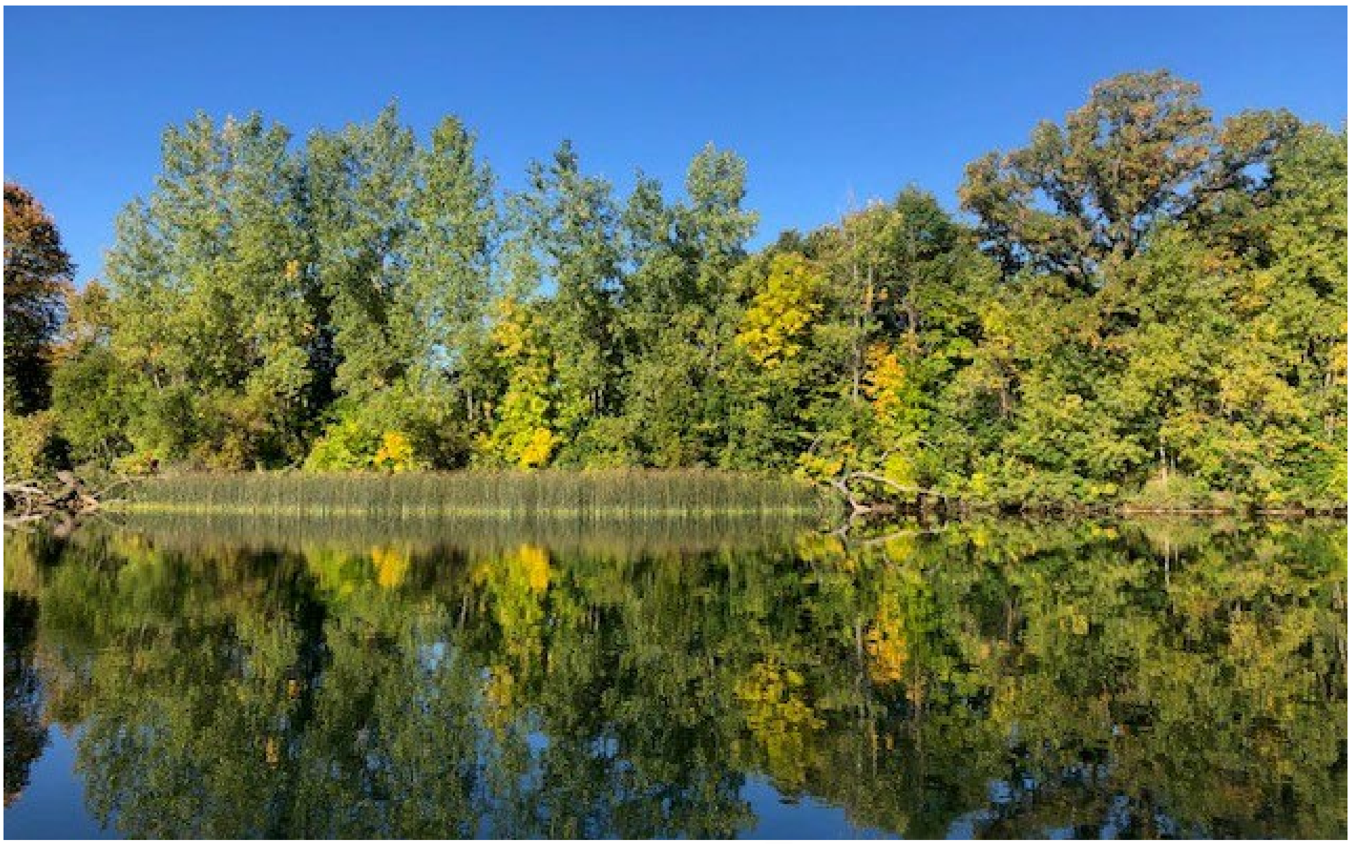
Water quality standards

January 2023

Water Quality Standards: Human Health Protective Water Quality Criteria for Per- and Polyfluoroalkyl Substances (PFAS)

This technical support document describes the basis for site-specific water quality criteria for five PFAS based on methods in Minn. R. ch. 7050.



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Per- and polyfluoroalkyl substances (PFAS) with Water Quality Criteria (WQC)

October 2020, November 2022 and January 2023-updates to Appendix B

- Perfluorooctane sulfonate (PFOS), main technical document (see MPCA 2020b) January 2023-described in this technical support document
- Perfluorobutane sulfonate (PFBS)
- Perfluorobutanoate (PFBA)
- Perfluorohexane sulfonate (PFHxS)
- Perfluorohexanoate (PFHxA)
- Perfluorooctanoate (PFOA)

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Acronyms

BAF	Bioaccumulation Factor
BCC	Bioaccumulative Chemical of Concern
CC_{DFR} /CS_{DFR}	Chronic Criterion or Standard (Class 2)– Drinking water, fish consumption, recreation uses
	$CC_{DFR-DEV}$ / CS $_{DFR-DEV}$ – Less-than-chronic or developmental toxicity-based
CC_{FR}/CS_{FR}	Chronic Criterion or Standard (Class 2)– Fish consumption and recreation uses
	CC_{FR-DEV} / CS $_{FR-DEV}$– Less-than-chronic or developmental toxicity-based
CC_{FT}/CS_{FT}	Chronic Criterion or Standard (Class 2)– Fish tissue-based
	CC_{FT-DEV}/CS_{FT-DEV} – Less-than-chronic or developmental toxicity-based
CWA	Clean Water Act
DC	Domestic Consumption (Class 1)–drinking water and food processing uses
DWIR	Drinking Water Intake Rate
EPA	U.S. Environmental Protection Agency
FCR	Fish Consumption Rate
FCMP	Fish Contaminant Monitoring Program (interagency team with MDH and MNDNR)
HBV	Health Based Value; developed by the MDH using the same methodologies as HRLs
HRL	Health Risk Limits; drinking water standards from MDH in Minn. R. ch. 4717
IWR	Incidental Water Intake Rate
MDH	Minnesota Department of Health
MNDNR	Minnesota Department of Natural Resources
MPCA	Minnesota Pollution Control Agency
Minn. R. ch.	Minnesota Rule chapter
Minn. Stat.	Minnesota Statute
NHANES	National Health and Nutrition Examination Survey
NPDES	National Pollutant Discharge Elimination System
PFAS	Per- and Polyfluoroalkyl Substances
RfD	Reference Dose for noncancer toxicants and nonlinear carcinogens
RME	Reasonable Maximum Exposure
RSC	Relative Source Contribution factor
USEPA	U.S. Environmental Protection Agency
WQC	Water Quality Criteria (developed for toxic pollutants on a site-specific basis)
WQS	Water Quality Standard (refers to a pollutant-specific numeric standard in rule; also, can refer to the three elements of a WQS)
WCBA	Women of Childbearing Age (refers to women and those who are or may become pregnant)

Executive summary: human health protective water quality criteria for per- and polyfluoroalkyl substances

The Minnesota Pollution Control Agency (MPCA) has multiple programs monitoring and responding to per- and polyfluoroalkyl substance (PFAS) contamination in groundwater, surface water, and aquatic life, mainly fish (MPCA 2021). This technical support document (TSD) describes the derivation of site-specific water quality criteria (WQC) for PFAS with toxicological profiles and Health Based Guidance available from the Minnesota Department of Health (MDH).

This technical document also provides an overview of the previously published site-specific WQC for the principal PFAS detected in Minnesota's freshwater fish at concentrations of concern for fish consumers: perfluorooctane sulfonate (PFOS) (MPCA 2020b).

The MPCA is the state agency responsible for setting water quality standards and criteria[1] under the federal Clean Water Act. Water quality standards (WQS) are used to:

- Protect water resources for uses such as drinking water, fishing, swimming and other aquatic recreation, and sustaining healthy communities of fish, bugs, plants, and other aquatic life.
- Identify polluted waters in need of restoration or healthy waters in need of additional protection.
- Guide the limits set on what regulated entities can discharge to surface water.

Minnesota's WQS are promulgated in Minn. R. ch. 7050 (Waters of the State), and 7052 (Lake Superior Basin Water Standards). Details on how WQS are implemented in point-source discharge permitting are contained in Minn. R. ch. 7053 (State Waters Discharge Restrictions), and parts of chapter 7052. WQS are the fundamental regulatory and policy foundation to preserve and restore the quality of all waters of the state. They consist of three elements:

1. Water use classifications (beneficial uses) that identify how people, aquatic communities, and wildlife use our waters.
2. Narrative and numeric standards to protect those uses by designating specific amounts of pollutants allowed in a body of water or making statements of unacceptable conditions in and on the water.
3. Antidegradation policies to maintain existing uses, protect high quality waters, and preserve waters of outstanding value.

The Clean Water Act requires states apply these three elements and other related protections as the framework for achieving the goals of this federal regulation.[2]

Minnesota's water quality rules establish the following seven beneficial use classifications for waters of the state:

[1] In Minnesota, the term "water quality standard" or "WQS" refers to a promulgated narrative or numeric standard. A "water quality criterion/criteria" or "WQC" is a site-specific value(s) established for a specific toxic pollutant detected in surface water, fish, or effluents that lacks a numeric standard in rule.
[2] In the U.S. Environmental Protection Agency (EPA) guidance the numeric values that underpin application of water quality standards are called "water quality criteria" or "National Ambient Water Quality Criteria." Minnesota's water quality standards' rules use "criterion" or "criteria" to mean numeric values not listed in Minn. R. chs. 7050 or 7052 but derived by EPA-approved methods in rule.

Table ES-1: Water quality standards beneficial use classifications

Use class	Beneficial use
Class 1	Domestic consumption (i.e., drinking water and food processing)
Class 2	Aquatic life and recreation (including aquatic consumption) ▪ 2A-cold water aquatic life and habitats (also Class 1) ▪ 2B-cool, warm water aquatic life and habitats (if 2Bd, also Class 1) ▪ 2D-wetlands
Class 3	Industrial consumption
Class 4	Agricultural (4A) and wildlife (4B)
Class 5	Aesthetics and navigation
Class 6	Other uses
Class 7	Limited Resource Value Water (LRVW)

These use classes reflect the multiple beneficial uses that Minnesota's surface waters provide, and accordingly all surface waters are assigned multiple use classes. The MPCA also has the authority to protect groundwater for domestic consumption (potable or drinking water) use per Minn. R. 7050.0221 and Minn. R. ch. 7060. Nearly all surface waters are designated Class 2 and require control of pollutants so that they are safe for people recreating and eating fish affected by contamination; if protected as source waters for drinking, waters are also designated Class 1 for domestic consumption as described in Minn. R. chs. 7050 and 7052.[3]

Derivation of the PFAS WQC falls under MPCA's authorities to protect human health from adverse impacts of toxic pollutants in Class 2 surface waters and fish. PFAS are categorized as toxic pollutants and lack numeric WQS in rule; therefore, MPCA has derived site-specific WQC that are as fully enforceable as WQS after allowing for the necessary opportunities for comment. The WQC are specific to protecting human health, and include several values, each specific to the surface water's designated beneficial uses. Class 2A and 2Bd surface waters are protected to support aquatic life (fish) consumption and recreation and are also designated Class 1 waters and therefore the final WQC must account for and protect domestic consumption uses. Most surface waters are designated as Class 2B and not specifically designated for domestic consumption, so the WQC are based only on fish consumption and recreation. Class 2B WQS/WQC are also applied to surface waters classified as Class 2D wetlands.[4]

The Class 2 WQC to protect human health are applied as Chronic Criteria (CC);[5] these values are developed to provide lifetime protection to people from exposure to toxic pollutants. The specific application of the different types of CC (that protect different pathways of exposure) are summarized in Table ES-2. The MPCA CC for PFAS are based on available toxicity values and Health Based Guidance for

[3] The MPCA's water quality standards also address impacts to aquatic life and fish-eating wildlife. Those evaluations are not covered in this TSD for human health-based WQC but should be reviewed in the future to determine if more stringent criteria are warranted to protect ecological species.
[4] Note that the WQC derived to protect people recreating are for the levels of PFAS in water. At the air-water interface of PFAS-containing waters, MPCA has documented that surface foams or scums can form. PFAS concentrations in these foams can be thousands of times higher than concentrations of the same chemical in the water column (AECOM 2020, 2021). Specific criteria are not derived for surface water foams; MPCA and MDH recommend that people and pets avoid contact with PFAS-containing or any surface water foam (see Section 10).
[5] WQS or WQC for toxic pollutants are more specifically derived as Maximum Standard (MS) or Maximum Criterion (MC) and Chronic Standard (CS) or Chronic Criterion (CC) based on Class 2 methods Class 2 values in Minn. R. chs. 7050 and 7052.

drinking water from the MDH and include application of the associated Health Risk Index Endpoints for additive evaluation of pollutant mixtures (see Section 11.2).

Many PFAS exhibit aspects of developmental toxicity including effects on fetal and infant development during prenatal and postnatal windows, short-term toxicity, and long-biological half-lives. In addition, exposure rates need to specifically apply to women and those who are or may become pregnant, termed *women of childbearing age* (WCBA) for risk assessment purposes. The MPCA's development of WQC for PFOS already includes a new interim fish consumption rate (FCR) for this subpopulation of fish consumers. The available data and information used for this FCR_{WCBA} are published in *Interim Fish Consumption Rate for Women of Childbearing Age* (MPCA 2020a).

The application of the site-specific WQC to specific water bodies is outlined in Appendix B and posted on the *Water Quality Standards: Site-Specific Criteria* webpage (https://www.pca.state.mn.us/business-with-us/site-specific-water-quality-criteria). Comparison of water and fish monitoring data to the CC should follow Minn. R. chs. 7050 and 7052 and MPCA 2017 and 2022a (see Section 11).

Table ES-2: Water quality criteria for PFAS for the protection of Class 1/2A, 1/2Bd, or Class 2B/2D surface waters

PFAS **(Date developed)** **(Names and CAS No. see Table 2-1)**	**Site-specific water quality criteria: Chronic Criteria (CC)**			***Health Risk Index Endpoints*** **(Additive risk)**
	Class 1/2A or Class 1/2Bd– drinking water, fish consumption and recreational exposure (30-day average)	**Class 2B/2D#** – fish consumption and recreational exposure (30-day average)	**Class 2 fish-tissue** (90th percentile of 5 fish minimum per water body)	
PFOS (October 2020)	0.05 ng/L ($CC_{DFR-DEV}$)	0.05 ng/L (CC_{FR-DEV})	0.37 ng/g (CC_{FT-DEV})	developmental, adrenal (endocrine), hepatic (liver), immune thyroid (endocrine)
PFBS (January 2023)	140 ng/L ($CC_{DFR-DEV}$)	350 ng/L (CC_{FR-DEV})	not applicable	thyroid (endocrine)
PFBA (January 2023)	5,700 ng/L ($CC_{DFR-DEV}$)	10,000 ng/L (CC_{FR-DEV})	not applicable	developmental, hematological (blood) system, hepatic (liver) system, thyroid (endocrine)
PFHxS (January 2023)	20 ng/L ($CC_{DFR-DEV}$)	36 ng/L (CC_{FR-DEV})	not applicable	hepatic (liver), thyroid (endocrine)
PFHxA (January 2023)	220 ng/L ($CC_{DFR-DEV}$)	950 ng/L (CC_{FR-DEV})	not applicable	developmental, hepatic (liver) system, respiratory system, thyroid (endocrine)
PFOA (January 2023)	25 ng/L ($CC_{DFR-DEV}$)	88 ng/L (CC_{FR-DEV})	not applicable	developmental, hepatic (liver), immune, pancreas, renal (kidney), thyroid (endocrine)

 # - See Section 10

Definitions of CC:

CC_{DFR}: Applied in Class 1/2A and Class 1/2Bd surface waters (D: Domestic Consumption, drinking water/food processing, F: Fish consumption, and R: Recreational exposure)

CC_{FR}: Applied in Class 2B surface waters (F: Fish consumption and R: Recreational exposure). [#]Class 1/2A and 1/2Bd CC may be applied in Class 2B/2D surface waters if needed to protect source waters used for Domestic Consumption.

CC_{FT}: Applied for Bioaccumulative Chemicals of Concern (BCC) in fish (fillet/muscle) for all Class 2 waters (FT: fish-tissue)

$CC_{DFR\text{-}DEV}$, $CC_{FR\text{-}DEV}$, and $CC_{FT\text{-}DEV}$: Used for a pollutant with acute, short-term, or subchronic ("less-than-chronic") toxicity, higher early-life exposure rates, or developmental toxicity as a Health Risk Index Endpoint.

Note: The Class 2 CC methods round down the calculated criterion to two significant figures (MPCA 2017).

1. Introduction

Water quality standards (WQS) provide the minimum conditions for waters of the state to meet their designated beneficial uses. Numeric standards are a key foundation for ensuring that the regulatory goals of Minnesota's water quality statutes and rules and the federal Clean Water Act (CWA) are met.

WQS in Minn. R. chs. 7050 and 7052 provide the foundation for:

- Effluent limits in National Pollutant Discharge Elimination System (NPDES) wastewater and stormwater permits;
- Remedial cleanup goals; and
- Assessment of available pollutant-specific monitoring data in surface waters and fish for the CWA 303(d) Impaired Waters List.

WQS are derived to be protective of both human health and aquatic life.[6] Minnesota's human health based WQS protect the beneficial uses of drinking water, fish consumption, and recreation. Human health based WQS are adopted into rule and are applicable to Class 2 surface waters across the state. For pollutants that do not have a human health-based WQS, human health-based water quality criteria (WQC) may be derived and applied at a specific site or sites, based on methods already adopted into rule and approved by EPA. To summarize:

- WQS: Chronic Standards (CS) – derived for Class 2 waters; pollutant-specific standards adopted into rule.
- WQC: Chronic Criteria (CC) – derived and applied on a site-specific basis; based on methods adopted into rule (Minn. R. 7050.0217 to 7050.0219; 7052.0100 for the Lake Superior Basin).

CS and CC are derived based on the potential for adverse effects to human health and, as with all water quality standards, do not consider economic impacts or the availability of treatment technologies. Exceedance of a CS or CC is considered indicative of a polluted condition, which is actually or potentially deleterious, harmful, detrimental, or injurious with respect to the designated uses of the waters of the state (Minn. R. 7050.0150; 7050.0210, subp. 13). CS and CC refer to human health throughout the remainder of this document.

This technical support document (TSD) details the derivation of site-specific CC for per- and polyfluoroalkyl substances (PFAS):

- Perfluorobutane sulfonate (PFBS)
- Perfluorobutanoate (PFBA)
- Perfluorohexane sulfonate (PFHxS)
- Perfluorohexanoate (PFHxA)
- Perfluorooctanoate (PFOA)

The TSD also includes a discussion of the CC for perfluorooctane sulfonate (PFOS), published in an earlier TSD (MPCA 2020b), when important to the application of the other CC to protect beneficial uses.

[6] The Minnesota Pollution Control Agency's (MPCA's) Water Quality Standards also address impacts to aquatic life and fish-eating wildlife. Those evaluations are not covered in this TSD, which is for human health-based WQC.

Class 2 CC are developed for application in surface waters; fish tissue-based CC are also developed when the toxic pollutant is highly bioaccumulative. Of the PFAS included in this TSD, only PFOS meets the criteria of a bioaccumulative chemical of concern (BCC) for a fish tissue-based CC. The CC are based on the most recent toxicity information from the Minnesota Department of Health (MDH) and MPCA's 2017 human health-based WQS/WQC derivation methods as adopted in Minn. R. chs. 7050 and 7052.

2. Problem formulation

2.1 Per-and polyfluoroalkyl substances

PFAS encompass a diverse suite of chemicals that are aliphatic carbon chain substances dominated by fluorine atoms in place of hydrogens (ITRC 2020c). These chemicals have many uses but have primarily been identified as stain or water repellants in clothes, furniture, and food packaging, specialized fire-fighting foams, and industrial chemicals (MPCA 2021, Table 2-1). Analytical methods used by MPCA and the MDH to detect PFAS started with 12 chemicals and has expanded to up to 40 PFAS (see Appendix A, Table A-1 for the 22 most monitored PFAS). Information regarding the environmental occurrence and toxicity of PFAS has been more readily available for PFOA and PFOS than for other PFAS included in the analytical methods (ITRC 2020b). MDH has developed toxicity values and Health Based Guidance for drinking water protection for PFOA, PFOS, and additional PFAS.[7] The MPCA and MDH have detected these PFAS– as well as others from the suites of PFAS monitored – in many of Minnesota's lakes and streams (MPCA 2022c). PFOS and a few other long-chain PFAS have also been detected in multiple fish species in these same and additional surface waters (Section 2.2). In some cases, surface waters are a conduit for these chemicals to migrate to groundwater. CC for PFAS are needed to evaluate potential risks to human health from environmental concentrations of these toxic pollutants in fish and water and to use as a basis to remediate and control known and potential sources of PFAS contamination to Minnesota's water resources.

Table 2-1: PFAS evaluated for water quality criteria (acronyms, names, carbon/chain lengths, and CAS numbers).

PFAS		Aliphatic Carbon No. (Chain length)	CAS Numbers
PFBS	perfluorobutane sulfonate	4	45187-15-3 (anion) 375-73-5 (acid) 29420-49-3 (potassium salt) 68259-10-9 (ammonium salt) 60453-92-1 (sodium salt)
PFBA	perfluorobutanoate	4	45048-62-2 (anion) 375-22-4 (acid)
PFHxS	perfluorohexane sulfonate	6	108427-53-8 (anion) 355-46-4 (acid) 3871-99-6 (potassium salt)
PFHxA	perfluorohexanoate	6	92612-52-7 (anion) 307-24-4 (acid)
PFOA	perfluorooctanoate	8	45285-51-6 (anion) 335-67-1 (free acid) 335-66-0 (acid fluoride) 3825-26-1 (ammonium salt, APFO)

[7] The MDH Health Based Guidance are described and found online at https://www.health.state.mn.us/communities/environment/risk/guidance/gw/table.html.

PFAS		Aliphatic Carbon No. (Chain length)	CAS Numbers
			2395-00-8 (potassium salt) 335-93-3 (silver salt) 335-95-5 (sodium salt)
PFOS	perfluorooctane sulfonate	8	45298-90-6 (anion) 1763-23-1 (acid) 29081-56-9 (ammonium salt) 70225-14-8 (diethanolamine salt) 2795-39-3 (potassium salt) 29457-72-5 (lithium salt)

The CC for PFAS are derived based on the methods in Minn. R. chs. 7050 and 7052 for protecting human health from toxic pollutants in surface water and fish tissue.[8] The specific algorithms that apply and subpopulations of concern depend on the use classification of the surface water and the toxicological profile of the pollutant. The MPCA developed CC for PFAS that have toxicological values and information available from the MDH. As more toxicity values become available, additional PFAS WQC may be developed and added to this TSD. In addition, there are PFAS that are manufactured as precursors to the PFAS that are evaluated for WQC. When exposed to environmental or biological processes these precursors break down to the forms with WQC and may be considered sources of equivalent exposure. The MPCA plans to develop guidance in the future for precursor assessments. Details regarding the WQC methods and how they were applied to develop the CC for the five PFAS with MDH toxicological profiles are described in Sections 4 through 8.

PFAS are widely detected in Minnesota's water resources (Section 2.2). The primary basis for concern and need for PFAS WQC include the contamination of sources of drinking water, mainly groundwater, by multiple PFAS and high potential for exposure to PFOS from consuming fish caught in Minnesota's many affected surface waters (MPCA 2020b). Recreational exposure from PFAS is relatively low based on surface water concentrations but is still accounted for in the WQC. However, PFOS, PFOA, and other long-chain PFAS can concentrate to high concentrations in foams in streams and along lake shorelines; this relates to other aspects of WQS discussed in Section 10.

2.2 Overview of fish and water monitoring datasets

Many fish species present in Minnesota's surface waters have been monitored to determine if PFAS are present in fish-fillet (muscle) tissue. PFAS concentrations in fish samples have been dominated by PFOS (MPCA 2020b). Other PFAS frequently detected in fish tissue at low concentrations include three long-chain PFAS (Table A-1): PFDA, PFUnA, and PFDoA. PFNA and PFOSA have also been detected, but less frequently. At more highly contaminated sites, like Mississippi River Pool 2, PFOA, PFHxS, PFBA, and PFBS have also been detected in fish. As of December 2022, there are no MDH toxicity values for PFOSA nor any PFAS that have nine or more aliphatic carbons. Consideration of PFAS mixtures when applying the PFOS CC in fish-tissue is discussed in Section 11 and MPCA 2020b.

[8] Methods are described in Minn. R. 7050.0217 to 7050.0219 for statewide and site-specific application and Minn. R. 7052.0110 for the Lake Superior Basin. Derived site-specific CC have the same regulatory applications as the CS listed in Minn. R. 7050.0220 to 7050.0222 or 7052.0100 after allowing for comment as specified in Minn. R. 7050.0218, subp. 2, or 7052.0110, respectively.

The MPCA has conducted most monitoring for PFAS in fish or in groundwater in contaminated areas undergoing remedial activities (MDH 2022c, MPCA 2022d). However, in 2018 MPCA's Water Assessment Section in the Environmental Analysis and Outcomes Division, in collaboration with the MDH, sampled for PFAS in fish and water in 69 surface water bodies across Minnesota. PFBA typically dominates the PFAS detections and in 2018 it was detectable in 100% of the water bodies tested. The next most frequently detected PFAS in Minnesota's surface waters sampled in 2018 are PFPeA, PFOA, and PFHxA, detected at 76, 73, and 67% of water bodies sampled, respectively. PFOS, PFHxS, and PFHpA had detections in about 25% of the water bodies sampled. A summary of mean detected concentrations (includes qualified results that had estimated concentrations) from two to three water samples per water body, excluding those water bodies associated with contaminated sites, is shown in Table 2-2. This summary is to provide general information about the presence of PFAS in Minnesota's surface waters.

Table 2-2: Summary of PFAS detected and mean water concentrations from 63 water bodies sampled in a MPCA 2018 study (excluded six water bodies associated with contaminated sites).

PFAS	Percent detected	Range of mean detected concentrations by water body in ng/L
PFBS	1%	2.7 – 9.5
PFBA	100%	4.5 – 228.7
PFPeA	76%	1.7 – 18.7
PFHxS	24%	2.1 – 51.0
PFHxA	67%	1.9 – 20.2
PFHpA	24%	1.5 – 10.2
PFOA	73%	2.1– 16.1
PFOS	25%	2.1 – 46.1
Precursor		
PFOSA	0.02%	4.2 (only one detection)

Besides the widespread presence of PFOS at concentrations of concern in fish-fillet tissues, PFOS and additional PFAS tend to be of greatest concern in surface waters in contaminated areas undergoing remedial activities. Sampling by MPCA's Remediation Division in 2019 and 2020 included many surface waters for PFAS and also PFAS-containing foam when observed on some of the same surface waters in the Twin Cities East Metro (Washington County) (AECOM 2020, 2021). Approximately 98 sites across creeks, ponds, lakes, wetlands, and the St. Croix River were sampled 1 to 17 times. Reference to PFAS-containing foams is helpful to provide context to the impacts of PFAS on water resources and beneficial uses but is not specific to the WQC (see other WQS approaches to address foam in Section 10).

Table 2-3: Summary of PFAS detected and mean water and foam concentrations associated with contaminated sites in the Twin Cities East Metro (Washington County, Project 1007) in 2019-2020.

PFAS	Percent detected in remedial area	Range of mean detected concentrations by water body in contaminated/ remedial areas in ng/L	Remedial area maximum in PFAS- foam in ng/L
PFBS	98%	0.85 – 33.4	21
PFBA	100%	13 – 4,360	963
PFPeA	100%	3.2 – 59.6	70.1
PFHxS	96%	0.96 – 104	1,130
PFHxA	99%	27.6 – 135	92
PFHpA	100%	1.5 – 111	155
PFOA	100%	3.4 – 983	175,000
PFOS	100%	1.6 – 3,130	13,800,000
Precursors			
PFOSA	63%	0.4 – 49.3	270,000
6:2 FTS	38%	0.6 – 0.3	592,000
N-MeFOSA	17%	0.5 – 2.0	not detected
N-MeFOSAA	3%	0.6 – 2.3	1,320
N-EtFOSAA	46%	0.6 – 109	263,000
N-EtFOSE	15%	0.1 – 18.2	not detected

Groundwater monitoring efforts found the same PFAS as described above for surface waters (MDH 2022c, MPCA 2022c). For example, MDH and MPCA monitoring studies have determined many surface waters in the Twin Cities East Metro (Project 1007) are conduits of PFAS to groundwater. The high mobility of PFAS means widespread surface water and groundwater contamination (ITRC 2020a). More information on these datasets is available from MDH (2022c).

3. Analysis plan: site-specific chronic criteria derivation

3.1 Overview: chronic criteria

In Class 2 designated surface waters, state and CWA goals are integrated as stated in 7050.0140, subp. 3:

> **Class 2 waters, aquatic life and recreation.** Aquatic life and recreation includes all waters of the state that support or may support aquatic biota, bathing, boating, or other recreational purposes and for which quality control is or may be necessary to protect aquatic or terrestrial life or their habitats or the public health, safety, or welfare.

Development of Class 2 WQS are more specifically cited in rule as:

- WQS: Chronic Standards (CS) – derived for Class 2 waters; pollutant-specific standards adopted into rule.
- WQC: Chronic Criteria (CC) – derived and applied on a site-specific basis; based on methods adopted into rule (Minn. R. 7050.0217 to 7050.0219; 7052.0100 for the Lake Superior Basin).

Use classifications for surface water are found in Minn. R. 7050.0400 to 7050.0470. The applicable Class 2 subclass (2A, 2Bd, 2B, or 2D) determines which beneficial uses are protected and the algorithms used to derive criteria to address them (MPCA 2017). Class 2A and 2Bd surface waters are also designated Class 1 for domestic consumption (DC). This additional beneficial use means those surface waters are protected as a source for drinking water and food processing water (Minn. R. 7050.0221). There are three possible exposure pathways that may be included in a specific CC:

- Drinking water source (DC).
- Recreation (incidental water intake).
- Fish consumption.

The classification of the specific water body that the CC is derived for will determine which of these exposure pathways are included.

- CC_{DFR} is derived for Class 1/2A and Class 1/2Bd waters, which include the following exposure pathways:
  - Drinking water source (D).
  - Fish consumption (F).
  - Recreation, the drinking water intake rate covers incidental ingestion exposure, but recreational exposure is considered in the relative source contribution factor (R).
- CC_{FR} is derived for Class 2B and 2D waters, which include the following exposure pathways:
  - Fish consumption (F).
  - Recreation, which includes an incidental water intake rate (R).

Two other types of CC are also derived when appropriate:

- CC_{DEV} (Developmental) is derived for less-than-chronic exposure periods (acute, short-term, subchronic) for contaminants that require the use of higher early-life exposure rates, early-life susceptibility factors, or those specific to women or those who are or may become pregnant (WCBA).

    - $CC_{DFR-DEV}$ is a CC_{DFR} that was derived to address the exposure pathways described above (DFR), and also specific parameters or approaches to address developmental toxicity.
    - CC_{FR-DEV} is CC_{FR} that was derived to address the exposure pathways described above (FR), and also specific parameters or approaches to address developmental toxicity.

- CC_{FT} (Fish Tissue) is derived for contaminants that are bioaccumulative contaminants of concern (BCC), to protect fish consumers. A BCC is defined as having a bioaccumulation factor (BAF) greater than 1,000 L/kg. This CC is applicable in most Class 2 waters[9], and is not based on the same subclasses as the CC described above for surface water application.
    - CC_{FT-DEV} (Fish Tissue-Developmental) may be derived when less-than-chronic exposure periods (acute, short-term, subchronic) for contaminants that require the use of higher early-life exposure rates, early-life susceptibility factors, or those specific to WCBA, require lower CC than calculated for chronic exposure.

The most stringent of the CC derived (CC_{DFR} or $CC_{DFR-DEV}$; CC_{FR} or CC_{FR-DEV}; CC_{FT} or CC_{FT-DEV}) are the final applicable CC.

Some toxic pollutants require chemical-specific data and methods that differ from the default methods and calculations used to derive CC (or CS); Minn. R. 7050.0217 to 7050.0219 and MPCA's *Human Health-based Water Quality Standards Technical Support Document* (Final 2017) describe when this is appropriate. To ensure protection of drinking water (DC) or potable water uses when a surface water is designated for this use (Class 1) or if the surface water influences a downstream drinking water source or groundwater, MPCA may also apply more stringent CC or the MDH Health Based Guidance for drinking water protection (see https://www.health.state.mn.us/communities/environment/risk/guidance/gw/table.html).

3.2 Toxicological values and exposure parameters used in chronic criteria

The site-specific WQC for PFAS have some aspects that require chemical-specific approaches (Section 3.3). However, the foundation for these criteria follows the methods contained in Minn. R. 7050.0217 to 7050.0219. These rules provide the details for the use of toxicological values to develop WQC based on noncancer, developmental, and cancer risks. The WQC use exposure parameters (drinking water intake rates, incidental water intake rate, fish consumption rates, bioaccumulation factors, and relative source contribution factors) that reflect risk assessment methods used by MDH and EPA that best match the chemical's toxicological profile by duration (acute to chronic) (MPCA 2017). The details for the PFOS WQC were published in 2020 (MPCA 2020b); the details of each additional PFAS chemical are discussed in Sections 4 through 8.

[9] CC_{FT} might be different if there are site specific or other information on fish consumption rates that differ from the initial values used.

3.3 PFAS chronic criteria

Physical-chemical properties

The methods to develop CC assume a person that is eating fish caught from Minnesota's surface waters might also be exposed to the same pollutant present in the fish tissue through recreating (swimming, water skiing, or other full-body or primary contact activities) in those waters and from getting their drinking water from that same water body (when designated Class 1 for domestic consumption). The exposure scenarios are always considered together. The physical-chemical properties of the toxic pollutant affect how much relative exposure occurs from each route as calculated for the final WQC. For PFOS, because of its very high bioaccumulation in fish-tissue, eating fish results in a very high potential exposure route for surface water users; therefore, including drinking water or recreational (incidental) water intake is not necessary for developing protective CC (MPCA 2020b).

For other PFAS, because they are not regularly detected in fish fillets and their bioaccumulation factors (BAFs) are all less than 1,000 L/kg (the threshold for a pollutant to be considered a bioaccumulative chemical of concern or BCC in fish), other exposure pathways in surface waters become relevant sources of exposure too for developing their CC. For many PFAS, the drinking water pathway, when included as a beneficial use for surface waters designated for domestic consumption (Class 1/2A and 1/2Bd), is the main route of exposure and basis behind the most stringent CC. Recreational exposure to PFAS is considered a much lower risk but may be higher when PFAS accumulates into surface water foams. Contact with such surface water foams should be avoided.

MDH toxicokinetic serum models

PFAS have multiple characteristics that make the development of CC complex and in some cases warrant the use of chemical-specific CC methods rather than the default methods (Minn. R. ch. 7050 and MPCA 2017). PFOS is a developmental toxicant with a long half-life in people. PFOA and PFHxS share these characteristics. The default method for MDH's Health Based Guidance development does not account for bioaccumulation or for the transfer of chemicals from mother to fetus or nursing infant. The MDH recognized that to develop health-based guidance protective of all sensitive subpopulations, a toxicokinetic serum model was necessary (Goeden et al. 2019, MDH 2020a, 2020b, 2022b). The MDH's serum model includes transfer of the chemical from mother to infant, ensuring that the most sensitive receptor, the infant, is protected from developmental effects. The model accounts for an infant's body burden of PFAS at birth from placental transfer and potential high neonatal intake, particularly via breast milk from a mother who is consuming contaminated water. The MDH modeled PFOS, PFOA, and PFHxS serum levels for both infants who were breastfed and those that were bottle-fed with formula made with contaminated tap water. This allowed the MDH to set final guidance values that, when met, ensure that serum levels or body burdens would not exceed adverse effect levels at any point throughout a lifetime.

The scientific information available to MPCA from the MDH's publication of Health Based Guidance for drinking water protection using toxicokinetic models for PFAS is reliable, peer-reviewed, and scientifically defensible for use in developing human health-based CC. Using a toxicokinetic model to develop risk-based guidance for environmental chemicals found in drinking water, food, and other media is recognized by the EPA and other scientists as a powerful tool to improve the accuracy of these values (Cohen Hubal et al. 2019; ITRC 2020a). Use of the model also accommodates data specific to different lifestages or age ranges and subpopulations, like WCBA.

For PFOS, the MDH toxicokinetic model was modified to replace drinking water with fish consumption intake rates. Modification of the model to include drinking water plus fish consumption intake is complex and is not strictly needed to develop health-protective CC for a highly bioaccumulative chemical in fish like PFOS (MPCA 2020b) nor the CC for PFOA and PFHxS. The CC for PFOA and PFHxS use the default algorithms for Class 1/2A and 1/2Bd waters with a single drinking water intake rate (DWIR) calculated from the MDH guidance values, use of a relative contribution factor (RSC = 0.2), and the MDH's reference doses (RfDs). [10] The application of the model-derived DWIRs paired with the FCR_{WCBA}, RSCs, and BAFs will ensure the CC meet the protection-level goals of WQC. The DWIRs from the MDH Health Based Guidance are used in the CC as published for PFBS, PFBA, and PFHxA.

Developmental toxicity: Interim fish consumption rate for WCBA

The methods to develop CC include default fish consumption rates (FCRs) for the general adult population of 0.43 g/kg-d (30 grams of fish consumed per day with an average 70 kg body weight) and for children ages 1 through 5 a rate of 0.86 g/kg-d (based on intake per kg of body weight, approximately twice that of adults). The basis for these rates and their use in Class 2 CC is described in Minn. R. 7050.0218 to 7050.0219 and MPCA 2017.

Many PFAS demonstrate toxicity at their lowest concentrations to aspects of fetal or neonatal development (i.e., developmental health endpoints). Therefore, an appropriate FCR is needed for women and those that are or may become pregnant – the fish consumers whose exposure is directly related to transgenerational (prenatal) to postnatal (breastfeeding) exposure. The datasets most relevant to this subpopulation have been defined based on the best available survey data for women ages 13 to 50, described as women of childbearing age (WCBA) (USEPA 2000, 2011). As specified in the human health-based WQS methods technical support document, if a pollutant affects development and prenatal through postnatal exposure is relevant to the toxicity, MPCA will review available survey and exposure data to ensure the adult FCR is representative of WCBA (MPCA 2017). The WQS rules allow for the application of chemical-specific data to support the most scientifically defensible CC (or CS) (Minn. R. 7050.0219, subp 2(A)).

An interim FCR for WCBA (FCR_{WCBA}) of 66 g/d of freshwater fish consumed per day using a 70 kg body weight (0.94 g/kg-d)[11] was applied to account for reasonable maximum exposure (RME)[12] for WCBA in Minnesota (MPCA 2020a). This FCR is based on the MDH's *Fish is Important to Superior Health* (FISH) survey of North Shore Minnesotans (MDH 2017d) and is consistent with similar rates found in other surveys of Minnesota's WCBA (MPCA 2020a). The detailed FISH survey was conducted in clinical settings in Grand Portage and Grand Marias, MN, with trained health professionals supporting accurate data collection on almost 500 Minnesotan WCBA (in this study defined as ages 16 to 50). This FCR is an interim rate used in CC_{DEV} for pollutants characterized as developmental toxicants to ensure protection under RME conditions during the prenatal and neonatal lifestages when women and those who are or

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[10] DWIR = RfD x RSC x unit conversion factor (CF) / Health Based Value (HBV) or Health Risk Limit (HRL) guidance value

[11] While EPA has recommended use of a higher body weight from NHANES for developing water quality criteria or standards (USEPA 2015) and the latest NHANES time weighted averages body weight for ages 16 to 50 is 74 kg (Table 8-5, USEPA 2011). However, these rates are not specific to fish consumers. The use of the standard 70 kg body weight is used for assigning portion sizes of 227 g to statistical estimates of fish meal size and is used in development of the interim FCR (MPCA 2020a).

[12] In the EPA's human health guidance for Superfund sites, reasonable maximum exposure (RME) is defined as the highest exposure that is reasonably expected to occur at a site. The estimate considers current and future exposure scenarios (USEPA 1989).

may become pregnant eat fish and shellfish as part of a healthy and balanced diet. This FCR is also relevant when protecting this subpopulation of fish consumers from short-term toxicity (e.g., thyroid effects).

Future plans for WQS/WQC include broader review and outreach on available fish consumption surveys and rates, especially for future CC developed for the Lake Superior basin. Tribal authorities with WQS applicable in the Lake Superior Basin include the Fond du Lac Band of Lake Superior Chippewa, who use a FCR of 60 g/d, and the Grand Portage Band of Lake Superior Chippewa, who use 142.5 g/d as their FCR.

Development of bioaccumulation factors (BAFs)

When developing CC to protect fish consumers that apply in surface water, the algorithms require a BAF. The PFAS evaluated for CC in this TSD (PFBS, PFBA, PFHxS, PFHxA, and PFOA) all had final BAFs less than 1,000 L/kg, so are not considered BCCs. For CC the methods generally focus on "average" bioaccumulation in fish fillet or muscle tissue. All the available datasets put their geometric mean BAFs in a similar range of 32 to 60 L/kg.

Because these PFAS are ionic organic chemicals, the best method for BAF development is to use field studies of paired fish and water (Minn. R. ch. 7050 and MPCA 2017). The MPCA and FCMP, other states, and researchers have conducted a number of field-BAF studies for PFAS (Appendix C). The focus for this review were those conducted in North America as being most representative of the fish caught and consumed in Minnesota. As with the PFOS CC (MPCA 2020b), the most defensible BAFs used the largest reliable and available field-BAF datasets to develop one final BAF for each PFAS. Details on the BAF development are found in the section describing each PFAS CC.

An overview of the exposure, toxicity, and methods considerations used to develop the CC are summarized in Table 3-1. The details of the PFOS CC are found in MPCA 2020b. The other PFAS are covered in subsequent sections.

Table 3-1: Basis for Final WQC as presented in Table ES-2

PFAS	Surface water class	Use protected	Criteria application	Method	Acronym
PFOS (MPCA 2020b)	All Class 2 Waters	Fish consumption	Fish tissue (fillet)	Toxicokinetic model	CC_{FT-DEV}
	Class 1/2A/2Bd Waters	Fish consumption, recreation + domestic consumption	Water column	CC_{FT-DEV}/BAF (< MDH guidance) (BAF: Bioaccumulation factor)	$CC_{DFR-DEV}$
	Class 2B/2D Waters #	Fish consumption + recreation	Water column	CC_{FT-DEV}/BAF	CC_{FR-DEV}
PFBS PFBA PFHxS PFHxA PFOA	All Class 2 Waters	Fish consumption	Fish tissue (fillet)	Not applicable; BAFs <1,000 L/kg in fish-tissue based on field datasets	CC_{FT}

PFAS	Surface water class	Use protected	Criteria application	Method	Acronym
PFBS PFHxA	Class 1/2A/2Bd Waters	Fish consumption, recreation + domestic consumption	Water column	Developmental algorithm in 7050.0219, subp. 13(B).	$CC_{DFR\text{-}DEV}$
PFBA	Class 1/2A/2Bd Waters	Fish consumption, recreation + domestic consumption	Water column	Chemical-specific fish consumption rate per 7050.0219, subp. 2 (A) used in algorithm in 7050.0219, subp. 13(A).	$CC_{DFR\text{-}DEV}$
PFBS PFBA PFHxA	Class 2B/2D Waters #	Fish consumption + recreation	Water column	Chemical-specific fish consumption rate per 7050.0219, subp. 2 (A) used in algorithm in 7050.0219, subp. 14(A).	$CC_{FR\text{-}DEV}$
PFHxS PFOA	Class 1/2A/2Bd Waters	Fish consumption, recreation + domestic consumption	Water column	Chemical-specific drinking water and fish consumption rates per 7050.0219, subp. 2 (A) used in algorithm in 7050.0219, subp. 13(A).	$CC_{DFR\text{-}DEV}$
	Class 2B/2D Waters #	Fish consumption + recreation	Water column	Chemical-specific fish consumption rate per 7050.0219, subp. 2 (A) used in algorithm in 7050.0219, subp. 14(A).	$CC_{FR\text{-}DEV}$

Note: The Class 2 CC methods round down the calculated criterion to two significant figures (MPCA 2017).

4. Chronic criteria: Perfluorobutane Sulfonate (PFBS)

4.1 Overview

PFBS is characterized as a four-carbon chain PFAS or short-chain perfluoroalkane sulfonate or sulfonic acid (PFSA) based on its carbon number and sulfonate (sulfur and oxygen) functional group (ITRC 2020c). PFOS is also a PFSA but has different characteristics than PFBS mainly due to its longer carbon chain and more hydrophobic properties. PFBS has much shorter half-lives in people and laboratory animals than PFOS (MDH 2022a).

The CC use the default and chemical-specific WQC algorithms based on the short-term and developmental toxicity profile of PFBS. When protecting surface waters as a source of domestic consumption (drinking water) in Class 1/2A or 1/2Bd water, the $CC_{DFR\text{-}DEV}$ is more stringent because of the much higher potential for exposure from drinking water (DWIR) vs. incidental ingestion (IWR) while swimming or other primary contact recreation, basis for the $CC_{FR\text{-}DEV}$. Fish consumption exposure contributes to the final Class 2B $CC_{FR\text{-}DEV,}$ but the estimated total exposure is still lower than when including drinking water, resulting in a higher $CC_{FR\text{-}DEV}$.

4.2 Toxicological values and health risk index endpoints

The toxicological values available from the MDH for PFBS cover short-term to chronic durations. Because the laboratory animal study used to develop the short-term duration reference dose (RfD) was the most stringent, it was applied to all three durations (MDH 2022a). The most sensitive Health Risk Index Endpoint from that study is the thyroid, which is also characterized as impacted through an endocrine mechanism of action. The key study used by MDH to develop the reference dose was not specific to prenatal exposure and a developmental health endpoint; however, thyroid toxicity is relevant for assessing developmental toxicity based on the WQC methods because of the less-than-chronic duration of exposure associated with this health effect. Therefore, the PFBS CC algorithm takes into account developmental toxicity. When monitoring PFBS in surface water, its concentration will need to be evaluated with other PFAS and other toxic pollutants that also include the thyroid as a target organ or the endocrine system.

Table 4-1: Toxicological value

PFAS	MDH RfD (Duration)	Health Risk Index (Additivity) Endpoints	Reference
PFBS	0.000084 mg/kg-d (short-term, subchronic, and chronic)	Thyroid (endocrine)	MDH 2022a based on 2019 National Toxicology Program study of juvenile to adult rats; the lowest dose for adverse effects occurred in female rats

4.3 Exposure factors

Exposure factors are based on the algorithms in Minn. R. 7050.0219. The exposure factors must fit the short-term toxicity profile of PFBS, meaning that less-than-chronic and chronic exposure factors are evaluated. The exposure routes for each use classification, either drinking water plus fish consumption

(Class 1/2A and 1/2Bd) or incidental water ingestion and fish consumption (Class 2B) also affect the appropriate factors used in the final algorithms.

Exposure assessments include information on freshwater fish as a source of PFAS and development of a BAF. As discussed previously, MPCA and Interagency Fish Contaminant Monitoring Program (FCMP) have been monitoring PFAS in fish-fillet (muscle) tissues since 2004. The detection and reporting limits for PFAS have gotten lower over that time and starting in 2019, the detection limit for PFBS in most fish is less than 0.1 ng/g. Review of MPCA and FCMP fish database rarely finds detections of PFBS in freshwater fish fillets. PFBS has only been detected in 5 fish out of approximately 4,000 fish sampled. The detects occur in surface waters with relatively higher concentrations of PFBS, so in that context, surface waters with high local discharges of PFBS can lead to fish consumption being a potential exposure route to people.

Table 4-2: Exposure parameters

Exposure parameter	Rate or Value	Basis
DWIR	0.290 L/kg-d (short-term)	Because the CC_{DFR} has to be the most stringent value for each duration of exposure, for PFBS the short-term duration has the highest DWIR and is the basis for the criteria in order to account for greater developmental exposure than the chronic DWIR plus fish intake. Therefore, the $CC_{DFR\text{-}DEV}$ algorithm is used to incorporate this DWIR, which is relevant to bottle-fed infants, and is also protective of human health across all lifestages. Minn. R. 7050.0219, subp. 13(B).
IWR	0.0013 L/kg-d (chronic)	The default WQS incidental water intake rate is applied. The rate is based on children ages one through eight.
FCR	0.00094 kg/kg-d (interim WCBA, short-term to chronic)	Again, because the RfD is based on thyroid impacts that can occur after even a short-term duration (between 24 hours and 30 days) and at any lifestage, all the available fish consumption rates: adult, child, and WCBA are informative for the CC. The appropriate FCR is the interim FCR_{WCBA} of 0.00094 kg/kg-d for women and those that are or may become pregnant (MPCA 2017 and 2020a). This rate is applied to protect this subpopulation, who are potentially more sensitive to the toxicity of PFBS than other adults.
BAF	49 L/kg	The location with the most detects, the Mississippi River in Pool 2 (Washington/Ramsey Counties), has local surface water discharges. Paired fish and water datasets from Minnesota and other North American studies yielded sufficient data to develop a BAF for PFBS. Following the hierarchy and procedures for ionic organic chemicals (MPCA 2017), Minnesota's field studies had quantified detects of PFBS in water and in two species of fish without qualifiers (Appendix C). The geometric species mean is 49 L/kg.
RSC	0.5 ($CC_{DFR\text{-}DEV}$) 0.2 ($CC_{FR\text{-}DEV}$)	Like the MDH Health Based Guidance for drinking water protection, MPCA $CC_{DFR\text{-}DEV}$ uses a relative source contribution factor of 0.5. For the $CC_{FR\text{-}DEV}$, the default RSC is 0.2 because other routes of exposure beside recreation and freshwater fish consumption are significant to people's total exposure to PFBS (ITRC 2020b).

4.4 Chronic criteria development by use classification

PFBS is characterized for CC as a developmental toxicant per the WQS methods based on short-term effects to the thyroid as one of the MDH's Health Risk Index Endpoint (MDH 2022a). CC developed for PFBS apply in two different surface water exposure scenarios:

- Class 1/2A and Class 1/2Bd surface waters with exposure relevant to drinking water, recreation, and fish consumption ($CC_{DFR\text{-}DEV}$); and
- Class 2B (2D) surface waters (wetlands) with exposure relevant to recreation and fish consumption ($CC_{FR\text{-}DEV}$).

PFBS is a noncarcinogen and so is evaluated using the noncancer algorithms for that toxicological profile in Minn. R. 7050.0219. The foundational equation is:

$$CC\ (ng/L) = RfD\ (mg/kg-d)\ x \frac{RSC\ (no\ units)\ x\ \ (1\ x\ 10^6\ \ ng/mg)}{[DWIR\ or\ IWR\ (L/kg-d) +\ FCR\ (kg/kg-d)\ x\ (BAF)\ L/kg]}$$

For the $CC_{DFR\text{-}DEV}$ the short-term, drinking water only exposure algorithm for developmental toxicity resulted in the most stringent value. This CC is lower than the one developed for chronic exposure that includes fish consumption. This short-term duration results in the most protective CC as is the case with the durations reviewed by MDH for Health Based Guidance (MDH 2022a).

$$CC_{\ DFR-DEV}\ (ng/L) = 140\, ng/L = 0.000084\ (mg/kg-d)\ x \frac{0.5\ (no\ units)\ x\ \ (1\ x\ 10^6\ \ ng/mg)}{0.290\ (L/kg-d)}$$

The $CC_{FR\text{-}DEV}$ uses the same RfD paired with the chronic IWR and FCR_{WCBA}. The toxicological profile of PFBS as demonstrated in the key toxicological study used by MDH includes thyroid disruption in female laboratory animals (MDH 2022a). Because of this, the use of the higher interim FCR_{WCBA} for this subpopulation of fish consumers is warranted.

$$CC_{FR-DEV}\ (ng/L) = 350\ \ ng/L\ \ = 0.000084\ (mg/kg-d)\ x \frac{0.2\ (no\ units)\ x\ \ (1\ x\ 10^6\ \ ng/mg)}{[0.0013\ (L/kg-d) +\ 0.00094\ (kg/kg-d)\ x\ 49\ \ (L/kg\ )]}$$

Table 4-3: Site specific CC

PFAS (Date developed)	**Site-specific water quality criteria: Chronic Criteria (CC)**			***Health Risk Index Endpoints*** **(Additive risk)**
	Class 1/2A or Class 1/2Bd – drinking water, fish consumption and recreational exposure (30-day average)	**Class 2B/2D#** – fish consumption and recreational exposure (30-day average)	**Class 2 fish-tissue** (90th percentile of 5 fish minimum per water body)	
PFBS (January 2023)	140 ng/L ($CC_{DFR\text{-}DEV}$) (Note: MDH Health Based Guidance is 100 ng/L based on one significant figure)	350 ng/L ($CC_{FR\text{-}DEV}$)	not applicable	thyroid (endocrine)

- See Section 10

Minnesota Department of Health (MDH), 2022a. *Health Based Guidance for Water, Toxicological Summary for: Perfluorobutane Sulfonate.* Online, https://www.health.state.mn.us/communities/environment/risk/docs/guidance/gw/pfbssummary.pdf.

5. Chronic criteria: Perfluorobutanoate (PFBA)

5.1 Overview

Like PFBS, PFBA is also a four-carbon or short-chain PFAS. This chemical has a carboxylate (oxygen) functional group (ITRC 2020c). This category of PFAS, perfluoroalkyl carboxylates or carboxylic acids (PFCA) also includes PFOA. PFOA as a long-chain PFCA has properties that differ from PFBA. PFBA has much shorter half-lives in people and laboratory animals than PFOA (MDH 2018).

The CC use the default and chemical-specific WQC algorithms based on the short-term and developmental toxicity profile of PFBA. PFBA is rarely detected in fish fillets, so the CC are mainly influenced by the amount of water ingested based on the surface water's use classification. When protecting surface waters as a source of domestic consumption (drinking water) in Class 1/2A or 1/2Bd water, the $CC_{DFR\text{-}DEV}$ is more stringent because of the much higher potential for exposure from drinking water (DWIR) vs. incidental ingestion (IWR) while swimming or other primary contact recreation, basis for the $CC_{FR\text{-}DEV}$. Fish consumption exposure contributes to the final Class 2B $CC_{FR\text{-}DEV,}$ but the estimated total exposure is still lower than when including drinking water, resulting in a higher $CC_{FR\text{-}DEV}$.

5.2 Toxicological values and health risk index endpoints

The toxicological values available from the MDH for PFBA cover short-term to chronic durations. The laboratory animal study used to develop the short-term duration RfD was less stringent than the subchronic and chronic RfD. The most sensitive Health Risk Index Endpoint for both RfDs includes the thyroid, which is impacted through an endocrine mechanism of action. The longer duration toxicological studies also found developmental toxicity occurs at similar doses. All of these factors are relevant for the CC. For this PFAS, the chronic algorithm with drinking water plus fish consumption exposure leads to the most stringent CC. When monitoring PFBA in surface water, its concentration will need to be evaluated with other PFAS and other toxic pollutants with the same Health Risk Index Endpoints.

Table 5-1: Toxicological profile

PFAS	MDH RfD (Duration)	Health Risk Index (Additivity) Endpoints	Reference
PFBA	0.0038 mg/kg-d (short-term)	Hepatic (liver) system, thyroid (endocrine)	MDH 2018
	0.0029 mg/kg-d (subchronic and chronic)	Developmental, hematological (blood) system, hepatic (liver) system, thyroid (endocrine)	

5.3 Exposure factors

Exposure factors are based on the algorithms in Minn. R. 7050.0219. The exposure factors have to consider the short-term (less-than-chronic) and chronic toxicity profiles of PFBA.

Exposure assessments include information on freshwater fish as a source of PFAS and development of a BAF. As discussed previously, MPCA, MDH and MDNR through the Interagency FCMP have been monitoring PFAS in fish-fillet (muscle) tissues since 2004. The detection and reporting limits for PFAS have gotten lower over that time; starting in 2019, the detection limit for PFBA in most fish is less than

0.4 ng/g. Review of MPCA and FCMP fish database rarely finds detections of PFBA in freshwater fish fillets. PFBA has been detected in about 56 fish out of approximately 4,000 fish sampled. The detects occur in surface waters with relatively higher concentrations of PFBA, so in that context, surface waters with local discharges of PFBA can lead to fish consumption being a potential exposure route to people.

Table 5-2: Exposure parameters

Exposure parameter	Rate or Value	Basis
DWIR	0.044 L/kg-d (chronic)	The CC_{DFR} has to be the most stringent value for each duration of exposure, for PFBA the chronic duration is the basis for the criteria in when paired with fish intake. The $CC_{DFR\text{-}DEV}$ chronic algorithm is used and is protective of human health across all lifestages. Minn. R. 7050.0219, subp. 2(A) and subp. 13(A)
IWR	0.0013 L/kg-d (chronic)	The default WQS incidental water intake rate is applied. The rate is based on children ages one through eight.
FCR	0.00094 kg/kg-d (interim WCBA, short-term to chronic)	Again, because the most stringent RfD is based on thyroid and developmental impacts that can occur after even a subchronic duration (>30 days) and at any lifestage, all the available fish consumption rates: adult, child, and WCBA are informative for the CC. Since PFBA is a developmental toxicant affecting prenatal to neonatal health endpoints, the appropriate FCR is for the interim FCR_{WCBA} of 0.00094 kg/kg-d for women and those that are or may become pregnant (MPCA 2017 and 2020a). This rate is applied to protect this subpopulation and all of Minnesota's fish consumers.
BAF	60 L/kg	The locations with the most detects, the Mississippi River in Pool 2 (Washington/Ramsey Counties) and the Twin Cities East Metro (Washington County, AECOM 2021), have local surface water discharges. Paired fish and water datasets from Minnesota and other North American studies yielded sufficient data to develop a BAF for PFBA. Following the hierarchy and procedures for ionic organic chemicals (MPCA 2017), Minnesota's and New Hampshire's (Pickard et al. 2022) field studies had quantified detects of PFBA in water and in six species of fish without qualifiers (Appendix C). The geometric species mean is 60 L/kg.
RSC	0.2 ($CC_{DFR\text{-}DEV}$) 0.2 ($CC_{FR\text{-}DEV}$)	For both the $CC_{DFR\text{-}DEV}$ and $CC_{FR\text{-}DEV}$, the default RSC is 0.2 because other routes of exposure beside recreation and freshwater fish consumption are significant to people's total exposure to PFBA (ITRC 2020b).

5.4 Chronic criteria development by use classification

PFBA is characterized for CC as a developmental toxicant, both because of the need to address short-term toxicity and identification of development as a Health Risk Index Endpoint. When short-term duration exposure of 24 hours to 30 days is relevant, higher intake rates may need to be applied to protect developmental lifestages (MPCA 2017). CC developed for PFBA apply in two different surface water exposure scenarios:

- Class 1/2A and Class 1/2Bd surface waters with exposure relevant to drinking water, recreation, and fish consumption ($CC_{DFR\text{-}DEV}$); and

- Class 2B (2D) surface waters (wetlands) with exposure relevant to recreation and fish consumption ($CC_{FR\text{-}DEV}$).

PFBA is a noncarcinogen and so is evaluated using the noncancer algorithms for that toxicological profile in Minn. R. 7050.0219. The foundational equation is:

$$CC\ (ng/L) = RfD\ (mg/kg-d)\ x \frac{RSC\ (no\ units)\ x\ \ (1\ x\ 10^6\ \ ng/mg)}{[DWIR\ or\ IWR\ (L/kg-d) +\ FCR\ (kg/kg-d)\ x\ (BAF)\ L/kg]}$$

Both the $CC_{DFR\text{-}DEV}$ and $CC_{FR\text{-}DEV}$ use the interim FCR_{WCBA}. The toxicological profile of PFBA as demonstrated in the key toxicological study used by MDH includes thyroid disruption in female laboratory animals (MDH 2018). Because of this, use of the higher interim FCR_{WCBA} for this subpopulation of fish consumers is warranted.

For the $CC_{DFR\text{-}DEV}$ the algorithm developed for chronic exposure that includes drinking water and fish consumption is the most stringent for this use classification. This duration results in the most protective CC.

$$CC_{DFR-DEV}\ (ng/L) = 5{,}700\ \ ng/L\ \ = 0.0029\ (mg/kg-d)\ x \frac{0.2\ (no\ units)\ x\ \ (1\ x\ 10^6\ \ ng/mg)}{[0.044\ (L/kg-d) +\ 0.00094\ (kg/kg-d)\ x\ 60\ (L/kg)]}$$

The $CC_{FR\text{-}DEV}$ uses the same RfD paired with the chronic IWR and FCR_{WCBA}.

$$CC_{FR-DEV}\ (ng/L) = 10{,}000\ \ ng/L\ \ = 0.0029\ (mg/kg-d)\ x \frac{0.2\ (no\ units)\ x\ \ (1\ x\ 10^6\ \ ng/mg)}{[0.0013\ (L/kg-d) +\ 0.00094\ (kg/kg-d)\ x\ 60\ (L/kg)]}$$

Table 5-3: Site specific CC

PFAS (Date developed)	**Site-specific water quality criteria: Chronic Criteria (CC)**			***Health Risk Index Endpoints* (Additive risk)**
	Class 1/2A or Class 1/2Bd – drinking water, fish consumption and recreational exposure (30-day average)	**Class 2B/2D#** – fish consumption and recreational exposure (30-day average)	**Class 2 fish-tissue** (90th percentile of 5 fish minimum per water body)	
PFBA (January 2023)	5,700 ng/L ($CC_{DFR\text{-}DEV}$)	10,000 ng/L ($CC_{FR\text{-}DEV}$)	not applicable	developmental, hematological (blood) system, hepatic (liver) system, thyroid (endocrine)

- See Section 10

MDH, 2018. *Health Based Guidance for Water, Toxicological Summary for: Perfluorobutanoate.* August 2018. Online, https://www.health.state.mn.us/communities/environment/risk/docs/guidance/gw/pfba2summ.pdf.

6. Chronic criteria: Perfluorohexane sulfonate (PFHxS)

6.1 Overview

PFHxS is a six-carbon chemical with a sulfonate functional group (ITRC 2020c). This category of PFAS, PFSA also includes PFBS and PFOS. PFHxS is characterized as a long-chain PFSA, with some properties similar to PFOS. Because PFHxS has a long half-life and transgenerational even short durations of exposure can lead to significant increases in chronic duration body burdens (MDH 2020a). Like PFOS and PFOA, the MDH developed a toxicokinetic serum model to fully account for the bioaccumulation and maternal transfer of PFHxS when setting health-protective guidance values for drinking water.

The CC use the default and chemical-specific WQC algorithms based on developmental toxicity and transgenerational exposure profile of PFHxS. PFHxS is rarely detected in fish fillets, so the CC are mainly influenced by the amount of water ingested based on the surface water's use classification. When protecting surface waters as a source of domestic consumption (drinking water) in Class 1/2A or 1/2Bd water, the $CC_{DFR\text{-}DEV}$ is based on the drinking water intake rate (DWIR) estimated from the MDH's toxicokinetic model and PFHxS guidance value. This value was combined with the FCR_{WCBA} for women and those who are or might become pregnant. The $CC_{DFR\text{-}DEV}$ is more stringent because of the much higher potential for exposure from drinking water (DWIR) vs. incidental ingestion (IWR) while swimming, basis for the $CC_{FR\text{-}DEV}$. Fish consumption exposure contributes to the final Class 2B $CC_{FR\text{-}DEV,}$ but the estimated total exposure is still lower than when including drinking water, resulting in a higher $CC_{FR\text{-}DEV}$.

6.2 Toxicological values and health risk index endpoints

The toxicological value, RfD, available from the MDH for PFHxS covers short-term to chronic durations of exposure (MDH 2020a). The most sensitive Health Risk Index Endpoints include the thyroid, which is also characterized as impacted through an endocrine mechanism of action. The key study used by MDH to develop the reference dose was not specific to prenatal exposure; however, PFHxS is relevant for assessing developmental toxicity because of the less-than-chronic duration of exposure associated with this health effect. The PFHxS toxicological value also includes a serum value for use in MDH's toxicokinetic model. All of these factors are relevant for the CC. When monitoring PFHxS in surface water, its concentration will need to be evaluated with other PFAS and other toxic pollutants with the same Health Risk Index Endpoints.

Table 6-1: Toxicological profile

PFAS	MDH RfD (Duration)	MDH-derived comparable RfD in serum	Health Risk Index Endpoints	Reference
PFHxS	0.0000097 mg/kg-d (short-term to chronic)	0.108 mg/L	hepatic (liver) system, thyroid (endocrine)	MDH 2020a based on 2018 National Toxicology Program study of juvenile to adult rats; while the lowest dose for adverse effects occurred in male rats, it was also noted that thyroid impacts occurred in female rodents and pups.

6.3 Exposure factors

Exposure factors are based on the algorithms in Minn. R. 7050.0219 and use of chemical-specific algorithms (7050.0219, subp. 2 (A)). The exposure factors have to consider the toxicity profiles of PFHxS.

Exposure assessments include information on freshwater fish as a source of PFAS and development of a BAF. The detection and reporting limits for PFAS have gotten lower over time and starting in 2019, the detection limit for PFHxS in most fish is less than 0.1 ng/g. Review of MPCA and FCMP fish database rarely finds detections of PFHxS in freshwater fish fillets. PFHxS has been detected in about 88 fish out of approximately 4,000 sampled. The detects though are in surface waters with relatively higher concentrations of PFHxS; in that context, surface waters with local discharges of PFHxS can lead to fish consumption being a potential exposure route to people.

For the Class 1/2A and 1/2Bd $CC_{DFR\text{-}DEV}$ for PFHxS, which has to protect drinking water users, is informed by the MDH's toxicokinetic model and Health Based Guidance. Their model provides the best tool for protecting this use, and for the PFHxS and PFOA CC, a chemical-specific DWIR can be calculated and used in the chronic CC algorithm.[13] The RSC of 0.2 also helps account for other potential routes of exposure. The MPCA did not modify the MDH's toxicokinetic model to add in fish consumption to the existing drinking water and neonatal breastmilk exposure scenarios given the complexity of this evaluation and lack of a specific need to use the model to ensure these WQC are health protective, but MPCA will evaluate if modified models are relevant in future updates to the CC or development of CS for adoption into rule.

Table 6-2: Exposure factors

Exposure parameter	Rate or Value	Basis
DWIR	0.041 L/kg-d (chemical-specific)	Calculated from the RfD (0.0000097 mg/kg-d) and final guidance value (0.047 µg/L) in the MDH Health Based Guidance (2020a) and RSC of 0.2.
IWR	0.0013 L/kg-d (chronic)	The default WQS incidental water intake rate is applied. The rate is based on children ages one through eight.
FCR	0.00094 kg/kg-d (interim WCBA, short-term to chronic)	Again, because the RfD is based on thyroid impacts that can occur after even a short-term duration (between 24 hours and 30 days) and at any lifestage, all the available fish consumption rates: adult, child, and WCBA are informative for the CC. The appropriate FCR is the interim FCR_{WCBA} of 0.00094 kg/kg-d for women and those that are or may become pregnant (MPCA 2017 and 2020a). This rate is applied to protect this subpopulation, who are potentially more sensitive to the toxicity of PFHxS, than other adults.
BAF	56 L/kg	The locations with the most detects, the Mississippi River in Pool 2 (Washington/Ramsey Counties) and the Twin Cities East Metro (Washington County, AECOM 2021), have local surface water discharges, explaining these detects. Paired fish and water datasets from Minnesota and other North American studies yielded sufficient data to develop a BAF for PFHxS. Following the hierarchy and procedures for ionic organic chemicals (MPCA 2017), Minnesota's, Wisconsin's, Massachusetts' (Department of Public Health 2021), New Jersey's (Goodrow et al. 2020), New Hampshire's (Pickard et al. 2022),

[13] DWIR = RfD x RSC x unit conversion factor (CF) / HBV or HRL guidance value

Exposure parameter	Rate or Value	Basis
		and Canadian (Lescord et al. 2015) field studies had quantified detects of PFHxA in water and in 11 species of fish without qualifiers (Appendix C). The geometric species mean is 56 L/kg.
RSC	0.2 ($CC_{DFR\text{-}DEV}$) 0.2 ($CC_{FR\text{-}DEV}$)	For both the $CC_{DFR\text{-}DEV}$ and $CC_{FR\text{-}DEV,}$ the default RSC is 0.2 because other routes of exposure beside recreation and freshwater fish consumption are significant to people's total exposure to PFHxS (ITRC 2020b).

6.4 Chronic criteria development by use classification

PFHxS is characterized for CC as a developmental toxicant based on short-term effects to the thyroid as one of the MDH's Health Risk Index Endpoint (MDH 2020a). PFHxS also has a very long half-life in people, meaning that exposure at birth is influenced by the lifetime exposure of the mother. Therefore, lifetime modeled and higher intake rates may need to be applied to protect developmental lifestages when exposure to a toxic pollutant is greater on a per body weight basis (MPCA 2017). CC developed for PFHxS apply in two different surface water exposure scenarios:

- Class 1/2A and Class 1/2Bd surface waters with exposure relevant to drinking water, recreation, and fish consumption ($CC_{DFR\text{-}DEV}$); and
- Class 2B (2D) surface waters (wetlands) with exposure relevant to recreation and fish consumption ($CC_{FR\text{-}DEV}$).

PFHxS is a noncarcinogen and so is evaluated using the algorithms for that toxicological profile in Minn. R. 7050.0219. The foundational equation is:

$$CC\ (ng/L) = RfD\ (mg/kg-d)\ x \frac{RSC\ (no\ units)\ x\ \ (1\ x\ 10^{6}\ \ ng/mg)}{[DWIR\ or\ IWR\ (L/kg-d) +\ FCR\ (kg/kg-d)\ x\ (BAF)\ L/kg]}$$

For the $CC_{DFR\text{-}DEV}$ the algorithm developed for chronic exposure that includes drinking water and fish consumption is the most appropriate for PFHxS and this use classification.

$$CC_{DFR-DEV}\ (ng/L) = 20\ \ ng/L\ = 0.0000097\ (mg/kg-d)\ x \frac{0.2\ (no\ units)\ x\ \ (1\ x\ 10^{6}\ \ ng/mg)}{[0.041 +\ 0.00094\ (kg/kg-d)\ x\ 56\ (L/kg)]}$$

The $CC_{FR\text{-}DEV}$ uses the same RfD paired with the chronic IWR and FCR_{WCBA}.

$$CC\ (ng/L) = 36\ \ ng/L\ = 0.0000097\ (mg/kg-d)\ x \frac{0.2\ (no\ units)\ x\ \ (1\ x\ 10^{6}\ \ ng/mg)}{[0.0013\ (L/kg-d) +\ 0.00094\ (kg/kg-d)\ x\ 56\ L/kg]}$$

Table 6-3: Site-specific CC

PFAS (Date developed)	Site-specific water quality criteria: Chronic Criteria (CC)			*Health Risk Index Endpoints* (Additive risk)
	Class 1/2A or Class 1/2Bd – drinking water, fish consumption and recreational exposure (30-day average)	**Class 2B/2D#** – fish consumption and recreational exposure (30-day average)	**Class 2 fish-tissue** (90th percentile of 5 fish minimum per water body)	
PFHxS (January 2023)	20 ng/L ($CC_{DFR\text{-}DEV}$)	36 ng/L ($CC_{FR\text{-}DEV}$)	not applicable	hepatic (liver), thyroid (endocrine)

- See Section 10

MDH, 2020a. *Health Based Guidance for Water, Toxicological Summary for: Perfluorohexane Sulfonate*. August 2020. Online, https://www.health.state.mn.us/communities/environment/risk/docs/guidance/gw/pfhxs.pdf.

7. Chronic criteria: Perfluorohexanoate (PFHxA)

7.1 Overview

PFHxA is a six-carbon chemical with a carboxylate (oxygen) functional group (ITRC 2020c). This category of PFAS, PFCA, also includes PFBA and PFOA. PFHxA has characteristics similar to PFBA, so is described as a short-chain PFCA. PFOA as a long-chain PFCA has properties that differ from PFHxA. PFHxA has much shorter half-lives in people and laboratory animals than PFOA (MDH 2021).

The CC use the default and chemical-specific WQC algorithms based on short-term and developmental toxicity profile of PFHxA. PFHxA is rarely detected in fish fillets, so the CC are mainly influenced by the amount of water ingested based on the surface water's use classification. When protecting surface waters as a source of domestic consumption (drinking water) in Class 1/2A or 1/2Bd water, the $CC_{DFR\text{-}DEV}$ is more stringent because of the much higher potential for exposure from drinking water (DWIR) vs. incidental ingestion (IWR) while swimming or other primary contact recreation, basis for the $CC_{FR\text{-}DEV}$. Fish consumption exposure contributes to the final Class 2B $CC_{FR\text{-}DEV,}$ but the estimated total exposure is still lower than when including drinking water, resulting in a higher $CC_{FR\text{-}DEV}$.

7.2 Toxicological values and health risk index endpoints

The toxicological values available from the MDH for PFHxA cover short-term to chronic durations. The laboratory animal study used to develop the short-term duration RfD was less stringent than the subchronic and chronic RfD, but results in the most stringent CC because of the higher short-term DWIR as compared to combining the chronic DWIR with fish consumption (MDH 2021). The most sensitive Health Risk Index Endpoints for both RfDs include the thyroid, which is also characterized as impacted through an endocrine mechanism of action, and developmental toxicity. Both of these factors are relevant for the CC. When monitoring PFHxA in surface water, its concentration will need to be evaluated with other PFAS and other toxic pollutants with the same Health Risk Index Endpoints.

Table 7-1: Toxicological profile

PFAS	**MDH RfD (Duration)**	**Health Risk Index (Additivity) Endpoints (chronic duration)**	**Reference**
PFHxA	0.00032 mg/kg-d (short-term)	developmental, thyroid (endocrine)	MDH 2021
	0.00015 mg/kg-d (subchronic and chronic)	developmental, hepatic (liver) system, respiratory system, thyroid (endocrine)	

7.3 Exposure factors

Exposure factors are based on the algorithms in Minn. R. 7050.0219. The exposure factors have to consider the short-term and chronic toxicity profiles of PFHxA.

Exposure assessments include information on freshwater fish as a source of PFAS and development of a BAF. As discussed previously, MPCA and Interagency FCMP have been monitoring PFAS in fish-fillet (muscle) tissues since 2004. The detection and reporting limits for PFAS have gotten lower over that time and starting in 2019, the detection limit for PFHxA in most fish is less than 0.1 ng/g. Review of MPCA and FCMP database rarely finds detections of PFHxA in freshwater fish fillets. PFHxA has only been detected in about 12 fish out of approximately 4,000 sampled. The detects though are in surface waters with relatively higher concentrations of PFHxA, so in that context, surface waters with local discharges of PFHxA can lead to fish consumption being a potential exposure route to people.

Table 7-2: Exposure parameters

Exposure parameter	Rate or Value	Basis
DWIR	0.290 L/kg-d (short-term)	Because the CC_{DFR} has to be the most stringent value for each duration of exposure, for PFHxA the short-term duration has the highest DWIR and is the basis for the criteria in order to account for this higher developmental exposure. Exposure during the short-term duration is higher due to the potential greater intake of a toxic pollutant per body weight in bottle-fed infants. Therefore, the $CC_{DFR\text{-}DEV}$ algorithm is used to be protective of human health across all lifestages. Minn. R. 7050.0219, subp. 13(B)
IWR	0.0013 L/kg-d (chronic)	The default WQS incidental water intake rate is applied. The rate is based on children ages one through eight.
FCR	0.00094 kg/kg-d (interim WCBA)	Again, because the most stringent RfD is based on thyroid and developmental impacts that can occur after even a short-term duration (>24 hours to 30 days) and at any lifestage, all the available fish consumption rates: adult, child, and WCBA are informative for the CC. Since PFHxA is a developmental toxicant affecting prenatal to neonatal health endpoints, the appropriate FCR is for the interim FCR_{WCBA} of 0.00094 kg/kg-d for women and those that are or may become pregnant (MPCA 2017 and 2020a). This rate is applied to protect this subpopulation and all of Minnesota's fish consumers.
BAF	32 L/kg	The location with the most detects, the Mississippi River in Pool 2 (Washington/Ramsey Counties), has local surface water discharges, explaining these detects. Paired fish and water datasets from Minnesota and other North American studies yielded sufficient data to develop a BAF for PFHxA. Following the hierarchy and procedures for ionic organic chemicals (MPCA 2017), Minnesota's, New Hampshire's (Pickard et al. 2022), and Canadian (Lescord et al. 2015) field studies had quantified detects of PFHxA in water and in five species of fish without qualifiers (Appendix C). The geometric species mean is 32 L/kg.
RSC	0.2 ($CC_{DFR\text{-}DEV}$) 0.2 ($CC_{FR\text{-}DEV}$)	The MPCA $CC_{DFR\text{-}DEV}$ uses a relative source contribution factor based on MDH guidance. For PFHxS MDH determined use of 0.2 versus the default value of 0.5 was more appropriate for the short-term duration. For the $CC_{FR\text{-}DEV}$, the RSC is 0.2 because other routes of exposure beside recreation and freshwater fish consumption are more significant for a person's total exposure to PFHxA (ITRC 2020b).

7.4 Chronic criteria development by use classification

PFHxA is characterized for CC as a developmental toxicant, both because of the need to address short-term toxicity and identification of development as a Health Risk Index Endpoint. When short-term duration exposure of 24 hours to 30 days is relevant, higher intake rates may need to be applied to protect developmental lifestages when exposure to a toxic pollutant is greater on a per body weight basis (MPCA 2017). CC developed for PFHxA apply in two different surface water exposure scenarios:

- Class 1/2A and Class 1/2Bd surface waters with exposure relevant to drinking water, recreation, and fish consumption ($CC_{DFR\text{-}DEV}$); and
- Class 2B (2D) surface waters (wetlands) with exposure relevant to recreation and fish consumption ($CC_{FR\text{-}DEV}$).

PFHxA is a noncarcinogen and so is evaluated using the noncancer algorithms for that toxicological profile in Minn. R. 7050.0219. The foundational equation is:

$$CC\ (ng/L) = RfD\ (mg/kg-d)\ x\ \frac{RSC\ (no\ units)\ x\ \ (1\ x\ 10^6\ \ ng/mg)}{[DWIR\ or\ IWR\ (L/kg-d) +\ FCR\ (kg/kg-d)\ x\ (BAF)\ L/kg]}$$

For the $CC_{DFR\text{-}DEV}$ the short-term, drinking water only exposure algorithm for developmental toxicity resulted in the most stringent value. This short-term duration results in the most protective CC as is the case with the durations reviewed by MDH for Health Based Guidance (MDH 2021).

$$CC_{\ DFR-DEV}\ (ng/L) = 220\ \ ng/L = 0.00032\ (mg/kg-d)\ x\ \frac{0.2\ (no\ units)\ x\ \ (1\ x\ 10^6\ \ ng/mg)}{0.290\ (L/kg-d)}$$

The $CC_{FR\text{-}DEV}$ uses the chronic RfD paired with the chronic IWR and FCR_{WCBA}.

$$CC\ (ng/L) = 950\ \ ng/L\ \ = 0.00015\ (mg/kg-d)\ x\ \frac{0.2\ (no\ units)\ x\ \ (1\ x\ 10^6\ \ ng/mg)}{[0.0013\ (L/kg-d) +\ 0.00094\ (kg/kg-d)\ x\ 32\ (L/kg)]}$$

Table 7-3: Site specific CC

PFAS (Date developed)	Site-specific water quality criteria: Chronic Criteria (CC)			*Health Risk Index Endpoints* (Additive risk)
	Class 1/2A or Class 1/2Bd – drinking water, fish consumption and recreational exposure (30-day average)	**Class 2B/2D#** – fish consumption and recreational exposure (30-day average)	**Class 2 fish-tissue** (90th percentile of 5 fish minimum per water body)	
PFHxA (January 2023)	220 ng/L ($CC_{DFR\text{-}DEV}$) note: MDH Health Based Guidance is 200 ng/L based on one significant figure)	950 ng/L ($CC_{FR\text{-}DEV}$)	not applicable	developmental, hepatic (liver) system, respiratory system, thyroid (endocrine)

- See Section 10

MDH, 2021. *Health Based Guidance for Water, Toxicological Summary for: Perfluorohexanoate*. December 2021. Online, https://www.health.state.mn.us/communities/environment/risk/docs/guidance/gw/pfhxa.pdf .

8. Chronic criteria: Perfluorooctanoate (PFOA)

8.1 Overview

PFOA is an eight-carbon chemical with a carboxylate (oxygen) functional group (ITRC 2020c). This category of PFAS, PFCA, also includes PFBA and PFHxA. PFOA as a long-chain PFCA has properties that differ from PFBA and PFHxA. Because PFOA has a long half-life and transgenerational transfer even short durations of exposure can lead to significant increases in chronic duration or lifetime body burdens (Goeden et al. 2019, MDH 2022b). Like PFOS and PFHxS, the MDH developed a toxicokinetic serum model to fully account for the bioaccumulation and maternal transfer of PFOA when setting health-protective guidance values for drinking water.

The CC use the default and chemical-specific WQC algorithms based on developmental toxicity and transgenerational exposure profile of PFOA. PFOA is rarely detected in fish fillets, so the CC are mainly influenced by the amount of water ingested based on the surface water's use classification. When protecting surface waters as a source of domestic consumption (drinking water) in Class 1/2A or 1/2Bd water, the $CC_{DFR\text{-}DEV}$ is based on the DWIR estimated from the MDH's toxicokinetic model and PFOA guidance value. This value was combined with the FCR_{WCBA} for women and those who are or might become pregnant. The $CC_{DFR\text{-}DEV}$ is more stringent because of the much higher potential for exposure from drinking water (DWIR) vs. incidental ingestion (IWR) while swimming, basis for the $CC_{FR\text{-}DEV}$. Fish consumption exposure contributes to the final Class 2B $CC_{FR\text{-}DEV}$, but the estimated total exposure is still lower than when including drinking water, resulting in a higher $CC_{FR\text{-}DEV}$.

8.2 Toxicological values and health risk index endpoints

The toxicological value, RfD, available from the MDH for PFHxS covers short-term to chronic durations of exposure (MDH 2022b). The most sensitive Health Risk Index Endpoints include the thyroid, which is also characterized as impacted through an endocrine mechanism of action. Toxicological studies also found developmental toxicity occurs at similar doses. The PFOA toxicological values also include a serum value for use in the toxicokinetic model. All of these factors are relevant for the CC. When monitoring PFOA in surface water, its concentration will need to be evaluated with other PFAS and other toxic pollutants with the same Health Risk Index Endpoints.

Table 8-1: Toxicological profile

PFAS	MDH RfD (Duration)	MDH-derived comparable RfD in serum	Health Risk Index Endpoints	Reference
PFOA	0.000018 mg/kg-d (short-term to chronic)	0.13 mg/L	developmental, hepatic (liver), immune, pancreas, renal (kidney), thyroid (endocrine)	MDH 2022b based on Lau et al. 2006

8.3 Exposure factors

Exposure factors are based on the algorithms in Minn. R. 7050.0219 and use of chemical-specific algorithms (7050.0219, subp. 2 (A)). The exposure factors have to consider the short-term to chronic toxicity profiles of PFOA.

Exposure assessments include information on freshwater fish as a source of PFAS and development of a BAF. As discussed previously, MPCA and Interagency FCMP have been monitoring PFAS in fish-fillet (muscle) tissues since 2004. The detection and reporting limits for PFAS have gotten lower over that time and starting in 2019, the detection limit for PFOA in most fish is less than 0.1 ng/g. Review of MPCA and FCMP database rarely finds detections of PFOA in freshwater fish fillets. PFOA has only been detected in about 120 fish out of approximately 4,000 fish sampled. The detects though are in surface waters with relatively higher concentrations of PFOA, so in that context, surface waters with local discharges of PFOA can lead to fish consumption being a potential exposure route to people.

For the Class 1/2A and 1/2Bd $CC_{DFR-DEV}$ for PFOA, which has to protect drinking water users, is informed by the MDH's toxicokinetic model and Health Based Guidance. Their model provides the best tool for protecting this use, and for the PFHxS and PFOA CC, a chemical-specific DWIR can be calculated and used in the chronic CC algorithm.[14] The RSC of 0.2 also helps account for other potential routes of exposure. The MPCA did not modify the MDH's toxicokinetic model to add in fish consumption to the existing drinking water and neonatal breastmilk exposure scenarios given the complexity of this evaluation and lack of a specific need to use the model to ensure these WQC are health protective, but MPCA will evaluate if modified models are relevant in in future updates to the CC or development of CS for adoption into rule.

Table 8-2: Exposure parameters

Exposure parameter	Rate or value	Basis
DWIR	0.103 L/kg-d (chemical-specific)	Calculated from the RfD (0.000018 mg/kg-d) and guidance value (0.035 µg/L) in the MDH Health Based Guidance (2022b) and RSC of 0.2.
IWR	0.0013 L/kg-d (chronic)	The default WQS incidental water intake rate is applied. The rate is based on children ages one through eight.
FCR	0.00094 kg/kg-d (interim WCBA)	Again, because the most stringent RfD is based on thyroid and developmental impacts that can occur after even a short-term duration (>24 hours to 30 days) and at any lifestage, all the available fish consumption rates: adult, child, and WCBA are informative for the CC. Since PFOA is a developmental toxicant affecting prenatal to neonatal health endpoints, the appropriate FCR is for the interim FCR_{WCBA} of 0.00094 kg/kg-d for women and those that are or may become pregnant (MPCA 2017 and 2020a). This rate is applied to protect this subpopulation and all of Minnesota's fish consumers.
BAF	42 L/kg	The locations with the most detects, the Mississippi River in Pool 2 (Washington/Ramsey Counties) and the Twin Cities East Metro (Washington County, AECOM 2021), have local surface water discharges, explaining these detects. Paired fish and water datasets from Minnesota and other North American studies yielded sufficient data to develop a BAF for PFOA. Following the hierarchy and procedures for ionic organic chemicals (MPCA 2017), Minnesota's, Wisconsin's, Massachusetts' (Department of Public Health 2021), New Jersey's (Goodrow et al. 2020), New Hampshire's (Pickard et al. 2022), and Canadian (Lescord et al. 2015) field studies had quantified detects of PFOA in water and in 15 species of fish without qualifiers (Appendix C). The geometric species mean is 42 L/kg.

[14] DWIR = RfD x RSC x unit conversion factor (CF) / HBV or HRL guidance value

Exposure parameter	Rate or value	Basis
RSC	0.2 ($CC_{DFR\text{-}DEV}$) 0.2 ($CC_{FR\text{-}DEV}$)	For both the $CC_{DFR\text{-}DEV}$ and $CC_{FR\text{-}DEV}$, the default RSC is 0.2 because other routes of exposure besides drinking water, recreation, and freshwater fish consumption are significant to people's total exposure to PFOA (ITRC 2020b).

8.4 Chronic criteria development by use classification

PFOA is characterized for CC as a developmental toxicant based on MDH's Health Risk Index Endpoint. PFOA also has a very long half-life in people, meaning that exposure at birth is influenced by the exposure of the mother. And as shown by the MDH, an infant's postnatal exposure is relevant too for developing protective health guidance. MDH modeled PFOS, PFOA, and PFHxS serum levels for both infants who were breastfed and those that were bottle-fed with formula made with contaminated tap water. This allowed the MDH to set final guidance values that, when met, ensure that serum levels or body burdens would not exceed adverse effect levels at any point throughout a lifetime. Therefore, other exposure scenarios and higher intake rates may need to be applied to protect developmental lifestages when exposure to toxic pollutants like PFAS are greater on a per body weight basis (MPCA 2017).

CC developed for PFOA apply in two different surface water exposure scenarios:

- Class 1/2A and Class 1/2Bd surface waters with exposure relevant to drinking water, recreation, and fish consumption ($CC_{DFR\text{-}DEV}$); and
- Class 2B (2D) surface waters (wetlands) with exposure relevant to recreation and fish consumption ($CC_{FR\text{-}DEV}$).

PFOA is evaluated as a noncarcinogen, but MDH determined that it is also "likely to be carcinogenic at high doses" (MDH 2022b). The available data though do suggest that health-based values developed based on noncancer approaches are protective of key events that could lead to tumor formation (MDH 2022b). Therefore, PFOA is evaluated using the algorithms for the noncancer and nonlinear carcinogen toxicological profiles in Minn. R. 7050.0219. The foundational equation is:

$$CC\ (ng/L) = RfD\ (mg/kg-d)\ x \frac{RSC\ (no\ units)\ x\ \ (1\ x\ 10^{6}\ \ ng/mg)}{[DWIR\ or\ IWR\ (L/kg-d) +\ FCR\ (kg/kg-d)\ x\ (BAF)\ L/kg]}$$

For the $CC_{DFR\text{-}DEV}$ the algorithm developed for chronic exposure that includes drinking water and fish consumption is the most appropriate for PFOA and this use classification.

$$CC_{DFR-DEV}\ (ng/L) = 25\ \ ng/L\ = 0.000018\ (mg/kg-d)\ x \frac{0.2\ (no\ units)\ x\ \ (1\ x\ 10^{6}\ \ ng/mg)}{[0.103 +\ 0.00094\ (kg/kg-d)\ x\ 42\ (L/kg)]}$$

The $CC_{FR\text{-}DEV}$ uses the same RfD paired with the chronic IWR and FCR_{WCBA}.

$$CC\ (ng/L) = 88\ \ ng/L\ = 0.000018\ (mg/kg-d)\ x \frac{0.2\ (no\ units)\ x\ \ (1\ x\ 10^{6}\ \ ng/mg)}{[0.0013\ (L/kg-d) +\ 0.00094\ (kg/kg-d)\ x\ 42\ L/kg]}$$

Table 8-3: Site specific CC

PFAS (Date developed)	Site-specific water quality criteria: Chronic Criteria (CC)			***Health Risk Index Endpoints*** **(Additive risk)**
	Class 1/2A or Class 1/2Bd – drinking water, fish consumption and recreational exposure (30-day average)	**Class 2B/2D#** – fish consumption and recreational exposure (30-day average)	**Class 2 fish-tissue** (90th percentile of 5 fish minimum per water body)	
PFOA (January 2023)	25 ng/L	88 ng/L ($CC_{FR\text{-}DEV}$)	not applicable	developmental, hepatic (liver), immune, pancreas, renal (kidney), thyroid (endocrine)

- See Section 10

MDH, 2022b. *Health Based Guidance for Water, Toxicological Summary for: Perfluorooctanoate.* March 2022. Online, https://www.health.state.mn.us/communities/environment/risk/docs/guidance/gw/pfoa2022.pdf .

9. Uncertainty and limitations in water quality criteria

The development of WQC is based on recently updated human health-based methods in Minn. R. chs. 7050 and 7052. Specifically, development of CC for these PFAS are based on the most currently available, reliable, and scientifically defensible toxicological and exposure information and monitoring data. As fully described in MPCA's 2017 *Human Health-based Water Quality Standards Technical Support Document*, there can be uncertainty in exposure factors, toxicity values, and risk characterization. The chemical-specific methods used in this TSD improve the accuracy of these regulatory values.

Ongoing research continues to find other PFAS in surface water and fish-fillet (muscle) tissue. As new analytical methods are developed or detection limits lowered, there may be other PFAS in water or fish that will need WQC. The MPCA has significant ongoing remediation efforts to continue to limit and remediate water resource contamination. US Environmental Protection Agency (EPA) is also focusing on grouping PFAS for development of best management practices, source control, and treatment technologies to improve cleanup or to reduce wastewater discharges. These efforts include water treatment systems that remove many PFAS, not just the ones with WQC, because of some similarity in physical-chemical properties. Because many PFAS lack sufficient toxicological data to develop health-based guidance, treatment that removes many is the main approach to reducing exposure, after pollution prevention.

In regard to pollution prevention, the EPA has put restrictions on the use and import of longer chain PFAS, specifically PFOA and other eight and longer carbon chain PFCAs and six and longer carbon chain PFSAs, including PFOS, thereby contributing to reductions in the future concentrations and presence of those PFAS in water resources (USEPA 2022). These restrictions are critical to reducing PFAS impacts on human health. Minnesota also published *Minnesota's PFAS Blueprint* in 2021, which provides many important short and long-term goals to address the ongoing challenges of PFAS, including lack of data on many fronts.

10. Other Water Quality Rules and Standards

In addition to these site-specific WQC, other water quality rules and standards continue to apply and may be relevant to protecting water quality from the impacts of PFAS.

Under Minn. R. 7050.0155, all waters must maintain a level of water quality that protects the downstream uses. When surface waters are a conduit and source of PFAS contamination to groundwater or downstream drinking water sources – something that is especially important given the mobility of many PFAS – ensuring protection of domestic consumption or potable water uses may need more stringent requirements. Implementation actions considering protection of downstream uses may result in lower levels of PFAS in a water than may be needed when protecting only the specific beneficial uses of that specific surface water (Minn. R. chs. 7050 and 7060).

Minnesota also has narrative water quality standards that apply to all waters. Specifically, the narrative water quality standard in Minn. R. 7050.0210, subp. 2 stipulates that:

> "No sewage, industrial waste, or other wastes shall be discharged from either point or nonpoint sources into any waters of the state so as to cause any nuisance conditions, such as the presence of significant amounts of floating solids, scum, visible oil film, excessive suspended solids, material discoloration, obnoxious odors, gas ebullition, deleterious sludge deposits,

undesirable slimes or fungus growths, aquatic habitat degradation, excessive growths of aquatic plants, or other offensive or harmful effects."

In PFAS containing waters, at the air-water interface, MPCA has documented that surface foams or scums can form. This foam has been shown to contain very high concentrations of certain PFAS, especially long-chain PFAS, like PFOS and PFOA, and precursors. Under specific situations, it may be important to consider whether foam or other characteristics of the water are leading to a violation of any narrative water quality standards.

Finally, Minnesota's antidegradation rules (Minn. R. 7050.0250 et seq.) and prevention policies aim to control pollutants to the lowest levels possible, to ensure that water quality standards and criteria are not "pollute up to" values.

11. Risk characterization

11.1 Application

It is appropriate to use the PFAS CC in the following ways:

- $CC_{FT\text{-}DEV}$: compare to concentration of PFOS in fish-tissue to evaluate potential risks at those water bodies for which this site-specific CC was derived (MPCA 2020b).
- $CC_{DFR\text{-}DEV}$: compare to PFAS concentrations in Class 1/2A/2Bd surface waters to evaluate potential risks at those water bodies for which this site-specific CC was derived.
- $CC_{FR\text{-}DEV}$: compare to PFAS concentrations in Class 2B/2D surface waters/wetlands to evaluate potential risks at those water bodies for which this site-specific CC was derived.

A sufficient number of samples should be used when comparing water and fish monitoring data to the CC. The $CC_{DFR\text{-}DEV}$ and $CC_{FR\text{-}DEV}$ are applied as a 30-day average concentration that should not be exceeded more than once in a water body in a three-year window. The $CC_{FT\text{-}DEV}$ requires at least five fish of the same species or a lesser number of fish from at least three species from a water body. Calculation of a 90^{th} percentile PFOS concentration by species with the minimum number of individuals or average across species in the fillet tissue for comparison to 0.37 ng/g. These details are found in the assessment methods in Chapter 6: Aquatic consumption and drinking water of the most recent MPCA *Guidance Manual for Assessing the Quality of Minnesota Surface Waters for Determination of Impairment: 305(b) and 303(d) List* (2022a).

In addition, not all PFAS can be evaluated at this time due to analytical method limitations or lack of available toxicological values. The methods to protect human health do incorporate additive risk from mixtures of two or more toxic pollutants in fish or water samples. Additive risks for noncancer effects are based on toxic pollutants that have numeric WQS or WQC and the same Health Risk Index Endpoints (Section 11.2, MPCA 2017).

11.2 Additive risks

Methods to develop CC require evaluation of additive risk when more than one toxic pollutant is present in surface water or fish tissue (Minn. R. 7050.0222, subp. 7 D). Additive risks are evaluated for both noncancer and cancer effects. The PFAS CC is derived based on noncancer effects. To evaluate additive risks from noncancer effects, hazard quotients are calculated by dividing the site fish-tissue concentration (for PFOS) or water concentrations by their respective CC for each individual contaminant present. All of the hazard quotients for individual chemicals that affect the same Health Risk Index Endpoint are summed to calculate a hazard index. If the hazard index is equal to or less than 1, it is not likely that exposure to those contaminants involved in the evaluation will lead to a health risk (Equation 1). Concentrations above would exceed the WQC for mixtures.

$$Noncancer\ Health\ Risk\ Index\ by\ Common\ Health\ Risk\ Index\ Endpoint = \frac{C_1}{CC_1} + \frac{C_2}{CC_2} + \cdots + \frac{C_n}{CC_n} \leq 1$$

Where:

$C_1 \ldots C_n$ - surface water concentrations (as a 30-day average) or fish-tissue concentrations for the first through the n^{th} noncancer pollutant with the same Health Risk Index Endpoints. These health endpoints are found in Table ES-2.

$CC_1 \ldots CC_n$ - CC for surface water or fish tissue concentrations for the first to the n^{th} noncancer pollutant.

11.3 Tribal and Environmental Justice communities

The MPCA has a published story map of areas of concern for environmental justice in the state–areas where the number of people of color exceeds 50% and/or more than 40% of the households have a household income of less than 185% of the federal poverty level (MPCA 2022b). The map also includes Native American Tribal areas. As PFAS WQC are applied on a site-specific basis, information specific to these areas will be considered in water bodies where the WQC are applied (Appendix B).

Environmental justice also considers populations that may be more susceptible to adverse effects from environmental pollutants or may be more highly exposed. For the PFAS with WQC, short-term adverse effects, long biological half-lives, developmental toxicity, and higher exposure during infancy to childhood are addressed by MDH Health Based Guidance and MPCA WQC. These PFAS WQC include chemical-specific data and approaches to ensure lifetime protection from health effects. As additional data become available, MPCA will add and refine these values for future statewide rulemaking.

In developing WQS for pollutants in surface water that can bioaccumulate in freshwater fish, MPCA considers the need to address subsistence fishing by communities or populations and to ensure those populations are adequately protected. The MDH FISH study was specifically used as the basis for an interim FCR for WCBA because it was conducted in communities on the North Shore of Minnesota with a high rate of freshwater fishing (MPCA 2020a). Specific demographics of the women that participated were kept confidential, except for the age range for participation of 16 to 50 years; the survey results indicated that 73% of the women consumed freshwater-caught fish. By contrast, most surveys of Minnesotans as a whole estimate consumption for WCBA at around 40%. Because more research and outreach are needed to finalize a FCR for WCBA, the rate being used for WQC is considered "interim."

Tribal nations have reserved fishing rights in many water bodies across the state, and therefore members of Tribal nations are important fish consumers. They are likely to consume fish at higher rates than the "average" Minnesotan. For water bodies in the Lake Superior Basin, there are Tribal Water Quality Standards that have different human health-based methods and intake rates. For example, the Fond du Lac Band of Lake Superior Chippewa use a FCR of 60 g/d and Grand Portage Band of Lake Superior Chippewa use a FCR of 142.5 g/d. These rates have provided important context to MPCA's decision on an interim FCR. If MPCA considers a statewide WQS for PFAS, or develops WQC for water resources that are important tribal fisheries, especially within the Lake Superior Basin, MPCA will engage with affected Tribes to consider the appropriate fish consumption rates.

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Appendix A. Additional background information

Table A-1: Twenty-two of the most commonly monitored PFAS by MPCA (Acronyms, carbon/chain lengths, and CAS numbers)

Perfluoroalkane sulfonate or sulfonic acids (PFSA)			
PFBS	perfluorobutane sulfonate	4	45187-15-3 (anion) 375-73-5 (acid) 29420-49-3 [potassium salt] 68259-10-9 [ammonium salt] 60453-92-1 [sodium salt]
PFHxS	perfluorohexane sulfonate	6	108427-53-8 (anion) 355-46-4 (acid) 3871-99-6 (potassium salt)
PFOS	perfluorooctane sulfonate	8	45298-90-6 (anion) 1763-23-1 (acid) 29081-56-9 (ammonium salt) 70225-14-8 (diethanolamine salt) 2795-39-3 (potassium salt) 29457-72-5 (lithium salt)

Perfluoroalkyl carboxylates or carboxylic acids (PFCA)			
PFBA	perfluorobutanoate	4	45048-62-2 (anion) 375-22-4 (acid)
PFPeA	perfluoropentanoate	5	45167-47-3 (anion) 2706-90-3 (acid)
PFHxA	perfluorohexanoate	6	92612-52-7 (anion) 307-24-4 (acid)
PFHpA	perfluoroheptanoate	7	120885-29-2 (anion) 375-85-9 (acid)
PFOA	perfluorooctanoate	8	45285-51-6 (anion) 335-67-1 (free acid) 335-66-0 (acid fluoride) 3825-26-1 (ammonium salt, APFO) 2395-00-8 (potassium salt) 335-93-3 (silver salt) 335-95-5 (sodium salt)
PFNA	perfluorononoate	9	72007-68-2 (anion) 375-95-1 (acid)
PFDA	perfluorodecanoate	10	73829-36-4 (anion) 335-76-2 (acid)
PFUnA (PFUnDA)	perfluoroundecanoate	11	196859-54-8 (anion) 2058-94-8 (acid)

Precursors			
PFOSA	perfluorooctane sulfonamide	8	754-91-6
4:2 FTS	4:2 fluorotelomer sulfonate	6	757124-72-4
6:2 FTS	6:2 fluorotelomer sulfonate	8	27619-97-2
8:2 FTS	8:2 fluorotelomer sulfonate	10	39108-34-4
10:2 FTS	10:2 fluorotelomer sulfonate	12	120226-60-0
N-EtFOSA	N-ethyl perfluorooctane sulfonamide	8 (10 with functional group)	4151-50-2
N-EtFOSAA	N-ethyl perfluorooctane sulfonamido acetic acid	8 (12 with functional group)	2991-50-6

Precursors			
N-EtFOSE	N-ethyl perfluorooctane sulfonamido ethanol	8 (12 with functional group)	1691-99-2
N-MeFOSA	N-methyl perfluorooctane sulfonamide	8 (11 with functional group)	31506-32-8
N-MeFOSAA	N-methyl perfluorooctane sulfonamido acetic acid	8 (11 with functional group)	2355-31-9
N-MeFOSE	N-methyl perfluorooctane sulfonamido ethanol	8 (11 with functional group)	24448-09-7

Appendix B. Application of additional PFAS water quality criteria to specific water bodies

https://www.pca.state.mn.us/sites/default/files/wq-s6-63a.pdf

Appendix C. Overview of the datasets used in bioaccumulation factors

The following information is provided as a reference for the development of the bioaccumulation factors (BAFs) used in the PFAS CC.

Study	Water body	Year	PFAS	Species (common name)	BAF (L/kg) - fillet	BAF calculated or mean from publication	Fish concentration (ng/g)	Water concentration (ng/L)	Comments
AECOM, Baseline Ecological Risk Assessment (Project 1007 in Minnesota), 2021	Brown's Pond, MN	2020	PFBA	Northern pike	46.7	calculated	6.07	130	2 sample geomean, water
AECOM 2021	Brown's Pond, MN	2020	PFBA	Northern pike	36.3	calculated	4.72	130	2 sample geomean, water
AECOM 2021	Brown's Pond, MN	2020	PFBA	Northern pike	23.7	calculated	3.08	130	2 sample geomean, water
AECOM 2021	Brown's Pond, MN	2020	PFBA	Yellow perch	16.2	calculated	2.1	130	2 sample geomean, water
AECOM 2021	Brown's Pond, MN	2020	PFBA	Yellow perch	18.9	calculated	2.46	130	2 sample geomean collected same month/year as fish
AECOM 2021	Eagle Point Lake, MN	2020	PFHxS	Black crappie	50.1	calculated	0.601	12	1 sample, water
AECOM 2021	Eagle Point Lake, MN	2020	PFHxS	Black crappie	69.2	calculated	0.602	8.7	2 sample geomean, water
AECOM 2021	Eagle Point Lake, MN	2020	PFHxS	Black crappie	60.0	calculated	0.558	9.3	2 sample geomean, water
AECOM 2021	Eagle Point Lake, MN	2020	PFOA	Black crappie	4.7	calculated	0.469	100	1 sample, water
AECOM 2021	Eagle Point Lake, MN	2020	PFOA	Black crappie	8.6	calculated	0.493	57.5	2 sample geomean, water

Study	Water body	Year	PFAS	Species (common name)	BAF (L/kg) - fillet	BAF calculated or mean from publication	Fish concentration (ng/g)	Water concentration (ng/L)	Comments
AECOM 2021	Eagle Point Lake, MN	2020	PFOA	Black crappie	8.8	calculated	0.737	83.5	2 sample geomean, water
AECOM 2021	Lake Elmo, MN	2020	PFOA	Northern pike	5.8	calculated	0.482	83.5	2 sample geomean, water
AECOM 2021	Lake Elmo, MN	2020	PFOA	Northern pike	5.4	calculated	0.412	76.3	2 sample geomean, water
AECOM 2021	Lake Elmo, MN	2020	PFOA	Tullibee / Cisco	6.3	calculated	0.483	76.3	2 sample geomean, water
Goodrow et al. 2020	Little Pine, NJ	2016	PFHxS	Yellow perch	10.4	calculated	1	95.9	1 sample, water and fish
Goodrow et al. 2020	Metedeconk, NJ	2016	PFOA	Common Carp	14.7	mean	0.5	33.9	Mean (2 fish) reported by author; 1 sample, water
Goodrow et al. 2020	Metedeconk, NJ	2016	PFOA	Largemouth Bass	14.7	calculated	0.5	33.9	1 sample, water and fish
Goodrow et al. 2020	Mirror, NJ	2016	PFHxS	Largemouth Bass	17.5	calculated	1	57	1 sample, water and fish
Goodrow et al. 2020	Little Pine, NJ	2016	PFHxS	Yellow perch	10.4	calculated	1	95.9	1 sample, water and fish
Lescord et al. 2015	Char, Cornwallis Island, Nunavut Territory, CA	2016	PFHxA	Char (adult)	96.7	mean	0.058	0.6	Means (13 fish-max and water) reported by author
Lescord et al. 2015	Char, Cornwallis Island, Nunavut Territory, CA	2016	PFHxA	Char (juvenile)	2.3	mean	0.001	0.43	Means (9 fish-max and water) reported by author
Lescord et al. 2015	Meretta, Cornwallis	2016	PFOA	Char (adult)	5.9	mean	0.1	17	Means (21 fish-max and water) reported by author

Study	Water body	Year	PFAS	Species (common name)	BAF (L/kg) - fillet	BAF calculated or mean from publication	Fish concentration (ng/g)	Water concentration (ng/L)	Comments
	Island, Nunavut Territory, CA								
Lescord et al. 2015	Meretta, Cornwallis Island, Nunavut Territory, CA	2016	PFHxS	Char (adult)	9.3	mean	0.28	30	Means (21 fish-max and water) reported by author
Lescord et al. 2015	Meretta, Cornwallis Island, Nunavut Territory, CA	2016	PFHxA	Char (juvenile)	0.0	mean	0.001	30	Means (5 fish-max and water) reported by author
Lescord et al. 2015	Meretta, Cornwallis Island, Nunavut Territory, CA	2016	PFHxS	Char (juvenile)	66.7	mean	2	30	Means (5 fish-max and water) reported by author
Lescord et al. 2015	North, Cornwallis Island, Nunavut Territory, CA	2016	PFHxA	Char (juvenile)	2.3	mean	0.001	0.43	Means (5 fish-max and water) reported by author
Lescord et al. 2015	Resolute, Cornwallis Island, Nunavut Territory, CA	2016	PFHxA	Char (adult)	1.6	mean	0.036	22	Means (18 fish-max and water) reported by author
Lescord et al. 2015	Resolute, Cornwallis Island,	2016	PFOA	Char (adult)	37.2	mean	0.35	9.4	Means (18 fish-max and water) reported by author

Study	Water body	Year	PFAS	Species (common name)	BAF (L/kg) - fillet	BAF calculated or mean from publication	Fish concentration (ng/g)	Water concentration (ng/L)	Comments
	Nunavut Territory, CA								
Lescord et al. 2015	Resolute, Cornwallis Island, Nunavut Territory, CA	2016	PFHxS	Char (adult)	60.9	mean	1.2	19.7	Means (18 fish-max and water) reported by author
Lescord et al. 2015	Resolute, Cornwallis Island, Nunavut Territory, CA	2016	PFHxA	Char (juvenile)	0.0	mean	0.001	22	Means (4 fish-max and water) reported by author
Lescord et al. 2015	Small, Cornwallis Island, Nunavut Territory, CA	2016	PFHxA	Char (juvenile)	5.0	mean	0.003	0.6	Means (9 fish-max and water) reported by author
Massachusetts (MA) Department of Public Health 2021	Johns Pond (Mashpee), MA	2021	PFHxS	Bluegill	5.9	mean	0.32	53.8	Means (3 fish) reported by author; 2 sample geomean, water
MA 2021	Johns Pond (Mashpee), MA	2021	PFHxS	Chain pickerel	15.4	calculated	0.83	53.8	Detected in only one fish; 2 sample geomean, water
MA 2021	Johns Pond (Mashpee), MA	2021	PFHxS	Largemouth Bass	3.0	mean	0.16	53.8	Means (3 fish) reported by author; 2 sample geomean, water
MA 2021	Johns Pond (Mashpee), MA	2021	PFOA	Pumpkinseed	12.3	mean	0.22	17.9	Means (3 fish) reported by author; 2 sample geomean, water

Study	Water body	Year	PFAS	Species (common name)	BAF (L/kg) - fillet	BAF calculated or mean from publication	Fish concentration (ng/g)	Water concentration (ng/L)	Comments
MA 2021	Johns Pond (Mashpee), MA	2021	PFHxS	Pumpkinseed	25.7	mean	1.38	53.8	Means (3 fish) reported by author; 2 sample geomean, water
MA 2021	Johns Pond (Mashpee), MA	2021	PFHxS	White perch	2.4	mean	0.13	53.8	Means (4 fish) reported by author; 2 sample geomean, water
MA 2021	Johns Pond (Mashpee), MA	2021	PFHxS	Yellow perch	18.8	mean	1.01	53.8	Means (3 fish) reported by author; 2 sample geomean, water
Minnesota (MPCA) Environmental Analysis and Outcomes (EAO)/ FCMP, 2004-2021	Bde Maka Ska (formerly Calhoun), MN	2006	PFOA	White sucker	193.4	calculated	3.81	19.7	3 sample geomean, water
MPCA/FCMP, 2004-2021	Bde Maka Ska (formerly Calhoun), MN	2006	PFOA	White sucker	121.3	calculated	2.39	19.7	3 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 3, MN	2009	PFBA	Common carp	242.7	calculated	2.67	11	9 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 3, MN	2009	PFHxA	Common carp	1980.0	calculated	5.94	3.0	8 sample geomean (didn't include nondetects), water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 3, MN	2009	PFOA	Common carp	1019.6	calculated	4.69	4.6	9 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2009	PFBA	Common carp	233.2	calculated	10.4	44.6	9 sample geomean, water

Study	Water body	Year	PFAS	Species (common name)	BAF (L/kg) - fillet	BAF calculated or mean from publication	Fish concentration (ng/g)	Water concentration (ng/L)	Comments
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2009	PFBA	Common carp	134.8	calculated	6.01	44.6	9 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2009	PFHxS	Common carp	279.3	calculated	4.58	16.4	9 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2009	PFHxS	Common carp	284.1	calculated	4.66	16.4	6 sample geomean (didn't include nondetects), water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2009	PFOA	Common carp	229.5	calculated	4.2	18.3	9 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2009	PFOA	Common carp	661.2	calculated	12.1	18.3	9 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2009	PFBA	Freshwater drum	87.0	calculated	3.88	44.6	9 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2009	PFBA	Freshwater drum	85.7	calculated	3.82	44.6	9 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2009	PFBA	Freshwater drum	84.8	calculated	3.78	44.6	9 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2009	PFHxS	Freshwater drum	446.3	calculated	7.32	16.4	6 sample geomean (didn't include nondetects), water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2009	PFHxS	Freshwater drum	335.4	calculated	5.5	16.4	6 sample geomean (didn't include nondetects), water

Study	Water body	Year	PFAS	Species (common name)	BAF (L/kg) - fillet	BAF calculated or mean from publication	Fish concentration (ng/g)	Water concentration (ng/L)	Comments
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2009	PFOA	Freshwater drum	513.1	calculated	9.39	18.3	9 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2009	PFOA	Freshwater drum	502.2	calculated	9.19	18.3	9 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2009	PFOA	Freshwater drum	430.1	calculated	7.87	18.3	9 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2009	PFBA	Smallmouth bass	62.6	calculated	2.79	44.6	9 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2009	PFOA	Smallmouth bass	162.3	calculated	2.97	18.3	9 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 3, MN	2012	PFOA	Common carp	61.7	calculated	0.5	8.1	9 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2012	PFOA	Bluegill	21.9	calculated	0.89	40.6	9 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2012	PFBS	Common carp	48.8	calculated	1.00	20.5	6 sample geomean (didn't include nondetects), water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2012	PFBS	Common carp	49.3	calculated	1.01	20.5	6 sample geomean (didn't include nondetects), water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2012	PFHxS	Common carp	698.4	calculated	13.2	18.9	6 sample geomean (didn't include nondetects), water

Study	Water body	Year	PFAS	Species (common name)	BAF (L/kg) - fillet	BAF calculated or mean from publication	Fish concentration (ng/g)	Water concentration (ng/L)	Comments
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2012	PFHxS	Common carp	80.4	calculated	1.52	18.9	6 sample geomean (didn't include nondetects), water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2012	PFOA	Common carp	219.0	calculated	8.89	40.6	9 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2012	PFOA	Common carp	32.5	calculated	1.32	40.6	9 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2012	PFOA	Common carp	31.8	calculated	1.29	40.6	9 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2012	PFOA	Common carp	16.5	calculated	0.67	40.6	9 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2012	PFBS	Freshwater drum	49.8	calculated	1.02	20.5	6 sample geomean (didn't include nondetects), water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2012	PFHxS	Freshwater drum	78.8	calculated	1.49	18.9	6 sample geomean (didn't include nondetects), water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2012	PFOA	Freshwater drum	39.7	calculated	1.61	40.6	9 sample geomean, water
MPCA/FCMP, 2004-2021	Mississippi River - Pool 2, Section 4, MN	2012	PFOA	Freshwater drum	27.8	calculated	1.13	40.6	9 sample geomean, water
MPCA/FCMP, 2004-2021	Lake Elmo, MN	2016	PFOA	Black crappie	38.8	calculated	2.76	71.1	2 sample geomean, water
MPCA/FCMP, 2004-2021	Lake Elmo, MN	2016	PFOA	Black crappie	20.3	calculated	1.44	71.1	2 sample geomean, water

Study	Water body	Year	PFAS	Species (common name)	BAF (L/kg) - fillet	BAF calculated or mean from publication	Fish concentration (ng/g)	Water concentration (ng/L)	Comments
MPCA/FCMP, 2004-2021	Lake Elmo, MN	2016	PFOA	Black crappie	15.6	calculated	1.11	71.1	2 sample geomean, water
MPCA/FCMP, 2004-2021	Lake Elmo, MN	2016	PFOA	Black crappie	11.4	calculated	0.812	71.1	2 sample geomean, water
Pickard et al. 2022	Baboosic Lake, Amherst, NH (CENTER)	2017	PFHxS	Bluegill	428.1	calculated	0.244	0.57	1 sample, water and fish
Pickard et al. 2022	Baboosic Lake, Amherst, NH (CENTER)	2017	PFOA	Bluegill	31.3	calculated	0.271	8.66	1 sample, water and fish
Pickard et al. 2022	Baboosic Lake, Amherst, NH (CENTER)	2017	PFOA	Bluegill	31.9	calculated	0.276	8.66	1 sample, water and fish
Pickard et al. 2022	Cocheco River, Rochester, Hanson Pines, NH	2017	PFHxA	Bluegill	18.7	calculated	0.038	2.03	1 sample, water and fish
Pickard et al. 2022	Cocheco River, Rochester, Hanson Pines, NH	2017	PFOA	Bluegill	126.9	calculated	0.283	2.23	1 sample, water and fish
Pickard et al. 2022	Cocheco River, Rochester, Hanson Pines, NH	2017	PFOA	Bluegill	96.9	calculated	0.216	2.23	1 sample, water and fish

Study	Water body	Year	PFAS	Species (common name)	BAF (L/kg) - fillet	BAF calculated or mean from publication	Fish concentration (ng/g)	Water concentration (ng/L)	Comments
Pickard et al. 2022	Cocheco River, Rochester, Hanson Pines, NH	2017	PFOA	Largemouth bass	104.5	calculated	0.233	2.23	1 sample, water and fish
Pickard et al. 2022	Cocheco River, Rochester, Hanson Pines, NH	2017	PFOA	Largemouth bass	89.7	calculated	0.2	2.23	1 sample, water and fish
Pickard et al. 2022	Cocheco River, Rochester, Hanson Pines, NH	2017	PFOA	Yellow perch	103.1	calculated	0.23	2.23	1 sample, water and fish
Pickard et al. 2022	Cocheco River, Rochester, Hanson Pines, NH	2017	PFOA	Yellow perch	97.3	calculated	0.217	2.23	1 sample, water and fish
Pickard et al. 2022	Cocheco River, Rochester, Hanson Pines, NH	2017	PFOA	Yellow perch	124.7	calculated	0.278	2.23	1 sample, water and fish
Pickard et al. 2022	Cocheco River, Rochester, Hanson Pines, NH	2017	PFOA	Yellow perch	113.5	calculated	0.253	2.23	1 sample, water and fish

Study	Water body	Year	PFAS	Species (common name)	BAF (L/kg) - fillet	BAF calculated or mean from publication	Fish concentration (ng/g)	Water concentration (ng/L)	Comments
Pickard et al. 2022	Great Pond, Kingston, NH (CENTER)	2017	PFOA	Bluegill	105.4	calculated	0.329	3.12	1 sample, water and fish
Pickard et al. 2022	Great Pond, Kingston, NH (CENTER)	2017	PFOA	Bluegill	70.5	calculated	0.22	3.12	1 sample, water and fish
Pickard et al. 2022	Greeley Launch Merrimack River, NH	2017	PFOA	Bluegill	203.2	calculated	0.386	1.9	1 sample, water and fish
Pickard et al. 2022	Greeley Launch Merrimack River, NH	2017	PFOA	Bluegill	133.2	calculated	0.253	1.9	1 sample, water and fish
Pickard et al. 2022	Greeley Launch Merrimack River, NH	2017	PFBA	Lake whitefish	72.9	calculated	0.638	8.75	1 sample, water and fish
Pickard et al. 2022	Greeley Launch Merrimack River, NH	2017	PFOA	Lake whitefish	125.3	calculated	0.238	1.9	1 sample, water and fish
Pickard et al. 2022	Greeley Launch Merrimack River, NH	2017	PFOA	Lake whitefish	106.3	calculated	0.202	1.9	1 sample, water and fish
Pickard et al. 2022	Greeley Launch Merrimack River, NH	2017	PFOA	Lake whitefish	116.3	calculated	0.221	1.9	1 sample, water and fish

Study	Water body	Year	PFAS	Species (common name)	BAF (L/kg) - fillet	BAF calculated or mean from publication	Fish concentration (ng/g)	Water concentration (ng/L)	Comments
Pickard et al. 2022	Greeley Launch Merrimack River, NH	2017	PFOA	Lake whitefish	126.3	calculated	0.24	1.9	1 sample, water and fish
Pickard et al. 2022	Greeley Launch Merrimack River, NH	2017	PFOA	Pumpkinseed	119.5	calculated	0.227	1.9	1 sample, water and fish
Pickard et al. 2022	Greeley Launch Merrimack River, NH	2017	PFOA	Pumpkinseed	137.9	calculated	0.262	1.9	1 sample, water and fish
Pickard et al. 2022	Greeley Launch Merrimack River, NH	2017	PFOA	Pumpkinseed	133.2	calculated	0.253	1.9	1 sample, water and fish
Pickard et al. 2022	Greeley Launch Merrimack River, NH	2017	PFOA	Pumpkinseed	137.4	calculated	0.261	1.9	1 sample, water and fish
Pickard et al. 2022	Hedgehog Pond, Salem, NH	2017	PFHxS	Bluegill	90.5	calculated	0.067	0.74	1 sample, water and fish
Pickard et al. 2022	Hedgehog Pond, Salem, NH	2017	PFHxS	Bluegill	598.6	calculated	0.443	0.74	1 sample, water and fish
Pickard et al. 2022	Hedgehog Pond, Salem, NH	2017	PFOA	Bluegill	15.7	calculated	0.231	14.68	1 sample, water and fish

Study	Water body	Year	PFAS	Species (common name)	BAF (L/kg) - fillet	BAF calculated or mean from publication	Fish concentration (ng/g)	Water concentration (ng/L)	Comments
Pickard et al. 2022	Hedgehog Pond, Salem, NH	2017	PFOA	Bluegill	10.5	calculated	0.154	14.68	1 sample, water and fish
Pickard et al. 2022	Horseshoe Pond, Merrimack, NH (CENTER)	2017	PFOA	Bluegill	9.2	calculated	0.24	26.12	1 sample, water and fish
Pickard et al. 2022	Horseshoe Pond, Merrimack, NH (CENTER)	2017	PFOA	Bluegill	9.9	calculated	0.258	26.12	1 sample, water and fish
Pickard et al. 2022	Horseshoe Pond, Merrimack, NH (CENTER)	2017	PFOA	Largemouth bass	8.2	calculated	0.215	26.12	1 sample, water and fish
Pickard et al. 2022	Horseshoe Pond, Merrimack, NH (CENTER)	2017	PFOA	Largemouth bass	7.9	calculated	0.207	26.12	1 sample, water and fish
Pickard et al. 2022	Horseshoe Pond, Merrimack, NH (CENTER)	2017	PFOA	Largemouth bass	7.7	calculated	0.2	26.12	1 sample, water and fish
Pickard et al. 2022	Horseshoe Pond, Merrimack, NH (CENTER)	2017	PFHxA	Pumpkinseed	6.6	calculated	0.053	7.97	1 sample, water and fish
Pickard et al. 2022	Horseshoe Pond, Merrimack, NH (CENTER)	2017	PFOA	Pumpkinseed	10.0	calculated	0.261	26.12	1 sample, water and fish

Study	Water body	Year	PFAS	Species (common name)	BAF (L/kg) - fillet	BAF calculated or mean from publication	Fish concentration (ng/g)	Water concentration (ng/L)	Comments
Pickard et al. 2022	Horseshoe Pond, Merrimack, NH (CENTER)	2017	PFOA	Pumpkinseed	8.1	calculated	0.211	26.12	1 sample, water and fish
Pickard et al. 2022	Horseshoe Pond, Merrimack, NH (CENTER)	2017	PFOA	Smallmouth bass	8.4	calculated	0.22	26.12	1 sample, water and fish
Pickard et al. 2022	Horseshoe Pond, Merrimack, NH (CENTER)	2017	PFOA	Smallmouth bass	10.0	calculated	0.26	26.12	1 sample, water and fish
Pickard et al. 2022	Horseshoe Pond, Merrimack, NH (CENTER)	2017	PFHxS	Yellow perch	26.2	calculated	0.088	3.36	1 sample, water and fish
Pickard et al. 2022	Horseshoe Pond, Merrimack, NH (CENTER)	2017	PFHxS	Yellow perch	108.3	calculated	0.364	3.36	1 sample, water and fish
Pickard et al. 2022	Horseshoe Pond, Merrimack, NH (CENTER)	2017	PFHxS	Yellow perch	10.1	calculated	0.034	3.36	1 sample, water and fish
Pickard et al. 2022	Horseshoe Pond, Merrimack, NH (CENTER)	2017	PFOA	Yellow perch	10.4	calculated	0.271	26.12	1 sample, water and fish
Pickard et al. 2022	Horseshoe Pond,	2017	PFOA	Yellow perch	17.6	calculated	0.46	26.12	1 sample, water and fish

Study	Water body	Year	PFAS	Species (common name)	BAF (L/kg) - fillet	BAF calculated or mean from publication	Fish concentration (ng/g)	Water concentration (ng/L)	Comments
	Merrimack, NH (CENTER)								
Pickard et al. 2022	Horseshoe Pond, Merrimack, NH (CENTER)	2017	PFOA	Yellow perch	10.2	calculated	0.267	26.12	1 sample, water and fish
Pickard et al. 2022	Merrimack River, downstream St. Gobain, NH	2017	PFOA	Bluegill	56.0	calculated	0.3	5.36	1 sample, water and fish
Pickard et al. 2022	Merrimack River, downstream St. Gobain, NH	2017	PFOA	Bluegill	38.4	calculated	0.206	5.36	1 sample, water and fish
Pickard et al. 2022	Merrimack River, downstream St. Gobain, NH	2017	PFOA	Bluegill	48.1	calculated	0.258	5.36	1 sample, water and fish
Pickard et al. 2022	Merrimack River, downstream St. Gobain, NH	2017	PFOA	Brown bullhead	42.5	calculated	0.228	5.36	1 sample, water and fish
Pickard et al. 2022	Merrimack River, downstream St. Gobain, NH	2017	PFHxA	Largemouth bass	116.7	calculated	0.252	2.16	1 sample, water and fish

Study	Water body	Year	PFAS	Species (common name)	BAF (L/kg) - fillet	BAF calculated or mean from publication	Fish concentration (ng/g)	Water concentration (ng/L)	Comments
Pickard et al. 2022	Merrimack River, downstream St. Gobain, NH	2017	PFOA	Largemouth bass	47.0	calculated	0.252	5.36	1 sample, water and fish
Pickard et al. 2022	Merrimack River, downstream St. Gobain, NH	2017	PFOA	Largemouth bass	53.9	calculated	0.289	5.36	1 sample, water and fish
Pickard et al. 2022	Merrimack River, downstream St. Gobain, NH	2017	PFOA	Largemouth bass	55.2	calculated	0.296	5.36	1 sample, water and fish
Pickard et al. 2022	Merrimack River, downstream St. Gobain, NH	2017	PFOA	Smallmouth bass	44.0	calculated	0.236	5.36	1 sample, water and fish
Pickard et al. 2022	Merrimack River, downstream St. Gobain, NH	2017	PFOA	Smallmouth bass	43.1	calculated	0.231	5.36	1 sample, water and fish
Pickard et al. 2022	Merrimack River, downstream St. Gobain, NH	2017	PFOA	Smallmouth bass	41.6	calculated	0.223	5.36	1 sample, water and fish
Pickard et al. 2022	Merrimack River,	2017	PFOA	Smallmouth bass	45.0	calculated	0.241	5.36	1 sample, water and fish

Study	Water body	Year	PFAS	Species (common name)	BAF (L/kg) - fillet	BAF calculated or mean from publication	Fish concentration (ng/g)	Water concentration (ng/L)	Comments
	downstream St. Gobain, NH								
Pickard et al. 2022	Nashua River, Mine Falls Dam, NH	2017	PFHxS	Bluegill	66.0	calculated	0.107	1.62	1 sample, water and fish
Pickard et al. 2022	Nashua River, Mine Falls Dam, NH	2017	PFOA	Bluegill	20.7	calculated	0.307	14.86	1 sample, water and fish
Pickard et al. 2022	Nashua River, Mine Falls Dam, NH	2017	PFOA	Bluegill	83.8	calculated	1.245	14.86	1 sample, water and fish
Pickard et al. 2022	Pine Island Pond, Manchester, NH (CENTER)	2017	PFOA	Bluegill	11.3	calculated	0.281	24.9	1 sample, water and fish
Pickard et al. 2022	Pine Island Pond, Manchester, NH (CENTER)	2017	PFOA	Bluegill	9.0	calculated	0.225	24.9	1 sample, water and fish
Pickard et al. 2022	Pine Island Pond, Manchester, NH (CENTER)	2017	PFHxS	Pumpkinseed	19.5	calculated	0.079	4.06	1 sample, water and fish
Pickard et al. 2022	Pine Island Pond, Manchester, NH (CENTER)	2017	PFHxS	Pumpkinseed	31.3	calculated	0.127	4.06	1 sample, water and fish
Pickard et al. 2022	Pine Island Pond,	2017	PFOA	Pumpkinseed	10.3	calculated	0.256	24.9	1 sample, water and fish

Study	Water body	Year	PFAS	Species (common name)	BAF (L/kg) - fillet	BAF calculated or mean from publication	Fish concentration (ng/g)	Water concentration (ng/L)	Comments
	Manchester, NH (CENTER)								
Pickard et al. 2022	Pine Island Pond, Manchester, NH (CENTER)	2017	PFOA	Pumpkinseed	13.1	calculated	0.327	24.9	1 sample, water and fish
Pickard et al. 2022	Pine Island Pond, Manchester, NH (CENTER)	2017	PFOA	Pumpkinseed	9.8	calculated	0.244	24.9	1 sample, water and fish
Pickard et al. 2022	Pine Island Pond, Manchester, NH (CENTER)	2017	PFOA	Pumpkinseed	10.2	calculated	0.254	24.9	1 sample, water and fish
Pickard et al. 2022	Pine Island Pond, Manchester, NH (CENTER)	2017	PFHxS	Yellow perch	33.5	calculated	0.136	4.06	1 sample, water and fish
Pickard et al. 2022	Pine Island Pond, Manchester, NH (CENTER)	2017	PFHxS	Yellow perch	36.7	calculated	0.149	4.06	1 sample, water and fish
Pickard et al. 2022	Pine Island Pond, Manchester, NH (CENTER)	2017	PFHxS	Yellow perch	27.8	calculated	0.113	4.06	1 sample, water and fish
Pickard et al. 2022	Pine Island Pond, Manchester, NH (CENTER)	2017	PFOA	Yellow perch	16.5	calculated	0.411	24.9	1 sample, water and fish

Study	Water body	Year	PFAS	Species (common name)	BAF (L/kg) - fillet	BAF calculated or mean from publication	Fish concentration (ng/g)	Water concentration (ng/L)	Comments
Pickard et al. 2022	Pine Island Pond, Manchester, NH (CENTER)	2017	PFOA	Yellow perch	11.0	calculated	0.274	24.9	1 sample, water and fish
Pickard et al. 2022	Pine Island Pond, Manchester, NH (CENTER)	2017	PFOA	Yellow perch	9.1	calculated	0.227	24.9	1 sample, water and fish
Pickard et al. 2022	Pine Island Pond, Manchester, NH (CENTER)	2017	PFOA	Yellow perch	11.2	calculated	0.28	24.9	1 sample, water and fish
Wisconsin Dept. of Natural Resources (WIDNR), 2006-2021 (data from Williams, M.)	Lake Monona, WI	2019	PFOA	Bluegill	1222.2	calculated	4.4	3.6	5 sample geomean, water
WIDNR, 2006-2021	Lake Monona, WI	2019	PFOA	Bluegill	916.7	calculated	3.3	3.6	5 sample geomean, water
WIDNR, 2006-2021	Starkweather Creek - Atwood Ave., WI	2019	PFOA	Northern pike	227.8	calculated	4.1	18	1 sample, water
WIDNR, 2006-2021	Starkweather Creek - Atwood Ave., WI	2019	PFOA	Northern pike	266.7	calculated	4.8	18	1 sample, water

Study	Water body	Year	PFAS	Species (common name)	BAF (L/kg) - fillet	BAF calculated or mean from publication	Fish concentration (ng/g)	Water concentration (ng/L)	Comments
WIDNR, 2006-2021	Starkweather Creek - Atwood Ave., WI	2019	PFOA	Walleye	288.9	calculated	5.2	18	1 sample, water
WIDNR, 2006-2021	Starkweather Creek - Atwood Ave., WI	2019	PFHxS	Yellow perch	48.6	calculated	3.5	72	1 sample, water
WIDNR, 2006-2021	Wisconsin River -Upper Petenwell Flowage, WI	2019	PFOA	Bluegill	213.6	calculated	2.35	11	1 sample, water
WIDNR, 2006-2021	Silver Creek - Fort McCoy, WI	2020	PFHxS	Brown trout	9310.3	calculated	2.7	0.29	3 sample geomean, water