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Federal Contaminated Sites Action Plan (FCSAP)

Interim Advice to Federal Custodian Departments for the Management of Federal Contaminated Sites Containing Perfluorooctane Sulfonate (PFOS) and other Per- and Polyfluoroalkyl Substances (PFAS)

Version 1.4.1, April 2018

Summary of Revisions

Revision Number	Date of Issue	Lead	Brief Description of Change
1.4.1	April 2018	FCSAP Secretariat	o Corrected groundwater guideline values in Table 5 (p.11), based on information from CCME (2017, draft for review). o Added Appendix II, an excerpt from CCME (2017, draft for review) regarding groundwater quality guidelines o Updated and added to text and values in Table 2, to incorporate information from Health Canada (July 2017) memorandum *Updates to Health Canada Soil Screening Values for Perfluosoalkylated Substances (PFAS)*. o Clarified the derivation of the Federal Tissue Guideline for Bird Eggs. o Added references for CCME (2017 draft for review), Health Canada (2017a), and ECCC (2017). o Removed reference for Rodriguez-Freire *et al.* (2016). o Removed Appendix I of v. 1.4, Supporting Document for PFOS Soil Screening Values.

1.4	January 2018	FCSAP Secretariat	o Broadened the scope of the document to include preliminary findings and guidance for PFAS substances other than PFOS. o Title changed to reflect this change of scope. o **Section III: Human Health Guidance Values (HHGV**) • Text has been updated, • Update to the PFOS Drinking Water Screening Values (increased) and Soil Screening Values (increased) • Added PFAS Drinking Water Screening Values and Soil Screening Values o **Section IV: Environmental Quality Guidelines (EQG)** • Text has been updated • Certain PFOS values have been updated using interim data. o **Section V – Remediation Approaches** • Text has been updated. o Removal of Appendix I and Appendix II of v 1.3 (Supporting Document for HC Provisional Drinking Water Guidance Value for PFOS, and Supporting Document for Provisional Soil Screening Levels) o Addition of Appendix I of v 1.4: Supporting Document for PFOS Soil Screening Values

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I. Introduction

The Federal Contaminated Sites Action Plan (FCSAP) is a 15-year, $4.54 billion program that was established in 2005 by the Government of Canada. The program's primary objective is to reduce environmental and human health risks and associated federal financial liabilities resulting from the highest risk federal contaminated sites.

This Interim Advice has been prepared by the FCSAP per- and polyfluoroalkyl substances (PFAS) Interdepartmental Working Group. The principal contributors to this advice are Environment and Climate Change Canada (ECCC)'s Science & Technology branch and National Guidelines and Standards Office (NGSO). This Interim Advice can assist Federal Custodians with responsibility for managing sites that may have been impacted by PFAS which include perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA).

This memo provides the following:

- Information on fate and transport of PFAS substances;
- Health Canada Drinking Water Screening Values for PFAS (HC 2017a);
- Human Health Soil Screening Values for PFAS (HC 2017b);
- Federal Environmental Quality Guidelines for water, fish tissue (for protection of aquatic life), wildlife diet (mammals and birds) and bird eggs for PFOS (ECCC 2017);
- Federal Soil Quality Guidelines for Agricultural, Residential/Parkland, Commercial and Industrial land uses for PFOS (ECCC 2017);
- Draft for review of Canadian Groundwater Quality Guidelines for PFOS, considering ecological receptors (CCME 2017, draft for review); and,
- Approaches for the remediation of PFAS-impacted sites.

PFAS are anthropogenic chemicals that have become present in the environment through their broad applications including but not limited to their use in manufacturing processes, and consumer products. PFAS are used in aqueous film forming foams (AFFFs) which are typically used during fire fighting training activities carried out at fire fighting training areas (FFTAs) at some airports and military bases across the country. As a result, PFAS concentrations in the environment at some FFTAs where AFFFs are used may be elevated.

Through risk assessment activities under the Canadian Environmental Protection Act, 1999 (CEPA), the Government of Canada concluded that PFOS, its salts and precursors are or may be entering the environment in quantities or concentrations or under conditions that have or may have an immediate or long-term harmful effect on the environment or its biological diversity. There was no unacceptable risk to human health identified. Based on the conclusions of the environmental risk assessment, PFOS, its salts, and precursors were added to Schedule 1 of CEPA, the List of Toxic Substances. PFOS and its salts were also added to the Virtual Elimination List compiled under CEPA. PFOA was included in the amendment of the Regulations Amending the Prohibition of Certain Toxic Substances Regulations, 2012 which came into effect in December 2016. PFOA, its salts, precursors and products containing them are now prohibited, with the exception of manufactured items.

Currently there are no approved Canadian Environmental Quality Guidelines (CEQG) for PFAS substances and the availability of PFOS and PFOA guidelines and standards from other jurisdictions is limited.

Interim human health-based values for groundwater as a potable water source and for soil quality have been prepared by HC to assist federal custodians in the assessment of PFAS substances in these media at federal contaminated sites. These values are based on a limited review of available information and have not been formally vetted or peer reviewed. The resultant uncertainty and limitations associated with the use of these values are discussed within the guidance.

Internationally, the Basel Convention published several technical guidelines on the environmentally sound management of wastes, including one for persistent organic pollutants (POPs) and one specific to perfluorooctane sulfonic acid (PFOS), its salts and perfluorooctane sulfonyl fluoride (UNEP 2015).

The advice herein is provisional, is intended for use at federal sites, and has been provided to meet the needs of federal custodians at this time. It is not intended for use in any other context. The present document and advice herein may change as more information becomes available regarding the toxicity of PFAS and as environmental quality guidelines are developed. Any decisions taken based on the advice provided herein are the responsibility of Federal Custodians making those decisions.

II. Fate and Transport

PFAS contain a main carbon backbone that is completely saturated with fluorine, involving carbon-fluorine bonds, which are the strongest known covalent bonds. The strength of these bonds means that the compounds are resistant to hydrolysis, photolysis, biodegradation and metabolism by animals (Key *et al.* 1997). They are of concern because of their global distribution, persistence, toxicity and tendency to bioaccumulate.

The term PFOS may refer to any of its anionic, acid or salt forms, although the PFOS anion (whose molecular formula is $C_8F_{17}SO_3^-$) is the most common form found at pH relevant to the environment and in the human body. PFOS is not found naturally in the environment, but it has been manufactured since the 1950s (Lehmler 2005). As well as being commercially produced, PFOS may be formed through microbial degradation of other compounds produced during the electrochemical fluorination process.

Once PFOS is released into the environment, it is not known to undergo further chemical, microbial or photolytic degradation, and is considered extremely persistent with a half-life of more than 41 years (United Nations Environment Programme [UNEP] 2007). Although PFOS has low volatility, its capacity for long-range transport to polar regions due to its high atmospheric half-life is of particular concern, because it has been shown to bioaccumulate in polar bears (EC 2006) and biomagnify in fish and birds (UNEP 2006).

PFOS is moderately soluble in water and can therefore migrate from soil to groundwater. This process is influenced by the presence of certain minerals to which PFOS has a high affinity (Ferrey *et al.* 2012), and especially by the organic carbon content of soil. PFOS has also demonstrated a strong affinity for hydrocarbon- contaminated soil, with sorption levels approximately one order of magnitude greater than sorption to organic carbon (Chen *et al.* 2009).

The corresponding pH level of the soil, sediment or solution is also an important factor in determining the level of sorption and migration of PFOS. Increased sorption occurs at lower pH levels, which are more likely associated with chemically impacted soils (e.g., at disposal sites, landfills) (Ferrey *et al.* 2012). High-iron sand (iron oxide–coated), other iron (II), iron (III) or calcium cations sorbed to mineral surfaces, and other positively charged surfaces, have high PFOS adsorption rates due to the electrostatic attraction of its negatively charged sulfonate head (Ferrey *et al.* 2012; Higgins and Luthy 2006). The combination of its electrostatic and hydrophobic properties complicates the environmental fate modelling of PFOS.

III. Human Health Guidance Values for PFAS

A. Groundwater as Potable Water Source

Drinking Water Screening Values for PFAS substances are presented in **Table 1**.

Drinking Water Screening Values are developed at the request of a federal department, a province or territory in the event of a spill, leak or other contamination event, and are based on readily available scientific studies. They are not subject to a review as thorough as the Guidelines for Canadian Drinking Water Quality, which undergo internal peer review and public consultation before being approved by the Federal-Provincial-Territorial Committees on Drinking Water and on Health and the Environment. Drinking Water Screening Values are provided as guidance, and apply to water intended for human consumption.

As drinking water is generally treated before consumption, Drinking Water Screening Values include treatment considerations and should not be interpreted as being applicable to water in the environment.

Full health risk assessments are now being developed by HC for PFOS and PFOA as part of the *Guidelines for Canadian Drinking Water Quality*. These two assessments underwent public consultation in 2016, and are expected to be finalized in 2018. Scientific information is limited on the majority of PFAS. Only PFOS and PFOA have been studied sufficiently to develop comprehensive health risk assessments. The drinking water screening values for most other PFAS were developed using PFOS and PFOA as surrogates, whereas they are expected to be less toxic because of their chemical structure.

Table 1: Health Canada Drinking Water Screening Values (DWSV) for Perfluoroalkyl Substances (PFAS) (HC 2017a)

PFAS Name	PFAS Acronym	DWSV (mg/L)	DWSV (μg/L)
perfluorooctanoic acid	PFOA	0.0002	0.2*
perfluorooctane sulfonate	PFOS	0.0006	0.6*
perfluorobutanoate	PFBA	0.03	30
perfluorobutane sulfonate	PFBS	0.015	15
perfluorohexanesulfonate	PFHxS	0.0006	0.6
perfluoropentanoate	PFPeA	0.0002	0.2
perfluorohexanoate	PFHxA	0.0002	0.2
perfluoroheptanoate	PFHpA	0.0002	0.2
perfluorononanoate	PFNA	0.0002	0.2

*Full health risk assessments are now being developed by HC for PFOS and PFOA as part of the *Guidelines for Canadian Drinking Water Quality*.

B. Soil

Human Health Soil Screening Values for PFAS for agricultural/residential/parkland, commercial, and industrial land uses are presented in **Table 2**.

Human Health Soil Screening Values are developed at the request of a federal department in the event of spill, leak or other contamination event, and are based on available scientific studies. They are not subject to a review as thorough as the Canadian Council of Ministers of the Environment (CCME) Soil Quality Guidelines, which undergo internal peer review and public consultation before being approved by the CCME. Therefore, although the approach used for developing Soil Screening Values is generally consistent with the CCME protocol for development of Soil Quality Guidelines for direct contact with soil (CCME 2006), these Soil Screening Values should not be considered as draft CCME guidelines.

The PFAS Soil Screening Values are provided as guidance, and apply to soil to which humans may be exposed. They are based on direct contact of people with soil and do not incorporate protection of groundwater or food grown on a site. As soil can be a significant source of PFAS in groundwater, it is recommended that where groundwater is a concern at a site, a site-specific assessment be conducted to identify a concentration of PFAS in soil that would be protective of groundwater quality. HC continues to monitor new research in this area.

The custodian should determine which Soil Screening Values for agricultural/residential/parkland, commercial, or industrial land uses are the most appropriate value for application at a site based on site use. Further information on the land use scenarios and default assumptions can be found in CCME (2006).

Soil screening values and supporting guidance may change without notice. Please check for published values and confirm these values are appropriate prior to use.

Table 2. Human Health Soil Screening Values (SSV) for Perfluoroalkyl Substances (PFAS) (HC 2017b)

PFAS Name	**PFAS Acronym**	**Soil Screening Values (SSVs) (mg/kg)**		
		Agricultural/ Residential Parkland Land Use	**Commercial Land Use**	**Industrial (Commercial without Toddler) Land Use**
Perfluorooctane sulfonate	PFOS	2.1	3.2	30.5
Perfluorooctanoic acid	PFOA	0.85	1.28	12.1
Perfluorobutanoate	PFBA	114	173	1630
Perfluorobutane sulfonate	PFBS	61	92	872
Perfluoropentanoate[b]	PFPeA	0.95	1.4	14
Perfluorohexane sulfonate[a]	PFHxS	2.3	3.5	33
Perfluorohexanoate[b]	PFHxA	0.95	1.4	14
Perfluoroheptanoate[b]	PFHpA	0.95	1.4	14
Perfluorononanoate	PFNA	0.35	0.52	5.0

a – SSV is based on PFOS toxicity and an estimated daily intake from other sources assumed to be 0 mg/kg-day.

b – SSV is based on PFOA toxicity and an estimated daily intake from other sources assumed to be 0 mg/kg-day.

Notes:

- The health effects of PFOS and PFOA are similar and well documented. Based on recent science (2015), we know that PFOS and PFOA affect the same organ in similar ways. Thus, when PFOS and PFOA are found together in soil, the best approach to protect human health is to consider both chemicals together when comparing to the soil screening values. This is done by adding the ratio of the measured concentration for PFOS to its screening value with the ratio of the measured concentration for PFOA to its screening value; if the result is below or equal to one (1.0), then the soil is considered acceptable for its land use. Science currently does not justify the use of this approach for other PFAS.

- Recommended Screening Approach:

$$\frac{[PFOA]}{SSV_{PFOA}} + \frac{[PFOS]}{SSV_{PFOS}} \leq 1$$

  Where:
  - [PFOS] and [PFOA] are the measured soil concentrations, and
  - SSV_{PFOA} and SSV_{PFOS} are the soil screening values.

- In order to ensure that the Soil Screening Values are protective of all contaminant media transfer pathways, the final Soil Screening Value is set at the lowest value of the applicable Soil Screening Values calculated for each pathway considered as per the 2006 CCME Protocol for the Derivation of Soil Quality Guidelines.
- Industrial land use SSVs are based on the off-site migration check value, which protects more sensitive lands from contamination due to industrial sites.
- The Soil Screening Value for the protection of potable groundwater could not be calculated due to insufficient data. Concerns about PFAS in groundwater used as drinking water should be addressed on a site specific basis.
- The Soil Screening Value check value for consumption of produce, meat and milk could not be calculated due to insufficient data. Concerns regarding consumption of foods and PFAS should be addressed on a site specific basis.
- Since PFAS are essentially non-volatile, the inhalation of indoor air check was not calculated.

IV. Environmental Quality Guidelines for PFOS

A. Federal Environmental Quality Guidelines for Water, Tissues, and Soil

Federal Environmental Quality Guidelines (FEQGs) are benchmarks for the quality of the ambient environment. They represent a voluntary, unless otherwise prescribed, target for acceptable environmental quality. FEQGs are developed under the federal Minister of the Environment under the Canadian Environmental Protection Act, 1999.

The draft FEQGs for PFOS presented in **Tables 3 and 4** include a Federal Water Quality Guideline (FWQG), a Federal Fish Tissue Guideline (FFTG) for the protection of aquatic life, Federal Wildlife Dietary Guidelines (FWiDGs) for the protection of mammalian and avian consumers of aquatic biota, and a Federal Tissue Guideline describing the acceptable contaminant levels in bird eggs (FTG-BE), as well as Federal Soil Quality Guidelines (FSQGs) for four land uses. Supporting information for these values is provided in Appendix I. No FEQGs for this substance have been developed for sediment at this time.

The draft FEQG for water quality was derived from a species sensitivity distribution (SSD) curve based on long-term toxicity data from two amphibian, four fish, five invertebrate and eight plant species. This value is meant to represent the concentration at which one would expect only a very low likelihood of adverse effects on freshwater aquatic life. As PFOS is known to bioaccumulate, the draft FEQG for fish tissue intends to protect freshwater and marine fish from direct adverse effects from bioaccumulation. Protection for mammalian and avian species that consume aquatic biota is represented in FWiDGs. FWiDGs are based on laboratory toxicity data and associated critical toxicity values (CTVs). For PFOS, this included nine studies for the development of mammalian values and three for avian species. The FEQG for bird eggs is the whole egg concentration meant to be protective of the developing bird, and was calculated from data on two avian wildlife species in which egg exposure was via maternal transfer.

Table 3. Draft Federal Environmental Quality Guidelines (FEQG) for Perfluooctane Sulfonate (PFOS) for the protection of aquatic life, wildlife that consume aquatic life, and developing birds (ECCC 2017)

PFAS acronym	Draft Federal Environmental Quality Guidelines (FEQG)					
	FWQG	FFTG	FWiDGs		FTG-BE	
	Water (µg/L)	Fish Tissue (mg/kg ww)	Wildlife Diet (µg/kg ww food)		Bird Egg (µg/g ww)	Sediment
			Mammalian	Avian		
PFOS	6.8	8.3	4.6	8.2	1.9	No recommended guideline

Draft Federal Soil Quality Guidelines (FSQGs) for PFOS are listed in **Table 4**. For additional values for soil contact, soil ingestion, livestock, and protection of freshwater life, refer to Appendix I.

Soil quality guidelines for commercial and industrial sites consider ecological receptors exposed to on-site soil. However, wind and water erosion of soil and subsequent deposition can transfer contaminated soil from one site to another. The Soil Quality Guidelines (SQG_{OM-E}) pathway (found in Appendix I) addresses the movement of soil from a commercial or industrial site to an adjacent, more sensitive site (e.g. agricultural property). Given the uncertainties surrounding the model used to generate the SQG_{OM-E}, it is considered to be a check mechanism and professional judgement should be used to determine whether the soil quality guideline should be modified by this pathway (CCME 2006).

Table 4. Draft Federal Soil Quality Guidelines (FSQG) for Perfluorooctane Sulfonate (PFOS) (ECCC 2017)

PFAS acronym	Federal Soil Quality Guideline (FSQG) (mg/kg)			
	Agricultural	Residential/ Parkland	Commercial	Industrial
PFOS	0.01	0.01	0.14 (coarse soil) 0.21 (fine soil)	0.14 (coarse soil) 0.21 (fine soil)

B. Canadian Groundwater Quality Guideline (CCME 2017, draft for review)

The draft Federal Groundwater Quality Guidelines (FGWQG; ECCC 2017) contained an error, which was subsequently transferred into Version 1.4 (January 2018) of the *Interim Advice to Federal Custodian Departments for the Management of Federal Contaminated Sites Containing Perfluorooctane Sulfonate (PFOS) and other Per- and Polyfluoroalkyl Substances (PFAS)*. The error represents an order of magnitude difference for the groundwater guidelines.

As presented in Table 5, the FCSAP Secretariat recommends the value of **6.8 µg/L (i.e. 0.0068 mg/L)** as the groundwater guideline for PFOS in coarse-grained and fine-grained soil, for consideration of ecological receptors (i.e. freshwater aquatic life and soil organisms). The Groundwater Quality Guideline is the lowest of the pathway–specific guidelines and considers other management factors such as substance solubility, analytical detection limits and background concentrations. The value of 0.0068 mg/L was taken from the review draft of the CCME (2017, draft for review) *Scientific Criteria Document for Canadian Soil and Groundwater Quality Guidelines for the Protection of Environmental and Human Health: Perfluorooctane sulfonate (PFOS)*, which was released to the Soil Quality Guidelines Task Group for review. An excerpt from this document, with additional information on the groundwater quality guidelines for PFOS considering ecological receptors, is included as Appendix II.

Table 5. Draft Canadian Groundwater Quality Guidelines for Perfluorooctane Sulfonate (PFOS), Considering Ecological Receptors (CCME 2017, draft for review)

PFAS Acronym	Soil Type	
	Coarse Soil	Fine Soil
PFOS	6.8 µg/L	6.8 µg/L

V. Remediation and Risk Management Approaches

PFAS were designed to withstand harsh conditions such as open flames and/or strong acids and bases. This in turn makes PFAS not only stable in the environment but also very resistant to most conventional treatment technologies. PFAS molecules contain strong carbon-fluorine bonds that cannot be easily broken, and, as a result, most conventional chemical and biological degradation methods have been reported ineffective (Król *et al.* 2012; Liou *et al.* 2010; U.S. EPA 2012; Vecitis *et al.* 2009; Yao *et al.* 2013). PFAS should therefore either be stabilized, contained, or destroyed thermally (e.g., via incineration).

A subset of existing and effective remedial and risk management approaches typically applied to volatile organic compounds (VOCs) are most relevant for PFAS remediation, with the added challenge and cost of either destroying or containing the more resilient PFAS from the impacted liquid or solid waste that is removed from the subsurface. These approaches generally include:

- Physical removal of impacted solid media (e.g. excavation and on- or off-site disposal, with or without treatment)
- In-situ mechanical extraction of groundwater with ex-situ treatment (e.g. pump-and-treat, hydraulic containment, soil flushing, granular activated carbon (GAC) water treatment)
- In-situ chemical oxidation (e.g. thermally or chemically activated persulfate)
- In-situ stabilization (e.g. large-diameter auger soil mixing, solidification, soil amendments)
- Point-of-use water treatment (e.g. GAC, reverse osmosis (RO))

In-situ thermal desorption enhancements may be of benefit in cases of co-contamination with petroleum hydrocarbons (PHCs) or other organic carbon contaminants. Trial applications of the above remedial approaches to PFAS-impacted sites are on-going in the US and elsewhere in the world (DiGuiseppi 2016; Government of Western Australia 2016; Magnus 2015; Suthersan 2016). Remedial approaches that are NOT considered effective for PFAS include the following:

- In-situ biodegradation (PFAS are not readily biodegradable)
- Soil vapour extraction (PFAS are not volatile)
- Monitored natural attenuation (PFAS are persistent)

Similar to sites affected by other contaminants, the choice of a treatment approach is site-specific and depends on the concentrations and physical properties of contaminants of concern, background levels of other organic and inorganic substances (which can of benefit to PFAS remediation, or not), hydrogeological conditions, and other factors. As with any in-situ remedial approach, the driving factor for successful remediation is most often overcoming the inherent heterogeneity of the subsurface.

Once removed from the subsurface, PFAS can be physically removed from contaminated water using adsorption on GAC or using RO membrane filtration (Atkinson *et al.* 2008; Hansen *et al.* 2010; Schröder *et al.* 2010; Tang *et al.* 2006; Yao *et al.* 2014). Both methods have been shown to reduce the residual PFOS levels to below 0.2 µg/L, and in one case below the limit of quantification (0.5 ng/L) (Takagi *et al.* 2011). One possible PFAS-specific limitation with GAC treatment is the faster breakthrough of the short-chain PFAS (Appleman *et al.* 2014). Other physical removal methods based on volatilization of contaminants are ineffective, because PFOS has very low vapour pressures (Vecitis *et al.* 2009).

Most of the published information on PFOS treatment relates to contaminated water, with very limited data on the treatment of soil (Yao *et al.* 2015). In one site-remediation case study, PFOS was removed from soil using in-situ vacuum-enhanced multi-phase extraction, along with groundwater and hydrocarbons. The extracted stream was treated to first remove hydrocarbons using oil-water separation, and to then remove PFOS using GAC adsorption (Paterson *et al.* 2008). One disadvantage of physical removal is generation of the toxic residue (spent GAC or RO concentrate), which must then be handled appropriately. Incineration of the residue is possible but requires temperatures in excess of 1,000˚C to destroy PFOS (Vecitis *et al.* 2009).

There have been significant international research efforts recently to address the challenges of PFAS treatment. For example, alternative technologies have been studied that included thermally induced reduction, and photochemical and activated persulfate oxidation (Chen *et al.* 2006; Park *et al.* 2009; Ross 2012; Vecitis *et al.* 2009; Yao *et al.* 2016). For example, a high PFOS removal efficiency (97%) was observed for both groundwater and soil/tap water mixture using the persulfate oxidation method (Yao *et al.* 2016). Sonochemical degradation showed promise in reducing the half-life of PFOS from more than 40 years in water with no treatment to between 20 and 63 minutes when treated. Research has been conducted to identify and evaluate alternative adsorbents that can be more effective and/or less costly than GAC (Chen *et al.* 2011; Deng *et al.* 2010).

PFOS and other PFAS may not be the only contaminants at a site; other compounds such as PHCs and glycols may also be present. This may in turn require more than one treatment step. In some cases, previous remediation activities at impacted sites may have addressed some contaminants but did not effectively deal with PFAS. Co-occurrence of PHC and PFAS contamination is relatively frequent at sites with known or potential PFAS impacts. Sites impacted by PHCs may have been remediated without consideration for the presence of PFAS. These circumstances could have resulted in the inadvertent relocation of PFAS-impacted media, such as the relocation of soils that had undergone bio-treatment for PHC contamination.

Further studies of innovative methods and combined treatment processes are needed to assess their technical and economic feasibility. The available information on economic feasibility is currently very limited. Reasonable estimates of liability for PFAS-affected sites can be implemented by assuming relevant VOC remediation and/or risk management approaches as proxies, with additional costs to be potentially included for the high-temperature thermal treatment or regeneration of PFAS-laden treatment media, such as GAC used in groundwater treatment. Although there are currently no regulatory restrictions in Canada for landfilling PFAS-impacted media, their eventual fate in landfill leachate and their potential to re-enter groundwater due to insufficient or inadequate treatment of the leachate when disposed of in a non-specially engineered landfill, may justify accounting for the complete destruction of PFAS in the impacted media. Since the majority of research was performed at bench-scale and primarily focusing on PFOS and PFOA. Evaluation of the effectiveness of a specific method should take into account a wider range of PFAS including short-chain compounds and include field demonstration.

VI. References

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Appendix I: Excerpt from ECCC (February 2017) *Draft Federal Environmental Quality Guidelines for Perfluorooctane Sulfonate (PFOS)*, excluding groundwater quality guidelines

Federal Environmental Quality Guidelines (FEQGs) provide benchmarks for the quality of the ambient environment. Where the FEQG is met there is low likelihood of adverse effects on the protected use (e.g., to aquatic life or the wildlife that may consume it). They are based on the toxicological effects or hazard of specific substances or groups of substances and do not take into account analytical capability or socioeconomic factors. FEQGs serve three functions: first, they can be an aid to prevent pollution by providing targets for acceptable environmental quality; second, they can assist in evaluating the significance of concentrations of chemical substances currently found in the environment (monitoring of water, sediment, and biological tissue); and third, they can serve as performance measures of the success of risk management activities. The use of FEQGs is voluntary unless prescribed in permits or other regulatory tools. Thus FEQGs, apply to the ambient environment. They are not effluent limits or "never-to-be-exceeded" values but may be used to derive them. The development of FEQGs is the responsibility of the federal Minister of the Environment under the *Canadian Environmental Protection Act* (CEPA 1999). The intent is to develop FEQGs as an adjunct to the risk assessment/risk management of priority chemicals identified in the Chemicals Management Plan (CMP) or other federal initiatives. This factsheet provides the Federal Water Quality Guideline (FWQG) (Figure 1), the Federal Fish Tissue Guideline (FFTG) for the protection of aquatic life, the Federal Wildlife Diet Guidelines (FWiDGs) for the protection of mammalian and avian consumers of aquatic biota, and the Federal Tissue Guideline describing the acceptable contaminant levels in bird eggs (FTG-BE) for perfluorooctane sulfonate (PFOS) (Table 1). This factsheet also provides Federal Soil Quality Guidelines for Agricultural, Residential/Parkland, Commercial and Industrial land uses (Table 2), and Federal Groundwater Quality Guidelines (FQWQG) (Table 3). No FEQGs for this substance have been developed for sediment at this time. Other environmental quality guidelines were reviewed but not further discussed due to methodological differences (MPCA 2007, Giesy *et al.* 2010).

Introduction

Perfluorooctane sulfonate (PFOS) belongs to a larger group of fluorochemicals called perfluorinated alkyl compounds (Kissa 1994). This classification indicates that the main carbon chain of the compound is completely saturated with fluorine, involving highly stable C-F bonds. While PFOS can exist in its anionic form ($C_8F_{17}SO_3^{-}$), it also exists as an acid (CAS No. 1763-23-1), potassium salt (CAS No. 2795-39-3), ammonium salt (CAS No. 29081-56-9), diethanolamine salt (CAS No. 70225-14-8) and lithium salt (CAS No. 29457-72-5). PFOS is not found naturally in the environment, however, it has been manufactured since the 1950s (Lehmler 2005). Based on the Screening Assessment Report (SAR), Environment Canada (2006) concluded that PFOS, its salts and its precursors (compounds containing the following groups: $C_8F1_7SO_2$, $C_8F1_7SO_3$ or $C_8F1_7SO_2N$) were entering the environment in a quantity that has, or may have, an immediate or long-term harmful effect on the environment and biological diversity. PFOS and its salts and its precursors meet the definition of toxic and PFOS and its salts (but not precursors) are also persistent according to the Persistence and Bioaccumulation Regulations (SOR/2000-107) under CEPA 1999 and are also considered bioaccumulative, despite not strictly meeting the regulatory criteria.

Table 1. Federal Environmental Quality Guidelines for Perfluorooctane Sulfonate (PFOS).

Water (µg/L)	Fish Tissue (mg/kg ww)	Wildlife Diet (µg/kg ww food)		Bird Egg (µg/g ww)	Sediment
		Mammalian	Avian		
6.8	8.3	4.6	8.2	1.9	No recommended guideline

Table 2. Federal Soil Quality Guidelines for Perfluorooctane Sulfonate (PFOS). See footnote 1 for explanation.

Pathway	Agricultural	Residential/ Parkland	Commercial	Industrial
Final Proposed Federal Soil Quality Guideline (FSQG)	**0.01 mg/kg**	**0.01 mg/kg**	**0.14 mg/kg (coarse soil) 0.21 mg/kg (fine soil)**	**0.14 mg/kg (coarse soil) 0.21 mg/kg (fine soil)**
Soil Contact ($FSQG_{SC}$)	11 mg/kg	11 mg/kg	61 mg/kg	61 mg/kg
Soil Ingestion ($FSQG_{1C}$)	2.2 mg/kg soil	2.2 mg/kg soil	NR	NR
Soil Ingestion ($FSQGC_{2C}$)	0.01 mg/kg soil	0.01 mg/kg soil	NR	NR
Soil Ingestion ($FSQG_{3C}$)	0.6 mg/kg soil	0.6 mg/kg soil	NR	NR
Agricultural (Livestock watering-$FSQG_{LW}$)	12 mg/kg coarse soil 9 mg/kg fine soil	NR	NR	NR
Soil Quality Guideline to Protect Freshwater Life ($FSQG_{FL}$) [1]	0.14 mg/kg (coarse soil) 0.21 mg/kg (fine soil)			
Check Mechanisms				
Nutrient and Energy Cycling	NC	NC	NC	NC
Offsite migration (SQG_{OM-E}) [2]	NR	NR	0.2 mg/kg	0.2 mg/kg

Notes:
NC = Not calculated due to lack of data
NR = Not required
1C = Primary consumer, 2C = Secondary consumer, 3C = Tertiary consumer; FL = Freshwater life; LW = Livestock watering;

OM-E = Off-site migration- environmental.

[1] $FSQG_{FL}$ is the concentration in soil that is expected to protect against potential impacts on freshwater life from PFOS originating in soil that may enter the groundwater and subsequently discharge to a surface water body. This pathway may be applicable under any land use category, where a surface water body sustaining aquatic life is present (i.e., within 10 kilometres of the site). Where the distance to the nearest surface water body is greater than 10 kilometres, application of the pathway should be evaluated on a case-by-case basis by considering the site-specific conditions.

[2] Soil quality guidelines for commercial and industrial sites consider receptors exposed to on-site soil. However, wind and water erosion of soil and subsequent deposition can transfer contaminated soil from one site to another. The SQG_{OM-E} pathway addresses the movement of soil from a commercial or industrial site to an adjacent, more sensitive site (e.g. agricultural property). Given the uncertainties surrounding the model used to generate the SQG_{OM-E}, it is considered to be a check mechanism and professional judgement should be used to determine whether the soil quality guideline should be modified by this pathway (CCME 2006).

Uses

Between 1997 and 2000, Canada imported approximately 600 tonnes of perfluorinated alkyl compounds. PFOS and its precursors, (the precursors contribute to overall loading in the environment), accounted for 43% of these compounds, while PFOS alone accounted for <2% (Environment Canada 2001). The uses of PFOS and PFOS-related compounds can be categorized into three main categories: surface treatment of apparel and home furnishings, paper protection, and performance chemicals. In the past, PFOS surface treatments were used in industrial manufacturing, in such settings as textile mills, leather tanneries, fibre production lines and carpet manufacturing plants (OECD 2002). Food and non-food industries used PFOS and PFOS-related chemicals in paper applications including food containers, food wrappers, folding cartons and masking papers (OECD 2002). As performance chemicals, PFOS-related chemicals were used in a variety of ways, for example, mining and oil well surfactants, photographic film, hydraulic fuel additives, electronics chemicals, denture cleaners and shampoos. Salts of PFOS were also used specifically as acid mist suppressants for metal plating and electronic etching baths, floor polishes, alkaline cleaners, insecticide in bait stations and as fire-fighting foams (3M Company 2000). By 2002, the primary producer phased out the production of PFOS chemicals and products containing PFOS.

Ambient concentrations

Concentrations of PFOS detected in the environment range from a few pg/m^3 in air (Kim and Kannan 2007) to high µg/kg levels in wildlife (Giesy and Kannan 2001, 2002; Kannan *et al.* 2001a,b, 2002a,b, 2005; Tao *et al.* 2006). PFOS is the most commonly found perfluorinated compound (PFC) in the tissues of wildlife, accumulating primarily in the blood and liver (Giesy and Kannan 2001). Kannan *et al.* (2006) reported that PFC concentrations in polar bears are the highest in any species to date. Maximum levels of PFOS in liver of Canadian Arctic biota have been reported for mink (20 µg/kg), seal (37 µg/kg), brook trout (50 µg/kg), fox (1400 µg/kg) (Martin *et al.* 2004) and polar bear (3770 µg/kg) (Smithwick *et al.* 2005). Average PFOS concentrations in suspended sediments from the Niagara River at Niagara-on-the-Lake, collected annually over a 22 year period (1980-2002) increased from <400 pg/g in the early 1980s to more than 1000 pg/g in 2002 (Lucacui *et al.* 2005).

PFOS precursors measured in the air of Toronto identified average concentrations of N-MeFOSE alcohol of 101 pg/m^3 and N-EtFOSE alcohol (see list of abbreviations below) of 205 pg/m^3 (Martin *et al.* 2002). Boulanger *et al.* (2004) reported mean surface water (4 m depth) concentrations of 31 (sd = 6.9) ng/L for Lake Erie and 54 (sd = 18) ng/L for Lake Ontario. More recent monitoring data (Environment Canada 2013) reported PFOS concentrations from locations across Canada. For each of these compartments, the maximum concentrations were: surface water 10 ng/L, fish tissue, 90 ng/g (whole body, wet-weight), sediment, 10 ng/g (dry-weight), air 18 pg/m^3, herring gull eggs (pooled) 626 ng/g (wet-weight) and European starling eggs 703 ng/g (wet weight), respectively. The highest concentrations were most often associated with areas of urbanization.

Fate, behaviour and partitioning

Understanding of the environmental fate of PFOS continues to improve with advances both in experimental data and predictive approaches, although the compounds' physical/chemical properties, notably its hydrophobic/oleophobic nature, continue to make this challenging (Rayne and Forest 2009a, Jing *et al.* 2009). Due to the high surface-active (surfactant) properties octanol/water (K_{ow}) partition coefficient cannot be measured simply (OECD 2002), although an indirect measure using ion-transfer cyclic voltammetry has determined a log P of 2.45 indicating lipophilicity (Jing *et al.* 2009). Also sediment organic carbon – water partition coefficients (K_{oc}) for PFCs (Rayne and Forest 2009b) indicate that although longer unbranched sulfonates and carboxylates tended to partition to organic matter, there was high variability in partitioning on a congener- and isomer-specific basis. PFOS is persistent in the environment and the strength of the carbon-fluorine bond renders it resistant to hydrolysis, photolysis and biodegradation. It is therefore considered to be an environmentally stable compound (Environment Canada 2006). PFOS appears to be the end stage metabolite or ultimate degradation product of several fluorochemicals produced using perfluorooctane sulphonyl fluoride (Giesy and Kannan 2002). Thus, PFOS precursors contribute to the overall loading of PFOS in the environment.

PFOS is expected to behave differently than traditional hydrophobic pollutants, as it contains both hydrophobic and hydrophilic functional groups. The potassium salt of PFOS has a solubility of approximately 680 mg/L in pure water, 370 mg/L in fresh water, and 12.4 mg/L in sea water (OECD 2002). As a strong acid, PFOS will completely dissociate to ionic forms in neutral water (Jones *et al.* 2003). In addition, PFOS is not expected to volatilize based on its vapour pressure and predicted Henry's Law constant (OECD 2002). A number of studies report significant sorption of PFOS to sediments (Higgins and Luthy 2006; Nakata *et al.* 2006) while others do not (Hansen *et al.* 2002; Senthilkumar *et al.* 2007). It has therefore been suggested that the sorption and desorption behaviour of PFOS may be greatly affected by different sorption conditions, such as the physiochemical characteristics of the sorbent and the environmental conditions of the aqueous system (Liu *et al.* 2001). You *et al.* (2010) inferred that PFOS would be largely removed from the water column with an increase in salinity or pH, and get trapped in the sediments with little bioavailability. In addition, these researchers found correlations between distribution coefficients (K_d) and the fraction of organic carbon, demonstrating that despite its surfactant properties hydrophobic partitioning is important to the sorption of PFOS to soil and sediments.

Bioconcentration factors (BCF – water exposures only) for PFOS ranged from 31.6 to 3614 L/kg for whole body measurements, with an average value of 779 L/kg. The highest value came from a laboratory study performed on bluegill sunfish (*Lepomis macrochirus*) (Drottar *et al.* 2002). BCFs ranged from 484 to 5400 L/kg in specific tissues, with an average value of 2660 L/kg. The maximum value of 5400 L/kg was calculated for rainbow trout (*Oncorhynchus mykiss*) liver (Martin *et al.* 2003). Bioaccumulation factors (BAF water and dietary exposure, or field measured) for whole body ranged from 113 to 11 150 L/kg and the maximum value of 11 150 L/kg was observed in brown mussel (*Perna perna*) (Quinete *et al.* 2009). Tissue-specific BAFs (liver) ranged from 460 to 275 000 L/kg; the highest value was for livers of tucuxi dolphin (*Sotalia guianensis*) (Quinete *et al.* 2009). Based on data presented in SAR (Environment Canada 2006), a geometric mean BAF value of 1614 L/kg was derived for aquatic organisms. The value was based on data for six fish and four invertebrate species. For freshwater organisms, whole body biomagnification factors (BMF) ranged from 0.17 to 7.5 with the mean value of 2.6. The maximum BMF of 7.5 was observed by Houde *et al.* (2008) and represents the trophic transfer from an invertebrate (*Diporeia hoyi*) to the forage fish, slimy sculpin (*Cottus cognatus*). Environment Canada (2006) therefore concluded that PFOS is bioaccumulative even though its surfactant properties resulted in it not meeting the strict definition in the Persistence and Bioaccumulation Regulations (SOR/2000-107).

BCFs for PFOS in 16 terrestrial plants species (dry weight basis) ranged from 0.003 to 1.6, with a geometric mean value of 0.35. The highest value came from a study of ryegrass (Brignole *et al.* 2003). BCFs (dry weight basis) in the terrestrial invertebrate, *Eisenia fetida*, ranged from 2.6 to 34.2, with a geometric mean value of 10.9 (Stubberud 2006). Biomagnification in a lichen-caribou-wolf food web indicated biomagnification was tissue specific ranging from a low of 0.8 for wolf $_{liver}$/caribou $_{liver}$ to a high of 9.1 caribou $_{whole}$/vegetation (Müller et al 2011). For the two caribou herds studied, the mean BMF from soil to caribou was 2.97. Small sample size studies with sheep (Kowaleczyk et al 2012) and cows (Vestegren *et al.* 2013) also indicate bioaccumulation of PFOS from diet (food and water). Bioconcentration and bioaccumulation studies indicate that FEQGs for soil for agricultural and residential/parkland uses should consider not only direct soil contact exposure to plants and invertebrates, but also exposure to primary, secondary and tertiary-level food web organisms.

Mode of Action

While the modes of action of PFOS are not entirely understood, they certainly seem diverse. Suggested modes of action include activation of the nuclear peroxisome proliferator activated receptor-alpha (PPAR-α) (Berthiaume and Wallace 2002; Rosen *et al.* 2010). These receptors alter many genes with a broad spectrum of action but include fatty acid metabolism and transport, cholesterol transport (Feige *et al.* 2006) glucose metabolism, inflammation response and development. In contrast, toxic effects have been demonstrated that do not involve PPAR mechanisms (O'Brien *et al.* 2009). PFOS is also believed to interfere at the mitochondrial level through the uncoupling of oxidative phosphorylation. This uncoupling causes a reduction in the production of ATP, thereby reducing energy stores. Other modes of action that have been hypothesized include inflammation-independent leakage of liver cell membranes in fish, which leads to cell necrosis (Hoff *et al.* 2003); an interference with the homeostasis of DNA metabolism (Hoff *et al.* 2003); inhibition of glycogen synthesis; increased glycogen breakdown (Hagenaars *et al.* 2008); and, the inhibition of intercellular communication processes involving gap junctions (Hu *et al.* 2002). Altered neurochemistry from a single dose of PFOS to neonatal mice resulted in developmental neurotoxicity (Johansson *et al.* 2008). Finally, endocrine modulation effects on the estrogen receptor and thyroid receptor occurred in the zebrafish (Du *et al.* 2013).

Aquatic Toxicity

Aquatic toxicity values for chronic (long-term) exposures to PFOS (87-99% active ingredient) ranged from 10 to 53000 µg/L, with sensitivities overlapping among taxa (Table 4). At 10 µg/L there were no effects on damselfly survival during a 320-d exposure whereas medaka showed reduced growth in a 14-d exposure (Table 4). Plant data were most diverse. The most sensitive plant species was watermilfoil (*Myriophyllum sibiricum*) with a 42-d EC10 for reduced growth of 100 µg/L. Data were found for two amphibians; there were no effects on survival of African clawed frog (*Xenopus laevis*) at 100 ug/L whereas the 60-d maximum acceptable toxicant concentration for development in leopard frog (*Rana pipiens*) was 1732 µg/L, respectively. There were no data for salmonid species.

Wildlife Toxicity

PFOS is hepatotoxic and the effects include increased liver weights, observed in mallards, northern bobwhite and laboratory rats (Gallagher *et al.* 2003a; Luebker *et al.* 2005; York 1999), as well as hepatocellular adenomas (Environment Canada 2006) and peroxisome proliferation (Luebker *et al.* 2005). McNabb *et al.* (2005) studied the effects of PFOS on the thyroid function in northern bobwhite. After seven days of exposure to a dose of 5 mg/kg body weight (bw), plasma thyroid hormones decreased, indicating organism-level hypothyroidism. When cynomolgus monkeys were administered PFOS (0.03, 0.15, 0.75 mg/kg bw.day for 26 weeks), they had reduced high density lipoprotein and cholesterol (Thomford 2000). Other previously-observed toxic effects of PFOS have included a reduction in testicular size and altered spermatogenesis in both quails and mallards, reduced survival of quail chicks exposed only *in ovo* (Gallagher *et al.* 2003a,b; Newsted *et al.* 2007), and a reduced dam body mass in rats (York 1999). Thresholds for effects are similar in mammals and birds (Newsted *et al.* 2007).

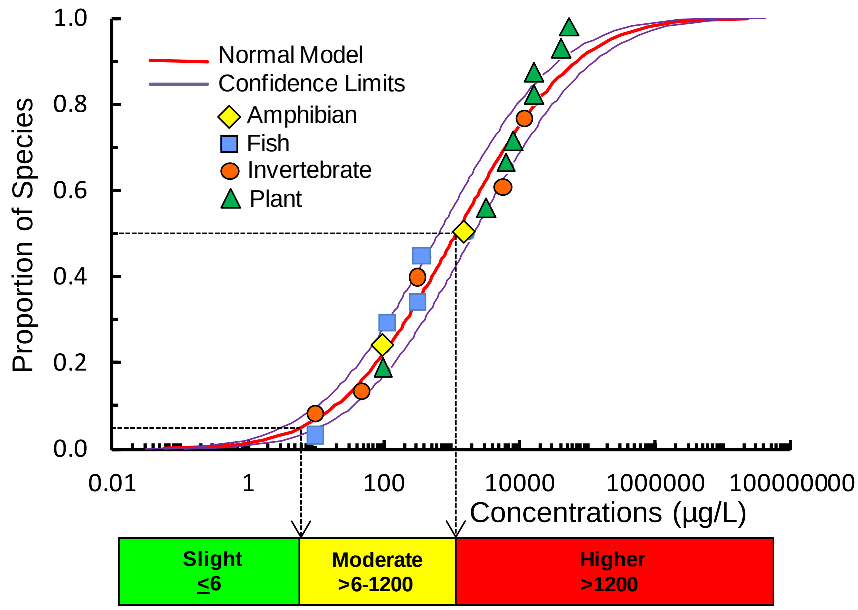
Terrestrial Toxicity

Terrestrial toxicity values for direct soil exposure to 8 plant species (alfalfa (*Medicago sativa*), ryegrass (*Lolium perenne*), soybean (*Glycine max*), lettuce (*Lactuca sativa*), flax (*Linum usitatissimum*), tomato (*Lycopersicon esculentum*), onion (*Allium cepa*) and pak choi (*Brassica chinensis)* (Brignole *et al.* 2003, Zhao *et al.* 2011)) and 3 invertebrate species, *Eisenia fetida*, *Folsomia candida* and *Oppia nitens*(Stubberud 2006, Joung *et al.* 2010 and Environment Canada 2015a) to PFOS ranged from 3.9 to 1000 mg/kg soil, with sensitivities overlapping between plants and invertebrates. At 3.9 mg/kg there was 23% reduction in height in lettuce (*Latuca sativa*) during 21-d exposure whereas soybean (*Glycine max*) showed no effect on emergence or mortality at 1000 mg/kg with a 21-d exposure (Brignole *et al.* 2003). EC_{25} and IC_{25} data were found for 7 plant species and 3 invertebrate species ranging from 3.9 to 393 mg/kg (Table 5).

Federal Environmental Quality Guidelines Derivation

Federal Water Quality Guidelines

The Federal Water Quality Guideline (FWQG) developed here identifies a benchmark for aquatic ecosystems that are intended to protect all forms of aquatic life for indefinite exposure periods. A species sensitivity distribution (SSD) curve was developed using the long-term toxicity data (Table 4) for two amphibian, four fish, five invertebrate and eight plant species (Figure 1 and Table 2). Each species for which appropriate toxicity data were available was ranked according to sensitivity, and its position on the SSD was determined. This guideline is only applicable to freshwater aquatic life first, because there were no marine data, and second, because PFOS is expected to behave differently due to reduced solubility in marine water, as discussed. A notable data gap was the absence of salmonids from the data set. Fish tissue guidelines or wildlife dietary guidelines (see below) should be used in conjunction with water quality guidelines where a substance may bioaccumulate in higher trophic levels.



Probability of Adverse Effect to Aquatic Life

Figure 1. Species sensitivity distribution (SSD) for PFOS for development of a water quality guideline for the protection of aquatic life.

Table 4. Chronic Aquatic Toxicity Data Used for Developing the Federal Water Quality Guideline for PFOS. (abbreviations for endpoints appended following the reference section).

◇ =Amphibian; ■ = Fish; ● = Invertebrate; ▲ = Plant

Species	Group	Endpoint	Concentration (µg/L)	Reference
Japanese medaka (*Oryzias latipes*)	■	14-d LOEC (growth)	10	Ji *et al.* 2008
Damselfly (*Enallagma cyathigerum*)	●	320-d NOEC (survival)	10	Bots 2010

Aquatic midge (*Chironomus tentans*)	●	10-d NOEC (growth, survival)	49	MacDonald *et al.* 2004
Watermilfoil (*Myriophyllum sibiricum*)	▲	42-d EC10 (growth)	100	Hanson *et al.* 2005
African clawed frog (*Xenopus laevis)*	◆	67-day NOEC (survival)	100	Cheng *et al.* 2011
Zebrafish (*Danio rerio*)	■	40-d MATC (growth)	112	Du *et al.* 2009
Bluegill sunfish (*Lepomis macrochirus*)	■	35-d MATC (survival)	300	Drottar *et al.* 2002
Water flea (*Moina macrocopa*)	●	7-d LOEC (reproduction)	313	Ji *et al.* 2008
Fathead minnow (*Pimephales promelas*)	■	42-d MATC (survival)	400	Drottar and Krueger 2000a
Leopard frog (*Rana pipiens*)	◆	60-d MATC (development)	1732	Ankley *et al.* 2004
Watermilfoil (*Myriophyllum spicatum*)	▲	28-d EC10 (dry weight)	3300	Hanson *et al.* 2005
Water flea (*Daphnia pulicaria*)	●	21-d EC10 (survival)	6000	Sanderson *et al.* 2004
Duckweed (*Lemna gibba*)	▲	7-d IC10 (wet weight)	6600	Boudreau *et al.* 2003
Green algae (*Chlorella vulgaris*)	▲	96-h IC10 (cell density)	8200	Boudreau *et al.* 2003
Water flea (*Daphnia magna*)	●	21-d EC10 (survival)[a]	12000	Boudreau *et al.* 2003 Sanderson *et al.* 2004
Green algae (*Selenastrum capricornutum*)	▲	96-h IC10 (cell density)[a]	16000	Boudreau *et al.* 2003 Drottar and Krueger 2000b
Diatom (*Navicula pelliculosa*)	▲	96-h MATC (growth)	16500	Sutherland and Krueger 2001
Blue-green algae *(Anabaena flos-aquae*)	▲	96-h IC10 (cell density)	42600	Desjardins *et al.* 2001
Green algae (*Scenedesmus obliquus*)	▲	72-h IC10 (growth)[a]	53000	Liu *et al.* 2008

[a]Effect concentration is the geometric mean of comparable endpoints

The Canadian Water Quality Guideline protocol (CCME 2007) was followed for developing the FWQG for PFOS, with the exception that no chronic salmonid data were available and three surrogate species were included. Several cumulative distribution functions were fit to the data using regression methods and the best model was selected based on consideration of goodness-of-fit. The log normal model provided the best fit for these data and the 5th percentile of the SSD plot is 6.0 μg/L, with lower and upper confidence limits of 3.3 and 11 μg/L, respectively (Figure 1).

Uncertainty (that which may be reduced through further investigation) is inherent in effects/hazard assessments and can influence the confidence in the outcome. Typically uncertainty focuses on such things as quality of the data, lab to field extrapolation, species sensitivity differences and endpoint extrapolation and is often accounted for by the use of safety or uncertainty factors. In this particular assessment, the freshwater quality guideline has a reasonably representative dataset although it did lack salmonid data.

The 5^{th} percentile of 6 μg/L, calculated from the SSD, is the Federal Water Quality Guideline for protection of freshwater organisms (Figure 1). No uncertainty factor was used here because the SSD is comprised mostly of "no effect" data (CCME 2007).The guideline represents the concentration at which one would expect only a very low likelihood of adverse effects on aquatic life. In addition to this guideline, two additional concentration ranges are provided for use in risk management. At concentrations between greater than the FWQG and the 50^{th} percentile of the SSD (i.e. >6 to 1200 μg/L) there is a moderate likelihood of adverse effects to aquatic life. Concentrations greater than the 50^{th} percentile (>1200 μg/L) have a higher likelihood of adverse effects. The "moderate" and "higher" benchmarks may be used in setting less protective interim targets for waters that are already degraded or where there may be socio-economic considerations that preclude the ability to meet the FWQG. This value is not designed to protect against possible bioaccumulation exposures of higher trophic levels. Instead, tissue residue concentrations are developed below.

Federal Fish Tissue Guideline

The Federal Fish Tissue Guideline (FFTG) is a benchmark for aquatic ecosystems that is intended to protect fish from the direct adverse effects of bioaccumulated contaminants. FFTGs supplement water quality guidelines in that they provide a different metric with which to assess potential adverse effects. FFTGs apply to both freshwater and marine fish, and specify the concentration of PFOS found in whole body fish tissue (wet weight) not expected to result in adverse effects to the fish themselves. The FFTG may not be appropriate to evaluate the impacts of PFOS found in other aquatic biota (amphibians, invertebrates or plants).

It is preferable to develop tissue guidelines from studies that relate tissue concentrations to toxic effects. A study with bluegill, designed to measure bioaccumulation also provided information on residues related to toxic effects (Drottar *et al.* 2002). Bluegill exposed to 0.086 mg/L PFOS for 62 days accumulated 81 mg/kg ww without significant effects on survival. In contrast, bluegill exposed to 0.87 mg/L experienced heavy mortality at tissue residues starting at 159±16 mg/kg ww ranging to 241±29 mg/kg ww on day 28, at which point mortality was nearly complete. Dividing the no effect value by a safety factor of 10 gives a FFTG of 8.1 mg/kg whole body wet weight.

This value is corroborated by using an equilibrium partitioning approach to estimate a whole body concentration from the federal water quality guideline and the degree to which fish accumulate PFOS either directly from water (bioconcentration factors) or via both food and water (bioaccumulation factors) Although PFOS accumulates in the liver, and is hepatotoxic, monitoring efforts have been directed at measuring the concentration of PFOS in the whole body of fish. Therefore, although liver BAF values were available for PFOS, the FFTG developed here is based on the whole-body accumulation of PFOS.

Accumulation factors, summarized in Environment Canada 2006, included lab and field studies with fish, invertebrates and algae from marine and fresh waters, and were reported on a wet-weight (ww) basis. The geometric mean values selected for the calculation were BCFs for bluegill sunfish (Drottar *et al.* 2002) and carp (Inoue et al 2012). BCF/BAF values for marine fish were generally higher, but were not considered.

The FFTG was developed as follows:

$$\text{FFTG} = (\text{FWQG})\ (\text{BAF}_{geomean}) = (6.0\ \mu g/L)\ (1378\ L/kg) = 8.3\ mg/kg\ ww$$

Therefore the FFTG is 8.3 mg/kg body weight.

There are several uncertainties inherent in this guideline. The direct correlation between tissue residue and toxic effect was only done in one fish species, using two toxicant concentrations but in other respects, of high quality and long duration. Uncertainties also include those in the FWQG in the section above, plus those involved in the BCF/BAF estimation (point estimates of both the tissue and waterborne concentrations). There were few data for freshwater fish.

Federal Wildlife Dietary Guidelines

The Federal Wildlife Dietary Guidelines (FWiDGs) are intended to protect mammalian and avian consumers of aquatic biota. These are benchmarks for concentrations of toxic substances in aquatic biota (whole body, wet-weight) that are consumed by terrestrial and semi-aquatic wildlife. The FWiDGs may not be appropriate to extrapolate the impacts of PFOS to terrestrial consumers other than mammalian and avian species (e.g., reptiles).

FWiDGs for PFOS were developed using laboratory-based toxicity data and associated critical toxicity values (CTVs). The CTV of a study was the lowest treatment dose at which adverse effects were observed amongst organisms as a result of PFOS consumption. CTVs were divided by an uncertainty factor (UF) of 100 to produce a set of tolerable daily intake (TDI) values. The UF of 100 was chosen to account for extrapolation from laboratory to field conditions, and for extrapolation from the observed effects level to a no-effect level. Finally, reference concentrations were calculated for a number of species based on the minimum mammalian TDI (for mammals) and avian TDI (for birds), and the food intake to body weight ratio (FI:BW) specific to that species.

Mammalian: Nine studies were evaluated for four different species, cynomolgus monkeys (*Macaca fasicularis*), rabbits (*Oryctolagus cuniculus*), mice and rats. TDIs, calculated as the critical toxicity value divided by an uncertainty factor of 100, ranged from 1.1 to 112 µg/kg bw.d. The lowest TDI of 1.1 µg/kg bw.d reported for rats came from a two-year, chronic toxicity diet study (Covance Laboratories 2002). The mammalian FWiDG of 4.6 µg/kg food was calculated by dividing the minimum observed TDI of 1.1 µg/kg bw.d by the maximum mammalian FI:BW of 0.24 kg food/kg bw.d for American mink (CCME 1998).

Avian: Dietary PFOS toxicity to three avian species, mallard (*Anas platyrhynchos*), northern bobwhite (quail) (*Colinus virginianus*) and Japanese quail (*Coturnix coturnix japonica*) were evaluated. For developing the avian FWiDG the selected CTV is the LOAEL dose rate in northern bobwhite of 772 µg/kg bw.d that resulted in reduced chick survival post exposure. By applying an UF of 100, a TDI of 7.7 µg/kg bw.d is produced and an avian FWiDG of 8.2 µg/kg food is calculated by dividing that TDI by the maximum avian FI:BW of 0.94 kg food/kg bw.d for Wilson's storm-petrel (CCME 1998). Given the long duration of both the avian and mammalian studies, the uncertainties relate primarily to lack of knowledge of interspecies sensitivity given the paucity of wildlife species in the data set. Therefore an uncertainty factor of 100 was selected (CCME 1998) for both the avian and mammalian dietary guidelines.

Federal Tissue Quality Guideline for Bird Egg (FTG-BE)

Laboratory studies provided egg toxicity data for three avian species: northern bobwhite, mallard and white leghorn chicken. For studies performed using mallard and quail as test subjects, the contaminant was administered via maternal transfer from the diet; in contrast, chicken studies administered PFOS via injection into the air cell of the egg.

The maternal transfer studies established a NOAEL of 53 µg PFOS/mL egg yolk in mallard; a LOAEL could not be determined. In quail, based on number of survivors as a percentage of eggs set, a LOAEL of 62 µg/mL egg yolk was established; the NOAEL in the pilot study with quail was 33 µg/mL yolk (Newsted *et al.* 2005).

Studies where PFOS was injected into the air cell of freshly-laid chicken eggs with subsequent incubation found that egg pipping (initial cracking of the egg by the chick during hatching) was reduced to about 67% at 5 µg/g PFOS whole egg compared with controls or with eggs injected with 0.1 µg/g whole egg (O'Brien *et al.* 2009). Peden-Adams *et al.* (2009) found no mortality in chicken eggs injected with 1, 2.5 or 5 µg/g egg and no effects on growth. They did however find significant tissue-level effects at all concentrations on development (brain asymmetry, significant only at the lowest concentration, no dose-response) and immune function (no dose response). The ecological significance of these effects is not known. A third study using PFOS injection into chicken eggs (Molina *et al.* 2006) was considered unacceptable (see O'Brien *et al.* 2009).

A field study compared reproductive success in tree swallows from a contaminated urban lake versus a reference lake (Custer *et al.* 2012). The authors concluded that PFOS concentrations above 0.15 µg/g egg were detrimental to hatching success, however, this study could not be considered in guideline development because of large variability in hatch success between the two field seasons, large variations in egg PFOS concentrations within clutches and concurrent exposure to other perfluorinated substances Nevertheless, the study should be borne in mind when interpreting PFOS residues in bird eggs.

The egg tissue residue guideline was developed by dividing the LOAEL for quail of 62 µg/mL yolk by a safety factor of 10 to give 6.2 µg/mL. This was subsequently converted to whole egg concentrations for easier comparison with archived whole egg tissue. Most PFOS is contained in the yolk (Newsted *et al.* 2007; Gebbink and Letcher 2012). Using yolk:albumin ratio of 3:7 (Gebbink and Letcher 2012), and assuming egg density of about 1, the final guideline is 1.9 µg/g whole egg.

Overall, the tests used two wildlife species. More importantly, egg exposure was via maternal transfer, a route of administration which is more natural than direct injection. Nevertheless there are few species studied and little replication.

Federal Soil Quality Guidelines (FSQG)

Federal soil quality guidelines were derived to protect key ecological function for four different land uses: agricultural, residential/parkland, commercial and industrial following "A Protocol for the Derivation of Environmental and Human Health Soil Quality Guidelines" (CCME 2006).

Given the physical and chemical properties of PFOS, the FEQGs for soil and groundwater were derived considering direct soil contact, the protection of primary, secondary and tertiary consumers exposed to PFOS via soil and food ingestion, the protection of freshwater life, the protection of livestock watering and irrigation water and the protection of more sensitive use sites (e.g., agricultural) from adjacent sites exposed via off-site migration (e.g., via wind erosion) (Environment Canada 2015b). The nutrient and energy cycling check was not derived because of lack of data. Details on data acceptability and guideline calculations for soil and groundwater are available in EC (2015b).

Soil contact

Laboratory studies provided toxicity data for 8 plant species (alfalfa, flax, lettuce, onion, potato, ryegrass, soybean tomato), and 3 invertebrate species (earthworm, springtail and mite) (Table 5). A total of 32 acceptable EC_{25} and IC_{25} endpoints were used in a species sensitivity distribution in which the 25^{th} percentile ($ESSD_{25}$) was 22.1 mg/kg soil (Figure 2). The soil contact value for Agricultural and Residential/Parkland is the threshold effects concentration (TEC) which is the $ESSD_{25}$/uncertainty factor = 22.1/2 = 11 mg/kg. An uncertainty factor of 2 was applied because of uncertainties associated with lab to field extrapolation. The soil contact value for Commercial and Industrial land uses is the Effects Concentration Low which is equal to the $ESSD_{50}$ (50^{th} percentile of the species sensitivity distribution) = 61 mg/kg.

Table 5: EC_{25}, IC_{25} and LC_{20} Data used for Species Sensitivity Distribution used to Derive the Soil Contact value for Agricultural, Residential/Parkland and Commercial and Industrial Land Uses for PFOS.

Common name	Exposure Duration (days)	Endpoint	Effect	Concentration (mg PFOS/ kg soil)	Magnitude of Effect (%)	Reference
Lettuce	21	LOEC	Height	3.91	23% reduction in height	Brignole *et al.* 2003
Ryegrass	21	IC25	Shoot weight	7.51	25	Brignole *et al.* 2003
Lettuce	21	IC25	Shoot weight	8.92	25	Brignole *et al.* 2003
Tomato	21	IC25	Shoot weight	11.7	25	Brignole *et al.* 2003
Earthworm	56	IC25	Avg weight per juvenile	12	25	Stubberud 2006
Onion	21	IC25	Shoot weight	12.9	25	Brignole *et al.* 2003
Soil mite	28	IC25	Number of juveniles	13	25	Environment Canada 2015

Tomato	21	IC25	Height	22.1	25	Brignole *et al.* 2003
Onion	21	IC25	Height	29.1	25	Brignole *et al.* 2003
Soil mite	28	IC25	Number of juveniles	33	25	Environment Canada 2015
Earthworm	56	LOEC	Total weight of juveniles	40		Stubberud 2006
Ryegrass	21	IC25	Height	46.3	25	Brignole *et al.* 2003
Earthworm	56	IC25	Number of juveniles	48	25	Stubberud 2006
Onion	21	EC25	Emergence	50.8	25	Brignole *et al.* 2003
Alfalfa	21	IC25	Shoot weight	53.3	25	Brignole *et al.* 2003
Springtail (soil inverte	28	IC25	Number of juveniles	61	25	Environment Canada 2015
Tomato	21	LOEC	Survival of emerged seedlings	62.5	27% reduction in seedling survival	Brignole *et al.* 2003
Earthworm	28	IC25	Number of cocoons	67	25	Stubberud 2006
Flax	21	IC25	Shoot weight	81.6		Brignole *et al.* 2003
Flax	21	IC25	Height	97.6	25	Brignole *et al.* 2003
Alfalfa	21	IC25	Height	102	25	Brignole *et al.* 2003
Soybean	21	IC25	Shoot weight	160	25	Brignole *et al.* 2003
Springtail (soil inverteb	28	IC25	Number of juveniles	177	25	Environment Canada 2015
Ryegrass	21	EC25	Emergence	203	25	Brignole *et al.* 2003
Ryegrass	21	LOEC	Survival of emerged seedlings	250	34% reduction in seedling survival	Brignole *et al.* 2003
Alfalfa	21	LOEC	Survival of emerged seedlings	250	29% reduction in survival	Brignole *et al.* 2003
Lettuce	21	LOEC	Survival	250	23% reduction in seedling survival	Brignole *et al.* 2003
Earthworm	14	LOEC	Survival	256	20% reduced survival	Joung *et al.* 2010
Soybean	21	IC25	Height	284	25	Brignole *et al.* 2003
Tomato	21	EC25	Emergence	311	25	Brignole *et al.* 2003
Alfalfa	21	EC25	Emergence	372	25	Brignole *et al.* 2003
Lettuce	21	EC25	Emergence	393	25	Brignole *et al.* 2003

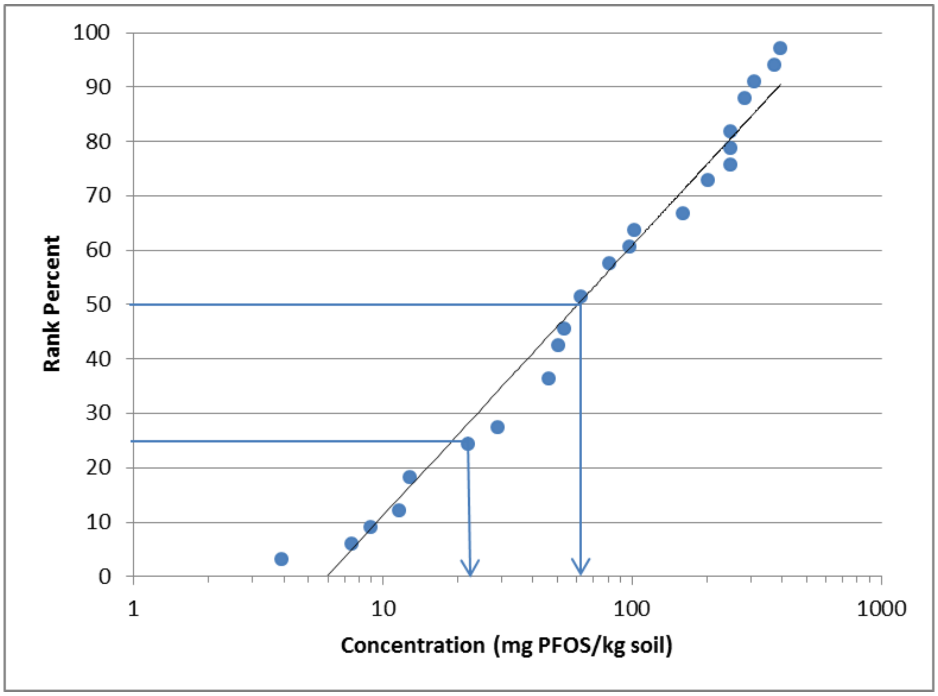


Figure 2. Estimated Species Sensitivity Distribution (ESSD) (Rank percent of EC_{25}/IC_{25} data) for PFOS for Terrestrial Plants and Invertebrates showing $ESSD_{25}$ and $ESSD_{50}$.

Soil and Food Ingestion

Since PFOS is bioaccumulative, the soil FEQG for agricultural and residential/parkland land uses also considers exposure to primary, secondary and tertiary consumers in the food web. Table 6 provides the characteristics of the representative species used in the soil quality guideline calculations. The method used to calculate the soil quality guidelines to protect these consumers is found in CCME (2006).

Primary-level consumers: Both herbivorous mammals (meadow vole) and birds (rock dove) were considered as indicator species (FCSAP 2012). For herbivorous mammals the lowest effects dose (ED_{1c}) of 0.1086 mg/kg bw/day (from Covance Laboratories Inc. 2002), was divided by an uncertainty factor of 2 according to methods described in the CCME protocol (2006) and based on the available data to obtain a daily threshold effects dose (DTED) of 0.0543 mg/kg bw-day. The SQC to protect herbivorous mammals was 2.2 mg PFOS/ kg dry soil and 5.1 mg PFOS/kg dry soil to protect herbivorous birds. Therefore the lowest of the available SQG_{1C} is 2.2 mg PFOS/kg dry soil.

Secondary consumers: The secondary food chain is more complex and involves up to three trophic levels. It can be represented by the following pathways:

a) Soil → Prey (earthworms)→ Predator (Secondary consumer) (mammal-Common shrew or bird-American robin)
b) Soil → Plant → Prey (primary consumer) → Predator (secondary consumer-deer mouse)

Table 6. Summary of Representative Species for Various Trophic Levels and Input Values for Calculation of Soil Quality Guidelines for PFOS.

Notes:

[1] Diet information provided in FCSAP (2012) and BC MOE (2001).

2 Bioavailability factor assumed to be equal to one in all cases.

Trophic Level	Feeding Guild	Representative Species	Diet[1]	Daily Threshold Effects Dose (mg/kg bw-day)	Body weight (kg)	Soil Ingestion Rate (kg dw/day)	Food Ingestion Rate (kg dw /day)	Bioconcentration Factor(s) (unitless) Soil → plant Soil → invertebrate Soil → animal	SQG to protect the receptor (mg PFOS/kg dry soil)[2]
Primary Consumer (1C)	Herbivorous mammal	Meadow vole	Plants	0.054	0.035	0.000041	0.00173	0.35 - -	2.2
	Herbivorous bird	Rock dove	Plants	0.386	0.31	0.0039	0.039	0.35 - -	5.1
Secondary Consumer (2C)	Insectivorous mammal	Common Shrew	Invertebrates (95%) Plants (2.5%) Small mammals (2.5%)	0.054	0.004	0.000032	0.0013	0.35 10.9 2.97	0.012
	Omnivorous mammal	Deer Mouse	Plants (50%) Invertebrates (50%)	0.054	0.02	0.000018	0.0009	0.35 10.9 -	0.17
	Omnivorous bird	American Robin	Plants (60%) Invertebrates (40%)	0.386	0.08	0.00059	0.015	0.35 10.9 -	0.33
Tertiary Consumer (3C)	Carnivorous mammal	Wolf	Mammals	0.054	80	0.0118	0.042	2.97	2.6
	Omnivorous mammal	Red Fox	Mammals and Birds (60%) Invertebrates (25%) Plants (15%)	0.054	3.8	0.0015	0.05	0.35 10.9 2.97	0.63

The model developed to represent this food chain and to derive the SQG_{2C} is similar to the one used in deriving SQG_{1C}. However, to account for biomagnification of PFOS from contaminated soil and food to the predator, the bioaccumulation factor from soil to prey (BAF_2) was used in addition to BCF_1. Three indicator species were considered: common shrew, deer mouse and American robin. Apportionment factors for foraging range and time spent on the site were both assumed to be one.

SQC_{2C} was 0.012 mg/kg dw soil (common shrew), 0.17 mg/kg dw soil (deer mouse) and 0.33 mg/kg dry soil (American robin). The lowest SQG_{2C} was therefore 0.012 mg PFOS/kg dry soil. This low value for SQC is a function of: 1) the low body weight of shrew 2) the high food ingestion rate (FIR) relative to its body weight and 3) most (95%) of the shrew's diet being insects and invertebrates which have been shown to bioaccumulate PFOS to the greatest extent.

Tertiary consumer: The pathways for tertiary consumers considered predators consuming prey items which themselves have fed on contaminated plants. Given the available data from Müller *et al.* (2011) which provided a plant→ caribou → wolf bioaccumulation factor data for PFOS, the following exposure pathways were considered for tertiary consumers:

a) soil→ plant → caribou→ carnivorous mammal (wolf)
b) soil →(plant + invertebrates + mammals + birds) → omnivorous mammal (Red fox)

The bioaccumulation factor for tertiary consumers (BAF_{3C}) was derived from the $BCF_{soil\ to\ plant}$ x $BAF_{plant\ to\ caribou}$

$$BAF_{3C} = \frac{[Herbivore]}{[Soil]} = \frac{[Plant]}{[Soil]} \times \frac{[Herbivore]}{[Plant]}$$

Data were available for two caribou herds (Bathurst and Porcupine) (Müller *et al.* 2011). The geometric mean BAF for the two herds is $BAF_{soil\text{-}herbivore}$ =SQRT(3.185 x 2.765) = 2.97. The SQG_{3C} (carnivorous mammal, wolf) = 2.6 mg PFOS/kg dw soil and for omnivorous mammal (red fox) was 0.63 mg PFOS/kg dry soil. Therefore the lowest SQG_{3C} was 0.63 mg PFOS/kg dry soil.

Final SQG soil and food ingestion

As described in CCME (2006), the lowest of SQG_{1C}, SQG_{2C} and SQG_{3C} was taken as the $SQG_{ingestion\ of\ soil\ and\ food}$ or SQG_I. In the case of PFOS, SQG_{2C} was the lowest and therefore SQG_I is 0.01 mg PFOS/kg dry soil.

Federal Soil Quality Guideline to Protect Livestock Watering

Contamination that migrates to groundwater may affect the water quality in dugouts, or water wells used for livestock watering or crop irrigation. These pathways apply only for the agricultural land use.

Determination of the soil quality guidelines for the protection of livestock watering (SQG_{LW}) and irrigation (SQG_{IR}) involves the application of the same groundwater model as for the SQG_{FL}, however transport through the saturated zone is not considered. That is, it assumes that dugouts or wells could be installed within the contaminated area. The guidelines are calculated by setting the allowable receptor groundwater concentration in the model equal to the livestock water (for the SQG_{LW}) and irrigation water (for the SQG_{IR}) from the Canadian Water Quality Guidelines. If a livestock water guideline is not available, the livestock water threshold value can be developed using the following equation:

$$LWT = \frac{DTED \times BW}{WIR}$$

where:
LWT = calculated livestock water threshold value
DTED = DTED for livestock (mg PFOS/kg bw-day)
BW = livestock body weight (kg) = 550 kg for cattle (CCME 2000)
WIR = livestock water ingestion rate (L/day) = 100 L/day for cattle (CCME 2000)

Since a Canadian Water Quality Guideline for livestock water is not available, a DTED for livestock was calculated as:

$$LWT = \frac{0.1086 \text{ mg PFOS/ kg body weight-day} \times 550 \text{ kg}}{100 \text{ L/day}}$$

$$= 0.597 \text{ mg/L}$$

Since the calculated livestock water threshold value is lower than the pure phase solubility of PFOS of 370 mg/L (see section 3 above), the calculation of the SQG_{LW} is required.

Using the same groundwater model as for the SQG_{FL}, but where transport through the saturated zone not considered, with an input livestock water threshold of 0.597 mg/L, the resulting SQG_{LW} was 12 mg PFOS /kg for coarse soil and 9 mg PFOS/kg for fine soil. Since an irrigation water guideline was not available, the calculation of the SQG_{IR} was not required (CCME 2006).

Therefore the SQG_{LW} was 12 mg PFOS/kg soil for coarse soil and 9 mg PFOS/kg soil for fine soil.

Derivation of Federal Soil Quality Guidelines for the Protection of Off-site Migration

The soil contact pathway for commercial and industrial sites considers contact of ecological receptors with on-site soil only. However, wind and water erosion of soil can move contaminated soil from one site to another. CCME (2006) Appendix G describes a model to address this movement of soil from a commercial or industrial site to protect adjacent, more sensitive agricultural site. Given the recognized imprecise nature of this model and the uncertainty associated with the input parameters, this pathway is considered a check mechanism. It is recommended that professional judgement be used to determine whether the SQG should be modified by this pathway. Parameters considered included:

- Susceptibility of soil to erosion: a soil with 3% organic carbon and a sandy loam texture (73% sand, 19% silt and 8% clay) was considered representative of soil susceptible to erosion.
- Soil loss at the site due to wind and water erosion: CCME (2006) recognizes that soil loss due to water and wind erosion vary widely across Canada. The generic default soil loss was based on the average of wind and water erosion (measured in tonnes/ha) at Halifax, NS (wind 0.0, water 11.3) and Lethbridge, AB (wind 13.2, and water 3.3).
- Site conditions: The representative site had a slope of 1% and 650 kg/ha of vegetative surface cover, a bulk density of 1 t/m^3 and depth of depositional area of 0.14 cm.

Using the Universal Soil Loss Equation and the Wind Erosion Equation, the concentration in eroded soil from the commercial or industrial site that would raise the contaminant concentration in the receiving soil of an adjacent property equal to the agricultural guideline within a specified period of time was calculated. This concentration was applied as the soil quality guideline for off-site migration (SQG_{OM-E}). At specific commercial or industrial sites, management actions may be needed to prevent or limit erosive losses of surface soils. Accommodation for such situations is provided in the guidance for the development of site-specific objectives (CCME 1996).

From CCME (2006)-Appendix G:

$SQG_{OM-E} = (14.3 \times FSQG_{Agr}) – (13.3 \times BSC)$
where:
$FSQG_{Agr}$ = the soil quality guideline protective of agricultural land uses (mg/kg) = 0.012 mg/kg
BSC = background soil concentration of the contaminant in the receiving soil (mg/kg)

Since PFOS is not naturally occurring, background soil concentrations (BSC) of PFOS in agricultural soils should be close to zero. Therefore the SQG_{OM-E} was 0.2 mg PFOS/kg soil.

Federal Soil Quality Guidelines ($FSQG_{FL}$) for the Protection of Freshwater Life

Contaminants present in soil can migrate to groundwater given the characteristics of the contaminant together with certain hydrologic and hydrogeologic conditions. Where there are surface water bodies (streams, rivers, lakes, etc.) nearby, then aquatic life in these surface water bodies may be affected by contamination, particularly if there is a permeable aquifer connecting the contaminated soil with the surface water body.

The federal soil quality guideline for the protection of freshwater life ($FSQG_{FL}$) is a concentration **in soil** which is calculated to protect surface water aquatic life.

By setting the surface water quality guideline equal to the Federal Environmental Quality Guideline for freshwater aquatic life (FWQG) = 6.8 µg/L (0.0068 mg/L) and using the models and default parameters in CCME (2006), the soil concentration ($FSQG_{FL}$) to prevent PFOS that might move through soil and groundwater from exceeding the surface water quality guideline was determined to be 0.21 mg/kg (for fine soil) and 0.14 mg/kg (for coarse soil) (Franz 2012).

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Appendix II: Excerpt from CCME (2017) *Scientific Criteria Document for Canadian Soil and Groundwater Quality Guidelines for the Protection of Environmental and Human Health: Perfluorooctane sulfonate (PFOS).* Draft for review by Soil Quality Guidelines Task Group. September 2017.

5.5 Canadian Soil Quality Guidelines (SQGFL) and Canadian Groundwater Quality Guidelines (GWQGFL) for the Protection of Freshwater Aquatic Life

Contaminants present in soil can migrate to groundwater given certain hydrologic and hydrogeological conditions and the characteristics of the contaminant. CCME (2015) is a companion document to CCME (2006) and provides a method for deriving groundwater quality guidelines based on various exposure scenarios of human and ecological receptors to contaminated groundwater. For ecological receptors, groundwater guidelines are developed to either maintain specific uses of groundwater (*e.g*. irrigation or livestock watering where water quality guidelines for these uses exist) or to protect receptors in environments that may come in contact with contaminated groundwater directly or indirectly, due to contaminant migration (*e.g*. plants and invertebrates living in soil or surface water bodies). The groundwater quality guidelines are not intended to protect organisms living in aquifers, but rather to protect the uses of groundwater or downgradient receptors.

The general conceptual model in CCME (2006; 2015) describes the fate and transport of a contaminant through soil and groundwater to a discharge point to surface water in four steps which account for:

1. Partitioning of the substance between soil, soil vapour and soil pore water (leachate).

2. Leaching of the contaminant through the unsaturated zone to the groundwater table.

3. Mixing and dilution of the leachate into groundwater.

4. Saturated-zone transport of the contaminant to a downgradient receptor (i.e., horizontal transport and attenuation of the substance in groundwater from edge of contamination to receptor (the surface water).

Because of the interrelationship between soil and groundwater, and the partitioning of contaminants between the solid, liquid and gas phases, the same conceptual model is used to derive the Canadian groundwater contact guideline ($GWQG_{GC}$), the Soil Quality Guideline for the protection of freshwater life (SQG_{FL}), and the Groundwater Quality Guideline for the protection of freshwater life ($GWQG_{FL}$) and the Groundwater Quality Guideline for the protection of drinking water ($GWQG_{DW}$).

It should be noted that not all four of the above steps will apply at all sites. Specifically, unsaturated zone transport (component 2) only applies if the contamination is not in contact with groundwater, and is therefore not applied in generic guideline development. Also, saturated zone transport (component 4) only applies if there is a lateral separation between the remediated site and the groundwater receptor. For generic guidelines, it is assumed that a well or livestock dugout could be installed at the edge of (or even within) the boundaries of the remediated area.

The SQG_{FL} is a concentration in soil, calculated to protect surface water aquatic life. The $GWQG_{FL}$ is the concentration in groundwater that is protective of surface fresh water aquatic life where there is a minimum of 10 m lateral separation between the point of measurement and the surface water body. Both the SQG_{FL} and $GWQG_{FL}$ guidelines were developed by Franz (2012) by applying the fate and transport model described in Appendices C and H of CCME (2006). The SQG_{FL} is independent of land use classifications and may be excluded on a site-specific basis if there are no surface water bodies in the vicinity of the site.

Although a number of groundwater exposure pathways may be considered, generally for PFOS, the relevant groundwater pathways and guidelines are:

1. contact with groundwater by soil-dependent organisms ($GWQG_{GC}$) and

2. groundwater to surface water transport modelling ($GWQG_{FL}$).

Setting the surface water quality guideline equal to the WQG_{FL} (6.8 μg/L) and using the models and default parameters in CCME (2015), the allowable concentration in groundwater is 6.8 μg/L. The soil concentration (SQG_{FL}) that is expected to protect against PFOS moving through soil and groundwater from exceeding the surface water quality guideline was determined to be 0.14 mg/kg (for coarse soil) and 0.21 mg/kg (for fine soil) (Franz 2012) (0). Inputs and results of the calculation are shown elsewhere.

The Groundwater Quality Guideline for the protection of freshwater life ($GWQG_{FL}$) was calculated as 6.8 μg/L (0.0068 mg/L) for both fine and coarse soil.

Given that DF1 = 7.3 L/kg, the groundwater value to protect soil organisms, (such as plants), from adverse effects *via* direct contact with groundwater ($GWQG_{GC}$), is calculated for both fine and coarse soil as (following CCME 2015):

$GWQG_{GC} = SQG_{SC}$ = 11 mg/kg = 1.5 mg/L, rounded to 2 mg/L

The candidate final groundwater guideline is checked against various management considerations. For PFOS these are:

1. GWQGM should not exceed 50% of the chemical's aqueous solubility due to the potential for chemical concentrations approaching maximum solubility to result in non-aqueous phase liquids (NAPLs), that may act as an ongoing contaminant source. In the case of PFOS, the candidate final guideline (0.0068 mg/L) (6.8 μg/L) is well below the aqueous solubility of PFOS (370 mg/L) and therefore NAPL formation at the guideline level is highly unlikely.

2. The candidate final guideline should be reasonable, workable and usable and therefore checked against the practical quantitation limit of the available analytical methods achievable in Canada. The GWQG is above the maximum Laboratory Reporting Limit (LRL) for PFOS in water of 0.02 μg/L recommended in CCME (2016) and is therefore reasonable, workable and useable.

3. The candidate guideline should not be below naturally occurring background levels of the substance. Since PFOS is not a naturally occurring substance, background levels of the substance in the environment should be essentially zero. The candidate final guideline is above this level.

Therefore, considering groundwater contact by soil-dependent organisms and the protection of freshwater life as well as the management considerations for PFOS, the GWQGF is 0.0068 mg/L.

Table 1. Groundwater Quality Guidelines for PFOS Considering Ecological Receptors.

	Soil Type[a]	
	Coarse	Fine
Guideline (GWQGF)[b]	**0.0068 mg/L**	**0.0068 mg/L**
Groundwater Contact ($GWQG_{GC}$) by soil-dependent organisms	2 mg/L	2 mg/L
Protection of freshwater life ($GWQG_{FL}$)c	0.0068 mg/L	0.0068 mg/L
Protection of marine life ($GWQG_{ML}$)	NC	NC
Protection of livestock watering ($GWQG_{LW}$)	NC	NC
Protection of irrigation water ($GWQG_{IR}$)	NC	NC
Management considerations (GWQ_{GM})-solubility	370 mg/L	370 mg/L

Notes:
NC = not calculated.
a Coarse-grained soil contains more than 50%, by mass, particles larger than 75 µm mean diameter (D50>75 µm). Fine-grained soils contain more than 50% by mass particles smaller than 75 µm mean diameter (D50<75 µm).
b The final groundwater quality guideline (GWQGF) is the lowest of the pathway–specific guidelines and considers other management factors such as substance solubility, analytical detection limits and background concentrations.
c $GWQG_{FL}$ is the concentration in groundwater that is expected to protect against potential impacts on freshwater life from PFOS originating in soil that may enter groundwater and subsequently discharge to a surface water body. This pathway may be applicable under any land use category where a surface water body sustaining aquatic life is present (*i.e.*, within 10 kilometres of the site). Where the distance to the nearest surface water body is greater than 10 kilometres, application of the pathway should be evaluated on a case-by-case basis by considering the site-specific conditions.