an aqueous waste stream containing high PFAS concentrations. In the case of separation by soil-washing, as described below, a reduced volume of PFAS-containing fine-grained soils is also a product of treatment.

As with ex-situ water treatment, efficient sediment treatment is expected to require a treatment train approach that may involve multiple technologies. One of the final products rendered by ex-situ separation technologies would be the cleaned sediment, which could be recycled and returned to site. Soil washing would generate a PFAS-containing aqueous waste stream that would need to be handled with some method of disposal, separation, or destruction. Any remaining contaminated sediment must also undergo some form of disposal or destruction.

Figure D.2 illustrates example treatment trains for extracted sediment: landfilling of raw sediment, treatment by stabilization followed by landfilling, and treatment by separation followed by recycling. As an example, a treatment train for excavated sediment could begin with soil-washing which first separates soils according to grain size. As defined by the Unified Soil Classification System (USCS), fine-grained soils comprise silts and clays, and coarse-grained soils comprise sands and gravels (USCS). Following size fractionation, the coarse-grained soil fraction could be washed and returned to site. The wash water could then be treated with foam fractionation to concentrate the PFAS-containing wash water, and the concentrate could be treated with a destruction technology such as SCWO. The fine-grained soil fraction initially separated out prior to soil washing could be incinerated. Due to the high energy consumption of destruction technologies, PFAS destruction in raw sediment may not be feasible. PFAS destruction is more cost- and energy-efficient with smaller volumes. Furthermore, destruction technology demonstration for raw sediment is limited at this time, and discussion of options in the following section is limited to incineration and HALT. For that reason, concentration of PFAS into a smaller aqueous waste stream or onto a filter media prior to destruction may be preferable.

The purpose of this section is to discuss the different sediment treatment technologies and whether they should be retained for future consideration within a treatment train approach.

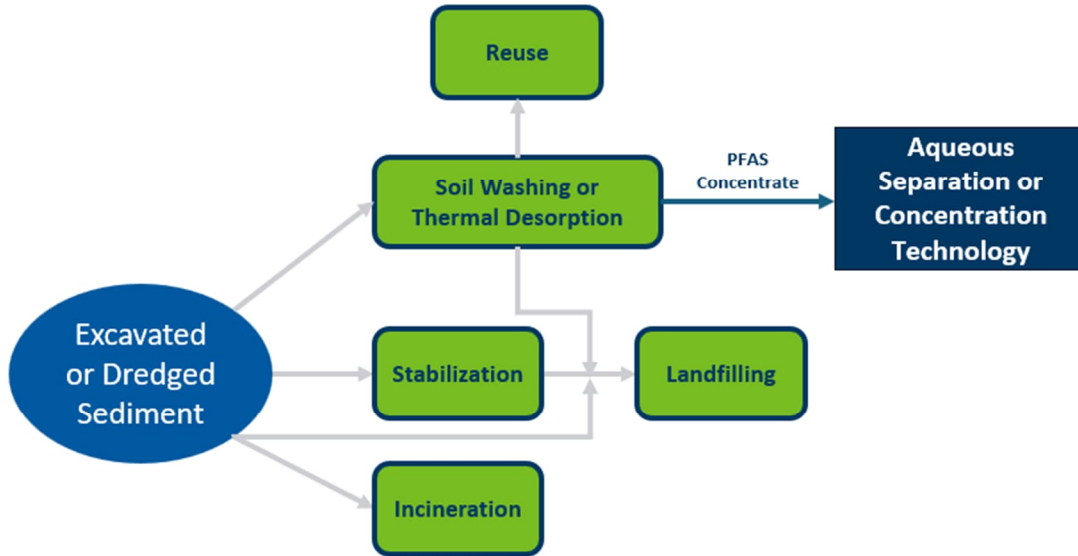


Figure D.2: Ex-Situ Sediment Treatment Technologies.

Similar to groundwater and surface water treatment, regulatory standards provide treatment targets for sediment remediation. Sediment standards are discussed further in Section 9.2.1 of the FS and applicable standards are summarized in Table 9.3.

D8.1 Extraction Technologies

Excavation and dredging physically remove impacted sediment from the source location for further offsite handling. Dredging is used for sediments that are submerged below a water body, while excavation is used for soils that are dry or that have had water bodies diverted or drained around the impacted soil. The secondary offsite handling stage can apply a combination of technologies to the extracted sediment to stabilize, separate, destroy, or dispose of PFAS.

D8.1.1 Excavation

Excavation is an extraction technique which transfers sediment from within a delineated area to an external staging, treatment, or disposal area using large machinery and physical removal (EPA, 2005). The excavated area can be backfilled with clean soil or with the native soil if it is treated and meets Site-specific criteria. All ex-situ technologies discussed for the treatment of impacted sediment rely on an initial removal step. Due to the large volume of water in Eagle Point Lake and the magnitude of dewatering activities that an excavation would require, excavation of the Eagle Point Lake Sediment AOC is considered to be technically infeasible. However, the upper Raleigh Creek and Anna's Grove Wetland Complex sediment AOCs have significantly less water and also experience dry periods, making dewatering to enable excavation technically feasible in these areas. Performing the excavation during times of lower flow/dry conditions (e.g. in late fall) could also minimize the amount of dewatering necessary. Control of water flow, however, may be necessary to facilitate excavation (EPA, 2005).

If excavation is pursued, additional sampling within the sediment AOCs would be necessary to determine the extent of excavation. It is currently estimated based on previous sampling that sediment in the upper Raleigh Creek and Anna's Grove Wetland Complex should be excavated to a depth of at least four feet to achieve removal to below the SDSVs, though depth of excavation would need to be

verified with confirmation sampling. While it is unlikely that excavation can achieve the MPCA Sediment SDSVs throughout an entire AOC, it could still achieve a large mass removal. If paired with upstream surface water treatment that eliminates PFAS transport from ODS, it could minimize sediment leaching into groundwater and downstream surface water bodies. It must be noted, though, that any excavation prior to elimination of PFAS transport from ODS risks recontamination of clean fill or treated sediment.

D8.1.1.1 Scoring

The effectiveness of excavation is scored as moderate to good. Effectiveness would be highly dependent on the degree of accuracy achieved by contaminant delineation and the degree of precision of the excavation when removing the contaminated sediment.

The implementability of excavation is moderate and would depend on the total volume to be removed and further managed. Seasonal variations will also impact implementability, as excavation would be easier during drought years as opposed to years with higher rainfall totals. There is regulatory uncertainty associated with excavating in the relevant AOCs (AOCs 11 and 12) due to the risk for extensive damage to wetland ecosystems. Transporting excavated material to secondary treatment facilities may be costly and labor intensive.

The relative cost is high. While total cost will depend on the extent of excavation and the secondary treatment option selected for the excavated material, excavation would generate a large volume of material requiring further treatment or disposal and would be expensive.

The technology readiness is good. Excavation is widely applied for extraction of contaminants, including PFAS, from the environment.

Excavation is retained for AOCs 11 and 12 as it could remove a large volume of PFAS-impacted sediment and in turn prevent human exposure to sediments above the relevant SDSVs and also reduce downgradient migrations of adsorbed PFAS. No excavation should be considered, however, until impacts from ODS are addressed. If excavation precedes the conclusion of work at ODS, any treated sediment or clean fill risks becoming contaminated again.

D8.1.2 Dredging

Dredging is an extraction technique which removes submerged sediment from below surface water bodies. Dredging can be performed mechanically or hydraulically. Mechanical dredging uses a mechanical means of removing sediment by grabbing, cutting, or raking the sediment, while hydraulic dredging uses a pump to remove sediment (EPA, 2005). Hydraulic dredging will typically generate more volume of waste to be treated, as sediment is slurried out with excess water, but can achieve better capture of contaminants than mechanical dredging (EPA, 2005). Mechanical dredging can be used in applications as deep as 50 feet below the water surface and hydraulic dredging can be used as deep as 150 feet (EPA, 2005). Many types of equipment are available for both mechanical and hydraulic dredging, and more detailed analysis would be required if dredging is pursued to identify the optimal type of equipment. Following dredging, engineered caps or sands are typically placed at the lakebed to create clean substrate for re-population of the benthic community (EPA, 2005).

While soil excavation in Eagle Point Lake is technically infeasible due to its large volume (and thus the inability to dewater the entire lake), dredging could provide a method of removing contaminated sediment in Eagle Point Lake, as well as for other sediment AOCs. Bathymetry limitations on dredging techniques would need to be further evaluated to determine the technical feasibility of dredging. Dredged material would need to be further handled, and either treated and recycled or disposed of offsite. Further investigation and sampling would be required to determine depth of dredging and areas to be dredged to minimize ecosystem impacts while still removing the maximum volume of PFAS-impacted sediment. Additionally, further studies would be needed to evaluate potential environmental

impacts of dredging on Eagle Point Lake and other AOCs, as well as evaluation of regulatory feasibility, as it is unknown if dredging would be allowed in this area.

D8.1.2.1 Scoring

The effectiveness of dredging is moderate. While reported material regarding dredging of PFAS-impacted sediments is limited, it is advertised by commercial dredging providers and widely applied for other contaminant extraction and stormwater applications. Effectiveness will depend on the necessary extent of sediment removal, but it could be good considering the depths accessible with commercial dredging equipment for lakes and ponds. It is unknown, however, the extent to which dredging will prevent leaching. Additionally, dredging can remobilize contaminants and increase suspended solids in downstream waters, increasing risk if this option is pursued.

The implementability of dredging is poor to moderate. Lakebed sediments could be dredged from the bottom of Eagle Point Lake or other sediment AOCs depending on the necessary extent of removal. Restorative substrate would likely need to be placed at the lakebed following removal. Dewatering the large anticipated volumes of dredged material and transporting waste to secondary treatment vessels or facilities may be costly and labor intensive. It is unknown, however, what permitting would be required to dredge, nor the expected extent of ecosystem damage that would be expected to occur. While technically feasible, the regulatory uncertainty is a risk for implementability.

The relative cost is high. A large portion of the cost will also come from the secondary treatment technology selected for the extracted sediment, as well as the storage and transportation of large volumes of material.

The technology readiness is good. A large variety of mechanical and hydraulic dredging equipment is widely available for removal of sediments from impacted areas and stormwater ponds. Their application for PFAS dredging is limited but applicable.

Dredging is not retained for AOC 11 as the wetlands in AOC 11 are more likely to be dry during parts of the year, allowing for traditional excavation to be performed. Although a poor to moderate implementability scoring would eliminate this technology from further consideration within another GRA, the limited availability of commercial technologies targeted for PFAS-impacted sediment treatment results in retention of dredging for treatment of AOC 12 (Anna's Grove Wetland Complex – Sediment) and AOC 13 (Eagle Point Lake – Sediment). Although there is regulatory uncertainty around whether dredging could occur, along with the risks of disruption to the Site and downstream risks of remobilized sediment, it is the only available technology available for physical removal of AOC 12 and AOC 13 sediment. If implemented correctly and precisely, it could remove a large volume of PFAS-impacted sediment and in turn prevent human exposure to sediments above relevant SDSVs and reduce downgradient migrations of adsorbed PFAS. No dredging should be considered, however, until impacts from ODS are addressed. If dredging precedes the conclusion of work at ODS, any treated sediment or clean fill risks becoming contaminated again.

D8.2 Stabilization

Once soil or sediment is contaminated with PFAS, mobilization of PFAS and transport from the contaminated soil or sediment can occur, and often lasts for many years (McDonough, 2022a). Stabilization of contaminated soil or sediment can decrease the mobilization of PFAS.

D8.2.1 Ex-Situ Stabilization

Ex-situ stabilization is similar to in-situ stabilization, discussed previously, but involves first excavating soil prior to treatment. Materials such as activated carbon, modified clays (e.g. ORGANOCCLAY), apatite, other modified sorbents (e.g. FLUORO-SORB), and biochar that are used for in-situ stabilization (ITRC,

2023; Askeland, 2020; CETCO, 2022a) can also be used for ex-situ stabilization. Soil or sediment is removed for mixing with amendments, for example in a pug mill, before being returned to the same location (ITRC, 2023). This is generally more disruptive to an ecosystem than in-situ stabilization and effectiveness can be impacted by the thoroughness of mixing (ITRC, 2023).

Use of stabilization amendments may reduce the leaching of PFAS from impacted soil (CETCO, 2022b). A field demonstration of ex-situ soil stabilization performed in Australia demonstrated similar performance to in-situ soil stabilization results discussed previously, with soil leachate measured at less than 10 ng/L for PFOS and PFOA after treatment with RemBind (Stewart, 2017).

Effectiveness is impacted by soil chemistry, PFAS charge, and mineral components of the soil (ITRC, 2023), thus pilot -scale testing would be required to identify the most effective amendment for a particular AOC. This treatment option may limit effectiveness of future soil treatments, and the ITRC recommends not employing this in flood-prone areas because of the potential for PFAS-containing, amendment-stabilized soils to erode and be transported downstream or offsite. Long-term project goals must be considered prior to implementation of soil mixing/stabilization for sediment AOCs. Introduction of stabilization amendments to sediment may decrease the efficiency of future separation and destruction technologies.

D8.2.1.1 Groundwater

This technology is not applicable to the treatment of groundwater AOCs.

D8.2.1.2 Surface Water

This technology is not applicable to the treatment of surface water AOCs.

D8.2.1.3 Sediment

The effectiveness of soil mixing is scored as poor if sediment is found to be a long-term source of PFAS onsite. While this technology does not remove PFAS and therefore cannot address concerns around public exposure to impacted sediment, it can address leaching. While significant reductions in PFAS leachability from sediments have been achieved with a variety of amendments, it is unknown the extent to which the high organic content in the sediment AOCs may impact the PFAS sorption capacity of these amendments. Additionally, sediment with high organic carbon content may sequester PFAS and limit opportunity for adsorption to the amendment. Because the sediment AOCs are in flood-prone wetland areas, it is possible for PFAS-containing, stabilized sediments to be transported downstream.

Furthermore, the longevity of this technology is unclear, and the degree to which changing Site conditions might impact PFAS leachability is unknown. Bench-scale studies may clarify the compatibility of various amendments with Site sediment. This technology could be applied to any dry or seasonally dry portion of the sediment AOCs to address leaching concerns, but permanently submerged sediments would require more invasive dewatering activities prior to installation.

The implementability is poor. Excavation of soil or sediment prior to mixing with amendments would be highly disruptive to the wetland environments of each sediment AOC.

The relative cost is high due to the labor required to excavate and mix amendments into the large AOCs areas.

Technology readiness is moderate. Several amendments are commercially available and have been applied as soil stabilization agents at the field level.

This technology is not retained due to uncertainty around the longevity of this technology. There are also concerns around transport of PFAS-stabilized sediment from flood-prone AOCs. However, this technology should be reconsidered as an interim measure if further Site investigation identifies areas with high PFAS concentrations that are found to be leaching a significant mass of PFAS.

D8.3 Separation

Separation technologies applied to extracted sediment transfer PFAS sorbed to sediment particles to an aqueous waste stream. Inclusion of a separation step, which creates a more concentrated aqueous waste stream, may reduce costs and energy consumption by decreasing the volume of material requiring destruction or disposal. The separation technologies discussed below are soil washing and thermal desorption.

D8.3.1 Soil Washing

Soil washing uses a wash solution to desorb contaminants from a solid matrix and transfer it to an aqueous waste stream; this process occurs after soil or sediment has been removed from an impacted area (Uwayezu, 2024). While recent research has focused on applicability to PFAS removal, this technique has historically been used for non-PFAS contaminants (Grimison, 2023). The wash solution typically uses water but can be enhanced with surfactants and extraction solvents to aid in PFAS desorption (Uwayezu, 2024). The end products are cleaned coarse soil, impacted fine soil, and impacted wash water. Cleaned coarse soil can be recycled or returned to site. PFAS tend to sorb to soil fractions with high organic content, typical of finer soils like silts and clays; these fine soils may need to be disposed of to remove the largest mass of PFAS possible (Grimison, 2023). Soil washing primarily targets removal of PFAS from the coarser grained soil fractions and separates the fine-grained soil into a separate waste stream. The process typically begins with soil fractionation based on size or density (Grimison, 2023). After fluidization of the coarse soil fraction with wash solution, the wash solution can be treated via coagulation and flocculation to settle out remaining particulates and concentrate PFAS into a sludge, while the wash water would undergo further treatment.

Removal efficiencies have reached up to 90 to 95 percent for coarser grained soil fractions (Grimison, 2023), though effectiveness has been demonstrated to depend on soil particle size and chain length (Uwayezu, 2024). PFAS removal was found to be more efficient on larger particle sizes, which correspond to sandy soils, and to be less efficient on smaller particle sizes, which correspond to silt and clay (Uwayezu, 2024). Short-chain PFAS were also found to be removed more efficiently than long-chain PFAS, which are retained preferentially by silt and clay (Uwayezu, 2024). Grimison et al (2023) found average removal efficiencies of 97% for perfluorocarboxylic acids, and 95 percent removal efficiencies for perfluorosulfonic acids, though removal efficiencies were dependent on head group and chain length. The total PFAS concentration did not appear to impact their results. These mixed results indicate sediment characteristics and speciation will play a large role in determining soil washing effectiveness.

Recently, the US Air Force started operations of a full-scale soil washing system at Eielson Air Force Base, Alaska (AFCEC, 2023). It is possibly the largest soil washing operation for PFAS in North America and will target treatment of 130,000 cubic yards of soil over the next two years (AFCEC, 2023). The pilot-scale testing demonstrated 70% removal of total PFAS in the soil, and a 99% reduction in the coarse soil (AFCEC, 2023), which is in line with results from other studies.

Soil washing could reduce cost and energy by concentrating PFAS into a smaller and more manageable waste stream for destruction. Foam fractionation or coagulation/flocculation could potentially be used to remove PFAS from sediment wash water; foam fractionation has been also demonstrated for use on wash water (Uwayezu, 2024). Alternatively, the wash water could potentially utilize a destruction technology discussed in Section D9 or be treated with GAC or IX and be reused or discharged. The fine sediment fraction, which would likely need to be retained from the coarser fraction due to removal differences, could be treated via incineration or potentially with other destruction technologies. More research is needed, however, on the effectiveness of soil washing in areas with high organic content. Compared to in-situ soil washing, ex-situ soil washing is more invasive but offers more control over the wash water and may result in higher removal efficiencies.

D8.3.1.1 Scoring

The effectiveness of ex-situ soil washing is scored as moderate, as research has shown significant removals of PFAS from removed soils, though results are mixed. Bench-scale testing would need to be performed to evaluate the Site sediment's capacity for soil washing.

The implementability is scored as moderate. The treatment train is expected to be labor-intensive for extracting, storing, transporting, and treating sediment and for handling the impacted wash water and fines following treatment.

The relative cost is high, as excavation or dredging would first need to occur, and after soil washing occurs, further treatment of the aqueous PFAS-containing waste would need to be treated. Sediment fines may also need to be treated or disposed.

The technology readiness is poor to moderate. Soil washing has been used for many years for other contaminants, but its application for PFAS treatment is not widespread. Some soil washing plants (SWPs) may not accept PFAS waste, and the commercial availability of PFAS-targeted SWPs is limited in North America.

Soil washing is not retained for any of the sediment AOCs at this time because of limited commercial availability for PFAS applications. This technology may be reevaluated if a sediment extraction treatment train is selected and if the technology readiness of washing as it applies to PFAS impacts improves.

D8.3.2 Thermal Desorption

Thermal desorption is a widely used treatment technology for sediment remediation, particularly for sediments impacted with volatile organic compounds (VOCs) (Zhao, 2019). Thermal desorption separates contaminants from solid media by heating it to near or above the contaminants' boiling point and volatilizing the contaminants into an air stream (Zhao, 2019). Common factors that impact removal efficiency are residence time in the heater and temperature of the heater (Gitipour, 2015). Longer residence times will decrease throughput, and higher temperatures will increase heating costs; conducting a pilot-scale test can reduce costs by optimizing operational set points. The mechanism of removal is similar to that of thermal GAC reactivation as described in Section D7.1.2, where heat is used to strip contaminants from a solid phase to which the contaminant is sorbed.

Thermal desorption, more recently, has been applied to PFAS removal as well (Clean Earth, 2019). Thermal desorption can be applied in-situ or ex-situ; for a discussion of in-situ thermal desorption, see Section D8.3.2. Ex-situ thermal desorption relies on excavation of contaminated sediment before transferring it to a mobile treatment unit or transporting it to a treatment facility. The process generates a volatilized PFAS gas stream that requires further treatment, typically via thermal oxidation, though carbon adsorption or other gas phase treatment could be applied (EA Engineering, 2020). The cleaned soil could potentially be re-used if it meets the relevant SDSVs.

Thermal desorption has been demonstrated at temperatures ranging from 450°C to 650°C (Clean Earth 2019; EA Engineering, 2020; Söregård, 2020). One bench-scale study demonstrated >99% removal of total PFAS for soil with an initial concentration of 4 mg/kg, and 71 to 99% removal for soil with an initial concentration of 0.025 mg/kg at temperatures between 450°C and 550°C (Söregård, 2020). Another bench-scale study, with initial concentrations ranging from 6 to 15 mg/kg, demonstrated 94% removal of total PFAS at 500°C and 99% removal of total PFAS at 650°C (EA Engineering, 2020). Perfluorocarboxylic acids were observed to preferentially desorb from soils compared to perfluorosulfonic acids, particularly at 500°C (EA Engineering, 2020). Further research is needed to study the impact of high soil organic matter on removal efficiency as well as removal efficiencies at lower initial concentrations of total PFAS to determine the applicability to a broader range of conditions.

D8.3.2.1 Scoring

The effectiveness of thermal desorption is scored as moderate. While bench-scale studies at other sites have demonstrated high removal efficiencies, they were performed with higher starting concentrations. The removal efficiency with lower starting concentrations or sediments with high organic content, as observed in the sediment AOCs, is not as well studied.

The implementability is scored as poor to moderate because the distance to the nearest thermal desorption facilities is far, and the footprint of mobile units and temporary staging is large.

The relative cost is high. Transportation, storage, and treatment costs are expected to be high.

The technology readiness of thermal desorption is scored as moderate. Thermal desorption has been widely applied for other contaminants but is not as widely applied for PFAS treatment.

Thermal desorption is retained for all sediment AOCs. Although its poor to moderate implementability scoring would screen the technology out of another GRA category, the commercially available options for sediment treatment are limited at this time.

D9 Ex-Situ Treatment: Disposal or Destruction

The previously discussed separation technologies offer a way to remove PFAS from a bulk water or sediment, however, fundamentally separation technologies simply transfer PFAS from one media (e.g. groundwater) to another (e.g. spent GAC). The previously discussed technologies do not destroy PFAS; instead, they remove them from the environment and condense them into a smaller waste stream. Ultimate disposal or destruction of PFAS must be carried out after the initial separation or concentration step(s) and is more economical and energy efficient when applied to reduced volumes of waste containing higher PFAS concentrations. In a treatment train, destruction or disposal occurs after the preliminary step of concentrating and removing PFAS from the impacted surface water, groundwater, or sediment.

Some destruction technologies are capable only of treating aqueous waste streams, while others are capable of destroying PFAS sorbed to solid media such as GAC or ion exchange resin. As a result, the technology selected for destruction or disposal will depend on the technology used for PFAS removal. Changes in water chemistry occurring in the initial PFAS removal step can impact destruction efficiency and therefore also influence disposal and destruction method selection. For example, ion exchange still bottoms have a high salt content which may inhibit the destruction of PFAS by some technologies. In addition, PFAS and fluoride mass balances lack test data for ultra-short chain PFAS and hydrofluoric acid (HF), and do not sufficiently close the fluorine mass balance, reducing absolute confidence that PFAS are mineralized rather than transformed to shorter-chain species.

A disposal or destruction technology will not be selected as part of this FS. Rather, the purpose of this technology screening is to outline potential technologies and identify those that should be further tested through either laboratory bench-scale or field pilot-scale studies. In 2023, a Request for Proposals was opened by the MPCA to assess the destruction efficiencies of technologies at the bench-scale using Site-specific PFAS concentrate generated through the SAFF® pilot study. The results of these bench-scale studies are discussed in the following sections, as applicable. Further details are included in Appendix G (PFAS Destruction Technology Bench-Scale Study Summary and Analysis). Each destruction technology described in the following sections was evaluated on the basis of total and individual PFAS reduction, reduction of total organic fluorine (TOF), production of fluoride anions, and energy consumed in the process. All vendors were provided with SAFF® concentrate from the same drum. However, the number of PFAS and their concentrations detected in the influent was highly variable, at least in part due to high PFOA and PFOS concentrations affecting laboratory reporting limits. Therefore, the number of PFAS treated and the extent of treatment should be considered in that context.

Finally, it should be noted that PFAS effluent concentrations are compared to U.S. EPA PFAS MCLs, but the MCLs are specific to drinking water and thus the comparison is not one-to-one. A complete assessment will require sufficient data for mass balance closure, quantification of disinfection byproducts, and detailed review of implementability, costs, and energy requirements.

The list of PFAS destruction technologies included in this technology screening is not meant to be a list of all potential technologies but rather only those that have been or are in the process of being tested at least at the pilot-scale, which correlates to a TRL of 6. Per discussion with the MPCA, technologies included in this FS were not limited to only full-scale options (i.e., TRL of 9) as the MPCA does not want to exclude rapidly developing destruction technologies that may soon provide a more viable option than those currently available.

D9.1 Landfill

Historically, PFAS-containing waste has been disposed of in both lined and unlined landfills. A major concern with landfill disposal is PFAS in leachate; as such, PFAS-containing waste should be disposed of in lined, hazardous waste-approved landfills that have leachate collection and treatment systems (EPA, 2024). Landfill leachate has been found to contain high levels of PFAS, and there is significant concern about the environmental risks from PFAS-containing leachate (Tolaymat, 2023). For aqueous wastes, super-loading of sorptive media, which is the process by which a small volume of highly concentrated PFAS solution is passed through a small volume of filtration media at a slow rate, can minimize the amount of solid waste entering a landfill (ITRC Case Studies, 2023). While solidifying the waste prior to landfilling reduces the potential for leaching, it can significantly increase costs, and traditional solidification techniques may not be highly effective (Tolaymat, 2023). Another method of reducing leaching potential of waste is stabilization, which can include the addition of amendments using methods and materials discussed in Section D5.2 (Navarro, 2023). Solidification and stabilization require more research to better understand performance over time and the effectiveness of various techniques (EPA 2024). Furthermore, while landfilling as a disposal option is included in this FS, many landfills are no longer accepting PFAS-containing waste as a result of the uncertainty around future regulations. No landfills in Minnesota are currently accepting PFAS-containing waste and the waste would have to be transported out of state for disposal, further increasing disposal cost. This would also transfer the risk of future PFAS contamination to other communities if the landfills leak in the future.

Landfilling is the only disposal option discussed in this technology screening. Although other disposal options such as deep-well injection are commercially available, they have been excluded due to concerns around reintroducing PFAS to the environment.

D9.1.1 Surface Water and Groundwater

The effectiveness of landfill disposal for IX resin or GAC derived from use with surface water and groundwater is scored as good, as all PFAS waste would be removed from the Site and accomplish RAOs; however, it would not be destroyed. Effectiveness is high as well for surface water or groundwater directly disposed of in a landfill, though this is likely to only be allowed with stabilization or additional treatment, as water is typically not directly landfilled. This scoring assumes that the landfill leachate will be appropriately handled to prevent leaching.

The implementability is scored as poor to moderate due to the long distances that the waste would need to be transported and the uncertainty of landfilling as a viable option as more landfills stop accepting PFAS-containing waste.

The cost is moderate as compared to other destruction technologies; however, costs associated with landfilling may increase depending on the proximity of the landfill to the Site and the need to stabilize

prior to final disposal. Cost is high for surface water and ground water first needing stabilization prior to final disposal.

The technology readiness is scored as good as PFAS-impacted waste can be sent to landfills currently.

Landfilling was not retained for further consideration as a long-term remedial solution for the PFAS-containing waste because of the uncertainty around the continuation of landfills accepting PFAS-containing waste. This option, however, may be used in the short-term to handle waste as other technologies are being implemented.

D9.1.1.1 Sediment

The effectiveness of landfill disposal for PFAS-impacted sediment is scored as good as all PFAS waste would be removed from the Site; however, it would not be destroyed. This scoring assumes that the landfill leachate will be appropriately handled to prevent leaching.

The implementability is scored as poor due to the long distances that large volumes of impacted sediment would need to be transported and the uncertainty of landfilling as a viable option as more landfills stop accepting PFAS-containing waste.

The relative cost is high because of the distance required to transport the impacted sediment and costs associated with landfilling PFAS impacted waste.

The technology readiness is scored as good.

Landfilling was not retained for further consideration due to the lack of any landfills within close proximity to the Site that will accept PFAS-impacted sediment.

D9.2 High Temperature Incineration and Thermal Oxidation

Two traditional methods exist for high temperature destruction of PFAS: incineration and thermal oxidation. Typically, an incinerator handles solid or liquid waste (e.g. waste sludge, foam fractionation PFAS concentrate, IX resin) while thermal oxidation refers to technology used to treat gaseous waste streams (e.g. thermal desorption offgas, GAC reactivation offgas) (EPA, 2017). There are many types and styles of incinerators (rotary kiln, fixed hearth, fluidized bed, direct flame, etc.) and thermal oxidizers (direct fire, catalytic, recuperative, regenerative, etc.), though all operate on the basic principle of using high temperatures and oxygen to combust contaminants (EPA, 2017). The goal of incineration and thermal oxidation is complete mineralization of PFAS, or complete conversion of the fluorochemical to fluoride salts, HF, and small hydrocarbons (Meegoda, 2022).

Incineration at temperatures above 1,000°C has been found to destroy PFAS in liquids and solids at an efficiency greater than 99.99%, with short-chain PFAS requiring temperatures as high as 1,400°C for destruction (EPA, 2020b). However, destruction efficiency of full-scale incinerators is in question as elevated concentrations of PFAS have been found in soil downwind of the facilities, attributed to volatilization and atmospheric transport and deposition (Meegoda, 2022), though incomplete combustion may play a role in this as well. High temperature incineration occurs at offsite licensed facilities; no facilities exist in Minnesota with the closest facility located in Kimball, Nebraska. Investigation-derived waste from the Site has previously been transported approximately 800 miles for incineration. Uncertainty around future regulations regarding the incineration of PFAS-containing wastes and the associated air emissions and the number of incineration facilities able to meet these future regulations could limit the long-term feasibility of incineration. Additionally, disposal of the ash from incinerators may be a concern, as PFAS may remain in the bottom ash (Meegoda, 2022).

Thermal oxidizers, operated at similar temperatures to incinerators, have been shown to remove PFAS in contaminated gas streams (DiStefano, 2023). Thermal oxidizers can be added to the emissions line of other treatment systems such as GAC reactivation facilities, thermal desorption of soil, or to an

incinerator to destroy PFAS transferred to the vapor phase during the process (DiStefano, 2023; EA Engineering, 2020). A bench-scale study of thermal oxidation of a soil desorption waste stream reported >99.999% destruction and removal efficiency (EA Engineering, 2020). This is supported by a study of a Calgon Carbon reactivation facility demonstrated >99.99% removal of PFAS through the process of reactivation and offgas treatment with a thermal oxidizer operation at a maximum temperature of ~1,100°C (DiStefano, 2023). Notably though, ultra-short chain PFAS species were not tested, raising questions about the presence of partially degraded species.

Incineration is applicable for both solid and liquid waste and could be used in a treatment train to destroy PFAS concentrate resulting from any of the separation and concentration technologies described in the previous section of this FS. To reduce costs and air emissions resulting from transportation, the volume of PFAS waste should be minimized by concentrating the PFAS.

D9.2.1 Surface Water and Groundwater

The effectiveness of incineration is scored as good because of the 99.99% destruction efficiency; however, this level of destruction is only achieved at temperatures of 1,000°C or more. Lower destruction efficiency, especially of shorter chain PFAS compounds, is observed with lower temperatures, which could result in PFAS being released through air emissions. As the process is managed by an outside vendor, the treatment system would be reliant on an outside vendor to properly control technology to completely mineralize PFAS.

The implementability is scored as good under current regulations as the PFAS-impacted solid media or concentrated liquid waste could easily be transported offsite to an incineration facility. If regulatory standards change and incineration is no longer permitted, however, the implementability would be poor.

The relative cost is moderate. While disposal costs are high, if the PFAS can be concentrated into a liquid or solid media, the costs are lower relative to the capital and O&M costs associated with other destruction technologies. Transportation costs will be high due to the distance required to move the waste.

The technology readiness is good because the required incineration facilities are already operational.

This technology was retained for future consideration for both the treatment of surface and groundwater. However, as regulations regarding the incineration of PFAS may change, incineration should only be viewed as a short-term option for destruction while other technologies for the destruction of PFAS are further developed and commercialized.

D9.2.2 Sediment

As with aqueous wastes, the effectiveness of incineration of solid wastes is scored as good because of the 99.99% destruction efficiency; however, this level of destruction is only achieved at temperatures of 1,000 °C or more. Lower destruction efficiency, especially of short-chain PFAS compounds, is observed with lower temperatures, which could result in PFAS being released through air emissions. As the process is managed by an outside vendor, the treatment system would be reliant on an outside vendor to properly control technology to completely mineralize PFAS.

The implementability is scored as moderate to good depending on extracted sediment volumes under current regulations as the PFAS-impacted solid media could easily be transported offsite to an incineration facility. If regulatory standards change and incineration is no longer permitted, however, the implementability would be poor.

The relative cost is high. Transportation costs will be high due to the distance required to move large volumes of extracted sediment.

The technology readiness is good because the required incineration facilities are already operational.

This technology was retained for future consideration for sediment. As there are not incinerators within close proximity to the Site that will accept PFAS-impacted sediment, and as regulations regarding the incineration of PFAS may change, incineration should only be viewed as a short-term option for destruction while other technologies for the destruction of PFAS are further developed and commercialized.

D9.3 Supercritical Water Oxidation

SCWO destroys PFAS utilizing the unique properties of water when at or above its supercritical point, which is defined as temperatures above 374°C and pressures above 22.1 megapascal (MPa). Under these conditions, water shares properties of both the vapor and liquid phases, increasing the organic solubility and promoting the oxidation of organic chemicals including PFAS. The reaction requires an oxidant such as oxygen or hydrogen peroxide and, if the organic content of the PFAS concentrate is too low, an organic co-fuel to sustain the reaction. A study comparing the destruction efficiency of AFFF by three vendors of the SCWO technology observed over 99% destruction efficiency of the 13 PFAS compounds quantified, including PFOS and PFOA, by the three SCWO systems (Krause, 2022). Similar results were observed with the degradation of PFAS in landfill leachate, wastewater, and slurries containing spent GAC and ion exchange media (EPA, 2022; Scheitlin, 2023; Chiang, 2023). As PFOS and PFOA are the main constituents of the Site-specific PFAS concentrate, it was expected that SCWO would have a high destruction efficiency with the Site-specific concentrate.

In addition to destruction, generation of HF, sulfuric acid, and hydrochloric acid by SCWO causes a significant decrease in pH and may lead to both reactor corrosion and the precipitation of large quantities of salt, which has the potential to clog the reactors and increase O&M costs. Quantification of acid generation was not detailed in the vendor reports and requires additional analysis. A pilot-scale study would be required to determine the extent to which this is problematic with Site-specific PFAS concentrate or media. SCWO is an energy-intensive technology, requiring between 1,398 and 1,506 kilowatt hours (kWh) per m³ at the field-scale for a stock solution of AFFF (McDonough, 2022b), and is furthermore known as a complex process with respect to managing exothermic reactions.

At the time of preparation of this FS, the technology is commercially available through several manufacturers, including Revive Environmental, 374Water°, Aquarden, and General Atomics, though capacity is still limited. However, greater capacities of 6-30 wet tons per day for waste streams involving solid media is in development (374Water°, 2024) as vendors continue to work on scaling up the technology.

Within a treatment train, SCWO has applications for the destruction of aqueous PFAS concentrate in addition to slurries with spent GAC media or ion exchange resin. The ability to treat the ion exchange still bottoms is unclear as the high concentrations of salt present in the still bottom could precipitate out of solution.

Three SCWO vendors (374Water°, Bay West, and Revive Environmental) were provided SAFF® concentrate samples from the Site for bench-scale treatment in bench-scale reactors. Method details are given in reports provided by each vendor. In general, the results achieved by the bench-scale studies are similar to the literature values presented above. TOF reduction was greater than 90 percent in all three studies with effluent concentrations of the majority of specific PFAS removed to below method detection limits. Energy consumption reported by 374Water° was 1.12 kWh/gal. The other vendors did not report energy consumption. Bay West was the only vendor to measure PFAS concentrations in the air effluent which were found to be non-detect. Air emissions are a concern for full-scale systems and should be evaluated in future pilot-scale testing.

D9.3.1 Surface Water and Groundwater

The effectiveness is scored as moderate to good for the destruction of aqueous PFAS concentrate and spent solid media as the destruction efficiency is typically greater than 99% for all PFAS and the formation of short-chain PFAS was not observed. However, effluent concentrations will likely remain above the drinking water HBVs/HRLs and surface water SSC, requiring the effluent to be recycled within the treatment train or treated by an additional PFAS treatment technology.

The implementability is scored as moderate. The commercially available unit can be housed in a shipping container and readily implemented at the Site. Reagents used as co-fuel are commercially available. The high temperature and pressure operating conditions may be a safety concern on Site, so discussions with manufacturers are required to better understand these potential concerns. The organic content of aqueous PFAS concentrate may not be high enough to sustain the reaction, requiring the addition of an organic co-fuel and slightly increasing O&M needs. This would not be a concern with the destruction of solid media, which can be, at least partially, accomplished with SCWO. Media regeneration using SCWO is unlikely because it tends to decompose the material rendering it unusable. There is uncertainty associated with the required O&M related to the buildup of salts and corrosiveness caused by low pH in the reactor. Similarly, the ability of SCWO to treat ion exchange still bottoms is unknown due to the high salt concentrations. If SCWO effluent is recirculated to media for polishing, the impact of elevated temperatures is unknown, and a cooling step may be necessary. A pilot-scale study is required to better evaluate the required O&M.

The relative cost is scored as high. In addition to high capital cost, O&M costs are expected to be high because of the electrical requirements and potentially the cleaning requirements to remove precipitates and prevent acid corrosion. The cost of consumables, such as a co-fuel, is dependent upon the starting organics concentrations in the concentrated feedstocks.

The technology readiness is scored as moderate to good with a TRL of 8. While this technology is still undergoing pilot-scale studies, it has been implemented with a variety of waste streams and is commercially available through several vendors.

SCWO is retained for further consideration as a technology capable of destroying aqueous PFAS concentrate and slurries with spent GAC and ion exchange resin. Additional pilot-scale testing would be required to confirm the effectiveness with Site-specific concentrate and to fully understand the required O&M.

D9.3.2 Sediment

This technology is not applicable for the treatment of sediment. SCWO does not perform well with excessive grit, abrasive materials, soils, or slurries with more than 50% solids due to the difficulty in pumping through a reactor (Scheitlin, 2023).

D9.4 Hydrothermal Alkaline Treatment

To destroy PFAS, HALT applies high heat (350°C) and pressure (3,625.9 psi) to a reactor of PFAS concentrate under alkaline conditions (pH >14). As the alkaline conditions allow for the degradation of PFAS at a lower temperature and pressure compared to SCWO, these conditions are sufficient to break the C-F bonds. A pilot-scale study completed at an AFFF-impacted site showed 99% destruction of total PFAS at a treatment rate of 0.63 liters per minute (LPM) (10 gallons per hour [gph]) (Aquagga, 2023; Pinkard, 2023). Bench-scale studies to regenerate GAC showed PFOS destruction above 99% (Soker, 2023), and additional bench-scale and field studies are ongoing with other waste streams (Aquagga, 2023). According to the manufacturer, there are no air emissions or toxic byproducts. The energy requirement for treatment is approximately 1 kWh/gal (Aquagga, 2023).

This technology is commercially available through one company, Aquagga, as a continuous flow reactor with a range in treatment capacity of 0.126 LPM (2 gph) to 9.46 LPM (150 gph) (Aquagga, 2024). Pilot-scale studies have been completed at the lower flow rates, but at the time of preparing this FS, the extent to which pilot-scale studies have been completed using systems with larger processing rates and how the increase in capacity affects the treatment efficiency is unclear. Additional work is planned to determine the ability of this technology to treat different waste streams.

As with other destruction technologies, HALT could be applied within a treatment train to destroy aqueous PFAS concentrate. Based on initial results, HALT is effective with PFAS concentrates, though additional pilot-scale testing would be required with Site-specific concentrate. Additionally, HALT could be used for onsite GAC regeneration.

D9.4.1 Surface Water and Groundwater

The effectiveness of this technology is scored as moderate to good for the destruction of PFAS concentrate from surface water and groundwater as the destruction efficiency is over 99% for total PFAS; however, the effluent concentrations are still above the drinking water HBVs/HRLs and the SSC requiring the effluent to be recycled within the treatment train. The technology may also be efficient in the regeneration of spent GAC resulting from the filtration of impacted surface water or groundwater. The higher organic content resulting from the concentration of surface water treatment would not impact the effectiveness. Additional field-scale testing, especially with larger treatment volumes, is needed to confirm the effectiveness of Site-specific treatment capacity. Site-specific bench-scale and pilot-scale studies are also required to determine the effectiveness with Site-specific PFAS concentrate.

The implementability is moderate. The commercially available unit can be housed in a trailer and readily implemented at the Site. Reagents are commercially available. Managing the use of the high concentration of sodium hydroxide will require additional controls during operations to protect operators. There is uncertainty with the required O&M and a pilot-scale study would be required to better evaluate the required O&M.

The relative cost is scored as high. Capital costs are expected to be high and the O&M costs are uncertain. Reagents are inexpensive; however, it is unknown if there will be maintenance challenges associated with the Site-specific water chemistry (high hardness) and cleaning requirements are uncertain.

The technology readiness is scored as moderate as the TRL is 7. A limited number of pilot-scale studies have been completed to date, but more tests are planned with additional waste streams. This technology readiness score may be updated pending those results.

HALT was retained for further consideration as a technology capable of treating PFAS concentrate and spent GAC resulting from the treatment of surface or groundwater. Additional pilot-scale testing would be required to confirm the effectiveness with Site-specific concentrate or spent GAC.

D9.4.2 Sediment

This technology is not applicable for the treatment of sediment.

D9.5 Electrochemical Oxidation

Electrochemical oxidation applies an electrical current through a conductive solution between a cathode and anode to defluorinate PFAS. The PFAS oxidation can occur either directly at the electrode through the transfer of electrons to the anode or indirectly by electrochemically formed radicals. This has been found to destroy over 99% of TOF in concentrated PFAS waste streams.

This technology was piloted as part of this FS using a DE-FLUORO™ system with both groundwater and surface water SAFF® concentrate. In this pilot-scale study, the TOF decreased by over 98% after 100 hours of treatment in the groundwater SAFF® concentrate as described in Appendix F (DE-FLUORO™ PFAS Destruction Pilot Study). Over 97% and 99% of PFOA and PFOS were destroyed, respectively, in the treatment of groundwater; however, these were converted to shorter-chain PFAS compounds and PFBA was observed to increase. The observed decrease in TOF and increase in fluoride ion concentration does however provide evidence that destruction is occurring. Similar observations of increases in or poor destruction of short-chain PFAS concentrations have been observed in other studies (Meegoda, 2022; Smith, 2023). A bench-scale study was also completed by Axine Water Technologies in which a reduction in TOF of over 99% was observed.

Hydrogen gas, HF, and perchlorate are formed as byproducts. The concentration of perchlorate in the effluent is proportional to the chloride concentration in the PFAS concentrate and may have to be treated in the effluent depending on the concentration. The hydrogen gas and HF can be managed by an air emissions system. The lifespan of the electrodes is unknown, but accumulation of precipitates on and degradation of the electrodes was observed during the pilot-scale study and is documented in other field systems suggesting a potentially high system maintenance and replacement parts cost. Throughout and electrical consumption are highly dependent on the influent water and desired treatment efficiency (Meegoda, 2022). The bench-scale study by Axine Water Technologies reduced all detected PFAS concentrations to below instrument detection limits at up to 800 kWh/m³.

Within a treatment train, electrochemical oxidation has applications for the destruction of high aqueous concentrations of PFAS. High concentrations of chloride result in increased perchlorate concentration in the effluent and potentially require additional downstream treatment. The effluent would be recirculated back to the treatment train to further concentrate the remaining PFAS. Depending on selected filtration or concentration technology selected, the perchlorate may also be removed by this recirculation.

D9.5.1 Surface Water and Groundwater

The efficiency of electrochemical oxidation is scored as moderate for the destruction of PFAS concentrated from surface water and groundwater. Long-chain PFAS compounds were reduced by over 99% but concentrations of short-chain PFAS did not decrease and, in some instances, increased, during the pilot-scale study as a result of sequential defluorination (Appendix F). This scoring may be changed with the results of subsequent field studies.

The implementability of this technology is scored as moderate. The systems are housed in a trailer and could easily be implemented at the Site. The DE-FLUORO™ pilot-scale study highlighted areas of increased O&M requirements for operators, but system modifications will continue to address these to decrease O&M frequency. The electrodes are expected to require cleaning and maintenance.

The relative cost is scored as high. The capital cost is predicted to be similar to other destruction technologies. Electrical requirements are less than other destruction technologies; however, the costs associated with electrode replacement could be high.

The technology readiness is scored as moderate based on TRL score of 8. Multiple companies have completed pilot-scale testing, and more field trials are planned. Systems utilizing electrochemical oxidation are available through multiple vendors.

Electrochemical oxidation was retained for further consideration as a technology capable of treating PFAS concentrate from the treatment of surface or groundwater. Electrochemical oxidation is not viable for destruction or regeneration of solid media.

D9.5.2 Sediment

This technology is not applicable for the treatment of sediment.

D9.6 Plasma

A plasma is an ionized gas that forms when a high energy electrical discharge is applied to a gas, forming highly reactive species capable of destroying PFAS when the gas is diffused through impacted water. This has been shown to destroy 97% of total PFAS from a PFAS concentrate resulting from filtration during a pilot-scale study at a different site (DMAX, 2023; Onvector, 2024). Similar results have been obtained with PFAS concentrate from a variety of sites and PFAS concentration technologies, with long-chain PFAS compounds degrading at a faster rate than short-chain PFAS compounds (Singh, 2019). Lower destruction has been observed with high organic matter concentrations, which could pose an issue with concentrate derived from surface water. The bench-scale study conducted by Onvector showed a reduction in TOF of 70% of Site-specific SAFF® concentrate.

Energy usage is approximately 1560 – 2370 kWh/m³ (5-9 kWh/gal) of PFAS concentrate (Meegoda, 2022). Plasma destruction technologies are currently commercially available and have undergone pilot-scale studies at other PFAS-impacted sites. The treatment capacity is dependent on reaction time but could be easily scaled up by adding additional treatment reactors with treatment capacity as high as over a thousand gpd (Nau-Hix, 2021). The technology can be housed in a trailer for installation at the Site.

As with other destruction technologies, plasma could be incorporated to treat a PFAS concentrate. The effluent would be recirculated back to the treatment train to further concentrate any remaining PFAS. Based on initial results, plasma is effective with PFAS concentrates resulting from various filtration and concentration processes, although additional pilot-scale testing is required with Site-specific concentrate.

D9.6.1 Surface Water and Groundwater

The efficiency of treating PFAS concentrate from both surface water and groundwater is scored as moderate to good as over 97% of the total PFAS was destroyed in testing completed with PFAS concentrated waste from other sites.

The implementability is moderate. The commercially available unit, currently produced by Onvector, can be housed within a trailer and easily installed at the Site. There is uncertainty associated with the required O&M and a pilot-scale study would be required to better evaluate the required O&M.

The relative cost is scored as high. Capital costs are expected to be similar to other destruction technologies. Costs associated with O&M are uncertain and would be better determined during a pilot-scale study.

The technology readiness is scored as moderate as the TRL is 7. Systems are commercially available by multiple vendors although full-scale testing is limited. DMAX plasma, for example, has completed bench-scale and pilot-scale demonstrations (Singh, 2019; Singh, 2020; Nau-Hix, 2021). For limited waste volumes (e.g., truck wash water, AFFF stock), a pilot-scale unit could be considered scaled but would not be sufficient for MPCA AOCs.

Plasma is retained for further consideration as a technology capable of destroying concentrated PFAS. Plasma is not anticipated to be compatible with solid media for regeneration or destruction. Additional pilot-scale studies are required with Site-specific PFAS concentrate to better evaluate efficiency and potential O&M concerns prior to the selection of a destruction technology.

D9.6.2 Sediment

This technology is not applicable for the treatment of sediment.

D9.7 Photolysis and Photochemical Destruction

Photolysis is the breakdown of chemicals using energy from light, including ultraviolet (UV) light. While the carbon-fluorine bonds in PFAS compounds are not efficiently broken during the direct application of light, referred to as directly photolysis, they are broken during indirect photolysis, which occurs when the addition of chemical oxidants or photocatalysts form reactive species in the presence of light. Two companies have used different systems which utilize light energy with different catalysts. Claros Technologies uses a proprietary photochemical reaction which has been observed to destroy 99% of TOF within one to three hours (Claros Technologies, 2023). Short-chain PFAS, including ultra-short chains (C2-C3) were also destroyed; however, across all waste tested by Claros Technologies, PFOS has a lower average destruction efficiency. As PFOS will comprise of a large percentage of PFAS concentrate resulting from a separation or filtration technology, this may be problematic for treatment of Site-specific water. A bench-scale study with SAFF® concentrate by Claros did show 85% reduction in TOF over 24 hours; however, dilution of the surface water SAFF® concentrate was required because of the reduced UV transmittance. It is uncertain if this would be required with groundwater concentrate as there is less natural organic matter in the groundwater.

This technology is currently commercially available through Claros Technologies as a batch mode reactor with available treatment capacities ranging from 5 L (1.3 gal) to 2,000 L (528 gal), although it is not clear if treatment efficiency is consistent with each of these batch sizes. It is also unclear if any field pilot-scale studies have been conducted at other PFAS-impacted sites and what the predicted energy usage is, although it is advertised as requiring less energy than other PFAS destruction technologies.

A second destruction technology vendor, Enspired Solutions, uses photoactivated reductive defluorination (PRD) to destroy PFAS through the addition of an electron donor which produces reactive hydrated electrons capable of breaking the carbon-fluorine bond in the presence of UV light. The efficiency is improved by concentrating the PFAS within a surfactant micelle structure through the addition of cetyl trimethylammonium bromide. In a bench-scale study with SAFF® concentrate, the TOF was reduced by 92%.

The energy requirement for PFAS destruction is dependent on the desired treatment efficiency. The predicted energy requirement ranges from 1,020 kWh/m³ (3.9 kWh/gal) for 99.9% reduction of only the PFAS compounds regulated under the proposed EPA MCLs to 4,000 kWh/m³ for 99% reduction in TOF.

This technology is commercially available by Enspired Solutions at a maximum treatment rate of 0.13 LPM (2.1 gph or 50 gpd) per unit. The initial testing of the commercially available unit shows destruction efficiency is similar to that observed at the bench-scale study. The first pilot-scale study at another site will be conducted in November 2023 by Enspired Solutions.

Photochemical destruction could be utilized with a PFAS concentrate resulting from upstream filtration or concentration. It has been shown to be effective with concentrates resulting from treatment with ion-exchange, reverse osmosis, GAC, and foam fractionation. As with other destruction technologies, the effluent would be recirculated back to the treatment train to further concentrate any remaining PFAS.

D9.7.1 Surface Water and Groundwater

The efficiency is scored as moderate as a large decrease of TOF concentrations is observed in PFAS concentrate from other sites; however, the PFAS concentrate from the Site is primarily composed of PFOS, which was observed to have a lower degradation rate in the Claros bench-scale study.

The implementability of this technology is scored as moderate. The commercially available units could easily be installed at the Site. There is uncertainty with the required O&M and a pilot-scale study is required to better evaluate the required O&M.

The relative cost is scored as high. The capital cost is predicted to be similar to other destruction technologies. Electrical requirements are less than other destruction technologies; however, it is unclear how expensive reagents are or what other O&M costs would be required.

The technology readiness is moderate as the TRL is 6. Treatment units are commercially available, but at the time of writing this report, data from additional pilot-scale studies at PFAS-impacted sites are needed to better evaluate the state of development.

Photochemical destruction is retained for further consideration as a technology capable of destroying PFAS concentrate from the treatment of surface water or groundwater. Photochemical treatment is not viable for destruction or regeneration of solid media.

D9.7.2 Sediment

This technology is not applicable for the treatment of sediment.

D10 References

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