



DRAFT Guidance for Investigating and Remediating PFAS Contamination in Washington State

Toxics Cleanup Program

Washington State Department of Ecology
Olympia, Washington

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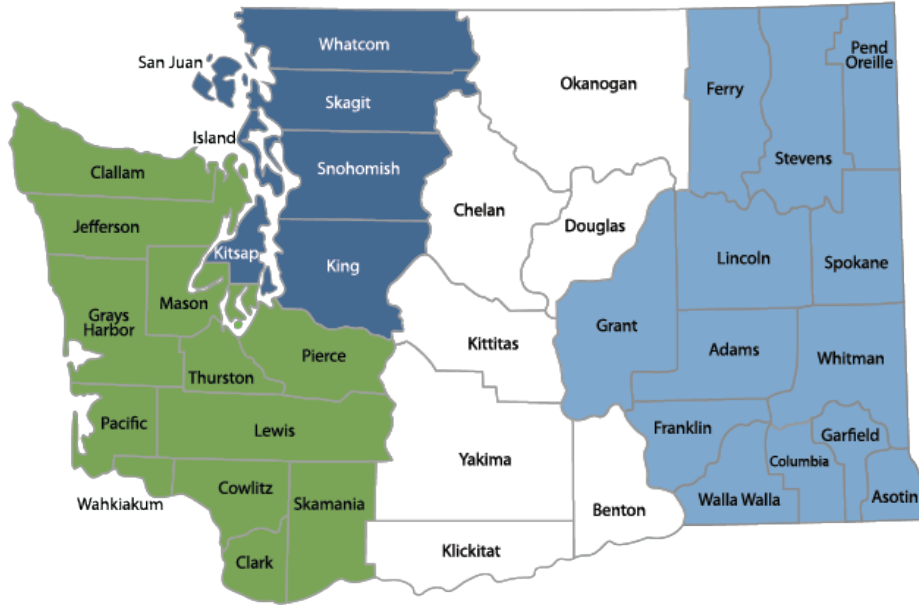
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Department of Ecology's Regional Offices

Map of Counties Served



Southwest Region 360-407-6300	Northwest Region 425-649-7000	Central Region 509-575-2490	Eastern Region 509-329-3400
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Region	Counties served	Mailing Address	Phone
Southwest	Clallam, Clark, Cowlitz, Grays Harbor, Jefferson, Mason, Lewis, Pacific, Pierce, Skamania, Thurston, Wahkiakum	PO Box 47775 Olympia, WA 98504	360-407-6300
Northwest	Island, King, Kitsap, San Juan, Skagit, Snohomish, Whatcom	P.O. Box 330316 Shoreline, WA 98133	206-594-0000
Central	Benton, Chelan, Douglas, Kittitas, Klickitat, Okanogan, Yakima	1250 W Alder St Union Gap, WA 98903	509-575-2490
Eastern	Adams, Asotin, Columbia, Ferry, Franklin, Garfield, Grant, Lincoln, Pend Oreille, Spokane, Stevens, Walla Walla, Whitman	4601 N Monroe Spokane, WA 99205	509-329-3400
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DEPARTMENT OF
ECOLOGY
State of Washington

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Acronyms and Abbreviations

Acronym or abbreviation	Definition
µg/L	microgram per liter
AB1	gastrointestinal absorption fraction
ABW	average body weight
ADD	California acceptable daily dose
AFFF	Aqueous Film Forming Form
ARAR	applicable or relevant and appropriate requirements
ASTM	American Society for Testing and Materials
AT _{nc}	averaging time – noncancer
ATSDR	Agency for Toxic Substances and Disease Registry
AWQC	ambient water quality criteria
BCF	bioconcentration factor
Board	Washington State Board of Health
BW	body weight
CAP	Chemical Action Plan
CERCLA	Comprehensive Environmental Response Compensation and Liability Act
CLARC	Cleanup Levels and Risk Calculations
COC	chemical of concern
CPF	carcinogenic potency factor (CPF and CSF have the same meaning)
CPHEA	Center for Public Health and Environmental Assessment (EPA)
CSF	cancer slope factor
CWB	State of California Water Board
DAF	dosimetric adjustment factor
DF	dilution factor
DOD	United States Department of Defense
DOH	Washington State Department of Health
DWF	drinking water fraction
DWIR	drinking water ingestion rate
Ecology	Washington State Department of Ecology
ED	exposure duration
EF	exposure frequency
EPA	United States Environmental Protection Agency
ESA	ASTM Environmental Site Assessment
foc	soil fraction of organic carbon
GenX	Trade name for a polymerization processing aid formulation that contains ammonium 2,3,3,3-tetrafluoro-2-(heptafluoropropoxy)propanoate
HA, HAL	health advisory, health advisory level (EPA)

Acronym or abbreviation	Definition
Hcc	Henry's law dimensionless constant
Hcp	Henry's law constant in atm-m ³ /mol
HEAST	Health Effects Assessment Summary Tables (EPA)
HFPO-DA	Hexafluoropropylene oxide [HFPO] dimer acid (a GenX chemical)
HQ	hazard quotient
IARC	International Agency for Research on Cancer
IL	Investigatory Level
INH	inhalation correction factor
IRIS	Integrated Risk Information System (EPA)
ITRC	Interstate Technology and Regulatory Council
JBLM	Joint Base Lewis McCord
Kd	soil water distribution coefficient
Koc	organic carbon-water partitioning coefficients
L/day	liters per day
L/kg	liters per kilogram
LC/MS/MS	Liquid Chromatography Tandem Mass Spectrometry
MCL	maximum contaminant level
MCLG	maximum contaminant level goal
MDEQ	Michigan Department of Environmental Quality
MDH	Minnesota Department of Health
MDHHS	Michigan Department of Health and Human Services
mg/kg	milligram per kilogram
mg/L	milligram per liter
MRL	Minimal Risk Level
MTCA	Model Toxics Control Act (Ecology)
NCEA	National Center for Environmental Assessment (EPA)
ng/kg	nanogram per kilogram
ng/L	nanogram per liter
NHDES	New Hampshire Department of Environmental Services
Nm	not measurable
NPDWR	National Primary Drinking Water Regulation (EPA)
ORD	Office of Research and Development (EPA)
ORNL	Oak Ridge National Labs
PFAA	Perfluoroalkyl alkyl acids
PFAS	Per- and polyfluoroalkyl substances
PFBA	Perfluorobutanoic Acid
PFBS	Perfluorobutane Sulfonic Acid
PFDA	Perfluorodecanoic Acid

Acronym or abbreviation	Definition
PFDODA	Perfluorododecanoic Acid
PFHpA	Perfluoroheptanoic Acid
PFHxA	Perfluorohexanoic Acid
PFHxS	Perfluorohexane Sulfonic Acid
PFNA	Perfluorononanoic Acid
PFOA	Perfluorooctanoic Acid
PFOS	Perfluorooctane Sulfonic Acid
PFUnDA	Perfluoroundecanoic Acid
PPRTV	Provisional Peer-Reviewed Toxicity Value (EPA)
ppt	parts per trillion
PQL	practical quantitation limit
PRG	Preliminary Remediation Goal
QA	quality assurance
QAPP	Quality Assurance Project Plan
QC	quality control
QSM	Quality Systems Manual
qTOF	quadropole time-of-flight
RAIS	Risk Assessment Information System (maintained by ORNL)
RCW	Revised Code of Washington (Washington statute)
RfD	reference dose
RSC	relative source contribution
RSL	Regional Screening Level (EPA)
SAL	State Action Level (DOH)
SAP	Sampling and Analysis Plan
SCUM	Sediment Cleanup User's Manual (Ecology)
SIR	soil ingestion rate
SL	screening level
SMS	Sediment Management Standards (Ecology)
STSC	Superfund Health Risk Technical Support Center (EPA)
TCP	Toxics Cleanup Program (Ecology)
TDS	total dissolved solids
Tgw	target potable groundwater level
TOP	Total Oxydizable Precursors
TSS	total suspended solids
TT	treatment technique
U.S.	United States
UCF	unit conversion factor
UCMR3	Third Unregulated Contaminant Monitoring Rule (EPA)

Acronym or abbreviation	Definition
VOC	volatile organic compound
WAC	Washington Administrative Code (rule, regulation)
θ_a	air-filled soil porosity
θ_w	water-filled soil porosity
ρ_b	dry soil bulk density

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Chapter 1: Introduction

1.0 A brief history of PFAS

Per- and polyfluoroalkyl substances are collectively known as PFAS. The group comprises thousands of unique synthetic organic chemicals that are extremely stable and persistent. Commercially manufactured since the 1940s, PFAS compounds have been used in manufacturing common consumer products, such as carpeting, clothing, furniture, outdoor equipment, and food packaging. Many industries have also used PFAS, including aerospace, automotive, aviation, electronics, and medical industries. One major source of PFAS contamination is Aqueous Film Forming Form (AFFF), which is used for fire training and extinguishing petroleum fires and other flammable liquids.²

The Interstate Technology Regulatory Council (ITRC) has much more background information about PFAS on their webpage. Access focus sheets, databases, and their online PFAS guidance (June 2022) at <https://pfas-1.itrcweb.org/>.

PFAS compounds have been commercially manufactured since the 1940s and extensively studied since the 1990s. Testing finds PFAS present throughout all environmental media such as groundwater, soil, sediments, and surface water, and in rainwater, snow, and ice worldwide. At the time this guidance was published, however, no legally enforceable Federal environmental standards had yet been established for any of these chemicals. While numerous studies are underway to determine how to limit the distribution of these compounds and successfully mitigate their environmental impacts, much work remains to be done.

Information related to PFAS investigation and remediation is rapidly evolving. This guidance is current as of the date of publication.

1.1 Purpose and applicability

The purpose of this guidance is to provide direction for investigating and cleaning up PFAS contamination in Washington state. The guidance is intended for people who are cleaning up a contaminated property, including property owners, potentially liable parties, and cleanup professionals. It is applicable for formal cleanups (those that are supervised by or conducted by the Washington State Department of Ecology (Ecology)), or independent cleanups conducted by the property owner on their own or with technical assistance from Ecology.

² Washington state law (Chapter [70A.400](#) RCW) restricts AFFF because of the PFAS danger. AFFF can no longer be manufactured, sold, or used for fire training, although it can still be used for emergencies and actual fire situations until an alternative is found.

A considerable volume of literature has already been published about PFAS, so we provide only a general overview of most topics here, with links to references that offer more comprehensive discussions. However, we do provide detail about **state-specific issues** such as:

- PFAS impacts in Washington state,
- Regulatory authority under the Model Toxics Control Act (MTCA),
- How the Washington State Department of Health (DOH) established State Action Levels (SALs) for five PFAS compounds, and
- How Ecology established MTCA cleanup levels.

We also provide recommendations on which PFAS compounds to analyze for, and factors to consider when evaluating which media should be investigated.

1.2 Chemical structure and terminology

The PFAS family includes thousands of chemicals. Many of the chemicals are considered “precursors” that can continue to degrade in the environment until they reach end products known as perfluoroalkyl acids (PFAAs), which are resistant to further degradation. The structure of a PFAA has a carbon chain backbone with most or all carbons fully fluorinated, and a “head group” that is typically a carboxyl group or a sulfonyl group. Because PFAAs are so persistent in the environment, they tend to be the focus of environmental investigations. For more information about this and other classes of PFAS, see Section 2.2 of the online ITRC guidance (ITRC 2022).

PFAS compounds can exist in various ionic states. Most PFAAs are present in the environment in their anionic form because the acid form typically dissociates (i.e., loses a hydrogen ion) in contact with water and other environmental media at environmentally relevant pH (e.g., >4). The acid and anionic forms of the compound have different physical and chemical properties and different CAS numbers (see Table 1).

This guidance document uses the acid form of the names. This is consistent with the naming convention found in most of the studies we evaluated during the literature review, and consistent with Ecology’s [Cleanup Levels and Risk Calculations \(CLARC\)](#)³ database. In addition, most labs report analytical results using the acidic form. The protective concentrations established in this document are applicable to either the acid or the anionic form of the molecule.

³ <https://ecology.wa.gov/CLARC>

Table 1: Test form of acid vs. anion form found in the environment. The Washington State Department of Ecology uses the acid form of these chemical names.

Acid compound	Acronym	CAS#		Anion found in the environment	CAS#
Perfluorobutanoic Acid	PFBA	375224	→	Perfluorobutanoate	45048622
Perfluorobutane Sulfonic Acid	PFBS	375735	→	Perfluorobutanesulfonate	45187153
Perfluorodecanoic Acid	PFDA	335762	→	Perfluorodecanoate	73829364
Perfluorododecanoic Acid	PFDoDA	307551	→	Perfluorododecanoate	171978953
Perfluoroheptanoic Acid	PFHpA	375859	→	Perfluoroheptanoate	120885292
Perfluorohexanoic Acid	PFHxA	307244	→	Perfluorohexanoate	92612527
Perfluorohexane Sulfonic Acid	PFHxS	355464	→	Perfluorohexanesulfonate	108427538
Perfluorononanoic Acid	PFNA	375951	→	Perfluorononanoate	72007682
Perfluorooctanoic Acid	PFOA	335671	→	Perfluorooctanoate	45285516
Perfluorooctane Sulfonic Acid	PFOS	1763231	→	Perfluorooctanesulfonate	45298906
Perfluoroundecanoic Acid	PFUnDA	2058948	→	Perfluoroundecanoate	196859548
Hexafluoropropylene Oxide – Dimer Acid	HFPO-DA	13252136	→	HFPO Carboxylate Anion	62037803

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Chapter 2: Potential Human Health Effects, Groundwater Impacts, and Regulation

2.0 Potential human health effects

To date, the potential human health effects of PFOS and PFOA have been the most intensively studied of the PFAS chemicals, but there is also considerable toxicological information on PFNA, PFHxS, PFBS, and the GenX chemical hexafluoropropylene oxide dimer acid (HFPO-DA; also known as (GenX)). Some PFAS chemicals can readily absorb into the human body, and national surveys have shown that nearly all people tested had detectable levels of PFAS in their blood serum (DOH, 2021a). Primary noncancer health effects that have been associated with PFAS are increases of serum cholesterol levels; liver toxicity; reproductive and developmental toxicity (e.g., lower birth weights); and immune toxicity (DOH, 2021a).

According to the United States Environmental Protection Agency's (EPA) Interim Health Advisories (HAs), and consistent with EPA's hazard descriptors in [Guidelines for Carcinogen Risk Assessment](#)⁴ (EPA, 2005), PFOA is classified as likely to be carcinogenic to humans based on evidence of increased risk of kidney and testicular cancer. There is also suggestive evidence that PFOS may be linked to human carcinogenicity (EPA, 2022a). However, at this time, EPA has not derived a cancer slope factor (CSF) for PFOS, and a preferred CSF has not been identified for derivation of a cancer-based drinking water HA level for PFOA.

EPA's initial evaluation of candidate CSFs suggests that the human health protective level in drinking water for PFOA based on noncancer effects is protective of a 1 in a million (1×10^{-6}) excess cancer risk (EPA, 2016b; 2022a). Based on the discussion in this section, therefore, noncancer endpoints provided the foundation for the human health-based protective levels developed for and described in this guidance. EPA is evaluating available toxicity data to derive a CSF for PFOA as part of the National Primary Drinking Water Regulation (NPDWR) (EPA, 2022a).

2.1 Impacts to groundwater and drinking water

The widespread use of PFAS chemicals, and their persistence and mobility in the environment, have impacted groundwater and drinking water systems. EPA sampled and detected PFAS chemicals in drinking water systems across the United States as part of a national survey conducted between 2013 and 2015 called the Unregulated Contaminant Monitoring Rule (UCMR3) sampling event.⁵ As part of this event, 132 public water systems in Washington state

⁴ <https://archive.epa.gov/raf/web/html/guidelines-carcinogen-risk-assessment.html#:~:text=Guidelines%20for%20Carcinogen%20Risk%20Assessment%20%282005%29%201%20Background,July%201999%20interim%20guidance.%20...%203%20Citation%20>

⁵ EPA's Third Unregulated Contaminant Monitoring Rule (UCMR3) for monitoring emerging contaminants in drinking water (<https://www.epa.gov/dwucmr/third-unregulated-contaminant-monitoring-rule>).

conducted monitoring that covered approximately 94% of Washington residents served by public water systems. This monitoring included sampling for six PFAS compounds:

- Perfluorooctane sulfonic acid (PFOS)
- Perfluorooctanoic acid (PFOA)
- Perfluorononanoic acid (PFNA)
- Perfluorohexane sulfonic acid (PFHxS)
- Perfluoroheptanoic acid (PFHpA)
- Perfluorobutane sulfonic acid (PFBS)

PFOA and PFOS were detected above the laboratory reporting limits in three public water systems: City of Issaquah, City of DuPont, and Joint Base Lewis-McChord (JBLM). At that time, only the City of Issaquah had exceedances of EPA's 2016 Health Advisory Level (HAL), which was 70 nanograms/liter (ng/L or parts per trillion [ppt]). In June 2022, EPA issued lower interim health advisories for PFOA and PFOS that are 0.004 ng/L and 0.02 ng/L, respectively. (See 3.3.1 Health advisories for timeline and more information).

Since the UCMR3 sampling event of 2013–15, several military bases in Washington state have tested drinking water sources in response to a directive from the U.S. Department of Defense (DOD). PFAS were discovered at McChord Airfield and Fort Lewis (located between Olympia and Tacoma), Naval Air Station Whidbey Island (located near Oak Harbor); Naval Base Kitsap-Bangor (located near Poulsbo and Silverdale); Fairchild Air Force Base (located near Airway Heights and Spokane), and the Yakima Training Center (located near Yakima), which is part of JBLM. Additional investigations are ongoing to determine the degree and extent of PFAS contamination in drinking water wells both on- and off-base.

As of May 2022, PFOA and PFOS were identified above the 2016 EPA HAL of 70 ng/L in 6 locations across Washington:

1. Joint Base Lewis McChord
2. Naval Air Station Whidbey Island, including the Coupeville and Oak Harbor areas
3. Fairchild Air Force Base and the City of Airway Heights
4. Naval Base Kitsap-Bangor
5. City of Issaquah
6. Yakima Training Center (part of JBLM).

AFFF used for fire suppression and training appears to be the primary source of contamination in all six locations.

The City of Issaquah and Eastside Fire and Rescue are voluntarily investigating the source of PFAS in the lower Issaquah Valley. EPA is overseeing the investigation and cleanup of PFAS at most of the federal military facilities with assistance from Ecology. Ecology's Hazardous Waste and Toxics Reduction Program is overseeing Yakima Training Center's investigation and cleanup. Find more information and the results of ongoing work at many of these locations in Ecology's PFAS Chemical Action Plan: <https://apps.ecology.wa.gov/publications/SummaryPages/2104048.html>

2.2 Regulatory authority

As of the date we published this guidance, EPA had not identified any PFAS compounds as hazardous substances under the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) and no maximum contaminant levels (MCLs) for PFAS compounds have been established under the federal Safe Drinking Water Act. EPA's [Strategic Roadmap](#)⁶ released in October 2021 identifies a number of actions they plan to complete over the next several years (EPA, 2021c). These include but are not limited to: 1) proposing to list PFOA, PFOS, and possibly other PFAS compounds as hazardous substances under CERCLA, and 2) establishing final National Drinking Water Standards for PFOA and PFOS. The U.S. Congress is considering the PFAS Action Act (HR 2467) to address both goals, but the fate of the bill is uncertain.

The Toxics Cleanup Program (TCP) evaluated Ecology's legal authority to regulate PFAS and concluded that PFAS compounds meet the definition of a hazardous substance under the Model Toxics Control Act (MTCA). We announced this conclusion on October 21, 2021, in Ecology's Site Register at <https://apps.ecology.wa.gov/publications/SummaryPages/2109041U.html>.

Just prior to this announcement, TCP presented our regulatory conclusion during the keynote address at the Northwest Environmental Business Council's (NEBC's) Remediation Conference on October 14, 2021. The purpose of the presentation was to:

- a. Explain the authority we used to reach the conclusion that PFAS are a hazardous substance;
- b. Discuss the anticipated implications for investigation and cleanup of PFAS contamination; and
- c. Answer questions and obtain feedback from participants.

Since TCP's 2021 announcement, Ecology has received a number of questions about reporting requirements for PFAS releases. In July 2022, we published a [PFAS Cleanup Levels focus sheet](#)⁷ (Ecology Publication No. 22-09-075) that provides preliminary soil and groundwater cleanup levels for the same five PFAS compounds for which the Washington Department of Health promulgated State Action Levels, as well as cleanup levels for HFPO-DA. The PFAS focus sheet will serve as interim guidance until this comprehensive guidance is finalized.

⁶ <https://www.epa.gov/pfas/pfas-strategic-roadmap-epas-commitments-action-2021-2024>

⁷ <https://apps.ecology.wa.gov/publications/SummaryPages/2209075.html>

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Chapter 3: Advisory, Action, and Cleanup Levels, and Historical Investigatory Levels

3.0 Overview

This chapter discusses regulatory levels. We outline the State Action Levels (SALs) developed by the Washington State Department of Health (DOH). We provide preliminary MTCA cleanup levels developed by Ecology, and the methods used for calculating those levels. We discuss the human health-based protective levels developed by EPA, then conclude with a brief discussion of PFAS investigatory levels Ecology developed in 2018 but no longer use.

Even when protective concentrations for PFAS in environmental media are developed for similar scenarios (e.g. drinking water and groundwater that could be used as drinking water), the concentrations can differ because of differences in exposure assumptions and toxicity values. Some regulatory levels for drinking water, for example, include relative source contribution (RSC) factors that account for potential exposures from sources other than drinking water (such as diet), whereas other regulatory levels do not include RSCs.

The toxicology of PFAS is currently an area of intense research. Each regulatory agency develops toxicity values using the best available information at the time. As new toxicological information emerges, the regulatory levels discussed in this chapter may change and regulatory levels for other PFAS compounds may become available.

3.1 Department of Health Drinking Water State Action Levels

In July 2017, the Department of Health received requests to establish drinking water standards for PFAS chemicals due to concerns over concentrations of PFAS identified in the drinking water supplies of several Washington state communities. In October 2017, the Washington State Board of Health (Board) authorized DOH to initiate a rulemaking process to amend Chapter [246-290](#) WAC,⁸ Washington's regulations for Group A Public Water Supplies, to address PFAS in drinking water. The final rule set State Action Levels (SALs) for five PFAS chemicals. It also set requirements for monitoring and reporting, follow-up actions, and public notice for contaminants without an MCL (DOH, 2021b).

In support of the Board and as part of the rulemaking, DOH developed recommendations for SAL values for PFOA, PFOS, PFNA, PFHxS, and PFBS. DOH identified these compounds for SAL development because they have been detected in Washington state drinking water supplies, had available toxicological information, and may be good indicators of PFAS occurrence in drinking water (DOH, 2021a; WAC [246-290-315](#)⁹). The Group A Drinking Water

⁸ <https://app.leg.wa.gov/WAC/default.aspx?cite=246-290> (Group A public water supplies)

⁹ <https://app.leg.wa.gov/WAC/default.aspx?cite=246-290-315> (State action levels (SALs) and state maximum contaminant levels (MCLs))

Rule with SALs for the five PFAS substances was adopted on November 17, 2021, and became effective on January 1, 2022.

Similar to the EPA 2016 health advisory levels for PFOS and PFOA, the Department of Health established the five PFAS State Action Levels to be protective of noncancer effects assuming a lifetime exposure to drinking water. Some PFAS such as PFOA, PFOS, PFHxS and PFNA are readily absorbed into the human body when ingested with food and water, but only slowly eliminated. They can accumulate in blood serum and other locations in the body and because of this, the SALs are designed to protect the most sensitive subpopulations including pregnant mothers, developing fetuses, and infants. During pregnancy, for instance, PFAS that accumulated in the mother's serum can cross the placenta and accumulate in the developing fetus. Another example: PFAS serum levels can quickly increase in infants who are breast-fed and bottle-fed due to their high intake of milk or formula (prepared with tap water) compared to their body weight (DOH, 2021a).

3.1.1 How DOH developed State Action Levels

The Department of Health considered key elements when deriving the SALs including: a) derivation of noncancer toxicity values, b) an estimation of the RSC from drinking water, and c) development of water ingestion rates. These are the same elements used by EPA to develop their Health Advisories and are discussed below.

Noncancer Toxicity Data

When DOH was identifying noncancer toxicity values to use for developing the SALs, they relied on values that had already been selected by U.S. federal and state governments based on reviews of existing, high-quality peer-reviewed toxicity studies. The noncancer toxicity values produced from these reviews included reference doses (RfDs) set by EPA and U.S. states; minimal risk levels (MRLs¹⁰) set by the Agency for Toxic Substances and Disease Registry (ATSDR); and California Acceptable Daily Doses (ADD; DOH, 2021a). DOH selected toxicity values that were based on noncancer effects in laboratory animals, particularly effects on immune function, offspring development, and thyroid hormones.

Relative Source Contribution (RSC)

Like EPA did with health advisories (Section 3.3.1), DOH applied an RSC when developing the SALs to account for other potentially significant exposure sources (that is, besides consuming contaminated drinking water). To do this, DOH first used EPA's Exposure Decision Tree to identify appropriate RSCs for each PFAS (EPA, 2000). With the exception of PFBS, DOH then applied an RSC of 50% to infants who breast- or bottle-feed since it was assumed these routes of exposure dominate the PFAS intake in young children. Based on criteria that included the potential for additional sources of exposure and adequacy of available data, DOH used an RSC

¹⁰ MRLs are developed by ATSDR and can be used as an RfD. An MRL is an estimate of the amount of a chemical a person can eat, drink, or breathe each day without a detectable risk to health. MRLs are developed for noncancer endpoints (DOH, 2021a).

of 50% for PFOA, PFHxS, and PFNA for all age groups. PFBS was assigned an RSC of 20% for all age groups. The RSCs for PFOS ranged from 50% for infants to 20% for adults (DOH, 2021a).

Water Ingestion

PFOA, PFOS, PFHxS, and PFNA can readily absorb into the human body and have much longer half-lives than PFBS. For the four chemicals, DOH applied a model developed by the Minnesota Department of Health (MDH model) that predicts blood serum levels. These levels are based on human exposure to PFAS contamination via placental transfer, breast-milk ingestion, and tap water ingestion, and includes infants who are bottle-fed. Upper-percentile (90th to 95th) breast-milk and drinking water ingestion rates were used in the model to predict drinking water levels needed to keep serum levels of adults and breast- or bottle-fed infants at or below the protective serum level. The serum level to protect mothers and children from PFAS exposure via tap water and breast-milk ingestion was determined by multiplying the target serum level identified in the toxicity study by the RSC (e.g., 20%, 50%; DOH, 2021a).

PFBS appears to clear from human serum much more rapidly than the other four PFAS chemicals evaluated and has a half-life of days compared to years (DOH, 2021a). Rather than apply the MDH model, DOH used a simple equation based on a standard residential drinking water intake scenario and an ingestion rate of 0.174 L/kg-day (Table 2 below). The ingestion rate selected by DOH is based on the 95th percentile water intake for infants less than a year old (bottle-fed with formula mixed with tap water) as identified in EPA's [2011 Exposure Factors Handbook](#)¹¹ (EPA, 2011).

¹¹ <https://www.epa.gov/expobox/about-exposure-factors-handbook>

Table 2: Drinking water State Action Levels (SALs) developed by the Washington State Department of Health.

PFAS chemical	Source for toxicity value	RfD or MRL ¹² (ng/kg-day)	Relative Source Contribution (RSC)	Ingestion Rate	State Action Level (SAL)
PFOA	ATSDR, 2021	3	50%	MDH model ¹³	10 ng/L
PFOS	MDH, 2020a; NHDES, 2019	3	20% adults 50% infants	MDH model	15 ng/L
PFNA	ATSDR, 2021 ¹⁴	2.5	50%	MDH model	9 ng/L
PFHxS	MDH, 2020b	9.7	50%	MDH model	65 ng/L
PFBS	EPA, 2021a	300	20%	0.174 L/kg-day	345 ng/L ¹⁵

The chemical-by-chemical approach to developing action levels for PFAS should be considered an interim solution due to the number of PFAS chemicals and the frequent detections of PFAS mixtures in environmental media. As more information becomes available, it may be possible to evaluate PFAS as a complex mixture according to subclasses based on key characteristics such as chemical structure, bioavailability, bioaccumulation potential, toxicity, or mechanism of action (DOH, 2021a).

3.1.2 State Action Level requirements

Under the DOH rulemaking, monitoring for PFAS will be required by community and nontransient noncommunity Group A water systems (DOH, 2021c). Transient noncommunity water systems located near known or suspected PFAS contamination will also be required to sample for PFAS and meet follow-up requirements if PFAS are detected (see WAC [246-290-320\(8\)](#)).¹⁶ Initial monitoring of systems must be completed no later than December 31, 2025.

¹² RfD = Oral Reference Dose. ATSDR uses the term minimal risk level or MRL rather than RfD.

¹³ MDH = Minnesota Department of Health toxicokinetic model for infant intake of bioaccumulative PFAS in drinking water.

¹⁴ DOH adjusted the ATSDR MRL from 3ng/kg-day to 2.5 ng/kg-day based on an updated half-life estimate of 3.52 years.

¹⁵ PFBS SAL (ng/L) = (300 ng/kg-day x 50%) ÷ 0.174 L/kg-day.

¹⁶ <https://apps.leg.wa.gov/WAC/default.aspx?cite=246-290> (Group A public water supplies.)

Ongoing monitoring will be required once every three years, unless the utility qualifies for a waiver as determined by DOH.

Water systems that detect PFAS will be required to continue monitoring on a more frequent schedule. Public notice to inform customers will be required if a system has PFAS levels exceeding a SAL (DOH, 2021c).

3.2 Establishing MTCA cleanup levels

The MTCA Cleanup Regulations (WAC [173-340-200](#)),¹⁷ define a cleanup level as the concentration of a hazardous substance in water, soil, air, or sediment¹⁸ that is determined to be protective of human health and the environment under specified exposure conditions. Since Ecology requires that remedial actions under MTCA address a threat to human health or the environment, a preliminary cleanup level gauges whether a hazardous substance is present at a concentration that warrants cleanup actions. While final cleanup levels for a site will be established in the Cleanup Action Plan, it helps to set preliminary cleanup levels early in the cleanup process so all parties have a common understanding of the potential severity of contamination that might be found during the site investigation.

MTCA cleanup levels may be established using [Method A](#)¹⁹ (Applicable Laws and Tables), [Method B](#)²⁰ (Unrestricted), or [Method C](#)²¹ (Industrial). Since Method A table values are not available for any PFAS chemicals, this guidance addresses establishing MTCA cleanup levels under Methods B and C.

Cleanup levels under Method B are established using applicable state and federal laws (referred to as ARARs) and the risk-based equations and other requirements specified for each medium (i.e., groundwater, surface water, soil, and air). The lifetime excess cancer risk²² under Method B is set at 1 in a million (1×10^{-6}) for individual substances, and 1 in 100,000 (1×10^{-5}) for the total cancer risk from all carcinogenic chemicals of concern (COCs) and pathways of exposure at a site.

¹⁷ <https://app.leg.wa.gov/WAC/default.aspx?cite=173-340-200> (Definitions)

¹⁸ Cleanup levels for PFAS chemicals in sediment are managed under a separate rule, the Sediment Management Standards (Chapter [173-204](#) WAC) and its associated guidance, the [Sediment Cleanup User's Manual \(SCUM\)](#) (Ecology Publication No. 12-09-057).

¹⁹ <https://app.leg.wa.gov/WAC/default.aspx?cite=173-340-704> (Method A)

²⁰ <https://app.leg.wa.gov/WAC/default.aspx?cite=173-340-705> (Method B)

²¹ <https://app.leg.wa.gov/WAC/default.aspx?cite=173-340-706> (Method C)

²² Risk is expressed in terms of lifetime excess cancer risk (in excess of one's background risk of developing cancer). For example, a risk of 1×10^{-6} equates to approximately one excess cancer case in a population of one million individuals due to exposure to the cancer-causing substance over a lifetime.

Method C is similar to Method B. However, Method C cleanup levels are based on less stringent exposure assumptions, and the lifetime excess cancer risk is set at 1×10^{-5} for both individual substances and for the total cancer risk caused by all COCs and pathways of exposure. In the following sections, we discuss how we developed (or will develop) MTCA cleanup levels for PFAS chemicals for each media (groundwater, surface water, soil, and air).

3.2.1 MTCA risk-based cleanup level equations

Calculating MTCA risk-based cleanup levels requires establishing chemical-specific human health toxicity criteria (e.g., noncancer RfDs and carcinogenic potency factors [CPFs]) that are used in combination with MTCA's default exposure parameters. Noncancer RfDs are used to evaluate potential noncancer health effects, and CPFs are used to evaluate the probability of cancer risk. Since data are limited to support quantitative assessment of cancer risk for PFAS chemicals (DOH, 2021a), and because using EPA's cancer slope factor for PFOA results in a higher level, noncancer endpoint, using RfDs provides the foundation for the development of MTCA cleanup levels described in this guidance.

MTCA risk-based equations to evaluate noncancer health effects require using an RfD established in accordance with WAC [173-340-708\(7\)\(d\)](#).²³ The MTCA Cleanup Regulations provide a hierarchy of human health toxicity databases where EPA's Integrated Risk Information System (IRIS) is the preferred source, followed by EPA's Health Effects Assessment Summary Tables (HEAST), followed by EPA's National Center for Environmental Assessment (NCEA). Details about the toxicity sources:

IRIS. No toxicity data are currently available for PFAS chemicals in EPA's IRIS database. EPA is conducting toxicity assessments for several PFAS in IRIS as discussed in Section 3.3.2.

HEAST. No toxicity data are available for PFAS chemicals in EPA's HEAST database. EPA has not updated chemical toxicity values in HEAST since 1997. Values in HEAST are archived when an IRIS or EPA Provisional Peer-Reviewed Toxicity Value (PPRTV) is released (see NCEA below). For more information, see Section 2.3 of EPA's [Regional Screening Level \(RSL\) user's guide](#).²⁴

NCEA. The NCEA develops toxicity data in support of EPA's PPRTV program. NCEA is now known as the Center for Public Health and Environmental Assessment (CPHEA) and is part of EPA's Office of Research and Development (ORD). PPRTV assessments are developed in response to requests from EPA's Superfund Program to the Superfund Health Risk Technical Support Center (STSC) located within the CPHEA. EPA

²³ <https://apps.leg.wa.gov/wac/default.aspx?cite=173-340-708> (Human health risk assessment procedures.)

²⁴ <https://www.epa.gov/risk/regional-screening-levels-rsls-users-guide#toxicity>

published a PPRTV oral RfD of 300 ng/kg-day for PFBS based on thyroid effects in 2021 (EPA, 2021a).

In accordance with the MTCA Cleanup Regulations: if an RfD is not available from IRIS, HEAST, or NCEA, or is demonstrated to be inappropriate, Ecology may determine that development of an alternate RfD is needed (WAC [173-340-708\(7\)\(f\)](#)).²⁵ This is the case for four of the five PFAS chemicals evaluated by DOH, since all but PFBS²⁶ lack toxicity data in the MTCA sources listed above. For HFPO-DA (GenX), Ecology adopted the oral RfD developed by EPA's Office of Water (EPA, 2022c).

For the purpose of developing MTCA cleanup levels for PFAS chemicals, Ecology concludes that the RfDs identified by DOH in the development of their SALs are appropriate and represent the best and latest science. The toxicity studies that form the basis for the SALs are high quality, peer-reviewed, comprehensive, and based on current scientific research (DOH, 2021a; Ecology 2022). In addition, the techniques used to develop the RfDs are consistent with those recommended in MTCA (WAC [173-340-708\(7\)\(f\)](#)). In accordance with MTCA, Ecology has consulted with both EPA and DOH on the selection of RfDs identified in this guidance for the development of MTCA cleanup levels (WAC [173-340-708\(7\)\(g\)](#)) (Ecology 2022). The six RfDs selected for developing MTCA cleanup levels are listed below. See Section 3.3.1 for more details on the Department of Health's RfDs.

- **PFOA** – 3 ng/kg-day (ATSDR, 2021)
- **PFOS** – 3 ng/kg-day (MDH 2020a; NHDES, 2019)
- **PFNA** – 2.5 ng/kg-day (ATSDR, 2021)
- **PFHxS** – 9.7 ng/kg-day (MDH, 2020b)
- **PFBS** – 300 ng/kg-day (EPA, 2021a)
- **GenX** – 3 ng/kg-day (EPA, 2022)

3.2.2 Compliance with ARARs

Cleanup levels must comply with applicable local, state, and federal laws in addition to requirements Ecology has determined to be relevant and appropriate (WAC [173-340-710\(4\)](#)).²⁷ These legally applicable, relevant and appropriate requirements are collectively referred to as ARARs. At the time we published this guidance, there were no legally applicable state or federal laws (such as MCLs or maximum contaminant levels) to apply when developing PFAS cleanup levels.

²⁵ <https://apps.leg.wa.gov/wac/default.aspx?cite=173-340-708> (Human health risk assessment procedures.)

²⁶ DOH applied EPA's published PPRTV oral RfD of 300 ng/kg-day to develop the SAL for PFBS (EPA, 2021a).

²⁷ <https://apps.leg.wa.gov/WAC/default.aspx?cite=173-340-710> (Applicable local, state and federal laws.)

However, Ecology can review each cleanup site to determine if there are relevant and appropriate requirements that, while not legally required, should be applied based on circumstances at the site. To make this determination, Ecology would need to evaluate the criteria identified in WAC 173-340-710(4) to establish whether the regulatory or guidance value under consideration was relevant and appropriate.

3.2.3 Potable groundwater cleanup levels

The process outlined in WAC [173-340-720](#)²⁸ is for setting cleanup levels for potable and non-potable groundwater. MTCA groundwater cleanup levels for PFAS chemicals discussed in this section are based on the assumption that the highest beneficial use and the reasonable maximum exposure at the site is the ingestion of groundwater as a current or potential potable drinking water source. The Department of Health's SALs are expected to serve as the groundwater cleanup levels for most sites that have potable groundwater.

Under Method B, or Method C if applicable, groundwater cleanup levels must be a) as stringent as applicable state and federal laws, b) protective of human health, and c) protective of surface water beneficial uses. Additional requirements for establishing Method C cleanup levels for potable groundwater are found in WAC 173-340-706(1) but note that Method C groundwater cleanup levels are rarely used.

Ecology applied the RfDs in Section 3.1.1 to calculate Method B and C cleanup levels using MTCA Equation 720-1. We used an inhalation correction factor of 1 for chemicals that are not volatile, and 2 for volatile PFAS compounds (HFPO-DA; see Appendix A, Table A-1), along with the other default exposure assumptions. Table 3 shows the three levels: calculated groundwater cleanup levels under Methods B and C, the DOH SALs, and Ecology's preliminary groundwater cleanup levels.

²⁸ <https://apps.leg.wa.gov/WAC/default.aspx?cite=173-340-720> (Groundwater cleanup standards.)

Table 3: Recommended groundwater cleanup levels for PFAS using Method B and Method C in Washington state’s MTCA Cleanup Regulations.

PFAS	Method B ²⁹	Method C ³⁰	DOH SAL ³¹	Preliminary Groundwater Cleanup Levels	Units
PFOA	48	110	10	10	ng/L
PFOS	48	110	15	15	ng/L
PFNA	40	88	9	9	ng/L
PFHxS	160	340	65	65	ng/L
PFBS	4,800	11,000	345	345	ng/L
HFPO-DA	24	53	---	24	ng/L

The calculated Method B and C groundwater equation values in this table are higher than the DOH SALs because the MTCA cleanup level equations do not account for relative source contribution or trans-lactational exposures to breast-fed children when contaminants accumulate in breast milk (see discussion in Sections 3.1.1, and 3.3.1). However, under MTCA the hazard index cannot exceed 1, so some downward adjustments would need to be made if there are multiple noncarcinogens that affect the same endpoint (target organ/critical effect).

The DOH SALs in Table 3 should be evaluated to determine if they constitute “relevant and appropriate requirements” as set forth in WAC 173-340-710(4). Ecology expects that the SALs will be considered ARARs and therefore applied as the cleanup levels at sites where groundwater is currently being used, or may be used in the future, as a potable drinking water source.³² The SALs are sufficiently protective (Hazard Quotient (HQ) less than 1) and represent the most stringent ARAR currently available.

Until Ecology determines that the DOH SALs are an ARAR for a site, they should be considered preliminary cleanup levels. However, the Method B and C equation levels were calculated using reference doses established under the options set forth in WAC 173-340-708(7), and those values are applicable under MTCA. The six PFAS compounds and their corresponding

²⁹ Method B – Based on child exposure with a HQ of 1, body weight of 16 kg, and a drinking water ingestion rate of 1 liter/day.

³⁰ Method C – Based on adult exposure with a HQ of 1, body weight of 70 kg, and a drinking water ingestion rate of 2 liters/day.

³¹ The development of DOH SALs is discussed in Section 3.3 of this guidance.

³² Each cleanup site should be reviewed to determine on a site-specific basis if there are relevant and appropriate requirements that should be applied, such as DOH’s SALs.

cleanup levels have been added to CLARC, Ecology's Cleanup Levels and Risk Calculation database.

As discussed in Section 3.3.2, EPA is conducting additional IRIS toxicity assessments and the number of PFAS compounds with available cleanup levels will increase over time. Until the Method B (or Method C, if applicable) levels are superseded by a site-specific determination that the DOH SALs are relevant and appropriate, compliance with the MTCA derived levels in Table 3 is required. For all contaminated sites, Ecology recommends using a laboratory that can achieve practical quantitation limits (PQLs) at or below the SALs listed in Table 3.

Note: Unless it can be demonstrated that the hazardous substances are not likely to reach surface water, the groundwater cleanup level must be at least as stringent as the surface water cleanup level established in accordance with WAC 173-340-730 (see Section 3.2.4 below).

3.2.4 Surface water cleanup levels

The process outlined in WAC 173-340-730 is for setting cleanup levels for surface water. Under Methods B and C, surface water cleanup levels must be a) as stringent as applicable state and federal laws, b) protective of human health and the environment, and c) protective of drinking water beneficial uses if surface water is suitable as a domestic water supply. Additional requirements for establishing Method C cleanup levels for surface water are the same as previously described for groundwater. Method C cleanup levels are rarely used.

Default standard Method B and C cleanup levels for PFAS chemicals in surface water that are based on consumption of fish may be calculated using MTCA [Equation 730-1](#)³³ for noncancer effects, in conjunction with a) the RfDs that formed the basis of the DOH SALs, b) chemical-specific bioconcentration factors (BCFs), and c) associated default exposure assumptions. However, these calculations can't be performed because chemical-specific BCFs are not available at this time for any PFAS. Ecology will seek to establish BCFs for PFAS chemicals in accordance with WAC 173-340-708(9) as new scientific data becomes available.

For sites where surface water is used or could be used in the future for drinking water, the most stringent level based on potable groundwater (see cleanup levels in Section 3.2.3) and the recommended surface water quality criteria provided in Table 7 (see Chapter 5) would apply as the surface water cleanup level. In cases where surface water is non-potable, Ecology recommends applying the surface water quality criteria in Table 7 for preliminary site screening. In the absence of available surface water quality criteria, Ecology recommends applying the potable groundwater cleanup levels for preliminary site screening in accordance with

³³ <https://apps.leg.wa.gov/WAC/default.aspx?cite=173-340-730> (Surface water cleanup standards.)

WAC 173-340-720(6)(b)(i). EPA is currently developing ambient water quality criteria for PFAS under Section 304 of the [Clean Water Act](#),³⁴ and these may be applied as ARARs under MTCA once they are finalized.

3.2.5 Soil cleanup levels

WAC [173-340-740](#)³⁵ is for setting unrestricted land use cleanup levels for soil (Method B).

WAC [173-340-745](#)³⁶ is for setting cleanup levels at industrial properties (Method C).

WAC [173-340-747](#)³⁷ is for setting soil cleanup levels for groundwater protection (both Method B and Method C). The MTCA soil cleanup levels for PFAS discussed in this section are based on direct human contact through incidental ingestion, and protection of groundwater as a potable drinking water source.

Under Methods B and C, soil cleanup levels must be a) as stringent as applicable state and federal laws, b) protective of human health (soil direct contact) and the environment (i.e., terrestrial ecological receptors³⁸), and c) protective of groundwater. Additional requirements for establishing Method C cleanup levels for soil are: d) the site meets the definition of an industrial property under the MTCA Cleanup Regulations (WAC 173-340-745(1)(a)(i)), e) institutional controls are in place, and f) residual hazardous substances will not pose a threat to human health or the environment.

Default standard Method B and C cleanup levels for PFAS in soil based on protection of noncancer effects from human direct contact were calculated using [MTCA Equations 740-1](#) and [745-1](#), respectively (Table 4). Ecology calculated these levels using the RfDs that formed the basis of the Department of Health's SALs and EPA's RfD for HFPO-DA, in addition to using the associated default exposure assumptions found in Appendix A, Table A-2.

³⁴ <https://www.epa.gov/laws-regulations/summary-clean-water-act>

³⁵ <https://apps.leg.wa.gov/WAC/default.aspx?cite=173-340-740> (Unrestricted land use soil cleanup standards.)

³⁶ <https://apps.leg.wa.gov/WAC/default.aspx?cite=173-340-745> (Soil cleanup standards for industrial properties.)

³⁷ <https://apps.leg.wa.gov/WAC/default.aspx?cite=173-340-747> (Deriving soil concentrations for groundwater protection.)

³⁸ Cleanup levels based on the protection of terrestrial ecological receptors are discussed in detail in Chapter 5 of this guidance.

Table 4: Method B and C soil direct contact cleanup levels for PFAS under Washington state's MTCA Cleanup Regulations.

PFAS	Method B ³⁹	Method C ⁴⁰	Units
PFOA	0.24	11	mg/kg
PFOS	0.24	11	mg/kg
PFNA	0.2	8.8	mg/kg
PFHxS	0.78	34	mg/kg
PFBS	24	1,100	mg/kg
HFPO-DA	0.24	11	mg/kg

The cleanup levels in Table 5 are soil concentrations for both the vadose zone and saturated zone that are protective of potable groundwater. These levels were calculated using MTCA Equation 747-1 and the default soil characteristics listed in the MTCA Cleanup Regulations. Ecology used SALs as the groundwater cleanup level when available. When no SAL was available, we used the Method B equation value. Organic carbon-water partitioning coefficients (K_{oc}) and Henry's Law constants (H_{cp}) were obtained from the Oak Ridge National Labs (ORNL) database of chemical-specific parameters in their Risk Assessment Information System (RAIS⁴¹; ORNL, 2022). Soil-water distribution coefficient (K_d) values were calculated from K_{oc} values using MTCA Equation 747-2. These calculations are shown in Appendix A, Table A-3.

³⁹ Method B: Based on child exposure with a body weight of 16 kg and a soil ingestion rate of 200 mg/day.

⁴⁰ Method C: Based on adult exposure with a body weight of 70 kg and a soil ingestion rate of 50 mg/day.

⁴¹ <https://rais.ornl.gov/>

Table 5: PFAS soil concentrations protective of potable groundwater under Washington state's MTCA Cleanup Regulations.

PFAS	Vadose zone	Saturated zone	Units
PFOA	6.3E-05	4.0E-06	mg/kg
PFOS	1.7E-04	9.9E-06	mg/kg
PFNA	8.0E-05	4.8E-06	mg/kg
PFHxS	4.1E-04	2.6E-05	mg/kg
PFBS	1.8E-03	1.2E-04	mg/kg
HFPO-DA	1.0E-04	7.2E-06	mg/kg

MTCA Equation 747-1 does not account for some of the unique transport characteristics of PFAS. Because of their surfactant properties, PFAS tend to sorb preferentially to air-water and NAPL-water interfaces. Studies have shown that air-water interfaces can account for up to 100% of the PFOS and PFOA retained in soil. The K_d parameter in Equation 747-1 accounts for adsorption to organic matter in soil but does not account for interfacial sorption.

Other soil characteristics that influence PFAS sorption include pH, cation exchange capacity, and micropore volume. These characteristics are not accounted for in Equation 747-1. Soil leaching cleanup levels for PFAS are associated with a higher level of uncertainty than for other chemicals. However, soil leaching cleanup levels for PFAS will often be below practical quantitation limits, so an emphasis on attaining low quantitation limits will be more important than the accuracy of the leaching cleanup levels. Another option for evaluating the leaching pathway would be to sample groundwater, then if appropriate, use an empirical demonstration in accordance with WAC 173-340-747(9).

3.2.6 Air cleanup levels

The process outlined in WAC [173-340-750](#)⁴² is for setting cleanup levels for air. Default standard Method B and C cleanup levels for inhalation of hazardous substances in air may be calculated using MTCA Equation 750-1 for noncancer effects, in conjunction with chemical-specific inhalation RfDs and the associated default exposure assumptions. Adjustments to Equation 750-1 for calculating Method C cleanup levels are discussed in WAC 173-340-750(4).

However, air cleanup levels could not be calculated because chemical-specific inhalation RfDs are not available at this time for any PFAS compounds. Ecology will seek to establish inhalation

⁴² <https://apps.leg.wa.gov/WAC/default.aspx?cite=173-340-750> (Cleanup standards to protect air quality.)

toxicity criteria for PFAS chemicals in accordance with WAC 173-340-708(7) as new scientific data becomes available.

3.3 EPA health advisory and screening levels

This section is primarily for informational purposes, since Washington state relies on levels calculated in accordance with requirements in the MTCA Cleanup Regulations. It provides a brief overview of the drinking water lifetime health advisories (HAs) and screening levels (SLs) that EPA established for several PFAS chemicals.

3.3.1 Health Advisories

EPA health advisories identify levels that are protective of noncancer effects over a lifetime exposure to contaminants in drinking water, including sensitive subpopulations and life stages. The HAs are non-enforceable and non-regulatory but provide technical information to drinking water system operators and officials in federal, state, tribal, and local governments about the health effects, analytical methods, and treatment technologies associated with contaminated drinking water (EPA, 2022c).

EPA initially developed provisional HAs for PFOS and PFOA in 2009 in response to levels detected in public drinking water systems (EPA, 2009). Developments since then:

- **May 2016.** Based on an assessment of newer science and toxicological data, EPA issued finalized lifetime HAs of 70 ng/L for PFOS and PFOA individually, as well as for the two chemicals combined (EPA, 2016a; 2016b).
- **June 2022.** EPA issued interim updated HAs for PFOS and PFOA, and final HAs for HFPO-DA (GenX) and PFBS (EPA, 2022c). The interim updated HAs for PFOS and PFOA are based on new studies and are several orders of magnitude lower than the 2016 HA (0.02 ng/L for PFOS, and 0.004 ng/L for PFOA). EPA's final HAs for HFPO-DA and PFBS are 10 ng/L and 2,000 ng/L, respectively.

EPA calculated the HAs for a drinking water exposure scenario using a chronic oral reference dose (RfD⁴³) to affectively achieve a hazard quotient (HQ) of 1. Methods for deriving the oral RfDs are found in EPA's [June 2022 technical fact sheet](#)⁴⁴ that discusses HAs for four PFAS compounds (EPA, 2022c). In the HA calculation, EPA applied a relative source contribution (RSC) of 20% for drinking water ingestion to allow for exposure from other sources such as

⁴³ An oral reference dose is an estimate of a daily oral intake not anticipated to cause adverse health effects over a lifetime (including sensitive subgroups). RfDs are developed for noncancer endpoints (DOH, 2021a).

⁴⁴ <https://www.epa.gov/sdwa/drinking-water-health-advisories-has#health>

food, dust, and soil. EPA then applied their Exposure Decision Tree to identify appropriate RSCs for each PFAS compound (EPA, 2000). Application of the RSCs assumes that exposure from contaminated drinking water accounts for only a portion (i.e., 20%) of the permissible dose (i.e., the oral RfD), and exposures from other sources account for 80% (EPA, 2022c). As a result, the protective drinking water level is lowered by 80% to generate the HAs. EPA uses the equation below to derive lifetime noncancer HAs.

HA Equation

$$\text{Lifetime HA} = \frac{RfD_o \times RSC}{DWIR/BW}$$

Definitions

HA = Drinking Water Health Advisory (mg/L)

BW = Average Body Weight (kg)

RfD_o = Oral Reference Dose (mg/kg-day)

DWIR = Drinking Water Ingestion Rate (liters/day)

RSC = Relative Source Contribution (20%)

DWIR/BW = Liters/kilogram-day⁴⁵

In December 2019, EPA issued [Interim recommendations for addressing groundwater contaminated with PFOA and PFOS](#)⁴⁶ at sites that were being evaluated and managed by federal cleanup programs (EPA, 2019a). Their guidance used the 2016 HA of 70 ng/L as the recommended Preliminary Remediation Goal (PRG)⁴⁷ for both PFOS and PFOA in groundwater that is a current or potential source of drinking water, where no state or tribal MCL, or other applicable or relevant and appropriate requirements (ARARs), are available or sufficiently protective.

Note: Due to the updated interim HAs for PFOS and PFOA in 2022, EPA no longer recognizes 70 ng/L as the PRG for these PFAS compounds. They are in the process of determining how the updates impact recommendations in their December 2019 memo.

In March 2020, EPA published its proposed *Preliminary regulatory determinations for PFOS and PFOA in drinking water* under the Safe Drinking Water Act.⁴⁸ EPA made a final determination in March 2021 to regulate PFOS and PFOA, and is moving forward to develop a National Primary

⁴⁵ EPA uses a 90th percentile drinking water ingestion rate that is adjusted for body weight (in units of L/kg-day). Values are provided in the June 2022 HA Fact sheet (EPA, 2022c).

⁴⁶ <https://www.epa.gov/pfas/interim-recommendations-addressing-groundwater-contaminated-pfoa-and-pfos>

⁴⁷ PRGs are generally initial targets for cleanup under federal cleanup programs, which may be adjusted on a site-specific basis as more information becomes available (EPA, 2019a).

⁴⁸ Announcement of Preliminary Regulatory Determinations for Contaminants on the Fourth Drinking Water Contaminant Candidate List, Vol. 85 Fed. Reg. No. 47, pg. 14098 (March 10, 2020).

Drinking Water Regulation (NPDWR) for these two PFAS chemicals.⁴⁹ An NPDWR sets a legal limit (called an MCL) or specifies a certain treatment technique (TT) for public water systems for a specific contaminant or group of contaminants.

EPA published a Notice of Proposed Rulemaking to designate PFOS and PFOA as CERCLA hazardous substances in September 2022. The final rule is expected in 2023 (EPA, 2021c).

Note: Ecology is not using the EPA HALs as preliminary cleanup levels because: 1) the levels for PFOA and PFOS are interim and subject to change, 2) the PFBS level exceeds the DOH SAL, and 3) the approach used to determine the level for HFPO-DA is not consistent with the process set out in the MTCA Cleanup Regulations.

3.3.2 Screening Levels

Federal programs such as Superfund incorporate the use of risk-based Screening Levels (SLs). EPA established SLs for six PFAS compounds: PFOS, PFOA, PFNA, PFHxS, PFBS, and HFPO-DA (GenX). The SLs are maintained in [EPA's Regional Screening Level \(RSL\) tables](#),⁵⁰ and are primarily used at CERCLA sites for screening chemicals to determine whether levels of contamination in site media may warrant further investigation or cleanup.

EPA provides SLs that are based on a cancer risk of 1×10^{-6} , and noncancer HQs of 1 and 0.1.⁵¹ In the case of PFAS compounds, EPA recommends using a noncancer HQ of 0.1 for screening to account for cumulative effects from multiple PFAS compounds that may be present (EPA, 2019a).

All PFAS compounds listed in EPA's RSL table have SLs based on noncancer effects, and only PFOA has an SL based on cancer risk. The cancer-based SL for PFOA is based on an oral CSF of 0.07 kg-day/mg. This CSF and several other candidate CSFs were derived by EPA's Office of Water in 2016, and at the time it was determined that the HA based on noncancer effects is protective for the cancer endpoint (EPA, 2016b).

As a result, EPA did not select one overall CSF for developing a cancer-based PFOA HA (based on a 1×10^{-6} cancer risk) (EPA, 2022a). As of the date of this document, the PFOA noncancer-based tap water SL of 60 ng/L (at an HQ = 1) is more than an order of magnitude

⁴⁹ Announcement of Final Regulatory Determinations for Contaminants on the Fourth Drinking Water Contaminant Candidate List, Vol. 86 Fed. Reg. No. 40, pg. 12272 (March 3, 2021).

⁵⁰ <https://www.epa.gov/risk/regional-screening-levels-rsls>

⁵¹ A noncancer SL @ HQ 0.1 is derived by dividing the SL @ HQ 1 by 10.

lower than its corresponding cancer-based SL of 1,100 ng/L (at a risk level = 1×10^{-6}). As previously noted, EPA is evaluating available toxicity data to derive a CSF for PFOA as part of the National Primary Drinking Water Regulation (EPA, 2022a).

EPA's RSL table contains PFAS SLs based on a) human direct contact with residential and industrial soil, b) soil concentrations that are protective of groundwater, and c) human exposure to tap water. PFAS soil and tap water SLs consider cumulative exposure via ingestion and dermal contact. Equations and exposure assumptions for calculating the SLs are provided in Section 4 of EPA's [RSL User's Guide](#).⁵²

Note: Unlike for the development of health advisories, risk-based EPA screening levels assume that all of the exposure is from tap water ingestion (i.e., the relative source contribution is 100%). This is the same assumption used in MTCA cleanup level equations for drinking water ingestion.

IRIS assessments currently underway

EPA is currently conducting IRIS toxicity assessments on perfluorodecanoic acid (PFDA), perfluorononanoic acid (PFNA), perfluorohexanoic acid (PFHxA), perfluorohexane sulfonic acid (PFHxS), and perfluorobutanoic acid (PFBA). The IRIS assessments will identify the potential human health effects from exposure to each PFAS chemical, and will derive toxicity values that may be used for developing EPA SLs and MTCA cleanup levels. The IRIS assessments will evaluate both cancer and noncancer effects. For information about the PFAS chemicals identified for assessment in IRIS, visit https://iris.epa.gov/AtoZ/?list_type=erd

3.4 Ecology's historical PFAS Investigatory Levels (now superseded)

In 2018, local agencies in Issaquah wanted to proactively clean up PFAS groundwater contamination and asked for guidance from Ecology to inform their decision-making. Ecology's Northwest Regional Office assisted Headquarters staff by calculating the following Investigatory Levels (ILs) for PFOS and PFOA, which are summarized in Table 6.

These ILs were developed in 2018 but following the promulgation of the Department of Health's SALs, Ecology no longer uses them. We're providing them here for background and informational purposes only.

⁵² <https://www.epa.gov/risk/regional-screening-levels-rsls-users-guide>

Table 6: Historical PFAS soil and groundwater investigatory levels developed for PFOS and PFOA in 2018, now superseded. Ecology stopped using these levels after Washington State Department of Health's State Action Levels became effective January 1, 2022.

Medium	Scenario	PFOS	PFOA	Units
Groundwater	Potable	70	70	ng/L
Soil	Unrestricted (residential) contact	1.6	1.6	mg/kg
Soil	Industrial contact	70	70	mg/kg
Soil	Leaching from the vadose zone	8.0×10^{-4}	4.4×10^{-4}	mg/kg
Soil	Leaching from the saturated zone	4.6×10^{-5}	2.8×10^{-5}	mg/kg

Chapter 4: Sampling for PFAS

4.0 Overview

Sampling and analysis of PFAS in environmental media have many challenges due to their ubiquitous nature and low screening/cleanup levels (sometimes in the low parts per trillion range). Methods for analyzing PFAS are still evolving, as well. This chapter summarizes sampling approaches for PFAS and provides analytical methods for environmental media, best practices for collecting representative samples and minimizing cross-contamination, and recommendations for when to sample for PFAS at a MTCA site.

4.1 General sampling approaches

Sampling for PFAS follows the same general approach as for other chemicals, but with additional considerations based on the challenges noted above. General protocols for PFAS sampling are summarized in Sections 11.1.1 through 11.1.7 of the [Interstate Technology and Regulatory Council \(ITRC\) PFAS guidance](#)⁵³ (ITRC, 2022), as well as in their fact sheets about site characterization, sampling precautions, and laboratory analytical methods (ITRC, 2022a; 2022b). ITRC intends to update their PFAS guidance as new data becomes available, so check their documents periodically for recent information and direction. Two other good sampling resources are:

1. **General PFAS Sampling Guidance** developed by the Michigan Department of Environmental Quality (MDEQ, 2018), along with media-specific PFAS sampling guidance located on their website:
<https://www.michigan.gov/pfasresponse/investigations/sampling-guidance>.
2. **PFAS sampling guidance** developed by the State of California Water Boards (CWB) for drinking water⁵⁴ and non-drinking water sources⁵⁵ (CWB, 2020a; 2020b).

Consistent with standard protocols for environmental investigation and WAC [173-340-820](#),⁵⁶ a sampling and analysis plan (SAP) and a site-specific Quality Assurance Project Plan (QAPP) need to be developed before conducting PFAS sampling. The QAPP and SAP should address any PFAS-specific considerations in addition to requirements surrounding analytical methods and quality control (QC). [Ecology's Quality Assurance](#)⁵⁷ webpage has guidance on developing

⁵³ <https://pfas-1.itrcweb.org/>

⁵⁴ https://www.waterboards.ca.gov/pfas/drinking_water.html

⁵⁵ https://www.waterboards.ca.gov/pfas/non_drinking_water.html

⁵⁶ <https://apps.leg.wa.gov/WAC/default.aspx?cite=173-340-820> (Sampling and analysis plans.)

⁵⁷ <https://ecology.wa.gov/About-us/How-we-operate/Scientific-services/Quality-assurance/Quality-assurance-for-NEP-grantees>

QAPPs for environmental investigation. Some important PFAS sampling considerations that should be reflected in the QAPP/SAP are:

4.1.1 Assemble a complete PFAS analyte list

At the time we published this guidance, screening levels/cleanup levels were only available for the six PFAS chemicals described in Chapter 3. As more toxicity information becomes available and assessments are completed, the list of PFAS compounds with screening or cleanup levels will expand. Therefore, Ecology recommends analyzing for a comprehensive set of PFAS compounds, consistent with current, available analytical methods and laboratory capabilities. This will allow future assessment of the site once additional screening/cleanup levels for the other PFAS chemicals have been established.

4.1.2 Use accredited laboratory analytical methods

Work closely with an [Ecology-accredited laboratory](#)⁵⁸ to ensure that whenever possible, the analytical methods achieve reporting limits that meet media-specific PFAS screening/cleanup levels. Section 4.3.1 summarizes the available analytical methods. More detail is provided in Section 11.2 of the ITRC PFAS guidance (ITRC, 2021), where the methods and other relevant information are summarized in downloadable Microsoft Excel tables (Tables 11-2 to 11-5). ITRC intends to periodically update the tables as new information becomes available. Find the resources on their [PFAS webpage](#).⁵⁹

4.1.3 Minimize cross contamination

Due to the ubiquitous nature of PFAS, as well as their very low screening/cleanup levels, PFAS sampling requires extra precautions to reduce the potential for cross contamination and false positive sample results. Section 4.4 provides options for minimizing this potential.

4.1.4 Collect field QC samples

Collecting field QC samples is an important element for any environmental sampling and is especially necessary for PFAS compounds. Sample collection and decontamination procedures should be designed and implemented to minimize introduction of PFAS into the sample. Collection of field blanks and equipment rinsate blanks are important for assessing potential cross contamination that may influence the interpretation of sample results. Field duplicates are used to assess the overall precision of sampling and analysis techniques. These types of QC samples are described in more detail in Section 4.4.3 of this document, and Section 11.1.6 of ITRC's PFAS guidance (ITRC, 2021)

⁵⁸ <https://ecology.wa.gov/Regulations-Permits/Permits-certifications/Laboratory-Accreditation/How-to-choose-an-analytical-laboratory> (Choosing an analytical laboratory)

⁵⁹ <https://pfas-1.itrcweb.org/>

4.2 Approved methods and compound list for drinking water

EPA has validated and published three methods (533, 537, and 537.1) to support the analysis of PFAS in drinking water. All three methods utilize solid phase extraction followed by analysis via liquid chromatography-tandem mass spectrometry (LC-MS/MS). [Method 537](#)⁶⁰ (published in 2009) was used extensively during EPA's UCMR3 sampling conducted between 2013 and 2015 and included 14 PFAS compounds. This method was updated in November 2018 to [Method 537.1](#)⁶¹ and can be used to analyze 18 PFAS compounds. [Method 533](#)⁶² was finalized in December 2019 and focused on shorter chain PFAS compounds. Both methods 533 and 537.1 measure all six PFAS with Ecology cleanup levels.

Method 533 includes all but four of the PFAS compounds listed in Method 537.1, for a total of 25 PFAS. When combined, Methods 537.1 and 533 may be used to measure up to 29 PFAS in drinking water—see Table 11.4 in ITRC's PFAS guidance (ITRC, 2021). When analyzing the PFAS compounds that are found in both methods, Method 533 is generally preferred over 537.1 because it uses a more robust method of quantitation (isotope dilution).

Protocols for sampling PFAS in drinking water are provided in EPA Methods 537.1 and 533, which include discussions on sample bottle preparation, sample collection, field reagent blanks, sample shipment and storage, and sample and extraction holding times. Section 11.1.7.1 of ITRC's PFAS guidance specifically addresses sampling of potable drinking water sources.

4.3 Options for unfinished aqueous and solid matrices

EPA Methods 537.1 and 533 are only approved and validated for finished drinking water (i.e., water ready to drink) that has low total suspended solids (TSS) and total dissolved solids (TDS). These methods are not designed for unfinished water (e.g., untreated surface water or groundwater), soil, or other media that could significantly interfere with the analytical procedures. Analytical options for media other than drinking water are discussed below. Protocols for sampling groundwater, surface water, porewater, sediment, surface soil, subsurface soil, fish, and air are provided in Sections 11.1.7.2 to 11.1.7.9, respectively, in the ITRC PFAS guidance (ITRC, 2022).

4.3.1 Current analytical options

EPA validated and published [SW-846 Method 8327](#)⁶³ in July 2021 (EPA, 2021b). Method 8327 is a direct injection method for non-drinking aqueous matrices (groundwater, surface water, and

⁶⁰

https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NERL&dirEntryId=198984&simpleSearch=1&searchAll=EPA%2F600%2FR-08%2F092+

⁶¹ https://cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryId=343042&Lab=NERL

⁶² <https://www.epa.gov/dwanalyticalmethods/method-533-determination-and-polyfluoroalkyl-substances-drinking-water-isotope>

⁶³ <https://www.epa.gov/hw-sw846/sw-846-test-method-8327-and-polyfluoroalkyl-substances-pfas-liquid-chromatographytandem>

wastewater) and has been validated for 24 PFAS chemicals. This method uses liquid chromatography/tandem mass spectrometry (LC/MS/MS) and external standards for quantitation (instead of isotope dilution or internal standards). Although the overall quality is less than if isotope dilution were used for quantification, EPA developed this method to find a balance between sensitivity, ease of implementation, and monitoring requirements.

Many laboratories have developed their own user-defined methods to analyze non-drinking water media. Some laboratories refer to their user-defined method as “537 Modified” if they are based on the existing EPA method(s). However, it is important to note that deviations from the procedures listed in 537 or 537.1 are not considered an approved, validated method by EPA.

When developing user-defined methods to analyze for PFAS compounds, some laboratories use the [U.S. Department of Defense/U.S. Department of Energy Quality Systems Manual \(QSM\) for Environmental Laboratories, Version 5.4](#)⁶⁴ (QSM 5.4) to set required QA/QC performance criteria (DOD, 2021). According to ITRC’s PFAS guidance, DOD’s QSM (specifically Appendix B, Table B-15) provides the most current and comprehensive set of quality standards for PFAS analysis (ITRC, 2021). DOD’s QSM requires isotope dilution quantitation of PFAS compounds and provides for specific quality processes for sample preparation, instrument calibration, and analysis for aqueous, solid, and biological matrices (DOD, 2021).

Based on the above information, Ecology recommends using the analytical⁶⁵ and QA/QC performance criteria set forth in Table B-15 of DOD’s QSM 5.4 for analyzing PFAS in non-drinking water media. Ecology-accredited laboratories with user-defined methods that are compliant with Table B-15 of DOD’s QSM 5.4 are preferred for non-drinking water aqueous samples.

4.3.2 Non-specific test methods

Due to the large number of PFAS compounds and the limited number that can currently be quantified, it can be helpful to use non-specific test methods to get a better understanding of the full extent of PFAS present and how they might affect the sampling results. These test methods should typically be used for situations where the source of the release is unknown or where only limited information is available.

Probably the most common non-specific test method is the Total Oxidizable Precursors (TOP) assay, and is used to help identify PFAS compounds that can be converted into PFAA end products that won’t degrade further. This can be important because not all the PFAS present

⁶⁴ <https://denix.osd.mil/edqw/documents/manuals/qsm-version-5-4-final/>

⁶⁵ Liquid Chromatography Tandem Mass Spectrometry (LC/MS/MS) with Isotope Dilution.

will be quantified regardless of the analytical method used, and other sub-classes of PFAS can degrade to PFAAs in the environment over time.

This is not an approved EPA Method but can provide additional information to help determine the total quantity of PFAS present. Section 11.2.2 of the ITRC PFAS guidance provides a detailed discussion on this and several other non-specific test methods (ITRC, 2021).

4.3.3 Future analytical options

EPA is collaborating with DOD to develop and validate [EPA Method 1633](#),⁶⁶ which is an LC-MS/MS isotope dilution method for non-drinking water aqueous matrices such as surface water, groundwater, wastewater influent/effluent, and landfill leachate, as well as fish tissue, biosolids, soil, and sediment. EPA Method 1633 will include 40 PFAS compounds with a target quantitation limit of 2 ng/L. This method is anticipated to be generally compliant with DOD's QSM 5.4 Table B-15. EPA draft Method 1633 was published in September 2021 and will undergo a multi-laboratory validation study that is expected to be completed in early 2023.

4.4 Approaches to minimize cross-contamination

Initial PFAS guidance documents often contained lists of materials with fluoropolymer components that should be avoided during sampling to minimize the potential for cross-contamination. These lists often included sampling equipment as well as other products, such as rain gear, food containers, and personal protective equipment that do not come in direct contact with the sample but were thought to be able to contribute to cross-contamination.

More recently, testing completed by Denly et al. (2019) and Rodowa et al. (2020) helps determine the potential for cross-contamination. This testing documented that, in many cases, the evaluated materials do not leach detectable levels of PFAS compounds. However, because this testing was limited, challenges still exist for ensuring sample integrity is maintained.

4.4.1 Materials that may contact the samples

When materials can come in direct contact with a sample, take the necessary actions to document the equipment is free from PFAS-containing substances. This should include either testing to ensure the equipment does not leach PFAS compounds or obtaining information from the manufacturer that their equipment is PFAS-free. Information about PFAS-free products can be found in MDEQ's [General PFAS Sampling Guidance](#)⁶⁷ and [PFAS Central website](#)⁶⁸ (MDEQ, 2018; PFAS Central, 2020).

⁶⁶ <https://www.epa.gov/cwa-methods/cwa-analytical-methods-and-polyfluorinated-alkyl-substances-pfas#draft-method-1633>

⁶⁷ https://www.michigan.gov/documents/pfasresponse/General_PFAS_Sampling_Guidance_634597_7.pdf

⁶⁸ <https://pfascentral.org/pfas-free-products/>

Before sampling, contact the laboratory to determine whether the materials they provide, such as sampling containers and distilled water, are certified as PFAS-free. If a separate source of rinse water will be used (i.e., water that is not certified as PFAS-free water supplied by the laboratory), at least one sample of that water should be collected and analyzed using the same analytical method and same compound list as for field samples collected at the site.

4.4.2 Other onsite materials that may contain PFAS

For those materials that do not directly contact the sample, a combination of two or all three of the following options can minimize the chance for cross-contamination:

1. Obtain information from the manufacturer on whether the materials are PFAS-free.
2. Implement a QA/QC program that includes a sufficient number of field blanks (see Section 4.4.3 below) to determine if these materials could introduce PFAS compounds into samples.
3. If sampling materials cannot be documented as PFAS-free, limit their use as much as possible.

Given the widespread presence of fluoropolymers, the low laboratory detection levels, and the cost for PFAS analysis, take extra care to ensure data quality is not compromised.

4.4.3 Recommended sampling procedures to minimize cross-contamination

To help minimize the potential for cross-contamination, Ecology recommends devoting a section in the project sampling and analysis plan (SAP) for identifying which specific PFAS sampling procedures will be used. The quality assurance project plan (QAPP) should identify all PFAS-specific quality control samples that will be taken.

If there is historical information about PFAS levels at the site, the preferred sampling sequence should start in areas with the least contamination, then move to more contaminated areas. During the sampling event, liquid PFAS samples should be collected first. For solid phase PFAS samples that are also targeted for VOC analysis, consider collecting the VOC sample first to limit the potential for contaminant volatilization.

When sampling for PFAS, Ecology recommends collecting the following field quality control samples:

1. **Trip blanks.** One trip blank for each cooler to assess whether contamination is introduced during sample shipment.
2. **Rinse blanks.** One sample collected from the last rinse each day for each type of sampling equipment used for each matrix, to assess the adequacy of the decontamination process.

3. **Duplicate samples.** A minimum of 10% (1 per 10) of the samples for each matrix should be collected in duplicate, but not less than one duplicate per sampling event per matrix to assess precision of the entire effort, including sampling, analysis, and site heterogeneity. Field duplicates should be submitted as discrete samples (i.e., given unique sample identification so the laboratory isn't aware the sample is a duplicate), and should be clearly noted in the field log. More frequent collection of duplicate samples from heterogeneous media—such as soil or sediments where homogenization of samples cannot be performed—should be assessed on a case-by-case basis.
4. **Field blanks.** One PFAS-free field blank sample should be collected daily where the risk for PFAS sample cross-contamination is the most likely, to evaluate the potential for contaminants to be introduced during sample collection, storage, and transport. Options: before the first sample is collected in the morning, before the first sample is collected after lunch, or where the potential for cross-contamination is determined to be the highest.
5. **Pre-field work blanks.** Prior to field work, collect rinse samples from each piece of equipment not certified as PFAS-free, which will be in contact with the samples to be analyzed prior to the start of the field sampling effort.

Potential sources for PFAS cross-contamination should be identified in the field notes. Actions to address these situations should be documented in the data validation section of the sampling report, such as collecting additional quality control samples or making changes to sample handling and decontamination procedures.

Note: Ecology recommends not using sampling devices that contain Teflon (PFTE) or other fluorine containing plastics. If the critical sampling equipment contain fluorinated plastics, collect a pre-field rinse blank to confirm that PFAS do not leach into the sample.

4.5 When to require PFAS sampling and what compounds to sample

4.5.1 Industries where PFAS may be encountered

Table 2.5 in ITRC's [PFAS guidance](#)⁶⁹ and Appendix 3 in Ecology's [PFAS Chemical Action Plan](#)⁷⁰ identify industries where PFAS compounds are commonly used or suspected to be used, and how likely they are to be encountered (ITRC, 2021; Ecology, 2021). Section 2.6 of the ITRC PFAS guidance provides a detailed discussion of potential sources of PFAS compounds

⁶⁹ <https://pfas-1.itrcweb.org/2-5-pfas-uses/>

⁷⁰ <https://apps.ecology.wa.gov/publications/summarypages/2104048.html>

to the environment. The multitude of PFAS compounds and variety of their applications necessitate looking at each facility or site on a case-by-case basis.

On January 1, 2022, a new ASTM Environmental Site Assessment (ESA) standard (E1527-21) became effective that added guidance for considering PFAS when completing an ESA. On March 14, 2022, EPA published a direct final rule to incorporate [ASTM E1527-21](https://www.astm.org/e1527-21.html)⁷¹ into the “all appropriate inquiry” procedures. While the reference to the previous standard (E1527-13) wasn’t changed, EPA issued concurrent guidance that allows for using either ASTM standard depending on the situation. Since PFAS compounds are hazardous substances in Washington state, their potential presence should be part of a Phase I evaluation. Trade names or generic descriptions are often used when describing these compounds in the manufacturing process, so give special consideration to employee interviews and carefully review invoices, material usage records, and material safety data sheets when completing a Phase I ESA.

4.5.2 Recommendations for obtaining comprehensive PFAS data

Section 4.2 in this guidance identifies the analytical methods currently approved for analyzing PFAS in finished drinking water. For drinking water samples, if the source of PFAS contamination is unknown or could include short and long chain PFAS compounds, Ecology recommends using both Method 533 and 537.1 to provide a comprehensive assessment of the potential for PFAS impacts.

As of November 2022, the only EPA-approved method for analyzing PFAS in non-drinking water samples was Method 8327. While this is an approved EPA method, it doesn’t use isotope dilution and has been viewed by many as a less preferred sample analysis method.

The Department of Defense has its own accreditation program for PFAS analyses and as discussed in Section 4.3.1, Ecology recommends using the analytical⁷² and QA/QC performance criteria set forth in Table B-15 of DOD’s QSM 5.4 for analyzing PFAS in non-drinking water media. Ecology-accredited laboratories that have user-defined methods consistent with Table B-15 in DOD’s QSM 5.4 are preferred when analyzing media other than finished drinking water. If other PFAS compounds require analysis beyond those mentioned elsewhere in this chapter, Ecology recommends contacting the laboratory before sampling to discuss what options are available for generating the necessary data.

Note: As discussed in Section 4.3.3, EPA is currently validating Method 1633, which will provide a comprehensive test method for non-drinking water and solid matrices. EPA hopes to have this method finalized in early 2023, so be sure to check the availability of this method before sampling. Ecology’s Laboratory Accreditation Unit has already begun accrediting labs for Draft 2 of EPA Method 1633.

⁷¹ <https://www.astm.org/e1527-21.html>

⁷² Liquid Chromatography Tandem Mass Spectrometry (LC/MS/MS) with Isotope Dilution.

Chapter 5: Protective Concentrations for Ecological Receptors

5.0 Introduction

Establishing protective concentrations for ecological receptors is an essential aspect of site cleanup work under the Model Toxics Control Act (Ecology, 2001a in Appendix B). Current research suggests that PFAS compounds are globally distributed in the environment and biota (e.g., plants, algae, invertebrates, mammals, birds, fish), including locally in Washington state. Both short- and long-chain PFAS are environmentally persistent. They bioaccumulate and the effects on ecological receptors range from subtle alterations in gene expression to deficits in apical endpoints (e.g., growth, survival, reproduction). Ecology's [PFAS Chemical Action Plan](#)⁷³ includes the following recommendations in Appendix 6: Ecotoxicology of PFAS (Ecology, 2021):

- Selected individual PFAS, as well as common PFAS mixtures, should be evaluated for ecotoxicity in aquatic and terrestrial biota, using both laboratory and field methods; and
- Cleanup levels should ultimately be developed for PFAS (individually and potentially as mixtures) for soil, sediment, freshwater, and saltwater to protect ecological receptors.

The development and determination of protective concentrations for ecological receptors in both surface waters (marine and freshwater) and upland soil should help achieve these goals. The protective concentrations that appear in this chapter were developed according to the MTCA Cleanup Regulations, guidance, and policy (Ecology, 2001a; Ecology, 2001b in Appendix B).

Note: Use of the terms “Concentration” and “Level.” Throughout this chapter, we reference the amount of chemical exposure in a study using the terms *concentration* and *level*. For example, the terms *Lowest Observed Adverse Effects Concentration* (LOAEC) and *Lowest Observed Adverse Effects Level* (LOAEL) are used to describe a similar concept, which is the lowest amount of chemical exposure in a study that resulted in significant effects to the exposed organisms. The term that best applies to a specific study is determined by the exposure route. *Concentration* is used for studies where the exposure is through an external medium, like plants growing in contaminated soil or fish swimming in contaminated water. *Level* is used for studies where the exposure is through ingestion, like most mammalian and avian toxicity studies.

⁷³ <https://apps.ecology.wa.gov/publications/SummaryPages/2104048.html>

5.1 Surface water

As of the date of this guidance document, environmental effects-based concentrations for PFAS compounds have not been established under applicable state or federal laws. Consequently, you must establish cleanup levels as provided in the MTCA Cleanup Regulations. Those cleanup levels must have either **no adverse effect** (under Method B) or **no significant adverse effect** (under Method C) on the protection and propagation of wildlife, fish, and other aquatic life.

5.1.1 Applicable Regulatory Authority

WAC [173-340-730\(3\)\(b\)\(ii\)](#)⁷⁴ **Environmental effects.** For hazardous substances for which environmental effects-based concentrations have not been established under applicable state or federal laws, concentrations that are estimated to result in no adverse effects on the protection and propagation of wildlife, fish, and other aquatic life.

Whole effluent toxicity testing using the protocols described in Chapter [173-205 WAC](#)⁷⁵ may be used to make this demonstration for fish and aquatic life.

The concentrations included in this chapter are predicted to have **no observed adverse effect** based on a literature review. These protective values should be used when establishing an environmental-effects-based water concentration for sites with PFAS contamination in surface water or for groundwater with the potential to discharge to surface water. If these values are not used, site-specific cleanup levels will need to be established as provided in the regulation (e.g., whole effluent toxicity testing using the protocols described in Chapter 173-205 WAC). In short, Chapter 5 of this guidance provides an off-ramp (screening tool) for some sites to avoid costly environmental studies.

5.1.2. Decision-making process

Table 7 contains a summary of the protective concentrations for marine and fresh surface waters. These protective concentrations were determined by a review of estimated no adverse effects on the protection and propagation of fish, invertebrates, and other aquatic life found in relevant literature. It is important to note that the documented protective concentration is not necessarily the lowest No Observed Effects Concentration (NOEC), but instead represents a value that was chosen to be protective of the individual class of receptors (fish, invertebrates, other) that is also below a Lowest Observed Effects Concentration (LOEC).

Note: Appendix B includes a review of the relevant literature and provides a description of how the levels in Table 7 meet the surface water regulations described in Section 5.1.1.

⁷⁴ <https://apps.leg.wa.gov/WAC/default.aspx?cite=173-340-730> (Surface water cleanup standards.)

⁷⁵ <https://apps.leg.wa.gov/WAC/default.aspx?cite=173-205> (Whole effluent toxicity testing and limits.)

5.2 Uplands

As of the date of this guidance document, soil concentrations for PFAS compounds have not been listed in Table 749-3. Consequently, you must establish protective soil concentrations as provided for in the MTCA Cleanup Regulations.

5.2.1 Applicable Regulatory Authority

WAC [173-340-7493\(3\)\(a\)](#)⁷⁶ **Literature Survey.** An analysis based on a literature survey shall be conducted in accordance with subsection (4) of this section and may be used for purposes including the following:

- (i) Developing a soil concentration for chemicals not listed in Table 749-3.
- (ii) Identifying a soil concentration for the protection of plants or soil biota more relevant to site-specific conditions than the value listed in Table 749-3.
- (iii) Obtaining a value for any of the wildlife exposure model variables listed in Table 749-5 to calculate a soil concentration for the protection of wildlife more relevant to site-specific conditions than the values listed in Table 749-3.

WAC [173-340-7493\(4\)](#) Literature surveys. (a) Toxicity reference values or soil concentrations established from the literature shall represent the lowest relevant LOAEL found in the literature. Bioaccumulation factor values shall represent a reasonable maximum value from relevant information found in the literature. In assessing relevance, the following principles shall be considered:

- (i) Literature benchmark values should be obtained from studies that have test conditions as similar as possible to site conditions.
- (ii) The literature benchmark values or toxicity reference values should correspond to the exposure route being assessed.
- (iii) The toxicity reference value or bioaccumulation factor shall be as appropriate as possible for the receptor being assessed. The toxicity reference value should be based on a significant endpoint, as described in subsection (2) of this section.
- (iv) The literature benchmark value or toxicity reference value should preferably be based on chronic exposure.
- (v) The literature benchmark value, toxicity reference value, or bioaccumulation factor should preferably correspond to the chemical form being assessed. Exceptions may apply for toxicity reference values where documented biological transformations occur following uptake of the chemical or where chemical transformations are known to occur in the environment under conditions appropriate to the site.

⁷⁶ <https://apps.leg.wa.gov/WAC/default.aspx?cite=173-340-7493> (Site-specific terrestrial ecological evaluation procedures.)

(b) A list of relevant journals and other literature consulted in the survey shall be provided to the department. A table summarizing information from all relevant studies shall be provided to the department in a report, and the studies used to select a proposed value shall be identified. Copies of literature cited in the table that are not in the possession of the department shall be provided with the report. The department may identify relevant articles, books, or other documents that shall be included in the survey.

5.2.2. Literature review

The concentrations included in this chapter are predicted to be protective based on a literature review. You should use these protective values when you need to establish an environmental-effects-based upland soil concentration for sites with PFAS contamination. If you don't use these values, you will need to establish site-specific cleanup levels as provided in the regulation (e.g. site-specific terrestrial ecological evaluation procedures in WAC 173-340-7493). In short, Chapter 5 of this guidance provides an off-ramp (screening tool) for some sites to avoid costly environmental studies.

Note: Appendix B includes a review of the relevant literature and provides a description of how the levels in Table 7 meet the regulations for determining upland soil concentrations protective of ecological receptors.

5.2.3. Decision-making process

Table 7 contains a summary of the protective concentrations that were established for upland ecological receptors. Literature was reviewed with a focus on determining relevant lowest observed adverse effect levels for wildlife. Relevant effects included significant impacts on apical endpoints (survival, growth, reproduction) relative to controls. The lowest relevant LOAEC or LOAEL identified in the literature was generally selected as the toxicity reference value. Toxicity reference values were not established for PFAS compounds when only one LOAEL was identified in the literature.

Plant and soil biota protective concentrations were determined based entirely on LOAECs identified in the literature review. The methods in Efroymsen et al. (1997a, 1997b) were used to determine how toxicity reference values were determined for plants and soil invertebrates, consistent with how the values in MTCA Table 749-3 were derived. Since fewer than 10 LOAEC values were identified for each PFAS compound, the lowest LOAEC identified in the literature was selected as the toxicity reference value, as opposed to using the 10th percentile of literature LOAEC values. Consistent with the derivation of values in Table 749-3, only toxicity studies in earthworms were considered when deriving a soil biota protective value.

Wildlife protective concentrations were established based on the Wildlife Exposure Model described in WAC 173-340-7493(3)(c) and tables [749-4](#)⁷⁷ and 749-5 in MTCA. The equations included in the model allow the calculation of protective soil concentrations for a mammalian herbivore (vole), mammalian predator (shrew), and avian predator (robin). Literature-derived values included toxicity reference values for both mammals and birds, earthworm bioaccumulation, and plant uptake. Toxicity reference values for birds and mammals are based on LOAELs identified in the literature.

For mammalian species, to account for differences between laboratory and wildlife species, allometric scaling was applied to toxicity reference values. This was done using the equations in Sample et al. (1996), consistent with the derivation of values in Table 749-3. The reference values for rat, mouse, shrew, and vole body weight were used in the calculations. This resulted in different toxicity reference values for voles and shrews for each PFAS compound.

The literature review provided enough data to establish at least one protective value (plant, soil biota, and/or wildlife) for eight individual PFAS compounds: PFBS, PFHxS, PFOS, PFHxA, PFOA, PFNA, PFDA, and PFDaA.

⁷⁷ <https://apps.leg.wa.gov/WAC/default.aspx?cite=173-340-900> (Tables.)

Table 7: PFAS concentrations protective of ecological receptors in surface waters and upland soils.

Contaminant	Organism	PFBS	PFDA	PFNA	PFHxA	PFHxS	PFOA	PFOS	PFBA	PFUnA	PFDoA
Marine (µg/L)	Invertebrates	1.27E+05	7.80E+01	1.04E+01	x	x	5.94E+02	3.30E+01	x	x	x
Marine (µg/L)	Fish	x	x	x	x	x	1.50E+03	1.50E+01	x	x	x
Marine (µg/L)	Other	x	x	x	x	x	1.19E+02	1.10E+00	x	x	x
Marine (µg/L)	Total protection	1.27E+05	7.80E+01	1.04E+01	x	x	1.19E+02	1.10E+00	x	x	x
Freshwater (µg/L)	Invertebrates	5.02E+05	1.00E+01	8.00E+00	7.24E+05	x	4.91E+01	2.30E+00	8.30E+02	1.00E+01	2.00E+01
Freshwater (µg/L)	Fish	8.88E+05	x	1.00E+01	6.28E+03	x	8.28E+00	5.00E+00	x	x	x
Freshwater (µg/L)	Other	1.08E+06	x	x	5.00E+04	1.00E+01	5.00E+03	1.00E+02	x	x	x
Freshwater (µg/L)	Total protection	5.02E+05	1.00E+01	8.00E+00	6.38E+03	1.00E+01	8.28E+00	2.30E+00	8.30E+02	1.00E+01	2.00E+01
Uplands (mg/kg)	Plants	x	x	x	x	x	5.00E+01	x	x	x	x
Uplands (mg/kg)	Soil biota	x	x	x	x	x	2.50E+01	1.00E+02	x	x	x
Uplands (mg/kg)	Wildlife	2.02E+01	1.37E-01	2.06E-01	5.92E+01	3.49E-02	4.60E-01	7.84E-02	x	x	1.78E-01
Uplands (mg/kg)	Total protection	2.02E+01	1.37E-01	2.06E-01	5.92E+01	3.49E-02	4.60E-01	7.84E-02	x	x	1.78E-01

Chapter 6: Treatment Technologies

6.0 Overview

This chapter briefly summarizes those technologies that are considered “field demonstrated” for treating or immobilizing various PFAS compounds in water and solid matrices. To be considered field demonstrated, sufficient supporting field data must be available to document that the technology can adequately address the site-specific situation. An in-depth discussion of the various factors that should be considered when selecting an appropriate technology is not included as there are other guidance documents and technical papers that provide this type of information. One of the best documents for a detailed description on all treatment options is available from ITRC at <https://pfas-1.itrcweb.org/12-treatment-technologies/>.

The Department of Defense (DOD) has an environmental technology demonstration and validation program known as Environmental Security Technology Certification Program (ESTCP). This program provides resources for ongoing research work regarding PFAS treatment. A list of the approved projects is available at [PFAS Remediation \(serdp-estcp.org\)](https://serdp-estcp.org/).⁷⁸

Remedial technologies that are not identified as field demonstrated will typically require additional evaluation and performance monitoring to provide the data necessary to confirm their viability for the site-specific circumstances. Since field-proven technologies will evolve over time, Ecology intends to update this chapter on a periodic basis as other options become available.

The technologies summarized herein represent both in-situ and ex-situ options, but the majority of proven technologies are based on ex-situ implementation. One of the challenges with evaluating performance data is that the number of PFAS compounds that can now be quantified using approved analytical methods has expanded, while the associated detection limits continue to decrease. As a result, earlier studies may not have as robust a data set as those conducted more recently. Even with these limitations, the number of previous studies provide good insights into those technologies that can effectively treat many PFAS compounds. One additional factor that needs to be accounted for is that PFAS compounds can be co-mingled with other contaminants (often petroleum) and previous remedial actions may have affected the concentration and distribution of PFAS present.

Note: Even though these remedial alternatives are considered to be field demonstrated, the selection of the preferred alternative needs to follow the procedures outlined in WAC [173-340-360](#).⁷⁹ This will typically require preparing a disproportionate cost analysis to demonstrate the cleanup action is permanent to the maximum extent practicable.

⁷⁸ [https://serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Contaminated-Groundwater-SONs/PFAS-Remediation/\(language\)/eng-US](https://serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Contaminated-Groundwater-SONs/PFAS-Remediation/(language)/eng-US)

⁷⁹ <https://apps.leg.wa.gov/WAC/default.aspx?cite=173-340-360> (Selection of cleanup actions.)

6.1 Liquid treatment technologies

The treatment options identified in this section have been well demonstrated to remove PFAS compounds from different liquid media, including drinking water, surface water, groundwater, municipal and industrial wastewater, and landfill leachate. However, not all of the identified technologies are appropriate for every situation. Often a site-specific evaluation will be necessary to identify the best alternative for a given media or scenario.

A number of factors can influence the performance of liquid treatment options such as the type of PFAS compounds present, the concentrations of the individual compounds, the presence of co-contaminants, natural organic matter, the volume and flow rate of liquid requiring treatment, characteristics and treatment of any residuals produced, and post-treatment remediation goals. Therefore, Ecology recommends completing treatability studies to determine the appropriate design parameters, and to provide the necessary data for establishing a performance monitoring program.

6.1.1. Sorption

Multiple sorption technologies have been used to treat PFAS in liquid media. The focus of this section is on ex-situ options since they are the most common, but a discussion is also included on the in-situ use of colloidal activated carbon (CAC). While there does not appear to be consensus on whether the use of CAC is a field-proven technology, there have been a number of field scale uses throughout the U.S. and abroad, and monitoring data continue to be collected to document performance. Use of the ex-situ technologies will require treating or disposing of the spent media.

6.1.1.1 Granular Activated Carbon (GAC)

Granular activated carbon has been used to remove numerous organic compounds from water for decades. Chapter 12 of the ITRC PFAS guidance provides a number of references to support the effectiveness of GAC in removing longer chain PFAS compounds from water. GAC has also been used to address removal of shorter chain PFAS, although these compounds tend to have faster breakthrough times, which can require more frequent change-out of the carbon.

Note: The distinction between long and short chain PFAS compounds is complicated and varies depending on whether the compound is a perfluororalkyl carboxylic acid (PFCAs) or perfluoroalkane sulfonic acid (PFSAAs). Table 2.2 of the ITRC PFAS guidance provides a visual distinction of which PFAS compounds are considered long chain and which are considered short chain.

6.1.1.2 Ion Exchange (IX) Resin

Ion exchange resins have also been used for water treatment for many years and, like GAC, adsorb PFAS (and other compounds) to the treatment media. These resins can provide improved removal efficiency over other adsorptive media for certain classes of PFAS compounds if they have positively charged functional groups, by bonding with the negatively charged functional head of the PFAS compound. In addition, the hydrophobic portion of the PFAS molecule can adsorb on the hydrophobic surface of the resin. As with GAC, the efficiency of the resin is also affected by the factors discussed in Section 6.1 and the type of resin selected will affect the overall performance of the system. Therefore, treatability studies should be conducted to help ensure the selected resin can meet the established treatment goals.

6.1.1.3 Reverse Osmosis (RO)

Reverse osmosis can remove PFAS compounds and many other contaminants by using pressure to move water through a semipermeable membrane. One of the most important issues to address when using RO is the reduction in water movement due to the accumulation of particulates on the membrane surface. In some cases, microbial growth on the membrane surface can occur and this will also reduce the efficiency of contaminant removal. This can result in the need for pre-treatment to remove these particulates from the feed water, which is often cheaper than providing for more frequent membrane cleaning or replacement. Other considerations with RO treatment include higher energy requirements and treatment of reject water, which contains PFAS enriched concentrate.

6.1.1.4 Liquid Colloidal Activated Carbon (CAC)

Liquid colloidal activated carbon contains very small particles of activated carbon, usually 1 to 2 microns in diameter, suspended in an aqueous solution. CAC can be injected into the subsurface either using gravity feed or under low pressure. After injection, the CAC will coat the soil grains below the water table and contaminants moving through the saturated zone are adsorbed to the carbon. CAC was initially used to remove petroleum and chlorinated contamination, but more recently has been used to address PFAS contamination.

There have been a number of pilot and full-scale projects that have used CAC to address PFAS impacts. While field scale monitoring data are available for a number of projects, often with impressive results, post-remediation monitoring is typically limited to less than five years.

Modeling studies have predicted positive long-term performance, but sufficient data are not yet available to empirically support this conclusion. While the use of CAC has not been uniformly concluded to be a field-proven technology, Ecology believes this option can provide short-term risk reduction. If this technology is chosen to address PFAS impacts to groundwater, long-term monitoring will be necessary to support the results of the corresponding modeling studies.

6.2 Treatment technologies for solid matrices

The treatment options identified in this section have been field demonstrated to address PFAS contamination in several solid matrices including soil, sediments, and various sludge materials. As with liquid treatment options, these proven technologies have been implemented almost exclusively ex-situ. There are currently two generally accepted field-proven technologies for treating soil contaminated with PFAS: sorption/stabilization and excavation/disposal.

Thermal treatment, which can be used to mobilize or in some cases destroy the compounds of concern, is also included in this section since it has been used for a long time for other contaminants and requires strict permitting criteria so environmental impacts are minimized. Thermal treatment can also provide a finishing step that can be used in conjunction with other technologies.

6.2.1 Sorption and stabilization (immobilization)

Immobilization treatment options are intended to minimize the potential for PFAS compounds to leach from solid media. While there are multiple different materials that have been used to bind PFAS compounds, the most common are Portland cement, fly ash, activated carbon, kaolinite clay, and amorphous (non-crystalline) aluminum hydroxide. Given the numerous variables that exist (i.e. PFAS concentrations, soil types, moisture content, treatment goals, etc.) bench scale testing should be completed to document that the preferred mixture can achieve the applicable treatment goals. The primary downside with the use of this technology is that PFAS compounds are not destroyed, but instead only bound in the amendment matrix to reduce leaching. If environmental conditions such as pH, ionic strength, or other variables change, it can result in leaching from the immobilized media. As a result, long-term monitoring will likely be required.

Given the difficulties that can occur with in-situ mixing of stabilization compounds, Ecology does not generally recommend using this approach. If in-situ stabilization will be pursued as the preferred remedial option, additional performance monitoring will likely be necessary to demonstrate the technology will achieve the desired treatment goals.

6.2.2 Excavation and off-site management

A more permanent option for addressing source area contamination is excavation followed by off-site management at a permitted facility. Off-site management options include: 1) landfilling, 2) treatment with a stabilizing agent prior to disposal to minimize leaching, and 3) thermal treatment. To minimize further leaching of PFAS compounds from source materials, strong consideration should be given to stabilization or thermal treatment of the media prior to final management. Since off-site management options may be limited, available alternatives should be evaluated as early as possible in the remedy selection process.

6.2.3 Thermal treatment

This option consists of heating the solids at high temperature to remove or destroy the PFAS compounds. While some field-scale testing has been completed, the performance of these systems is highly site specific. To destroy the PFAS compounds that are present, the treatment unit must use extremely high heat that is delivered uniformly over a sufficient period of time. Significant environmental controls are also necessary to minimize the generation of products of incomplete combustion, and to ensure air emissions meet all applicable standards that are specifically established for the treatment unit. In addition, incineration technology is associated with high energy consumption, which should be considered as part of using sustainable technologies.

6.2.4 Soil washing

Soil washing is an ex-situ process that can reduce the volume of contaminated material that needs to be treated further or disposed. This technology is based on the concept that most contaminants of concern bind to finer-grained soils. The larger-sized materials, such as sand and gravel, are segregated and subjected to a wash solution that generally consists of water, surfactants, and/or a leaching agent. This approach can reduce the volume of soil needing further treatment or disposal. Before final management, the wash water may require treatment to remove the fine particles and COCs that had leached into the water.

6.3 Other treatment technologies

There are a significant number of other technologies being evaluated to treat PFAS contamination. Many of these options are discussed in detail in other guidance documents and research papers. While Ecology does not specify that a proven remedial technology be used to address PFAS contamination, it is very likely that additional testing and documentation will be necessary to select a “non-proven” treatment option.

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Glossary

Term	Definition
CLARC	Cleanup Levels and Risk Calculation, Ecology's compendium of technical information related to calculating cleanup levels under Washington's MTCA Cleanup Regulations, Chapter 173-340 WAC @ https://apps.leg.wa.gov/WAC/default.aspx?cite=173-340&full=true
Clean Water Act	33 U.S.C. §1251 et seq. (1972). Federal law that establishes the basic structure for regulating discharges of pollutants into the waters of the United States and regulating quality standards for surface waters.
community water system	Provides service to 15 or more service connections used by year-round residents for 180 or more days in a calendar year. Examples might be a municipality, subdivision, mobile home park, apartment complex, college with dormitories, nursing home, or prison (WAC 256-290-020 @ https://apps.leg.wa.gov/WAC/default.aspx?cite=246-290&full=true#246-290-010).
contaminated site	Also known as a cleanup site or hazardous waste site. Contaminated sites are often considered to be construction projects that remove or immobilize harmful contamination from our environment and put properties back into use. Contaminated sites can be as small as a gas station spill, or as large and complex as the Tacoma Smelter Plume (CSID 3657) that impacts thousands of acres. (https://apps.ecology.wa.gov/cleanupsearch/site/3657)
equipment rinsate blank	The analyte free water collected after it has been poured over or through contaminated field sampling equipment prior to the collection of environmental samples. (iEnvi, 2022 @ https://www.ienvi.com.au/blanks-for-the-field-and-lab-what-are-they/)
field blank	The analyte free water poured into a sampling container in the field and carried with the field samples. This is to assess whether contamination may have occurred in the field during sampling. (iEnvi, 2022 @ https://www.ienvi.com.au/blanks-for-the-field-and-lab-what-are-they/)
formal cleanup	Conducted by a potentially liable person under an order or decree that are supervised by Ecology, or conducted by Ecology through contracted private companies.
Group A public water system	Public water system providing water for human consumption through pipes or other constructed conveyance. Further defined as community and noncommunity water systems (WAC 256-290-020 @ https://apps.leg.wa.gov/WAC/default.aspx?cite=246-290&full=true#246-290-010)
independent cleanup	Conducted by property owners on their own or with technical assistance from Ecology or the Pollution Liability Insurance Agency (PLIA).
Model Toxics Control Act (statute)	Washington's environmental cleanup law, Chapter 70A.305 RCW. https://app.leg.wa.gov/rcw/default.aspx?cite=70A.305.030
Model Toxics Control Act Cleanup Regulations (rule)	Chapter 173-340 WAC, Washington's regulations for cleaning up upland and sediment sites under the Model Toxics Control Act. In 2018, Ecology began updating the rule in stages. http://apps.leg.wa.gov/WAC/default.aspx?cite=173-340 and https://ecology.wa.gov/Regulations-Permits/Laws-rules-rulemaking/Rulemaking/WAC-173-340

Term	Definition
noncommunity nontransient water system	Provides service opportunity to 25 or more of same nonresidential people for 180 or more days in a calendar year. Examples might be a school, day care center, business, factory, motel, or restaurant with 25 or more employees onsite (WAC 256-290-020 @ https://apps.leg.wa.gov/WAC/default.aspx?cite=246-290&full=true#246-290-010)
noncommunity transient water system	Provides service opportunity to 25 or more different people for 60 or more days in a calendar year, among other distinctions. Examples might be a restaurant, tavern, motel, campground, state or county park, RV park, vacation cottages, highway rest area, or public concert facility (WAC 256-290-020 @ https://apps.leg.wa.gov/WAC/default.aspx?cite=246-290&full=true#246-290-010)
rule, also called regulations	A law adopted by an executive branch agency (such as the Department of Ecology) under the authority of a statute to carry out programs authorized or directed by the statute. Rules specify procedures and set standards and other requirements to implement a statutory program. Rules are developed and enacted through a rulemaking process specified in statute. The public process allows stakeholders to participate in the creation of rules. Agencies can't exceed their statutory authority when adopting rules, and rules can't change statutes. Rules can clarify confusing or unclear statutory directives. Washington's Legislature and voters can change rules by passing new bills or initiatives. The Washington Administrative Code (WAC) codifies rules and arranges them by subject or agency.
Sediment Management Standards (rule)	Chapter 173-204 WAC, Washington's regulations for cleaning up contaminated sediment under the Model Toxics Control Act. Also called the Sediment Rule. http://apps.leg.wa.gov/WAC/default.aspx?cite=173-204
sediment site	A contaminated site in riverbeds and seabeds where aquatic animals such as crabs and clams live. Sediment can include silt, sand, cobble, and beaches.
Site Register	Ecology's electronic newsletter containing information on cleanups and announcements of public comment opportunities. https://apps.ecology.wa.gov/publications/UIPages/PublicationList.aspx?IndexTypeName=Topic&NameValue=Site+Register&DocumentTypeName=Newsletter
statute	A law passed by the Legislature in a bill or by voters in an initiative. Statutes usually direct or authorize the establishment and implementation of government programs (such as Ecology's Remedial Action Grant Program). Agencies (such as Ecology) are part of the executive branch of state government, and are tasked with carrying out the programs directed or authorized by statute. To carry out these programs, agencies are usually authorized by statute to adopt rules. The Revised Code of Washington (RCW) codifies statutes and arranges them by subject.
upland site	A contaminated site on land or in groundwater.

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Appendix A: Tables with Supporting Calculations for Human Health Protective Cleanup Levels

Table A-1. Method B and C groundwater Cleanup Levels for PFAS chemicals in potable water in Washington state.

Parameter	Abbrev.	Method B Unrestricted (Eq. 720-1)	Method C Industrial (Eq. 720-1)	Units	Source
Reference dose (PFOA, PFOS)	RfD	3E-06	3E-06	mg/kg-day	DOH SALs
Reference dose (PFHxS)	RfD	9.7E-06	9.7E-06	mg/kg-day	DOH SALs
Reference dose (PFBS)	RfD	3E-04	3E-04	mg/kg-day	DOH SALs
Reference dose (PFNA)	RfD	2.5E-06	2.5E-06	mg/kg-day	DOH SALs
Reference dose (HFPO-DA)	RfD	3E-06	3E-06	mg/kg-day	EPA – Office of Water
Average body weight	ABW	16	70	kg	MTCA default
Unit conversion factor	UCF	1E+03	1E+03	µg/mg	MTCA default
Hazard quotient	HQ	1	1	unitless	MTCA default
Averaging time	AT	6	6	years	MTCA default
Drinking water ingestion rate	DWIR	1	2	L/day	MTCA default
Inhalation correction factor	INH	1	1	unitless	MTCA default for nonvolatile chemicals
Inhalation correction factor	INH	2	2	unitless	MTCA default for volatile chemicals
Drinking water fraction	DWF	1	1	unitless	MTCA default
Exposure duration	ED	6	6	years	MTCA default
Potable water ingestion for PFOS+PFOA		0.048	0.11	µg/L	MTCA Equation 720-1
Potable water ingestion for PNFA		0.04	0.088	µg/L	MTCA Equation 720-1
Potable water ingestion for PFHxS		0.16	0.34	µg/L	MTCA Equation 720-1
Potable water ingestion for PFBS		4.8	11	µg/L	MTCA Equation 720-1
Potable water ingestion for HFPO-DA		0.024	0.053	µg/L	MTCA Equation 720-1

MTCA Equation 720-1: $GW-Eq = RfD \times ABW \times UCF \times HQ \times AT / (DWIR \times INH \times DWF \times ED)$

Table A-2: Method B and C direct contact Cleanup Levels in soil for PFAS chemicals in Washington state.

Parameter	Abbrev.	Method B Unrestricted (Eq. 740-1)	Method C Industrial (Eq. 745-1)	Units	Source
Reference dose (PFOS, PFOA)	RfD	3E-06	3E-06	mg/kg-day	DOH SALs
Reference dose (PFHxS)	RfD	9.7E-06	9.7E-06	mg/kg-day	DOH SALs
Reference dose (PFBS)	RfD	3E-04	3E-04	mg/kg-day	DOH SALs
Reference dose (PNFA)	RfD	2.5E-06	2.5E-06	mg/kg-day	DOH SALs
Reference dose (HFPO-DA)	RfD	3E-06	3E-06	mg/kg-day	EPA – Office of Water
Average body weight	ABW	16	70	kg	MTCA default
Unit conversion factor	UCF	1E+06	1E+06	mg/kg	MTCA default
Hazard quotient	HQ	1	1	unitless	MTCA default
Averaging time	AT	6	20	years	MTCA default
Soil ingestion rate	SIR	200	50	mg/day	MTCA default
Gastrointestinal absorption fraction	AB1	1	1	unitless	MTCA default
Exposure frequency	EF	1	0.4	unitless	MTCA default
Exposure duration	ED	6	20	years	MTCA default
Soil contact for PFOS+PFOA+PNFA		0.24	11	mg/kg	MTCA Equations 740-1 and 745-1
Soil contact for PNFA		0.2	8.8	mg/kg	MTCA Equations 740-1 and 745-1
Soil contact for PFHxS		0.78	34	mg/kg	MTCA Equations 740-1 and 745-1
Soil contact for PFBS		24	1100	mg/kg	MTCA Equations 740-1 and 745-1
Soil contact for HFPO-DA		0.24	11	mg/kg	MTCA Equations 740-1 and 745-1

MTCA Equations 740-1 and 745-1: $SC-IL = RfD \times ABW \times UCF \times HQ \times AT / (SIR \times AB1 \times EF \times ED)$

Table A-3a: Default Screening Levels (SL) for soil leaching of PFAS to potable groundwater in Washington state: Chemical properties

Parameter	Abbrev.	PFOS	PFOA	PFNA	PFHxS	PFBS	HFPO-DA	Units	Source
Groundwater SAL	SAL	0.015	0.01	0.009	0.07	0.345	—	µg/L	DOH State Action Levels
Henry's law constant	Hcp	nm	4.0E-06	nm	nm	nm	2.5E-04	atm-m ³ /mol-K	ORNL RAIS, 2020
Henry's law constant	Hcc	0.0E+00	1.46E-04	0.0E+00	0.0E+00	0.0E+00	0.01	unitless	Hcc = Hcp / (R x T)
Soil organic carbon-water partitioning coefficient	Koc	371.5	114.8	246	112	62	12	L/kg	ORNL RAIS, 2020
Soil fraction of organic carbon	foc	0.001	0.001	0.001	0.001	0.001	0.001	g/g	MTCA default
Distribution coefficient	Kd	0.37	0.11	0.25	0.11	0.06	0.01	L/kg	MTCA Equation 747-2

Abbreviations for Table A-3a

ARAR = applicable or relevant and appropriate requirement

Hcp = Henry's Law constant expressed in atm-m³/mol

Hcc = Henry's Law constant expressed in unitless form

SAL = State Action Level

MTCA Equation 747-1: $SL-IL = GW-IL \times UCF \times DF [Kd + (\theta_w + \theta_a \times Hcc) / \rho_b]$

MTCA Equation 747-2: $Kd = Koc \times foc$

nm = not measurable

R = universal gas constant (8.20575 x 10⁻⁵ atm-m³/mol-K)

T = temperature (298.15 °K, equivalent to 25 °C)

R x T (25 °C) = 0.02447

Table A-3b: Default Screening Levels (SL) for soil leaching of PFAS to potable groundwater in Washington state: Soil properties and Investigatory Levels

Parameter	Abbreviation	Vadose Zone	Saturated Zone	Units	Source
Unit conversion factor	UCF	1E-03	1E-03	mg/μg	MTCA default
Dilution factor	DF	20	1	unitless	MTCA default
Water-filled soil porosity	θ _w	0.3	0.43	ml/ml	MTCA default
Air-filled soil porosity	θ _a	0.13	0	ml/ml	MTCA default
Dry soil bulk density	ρ _b	1.5	1.5	kg/L	MTCA default
Soil leaching SL for PFOS		1.7E-04	9.9E-06	mg/kg	MTCA Equation 747-1
Soil leaching SL for PFOA		6.3E-05	4.0E-06	mg/kg	MTCA Equation 747-1
Soil leaching SL for PFNA		1.2E-04	7.5E-06	mg/kg	MTCA Equation 747-1
Soil leaching SL for PFHxS		4.4E-04	2.8E-05	mg/kg	MTCA Equation 747-1
Soil leaching SL for PFBS		6.8E-03	4.5E-04	mg/kg	MTCA Equation 747-1
Soil leaching SL for HFPO-DA		1.0E-04	7.2E-06	mg/kg	MTCA Equation 747-1

Abbreviations for Table A-3b

ARAR = applicable or relevant and appropriate requirement

H_{cp} = Henry's Law constant expressed in atm-m³/mol

H_{cc} = Henry's Law constant expressed in unitless form

SAL = State Action Level

MTCA Equation 747-1: $SL-IL = GW-IL \times UCF \times DF [K_d + (\theta_w + \theta_a \times H_{cc}) / \rho_b]$

MTCA Equation 747-2: $K_d = K_{oc} \times f_{oc}$

nm = not measurable

R = universal gas constant (8.20575 x 10⁻⁵ atm-m³/mol-K)

T = temperature (298.15 °K, equivalent to 25 °C)

R x T (25 °C) = 0.02447

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Appendix B – Ecological Receptors: Concentrations Protective of Surface Water and Upland Soil

B-1 Background information

Chapter 5 of the guidance provides a summary of the recommendations for addressing ecotoxicity from Ecology's PFAS Chemical Action Plan, identifies the applicable regulatory authority in MTCA, summarizes the decision-making process and includes the calculated protective values. This Appendix, along with the supporting Attachments, provides the details for how the protective values were calculated. The methodology is consistent with current rule language and generally accepted approaches for these types of calculations.

B-2 Surface water

Section B-2 provides information on the process used to determine surface water cleanup levels. A table summarizing the protective concentrations is included at the end of this Section.

B-2.1 Literature review

Protective concentrations that were included in the literature review are summarized in Attachment 1 of this Appendix. The literature review includes relevant publications that meet the surface water regulations described above.

B-2.2 Decision-making process

Protective concentrations were determined by a review of estimated no adverse effects on the protection and propagation of fish, invertebrates, and other aquatic life found in relevant literature. It is important to note that the documented protective concentration is not necessarily the lowest No Observed Adverse Effects Concentration (NOAEC), but instead a value was chosen that would be protective of the individual class of receptors (fish, invertebrates, other) that is also below a Lowest Observed Adverse Effects Concentration (LOAEC).

B-2.2.1 Perfluorobutane Sulfonic Acid (PFBS) – CAS# 375735:

- *Marine* – Acute 96 hr. test based on the Mysid, *Mysidopsis bahia*. *Marine water matrix* (Drottar et al., 2001a).
 - Protective value = 1.27E+05 ug/L. This value is based on a no-mortality concentration. A LOAEC was measured at 2.69E+05 ug/L, and an LC50 was measured at 3.72E+05 ug/L.
 - Confidence in value is low-medium due to a single acute test. Inclusion of both a NOAEC, LOAEC, and LC50 does improve confidence a bit. Also, this value appears consistent with the chronic freshwater value documented below.
- *Freshwater* – Chronic 21 day test based on *Daphnia Magna*. *Freshwater matrix* (Drottar et al., 2001b).

- **Protective value = 5.02E+05 ug/L.** This value is based on no adverse effects measured towards survival, reproduction, or growth. 9.95E+05 ug/L indicated reduced reproduction and length. *Daphnia magna* exposed to 1.88E+06 ug/L had significantly reduced survival. Second generation acute exposure indicated a NOAEC of 9.95E+05 ug/L.
- Confidence in value is medium-high due to a chronic test. Inclusion of both a NOAEC and LOAEC does improve confidence. Also this value appears consistent with the marine water value documented above.

B-2.2.2 Perfluorodecanoic Acid (PFDA) – CAS# 335762:

- **Marine** – 7 day test followed by another 7 days of depuration on the green mussel, *Perna viridis*. Marine water matrix (Lui et al., 2014).
 - **Protective value = 7.80E+01 ug/L.** This value is based on an EC50. The effects measured were DNA strand breaks and fragmentation, chromosomal breaks and apoptosis (death of cells).
 - Confidence in value is low-medium due to a single test with an EC50 endpoint. However, this value does appear consistent with freshwater values (NOAEC, EC50, Ding et al., 2011).
- **Freshwater** – 48 hour acute test (immobilization) on the freshwater invertebrate, *Chydorus sphaericus*. Freshwater matrix (Ding et al., 2011).
 - **Protective value = 1.0E+01 ug/L.** This value is based on a NOAEC. The effects measured was immobilization. A 48-hour EC50 was measured at 8.88E+01 ug/L, a 24-hour NOAEC was measured at 8.00E+01 ug/L, and a 24-hour EC50 was measured at 1.41E+02 ug/L.

Note: Confidence in value is medium due to NOAEC and EC50 values. In addition, test was completed on another species (*Daphnia magna*), and the freshwater protective value does appear consistent with the marine water value documented above.

B-2.2.3 Perfluorononanoic Acid (PFNA) – CAS# 375951:

- **Marine** – 7 day test followed by 7 day depuration period on the green mussel *Perna viridis*. Marine water matrix (Liu and Gin, 2018).
 - **Protective value = 1.04E+01 ug/L.** This value is based on a NOAEC. The effect measured was biomarkers of the immune profile (neutral red retention, phagocytosis, and spontaneous cytotoxicity). A significant reduction of the immune profile was observed at 1.00E+02 ug/L.
 - Confidence in the value is medium-high due to the chronic test along with consistency with a similar test conducted a few years earlier on the same species with an EC50 (Liu et al., 2014).
- **Freshwater** – 48-hour acute toxicity test, a 21-day chronic test, a feeding experiment, and a biomarker assay were performed on *Daphnia magna*. Freshwater matrix. (Lu et al., 2014).

- **Protective value = 8.00E+00 ug/L.** This value is based on a NOAEC. The effects measured were body length, time to first pregnancy, time to first brood, number of first brood and number of offspring per brood per female. A significant difference was found at 4.00E+01 ug/L.

Note: Confidence in this value is high due to chronic testing, endpoints, and consistency with similar tests on invertebrates (Ding et al, 2012, Zhai et al, 2016).

B-2.2.4 Perfluorohexanoic Acid (PFHxA) – CAS# 307244:

- **Marine** – No testing information found/available at the time of this summary.
- **Freshwater** – 120 hours post fertilization toxicity test on larval zebrafish (*Danio rerio*). Additionally, exposed larvae were transferred to clean water and reared until 14 days post fertilization. Freshwater matrix (Annunzaito et al., 2019).
 - **Protective value = 6.28E+03 ug/L.** This value is based on 120-hours post fertilization test with endpoints of morphometric and gene expression – at 2 µM .
 - Confidence in this value is medium-high with other freshwater fish testing displaying consistent values (Germany Annex, 2018).

B-2.2.5 Perfluorohexane Sulfonic Acid (PFHxS) – CAS# 355464:

- **Marine** – No testing information found/available at the time of this summary.
- **Freshwater** – Two phase experimental design to assess the effects of exposure on trematode infection risk. Following exposures, parasite exposure on individual tadpoles. Tadpoles were exposed to chemicals for 10 days (Brown et al., 2020).
 - **Protective value = 1.00E+01 ug/L.** This value is based on a 10 ppb PFHxS treatment, which increased parasite loads by 17.5% compared with the control (p=0.006).
 - Confidence in this value is medium-high with other testing/recommendations consistent with these results (Persistent Organics Review Committee, 2018).

B-2.2.6 Perfluorooctanoic Acid (PFOA) – CAS# 335671:

- **Marine** – Effects on early life stages of microalgae (*Isochrysis galbana*), a primary consumer (*Paracentrotus lividus*), and two secondary consumers (*Siriella armata* and *Psetta maxima*) (Mhadhbi et al., 2012),
 - **Protective value = 1.19E+02 ug/L.** This value is based on a Predicted No Effect Concentration (PNEC) for algae, crustaceans, and fish in marine water. An assessment factor of 100 was used to derive these concentrations.
 - Confidence in this value is high. This value does appear consistent with other studies (Liu et al., 2014).
- **Freshwater** – Morphometric, behavior, and gene expression effects in both yolk fry sac and larval zebrafish. Zebrafish were exposed to the chemical for the first five days post fertilization and analyzed for up to 14 days post fertilization for effects (Jantzen et al., 2016).

- **Protective value = 8.28E+00 ug/L.** This value is based on exposure to a low range of concentrations (0.02 uM – 2.0 uM; 20 – 2000 ppb) resulted in chemical specific developmental defects and reduced post hatch survival.
- Confidence in this value is medium-high. While this value is more conservative than other literature values, it remains consistent with other document freshwater references (Ding et al., 2012; Ji et al., 2008; Spachmo and Arukwe, 2012).

B-2.2.7 Perfluorooctane Sulfonic Acid (PFOS) – CAS# 1763231:

- **Marine** – Effects on early life stages of microalgae (*Isochrysis galbana*), a primary consumer (*Paracentrotus lividus*), and two secondary consumers (*Siriella armata* and *Psetta maxima*) (Mhadhbi et al., 2012),
 - **Protective value = 1.10E+00 ug/L.** This value is based on a PNEC for algae, crustaceans, and fish in marine water. An assessment factor of 100 was used to derive these concentrations.
 - Confidence in this value is medium-high. This value is more conservative but does appear consistent with other studies (Liu et al., 2014).
- **Freshwater** – Effects are based on total emergence of the insect *Chironomus tentans*. Total emergence was decreased by 32% as compared to the control. The authors also report an EC10 of 8.9E+01 ug/L for total emergence. When taking a closer look at the data, however, this EC10 seems to be rather uncertain and preference is given to the NOAEC (Moermond et al., 2010; MacDonald et al., 2004).
 - **Protective value = 2.3E+00 ug/L.** See above.
 - Confidence in this value is high. Numerous studies support this concentration as a NOAEC (Moermond et al., 2010; MacDonald et al., 2004; Stefani et al., 2014).

B-2.2.8 Perfluorobutanoic Acid (PFBA) – CAS# 375244:

- **Marine** – No testing information found/available at the time of this summary.
- **Freshwater** – 48 hour acute test (immobilization) on the freshwater invertebrate, *Daphnia magna*. Freshwater matrix (Ding et al., 2011).
 - **Protective value = 8.30E+02 ug/L.** This value is based on a NOAEC. The effects measured was immobilization. A 48-hour EC50 was measured at 8.48E+02 ug/L, a 24-hour NOAEC was measured at 8.50E+02 ug/L, and a 24-hour EC50 was measured at 8.65E+02 ug/L.
 - Confidence in value is medium due to NOEC and EC50 values. In addition, test was also completed on another species (*Chydorus sphaericus*).

B-2.2.9 Perfluoroundecanoic Acid (PFUnA) – CAS# 2058948:

- **Marine** – No testing information found/available at the time of this summary.
- **Freshwater** – 48 hour acute test (immobilization) on the freshwater invertebrate, *Chydorus sphaericus*. Freshwater matrix (Ding et al., 2011).
 - **Protective value = 1.00E+01 ug/L.** This value is based on a NOAEC. The effects measured was immobilization. A 48-hour EC50 was measured at

3.40E+01 ug/L, a 24-hour NOAEC was measured at 4.00E+01 ug/L, and a 24-hour EC50 was measured at 6.90E+01 ug/L.

- Confidence in value is medium due to NOAEC and EC50 values. In addition, test was completed on another species (*Chydorus sphaericus*).

B-2.2.10 Perfluorododecanoic Acid (PFDoA) – CAS# = 307551:

- **Marine** – No testing information found/available at the time of this summary.
- **Freshwater** – 48 hour acute test (immobilization) on the freshwater invertebrate, *Chydorus sphaericus*. Freshwater matrix (Ding et al., 2011).
 - **Protective value = 2.00E+01 ug/L.** This value is based on a NOAEC. The effects measured was immobilization. A 48-hour EC50 was measured at 4.60E+01 ug/L, a 24-hour NOAEC was measured at 2.00E+01 ug/L, and a 24-hour EC50 was measured at 5.40E+01 ug/L.

B-2.3 Summary of Protective Concentrations in Surface Water

Table B-1 Summary of protective concentrations in surface water based on a literature review of select PFAS.

Contaminant	Organism	PFBS	PFDA	PFNA	PFHxA	PFHxS	PFOA	PFOS	PFBA	PFUnA	PFDoA
Marine (µg/L)	Invertebrates	1.27E+05	7.80E+01	1.04E+01	x	x	5.94E+02	3.30E+01	x	x	x
Marine (µg/L)	Fish	x	x	x	x	x	1.50E+03	1.50E+01	x	x	x
Marine (µg/L)	Other	x	x	x	x	x	1.19E+02	1.10E+00	x	x	x
Marine (µg/L)	Total protection	1.27E+05	7.80E+01	1.04E+01	x	x	1.19E+02	1.10E+00	x	x	x
Freshwater (µg/L)	Invertebrates	5.02E+05	1.00E+01	8.00E+00	7.24E+05	x	4.91E+01	2.30E+00	8.30E+02	1.00E+01	2.00E+01
Freshwater (µg/L)	Fish	8.88E+05	x	1.00E+01	6.28E+03	x	8.28E+00	5.00E+00	x	x	x
Freshwater (µg/L)	Other	1.08E+06	x	x	5.00E+04	1.00E+01	5.00E+03	1.00E+02	x	x	x
Freshwater (µg/L)	Total protection	5.02E+05	1.00E+01	8.00E+00	6.28E+03	1.00E+01	8.28E+00	2.30E+00	8.30E+02	1.00E+01	2.00E+01

B-3 Uplands

Section B-3 provides information on the process used to determine upland cleanup levels. It is important to note that the methods used to develop the protective concentrations for PFAS are consistent with those methods used to establish the protective concentrations documented in MTCA Table 749-3.

Ecology developed the values in Table 749-3 in consultation with the MTCA Science Advisory Board Ecological Risk Subcommittee. The values are for use at sites where a site-specific terrestrial ecological evaluation is required or otherwise conducted, and are intended to be protective of terrestrial ecological receptors at any site. The values in Table 749-3 were calculated based on a lower level of acceptable risk than the values specified in Table 749-2 for conducting a simplified evaluation. This is the baseline or default level of acceptable risk. A higher level of acceptable risk is allowed for simplified terrestrial ecological evaluations.

Allowing for a lower level of risk, plant and soil biota values are based on the 10th percentile (Q10) of LOAECs instead of the 50th percentile (Q50) used to calculate values in Table 749-2. Wildlife values are the lowest of three values calculated for different wildlife groups using standardized exposure assumptions and chemical-specific toxicity reference values (TRVs) and uptake factors.

The value for unrestricted land use (the total protection value in Table B-4) is the lowest of the values specified for each of the three categories of terrestrial ecological receptors – plant, soil biota, and wildlife. The value for industrial and commercial land uses is the wildlife value.

Table B-2: Values used in Wildlife Exposure Model to calculate protective soil concentrations for wildlife. The equations used to calculate protective concentrations can be found in MTCA Table 749-4.

Parameter in equation	Details	Value
K_{plant}	plant uptake coefficient (mg/kg plant / mg/kg soil; dry weight basis)	derived from literature survey
BAF_{worm}	earthworm bioaccumulation factor (mg/kg worm / mg/kg soil; dry weight basis)	derived from literature survey
P_{SB}	proportion of contaminated food in diet (earthworms for shrew and robin, plants for vole)	0.5 - shrew 1.0 - vole 0.52 - robin
FIR	food ingestion rate (kg food/kg body weight; dry weight basis)	0.45 – shrew 0.315 – vole 0.207 - robin
SIR	soil ingestion rate (kg soil/kg body weight; dry weight basis)	0.0045 – shrew 0.0079 – vole 0.0215 - robin
$RGAF$	relative gut absorption factor (absorption from soil relative to absorption from food)	1
T	toxicity reference value (mg/kg/day)	derived from literature survey

B-3.1 Literature review

References included in the literature review and values taken from the literature for use in determining protective soil concentrations are presented in Appendix C and D.

Plant and soil biota protective concentrations were determined based entirely on LOAECs identified in the literature review. Details on the derivation of these values is included in the Derivation Process – Toxicity Values section below.

Wildlife protective concentrations were established based on the Wildlife Exposure Model described in the text (WAC 173-340-7493(3) (c)) and tables (Table 749-4 and 749-5) in MTCA. The equations included in the model allow the calculation of protective soil concentrations for a mammalian herbivore (vole), mammalian predator (shrew), and avian predator (robin). The model uses a combination of default and literature-derived values (Table B-2). Literature-derived values included toxicity reference values for both mammals and birds, earthworm bioaccumulation, and plant uptake. Toxicity reference values for birds and mammals are based on Lowest Observed Adverse Effects Levels (LOAELs) identified in the literature. Additional details on the literature-derived values are included in the following sections.

B-3.2 Derivation process – Toxicity values

Literature was reviewed with a focus on determining wildlife relevant lowest observed adverse effect levels. Relevant effects included significant impacts on apical endpoints (survival, growth, reproduction) relative to controls. The lowest relevant LOAEL or LOAEC identified in the literature was generally selected as the toxicity reference value. All relevant LOAELs or LOAECs identified in the literature are included in Appendix C. Toxicity reference values were not established for PFAS with only one LOAEL or LOAEC identified in the literature.

The methods in Efroymsen et al. (1997a, 1997b) were used to determine how toxicity reference values were determined for plants and soil invertebrates, consistent with how the values in Table 749-3 were derived. Since less than 10 LOAEC values were identified for each PFAS, the lowest LOAEC identified in the literature was selected as the toxicity reference value, as opposed to using the 10th percentile of literature LOAEC values. Consistent with the derivation of values in Table 749-3, only toxicity studies in earthworms were considered when deriving a soil biota protective value.

For mammalian species, to account for differences between laboratory and wildlife species, allometric scaling was applied to toxicity reference values. This was done using the equations in Sample et al. (1996), consistent with the derivation of values in Table 749-3. The reference values for rat, mouse, shrew, and vole body weight were used in the calculations. This resulted in different toxicity reference values for voles and shrews for each PFAS.

The outcome of the literature review was enough data to establish at least one protective value (plant, soil biota, and/or wildlife) for eight individual PFAS – PFBS, PFHxS, PFOS, PFHxA, PFOA, PFNA, PFDA, and PFDoA.

B-3.2.1 Perfluorobutane Sulfonic Acid (PFBS) – CAS# 375735

- **Plants** – Insufficient literature values identified to establish a protective value.
- **Soil Biota** – Insufficient literature values identified to establish a protective value.
- **Birds** – Insufficient literature values identified to establish a protective value.
- **Mammals** – Multiple studies with relevant LOAELs identified in the literature.
 - **Toxicity reference value = 250 mg/kg/day**
 - Based on: NTP 2019a
 - In this study, rats were dosed twice daily via oral gavage for 28 days. One half of the desired total daily dose was administered in each dose. Selected LOAEL is based on increased percentage of females with abnormal estrous cycles.
 - Toxicity reference values, following allometric scaling, are 420 mg/kg/day for vole and 549.5 mg/kg/day for shrew.

B-3.2.2 Perfluorohexane Sulfonic Acid (PFHxS) – CAS# 355464

- **Plants** – Insufficient literature values identified to establish a protective value.
- **Soil Biota** – Insufficient literature values identified to establish a protective value.
- **Birds** – Insufficient literature values identified to establish a protective value.
- **Mammals** – Multiple studies with relevant LOAELs identified in the literature.
 - **Toxicity reference value = 1 mg/kg/day**
 - Based on: Chang et al. 2018
 - In this study, mice were dosed daily via oral gavage beginning 14 days prior to mating and continuing through lactation day 21 (females) or 42 days of dosing (males). Pups were dosed for an additional 14 days following weaning, beginning on lactation day 22. Selected LOAEL is based on significantly reduced litter size.
 - Toxicity reference values, following allometric scaling, are 0.9 mg/kg/day for vole and 1.2 mg/kg/day for shrew.

B-3.2.3 Perfluorooctane Sulfonic Acid (PFOS) – CAS# 1763231

- **Plants** – Insufficient literature values identified to establish a protective value.
- **Soil Biota** – Multiple studies with relevant LOAECs identified in the literature.
 - **Protective soil concentration = 100 mg/kg soil**
 - Based on: Zareitalabad et al. 2013
 - Earthworms (*Aporrectodea caliginosa*) in this study were exposed to contaminated soil for 40 days. LOAEC based on significantly decreased survival at day 40.
- **Birds** – Multiple studies with relevant LOAELs found in the literature.
 - **Toxicity reference value = 0.77 mg/kg/day**
 - Based on: Newsted et al. 2007, Gallagher et al. 2003a
 - In this study, bobwhite quail were exposed to PFOS in their feed for 21 weeks. Selected LOAEL is based on decreased survival of offspring at 14 days post-hatch.

- **Mammals** – Multiple studies with relevant LOAELs identified in the literature.
 - **Toxicity reference value = 1.6 mg/kg/day**
 - Based on: Luebker et al. 2005
 - This study was a 2-generation reproduction study in rats. Rats were dosed via oral gavage for at least 42 days prior to mating through mating (males) or postnatal day 20. Dosing of F1 pups began on postnatal day 22. Selected LOAEL is based on significantly reduced viability index for F1 pups.
 - There were other studies with slightly lower LOAELs (1 mg/kg/day). Those LOAELs were based on decreases in adult body weight. The reproductive effects observed in the Luebker study were considered more relevant at the population level, and were selected as the basis for the toxicity reference value.
 - Toxicity reference values, following allometric scaling, are 2.7 mg/kg/day for vole and 3.5 mg/kg/day for shrew.

B-3.2.4 Perfluorohexanoic Acid (PFHxA) – CAS# 307244

- **Plants** – Insufficient literature values identified to establish a protective value.
- **Soil Biota** – Insufficient literature values identified to establish a protective value.
- **Birds** – Insufficient literature values identified to establish a protective value.
- **Mammals** – Multiple studies with relevant LOAELs identified in the literature.
 - **Toxicity reference value = 200 mg/kg/day**
 - Based on: Klaunig et al. 2015
 - In this study, rats were dosed daily via oral gavage for 104 weeks. Selected LOAEL is based on significantly decreased survival in females.
 - Toxicity reference values, following allometric scaling, are 336 mg/kg/day for vole and 439.6 mg/kg/day for shrew.

B-3.2.5 Perfluorooctanoic Acid (PFOA) – CAS# 335671

- **Plants** – Multiple studies with relevant LOAECs identified in the literature.
 - **Protective soil concentration = 50 mg/kg**
 - Based on: Kwak et al. 2020
 - Soil algae (*Chlorococcum infusionum*) was exposed to varying concentrations of PFOA for 6 days. LOAEC based on reduced algal biomass.
- **Soil Biota** – Multiple studies with relevant LOAECs identified in the literature.
 - **Protective value = 25 mg/kg**
 - Based on: He et al. 2016
 - Earthworms (*Eisenia fetida*) in this study were exposed to contaminated soil for 28 days. LOAEC is based on decreased body weights at day 28.
- **Birds** – Insufficient literature values identified to establish a protective value.
- **Mammals** – Multiple studies with relevant LOAELs identified in the literature.
 - **Toxicity reference value = 5 mg/kg/day**
 - Based on: Lau et al. 2006, Wolf et al. 2007

- In both of these studies, mice were dosed daily via oral gavage throughout pregnancy, beginning on gestation day 1. Dosing in the Lau study ended on gestation day 17 or 18 and in the Wolf study dosing continued through lactation for some dose groups. Selected LOAEL is based on significant decreases in reproductive success in both studies.
- Toxicity reference values, following allometric scaling, are 4.5 mg/kg/day for vole and 5.9 mg/kg/day for shrew.

B-3.2.6 Perfluorononanoic Acid (PFNA) – CAS# 375951

- **Plants** – Insufficient literature values identified to establish a protective value.
- **Soil Biota** – Insufficient literature values identified to establish a protective value.
- **Birds** – Insufficient literature values identified to establish a protective value.
- **Mammals** – Multiple studies with relevant LOAELs identified in the literature.
 - **Toxicity reference value = 1.1 mg/kg/day**
 - Based on: Wolf et al. 2010
 - In this study, mice were dosed daily via oral gavage throughout pregnancy. Dosing began on gestation day 1. Selected LOAEL is based on significantly decreased reproductive success.
 - Toxicity reference values, following allometric scaling, are 1.0 mg/kg/day for vole and 1.3 mg/kg/day for shrew.

B-3.2.7 Perfluorodecanoic Acid (PFDA) – CAS# 335762

- **Plants** – Insufficient literature values identified to establish a protective value.
- **Soil Biota** – Insufficient literature values identified to establish a protective value.
- **Birds** – Insufficient literature values identified to establish a protective value.
- **Mammals** – Multiple studies with relevant LOAELs identified in the literature.
 - **Toxicity reference value = 1 mg/kg/day**
 - Based on: Harris and Birnbaum 1989
 - In this study, mice were dosed daily via oral gavage during pregnancy. Two different dosing regimes were used: mothers were dosed daily on either gestation days 10-13 or on gestation days 6-15. Selected LOAEL is based on significantly decreased fetal weight.
 - Toxicity reference values, following allometric scaling, are 0.9 mg/kg/day for vole and 1.2 mg/kg/day for shrew.

B-3.2.8 Perfluorododecanoic Acid (PFDoA) – CAS# 307551

- **Plants** – Insufficient literature values identified to establish a protective value.
- **Soil Biota** – Insufficient literature values identified to establish a protective value.
- **Birds** – Insufficient literature values identified to establish a protective value.
- **Mammals** – Multiple studies with relevant LOAELs identified in the literature.
 - **Toxicity reference value = 2.5 mg/kg/day**
 - Based on: Kato et al. 2015

- In this study, rats were dosed daily via oral gavage beginning 14 days prior to mating and continuing through postnatal day 5 (females) or 42 days of dosing (males). Selected LOAEL is based on decreased female survival and reproductive success.
- Toxicity reference values, following allometric scaling, are 4.2 mg/kg/day for vole and 5.5 mg/kg/day for shrew.

B-4 Derivation process – Bioaccumulation values

The studies selected for inclusion in determining the bioaccumulation values to use in the Wildlife Exposure Model were generally conducted in the laboratory, using either PFAS contaminated soils collected from field sites or clean soils spiked with PFAS. Studies that used paired measurements of PFAS in soil and plants or earthworms from a specific location in the field were considered if it seemed likely that the plant or earthworm exposure was primarily from contaminated soil, and not from, for example, potentially contaminated groundwater in the same location. In most of the reviewed studies, the organisms were exposed to a mixture of PFAS.

The 90th percentile of the distribution was selected as the reasonable maximum value of the literature-derived bioaccumulation factors. Statistical analysis, including goodness-of-fit tests and determination of the 10th percentile of the best fitting distribution, were done using ProUCL software.

B-4.1 Plants

Studies identified in the literature primarily focused on uptake in agricultural plants (vegetables, grains, etc.) Observed differences in uptake values for different PFAS were attributed to a number of factors, including carbon chain length, whether they contained a carboxylic acid or sulfonic acid functional group, and the characteristics of the tested soil. Percent organic carbon in the soil was specifically identified as a soil characteristic that impacted uptake into plant tissue. Plants grown in soils with higher organic carbon content exhibited less uptake of PFAS. Soils from studies in the literature review had varying organic carbon content, but generally were between 0 and 5% OC. Another general trend noted in the studies was that uptake factor decreased as the soil concentration of PFAS increased.

In most studies, uptake factors were calculated for subsections of the plant. Uptake factors for each plant part were included as distinct values in the distribution.

Values derived from the literature are presented in Appendix C. The K_{plant} values derived from those and used in the Wildlife Exposure Model and presented in Table 4.

B-4.2 Earthworms

Bioaccumulation values for earthworms were reported in a variety of units, depending on the study. All values were converted to dry weight worm / dry weight soil values, with adjusted values presented in Appendix C. For studies where the reported values were based on organic

carbon-normalized soil concentrations, the organic carbon values reported in the study were used to adjust the values to total soil. For studies where wet weight worm concentrations were used, a worm wet weight to dry weight adjustment factor of 0.3 was applied to adjust the values, consistent with the value used in the derivation of values in Table 749-3.

Values derived from the literature are presented in Appendix C. The BAF values derived from those and used in the Wildlife Exposure Model and presented in Table 4.

Table B-3: Bioaccumulation Factors (K_{plant} and BAF_{worm}) derived from literature survey and used in Wildlife Exposure Model.

Organism	PFBS	PFDA	PFNA	PFHxA	PFHxS	PFOA	PFOS	PFBA	PFUnA	PFDoA
Plant	6.60E+01	1.80E+00	1.20E+01	1.80E+01	2.20E+01	3.10E+01	1.00E+01	x	x	1.00E+00
Earthworm	2.40E+01	3.90E+01	2.80E+01	2.60E+00	1.53E+02	8.00E+00	9.10E+01	x	x	1.37E+02

B-5 Summary of protective soil concentrations in uplands

Table B-4: Summary of protective soil concentrations in uplands for PFAS.

Uplands Organism (mg/kg)	PFBS	PFDA	PFNA	PFHxA	PFHxS	PFOA	PFOS	PFBA	PFUnA	PFDoA
Plants	x	x	x	x	x	5.00E+01	x	x	x	x
Soil biota	x	x	x	x	x	2.50E+01	1.00E+02	x	x	X
Wildlife	2.02E+01	1.37E-01	2.06E-01	5.92E+01	3.49E-02	4.60E-01	7.84E-02	x	x	1.78E-01
Total protection	2.02E+01	1.37E-01	2.06E-01	5.92E+01	3.49E-02	4.60E-01	7.84E-02	x	x	1.78E-01

Appendix B Attachment 1: Surface Water Literature Summary

1.1 Marine Invertebrates

Chemical	Species	Concentration (µg/L)	Benchmark	Reference
PFBS	Mysid - <i>Mysidopsis bahia</i>	1.27E+05	NOAEC	Drottar, 2001 (a)
PFDA	Green Mussel - <i>Perna viridis</i>	7.80E+01	EC 50	Liu et al., 2014
PFNA	Green Mussel - <i>Perna viridis</i>	1.95E+02	EC 50	Liu et al., 2014
PFNA	<i>Perna viridis</i>	1.04E+01	NOAEC	Liu and Gin, 2018
PFOA	Sea urchin - <i>Paracentrotus lividius</i>	1.00E+04	NOAEC	Mhadhbi et al., 2012
PFOA	Zooplankton - <i>Siriella ormata</i>	5.00E+03	NOAEC	Mhadhbi et al., 2012
PFOA	Green Mussel - <i>Perna viridis</i>	5.94E+02	EC 50	Liu et al., 2014
PFOA	Sea urchin - <i>Paracentrotus lividius</i>	2.00E+04	LOAEC	Mhadhbi et al., 2012
PFOA	Zooplankton - <i>Siriella armata</i>	5.00E+03	NOAEC	Mhadhbi et al., 2012
PFOA	Sea urchin - <i>Paracentrotus lividius</i>	3.07E+04	EC 10	Mhadhbi et al., 2012
PFOA	Sea urchin - <i>Paracentrotus lividius</i>	1.10E+05	EC 50	Mhadhbi et al., 2012
PFOA	Zooplankton - <i>Siriella ormata</i>	5.00E+03	NOAEC	Mhadhbi et al., 2012
PFOA	Zooplankton - <i>Siriella ormata</i>	5.00E+03	NOAEC	Mhadhbi et al., 2012
PFOA	Zooplankton - <i>Siriella ormata</i>	5.00E+03	NOAEC	Mhadhbi et al., 2012
PFOA	Zooplankton - <i>Siriella ormata</i>	1.00E+04	LOAEC	Mhadhbi et al., 2012
PFOA	Zooplankton - <i>Siriella ormata</i>	7.80E+03	EC 10	Mhadhbi et al., 2012
PFOA	Zooplankton - <i>Siriella ormata</i>	1.55E+04	EC 50	Mhadhbi et al., 2012
PFOS	Zooplankton - <i>Siriella ormata</i>	1.25E+03	NOAEC	Mhadhbi et al., 2012
PFOS	Sea urchin - <i>Paracentrotus lividius</i>	1.00E+03	NOAEC	Mhadhbi et al., 2012
PFOS	Mysid - <i>Mysidopsis bahia</i>	1.10E+03	NOAEC	OECD, 2002
PFOS	Eastern oyster - <i>Crassostrea virginica</i>	1.90E+03	NOAEC	OECD, 2002
PFOS	Mysid - <i>Mysidopsis bahia</i>	2.50E+02	NOAEC	OECD, 2002
PFOS	Copepod - <i>Tigriopus japonicus</i>	1.00E+03	Effects	Jeonghoon et al., 2015
PFOS	Green Mussel - <i>Perna viridis</i>	3.30E+01	EC 50	Liu et al., 2014
PFOS	Zooplankton - <i>Siriella ormata</i>	1.25E+03	NOAEC	Mhadhbi et al., 2012
PFOS	Crustacean - <i>Americamysis bahia</i>	2.50E+02	NOAEC	Moermond et al., 2010
PFOS	<i>Mysidopsis bahia</i>	5.30E+02	NOAEC	Drottar and Krueger, 2000
PFOS	Sea urchin - <i>Paracentrotus lividius</i>	2.00E+03	LOAEC	Mhadhbi et al., 2012
PFOS	Sea urchin - <i>Paracentrotus lividius</i>	2.60E+03	EC 10	Mhadhbi et al., 2012
PFOS	Sea urchin - <i>Paracentrotus lividius</i>	2.00E+04	EC 50	Mhadhbi et al., 2012
PFOS	Zooplankton - <i>Siriella ormata</i>	2.50E+03	LOAEC	Mhadhbi et al., 2012
PFOS	Zooplankton - <i>Siriella ormata</i>	3.20E+03	EC 10	Mhadhbi et al., 2012

Chemical	Species	Concentration (µg/L)	Benchmark	Reference
PFOS	Zooplankton - <i>Siriella ormata</i>	6.90E+03	EC 50	Mhadhbi et al., 2012
PFOS	<i>Crassostrea virginica</i>	1.80E+03	NOAEC	Robertson, 1986

1.2 Marine Fish

Aquatic - Marine (ug/L)				
Fish				
Chemical	Species	Concentration (µg/L)	Benchmark	Reference
PFOA	Turbot - <i>Psetta maxima</i>	1.50E+03	NOAEC	Mhadhbi et al., 2012
PFOA	Turbot - <i>Psetta maxima</i>	3.00E+03	LOAEC	Mhadhbi et al., 2012
PFOA	Turbot - <i>Psetta maxima</i>	3.90E+03	EC 10	Mhadhbi et al., 2012
PFOA	Turbot - <i>Psetta maxima</i>	1.19E+04	EC 50	Mhadhbi et al., 2012
PFOS	Turbot - <i>Psetta maxima</i>	1.50E+01	NOAEC	Mhadhbi et al., 2012
PFOS	Turbot - <i>Psetta maxima</i>	3.00E+01	LOAEC	Mhadhbi et al., 2012
PFOS	Turbot - <i>Psetta maxima</i>	2.00E+01	EC 10	Mhadhbi et al., 2012
PFOS	Turbot - <i>Psetta maxima</i>	1.10E+02	EC 50	Mhadhbi et al., 2012
PFOS	<i>Cypinodon variegatus</i>	1.50E+04	NOAEC	Palmer et al., 2002
PFOS	<i>Oryzias melastigma</i>	1.00E+03	NOAEC	Huang et al., 2011

1.3 Marine Other

Aquatic - Marine (ug/L)				
Other				
Chemical	Species	Concentration (µg/L)	Benchmark	Reference
PFOA	Microalgae - <i>Isochrysis galbana</i>	2.50E+04	NOAEC	Mhadhbi et al., 2012
PFOA	Microalgae - <i>Isochrysis galbana</i>	5.00E+04	LOAEC	Mhadhbi et al., 2012
PFOA	Microalgae - <i>Isochrysis galbana</i>	4.16E+04	EC 10	Mhadhbi et al., 2012
PFOA	Microalgae - <i>Isochrysis galbana</i>	1.64E+05	EC 50	Mhadhbi et al., 2012
PFOA	Baseline Marine Organisms	1.19E+02	PNEC	Mhadhbi et al., 2012
PFOS	Algae - <i>Skeletonoma costatum</i>	>3200	NOAEC	OECD, 2002
PFOS	Microalgae - <i>Isochrysis galbana</i>	7.50E+03	NOAEC	Mhadhbi et al., 2012
PFOS	Microalgae - <i>Skeletonema costatum</i>	3.20E+03	NOAEC	Desjardins et al., 2001b
PFOS	Microalgae - <i>Isochrysis galbana</i>	1.50E+04	LOAEC	Mhadhbi et al., 2012
PFOS	Microalgae - <i>Isochrysis galbana</i>	1.22E+04	EC 10	Mhadhbi et al., 2012

Aquatic - Marine (ug/L)				
Other				
Chemical	Species	Concentration (µg/L)	Benchmark	Reference
PFOS	Microalgae - <i>Isochrysis galbana</i>	3.75E+04	EC 50	Mhadhbi et al., 2012
PFOS	Baseline Marine Organisms	1.10E+00	PNEC	Mhadhbi et al., 2012

1.4 Freshwater Invertebrates

Aquatic - Freshwater (ug/L)				
Invertebrates				
Chemical	Species	Concentration (µg/L)	Benchmark	Reference
PFBS	Water flea - <i>Daphnia magna</i>	5.02E+05	NOAEC	Drottar et al., 2001(b)
PFHxA	<i>Daphnia Magna</i>	7.24E+05	EC5	Germany Annex, 2018
PFDA	<i>Chydorus sphaericus</i>	1.00E+01	NOAEC	Ding et al., 2012
PFDA	<i>Daphnia Magna</i>	1.50E+02	NOAEC	Ding et al., 2012
PFBA	<i>Chydorus sphaericus</i>	2.00E+03	NOAEC	Ding et al., 2012
PFBA	<i>Daphnia Magna</i>	8.30E+02	NOAEC	Ding et al., 2012
PFNA	<i>Chydorus sphaericus</i>	5.00E+01	NOAEC	Ding et al., 2012
PFNA	<i>Daphnia Magna</i>	2.00E+02	NOAEC	Ding et al., 2012
PFNA	<i>Daphnia Magna</i>	8.00E+00	NOAEC	Lu et al., 2015
PFNA	<i>Chironomus plumosus</i>	9.60E+00	NOAEC	Zhai et al., 2016
PFOA	<i>Chydorus sphaericus</i>	1.00E+01	NOAEC	Ding et al., 2012
PFOA	<i>Daphnia Magna</i>	1.00E+02	NOAEC	Ding et al., 2012
PFOA	<i>Chironomus plumosus</i>	9.32E+02	NOAEC	Zhai et al, 2016
PFOA	<i>Chydorus sphaericus</i>	2.00E+01	NOAEC	Ding et al., 2012
PFOA	<i>Daphnia Magna</i>	1.20E+02	NOAEC	Ding et al., 2012
PFOA	<i>Daphnia magna</i>	2.50E+05	NOAEC	Ji et al., 2008
PFOA	<i>Moina macrocopa</i>	6.25E+04	NOAEC	Ji et al., 2008
PFOA	<i>Chydorus sphaericus</i>	1.00E+02	NOAEC	Ding et al., 2012

Aquatic - Freshwater (ug/L)				
Invertebrates				
Chemical	Species	Concentration (ug/L)	Benchmark	Reference
PFOA	<i>Daphnia Magna</i>	5.00E+02	NOAEC	Ding et al., 2012
PFOS	<i>Daphnia magna</i>	1.25E+04	NOAEC	Ji et al., 2008
PFOS	<i>Moina macrocopa</i>	6.25E+03	NOAEC	Ji et al., 2008
PFOS	zooplankton community	3.00E+03	NOAEC	Boudreau et al., 2003
PFOS	cladocera/copepoda	2.00E+02	NOAEC	Boudreau et al., 2003
PFOS	Crustacean - <i>Daphnia magna</i>	7.00E+03	NOAEC	Moermond et al., 2010
PFOS	Crustacean - <i>Moina macrocopa</i>	4.00E+02	NOAEC	Moermond et al., 2010
PFOS	Insect - <i>Chironomus tentans</i>	<2.3	NOAEC	Moermond et al., 2010
PFOS	Insect - <i>Enallagma cyathigerum</i>	<10	NOAEC	Moermond et al., 2010
PFOS	<i>Daphnia pulicaria</i>	2.20E+03	NOAEC	Boudreau et al., 2003
PFOS	<i>Daphnia magna</i>	6.00E+02	NOAEC	Boudreau et al., 2003
PFOS	Chironomid - <i>Chironomus tentans</i>	5.00E+01	NOAEC	MacDonald et al., 2004
PFOS	<i>Chironomus riparius</i>	3.50E+00	NOAEC	Stefani et al., 2014
PFOS/PFOA	<i>Chironomus tentans</i>	4.91E+01	NOAEC	MacDonald et al., 2004

1.5 Freshwater Fish

Aquatic - Freshwater (ug/L)				
Fish				
Chemical	Species	Concentration (ug/L)	Benchmark	Reference
PFBS	<i>Pimephales promelas</i>	8.88E+05	NOAEC	WLI, 2001 (c)
PFBS	<i>Lepomis macrochirus</i>	2.72E+06	NOAEC	WLI, 2001 (d)
PFHxA	<i>Oncorhynchus mykiss</i>	9.96E+03	LOAEC	Germany Annex, 2018
PFHxA	<i>Danio rerio</i>	6.28E+03	NOAEC	Annunzaito et al., 2020
PFNA	<i>Danio rerio</i>	1.00E+01	NOAEC	Zhang et al., 2016
PFNA	<i>Danio rerio</i>	9.20E+02	NOAEC	Jantzen et al., 2016

Aquatic - Freshwater (ug/L)				
Fish				
Chemical	Species	Concentration (ug/L)	Benchmark	Reference
PFOA	<i>Salmo salar</i>	1.00E+02	LOAEC	Spachmo and Arukwe, 2012
PFOA	<i>Oryzias latipes</i>	1.00E+02	NOAEC	Ji et al., 2008
PFOA	<i>Danio rerio</i>	8.28E+00	NOAEC	Jantzen et al., 2016
PFOA	<i>Salmo salar</i>	1.00E+02	NOAEC	Spachmo and Arukwe, 2012
PFOS	<i>Pimephales promelas</i>	3.20E+03	NOAEC	Drottar and Krueger, 2000 (h)
PFOS	Fathead minnow - <i>Pimephales promelas</i>	3.00E+02	NOAEC	OECD, 2002
PFOS	Bluegill sunfish - <i>Lepomis macrochirus</i>	> 86, < 870	NOAEC	OECD, 2002
PFOS	Fathead minnow - <i>Pimephales promelas</i>	2.70E+01	NOAEC	Moermond et al., 2010
PFOS	Japanese rice fish - <i>Oryzias latipes</i>	<10	NOAEC	Moermond et al., 2010
PFOS	<i>Onchorhynchus mykiss</i>	6.30E+03	NOAEC	Palmer et al., 2002
PFOS	<i>Oryzias latipes</i>	1.00E+01	NOAEC	Ji et al., 2008
PFOS	<i>Pimephales promelas</i>	2.90E+02	NOAEC	Drottar and Krueger, 2000
PFOS	<i>Zebra danio</i>	5.00E+00	NOAEC	Wang et al., 2011

1.6 Freshwater Other

Aquatic - Freshwater (ug/L)				
Other				
Chemical	Species	Concentration (ug/L)	Benchmark	Reference
PFBS	Algae - <i>Selenastrum capricornum</i>	1.08E+06	NOAEC	WLI, 2001 €
PFHxA	Cyanobacteria	5.00E+04	NOAEC	Germany Annex, 2018
PFHxS	<i>Rana pipiens</i>	1.00E+01	LOAEC	Persistent Organics Review, 2018
PFHxS	<i>Lithobates pipiens</i>	1.00E+01	LOAEC	Brown et al., 2020
PFOA	blue-green algae	5.00E+03	LOAEC	Rodea-Palomares et al., 2015
PFOS	<i>Xenopus laevis</i>	1.00E+02	NOAEC	Cheng et al., 2011

Aquatic - Freshwater (ug/L)				
Other				
Chemical	Species	Concentration (µg/L)	Benchmark	Reference
PFOS	Algae - <i>Selenastrum capricornutum</i>	<26000	NOAEC	OECD, 2002
PFOS	Algae - <i>Selenastrum capricornutum</i>	1.60E+04	EC 10	OECD, 2002
PFOS	Algae - <i>Chorella vulgaris</i>	8.20E+03	NOAEC	Moermond et al., 2010
PFOS	Algae - <i>Navicula pelliculosa</i>	1.91E+05	NOAEC	Moermond et al., 2010
PFOS	Algae - <i>Pseudokirchneriella subcapitata</i>	5.30E+04	NOAEC	Moermond et al., 2010
PFOS	Lemna Gibba	6.60E+03	NOAEC	Boudreau et al., 2003a
PFOS	Zooplankton Community	3.00E+03	NOAEC	Boudreau et al., 2003b
PFOS	Macroalgae - <i>Myriophyllum sibiricum</i>	3.00E+02	NOAEC	Hansen et al., 2005
PFOS	Xenopus laevis	4.82E+03	NOAEC	Palmer and Krueger, 2001
PFOS	Microalgae - <i>Chlorella vulgaris</i>	8.20E+03	NOAEC	Boudreau et al. 2003a
PFOS	Cyanobacteria - <i>Anabaena flos-aqua</i>	9.40E+04	NOAEC	Moermond et al., 2010
PFOS	Amphibian - <i>Xenopus laevis</i>	5.00E+03	NOAEC	Moermond et al., 2010
PFOS	<i>Selenastrum capricortum</i>	5.30E+03	NOAEC	Boudreau et al., 2003a
PFOS	Macrophyte - <i>Lemna gibba</i>	6.60E+03	NOAEC	Moermond et al., 2010
PFOS	Macrophyte - <i>Myriophyllum sibiricum</i>	5.60E+02	NOAEC	Moermond et al., 2010
PFOS	Macrophyte - <i>Myriophyllum spicatum</i>	3.20E+03	NOAEC	Moermond et al., 2010

Appendix B Attachment 2: Surface Water References

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Appendix B Attachment 3: Upland Literature Summary

3.1 Background

Toxicity tables include relevant LOAELs found during the literature survey. These values were considered in the selection of final protective concentrations for plants and soil biota and toxicity reference values for mammals and birds. Bioaccumulation tables include relevant values identified in the literature and included in the derivation of 90th percentile values. Many of the bioaccumulation studies evaluated multiple soil types or multiple concentrations of PFAS, leading to multiple entries in the tables for a specific PFAS.

The reference list in Appendix D includes all reviewed studies. Reasons a study may be listed in the References but not appear in these tables include providing bioaccumulation data for a PFAS with no identified toxicity data; providing the only relevant LOAEL or LOAEC for a specific PFAS; and that a relevant LOAEL, LOAEC, or bioaccumulation value could not be identified in the study.

3.2 Plant toxicity

CHEMICAL	SPECIES	SOIL CONCENTRATION (mg/kg)	BENCHMARK - EFFECT	REFERENCE
PFOA	sorghum	66	EC50 – chlorophyll	Gonzalez-Naranjo et al. 2015
PFOA	mung bean	100	LOAEC - growth	Kwak et al. 2020
PFOA	rice	300	LOAEC - growth	Kwak et al. 2020
PFOA	soil algae (<i>Chlorococcum infusioenum</i>)	50	LOAEC - growth	Kwak et al. 2020
PFOA	soil algae (<i>Chlamydomonas reinhardtii</i>)	700	LOAEC - growth	Kwak et al. 2020
PFOA	Chinese cabbage	100	LOAEC - growth	Zhao et al. 2011
PFOA	wheat	800	LOAEC - growth	Zhou et al. 2016

3.3 Soil biota (earthworm) toxicity

CHEMICAL	SOIL CONCENTRATION (mg/kg)	BENCHMARK – EFFECT	REFERENCE
PFOA	25	LOAEC - growth	He et al. 2016
PFOA	600	LOAEC - survival	Kwak et al. 2020
PFOA	100	LOAEC - survival	Zareitalabad et al. 2013
PFOS	141	LOAEC - survival	Sindermann et al. 2002
PFOS	120	LOAEC - growth	Xu et al. 2013
PFOS	100	LOAEC - survival	Zareitalabad et al. 2013

3.4 Avian toxicity

CHEMICAL	SPECIES	DOSE (mg/kg/day)	BENCHMARK – EFFECT	REFERENCE
PFOS	bobwhite quail	0.77	LOAEL - reproduction	Newsted et al. 2007/Gallagher 2003a
PFOS	mallard duck	6.4	LOAEL - survival	Newsted et al. 2007/Gallagher 2003b
PFOS	bobwhite quail	61	LD50	Newsted et al. 2006/Gallagher 2004a
PFOS	mallard duck	150	LD50	Newsted et al. 2006/Gallagher 2004b
PFOS	Japanese quail	11	LOAEL - growth	Bursian et al 2020

3.5 Mammalian toxicity

CHEMICAL	SPECIES	LOAEL (mg/kg/day)	REFERENCE
PFBS	rat	600	Lieder et al. 2009a
PFBS	rat	1000	Lieder et al. 2009b
PFBS	rat	250	NTP 2019b
PFDA	mouse	1	Harris and Birnbaum 1988
PFDA	rat	1.25	NTP 2019a
PFDoA	rat	2.5	Kato et al. 2015
PFDoA	rat	3	Shi et al. 2009
PFDoA	rat	5	Shi et al. 2007
PFHxA	rat	200	Klaunig et al. 2015
PFHxA	rat	1000	NTP 2019a
PFHxS	rat	1	Butenhoff et al. 2009a
PFHxS	mouse	1	Chang et al. 2018
PFHxS	rat	5	Ramhoj et al. 2018
PFNA	mouse	5	Das et al. 2015
PFNA	rat	5	NTP 2019a
PFNA	mouse	1.1	Wolf et al. 2010
PFOA	rat	30	Butenhoff et al. 2004/York et al. 2010
PFOA	mouse	5	Lau et al. 2006
PFOA	rat	5	NTP 2019a
PFOA	rat (males only)	6.5	Perkins et al. 2004
PFOA	mouse	5	Wolf et al. 2007/White et al. 2009
PFOS	rat	10	Austin et al. 2003
PFOS	rat	1	Butenhoff et al. 2009b
PFOS	rabbit	1	Case et al. 2001
PFOS	mouse	25	Dong et al. 2009
PFOS	rat	10	Gortner 1980
PFOS	rat	3	Lau et al. 2003/Thibodeaux et al. 2003
PFOS	mouse	10	Lau et al. 2003/Thibodeaux et al. 2003
PFOS	rat	1.6	Luebker et al. 2005b
PFOS	rat	20	Thomford 2002/Seacat et al. 2003

3.6 Plant bioaccumulation

CHEMICAL	SPECIES/PART OF PLANT	K_{plant}	REFERENCE
PFBS	alfalfa shoot	107	Lasee et al. 2019
PFBS	alfalfa root	36	Lasee et al. 2019
PFBS	carrot shoot	58	Lasee et al. 2019
PFBS	carrot root	5.9	Lasee et al. 2019
PFBS	radish shoot	69	Lasee et al. 2019
PFBS	radish root	72	Lasee et al. 2019
PFBS	radish root	1.3	Blaine et al. 2014
PFBS	radish shoot	3.4	Blaine et al. 2014
PFBS	celery root	2.5	Blaine et al. 2014
PFBS	celery shoot	2.2	Blaine et al. 2014
PFBS	tomato root	0.71	Blaine et al. 2014
PFBS	tomato shoot	3.7	Blaine et al. 2014
PFBS	tomato fruit	0.42	Blaine et al. 2014
PFBS	pea root	0.89	Blaine et al. 2014
PFBS	pea shoot	4.1	Blaine et al. 2014
PFBS	pea fruit	0.33	Blaine et al. 2014
PFBS	radish stem	69	Lasee et al. 2020
PFBS	radish root	72	Lasee et al. 2020
PFBS	carrot stem	77	Lasee et al. 2020
PFBS	carrot root	7.5	Lasee et al. 2020
PFBS	alfalfa stem	114	Lasee et al. 2020
PFBS	alfalfa root	3	Lasee et al. 2020
PFBS	radish stem	22	Lasee et al. 2020
PFBS	radish root	0.86	Lasee et al. 2020
PFBS	carrot stem	24	Lasee et al. 2020
PFBS	carrot root	0.06	Lasee et al. 2020
PFBS	alfalfa stem	6.7	Lasee et al. 2020
PFBS	alfalfa root	0.74	Lasee et al. 2020
PFBS	tomato leaf	3.8	Lasee et al. 2020
PFBS	tomato root	0.61	Lasee et al. 2020
PFBS	tomato stem	0.29	Lasee et al. 2020
PFBS	tomato fruit	0.19	Lasee et al. 2020
PFBS	wheatgrass	28	Braunig et al. 2019
PFBS	wheatgrass	36	Braunig et al. 2019

CHEMICAL	SPECIES/PART OF PLANT	K _{plant}	REFERENCE
PFBS	maize straw	3.9	Krippner et al. 2015
PFBS	maize straw	1.8	Krippner et al. 2015
PFBS	maize kernels	0.008	Krippner et al. 2015
PFBS	maize kernels	0.005	Krippner et al. 2015
PFBS	wheat whole plant	39	Zhao et al. 2014
PFBS	wheat whole plant	34	Zhao et al. 2014
PFBS	wheat whole plant	26	Zhao et al. 2014
PFBS	corn leaf	4.0	Navarro et al. 2017
PFDA	maize straw	0.03	Krippner et al. 2015
PFDA	maize straw	0.04	Krippner et al. 2015
PFDA	radish root	0.44	Blaine et al. 2014
PFDA	radish shoot	1.1	Blaine et al. 2014
PFDA	celery root	1.1	Blaine et al. 2014
PFDA	celery shoot	0.32	Blaine et al. 2014
PFDA	tomato root	1.9	Blaine et al. 2014
PFDA	tomato shoot	1.4	Blaine et al. 2014
PFDA	pea root	1.4	Blaine et al. 2014
PFDA	pea shoot	0.15	Blaine et al. 2014
PFDA	wheat whole plant	1.8	Zhao et al. 2014
PFDA	wheat whole plant	1.7	Zhao et al. 2014
PFDA	wheat whole plant	1.5	Zhao et al. 2014
PFDA	tomato stem	0.24	Navarro et al. 2017
PFDA	tomato fruit	0.02	Navarro et al. 2017
PFDA	grass leaf	1.1	Zhu et al. 2019
PFDoA	wheat whole plant	1.0	Zhao et al. 2014
PFDoA	wheat whole plant	1.0	Zhao et al. 2014
PFDoA	wheat whole plant	0.9	Zhao et al. 2014
PFHxA	wheatgrass	15	Braunig et al. 2019
PFHxA	wheatgrass	18	Braunig et al. 2019
PFHxA	maize straw	3.2	Krippner et al. 2015
PFHxA	maize straw	2.8	Krippner et al. 2015
PFHxA	maize kernels	0.12	Krippner et al. 2015
PFHxA	maize kernels	0.22	Krippner et al. 2015
PFHxA	radish root	1.2	Blaine et al. 2014
PFHxA	radish shoot	3.9	Blaine et al. 2014

CHEMICAL	SPECIES/PART OF PLANT	K _{plant}	REFERENCE
PFHxA	celery root	4.8	Blaine et al. 2014
PFHxA	celery shoot	12	Blaine et al. 2014
PFHxA	tomato root	1.5	Blaine et al. 2014
PFHxA	tomato shoot	8.9	Blaine et al. 2014
PFHxA	tomato fruit	2.9	Blaine et al. 2014
PFHxA	pea root	1.0	Blaine et al. 2014
PFHxA	pea shoot	3.5	Blaine et al. 2014
PFHxA	pea fruit	1.5	Blaine et al. 2014
PFHxA	wheat kernels	6.8	Liu et al. 2017
PFHxA	maize kernels	2.0	Liu et al. 2017
PFHxA	wheat whole plant	16	Zhao et al. 2014
PFHxA	wheat whole plant	15	Zhao et al. 2014
PFHxA	wheat whole plant	14	Zhao et al. 2014
PFHxA	tomato stem	1.8	Navarro et al. 2017
PFHxA	tomato leaf	6.9	Navarro et al. 2017
PFHxA	tomato fruit	3.6	Navarro et al. 2017
PFHxS	alfalfa shoot	12	Lasee et al. 2019
PFHxS	alfalfa root	11	Lasee et al. 2019
PFHxS	carrot shoot	28	Lasee et al. 2019
PFHxS	carrot root	1.1	Lasee et al. 2019
PFHxS	radish shoot	33	Lasee et al. 2019
PFHxS	radish root	13	Lasee et al. 2019
PFHxS	radish root	2.1	Blaine et al. 2014
PFHxS	radish shoot	7.4	Blaine et al. 2014
PFHxS	celery root	5.0	Blaine et al. 2014
PFHxS	celery shoot	2.3	Blaine et al. 2014
PFHxS	tomato root	1.8	Blaine et al. 2014
PFHxS	tomato shoot	5.6	Blaine et al. 2014
PFHxS	tomato fruit	0.5	Blaine et al. 2014
PFHxS	pea shoot	4.3	Blaine et al. 2014
PFHxS	pea fruit	0.17	Blaine et al. 2014
PFHxS	radish stem	34	Lasee et al. 2020
PFHxS	radish root	13	Lasee et al. 2020
PFHxS	carrot stem	40	Lasee et al. 2020
PFHxS	carrot root	1.6	Lasee et al. 2020

CHEMICAL	SPECIES/PART OF PLANT	K _{plant}	REFERENCE
PFHxS	alfalfa stem	14	Lasee et al. 2020
PFHxS	alfalfa root	12	Lasee et al. 2020
PFHxS	radish stem	23	Lasee et al. 2020
PFHxS	radish root	0.59	Lasee et al. 2020
PFHxS	carrot stem	10	Lasee et al. 2020
PFHxS	carrot root	0.09	Lasee et al. 2020
PFHxS	alfalfa stem	2.3	Lasee et al. 2020
PFHxS	alfalfa root	0.45	Lasee et al. 2020
PFHxS	tomato leaf	2.5	Lasee et al. 2020
PFHxS	tomato root	0.4	Lasee et al. 2020
PFHxS	tomato stem	0.11	Lasee et al. 2020
PFHxS	tomato fruit	0.11	Lasee et al. 2020
PFHxS	wheatgrass	12	Braunig et al. 2019
PFHxS	wheatgrass	9.7	Braunig et al. 2019
PFHxS	maize straw	0.84	Krippner et al. 2015
PFHxS	maize straw	0.85	Krippner et al. 2015
PFHxS	wheat whole plant	4.2	Zhao et al. 2014
PFHxS	wheat whole plant	4.0	Zhao et al. 2014
PFHxS	wheat whole plant	3.6	Zhao et al. 2014
PFHxS	corn leaf	9.4	Navarro et al. 2017
PFNA	alfalfa shoot	1.7	Lasee et al. 2019
PFNA	alfalfa root	5.3	Lasee et al. 2019
PFNA	carrot shoot	18	Lasee et al. 2019
PFNA	carrot root	1.4	Lasee et al. 2019
PFNA	radish shoot	36	Lasee et al. 2019
PFNA	radish root	9.6	Lasee et al. 2019
PFNA	radish root	1.3	Blaine et al. 2014
PFNA	radish shoot	5.3	Blaine et al. 2014
PFNA	celery root	1.9	Blaine et al. 2014
PFNA	celery shoot	0.69	Blaine et al. 2014
PFNA	tomato root	1.9	Blaine et al. 2014
PFNA	tomato shoot	2.4	Blaine et al. 2014
PFNA	pea root	1.7	Blaine et al. 2014
PFNA	pea shoot	0.44	Blaine et al. 2014
PFNA	pea fruit	0.07	Blaine et al. 2014

CHEMICAL	SPECIES/PART OF PLANT	K _{plant}	REFERENCE
PFNA	radish stem	38	Lasee et al. 2020
PFNA	radish root	10	Lasee et al. 2020
PFNA	carrot stem	23	Lasee et al. 2020
PFNA	carrot root	1.9	Lasee et al. 2020
PFNA	alfalfa stem	1.7	Lasee et al. 2020
PFNA	alfalfa root	5.5	Lasee et al. 2020
PFNA	radish stem	6.9	Lasee et al. 2020
PFNA	radish root	0.61	Lasee et al. 2020
PFNA	carrot stem	1.4	Lasee et al. 2020
PFNA	carrot root	0.21	Lasee et al. 2020
PFNA	alfalfa stem	0.46	Lasee et al. 2020
PFNA	alfalfa root	0.64	Lasee et al. 2020
PFNA	tomato leaf	0.59	Lasee et al. 2020
PFNA	tomato root	0.46	Lasee et al. 2020
PFNA	tomato stem	0.09	Lasee et al. 2020
PFNA	tomato fruit	0.02	Lasee et al. 2020
PFNA	wheatgrass	0.13	Braunig et al. 2019
PFNA	maize straw	0.12	Krippner et al. 2015
PFNA	maize straw	0.16	Krippner et al. 2015
PFNA	wheat kernels	1.1	Liu et al. 2017
PFNA	wheat whole plant	2.1	Zhao et al. 2014
PFNA	wheat whole plant	2.0	Zhao et al. 2014
PFNA	wheat whole plant	1.6	Zhao et al. 2014
PFNA	tomato leaf	0.28	Navarro et al. 2017
PFNA	grass leaf	2.0	Zhu et al. 2019
PFOA	alfalfa shoot	10	Lasee et al. 2019
PFOA	alfalfa root	19	Lasee et al. 2019
PFOA	carrot shoot	54	Lasee et al. 2019
PFOA	carrot root	3.1	Lasee et al. 2019
PFOA	radish shoot	47	Lasee et al. 2019
PFOA	radish root	18	Lasee et al. 2019
PFOA	radish root	0.85	Blaine et al. 2014
PFOA	radish shoot	7.6	Blaine et al. 2014
PFOA	celery root	1.4	Blaine et al. 2014
PFOA	celery shoot	0.71	Blaine et al. 2014

CHEMICAL	SPECIES/PART OF PLANT	K _{plant}	REFERENCE
PFOA	tomato root	0.96	Blaine et al. 2014
PFOA	tomato shoot	2.4	Blaine et al. 2014
PFOA	tomato fruit	0.11	Blaine et al. 2014
PFOA	pea root	0.79	Blaine et al. 2014
PFOA	pea shoot	0.52	Blaine et al. 2014
PFOA	pea fruit	0.03	Blaine et al. 2014
PFOA	alfalfa shoot	3.1	Wen et al. 2016
PFOA	radish stem	46	Lasee et al. 2020
PFOA	radish root	18	Lasee et al. 2020
PFOA	carrot stem	74	Lasee et al. 2020
PFOA	carrot root	3.8	Lasee et al. 2020
PFOA	alfalfa stem	10	Lasee et al. 2020
PFOA	alfalfa root	19	Lasee et al. 2020
PFOA	radish stem	8.8	Lasee et al. 2020
PFOA	radish root	0.54	Lasee et al. 2020
PFOA	carrot stem	2.7	Lasee et al. 2020
PFOA	carrot root	0.1	Lasee et al. 2020
PFOA	alfalfa stem	0.61	Lasee et al. 2020
PFOA	alfalfa root	0.19	Lasee et al. 2020
PFOA	tomato leaf	1.9	Lasee et al. 2020
PFOA	tomato root	0.23	Lasee et al. 2020
PFOA	tomato stem	0.08	Lasee et al. 2020
PFOA	tomato fruit	0.04	Lasee et al. 2020
PFOA	wheatgrass	0.58	Braunig et al. 2019
PFOA	wheatgrass	1.1	Braunig et al. 2019
PFOA	maize straw	0.56	Krippner et al. 2015
PFOA	maize straw	0.65	Krippner et al. 2015
PFOA	maize kernels	0.002	Krippner et al. 2015
PFOA	wheat kernels	0.04	Liu et al. 2017
PFOA	maize kernels	0.002	Liu et al. 2017
PFOA	wheat whole plant	2.7	Zhao et al. 2014
PFOA	wheat whole plant	2.1	Zhao et al. 2014
PFOA	wheat whole plant	1.7	Zhao et al. 2014
PFOA	spinach	1.6	Navarro et al. 2017
PFOA	tomato stem	0.55	Navarro et al. 2017
PFOA	tomato leaf	3.6	Navarro et al. 2017

CHEMICAL	SPECIES/PART OF PLANT	K _{plant}	REFERENCE
PFOA	tomato fruit	0.08	Navarro et al. 2017
PFOA	grass leaf	113	Zhu et al. 2019
PFOS	alfalfa shoot	1.4	Lasee et al. 2019
PFOS	alfalfa root	4.3	Lasee et al. 2019
PFOS	carrot shoot	54	Lasee et al. 2019
PFOS	carrot root	1	Lasee et al. 2019
PFOS	radish shoot	10	Lasee et al. 2019
PFOS	carrot shoot	2.9	Lasee et al. 2019
PFOS	radish root	0.7	Blaine et al. 2014
PFOS	radish shoot	3.7	Blaine et al. 2014
PFOS	celery root	4.2	Blaine et al. 2014
PFOS	celery shoot	1.4	Blaine et al. 2014
PFOS	tomato root	4.5	Blaine et al. 2014
PFOS	tomato shoot	4.2	Blaine et al. 2014
PFOS	pea root	2.4	Blaine et al. 2014
PFOS	pea shoot	1.2	Blaine et al. 2014
PFOS	pea fruit	0.03	Blaine et al. 2014
PFOS	alfalfa shoot	0.4	Wen et al. 2016
PFOS	radish stem	9.6	Lasee et al. 2020
PFOS	radish root	2.7	Lasee et al. 2020
PFOS	carrot stem	25	Lasee et al. 2020
PFOS	carrot root	1.2	Lasee et al. 2020
PFOS	alfalfa stem	1.3	Lasee et al. 2020
PFOS	alfalfa root	4.0	Lasee et al. 2020
PFOS	radish stem	14	Lasee et al. 2020
PFOS	radish root	1.1	Lasee et al. 2020
PFOS	carrot stem	4.7	Lasee et al. 2020
PFOS	carrot root	0.17	Lasee et al. 2020
PFOS	alfalfa stem	0.49	Lasee et al. 2020
PFOS	alfalfa root	1.2	Lasee et al. 2020
PFOS	tomato leaf	1	Lasee et al. 2020
PFOS	tomato root	1.7	Lasee et al. 2020
PFOS	tomato stem	0.17	Lasee et al. 2020
PFOS	tomato fruit	0.03	Lasee et al. 2020
PFOS	wheatgrass	0.16	Braunig et al. 2019

CHEMICAL	SPECIES/PART OF PLANT	K_{plant}	REFERENCE
PFOS	wheatgrass	0.37	Braunig et al. 2019
PFOS	maize straw	0.32	Krippner et al. 2015
PFOS	maize straw	0.62	Krippner et al. 2015
PFOS	wheat kernels	1.2	Liu et al. 2017
PFOS	maize kernels	1.1	Liu et al. 2017
PFOS	wheat whole plant	3.7	Zhao et al. 2014
PFOS	wheat whole plant	3.1	Zhao et al. 2014
PFOS	wheat whole plant	2.5	Zhao et al. 2014
PFOS	spinach	3.8	Navarro et al. 2017
PFOS	tomato stem	0.45	Navarro et al. 2017
PFOS	tomato leaf	1.2	Navarro et al. 2017
PFOS	tomato fruit	0.06	Navarro et al. 2017
PFOS	corn leaf	0.8	Navarro et al. 2017

3.7 Earthworm bioaccumulation

BAF values in the table are the adjusted literature values, to yield final values of mg/kg worm_{dw} / mg/kg soil_{dw}.

CHEMICAL	BAF	REFERENCE
PFBS	0.83	Karnjanapiboonwong et al. 2018
PFBS	4.7	Karnjanapiboonwong et al. 2018
PFBS	7.7	Karnjanapiboonwong et al. 2018
PFBS	1.4	Zhao et al. 2013b
PFBS	0.75	Zhao et al. 2013b
PFBS	0.55	Zhao et al. 2013b
PFBS	17	Braunig et al. 2019
PFBS	16	Braunig et al. 2019
PFBS	15	Zhao et al. 2014
PFBS	14	Zhao et al. 2014
PFBS	12	Zhao et al. 2014
PFBS	2.8	Navarro et al. 2017
PFDA	5.2	Rich et al. 2015
PFDA	18	Rich et al. 2015
PFDA	21	Rich et al. 2015
PFDA	6.3	Rich et al. 2015
PFDA	8.0	Zhao et al. 2013b
PFDA	7.1	Zhao et al. 2013b
PFDA	5.3	Zhao et al. 2013b
PFDA	5.7	Braunig et al. 2019
PFDA	12	Braunig et al. 2019
PFDA	12	Navarro et al. 2016
PFDA	44	Zhao et al. 2014
PFDA	39	Zhao et al. 2014
PFDA	38	Zhao et al. 2014
PFDA	6.7	Zhu et al. 2019
PFD _o A	9.8	Rich et al. 2015
PFD _o A	41	Rich et al. 2015
PFD _o A	91	Rich et al. 2015
PFD _o A	51	Rich et al. 2015
PFD _o A	37	Zhao et al. 2013b
PFD _o A	22	Zhao et al. 2013b

CHEMICAL	BAF	REFERENCE
PFDoA	18	Zhao et al. 2013b
PFDoA	30	Braunig et al. 2019
PFDoA	76	Braunig et al. 2019
PFDoA	199	Navarro et al. 2016
PFDoA	112	Zhao et al. 2014
PFDoA	88	Zhao et al. 2014
PFDoA	80	Zhao et al. 2014
PFDoA	49	Zhu et al. 2019
PFHxA	2.3	Zhao et al. 2013b
PFHxA	1.2	Zhao et al. 2013b
PFHxA	0.89	Zhao et al. 2013b
PFHxA	1.1	Braunig et al. 2019
PFHxA	0.40	Braunig et al. 2019
PFHxA	2.4	Zhao et al. 2014
PFHxA	1.6	Zhao et al. 2014
PFHxA	1.3	Zhao et al. 2014
PFHxS	24.6	Rich et al. 2015
PFHxS	14.2	Rich et al. 2015
PFHxS	139	Rich et al. 2015
PFHxS	100	Rich et al. 2015
PFHxS	2.2	Karnjanapiboonwong et al. 2018
PFHxS	20	Karnjanapiboonwong et al. 2018
PFHxS	40	Karnjanapiboonwong et al. 2018
PFHxS	113	Karnjanapiboonwong et al. 2018
PFHxS	4.9	Zhao et al. 2013b
PFHxS	4.0	Zhao et al. 2013b
PFHxS	2.7	Zhao et al. 2013b
PFHxS	20	Braunig et al. 2019
PFHxS	21	Braunig et al. 2019
PFHxS	58	Zhao et al. 2014
PFHxS	50	Zhao et al. 2014
PFHxS	48	Zhao et al. 2014
PFHxS	3.4	Navarro et al. 2016
PFNA	3.6	Rich et al. 2015
PFNA	5.0	Rich et al. 2015
PFNA	18	Rich et al. 2015

CHEMICAL	BAF	REFERENCE
PFNA	14	Rich et al. 2015
PFNA	4.2	Karnjanapiboonwong et al. 2018
PFNA	29	Karnjanapiboonwong et al. 2018
PFNA	80	Karnjanapiboonwong et al. 2018
PFNA	5.5	Zhao et al. 2013b
PFNA	3.1	Zhao et al. 2013b
PFNA	3.0	Zhao et al. 2013b
PFNA	3.3	Braunig et al. 2019
PFNA	6.7	Braunig et al. 2019
PFNA	17	Zhao et al. 2014
PFNA	13	Zhao et al. 2014
PFNA	12	Zhao et al. 2014
PFNA	5.6	Zhu et al. 2019
PFOA	2.1	Rich et al. 2015
PFOA	4.0	Rich et al. 2015
PFOA	8.3	Rich et al. 2015
PFOA	6.0	Rich et al. 2015
PFOA	2.5	Zhao et al. 2013b
PFOA	1.6	Zhao et al. 2013b
PFOA	0.96	Zhao et al. 2013b
PFOA	2.7	Braunig et al. 2019
PFOA	2.2	Braunig et al. 2019
PFOA	2.0	Navarro et al. 2016
PFOA	7.7	Zhao et al. 2014
PFOA	7.2	Zhao et al. 2014
PFOA	6.8	Zhao et al. 2014
PFOA	3.3	Zhu et al. 2019
PFOS	18	Rich et al. 2015
PFOS	23	Rich et al. 2015
PFOS	75	Rich et al. 2015
PFOS	55	Rich et al. 2015
PFOS	9.9	Zhao et al. 2013b
PFOS	8.9	Zhao et al. 2013b
PFOS	6.6	Zhao et al. 2013b
PFOS	16	Braunig et al. 2019
PFOS	27	Braunig et al. 2019

CHEMICAL	BAF	REFERENCE
PFOS	23	Navarro et al. 2016
PFOS	102	Zhao et al. 2014
PFOS	82	Zhao et al. 2014
PFOS	72	Zhao et al. 2014
PFOS	3.9	Navarro et al. 2016

Appendix B Attachment 4: Upland References

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