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**Guidance for the Assessment and Remediation of
Per- and Polyfluoroalkyl Substances in British Columbia**

**Submitted to:
Society of Contaminated Sites Approved Professionals of British Columbia**

**May 2019
SLR Project No.: 219.05420**

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**GUIDANCE FOR THE ASSESSMENT AND REMEDIATION OF
PER- AND POLYFLUOROALKYL SUBSTANCES IN BRITISH COLUMBIA**

SLR Project No.: 219.05420

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May 2019



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EXECUTIVE SUMMARY

In November 2017, the BC Ministry of Environment and Climate Change Strategy (BC ENV) released soil and/or water standards for three chemicals which belong to the group of contaminants known as per- and polyfluoroalkyl substances (PFAS). As PFAS are newly regulated substances under the BC Contaminated Sites Regulation (BC CSR), the Society of Contaminated Sites Approved Professionals of British Columbia (CSAP) has retained SLR Consulting (Canada) Ltd. (SLR) to develop a guidance document for the investigation and remediation of PFAS at contaminated sites in BC to serve as a resource for CSAP members, regulators, and other contaminated sites practitioners. To support this objective, this report:

- Reviews the physical/chemical properties of the BC CSR-regulated PFAS;
- Details the PFAS regulatory frameworks that may be encountered in BC;
- Identifies potential point sources of PFAS at contaminated sites in BC;
- Reviews PFAS analytical methods and BC Environmental Laboratory Manual considerations;
- Discusses contaminant migration pathways and environmental media to be considered by investigators;
- Summarizes best practices for the collection of representative environmental samples for PFAS analysis; and
- Compiles information on field-scale evaluations of soil and water treatment technologies.

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ACRONYM LIST

| | |
|--------|---|
| µg/L | micrograms per litre |
| AA-EQS | Proposed Average Annual Concentration Quality Standard |
| AA-QS | Average Annual Concentration Quality Standard |
| AB | Alberta |
| AER | anion exchange resin |
| AFFF | aqueous film forming foam |
| AGAT | AGAT Laboratories |
| ALS | ALS Limited |
| ASTM | ASTM International |
| ATSDR | Agency for Toxic Substances and Disease Registry |
| BAF | bioaccumulation factors |
| BC CSR | BC Contaminated Sites Regulation |
| BC ENV | BC Ministry of Environment and Climate Change Strategy |
| BC HWR | BC Hazardous Waste Regulation |
| BC | British Columbia |
| CARO | CARO Analytical Services |
| CAS | Chemical Abstract Services |
| CCME | Canadian Council of Ministers of the Environment |
| CEPA | Canadian Environmental Protection Act |
| CFB | Canadian Forces Base |
| CSAP | Society of Contaminated Sites Approved Professional of British Columbia |
| CSM | Conceptual Site Model |
| DEQ | Michigan Department of Environmental Quality |
| DoD | Australia Department of Defence |
| DoEE | Australian Government Department of the Environment and Energy |
| ECCC | Environment and Climate Change Canada |
| ECF | electrochemical fluorination |
| EMA | Environmental Management Act |
| ETFE | ethylene tetrafluoroethylene |
| Exova | Exova Group Limited |
| FEP | fluorinated ethylene propylene |
| FEQGs | Federal Environmental Quality Guidelines |
| FSA | perfluoroalkane sulfonamides |
| FTS | fluorotelomer sulfonate |
| g/mole | grams per mole |
| GAC | granular activated carbon |
| HC | Health Canada |
| HEPA | Heads of EPAs Australia and New Zealand |
| HHERA | human health and ecological risk assessment |
| IL | industrial land use |

| | |
|--|---|
| ITRC | Interstate Technology Regulatory Council |
| K _{oc} | organic carbon partition coefficient |
| LC-MS/MS | liquid chromatography tandem mass spectrometry |
| LDPE | low density polyethylene |
| MAC | maximum acceptable concentration |
| MDH | Minnesota Department of Health |
| mg/kg | milligrams per kilogram |
| mg/L | milligrams per litre |
| MPCA | Minnesota Pollution Control Agency |
| NEMP | National Environmental Management Plan |
| NHDES | New Hampshire Department of Environmental Services |
| NICOLE | Network for Industrially Contaminated Land in Europe |
| °C | degree Celsius |
| ON | Ontario |
| PCL | Protective Concentration Levels |
| PCTFE | polychlorotrifluoroethylene |
| pers. comm. | Personal Communication |
| PFAA | perfluorinated alkyl acids |
| PFAS | Per- and Polyfluoroalkyl Substances |
| PFBA | perfluorobutanoic acid/perfluorobutanoate |
| PFBS | perfluorobutane sulfonic acid/perfluorobutane sulfonate |
| PFCAs | perfluoroalkyl carboxylates |
| PFDA | perfluorodecanoic acid/perfluorodecanoate |
| PFD _o DA | perfluorododecanoic acid/perfluorododecanoate |
| PFD _o S / PFD _o DS | perfluorododecane sulfonic acid/perfluorododecane sulfonate |
| PFDS | perfluorodecane sulfonic acid/perfluorodecane sulfonate |
| PFECHS | perfluoroethylcyclohexane sulfonate |
| PFHpA | perfluoroheptanoic acid/perfluoroheptanoate |
| PFHpS | perfluoroheptane sulfonic acid/perfluoroheptane sulfonate |
| PFHxA | perfluorohexanoic acid/perfluorohexanoate |
| PFHxS | perfluorohexane sulfonic acid/perfluorohexane sulfonate |
| PFNA | perfluorononanoic acid/perfluorononanoate |
| PFNS | perfluorononane sulfonic acid/perfluorononane sulfonate |
| PFOA | perfluorooctanoic acid/perfluorooctanoate |
| PFOS | perfluorooctane sulfonic acid/perfluorooctane sulfonate |
| PFOSA | perfluorooctane sulfonamide |
| PFOSF | perfluorooctane sulfonyl fluoride |
| PFPeA | perfluoropentanoic acid/perfluoropentanoate |
| PFPeS | perfluoropentane sulfonic acid/perfluoropentane sulfonate |
| PFSAs | perfluoroalkane sulfonates |
| PFTeDA | perfluorotetradecanoic acid/perfluorotetradecanoate |

| | |
|-----------|---|
| PFTTrDA | perfluorotridecanoic acid/perfluorotridecanoate |
| PFUnA | perfluoroundecanoic acid/perfluoroundecanoate |
| PFUnDA | perfluoroundecanoic acid/perfluoroundecanoate |
| PIGE | Particle Induced Gamma Ray Emission |
| pKa | acid dissociation constant |
| PNEC | Predicted No Effect Concentration |
| PTFE | polytetrafluoroethylene |
| PVDF | polyvinylidene fluoride |
| QA/QC | Quality Assurance/Quality Control |
| QC | Quebec |
| QS | Quality Standard |
| RIVM | National Institute for Public Health and the Environment |
| RMC | Royal Military College |
| RPF | relative potency factor |
| SERDP | Strategic Environmental Research and Development Program |
| SGS AXYS | SGS AXYS Analytical Services Ltd. |
| SLR | SLR Consulting (Canada) Ltd. |
| SPE | solid phase extraction |
| TCEQ | Texas Commission of Environmental Quality |
| TOF | total organic fluorine |
| TOP | total oxidizable precursor |
| UHP | ultra-high pressure |
| UNEP | United Nations Environment Programme |
| US | United States |
| US Army | United States Department of the Army |
| US EPA | United States Environmental Protection Agency |
| USEPA RSL | United States Environmental Protection Agency Regional Screening Levels |
| WAX | weak anion exchange |

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1.0 INTRODUCTION

In November 2017, the BC Ministry of Environment and Climate Change Strategy (BC ENV) released soil and water standards for a number of emerging contaminants within amendments to the British Columbia Contaminated Sites Regulation (BC CSR), the principal regulatory document defining requirements for contaminated sites management in British Columbia. In particular, BC CSR standards were derived for three chemicals which belong to the group of contaminants known as per- and polyfluoroalkyl substances (PFAS).

PFAS encompasses a wide variety of aliphatic chemicals that contain at least one carbon atom in which all the hydrogen atoms have been replaced by fluorine (Buck et al., 2011). The PFAS of regulatory focus in BC include perfluorobutane sulfonate (PFBS), perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA). These three substances were selected for inclusion in the BC CSR from an original list of fourteen PFAS deemed high priority substances by BC ENV based on the availability of toxicological information as of November 2015 from specific external sources (pers. comm., H. Osachoff).

As PFAS are newly regulated substances under the BC CSR, the Society of Contaminated Sites Approved Professionals of British Columbia (CSAP) retained SLR Consulting (Canada) Ltd. (SLR) to develop a guidance document for the investigation and remediation of PFAS at contaminated sites in BC to serve as a resource for CSAP members, regulators, and other contaminated sites practitioners.

1.1 Project Objective

The objective of this project is to compile current information on PFAS investigation and remediation from various jurisdictions and organizations, and to present it in a manner that is user-friendly and relevant to a BC-based audience. This guidance document will improve consistency in PFAS investigations in BC and will assist CSAP and non-CSAP practitioners in remediation and risk management decision-making.

1.2 Scope of Work

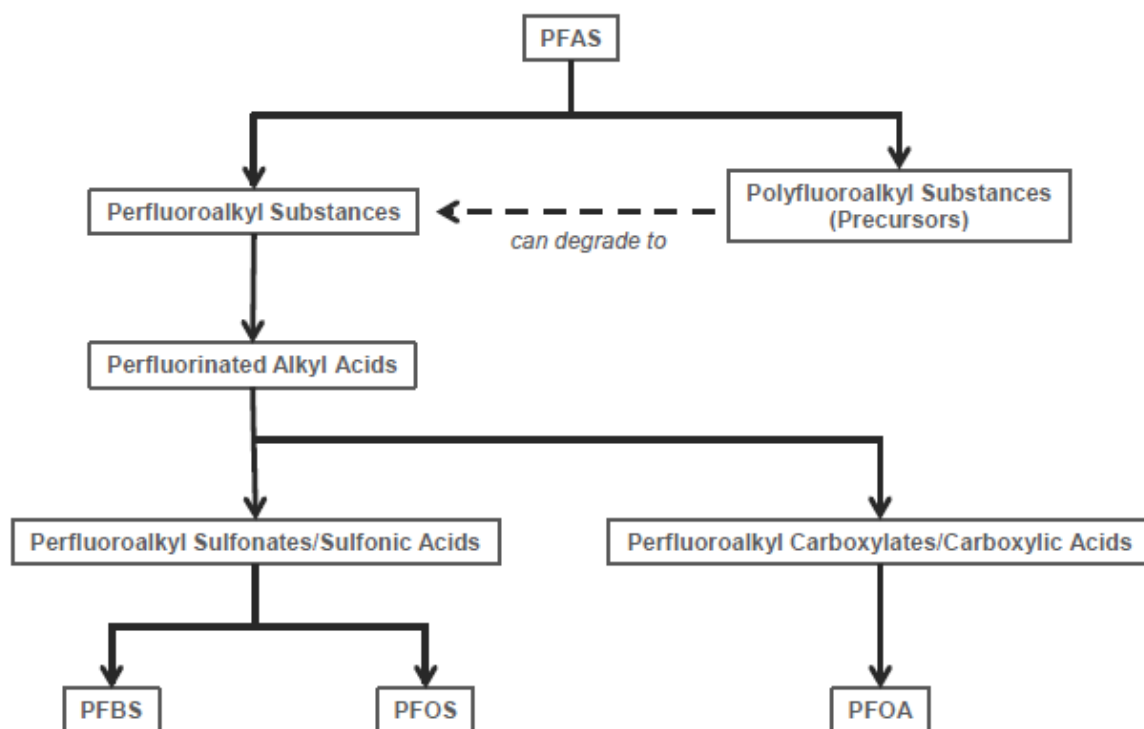
To support the project objectives, SLR:

- Conducted a literature review which identified relevant guidance materials related to the investigation and characterization of the BC CSR-regulated PFAS and included items such as:
 - Chemical properties;
 - Potential sources, contaminant migration pathways, and environmental media of relevance in BC site investigations; and
 - Considerations for the collection of representative environmental samples;
- Liaised with personnel at Canadian and international regulatory agencies and other organizations to identify additional guidance materials and best management practices not readily identified through online searches;
- Contacted personnel at Canadian commercial laboratories offering PFAS analysis and evaluated Canadian analytical offerings in comparison to recommended PFAS analytical approaches in other jurisdictions;
- Compiled information on field-confirmed PFAS remediation techniques; and
- Prepared this report to present the information gathered above within the framework of the British Columbia regulatory regime.

2.0 CHEMICAL INFORMATION

PFAS include aliphatic chemicals that are either fully fluorinated (i.e., perfluoroalkyl substances) or partially fluorinated (polyfluoroalkyl substances). The PFAS of regulatory focus in BC belong to a family of chemicals known as the perfluorinated alkyl acids (PFAAs). The PFAAs consist of a fully fluorinated alkyl chain and a hydrophilic end group. The PFAAs that are subject of this report belong to two classes: perfluoroalkyl carboxylates (PFCAs) and perfluoroalkane sulfonates (PFSAs).

Practitioners should also be aware of PFAS “precursor” compounds. These are chemicals which may co-occur with the regulated PFAAs at PFAS contaminated sites in BC. Precursors are polyfluoroalkyl substances that can transform to create PFAAs, which then do not degrade further in the environment (ITRC, 2018a).



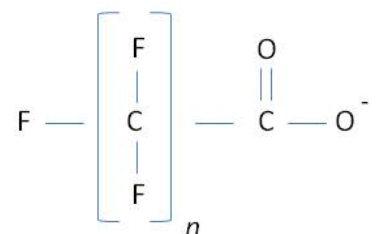
This section presents information on the physical/chemical properties of the PFAS of current regulatory focus in BC and summarizes the partitioning behaviour, transport, and environmental occurrence of these chemicals.

2.1 Physical/Chemical Properties

Although the focus of this report is on the parameters regulated under the BC CSR, a brief description of the chemical classes to which these chemicals belong (i.e., the PFCAs and PFSAs) is provided below as it is expected that a wider range of PFAS, including other members of these chemical classes, will be encountered by practitioners conducting site assessments.

2.1.1 Perfluoroalkyl Carboxylates/Perfluoroalkyl Carboxylic Acids (PFCAs)

PFCAs are comprised of completely fluorinated alkyl chains with a carboxylate or carboxylic acid end group and are generally described as $F(CF_2)_nCO_2^-$ or $F(CF_2)_nCO_2H$, respectively. However, the PFCAs are typically present in the anionic form under most environmental conditions (i.e., the former form). The general chemical structure of the anionic PFCAs (i.e., perfluoroalkyl carboxylates) is presented below:



The PFCAs can then be further divided into long-chain and short-chain members (Buck et al., 2011). The long-chain members are comprised of chemicals with a fully fluorinated carbon chain of 7 carbons or longer and have been the focus of most regulatory efforts to date due to observations on their persistence, bioaccumulation and effects in the environment. Further, the distinction between short-chain and long-chain PFCAs is useful in understanding the general differences in their environmental fate and transport (discussed further in Section 2.1.5).

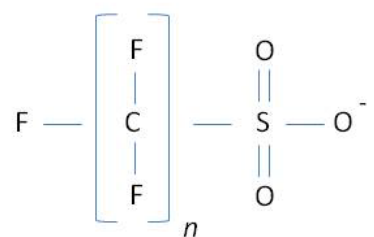
The PFCA of regulatory focus in British Columbia is PFOA which is considered to be a long-chain PFCA ($n = 7$ in the chemical structure depicted above).

The Chemical Abstract Services (CAS) number for PFOA, and nomenclature for other non-regulated PFCAs which may commonly be encountered at contaminated sites in BC, are listed in Table A-1 in Appendix A. As CAS numbers vary for the anionic and acid forms of the chemicals, both are presented.

2.1.2 Perfluoroalkane Sulfonates/Perfluoroalkane Sulfonic Acids (PFSA)s

The PFSA)s also consist of fully fluorinated alkyl chains, but differ from the PFCAs in the presence of a sulfonate or sulfonic acid end group rather than a carboxylate or carboxylic acid end group. As noted previously for the PFCAs, the PFSA)s are typically present in the anionic form under most environmental conditions (i.e., the sulfonate form).

The general chemical structure of the anionic PFSA)s (i.e., perfluoroalkane sulfonates) is presented below:



The PFASs are also further divided into long-chain and short-chain members. Unlike the PFCAs discussed in Section 2.1.1 above, the long-chain members are comprised of chemicals with a fully fluorinated carbon chain of 6 carbons or longer (Buck et al., 2011).

The PFASs of regulatory focus in British Columbia are PFBS and PFOS. PFBS is a short-chain PFSA ($n = 4$ in the chemical structure above) while PFOS is considered to be a long-chain PFSA ($n = 8$).

The CAS numbers for PFBS and PFOS, and nomenclature for other non-regulated PFASs which may be encountered at contaminated sites in BC, are listed in Table A-2 in Appendix A (nomenclature and CAS numbers provided for both anionic and acid forms of the substances).

2.1.3 Other PFAS of Potential Interest at Contaminated Sites in BC

In addition to the non-regulated PFASs and PFCAs summarized in Tables A-1 and A-2 in Appendix A, other PFAS compounds may commonly co-occur with the chemicals of regulatory focus at PFAS contaminated sites in BC. Additional information on some of these chemicals is provided in Appendix B.

2.1.4 Linear versus Branched Isomers

The PFASs and PFCAs described in Sections 2.1.1 and 2.1.2 have been produced by two different methods: electrochemical fluorination (ECF) and telomerisation. Specifically, the PFASs have been produced by only the ECF process, while the PFCAs have been produced by both the ECF and telomerisation processes.

Due to the nature of the ECF process, the resulting chemicals are comprised of both straight-chain isomers and branched isomers. In telomerisation, the structure of the products reflects that of the starting materials; if a linear starting material is used, then purely straight-chain isomers are produced by telomerisation¹. Published literature indicates that the physical-chemical properties of the straight-chain and branched isomers may be quite different. Despite these differences, the few toxicological comparisons of branched and linear isomers have suggested that there may be only subtle toxicological differences between linear and total branched isomers (Benskin, 2011). Laboratory analysis of PFOS in water and soil in British Columbia is required to report the sum of all identifiable linear and branched isomers (BC ENV, 2017a; BC ENV, 2017b) due to the expected presence of both forms in environmental media, as well as their expected similar effects.

2.1.5 Partitioning Behaviour of Regulated PFAS

To understand the fate and transport of the regulated PFAS at contaminated sites in BC, it is important to understand and recognize differences in the physical and chemical properties of the individual chemicals. Table 2-1 presents some of the key properties for understanding environmental partitioning behavior of PFBS, PFOS and PFOA. Physical-chemical properties of non-regulated PFAS are provided in Appendix D.

¹ Production of branched isomers from the telomerization process is possible but would require a branched starting material (De Silva et al, 2009). All products would be branched (no linear isomers would be produced). However, most information sources suggest that telomerisation products are generally linear.

Table 2-1: Physical and Chemical Properties of PFAS Regulated in BC

| Compound Name | # Fully Fluorinated Carbons | Short/ Long Chain | Molecular weight (g/mole) ^a | Physical State (20° C) ^a | pK _a ^b | Water Solubility (mg/L) ^a | Dimensionless Henry's Constant ^{a,c} | Log K _{oc} (unitless) ^{a,d} |
|---------------|-----------------------------|-------------------|--|-------------------------------------|------------------------------|--------------------------------------|---|---|
| PFCAs | | | | | | | | |
| PFOA | 7 | Long | 413.1 | Solid | 3.8 | 9.5E+03 | 3.31E-08 | 2.31 |
| PFSAs | | | | | | | | |
| PFBS | 4 | Short | 299.1 | Solid | 0.14 (estimated) | 1.74E+04 | 1.12E-11 | 1.47 |
| PFOS | 8 | Long | 499.1 | Solid | 0.14 (estimated) | 5.7E+02 | 3.25E-08 | 3.34 |

Notes:

^a - Data obtained from TCEQ, 2018.

^b – Data obtained from ATSDR, 2018. As reported by Health Canada (HC, 2018a; HC, 2018b), pK_a values range from -0.5 to 4 for PFOA and an estimated value of -3.27 has been provided for PFOS.

^c - Higher Henry's Constants have been reported by other sources (i.e., ATSDR, 2018; HC, 2018a; HC, 2018b).

^d - Log K_{oc} values provided above are consistent with ranges reported by ITRC (ITRC, 2018c) and Health Canada (HC, 2018b).

As noted in Table 2-1 above, the regulated PFAS have molecular weights higher than substances such as benzo(a)pyrene and, in their pure form, are solids at room temperature. Given the likely sources of PFAS at contaminated sites in British Columbia (i.e. as constituents in products that are further diluted in water prior to release to the environment) and the absence of PFAS manufacturing facilities in Canada (ECCC, 2006), encountering pure form PFAS is considered unlikely.

Estimation of acid dissociation constants (i.e., pK_a values, quantitative measures of the strength of an acid in solution) for PFCAs and PFSA is challenging, leading to a wide range of reported values in the literature. Despite this variability, the reported pK_a values presented in Table 2-1 above reflect that PFBS, PFOS and PFOA will be predominantly present in the dissociated (anionic) form under most environmental conditions.

In their anionic form, PFBS, PFOS and PFOA are considered to be soluble in water and are likely to be encountered at contaminated sites in the dissolved phase, with solubilities in the same range as chloroethane, toluene and 1,2-dichloroethane, respectively. Solubility of the PFAAs is reported to vary depending on chemical structure (i.e., carbon chain length, functional end groups), pH, and water salt content (e.g., pure water versus freshwater versus saltwater). Generally, PFCAs are considered more soluble than their PFSA counterparts and shorter-chain substances are more soluble than long-chain compounds. Like many organic compounds, the solubilities of PFCAs and PFSA are considered higher in freshwater than in saline waters.

The regulated PFAS are generally considered mobile in soil, but mobility differs based on chemical structure (i.e., carbon chain length, functional end groups) as well as on characteristics of the soil itself (e.g., organic carbon content, presence of iron oxides and other positively charged compounds on soil/sediment surfaces, and soil pH). Log K_{oc} values, and by extension adsorption to soil, are reported to increase with increasing carbon chain length, and also tend to be higher for PFSA than their carbon chain equivalent PFCAs. Additionally, soil adsorption is expected to increase with increasing chain linearity (Rayne and Forest, 2009b).

In addition to the potential for PFCAs and PFSA to partition to both the aqueous phase and to solid matrices (as discussed above), the structure of PFCAs and PFSA, specifically the hydrophobic/lipophobic carbon chains and hydrophilic functional end groups, can also result in the partitioning of the chemicals to soil/water, water/air interfaces and water/non-aqueous phase liquid interfaces. One researcher (Brusseau, 2018) reported that air-water interfaces contributed approximately 50% of the total retention of PFOS and PFOA under the conditions studied.

As noted in Table 2-1 above, the regulated PFAS generally have low dimensionless Henry's constants for their anionic forms, indicating these substances are not expected to appreciably volatilize from water or to soil pore space under ambient environmental conditions. It is noted that the PFCAs in particular are considered to be more volatile in their acid form (Kaiser et al, 2010). However, even at low environmental pH (e.g., pH 4.5-5.0), only a very small fraction of PFOA would be expected to exist as an acid, indicating that potential partitioning to the vapour phase is not expected to be a significant process at contaminated sites in British Columbia.

2.1.6 Bioaccumulation Potential of Regulated PFAS and Uptake to Biota

SLR (2015) prepared a guidance document on behalf of CSAP on an approach for identifying bioaccumulative substances at contaminated sites in British Columbia. Among its

recommendations, the paper highlighted the use of various parameters and metrics to identify bioaccumulative contaminants, including Log K_{ow} which has routinely been relied upon to identify chemicals warranting further evaluation of bioaccumulation potential. However, K_{ow} values for PFAS cannot be determined directly using routine determination methods as PFAS are hydrophobic and lipophobic at the same time and therefore tend to form multiple layers in water/hydrocarbon mixtures (Renner, 2001 as reported in Stock et al., 2010; Valsecchi et al., 2016). It is SLR's understanding that a definition of bioaccumulative substances is in preparation by BC ENV as no definition is currently contained within BC ENV Procedure 8 (BC ENV, 2017c)

The evaluation of the potential transfer of PFAS to higher trophic levels on a site-specific basis, within the context of human health and ecological risk assessment (HHERA), may be necessary. The BC CSR standards for soil and groundwater are not protective of these exposure routes.

The following is noted:

- Bioaccumulation potential generally increases with increasing chain-length (ITRC, 2018c; various researchers as reported in ATSDR, 2018). The bioaccumulation potential of PFAAs is reported to increase with increasing chain length from 4 to 8 carbon units, and then declines with further increases in chain length (various researchers as reported in ATSDR, 2018);
- PFCAs and PFSA's containing less than seven and six perfluorinated carbons, respectively, are considered short-chain substances. The short-chain substances are not considered as bioaccumulative as the longer-chain substances (Conder et al., 2008; ATSDR, 2018);
- PFSA's are more bioaccumulative than PFCAs of the same fluorinated carbon chain length (Danish EPA, 2015);
- PFOS is considered bioaccumulative in numerous terrestrial and aquatic organisms by a variety of organizations (US EPA, 2017; MDH, 2017; ITRC, 2018c; ECCC, 2018; HEPA, 2018);
- US EPA (2017) reports that PFOA has been shown to bioaccumulate in air breathing species, including humans, but not in fish. Environment and Climate Change Canada (ECCC) has reported that although whole-body data indicates PFOA has a low to moderate potential to accumulate in aquatic species, organ-specific data suggests that PFOA may bioaccumulate and biomagnify (i.e. progressively higher contaminant concentrations are attained in organisms at higher levels in the food chain) in both terrestrial and marine mammals (ECCC, 2012);
- One study conducted downstream of a former firefighting training facility in Ontario summarized field-derived bioaccumulation factors (BAF) for PFOS and PFOA in a variety of fish species (Bhavsar et al., 2016). On average BAFs were higher for PFOS than PFOA (average log BAF across all species of 2.4-4.7 for PFOS and 0.9-1.8 for PFOA), and are consistent with views that PFOA is not highly bioaccumulative in fish; and
- Within biota, PFCAs and PFSA's are expected to bind primarily to proteins rather than partitioning to lipids like other persistent organic contaminants.

2.2 Environmental Occurrence

The extreme stability of the carbon-fluorine bonds in PFCAs and PFSA's make these substances highly persistent in the environment and contribute to their detection worldwide (including in Arctic and other remote regions far removed from source locations) in all manner of

environmental media including vegetation, wildlife and humans (e.g., breast milk, serum, umbilical cord blood).

The sources of human exposure to PFAS are not fully understood, but dietary intake (including ingestion of breast milk) is considered to be one of the important routes of exposure. Food items may acquire PFAS directly from food packaging treated with grease- and water-repellent coatings, or as a result of bioaccumulation during animal or plant growth (Tittlemier et al., 2007). Canadians may also be exposed to PFAS through direct contact with impacted media (e.g., ingestion of drinking water or soil, particularly where impacted by industrial or fire-fighting activities, and inhalation of household dusts) and PFAS-containing consumer products.

2.3 Manufacturing Timelines

As discussed in Section 2.1.4, two methods (ECF and telomerisation) have been used to manufacture PFAS. The ECF method was principally used by 3M starting in the 1940s, while the manufacture of PFAS by other companies via telomerisation did not occur until the 1970s (Stock et al, 2010; ITRC, 2017).

By 2002, 3M had mostly phased-out its production of PFOS; production of PFOS did continue in other countries after this time however. As of 2017, the only known producer of PFOS was China (ITRC, 2017).

Between 2006 and 2015, the eight major manufacturers of long-chain PFCAs (such as PFOA) and related precursors in the United States progressively reduced, and eventually eliminated, production of these compounds. However, this reduction in production in the United States was offset by increased manufacturing activities in other countries.

Due to the above phase-out measures, manufacturers of PFAS have focused recent production efforts on replacement chemistries for long-chain PFAAs, including short-chain PFAS (such as PFBS) and polyfluorinated substances.

Investigators are encouraged to review dates of potential source product use at PFAS contaminated sites in BC (discussed further in Section 4.0) to support their understanding of the specific PFAS which may be present at the site.

3.0 REGULATORY FRAMEWORK

The following sections summarize the provincial, federal and international regulatory efforts to address PFAS in the environment.

3.1 Provincial Regulations and Standards

Provincial regulations pertaining to PFAS are reviewed below.

3.1.1 BC Contaminated Sites Regulation

Numerical standards for PFBS, PFOS and PFOA were released by BC ENV in the Stage 10/11 amendments to the BC CSR, effective November 1, 2017. Footnotes provided in BC CSR Schedule 3.2 indicate the standards are only to be applied at sites with specific BC CSR Schedule 2 activities². Schedule 2 of the BC CSR is comprised of a list of commercial and industrial purposes or activities, which BC ENV has determined to have the potential to cause contamination at a property.

The specified Schedule 2 uses are those which were considered by BC ENV to be the most relevant in BC at the time of the development of the PFAS standards (pers. comm. H. Osachoff) and are limited to:

- A4 – Fire Retardant Manufacturing or Wholesale Bulk Storage: PFAS have been and continue to be used as constituents in aqueous film forming foams (AFFF), fluoroprotein foams, and other fluorine-based firefighting foams that are effective against flammable liquid (or Class B) fires (Dewitt, 2016; Rotander et al., 2015). The PFAS constituents allow the AFFF to form a thin film over the flammable liquids and extinguish the fire, and to also suppress the volatilization of vapours and subsequent re-ignition of the liquids (ITRC, 2018f). It is noted that A4 refers to “wholesale bulk storage” and not simply to “bulk storage”. Although neither term is defined under the Environmental Management Act (EMA) or BC CSR, BC ENV Administrative Guidance 13 (BC ENV, 2013a) defines wholesale bulk storage as “storage of substances, materials or equipment, in large quantities for resale to retailers, or to industrial, commercial or institutional users.” A more detailed discussion of firefighting foam sources of PFAS is provided in Section 4.1.1.
- C3 – Metal Plating or Finishing: Electroplating facilities in Canada are another industrial point source of PFAS as these chemicals have been identified in products used for suppressing hexavalent chromium emissions/fumes during electroplating operations (MDH, 2008; US EPA, 2009). A more detailed discussion of metal plating sources of PFAS is provided in Section 4.1.2.
- G1 – Aircraft Maintenance, Cleaning or Salvage: Schedule 2 activity G1 will capture PFAS-contaminated sites at airports due to the historical or current presence of firefighter training areas (and associated use of firefighting foams), due to aviation fuel storage and handling operations (and associated use of firefighting foams to extinguish fires), and also due to the potential presence of other PFAS-containing products such as

² A footnote regarding applicable Schedule 2 activities appears to be only partially applied to the soil standards for PFOS in Schedule 3.1 (Part 1) and is not provided in association with the PFBS soil standard in Schedule 3.1 (Part 2).

aviation hydraulic fluids. A more detailed discussion of aircraft maintenance sources of PFAS is provided in Section 4.1.3.

- E10 – Sites Contaminated by Migrating Substances: In addition to A4, C3, and G1 Schedule 2 activities, the BC CSR standards are also considered applicable on lands which have the potential to have been contaminated by migrating substances (i.e., E10 activity under BC CSR Schedule 2). Based on SLR's discussions with BC ENV (pers. comm., H. Osachoff), it appears that as written in the BC CSR, the PFAS standards are considered applicable to any off-site migration to a parcel of land, irrespective of the Schedule 2 activity which is the source of the contamination. Further, the PFAS would need to be investigated in accordance with BC ENV's process for properties affected by migration from off-site sources (i.e., Notification of Likely or Actual Migration, investigation, reporting, etc.). The inclusion of E10 without a direct link to A4, C3 or G1 Schedule 2 uses at the source sites appears consistent with the prohibition on the creation of pollution under EMA. To that end, practitioners should be aware that potential PFAS source sites without A4, C3 and G1 Schedule 2 uses (discussed further in Section 4.2) would be captured by the regulations where PFAS originating at the source site migrates to off-site lands.

In light of the above and based on discussions with BC ENV (pers. comm. H. Osachoff), it is SLR's understanding that BC ENV may consider either expanding the list of Schedule 2 uses associated with the BC CSR PFAS soil and water standards, or possibly eliminating reference to specific Schedule 2 uses altogether.

The BC CSR numerical standards for PFBS, PFOS and PFOA include the following:

- PFOS – Standards for soil (multiple pathways) in Schedule 3.1, Part 1, and for groundwater (aquatic life and drinking water uses) in Schedule 3.2.;
- PFBS – Standards for soil (human health protection only) in Schedule 3.1., Part 2, and for groundwater (drinking water only) in Schedule 3.2.; and
- PFOA – A standard for groundwater (drinking water only) in Schedule 3.2.

For the most current version of the BC CSR numerical standards, please reference the BC ENV website (<https://www2.gov.bc.ca/gov/content/environment/air-land-water/site-remediation/laws-regulations-compliance>).

3.1.2 BC Hazardous Waste Regulation

PFAS are not currently regulated under the BC Hazardous Waste Regulation (BC HWR). The BC HWR precludes re-use of waste oil, restricts effluent discharges from hazardous waste treatment facilities, and prohibits disposal of waste when organic halogen levels exceed targeted levels; however, it appears that the intent of the regulation is to limit presence of chlorinated organic compounds as opposed to fluorinated organic compounds. It is noted that the organic halogen analyses typically conducted by laboratories for determination of the HWR regulated parameters are not expected to meaningfully reflect organic fluorine concentrations or potential PFAS levels present.

3.1.3 BC Approved, Working and Draft Water Quality Guidelines

At the time of this report, no BC Approved Water Quality Guidelines, Working Water Quality Guidelines, or Draft Water Quality Guidelines had been released for PFAS. Section 3.4 of this

document reviews information resources for practitioners for media without provincial regulatory criteria.

3.2 Canadian Federal Regulations, Guidelines and Screening Values

The following sections outline federal regulatory efforts relating to PFAS and are included in this report for information purposes only, recognizing that management of contaminated sites on non-federal lands falls under provincial jurisdiction. However, for PFAS or media without provincial standards, federal environmental screening values and guidelines can provide a starting point for further inquiry by practitioners.

3.2.1 Canadian Environmental Protection Act

Both PFOS and PFOA are listed as toxic substances under the Canadian Environmental Protection Act (CEPA). Under CEPA and its regulations, the manufacture, use, sale, and importation of PFOS, PFOA, and PFCAs with a carbon chain longer than PFOA (i.e., containing more than 7 fully fluorinated carbons), as well as products containing these compounds, is restricted in Canada.

3.2.2 Canadian Council of Ministers of the Environment

Draft guidelines for PFOS in soil and groundwater were released for public comment by CCME in August 2018. A timeline for release of the final guidelines has not been provided.

3.2.3 Environment and Climate Change Canada

Federal Environmental Quality Guidelines (FEQGs) for PFOS in surface water and biota tissue were finalized by ECCC in June 2018 (ECCC, 2018). The FEQGs were developed under Section 54 of CEPA to allow for monitoring of PFOS in the environment in the absence of Canadian Environmental Quality Guidelines. The use of FEQGs is voluntary unless prescribed in permits or other regulatory tools.

FEQG for PFOA are reportedly under development (pers. comm. J. Roy).

3.2.4 Health Canada

Health Canada released Guidelines for Canadian Drinking Water Quality for PFOS and PFOA in December 2018 (HC, 2018a; HC, 2018b). A maximum acceptable concentration (MAC) of 0.2 µg/L has been developed for PFOA and a MAC of 0.6 µg/L has been developed for PFOS. Further, Health Canada has indicated that where PFOS and PFOA co-occur in drinking water, the ratio of the PFOA concentration to its MAC and the ratio of the PFOS concentration to its MAC when summed together should not exceed one. If the result is below or equal to one, then Health Canada considers the water safe for drinking.

Drinking water screening values have been developed by Health Canada (HC, 2019a) for seven additional PFAAs (i.e., PFBA, PFPeA, PFHxA, PFHpA, PFNA, PFBS, and PFHxS) and two fluorotelomer sulfonates (i.e., 6:2 FTS and 8:2 FTS, refer to Appendix B). Soil screening values have also been developed for nine PFAAs (HC, 2019b). Of particular note, the Health Canada soil screening values are protective of direct contact with soil but are not protective of the soil-to-drinking water migration pathway, or of potential exposures via ingestion of garden produce. Further, similar to drinking water, Health Canada has recommended an additive approach

where both PFOS and PFOA are detected in soil (i.e., the sums of the ratios of detected concentrations to screening values should not exceed one). Health Canada has indicated that science currently does not justify the use of this approach for other PFAS (HC, 2019b).

3.3 International Regulatory Considerations

PFAS are recognized as an environmental issue internationally. The Stockholm Convention on Persistent Organic Pollutants is an international treaty which aims to protect human and environmental health from organic chemicals that are environmentally persistent, toxic, accumulate in humans and wildlife, and have the potential for long-range transport. PFOS was listed in Annex B of the Convention in 2009 (which restricts the production, use, import and export of the chemical), while PFOA is currently under review for inclusion along with PFHxS. Based on information provided by ECCC (pers. comm., R. Mroz), it is expected that PFOA may be listed as early as Spring 2019.

International efforts to protect human and environmental health against the adverse effects of PFOS in particular have also occurred under the Basel Convention, with the development of technical guidelines for the environmentally sound management of wastes containing PFOS (discussed further in Section 7.3).

Regulatory efforts in countries other than Canada have primarily focused on the development of criteria for PFOS and PFOA in drinking water. In some jurisdictions, regulatory limits for other PFAS in drinking water, and for PFOS and PFOA in media other than drinking water, have been derived and are summarized in the following section.

3.4 Information Resources for Media/Receptor Exposure Pathways not Covered by BC CSR Standards

Media/exposure route combinations not covered by the BC CSR standards for PFBS, PFOS and PFOA are expected to exist at PFAS-contaminated sites in British Columbia (e.g., leaching of PFOA from soil to groundwater used as drinking water, exposure of aquatic life to PFOA in surface water). These exposure pathways may be assessed within the context of HHERA or they may be evaluated by practitioners for due diligence purposes. To support the management of such sites, criteria from Health Canada, ECCC, and US EPA sources have been compiled and summarized (Table C-1 in Appendix C). Where criteria are not available from Health Canada, ECCC, or US EPA sources for a particular media/receptor exposure pathway combination, information from international sources has been provided.

The underlying assumptions and protection goals relied upon in the derivation of the criteria in Appendix C may differ significantly from those applied in British Columbia. Further, the derivation of new criteria and revision of existing values by some jurisdictions is expected over time due to ongoing toxicological research activities globally. Consequently, the application of the criteria on a project-specific basis should be conducted with caution and should be confirmed by the practitioner to be consistent with regulator expectations and/or appropriate for the project objectives. The criteria in Appendix C are provided as a starting point for further inquiry by practitioners.

3.5 Information Resources for Other PFAS Anticipated to be Present at Contaminated Sites in BC

As stated in the introduction, BC ENV originally identified fourteen PFAS as priority substances for the development of BC CSR standards; however, standards were only developed for PFBS, PFOS and PFOA based on availability of toxicological information as of November 2015. Numerous non-regulated PFAS are expected to co-occur with the regulated parameters at contaminated sites in British Columbia. To assist practitioners in the management of sites with non-regulated PFAS present (e.g., PFBA, PFNA) for due diligence purposes, criteria from Health Canada and US EPA sources have been compiled and summarized (Table C-2 in Appendix C). Where criteria are not available from Health Canada or US EPA sources for a particular media/receptor exposure pathway combination, information from international sources has also been provided.

As noted in the previous section, the underlying assumptions and protection goals relied upon in the derivation of the values may differ significantly from those applied in British Columbia, and changes to the values and derivation of new values are anticipated over time. Caution in the application of these criteria is advised. Values/information sources have been provided to support further contaminant-specific evaluations by practitioners.

3.6 Chemical Additivity

A number of jurisdictions recommend approaches in which additive risk of certain PFAS is taken into consideration when these substances are found together in environmental media, given concerns about the potential for similar health effects (discussed further in Appendix C). Currently, use of an additive approach is not required for comparison to the numerical standards of the regulated PFAS parameters under the BC CSR, but may be considered in future standards development (pers. comm., H. Osachoff). However, consideration of chemical additivity is expected within the context of detailed risk assessment as noted in BC ENV Technical Guidance 7 Supplemental Guidance for Risk Assessments (BC ENV, 2017d).

4.0 POTENTIAL SOURCES OF PFAS

According to ECCC, there are no PFAS manufacturing facilities in Canada (ECCC, 2006). However, PFAS are, or have historically been, imported and sold in Canada for use primarily in fire-fighting foams and consumer and industrial products to provide oil/water resistance for application to paper, textiles, carpets, flooring, leather, and other products. Results of an environmental survey conducted by ECCC in 2004 (EC, 2006) indicated that approximately 400 tonnes of over 60 different PFAS or their precursors were used in industries. Importation of some of the PFAS to Canada is thought to be declining based on the inclusion of select substances in the amended list of chemicals in US EPA's significant new use rule (US EPA, 2007) and potentially also by specific measures taken with respect to PFOS, PFOA, and longer-chain PFCAs (and their salts and precursors) under the Canadian Environmental Protection Act (CEPA). Regulatory measures recently proposed under CEPA (Government of Canada, 2018) are expected to cause further decline in the importation and use of these chemicals (i.e., by eliminating exemptions for specific uses of these chemicals currently allowed under CEPA).

4.1 Point Sources of Relevance under BC CSR

Despite the absence of PFAS manufacturing facilities in BC, it is expected that both point and non-point sources of PFAS emissions to the environment exist as a result of current and historic handling, storage and use of PFAS-containing commercial/industrial products. The largest point sources of PFAS release to the environment are expected to be through bulk or higher volume product use, or through accidental releases during the handling or storing of the products (e.g., frequent repeated releases of smaller product quantities, or single events comprising large product volumes). Non-point sources of PFAS to the environment include processes such as surface runoff from roads and wet/dry atmospheric deposition.

As discussed in Section 3.1.1, BC ENV developed PFAS standards for specific BC CSR Schedule 2 industrial and commercial purposes and activities related to the historical or current use of firefighting foams, metal plating fume suppressant products, and aviation products. These sources are further discussed below.

4.1.1 Firefighting Foams

PFAS have been used and continue to be used as constituents in firefighting foams that are effective against flammable liquid (or Class B) fires. One well-known Canadian firefighting foam site is L.B. Pearson Airport in Toronto, where 22 000 L of AFFF was accidentally released in June 2000 and an additional 48 000 L of AFFF was released in August 2005 (following the onboard fire of an Air France aircraft) (Moody et al., 2002; Oakes et al., 2010). Milley et al. (2018) reviewed available records for 2071 Canadian heliports and airports to identify locations that may have PFAS contamination due to the historical or current presence of firefighter training areas and aviation fuel storage and handling operations. It was postulated that use of AFFF at airports may be associated with both activities. The researchers concluded that approximately 7% of the 2071 sites appeared to have a firefighter training area, and an additional 13% appeared to have fuel storage and handling facilities that may have required AFFF storage on-site. The researchers identified 28 airport sites in British Columbia which they considered to be likely contaminated by PFAS.

The United States Department of Defense (Field et al., 2017a) has estimated the US military comprises approximately 75% of the US AFFF market, while municipal airports, petroleum facilities, and other industries utilize the remaining 25%. Interestingly, a firefighting foam survey

completed in Australia by Queensland Department of Environment and Heritage Protection (as reported in HEPA, 2018), identified 425 tonnes of PFAS-containing foam at bulk fuel and chemical storage facilities, which provides an indication of the extent to which PFAS-containing firefighting materials may be used at facilities other than military bases and airports.

Types of facilities which may be associated with a risk of fire and consequently, the use of firefighting foam suppression systems or historical releases of firefighting foams include battery production facilities, coal facilities and power generating facilities using coal, diesel or gas, etc. (HEPA, 2018).

Firefighting products with PFAS constituents have been manufactured and used globally since at least 1965 (Prevedouros et al., 2006; Field et al., 2017a). Estimates of total PFAS content in AFFF have ranged from approximately 0.5% (Hekster et al., 2002; Vecitis et al., 2010) to 16% (Paul et al., 2009). Approximately 40 different classes of PFAS have been identified in historical AFFF formulations and AFFF-impacted groundwater (Barzen-Hanson et al., 2017); this study may be of use to site investigators when the type/brand of AFFF products historically used at a site is known.

PFAS in the earliest versions of AFFF reportedly consisted of PFCAs (refer to Section 2.1.1 and Appendix A) produced by the ECF process and were in use from approximately 1965 until 1975 (Prevedouros et al., 2006). Starting in the 1970s, PFSAAs (refer to Section 2.1.2 and Appendix A) were predominant in AFFF and remained the main PFAS constituents until approximately 2002 when 3M, the primary global manufacturer employing the ECF process in PFAS production, voluntarily ceased production of PFOS. A review (Field et al., 2017a) of 1993 3M AFFF suggests that the PFAS present were mostly comprised of PFSAAs (78%) and PFCAs (3%), with small amounts of other PFAS. Reportedly, older formulations of 3M AFFF may have had a higher PFCA content (Field et al., 2017b). PFCAs were reportedly present at approximately 0.1-1.0 % by weight during this time period (Prevedouros et al., 2006; Field et al., 2017a).

Fluorotelomer PFAS appeared in AFFF starting in the 1970s (Prevedouros et al., 2006). Fluorotelomer precursors are reported constituents of Ansul AFFF (Field et al., 2017a; Field et al., 2017b), a commonly encountered AFFF product in Canada, as well as in AFFF produced by Chemguard, Buckeye, National Foam and Angus (Field et al., 2017b). These precursors may be transformed in the environment to FTS (refer to Appendix B) and further transformed to terminal PFCAs (refer to Appendix A). Work completed at Wurtsmith and Tyndall Air Force Bases in the United States identified 4:2 FTS, 6:2 FTS and 8:2 FTS in groundwater in AFFF source areas, with 6:2 FTS present in the greatest proportion (Schultz et al., 2004).

Since 2002, AFFF formulations have reportedly included shorter-chain PFSAAs (i.e., PFBS) and fluorotelomers.

Currently, PFOS at concentrations below 10 ppm, and PFOA and long-chain PFCAs present in AFFF, are exempted from the federal Prohibition of Certain Toxic Substances Regulations, 2012, meaning that AFFF with PFOS at concentrations less than 10 ppm or with PFOA and long-chain PFCAs present may be imported, sold, and used in Canada. However, the Government of Canada has recently signalled that they are planning to remove these exemptions from the regulations (Government of Canada, 2018). Consequently, it is anticipated that PFAS present in AFFF products used in Canada in the future will likely be predominantly short-chain PFAS or precursors which degrade to short-chain terminal PFAAs. As well, guidance from organizations such as ITRC (2018f) recommends the use of fluorine-free foams

where possible. In the United States, legislation has recently been enacted to allow the use of fluorine-free foams at civilian airports; formerly foams for use at civilian airports were required to meet military specifications which stipulated fluorosurfactant constituents. Consequently, it is expected that the use of fluorine-free Class B firefighting materials will increase in the future, provided such foams can meet performance requirements.

4.1.2 Metal Plating Fume Suppressants

Electroplating facilities in Canada are another industrial point source of PFAS as these chemicals have been identified in products used for suppressing hexavalent chromium emissions/fumes during electroplating operations (MDH, 2008; US EPA, 2009).

An investigation of an electroplating facility conducted jointly by the Minnesota Pollution Control Agency (MPCA) and Minnesota Department of Health (MDH) (MDH, 2008) reported the use of fume suppressant products (i.e., Fumetrol-140) with an organic fluorosulfonate content of 1-7% by weight. US EPA Region 5 (2009) surveyed numerous electroplating facilities in Cleveland, Ohio and Chicago, Illinois and found that at least eight different mist suppressant products were used by the facilities (i.e., Benchmark Benchbrite STX AB, Benchmark Benchbrite STX, Benchmark CFS, MacDermid Proquel B, MacDermid Macuplex STR, Plating Process Systems PMS-R, Fumetrol-140 and Brite-Guard AF-1 Fume Control). A survey conducted by the California Air Resource Board (2006) indicated that of the 183 facilities that reported the use of specific fume suppressant products, approximately 70% used Fumetrol-140. Investigation of PFBS and PFOS in chrome plating solution tanks in Minnesota (MDH, 2008) identified very high concentrations of both chemicals (e.g., 176 mg/L PFBS).

PFAS concentrations in wastewaters leaving electroplating facilities have been investigated by some agencies (MDH, 2008; US EPA, 2009). Generally, PFOA, PFNA, PFBS, PFHxS, and PFOS were identified as the major fume suppressant constituents encountered in wastewater, with detections of PFBA, PFPeA, PFHxA, PFHpA, PFDA, and PFUnDA also encountered.

Usage information obtained by MDH (2008) and US EPA Region 5 (US EPA, 2009) indicated variable consumption of fume suppressants by the electroplating facilities, ranging from 0.2 L/week to approximately 35 L/week.

4.1.3 Other Aviation Products

Other aviation products reported to contain PFAS are aviation hydraulic fluids where the chemicals are reportedly used to prevent corrosion and fires. Although many literature sources refer to the use of PFOS as a constituent in aviation hydraulic fluids, limited information on the PFOS content of these materials, and no information on PFOS concentrations in environmental media impacted by these materials, was identified. One source (UNEP, 2012) reported the PFOS or PFOS-precursor content in aviation hydraulic fluids to be < 0.1%.

De Silva et al. (2011) indicated that perfluoroethylcyclohexane sulfonate (PFECHS) is used as a corrosion inhibitor in aviation hydraulic fluids and has been detected in environmental media. PFECHS is not a PFAS of regulatory focus in BC, nor is it expected to degrade in the environment to the regulated PFAS (De Silva et al., 2011). There is very little available information on the occurrence and scale of use of PFAS-containing aviation hydraulic fluids. Based on information provided to SLR, Transport Canada has not conducted any internal studies on PFAS in aviation hydraulic fluids and recommends that manufacturers of aviation hydraulic systems fluids be contacted to determine if their product contains PFAS (pers. comm.,

L. Warner). One source suggests that the PFECHS content in aviation hydraulic fluids is about 0.1% (Kemikalieinspektionen, 2004 as reported in Danish EPA, 2005) and the annual global market for PFAS in aviation hydraulic fluids is about 2.2 tonnes (Risk & Policy Analysts Limited, 2004 as reported in Danish EPA, 2005).

4.2 Other Potential Sources

Other potential sources of PFAS include sites at which industrial or commercial products containing PFAS constituents are used in high volumes or are used on a repeated basis and there is potential for direct release to the environment. The Australian government has provided a summary of several activities associated with PFAS-containing materials (HEPA, 2018). Activities noted to potentially utilize PFAS-containing products include fertilizer production facilities, automotive factories, pulp and paper facilities, and sports facilities; however, no indication of relative volumes/quantities of products associated with each noted activity is provided nor is the likelihood of risk to the environment from the activity discussed. A similar list of PFAS-related activities is provided by ITRC (ITRC, 2017); similar to the Australian document, the relative volumes/quantities of products associated with each activity and likelihood of risk to the environment from the activity are not discussed.

Although releases of PFAS-containing products to the environment may occur at some commercial/industrial facilities in British Columbia, it is considered more likely that PFAS-containing products will be released to the environment through waste or wastewater disposal streams. Landfills, wastewater treatment plants, and areas where biosolids have been applied to lands are considered locations where PFAS-containing wastes may be deposited or directed in high volumes (Ikonomou, 2006; Li, 2011; US Army, 2018; ITRC, 2017; HEPA, 2018).

In Canada, Ikonomou (2006) evaluated concentrations of several PFAS in Canadian biosolids and leachate on behalf of ECCC. Several PFAS were detected in the biosolids samples analysed from one wastewater treatment plant in British Columbia (maximum concentrations of 1.69 ng/g, 15 ng/g, and 12 ng/g of PFBS, PFOS, and PFOA respectively). Numerous PFAS were also detected in landfill leachate collected from Canadian landfills (PFOS detected at a concentration of 0.021 µg/L and PFOA detected at a concentration of 0.146 µg/L at the one British Columbia study site). Li (2011) investigated the presence of several PFAS in leachate samples collected from 27 Canadian landfills located across the country (locations not disclosed). Average concentrations of PFBS, PFOS, and PFOA in Canadian landfill leachate were 0.114 µg/L, 0.279 µg/L, and 0.439 µg/L, respectively, with maximum concentrations of 1.37 µg/L, 4.84 µg/L, and 3.45 µg/L, respectively, also measured. Numerous other PFAS were also detected in the leachate samples.

Further considerations in regard to waste disposal (e.g., Basel Convention prohibitions on the disposal of PFAS-containing wastes) are discussed in Section 7.3.

4.3 Summary

The following table summarizes the potential sources of PFAS discussed in the preceding sections as well as concentration ranges and related BC CSR Schedule 2 activities.

Table 4-1: Potential Sources, Concentrations and Associated BC CSR Schedule 2 Activities

| Potential Source | Potential Source Area Concentrations (Groundwater/Wastewater/Leachate/Biosolids) | Associated Schedule 2 Activity |
|--|---|--|
| Class B Firefighting Foams | PFBS (groundwater) = 210 µg/L (Schultz et al, 2004) PFOS (groundwater) = 2300 µg/L (Schultz et al, 2004) PFOA (groundwater) = 6570 µg/L (Schultz et al, 2004) | A4 – fire retardant manufacturing and wholesale bulk storage Indirectly by G1 – aircraft maintenance, cleaning and salvage where foams stored/used at aviation facilities- Indirectly by F2 - petroleum or natural gas production facilities, F8 - petroleum product, other than compressed gas, wholesale bulk storage or distribution, F9 - petroleum refining wholesale bulk storage or shipping, F10 - solvent manufacturing or wholesale bulk storage where foams stored/used at large-scale petroleum and solvent facilities. Indirectly by H7 – contaminated soil storage, treatment or disposal where there is excavation of impacted soil after a fire or during remediation. |
| Metal Plating Fume Suppressants | PFBS (wastewater) = 19.1 µg/L (MDH, 2008) PFOS (wastewater) = 49.8 µg/L (MDH, 2008) PFOA (wastewater) = 0.027 µg/L (MDH, 2008) | C3 – metal plating or finishing |
| Aviation hydraulic fluids | No information on concentrations in environmental media. Reported PFOS content < 0.1% (UNEP, 2012) | G1 – aircraft maintenance, cleaning and salvage |
| Landfills | PFBS (leachate) = 1.37 µg/L (Li, 2011) PFOS (leachate) = 4.84 µg/L (Li, 2011) PFOA (leachate) = 3.45 µg/L (Li, 2011) | H7 – contaminated soil storage, treatment or disposal H8 – dredged waste disposal H12 – industrial waste storage, recycling or landfilling H15 – municipal waste storage, recycling, composting or landfilling H20 – hazardous waste storage, treatment or disposal |
| Biosolids and landfarmed industrial wastes | PFBS (biosolids) = 0.00169 µg/g (Ikonomou, 2006) PFOS (biosolids) = 0.015 µg/g (Ikonomou, 2006) PFOA (biosolids) = 0.012 µg/g (Ikonomou, 2006) | H11 – industrial waste lagoons or impoundments H16 – organic or petroleum material landspreading (landfarming) H18 – septic tank pumpage storage or disposal H19 – sewage lagoons or impoundments H21 – sludge drying or composting |

5.0 LABORATORY ANALYSIS

Standardized methods for analysis of PFAS in soil or water have not yet been developed in Canada. Rather, Canadian commercial laboratories accredited for PFAS analysis have developed and validated their own in-house methodologies. Health Canada has stated that the preferred analytical method for the determination of PFOS in environmental water samples employs solid phase extraction (SPE) with analysis of the extracts by liquid chromatography combined with tandem mass spectrometry (LC-MS/MS) (HC, 2018a); Health Canada further states that isotope dilution techniques are considered the most suitable approach for quantification of PFAS (HC, 2018a; HC, 2018b).

In isotope dilution techniques, isotopically labelled quantification standards (i.e., stable isotopically labelled analogs of the target analytes) are added to the samples at the first step in sample handling. Physical and chemical properties of each labelled compound are virtually the same as its unlabelled "native" analog (US EPA, 2014). The gains or losses of the isotopically labelled quantification standards are measured. It is assumed that the native analytes will have mirrored the gains/losses in the labelled standards. This assumption, termed recovery correction, allows for correction to observed concentrations of the target analyte relative to their labelled counterparts (US EPA, 2014).

Once the quantification standards have been added to the sample, the samples are extracted via weak anion exchange (WAX) SPE. The extract is subsequently analyzed by LC/MS-MS or ultra-high pressure (UHP) LC/MS-MS and the native substances quantified.

Practitioners are advised to contact the project laboratory to obtain information on whether the in-house methodology employs SPE, and isotope dilution and analysis with LC-MS/MS. It is noted that laboratories may employ a direct injection approach as opposed to SPE when high concentration samples are submitted for analysis (see further considerations in Section 5.1).

5.1 BC Environmental Laboratory Manual Performance-Based Requirements

BC ENV released performance-based methods for the analysis of perfluorinated alkyl substances in soil and water in conjunction with the release of the BC CSR standards (BC ENV, 2017a; BC ENV, 2017b). The BC ENV laboratory manual documents state that "*laboratories may adopt alternative options to improve performance or efficiency provided all stated performance requirements and prescribed (mandatory) elements are met.*"

It is noted that some of the prescribed/mandatory elements of the BC ENV methods may not be met by the in-house methodology typically employed by the laboratory conducting the PFAS analysis. It is recommended that practitioners contact the laboratory which will be conducting the analysis in advance of sample submission to confirm that the laboratory is familiar with the BC ENV prescribed elements and that the mandatory requirements will be met.

Items of particular note for discussion with the project laboratory include:

- Sample container materials;
- Sample and extract hold times;
- Sample storage conditions;
- Handling and analysis of sediment fractions in aqueous samples;
- Use of Trizma or sodium thiosulfate preservative for collection of chlorinated water samples;

- Use of SPE cartridges;
- Use of specific isotopically-labelled quantification standards;
- Recovery of isotopically labelled quantification standards;
- Matrix spike analysis; and
- Laboratory duplicate (NOTE: Analysis of laboratory duplicates is not possible when whole sample analysis is employed. Rather, the equivalent of a field duplicate is typically analyzed as the “laboratory” duplicate.)

5.2 BC Laboratories Offering PFAS Analysis

Four laboratories with operations in British Columbia currently offer PFAS analysis in-house, although analysis is often performed at locations outside of British Columbia. In addition, two laboratories which do not conduct PFAS analysis in-house have indicated that they are able to contract PFAS analysis through another analytical laboratory located out-of-province. Consequently, sample shipping to the location conducting the analysis needs to be accounted for when considering sample hold times. Laboratories (and locations) offering PFAS analysis in soil and water matrices are as follows:

- Maxxam in Mississauga, ON;
- SGS AXYS Analytical Services Ltd. in Sidney, BC;
- AGAT Laboratories in St. Laurent, QC;
- ALS Limited in Waterloo, ON;
- CARO Analytical Services (reportedly sub-contracted to Paracel Laboratories in Calgary, AB); and
- Exova Group Limited (reportedly sub-contracted to Paracel Laboratories in Calgary, AB).

The laboratories listed above represent those that were identified as currently offering PFAS analysis. It is recognized that this will change over time and no endorsement of the capability of any lab to perform PFAS analysis meeting the requirements of the BC Environmental Laboratory Manual is implied or should be construed. Practitioners are advised to contact the individual laboratories to confirm scope of accreditation, analytical packages, detection limits and other aspects of the analytical methodology.

5.3 Analytical Approaches – Other Methodologies

Methodologies and analytical approaches used in jurisdictions other than BC for the analysis of PFAS are discussed further in Appendix E.

6.0 SITE INVESTIGATION CONSIDERATIONS

Considerations specific to the investigation of PFAS-contaminated sites are discussed in the following sections. It is assumed that practitioners will be familiar with guidance and protocols for environmental site investigations provided by BC ENV (e.g., Technical Guidance, Administrative Guidance, Protocols and Procedures), CCME, CSA, and other organizations, as discussion of the information contained in these documents is outside the scope of this report.

6.1 Development of Conceptual Site Model

The first step of the environmental site investigation process is the development of a Conceptual Site Model (CSM) which should be continually reviewed and refined as new data and information is obtained. The CSM should provide information on the sources, types and extent of the contamination, its release and transport mechanisms, possible subsurface migration pathways, as well as potential receptors (including current and probable future receptors) and the routes of exposure (CCME, 2016).

With respect to development of PFAS-focused CSMs, the sources and probable release mechanisms of PFAS to the environment have been discussed in general terms in Section 4.0. However, site investigators should conduct site-specific and detailed reviews as part of the Stage 1 PSI. For instance, site investigators should identify all areas where PFAS-containing materials are or have been stored, used, released or disposed, including training areas where firefighting exercises were conducted, operational areas where firefighting infrastructure existed (e.g., fire stations), unplanned release areas (e.g., crash sites, fire suppression systems), chrome plating facilities, landfill and waste disposal areas, and wastewater effluent/biosolid discharge areas. Interviews with knowledgeable personnel are deemed particularly critical to understanding past practices and potential source areas (US Army, 2018).

The CSM should also demonstrate the site investigators understand the mixture of PFAS present (short-chain, long-chain, polyfluorinated substances, etc.) and their degradation products (if applicable), and the differing partitioning behaviour and physical-chemical properties of each. These concepts were reviewed at a general level in Section 2.0 of this report; however site investigators will need to consider PFAS partitioning behaviour in light of the site-specific conditions which will dictate their transport through the environmental media of interest at a particular contaminated site.

Site-specific conditions, potential receptors, and media of interest to consider at PFAS-contaminated sites in particular, are covered in the following sub-sections.

6.1.1 Site-Specific Conditions to Consider

As with all contaminated sites, information on the physical setting of the site (including meteorological, geological, hydrogeological, hydrological, and preferential pathway components) is critical to understanding the migration and fate of PFAS contamination. Additional consideration of or emphasis on the following is recommended at PFAS-contaminated sites (ITRC, 2018c; HEPA, 2018):

- Understanding interactions between surface soil and precipitation, irrigation water and/or surface runoff due to the frequent release of PFAS-containing materials to surface soils at some source sites (e.g., as a result of AFFF application or spillage);
- Understanding groundwater-surface water interactions including:

- Presence of shallow groundwater and potential for discharge to surface drainages with subsequent off-site migration;
- Seasonally inundated conditions and potential for discharge to surface drainages (particularly in British Columbia coastal areas);
- Recharge of groundwater by surface water (e.g., losing streams), including seasonally during summer drought periods; and
- Groundwater infiltration of stormwater systems and the eventual discharge of stormwater to surface water bodies;
- Understanding of other factors that may affect groundwater transport processes, including presence, depths and pumping rates of wells (e.g., domestic use or water supply wells, remedial system) in the vicinity of the source.

6.1.2 Receptor Identification

Given the potential for extensive groundwater and surface water transport of PFAAs such as PFBS, PFOS, and PFOA due to both the persistence and mobility of these chemicals (ITRC, 2018), site investigators should give consideration to potential (current and probable future) receptors at significant distances removed from source areas in the development of CSMs. ITRC (2018c; 2018d) has reported that PFAS may travel in groundwater for several kilometres (and hundreds of kilometres in surface water) from the source location. For these reasons, it is also recommended that PFAS investigations be expedited where there is a potential for impacts to off-site receptors, particularly drinking water consumers (HC, 2019c; ITRC, 2018d).

It is noted that the BC CSR numerical standards for PFAS have only been derived for specific receptor exposure pathways, and that the bioaccumulation of select PFAS (e.g., PFOS) has not been accounted for in the standards derivation. However, evaluation of bioaccumulation is to be considered within the context of BC CSR risk-based standards (BC ENV, 1998; SLR, 2015). To that end, where detailed quantitative risk assessment is being employed (under Protocol 13 the use of Screening Level Risk Assessment is precluded for bioaccumulative substances) and for due diligence purposes, site investigators should consider the identification of human and ecological receptors potentially exposed through consumption of food items where chemical uptake into food items is suspected. In Australia (HEPA, 2018), government agencies have directed that site investigators consider “the need to sample aquatic and other biota and animal/human food sources wherever a plausible transport pathway from a contaminated source exists, even if water concentrations are below the limit of reporting” due to the bioaccumulative and biomagnifying nature of specific PFAS.

ECCC has derived PFOS guidelines for fish tissue, bird eggs, and wildlife dietary tissues to support the evaluation of exposures to higher trophic-level ecological receptors. In regards to human exposure, it is noted that maximum levels for PFAS in retail foods (which are enforceable by the Canadian Food Inspection Agency) have not yet been developed by Health Canada's Bureau of Chemical Safety, Food Directorate. Further, it is SLR's understanding that Health Canada's Contaminated Sites Division is not planning to derive screening values for PFAS in biota/crop tissues consumed by humans (pers. comm., T. Zis). Rather, at federal sites impacted with PFAS, Health Canada has recommended that concerns regarding human consumption of foods associated with PFAS-contaminated sites should be addressed on a site-specific basis (HC, 2019c). It is noted that a report contracted by Health Canada (Intrinsik, 2018) concluded that the derivation of generic transfer factors for non plant-based organisms or foods for use in contaminated site risk assessment could not be completed for PFAS, and that the use of K_{ow} to evaluate bioaccumulation potential or in the derivation of generic transfer factors for use in risk assessment was not recommended.

6.1.3 Media of Interest

Due to the partitioning behaviour of the regulated PFAS and the availability of BC CSR numerical standards, both soil and groundwater are considered media of interest at PFAS-contaminated sites in BC. Due to the low volatility of these chemicals under ambient environmental conditions, site vapour is not considered a media of interest. Additional media which may be of interest with respect to the application of BC CSR risk-based standards, as well as for due diligence purposes, include surface water, sediment and biota (US Army, 2018; Field et al., 2017a; ITRC, 2018c).

The Australia Department of Defence (DoD) considers sediment in surface runoff drains at military bases to be a medium of concern with respect to the migration of PFAS in surface water and groundwater. Sediments in open drains/ditches at select bases (i.e., Army Aviation Centre Oakey and RAAF Base Williamtown) have been excavated and replaced with new material to reduce partitioning of PFAS into surface runoff and subsequent migration off-site.

Uptake of PFAS into biota has led individual regulatory jurisdictions (e.g., Ontario, Michigan) to issue consumption advisories for biota such as fish and deer. In particular, research in Ontario (Bhavsar et al., 2016) suggests that PFOS may accumulate in fish at levels exceeding acceptable human health risk levels at concentrations below surface water screening values or guidelines protective of direct contact. Guidance provided by Health Canada (HC, 2019c) for federal PFAS-contaminated sites recommends investigation of PFAS concentrations in fish if the fish-consumption pathway is active, even if water concentrations meet the federal drinking water screening values/guidelines or surface water guidelines.

ITRC (ITRC, 2018d) highlights the potential for PFAS to be present in ambient air and in house dust in proximity to PFAS-contaminated sites. It is noted that the PFAS of regulatory focus are considered to have limited volatility and are expected to be predominantly associated with air-borne particulate as opposed to being present in the vapour phase. The potential for association of PFAS with water aerosols is also recognized. However, these are not expected to be a significant route of current exposure at contaminated sites in BC, given the types of industries which give rise to such aerosols, and measures implemented or currently proposed for implementation under the Canadian Environmental Protection Act.

Finally, in its guidance for federal sites impacted with PFAS, Health Canada (HC, 2019c) recommends that nearby drinking water sources be tested for PFAS at the earliest opportunity when on-site groundwater is contaminated with PFAS. A similar recommendation is made within the ITRC guidance (ITRC, 2018d), specifically that drinking water supply sampling should be considered a “top priority” given the potential for extensive groundwater and surface water transport of PFAS; once drinking water has been confirmed to be uncontaminated, delineation of soil and groundwater plumes at source areas and collection of other media can be considered. Although site-specific factors may suggest that such an approach is not immediately warranted (e.g., due to concentrations observed, subsurface geology/hydrogeology, proximity of drinking water receptors), the precautionary and expedited collection of drinking water samples is recommended where the CSM is not well understood and PFAS are suspected to have migrated off-site.

6.2 Field Precautions

Additional field precautions specific to the investigation of PFAS-contaminated sites are discussed below.

6.2.1 *Materials to Avoid*

There is little published research on cross-contamination of field samples from personnel, equipment and sampling supplies (RMC, 2015; ITRC, 2018d). However, a variety of organizations and regulatory agencies (Transport Canada, 2017; US Army, 2018; ITRC, 2018d; Michigan DEQ, 2018a; NHDES, 2016; HEPA, 2018) advise a precautionary approach which avoids certain materials during sample collection and handling. Materials to avoid in particular include:

- Fabrics treated with water, stain, or oil repellent materials, such as Gore-Tex or fabrics chemically treated for insect resistance and ultraviolet protection. Coated Tyvek suits should also be avoided. The Michigan DEQ (2018a) provides a summary of some field clothing brands which may pose a risk of cross-contamination;
- New clothing. All clothing should be washed at least six times and no fabric softening agents should be used during washing/drying;
- Paper products likely to be treated with water, stain, or oil repellent materials, including waterproof field books/papers, Post It Notes, and food packaging materials (e.g., fast food wrappers, pizza boxes, etc.). Hands are to be thoroughly washed and rinsed after coming into contact with such materials. Foods wrapped in treated paper or foil packaging should not be consumed or handled during the sampling program (including during sample shipping);
- Aluminum foil (unless equipment blank testing indicates the foil is PFAS-free);
- Blue ice (unless equipment blank testing indicates the blue ice is PFAS-free);
- Low density polyethylene (LDPE) that comes into direct contact with the sample media (unless equipment blank testing confirms the material is PFAS-free);
- Glass containers (due to potential for PFAS adsorption);
- Gel markers/pens;
- Personal hygiene and personal care products, sunscreens, and insect repellents containing fluorinated constituents (Transport Canada, 2017). Refer to Section 6.2.2 below for guidance on allowable sunscreens and insect repellents. Due to the ubiquitous presence of fluorinated chemicals in personal care products, field personnel should not handle or apply these materials during and immediately prior to field sampling or during donning of clothing to be worn during sampling and should shower with only water in mornings prior to sample collection; and
- Any products containing polytetrafluoroethylene (PTFE, including Teflon® and Hostaflon®), fluorinated ethylene propylene (FEP), polychlorotrifluoroethylene (PCTFE, including Neoflon®), ethylene tetrafluoroethylene (ETFE, including Tefzel®), polyvinylidene fluoride (PVDF, including Kynar®) and generally any product with “perfluoro” or “fluoro” in the name. For instance, PTFE-lined tubing and Grundfos pumps with PTFE components have been demonstrated to produce blanks with PFAS concentrations approaching drinking water screening values in one study (DiGuiseppi et al., 2015).

Avoidance of treated footwear and certain apparel required for health and safety purposes (i.e., high visibility vests) may be more difficult. For instance, although steel toed rubber boots are recommended for PFAS investigations, they may not be appropriate for use during winter sampling conditions from a health and safety perspective. Non-coated Tyvek boot covers may be used to cover treated footwear. In cases where use of treated footwear and apparel cannot be avoided, field personnel should frequently change nitrile gloves and should ensure no transfer occurs between these materials and any samples.

The recommendations above are based on a precautionary approach. In Europe, organizations such as Concawe and the Network for Industrially Contaminated Land in Europe (NICOLE) have suggested that analysis of water samples to a sub-ng/L level is difficult due to cross-contamination from sampling materials, laboratory equipment and consumer products (Concawe, 2016; NICOLE, 2016). For this reason, the collection of a variety of blanks (trip/reagent blanks, field blanks, equipment blanks) is recommended to assist the investigator in interpreting reported sample results (discussed further in Section 6.3.2 of this report).

As well, work by some researchers (RMC, 2015) has suggested that in PFAS source areas with known high concentrations of PFAS (i.e., in the range of mg/L), the implementation of standard best practices for groundwater sampling may be sufficient for collection of representative samples. However, given the potential for investigators to be working in areas with a wide range of PFAS concentrations, a precautionary approach to minimize the potential for cross-contamination is recommended.

6.2.2 Acceptable Materials

Materials deemed acceptable for use in site investigations include the following (Transport Canada, 2017; ITRC, 2018d; Michigan DEQ, 2018a; NHDES, 2016):

- Nitrile gloves;
- Well-laundered, natural fibre clothing (wool, cotton) that has not been treated with water/oil repellency products. As discussed above, no fabric softening agents should be used during washing/drying;
- Non-coated or plain Tyvek (see comments in previous section regarding coated Tyvek) although collection of a specific equipment blank is recommended;
- HDPE;
- PVC;
- Rubber;
- Neoprene;
- Polyurethane;
- Stainless steel;
- Silicone;
- Ziploc bags;
- Double-bagged ice;
- Fine point Sharpies (Michigan DEQ, 2018a), ballpoint pens, and pencils; and
- PFAS-free personal care products, sunscreens, and insect repellents. The Michigan DEQ (2018a) has tested a number of sunscreens and insect repellents for PFAS. Although brand names of specific products are provided, caution is advised due to the potential for cross-border differences in formulations/ingredients.

Where possible, it is recommended that practitioners utilize dedicated and single-use equipment/materials for the collection of PFAS samples to reduce the potential for cross-contamination and the need for decontamination (discussed further in Section 6.2.4).

6.2.3 Water Sources for Investigation Programs

Laboratories will provide PFAS-free water for a cost upon request. Given shipping and transport considerations, this supply is best suited for collection of blanks (discussed further in Section 6.3.2). For most environmental investigations, a much larger supply of PFAS-free water

for cleaning equipment and for use during drilling will need to be identified *in advance* of the site investigation. This may entail pre-testing of nearby water supplies and evaluation of PFAS concentrations.

6.2.4 Equipment Decontamination

Transport Canada (2017) recommends the following process for equipment decontamination:

- Wash equipment in a solution of Alconox, Citranox, or Liquinox and PFAS-free water. If an alternative detergent is used, it should be reviewed to ensure no fluorinated products are present. Decon90 has been noted by some agencies/organizations to contain fluorinated products;
- Rinse equipment with PFAS-free water;
- Rinse equipment with methanol. Some laboratories will provide proofed methanol for a cost upon request. Alternatively, site investigators can contact the laboratories to identify the supplier of the methanol used in their PFAS laboratory methods (e.g., Caledon Laboratories Ltd., Sigma-Aldrich);
- Repeat above in triplicate if working in a likely or known source area (e.g., firefighting mock-up);
- Transfer rinsate generated above to appropriate containers for disposal; and
- Conduct a final rinse with PFAS-free water (a portion of this rinsate water can be collected for laboratory analysis, discussed further in Section 6.3.2).

Alternatively, site investigators may want to request the drilling contractor pre-clean and bring the total anticipated amount of drill rods/augers/bits required for the investigation program so that field personnel do not have to spend time decontaminating large pieces of equipment between borehole locations. Drill equipment rinsate samples should still be collected however, to confirm adequacy of decontamination procedures or if possible, collected in advance from any “set aside” equipment for the field program.

6.2.5 Other Field Considerations

Other field considerations for the execution of environmental site investigations at PFAS-contaminated sites are provided below. As noted previously, there is little published research on cross-contamination of field samples from personnel, equipment, and sampling supplies and many of the recommendations below are based on a precautionary approach.

Field Vehicles

When possible, consideration should be given to the avoidance of newer vehicles when conducting field sampling as newer vehicles will have upholstery recently treated with water and oil repellent products. Well-laundered cotton blankets or plastic sheeting should be placed over field vehicle seats and storage areas to prevent transfer from treated upholstery onto field clothing, and sampling gear and supplies.

Gloves

Frequent changing of disposable nitrile gloves is recommended, particularly if avoidance of treated apparel (footwear, high visibility vests) is not possible. Nitrile gloves should be donned prior to decontamination of sampling equipment, contact with sample bottles or PFAS-free sampling materials, contact with any sampling ports, contact with any QA/QC samples, after

handling of any non-dedicated equipment, or contact with non-decontaminated surfaces (Transport Canada, 2017). If in doubt, don new gloves.

Climate/Precipitation

If possible, sampling should be avoided during times of high rainfall due to potential for contact between sampling materials and saturated ground surfaces or rain splashes.

Sample Collection Sequencing

Sampling programs should proceed from background (i.e., upgradient) locations to low level (i.e., most downgradient) locations and then move toward the source areas or areas with highest anticipated concentrations.

Drilling

Given the release mechanism of PFAS to surficial soils at many PFAS-contaminated sites, drilling methods that avoid sloughing of surficial soil into the borehole or water table should be utilized. For this same reason, soil samples should be collected immediately at the soil surface, at suspected historical soil surfaces (if importation of fill or earth movement is suspected to have occurred over time) and at the water table. However, if the CSM suggests that the mechanism of release at the site was not to surface, consideration should be given to alternate sampling locations.

Due to the persistence and mobility of PFAS, as well as potential source zone concentrations which may be up to three to four orders of magnitude higher than applicable BC CSR standards, extreme caution should be exercised when drilling in PFAS-source areas. Care must be taken to avoid migration of contamination between aquifers or between stratigraphic layers in areas of complex geology. Collection of soil samples should be completed using methods that prevent potential for smearing or contact with soil from upper portions of the soil profile.

PFAS may co-occur with other contaminants at certain sites (e.g., with petroleum hydrocarbons at firefighting training sites). Although PFAS of regulatory focus are not considered to be volatile under typical environmental conditions, field screening of soil samples for headspace vapour levels is recommended to assist with selection of samples for analysis and interpretation of results.

Monitoring Well Installation and Development

Given the potential for certain PFAS to sorb to particulates, and the requirement in the BC Environmental Laboratory Manual for the sediment fraction in aqueous samples to be quantified, the installation of an adequate sand filter pack around the well screen and subsequent development of monitoring wells to remove fines from the filter pack and well materials are considered critical. For these reasons, use of hollow stem and sonic drilling methods are recommended. If other drilling methods are employed, site investigators should consider controls for managing the aforementioned risks.

As well, practitioners are reminded to select monitoring well screen intervals to mitigate potential cross-communication between aquifers or between stratigraphic layers within the same aquifer, in accordance with BC ENV guidance (BC ENV, 2017e; Golder, 2010).

Practitioners should also consider well development with dedicated disposable materials such as inertial lift methods, as opposed to submersible pumps, to reduce cross-contamination concerns. Submersible pumps may have internal components that contain fluorinated materials, so the collection of blanks to confirm adequacy of decontamination procedures and to assess presence of fluorinated internal components is strongly recommended.

Groundwater Sampling

As mentioned, the BC Environmental Laboratory Manual requires the quantification of PFAS associated with the sediment fraction in aqueous samples. For this reason, turbidity should be monitored during groundwater sample collection using a probe to assist in interpretation of results and representativeness of the data. In addition, field filtering of samples is not recommended due to the potential for loss of PFAS to filter materials through adsorption (ITRC, 2018d; Michigan DEQ, 2018b).

For groundwater sampling, low flow sampling with HDPE and silicone tubing or, in cases where groundwater depth precludes sample collection, bailer sampling with HDPE bailers is recommended (Michigan DEQ, 2018b). It is noted that the use of no-purge sampling methods, such as HDPE HydraSleeves, may not be valid depending on the specific characteristics of the formation; further, BC ENV guidance recommends that where such methods are used for sample collection, they should be validated to conventional techniques on a site-specific basis (Golder, 2010). For multi-year projects, or at sites where entrainment of sediments during bailer sampling is a significant concern, consideration may also be given to dedicated submersible pumps. However, as stated earlier, these pumps may have internal components that contain fluorinated materials and a blank should be collected prior to use.

Surface Water Sampling

Surface water sampling should be completed in accordance with BC ENV (BC ENV, 2013b) and CCME guidance (CCME, 2011; CCME, 2016). However, as BC ENV laboratory methods require the analysis of particulate fractions in aqueous samples, it is strongly recommended practitioners employ sampling methods that do not require entry into the waterbody and which minimize the disturbance of sediments during sampling. Turbidity should be monitored during sample collection and samples should not be filtered. ECCC (pers. comm., D. St-Laurent) has indicated the PFAS content in the solid phase of aqueous samples may not be negligible and consequently, should be accounted for in sampling and analysis (i.e., surface water samples should not be filtered).

Due to potential for PFAS stratification, some agencies do not recommend collection of surface water samples at the air-water interface unless specifically required by project objectives (Michigan DEQ, 2018e; HEPA, 2018).

Sediment Sampling

Sediment sampling may be undertaken by practitioners as a matter of due diligence to understand the extent of PFAS migration at contaminated sites in BC as no BC CSR standards currently exist for PFAS in sediment. Further, evaluation of sediment exposures may be necessary within the context of HHERA.

Sediment sampling should be completed in accordance with BC ENV (BC ENV, 2013b) and CCME (CCME, 2011; CCME, 2016) guidance. Collection and submission of samples for

analysis of organic carbon content is also advised due to the known sorption of PFAS to this sediment constituent.

Finally, sediment present in stormwater drainage features meeting the definition of a maintained watercourse should be compared to BC CSR soil standards in accordance with BC ENV Technical Guidance 15 (BC ENV, 2017f). Similarly, sediment in the intertidal zone (between the high water mark and low water mark) should be compared to BC CSR soil standards in accordance with BC ENV Technical Guidance 15.

General Sampling Precautions

Direct contact of PFAS sampling containers and sample tubing with potentially PFAS-contaminated surfaces should be avoided. This can be accomplished by placing polyethylene sheeting on the ground surface (if site conditions allow) and by ensuring that the sample container and lid do not leave the sampler's hands.

Drinking Water Sampling

In terms of project sequencing, collection of drinking water samples should occur prior to collection of surface water samples, and finally groundwater samples (if all media are being collected during a single sampling event) to mitigate cross-contamination concerns (Michigan DEQ, 2018a). Drinking water samples should be collected from point-of-use locations where water for human consumption is obtained (i.e., kitchen, bathroom or outdoor faucet). If a water treatment system is in place (e.g., filtration system), a pre-treatment water sample should also be obtained and analyzed. The water system should be flushed for a minimum of five minutes prior to sample collection. Field personnel should make note of any Teflon tape observed in the plumbing and remove hoses from faucets prior to sample collection. As outlined in the BC Environmental Laboratory Manual, Trizma is used for preservation of chlorinated water samples. Field personnel should not overfill bottles and lose preservative in such cases. Once a sample is collected, the bottle should be gently inverted until the Trizma is dissolved.

Sample Shipping

High level or source area samples should not be shipped with low level samples to mitigate cross-contamination concerns. Practitioners are advised to provide the project laboratory with advance warning if suspected high level samples are being submitted. Samples of PFAS-containing products (i.e., Class B foams) should also be considered high level samples and handled/shipped separately from site investigation samples.

Storage

Finally, special care should be given to storage of equipment and sampling supplies at the office (e.g., equipment room) when conducting PFAS sampling programs to prevent potential cross-contamination. It may be prudent to create sample and equipment storage sub-areas when undertaking an active PFAS sampling program.

6.3 Quality Assurance/Quality Control Considerations

Quality Assurance/Quality Control (QA/QC) considerations for investigations at PFAS contaminated sites are provided below.

6.3.1 Laboratory Detection Limits

Practitioners should liaise with the project laboratory at the earliest opportunity during the planning phase to review reportable detection limits in the media to be sampled. Detection limits should be reviewed prior to sample collection in consideration of BC CSR standards and any other screening values that may be employed for due diligence purposes. It is noted that laboratories may offer lower detection limits in some matrices at the expense of not being able to quantify certain non-regulated PFAS parameters.

6.3.2 Blanks

Collection and analysis of blanks will help field investigators evaluate whether field materials and procedures may have resulted in cross-contamination of or introduction of low levels of PFAS to environmental samples. Specifically, the collection of trip blanks³, field blanks⁴ and equipment blanks⁵, and equipment rinsate blanks⁶ should be considered in the sampling program (Transport Canada, 2017; Michigan DEQ, 2018a; ITRC, 2018d; HEPA, 2018). Site investigators will need to obtain a sufficient quantity of PFAS-free water (either from the project laboratory or from a pre-tested water source) for the collection of these QA/QC samples.

6.3.3 Blind Field Duplicates

Blind field duplicates should be collected and analyzed as per standard field investigation guidance (e.g., 1 per 10) (CCME, 2016). As indicated by CCME (2016), both matrix variability and sampling and handling procedures will result in higher variability in field duplicates as compared to laboratory duplicates, with acceptance limits typically 1.5 to 2 times the laboratory duplicate acceptance limits. It is noted that although BC ENV has referenced the use of 1.5 times the laboratory duplicate acceptance limits in the past (BC ENV, undated), it may be reviewing acceptable field duplicate acceptance limits in the future (pers. comm., L. Zanini).

6.3.4 Laboratory QA/QC Metrics

Laboratories will review their internal QA/QC metrics relative to their in-house methodologies. It is recommended that practitioners liaise with the project laboratory to ensure that laboratory metrics are also being reviewed in consideration of the performance-based requirements outlined in the BC Environmental Laboratory Manual; further, practitioners should request that

³ Trip blanks are collected to assess potential introduction of PFAS during sample transportation and handling at the project laboratory. Frequency may depend on client requirements, but at least one per sampling program should be analyzed.

⁴ Field blanks are collected to assess potential introduction of PFAS in the field during sample handling by the field technician. Frequency may depend on client requirements, but at least one per sampling program should be analyzed, ideally one per day of sampling.

⁵ Equipment blanks are collected to assess potential PFAS concentrations associated with sampling materials in contact with the field samples and should be collected prior to use if there is any concern about potentially fluorinated equipment components. Frequency may depend on client requirements, but it is recommended that at least one per piece of equipment used and in direct contact with field samples during the sampling program (e.g., low flow tubing) be analyzed.

⁶ Equipment rinsate blanks are collected to confirm adequacy of decontamination methods. Frequency of collection may depend on client requirements, but it is recommended that at least one per piece of equipment used and in direct contact with field samples during the sampling program be analyzed.

laboratory certificates record the results of this review. In particular, site investigators should review laboratory certificates for reported concentrations in laboratory method blanks, for recovery of labelled quantification standards, and for relative percent differences of laboratory duplicates. It is noted that for laboratories conducting whole sample analysis, a true laboratory duplicate cannot be prepared as the whole sample is utilized in the analysis; the equivalent of a field blank (i.e., second container collected in the field) is analyzed as the laboratory duplicate.

6.4 Investigation Derived Waste

Investigation-derived waste may include hydroexcavator slurries, drill cuttings, and well development and purge water. Due to the cost of treating/disposing PFAS-contaminated materials (discussed in Section 7.0), consideration should be given to minimizing the generation of investigation derived waste where possible.

7.0 REMEDIATION CONSIDERATIONS

Field-proven remediation options to address soil and groundwater PFAA contamination (i.e., PFCAs and PFSAAs such as PFBS, PFOS, and PFOA) are discussed in the following section.

To gain an appreciation of technologies that have been proven to successfully address PFAA contamination at the field-scale, it is first necessary to understand the significant challenges associated with the application of techniques that have been successful for other contaminants, such as hydrocarbons. Specifically, PFCAs and PFSAAs are extremely chemically and thermally stable. Interestingly, even the most efficient PFAA destruction methods still require three to four orders of magnitude more energy than is required to produce the chemicals in the first place (Vecitis, 2009). This stability has resulted in resistance of PFAAs to biodegradation, direct photolysis, and traditional oxidation techniques, as discussed further below.

Biodegradation of PFAAs would require reductive defluorination to occur before microbial degradation can be initiated (Rayne and Forest, 2009a); however, reductive defluorination under ambient environmental conditions is not likely to occur. It has been postulated that such a process may occur under anaerobic conditions and that microorganisms may adapt over time to utilize the energy yielded (Parsons et al., 2008). A recent review (Ross et al., 2018) suggested such an evolution would be challenging due to the number of metabolic steps required to completely mineralize the PFAAs.

Direct photolysis under ambient environmental conditions is considered insignificant as PFCAs and PFSAAs absorb little light in the natural light spectrum.

Due to the complete substitution of fluorine atoms on the PFAA carbon chains, these chemicals are significantly more resistant to oxidation than non-fluorinated alkyl compounds (Vecitis, 2009). Advanced oxidative methods (e.g., ozone, hydrogen peroxide, Fenton's reagent, etc.) are also unlikely to be successful in addressing the range of typical PFAS expected to be present at contaminated sites in BC (Schröder and Meesters, 2005 as reported in Rayne and Forest, 2009a; Moriwaki et al., 2005; Colosi et al., 2009). Although some advanced oxidative techniques have demonstrated success in degrading PFCAs, such success has not been demonstrated with PFSAAs. Further, oxidative techniques have been demonstrated to convert precursor compounds to terminal PFAAs; where precursors are less mobile than the generated PFAAs, groundwater contaminant migration may be exacerbated.

The Australian government has developed the following hierarchy of preferred remediation approaches at sites contaminated by PFAS (HEPA, 2018):

1. Separation, treatment, and destruction;
2. On-site encapsulation in engineered facilities with/without immobilization; and
3. Off-site removal to a specific landfill cell with collection, treatment, and destruction of PFAS in landfill leachate.

The specific methods and technologies comprising these approaches are described in subsequent sections.

7.1 Water Treatment Overview – Field Confirmed Methods

Substantial research into novel methods for treating PFAS in the aqueous phase has been, and continues to be, conducted. However, although a number of treatment technologies have been

applied to PFAS in the aqueous phase, many are likely to be impractical for application to contaminated sites due to the energy requirements and/or degradation rates involved.

The focus of this section is on field-proven methods for remediating PFAAs in the aqueous phase. Techniques which have been or are currently being investigated, but which will not be covered here due to the absence of proven scaling to contaminated sites, include:

- Sonolysis (an ultrasonic destructive technique);
- Photolysis with catalysts or with higher energy wavelengths (e.g., vacuum ultraviolet light);
- Modified silica absorbents;
- Reductive techniques;
- Electrochemical technologies including electrochemical oxidation, combined photo/electrochemical reduction and electrochemical membranes; and
- Plasma treatment.

The above techniques are discussed in further detail in Ross et al. (2018).

The field-scale evaluations discussed in the following sections have largely been conducted outside of Canada. It is SLR's understanding that Transport Canada has only conducted field evaluations of granular activated carbon for treating PFAS in water (pers. comm., L. Warner). Field trials of various water treatment technologies have reportedly been conducted by Department of Defence (pers. comm., P. Cushing); publicly accessible details on one of these trials are discussed further in Section 7.1.1.

7.1.1 Sorption Methods

Sorption (i.e., granular activated carbon and ion exchange resin) methods are considered the most well-studied and field-verified PFAS water treatment options. Ross et al. (2018) report hydraulic containment in conjunction with adsorption on granular activated carbon or ion exchange resins is the standard rapid response measure for addressing aqueous phase PFAS plumes.

The use of ion exchange resins to remove PFAS from contaminated water has been well documented. The presence of sediment and other compounds and co-contaminants is expected to affect the efficiency of resins. Further, some resins may not be effective in the removal of shorter chain PFCAs (i.e., PFBA, PFPeA). To that end, the selection of a variety of different resins may be necessary to effectively remove the range of PFAAs likely present at contaminated sites. In comparison to activated carbon (discussed further below), ion exchange resins are considered to be more expensive. Ross et al. (2018) reported incineration of single use ion exchange resins is considered more practical and cost effective than resin regeneration.

Numerous studies have investigated sorption of PFAS to activated carbon. Factors affecting sorption to activated carbon include pH (acidification increases sorption presumably due to the protonation of the activated carbon which results in less electrostatic repulsion), chain length (removal performance typically decreases with decreasing carbon chain length), end group of the PFAA (i.e., sulfonates tend to be removed more readily than carboxylates of equivalent perfluoroalkyl chain length), and contact times (increased sorption observed with increased contact time). As well, presence of co-contaminants and constituents which result in fouling of the activated carbon (e.g., particulates) are also expected to affect the efficacy of sorption; pre-treatment methods to address these factors are discussed in Section 7.1.3.

A bench-scale comparative study completed by Canadian researchers (Yao et al., 2014) assessed sorption of PFOS and PFOA to a number of commercially-available materials including:

- GAC (Filtrisorb 400);
- Powdered Activated Carbon;
- Multi walled carbon nanotube;
- Double walled carbon nanotube;
- Anion exchange resins (AER: IRA67 and IRA400);
- Non ion exchange polymer (Amb XAD4);
- Alumina; and
- Silica.

Filtrisorb 400 (granular activated carbon) and IRA67 (anion exchange resin) were determined to be the most effective materials in terms of adsorption capacity and removal efficiency (>98%). Multi-walled carbon nanotube also demonstrated high removal efficiency in the tests performed. Of these three materials, adsorption equilibration time was longest for Filtrisorb 400 (24 hours), followed by multi walled carbon nanotube (4 hours), and IRA67 (2 hours). In terms of cost, Filtrisorb 400 and IRA67 were identified as being more cost effective than multi-walled carbon nanotube.

Filtrisorb 400 and IRA67 are reported to be undergoing field scale evaluation in Cold Lake Alberta. SLR contacted the federal department responsible for the evaluation (Wing Environment, CFB Cold Lake), but was unable to obtain information regarding the study results as the testing is still underway (pers. comm., S. Lawson).

Australia DoD (2019b) has a number of water treatment systems operating at and around various military installations. A variety of treatment technologies are being employed, mostly utilizing anionic exchange resins and activated carbon, for the treatment of PFAS, including PFOS and PFOA. The Williamtown Lake Cochran treatment system is comprised of powdered activated carbon pre-treatment followed by treatment through anionic exchange resin, and finally granular activated carbon. Flow rates were reported to vary from 15 to 70 L/s as part of the treatment design and reduced concentrations of PFOA and PFOS to less than 0.02 µg/L (influent concentrations in the range of 1-10 µg/L). Another system deployed as part of a phased study at the Williamtown base (Moors Drain) was designed to treat PFOS in stormwater flows to less than 0.01 µg/L (influent concentrations ranging from 1-10 µg/L) at flow rates of up to 192 L/min. A system installed at the former fire training area at the Williamtown base to treat extracted groundwater from the reported source area also demonstrated success in treating PFOS to less than 0.01 µg/L (influent concentrations of 10-50 µg/L); system details could not be verified but are expected to solely employ anionic exchange resins. Anionic exchange resin treatment is also being employed at Army Aviation Centre Oakey, where groundwater from the area of the former fire station is being extracted and treated prior to being reinjected into the aquifer; the system is treating PFOS to less than 0.01 µg/L (influent concentrations of 1-10 µg/L).

Regeneration of spent sorbent media is difficult. Some organizations suggest that the current best practice for spent media is high-temperature incineration, a costly process in British Columbia where transport and incineration costs may be in the \$3-\$6/kg range. US Department of Defense (SERDP, 2018) estimates the annual cost of operating a 250 gallon granular activated carbon system at one air force base to be \$500,000, primarily driven by carbon

changeouts/disposal. Further discussion of considerations for waste disposal (including waste carbon disposal) are provided in Section 7.3.

Despite the above, given the size of many PFAA plumes, low target concentrations for remediation and confounding presence of potential precursor compounds in source areas, the application of groundwater pumping methods with ex situ filtration or sorption as sustainable long term solutions for addressing PFAA plumes is questionable (Ross et al., 2018). As stated above, operational costs and energy needs are substantial, and these measures are less effective with shorter chain PFAAs. Ross et al. (2018) reported that advances in groundwater pumping have been achieved through dynamic groundwater recirculation to maximize flushing and recovery of contaminants.

Due to the efficacy of activated carbon at sorbing PFAAs, particularly longer chain PFAAs such as PFOS, evaluations of the injection of colloidal activated carbon into aquifer materials have reportedly been conducted in Canada (InSitu Remediation Services Ltd., 2018). Similar to the use of activated carbon ex situ, it is expected that sorption of shorter chain PFAAs is expected to be lower than the longer chain compounds and that the adsorption sites will likely become saturated over time and could pose a long term secondary source of PFAS (Ross et al., 2018). Further, the efficacy of the technology is expected to be dependent on the properties of the aquifer.

Finally, activated carbon is routinely used as a point of use treatment method for PFAS, at both municipal water system and individual residential water supply scales. This is considered a risk management application of the technology, as opposed to contaminated site remediation, as the plume continues to exist in the subsurface.

7.1.2 Filtration

Filtration (i.e., reverse osmosis, nanofiltration) is another well studied area of PFAS water treatment. However, costs are reported to be high (Ross et al., 2018).

Reverse osmosis membranes rejected >99% of influent PFOS in a study completed by Tang et al. (2006) in which PFOS influent concentrations ranged from 500 µg/L to approximately 1600 mg/L. Reverse osmosis membranes were noted to perform better than nanofiltration membranes (Tang et al. 2007), although both demonstrated >90% efficiency with an influent PFOS concentration of 10 mg/L. The use of reverse osmosis membranes to treat PFAS contaminated water to below laboratory reporting limits at a wastewater reclamation plant in Australia has been documented (Thompson et al., 2011).

Steinle-Darling and Reinhard (2008) investigated the performance of nanofiltration membranes. A variety of PFASs and PFCAs were found to be rejected with variable efficiency depending on pH (>95% efficiency at pH 5.6, 60-80% efficiency at pH 3). Rejection of short chain PFCAs was substantially lower than other PFCAs. The researchers also noted that sorption of the PFAAs to the membranes cannot be readily reversed per typical membrane cleaning processes.

A key drawback to the use of reverse osmosis and nanofiltration technologies is the generation of a high concentration waste which would require further treatment or destruction. As well, other groundwater constituents or co-contaminants are expected to contribute to fouling of the membranes. Further discussion of considerations for waste disposal are provided in Section 7.3.

7.1.3 Water Pre-Treatment Methods

A number of technologies have been developed which could be used as pre-treatment methods to extend the life of sorbents (Section 7.1.1) or improve filtration performance (Section 7.1.2). These technologies include:

- Coagulation;
- Foam extraction;
- Ozofractionation; and
- Electrochemical oxidation.

The above pre-treatment methods are unlikely to reduce PFAA concentrations to desired discharge levels on their own, or may only address some PFAAs; consequently, these methods have been considered as preliminary steps in water treatment.

7.2 Soil Treatment Overview – Field Confirmed Approaches

Field-scale options for addressing soil PFAS contamination include incineration, engineered containment (including excavation and off-site disposal at a suitable facility, and on-site containment or capping), soil washing, and contaminant immobilization.

As in Section 7.1, the focus of this section is on field-proven methods for addressing PFAA contamination. Techniques which have been, or are currently being investigated, but which will not be covered here due to the absence of proven scaling to contaminated sites include:

- Soil capping;
- Thermal desorption;
- Advanced oxidation/reduction techniques (including electron beam irradiation);
- High temperature steam treatment;
- Phytoremediation; and
- Ball milling.

It is noted that many of the field-scale evaluations discussed in the following sections have been conducted outside of Canada. Based on information provided to SLR, Transport Canada and Department of Defence have not conducted field evaluations of soil treatment options for PFAS (pers. comm., L. Warner and P. Cushing).

7.2.1 Incineration

Of the available soil remediation options reviewed, only incineration results in the mineralization and destruction of PFAS, although required temperatures and residence times are not well-defined. Schultz et al. (2003) have suggested that temperatures of > 1200 degrees Celsius and residence times of 20 seconds are required for destruction of PFAS. However, reviews of incineration studies by Rayne and Forest (2009a) and Vecitis (2009) have suggested that lower temperatures may be sufficient for destruction of PFAS; required temperatures are expected to decrease with increased perfluorinated chain branching and with decreasing perfluorinated chain length (Rayne and Forest, 2009a).

Costs for incineration of PFAS-contaminated solids are high (e.g., in the range of \$3/kg).

7.2.2 Engineered Containment

Engineered containment involves the placement of contaminated materials in a lined cell from which leaching is prevented. An impermeable liner is placed below the materials, along with a leachate collection system within the cell. An impermeable cover is placed over the materials to prevent infiltration of water/precipitation and to minimize additional leaching. This remediation method does not result in the degradation of the PFAS. Rather the contamination is environmentally isolated to prevent direct exposure to the material and the production of leachate. Off-site disposal of PFAS-contaminated materials at an appropriately engineered/designed and permitted landfill is also considered to fall under this approach.

Engineered containment has been employed by the Minnesota Pollution Control Agency to address PFAS contaminated industrial wastes placed historically in non-engineered landfills and which have resulted in widespread groundwater contamination (MPCA, 2011). The materials were excavated from the landfill and placed in engineered landfill cells. The cells consisted of a layer of compacted clay followed by three synthetic/plastic liners which were sealed and leak-tested. A layer of sand was placed above the sealed liners to provide drainage and to protect the liners during the deposition of the wastes. Piping for leachate collection and recirculation was placed within the cell. The waste material was capped and the cell surface was covered with topsoil and an erosion control blanket. The cost to place approximately 1,900,000 m³ of landfill waste in the engineered containment was projected to be \$31,000,000 (in 2011 dollars).

7.2.3 Contaminant Immobilization

Contaminant immobilization entails the incorporation of materials such as activated carbon, organo-modified clays, and mixtures of activated carbon, clay, and aluminum hydroxides into the soil matrix to adsorb mobile PFAS and prevent further migration.

Discussion of Canadian trials involving injectable colloidal activated carbon was previously provided in Section 7.1.1. Australia DoD undertook a soil solidification and stabilization trial in 2017 to evaluate the effectiveness of nine products to immobilize PFAS (Australia DoD, 2016; Australia DoD, 2019a). Although some of the products reportedly showed immobilization, Australia DoD and Australian regulators reportedly had concerns about the long term effectiveness of the products, as well as associated effects of the products on ecosystem functionality.

As noted in the previous paragraph, the primary concern with this technology is its permanence, since PFAS are not destroyed but are simply immobilized. Further, Ross et al. (2018) postulated that the leaching tests typically used by product manufacturers to demonstrate product effectiveness in immobilizing soil contaminants may not be appropriate for PFAS since improved sorption is expected under the acidic conditions of most conventional leaching tests. Differences in sorption performance as a result of incorporation of other additives that may affect soil pH should also be considered.

7.2.4 Soil Washing

Soil washing entails flushing of contaminated soil with water to generate PFAS-rich leachate followed by subsequent collection and treatment of the generated leachate. This method is not considered practical for soil with appreciable fine particle content (Ross et al., 2018).

Australia DoD is currently undertaking a four month trial at RAAF Base Edinburgh to treat approximately 2500 tonnes of PFAS-contaminated soil by soil washing (Australia DoD, 2019b). At the time of this report, the results of the trial were not available.

7.3 Waste Disposal Considerations

Part 1 of the Environmental Management Act links the definition of waste to prescribed substances under provincial regulations. As discussed in Section 3.1.2, PFAS are not currently regulated under the BC HWR. Until PFAS are included in the BC HWR, excepting cases where facilities have permits which reflect maximum allowable limits of PFAS in waste disposed at the facility, it is presumed that the BC CSR industrial land use (IL) standards (including mandatory and relevant site-specific standards) would apply to disposal of PFAS-contaminated soil at landfills in British Columbia. However, individual facilities may implement operational thresholds for PFAS-contaminated materials at concentrations below the BC CSR IL standards. Of note, materials with a total PFOS concentration of 50 mg/kg are not considered suitable for landfill disposal based on United Nations guidance under the Basel Convention (UNEP, 2015; UNEP, 2017); this threshold is lower than the BC CSR IL standards for PFOS at sites with no operable groundwater pathways. Further, notwithstanding the absence of regulation of PFAS under the BC HWR, provisions of the Environmental Management Act require that individuals not introduce waste into the environment in such a manner or quantity as to cause pollution. To that end, practitioners are advised to review PFAS data for wastes intended for landfill disposal in consideration of the Basel Convention requirements and the potential for the materials to cause pollution, and to contact disposal facilities directly to discuss operational thresholds for PFAS that may be in place at the specific facility. For materials exceeding the Basel Convention threshold of 50 mg/kg, it is expected that wastes may need to be incinerated or otherwise disposed of such that the PFOS content is destroyed or irreversibly transformed (UNEP, 2015).

Guidance from ECCC (2017) to federal custodians regarding the disposal of granular activated carbon and other treatment wastes impacted by PFAS recommends destruction of the materials via incineration. ECCC further suggests that where custodians are unable to implement the recommended option of incineration, disposal in a specially engineered landfill (i.e., authorized hazardous waste facility designed and operated to prevent any release of treated or non-treated leachate into the environment, such as engineered landfills or permanent storage in underground mines and formations) be considered.

Finally, Australia (HEPA, 2018) provides guidance on landfill acceptance criteria based on landfill type and leachable and total PFAS concentrations. General siting recommendations from Australia (HEPA, 2018) state that landfills accepting waste containing PFAS must not be located on high or very high vulnerability aquifers, within 1 km of a surface water body supporting aquatic life, or within 1 km of a surface drainage network that either discharges to groundwater or to an aquatic receiving environment.

7.4 Waste Containment Considerations

Earlier sections of this report reviewed treatment options for soil and water at PFAS-contaminated sites. It is noted that requirements under the Waste Discharge Regulation of the Environmental Management Act would apply to some of the remedial approaches reviewed.

As noted in BC ENV Administrative Bulletin 6, released in January 2019 (BC ENV, 2019a), contaminated site contaminant management is a prescribed activity under the Waste Discharge

Regulation. A discharge authorization is required for any remediation activities that involve the on-site management of wastes including both the long term management of contaminated soil above industrial land use standards (including both mandatory and applicable site-specific factors) and discharge of effluent to ground or to a receiving water body from a groundwater remediation system. Practitioners are advised to review the requirements of the Waste Discharge Regulation and evaluate applicability to the PFAS-contaminated site prior to implementing any remedial approach.

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APPENDIX A

Nomenclature and CAS Numbers of PFSA's and PFCAs

Guidance for the Assessment and Remediation of
Per- and Polyfluoroalkyl Substances on British Columbia
SLR Project No.: 219.05420

Appendix A: Nomenclature and CAS Numbers of PFSA and PFCAs

Table A-1: Summary of PFCA

| NAME | # FULLY FLUORINATED CARBONS | SHORT/ LONG CHAIN | ABBREVIATION | CAS# |
|-------------------------------|-----------------------------------|----------------------|--------------|-------------------|
| Anion Forms | | | | |
| Perfluorobutanoate | 3 | Short | PFBA | 45048-62-2 |
| Perfluoropentanoate | 4 | Short | PFPeA | 45167-47-3 |
| Perfluorohexanoate | 5 | Short | PFHxA | 92612-52-7 |
| Perfluoroheptanoate | 6 | Short | PFHpA | 120885-29-2 |
| Perfluorooctanoate | 7 | Long | PFOA | 45285-51-6 |
| Perfluorononanoate | 8 | Long | PFNA | 72007-68-2 |
| Perfluorodecanoate | 9 | Long | PFDA | 73829-36-4 |
| Perfluoroundecanoate | 10 | Long | PFUNDA | 196859-54-8 |
| Perfluorododecanoate | 11 | Long | PFDoA | 171978-95-3 |
| Perfluorotridecanoate | 12 | Long | PFTTrDA | 862374-87-6 |
| Perfluorotetradecanoate | 13 | Long | PFTeDA | 365971-87-5 |
| Acid Forms | | | | |
| Perfluorobutanoic acid | 3 | Short | PFBA | 375-22-4 |
| Perfluoropentanoic acid | 4 | Short | PFPeA | 2706-90-3 |
| Perfluorohexanoic acid | 5 | Short | PFHxA | 307-24-4 |
| Perfluoroheptanoic acid | 6 | Short | PFHpA | 375-85-9 |
| Perfluorooctanoic acid | 7 | Long | PFOA | 335-67-1 |
| Perfluorononanoic acid | 8 | Long | PFNA | 375-95-1 |
| Perfluorodecanoic acid | 9 | Long | PFDA | 335-76-2 |
| Perfluoroundecanoic acid | 10 | Long | PFUNDA | 2058-94-8 |
| Perfluorododecanoic acid | 11 | Long | PFDoA | 307-55-1 |
| Perfluorotridecanoic acid | 12 | Long | PFTTrDA | 72629-94-8 |
| Perfluorotetradecanoic acid | 13 | Long | PFTeDA | 376-06-7 |

Notes:

For the PFCAs, the various compounds are typically referred to based on their total carbon chain length.

CAS numbers obtained from ITRC, 2018a.

Bold indicates PFCA regulated under the BC CSR.

**Appendix A:
Nomenclature and CAS Numbers of PFSA and PFCAs**

Table A-2: Summary of PFSA

| NAME | # FULLY FLUORINATED CARBONS | SHORT/ LONG CHAIN | ABBREVIATION | CAS# |
|--------------------------------------|-----------------------------------|-------------------------|----------------|-------------------|
| Anion Forms | | | | |
| Perfluorobutane sulfonate | 4 | Short | PFBS | 45187-15-3 |
| Perfluoropentane sulfonate | 5 | Short | PFPeS | NA |
| Perfluorohexane sulfonate | 6 | Long | PFHxS | 108427-53-8 |
| Perfluoroheptane sulfonate | 7 | Long | PFHpS | NA |
| Perfluorooctane sulfonate | 8 | Long | PFOS | 45298-90-6 |
| Perfluorononane sulfonate | 9 | Long | PFNS | NA |
| Perfluorodecane sulfonate | 10 | Long | PFDS | 126105-34-8 |
| Perfluorododecane sulfonate | 12 | Long | PFDoS / PFDoDS | NA |
| Acid Forms | | | | |
| Perfluorobutane sulfonic acid | 4 | Short | PFBS | 375-73-5 |
| Perfluoropentane sulfonic acid | 5 | Short | PFPeS | 2706-91-4 |
| Perfluorohexane sulfonic acid | 6 | Long | PFHxS | 355-46-4 |
| Perfluoroheptane sulfonic acid | 7 | Long | PFHpS | 375-92-8 |
| Perfluorooctane sulfonic acid | 8 | Long | PFOS | 1763-23-1 |
| Perfluorononane sulfonic acid | 9 | Long | PFNS | 474511-07-4 |
| Perfluorodecane sulfonic acid | 10 | Long | PFDS | 335-77-3 |
| Perfluorododecane sulfonic acid | 12 | Long | PFDoS / PFDoDS | 79780-39-5 |

Notes:

For the PFSA, the compounds are conventionally identified by the perfluorinated carbon chain length.

CAS numbers obtained from ITRC, 2018a.

NA – CAS number not available from source reviewed.

Bold indicates PFSA regulated under the BC CSR.

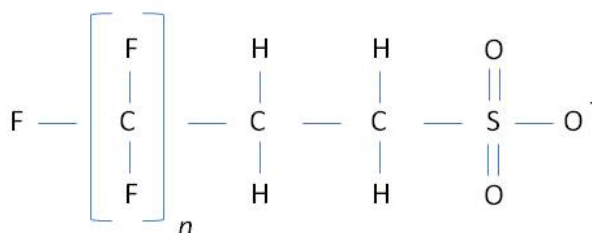
APPENDIX B
Background Information
– Other PFAS Encountered
at Contaminated Sites in BC

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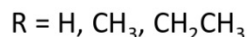
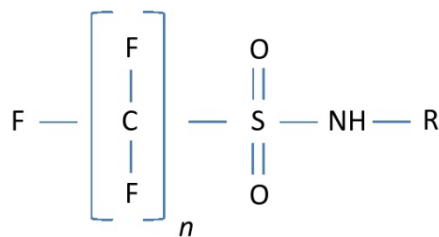
Appendix B: Background Information – Other PFAS Encountered at Contaminated Sites in BC

Other chemicals of particular note with respect to PFAS contaminated sites in BC include the fluorotelomer sulfonates (FTSs) and perfluoroalkane sulfonamides (FSAs).

Under ambient environmental conditions, FTSs are comprised of a partially fluorinated alkyl chain connected to a sulfonate end group (general structure $\text{F}(\text{CF}_2)_n\text{CH}_2\text{CH}_2\text{SO}_3^-$). The chemicals are named based on the ratio of the fluorinated carbons to hydrogenated carbons (e.g., 6:2 fluorotelomer sulfonate).



FSAs consist of fluorinated alkyl chains with a sulfonamide end group ($\text{F}(\text{CF}_2)_n\text{SO}_2\text{NH}_2$) which may or may not be methylated ($\text{F}(\text{CF}_2)_n\text{SO}_2\text{N}(\text{CH}_3)\text{H}$) or ethylated ($\text{F}(\text{CF}_2)_n\text{SO}_2\text{N}(\text{CH}_2\text{CH}_3)\text{H}$).



Chemical Abstract Services (CAS) numbers (provided for both anion and acid forms of the substances) of select FTSs and FSAs are provided in the table below.

Appendix B:
Background Information – Other PFAS Encountered at Contaminated Sites in BC

Table B-1: Summary of Other Non Regulated PFAS

| NAME | # FULLY FLUORINATED CARBONS | SHORT/ LONG CHAIN | ABBREVIATION | CAS# |
|-------------------------------------|-----------------------------------|-------------------------|--------------|-------------|
| Fluorotelomer Sulfonates | | | | |
| 4:2 Fluorotelomer sulfonate | 4 | - | 4:2 FTS | 414911-30-1 |
| 6:2 Fluorotelomer sulfonate | 6 | - | 6:2 FTS | 425670-75-3 |
| 8:2 Fluorotelomer sulfonate | 8 | - | 8:2 FTS | 481071-78-7 |
| Fluorotelomer Sulfonic Acids | | | | |
| 4:2 Fluorotelomer sulfonic acid | 4 | - | 4:2 FTS | 757124-72-4 |
| 6:2 Fluorotelomer sulfonic acid | 6 | - | 6:2 FTS | 27619-97-2 |
| 8:2 Fluorotelomer sulfonic acid | 8 | - | 8:2 FTS | 39108-34-4 |
| Sulfonamides | | | | |
| Perfluorooctane sulfonamide | 4 | Long | PFOSA | 754-91-6 |
| N-Methylperfluorooctane sulfonamide | 6 | Long | N-MeFOSA | 31506-32-8 |
| N-Ethylperfluorooctane sulfonamide | 8 | Long | N-EtFOSA | 4151-50-2 |

Notes:

CAS numbers obtained from SGS AXYS (pers. comm.).

In addition to the above, chemicals such as GenX, ADONA, and F35 are gaining interest due to their use as replacement chemistries for applications that have historically used the longer chain PFCA and PFSA (ITRC, 2018a). At this point in time, the occurrence and use of these replacement chemistries in Canada is not well understood given the reported absence of PFAS manufacturing facilities in this country.

APPENDIX C

Soil and Water Screening Values from Other Jurisdictions

Guidance for the Assessment and Remediation of
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Appendix C: Soil and Water Screening Values from Other Jurisdictions

Table C-1: Screening/guidance values and guidelines from other jurisdictions for PFBS, PFOS and PFOA for media/receptor exposure pathways not covered under the CSR

| Compound | Jurisdiction | Criterion/Guideline | Concentration |
|---|----------------------|---|---------------|
| WATER (EXCLUDING DRINKING WATER) | | | |
| PFBS | Germany | Predicted No Effect Concentration (PNEC), Surface Water (Ecological) | 3700 ug/L |
| | Italy | Average Annual Concentration Quality Standard (AA-QS), Surface Water, Pelagic community – freshwater | 372 ug/L |
| | | AA-QS, Surface Water, Pelagic community – saltwater | 37 ug/L |
| PFOS | Canada (ECCC) | Federal Environmental Quality Guideline for Surface Water – protection of freshwater organisms (direct contact) | 6.8 ug/L |
| | Canada (CCME, draft) | Groundwater in contact with soil dependent organisms | 2000 ug/L |
| | | Management Limit (based on solubility) | 370 000 ug/L |
| | Australia | Recreation Water (based on 10x drinking water guideline) | 0.7 ug/L |
| | | Interim Aquatic Marine Surface Water Value - 99% species protection (adopted from freshwater value) | 0.00023 ug/L |
| | Netherlands | Proposed environmental risk limit in groundwater, protective of drinking water, groundwater contact by soil organisms, food chain transfers | 0.023 ug/L |
| | | Proposed maximum permissible concentration, Surface Water, protective of human consumption of fish | 0.00065 ug/L |
| | | Proposed maximum permissible concentration, Surface Water, protective of secondary poisoning to predators | 0.00053 ug/L |
| | European Commission | Inland Surface Water protective of consumption of fisheries products | 0.00065 ug/L |
| PFOA | Michigan | Aquatic Maximum Value | 7700 ug/L |
| | Australia | Recreation Water | 5.6 ug/L |
| | | Aquatic Freshwater Draft Guidelines Values - 99% species protection | 19 ug/L |
| | | Interim Aquatic Marine Value - 99% species protection (adopted from freshwater value) | 19 ug/L |
| | Germany | PNEC, Surface Water (Ecological) | 570 ug/L |

Appendix C: Soil and Water Screening Values from Other Jurisdictions

| Compound | Jurisdiction | Criterion/Guideline | Concentration |
|----------|---------------------------|---|---|
| | Netherlands | Proposed Water Quality Standard (marine and freshwater) protective of consumption of fish by humans | 0.048 ug/L |
| | | Proposed Average Annual Concentration Quality Standard (AA-EQS), Surface Water, direct ecotoxicity - freshwater | 30 ug/L |
| | | Proposed AA-EQS, Surface Water, direct ecotoxicity - saltwater | 3.0 ug/L |
| | | Proposed AA-EQS, Surface Water, secondary poisoning to predators - freshwater | 0.99 ug/L |
| | | Proposed AA-EQS, Surface Water, secondary poisoning to predators - saltwater | 0.13 ug/L |
| | Italy | AA-QS, Surface Water, Pelagic community – freshwater | 30 ug/L |
| | | AA-QS, Surface Water, Pelagic community – saltwater | 3 ug/L |
| | | Quality Standard (QS) Secondary poisoning to predators – freshwater | 0.1 ug/L |
| | | QS Secondary poisoning to predators – saltwater | 0.02 ug/L |
| | | QS Human health protection – consumption of fishery products - freshwater | 9.7 ug/L |
| | | QS Human health protection – consumption of fishery products - saltwater | 1.9 ug/L |
| SOIL | | | |
| PFBS | United States (USEPA RSL) | Protection of Groundwater used as Drinking Water | 0.13 mg/kg |
| PFOS | Canada (CCME, draft) | Protection of Groundwater used for Livestock Watering and Irrigation | 12 mg/kg (coarse soil) 9 mg/kg (fine soil) |
| | Australia | Human Health Protection - Residential soil with garden produce consumption | 0.009 mg/kg* |
| | Netherlands | Protection of Uptake into Food | 0.0032 mg/kg |

Appendix C: Soil and Water Screening Values from Other Jurisdictions

| Compound | Jurisdiction | Criterion/Guideline | Concentration |
|----------|---------------------------|--|----------------|
| PFOA | United States (USEPA RSL) | Protection of Groundwater used as Drinking Water (as reported in ITRC Table 4) | 0.000172 mg/kg |
| | | Human Health Protection - Direct Contact (as reported in ITRC Table 4) | 1.26 mg/kg |
| | Michigan | Surface Water Protection | 10 mg/kg |
| | Australia | Human Health Protection - Residential soil with garden produce consumption | 0.1 mg/kg |
| | | Ecological Health Protection – interim value for direct soil contact, public open space land use | 10 mg/kg |
| | Canada (Health Canada) | Human Health Protection – Direct Contact Residential Soil Screening Value | 0.70 mg/kg |

Notes:

*Australia – value applied to PFOS and also to summed concentration of PFHxS and PFOS when found together.

Appendix C: Soil and Water Screening Values from Other Jurisdictions

Table C-2: Soil and water screening/guidance values and guidelines for PFAS other than PFBS, PFOS and PFOA from other jurisdictions

| Compound | Jurisdiction | Criterion/Guideline | Concentration |
|--------------|------------------------|--|---------------|
| WATER | | | |
| PFBA | Germany | PNEC, Surface Water (Ecological) | 1260 µg/L |
| | Italy | AA-QS, Surface Water, Pelagic Community – freshwater | 110 µg/L |
| | | AA-QS, Surface Water, Pelagic Community – saltwater | 11 µg/L |
| | Canada (Health Canada) | Drinking Water Screening Value | 30 µg/L |
| PFPeA | Germany | PNEC, Surface Water (Ecological) | 320 µg/L |
| | Italy | AA-QS, Surface Water, Pelagic Community – freshwater | 32 µg/L |
| | | AA-QS, Surface Water, Pelagic Community – saltwater | 3.2 µg/L |
| | Canada (Health Canada) | Drinking Water Screening Value | 0.2 µg/L |
| PFHxA | Germany | PNEC, Surface Water (Ecological) | 1000 µg/L |
| | Canada (Health Canada) | Drinking Water Screening Value | 0.2 µg/L |
| PFHpA | Oregon | Initiation Level (Effluent Criteria) | 300 µg/L |
| | Canada (Health Canada) | Drinking Water Screening Value | 0.2 µg/L |
| PFNA | Oregon | Initiation Level (Effluent Criteria) | 1 µg/L |
| | Germany | PNEC, Surface Water (Ecological) | 8 µg/L |
| | Canada (Health Canada) | Drinking Water Screening Value | 0.02 µg/L |
| PFDA | Texas | Groundwater used as Drinking Water Residential PCL | 0.37 µg/L |
| | Germany | PNEC, Surface Water (Ecological) | 10 µg/L |
| | Denmark | Drinking Water Criteria | 0.1 µg/L** |
| PFUnA | Texas | Groundwater used as Drinking Water Residential PCL | 0.29 µg/L |
| PFDoA | Texas | Groundwater used as Drinking Water Residential PCL | 0.29 µg/L |
| PFTTrDA | Texas | Groundwater used as Drinking Water Residential PCL | 0.29 µg/L |
| PFTeDA | Texas | Groundwater used as Drinking Water Residential PCL | 0.29 µg/L |
| PFHxS | Australia | Recreation Water | 0.7 µg/L* |
| | Germany | PNEC, Surface Water (Ecological) | 250 µg/L |
| | Canada (Health Canada) | Drinking Water Screening Value | 0.6 µg/L |

Appendix C: Soil and Water Screening Values from Other Jurisdictions

| Compound | Jurisdiction | Criterion/Guideline | Concentration |
|-------------|------------------------|---|-----------------------|
| PFDS | Texas | Groundwater used as Drinking Water Residential PCL | 0.29 µg/L |
| PFOSA | Oregon | Initiation Level (Effluent Criteria) | 0.2 µg/L |
| | Texas | Groundwater used as Drinking Water Residential PCL | 0.29 µg/L |
| | Denmark | Drinking Water Criteria | 0.1 µg/L ** |
| 6:2 FTS | Denmark | Drinking Water Criteria | 0.1 µg/L ** |
| | Canada (Health Canada) | Drinking Water Screening Value | 0.2 µg/L |
| 8:2 FTS | Canada (Health Canada) | Drinking Water Screening Value | 0.2 µg/L |
| Gen-X | North Carolina | Drinking Water Health Goal | 0.14 µg/L |
| SOIL | | | |
| PFBA | Texas | Groundwater used as Drinking Water Protection Residential PCL | 0.098-0.2 mg/kg |
| | Canada (Health Canada) | Human Health Protection – Direct Contact Residential Soil Screening Value | 114 mg/kg |
| PFPeA | Texas | Groundwater used as Drinking Water Protection Residential PCL | 0.00016-0.00032 mg/kg |
| | Canada (Health Canada) | Human Health Protection – Direct Contact Residential Soil Screening Value | 0.80 mg/kg |
| PFHxA | Texas | Groundwater used as Drinking Water Protection Residential PCL | 0.00024-0.00048 mg/kg |
| | Canada (Health Canada) | Human Health Protection – Direct Contact Residential Soil Screening Value | 0.80 mg/kg |
| PFHpA | Texas | Groundwater used as Drinking Water Protection Residential PCL | 0.0023-0.0046 mg/kg |
| | Canada (Health Canada) | Human Health Protection – Direct Contact Residential Soil Screening Value | 0.80 mg/kg |
| PFNA | Texas | Groundwater used as Drinking Water Protection Residential PCL | 0.0015-0.0031 mg/kg |
| | Canada (Health Canada) | Human Health Protection – Direct Contact Residential Soil Screening Value | 0.08 mg/kg |
| PFDA | Texas | Groundwater used as Drinking Water Protection Residential PCL | 0.011-0.022 mg/kg |
| | | Human Health Protection – Direct Contact Residential PCL | 0.98-0.99 mg/kg |
| | Denmark | Human Health Protection | 0.4 mg/kg** |
| PFUnA | Texas | Groundwater used as Drinking Water Protection Residential PCL | 0.0092-0.018 mg/kg |
| | | Human Health Protection – Direct Contact Residential PCL | 0.8 mg/kg |

Appendix C: Soil and Water Screening Values from Other Jurisdictions

| Compound | Jurisdiction | Criterion/Guideline | Concentration |
|----------|------------------------|--|-------------------|
| PFDoA | Texas | Groundwater used as Drinking Water Protection Residential PCL | 0.017-0.034 mg/kg |
| | | Human Health Protection – Direct Contact Residential PCL | 0.78-0.79 mg/kg |
| PFTTrDA | Texas | Groundwater used as Drinking Water Protection Residential PCL | 0.03-0.061 mg/kg |
| | | Uptake to Vegetables Residential PCL | 2.5 mg/kg |
| | | Human Health Protection – Direct Contact Residential PCL | 0.61 mg/kg |
| PFTeDA | Texas | Groundwater used as Drinking Water Protection Residential PCL | 0.056-0.11 mg/kg |
| | | Uptake to Vegetables Residential PCL | 1.4 mg/kg |
| | | Human Health Protection – Direct Contact Residential PCL | 0.51 mg/kg |
| PFHxS | Texas | Groundwater used as Drinking Water Protection Residential PCL | 0.001-0.002 mg/kg |
| | Australia | Human Health Protection - Residential soil with garden produce consumption | 0.009 mg/kg* |
| | Canada (Health Canada) | Human Health Protection – Direct Contact Residential Soil Screening Value | 2.3 mg/kg |
| PFDS | Texas | Groundwater used as Drinking Water Protection Residential PCL | 0.02-0.04 mg/kg |
| | | Human Health Protection – Direct Contact Residential PCL | 0.8 mg/kg |
| PFOSA | Texas | Groundwater used as Drinking Water Protection Residential PCL | 0.46-0.92 mg/kg |
| | | Human Health Protection – Direct Contact Residential PCL | 0.031-0.058 mg/kg |
| | Denmark | Human Health Protection | 0.4 mg/kg** |
| 6:2 FTS | Denmark | Human Health Protection | 0.4 mg/kg** |

Notes:

*Australia – value applied to PFHxS and also to summed concentration of PFHxS and PFOS when found together.

**Denmark – value applied to individual PFAS and also to summed concentration of 12 PFAS (PFBA, PFPeA, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFBS, PFHxS, PFOS, PFOSA, 6:2 FTS).

Appendix C: Soil and Water Screening Values from Other Jurisdictions

CHEMICAL ADDITIVITY

Within Canada, Health Canada recommends an additive approach for the protection of human health where PFOS and PFOA are found together in drinking water (HC, 2018a; HC, 2018b). A similar recommendation has been made in regards to PFOS and PFOA in soil (HC, 2019b). Health Canada has stated that based on the lack of toxicological data on PFAS other than PFOS and PFOA, an additive approach has not been extended to other PFAS (HC, 2018a; HC, 2018b; HC, 2019b). However, it is SLR's understanding that Health Canada may review the additivity of PFAS other than PFOS and PFOA as toxicological information becomes available.

Internationally, Alaska, Connecticut, Massachusetts and Vermont require comparison of summed concentration of 5 PFAS (PFOS, PFOA, PFNA, PFHxS, PFHpA) in drinking water to the target criteria, while Sweden compares the summed concentration of 7 PFAS (PFBS, PFHxS, PFOS, PFPeA, PFHxA, PFHpA and PFOA) to its drinking water criteria. As noted in the previous section, Denmark's drinking water and soil criteria are applied to individual PFAS and also to the summed concentration of 12 PFAS (PFBA, PFPeA, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFBS, PFHxS, PFOS, PFOSA, 6:2 FTS). In Australia, the human health protective guidance values for PFHxS and PFOS in water (drinking water, recreation water) are to be applied to the summed concentrations of the two substances where they are found to co-occur (HEPA, 2018). The Netherlands (RIVM, 2018) has developed a relative potency factor (RPF) approach for PFAS mixtures. RPF for 19 PFAS have been derived relative to PFOA. Concentrations with RPF applied are summed and expressed as PFOA equivalents and compared to the environmental quality standard for PFOA in soil or water.

APPENDIX D
Physical-Chemical Properties
– Non-Regulated PFSA's, PFCAs and FSAs

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Appendix D: Physical and Chemical Properties of Non-Regulated PFCAs, PFSA's and FSAs

Table D-1
Physical and Chemical Properties of Non-Regulated PFCAs, PFSA's and FSAs

| Compound Name | # Fully Fluorinated Carbons | Short/ Long Chain | Molecular weight (g/mole) ^a | Physical State (20° C) ^a | pK _a ^b | Water Solubility (mg/L) ^a | Dimensionless Henry's Constant ^a | Log K _{oc} (unitless) ^a |
|---------------|-----------------------------|-------------------|--|-------------------------------------|------------------------------|--------------------------------------|---|---|
| PFCAs | | | | | | | | |
| PFBA | 3 | Short | 213.1 | Solid | 0.08 (estimated) | 7.58E+05 | 1.51E-11 | 1.318 |
| PFPeA | 4 | Short | 263.1 | Solid | not reported | 1.07E+05 | 1.03E-10 | 1.584 |
| PFHxA | 5 | Short | 313.1 | Solid | -0.16 | 1.15 E+05 | 7.07E-10 | 1.91 |
| PFHpA | 6 | Short | 363.1 | Solid | -0.15 (estimated) | 1.94E+03 | 4.84E-09 | 2.19 |
| PFNA | 8 | Long | 463.1 | Solid | -0.17 (estimated) | 3.28E+01 | 2.33E-07 | 2.33 |
| PFDA | 9 | Long | 513.1 | Solid | -0.17 (estimated) | 4.20E+00 | 1.72E-06 | 3.17 |
| PFUnA | 10 | Long | 563.1 | Solid | -0.17 (estimated) | 5.33E-01 | 1.27E-05 | 3.18 |
| PFDoDA | 11 | Long | 613.1 | Solid | -0.17 (estimated) | 6.71E-02 | 9.36E-05 | 3.446 |
| PFTeDA | 12 | Long | 663.1 | Solid | not reported | 8.39E-03 | 6.88E-04 | 3.712 |
| PFTeDA | 13 | Long | 713.1 | Solid | not reported | 1.05E-03 | 5.09E-03 | 3.978 |

Appendix D: Physical and Chemical Properties of Non-Regulated PFCAs, PFSA's and FSAs

Table D-1
Physical and Chemical Properties of Non-Regulated PFCAs, PFSA's and FSAs

| Compound Name | # Fully Fluorinated Carbons | Short/ Long Chain | Molecular weight (g/mole) ^a | Physical State (20° C) ^a | pK _a ^b | Water Solubility (mg/L) ^a | Dimensionless Henry's Constant ^a | Log K _{oc} (unitless) ^a |
|---------------|-----------------------------|-------------------|--|-------------------------------------|------------------------------|--------------------------------------|---|---|
| PFSA's | | | | | | | | |
| PFBS | 4 | Short | 299.1 | Solid | 0.14 (estimated) | 1.74E+04 | 1.12E-11 | 1.47 |
| PFHxS | 6 | Long | 399.1 | Solid | 0.14 (estimated) | 3.07E+02 | 6.02E-10 | 2.7 |
| PFDS | 10 | Long | 599.1 | Solid | not reported | 8.20E-02 | 1.76E-06 | 3.53 |
| FSAs | | | | | | | | |
| PFOSA | 8 | Long | 499.2 | Solid | 6.24 (estimated) | 4.88E-02 | 1.05E+03 | 4.1 |

Notes:

^a - Data obtained from TCEQ, 2018.

^b – Data obtained from ATSDR, 2018.

APPENDIX E

Analytical Approaches - Other Methodologies

Guidance for the Assessment and Remediation of
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Appendix E: Analytical Approaches – Other Methodologies

The CCME document Guidance Manual for Environmental Site Characterization in Support of Environmental and Human Health Risk Assessment Volume 4 Analytical Methods (CCME, 2016) provides some discussion on the analysis of PFAS. CCME indicates that both direct injection and SPE methods may be applied depending on required sensitivity of the analysis, with analysis by LC-MS/MS. Solid samples are mixed with an ion-pairing agent prior to extraction and extracts are evaporated to dryness and reconstituted in methanol prior to analysis by LC-MS/MS. Methods referenced in the CCME document include US EPA Method 537 (discussed further below) and Ontario Ministry of Environment and Climate Change Methods E3506 (soil) and E3457 (water) (limited information was obtained regarding these methods and therefore they have not been discussed further herein).

SLR contacted ECCC to determine whether ECCC has developed an analytical method for the determination of PFAS in environmental matrices and ECCC (pers. comm., D. St-Laurent) confirmed it does not have a standardized PFAS laboratory protocol. However, ECCC did confirm that they recommend analysis of any sediment fractions present in aqueous samples, similar to the requirements of the BC Environmental Laboratory Manual and an internal ECCC protocol for dioxin and furan analysis, and also advised whole sample extraction and analysis in order to mitigate against potential underestimation of PFAS concentrations (which suggests that an SPE approach is recommended by ECCC over direct injection).

The US EPA has derived a laboratory method for analysis of up to 18 PFAS in finished (treated) drinking water (EPA Method 537.1, released in November 2018). Method 537.1 is not recommended for matrices other than drinking water due to the challenges of matrix interferences in other environmental media and the presence of other co-contaminants which may impact the method.

ASTM has developed a method for PFAS in environmental waters (ASTM method D7979-17) and solids (ASTM D7968) which employs direct injection and analysis by LC/MS-MS. It is noted that the BC Environmental Laboratory Manual refers to both EPA Method 537 (presumably the pre-November 2018 version of the method) and ASTM Methods D7979 and D7968 as providing additional guidance on sample extraction and instrumental analysis. Currently, EPA is in the process of validating methods for environmental matrices other than treated drinking water (SW-846 draft methods 8327 and 8328) and is also reportedly developing methods for identification of PFAA precursors and other currently unknown PFAS in different environmental matrices.

In Canada, at least four commercial laboratories offer the total oxidizable precursor (TOP) assay (Houtz and Sedlak, 2012) to evaluate the environmental presence of certain PFAS which could not be identified using previous laboratory approaches. Specifically, the TOP assay uses chemical oxidation to break down larger, difficult-to-measure polyfluoroalkyl compounds (referred to as “precursor” compounds) into smaller, more readily identifiable PFAS, namely PFAAs. Once the oxidation process is complete, the terminal PFAAs are measured by the laboratory and compared to pre-oxidation results for the same sample, giving an indirect estimate of the amount of precursors in the sample. Another methodology, Particle Induced Gamma Ray Emission (PIGE), can provide estimates of total fluorine content of materials, thereby providing an indication of the presence of precursor and unknown PFAS compounds; however, the availability of PIGE analysis at commercial laboratories in Canada was not confirmed by SLR for this project. Australia (HEPA, 2018) recommends the use of the TOP assay and total organic fluorine (TOF) assay for evaluation of potential precursor presence.



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