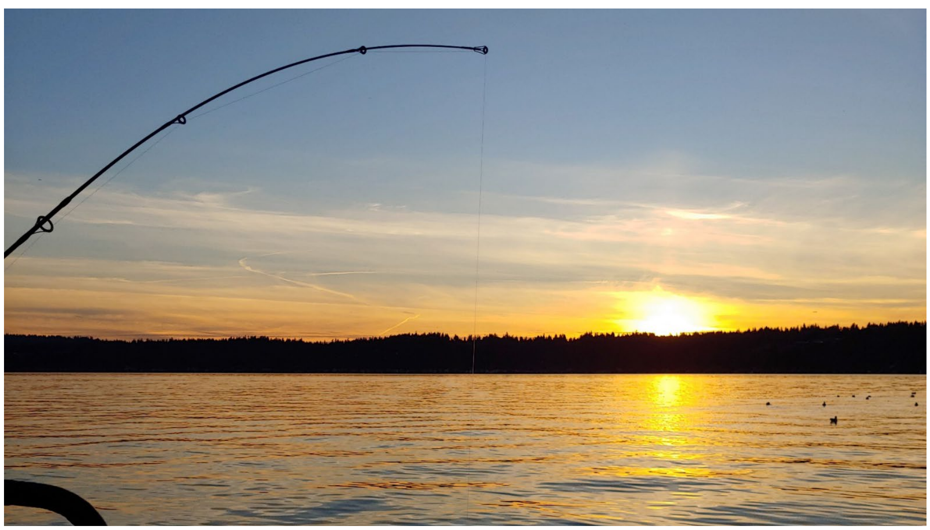
Per- and Polyfluoroalkyl Substances in Freshwater Fish of Ten Lakes

2023 Results



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Cover Photo: Callie Mathieu, 2023. Lake Sammamish angling.

Per- and Polyfluoroalkyl Substances in Freshwater Fish of Ten Lakes

2023 Results

by

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Abstract

In the fall of 2023, the Washington State Department of Ecology (Ecology) conducted a study to fill data gaps on per- and polyfluoroalkyl substances (PFAS) in various freshwater fish species across a range of water bodies. Ecology collected 324 fish from ten lakes in Washington: American, Goodwin, Horsethief, Leland, Loomis, McIntosh, Nahwatzel, Sammamish, Spanaway, and Stevens. Fillet tissues were analyzed for PFAS as 75 composites and 13 individual samples. Three surface water samples were also collected from each lake for PFAS analysis.

PFAS were detected in 83 out of the 88 fish tissue samples. Total (T-) PFAS concentrations were highest in American Lake fish (8.4 – 204 ng/g), followed by Spanaway (24 – 99 ng/g) and Stevens (6.2 – 99 ng/g), all of which had fish tissue median and means above 10 ng/g across all species collected. Lake Goodwin had T-PFAS concentrations above 10 ng/g in several bass samples. All other lakes sampled contained fish tissue T-PFAS concentrations below 5 ng/g.

Detected T-PFAS concentrations in surface water ranged from 0.4 ng/L (Lake Nahwatzel) to 39.6 ng/L (American Lake), with a median of 12.4 ng/L for all samples collected. Average bass and sunfish PFAS concentrations were correlated with paired surface water PFAS concentrations, with fillet levels increasing as surface water levels increased, suggesting that preliminary screening of surface water could help prioritize water bodies for future fish collections.

PFAS levels in American, Spanaway, Stevens, and some Goodwin fish were high enough to be harmful to wildlife consuming the fish. The other lakes sampled were below levels of expected ecological impacts. PFAS concentrations in fish and surface water were not at levels that would indicate direct harm to the fish, according to state thresholds. However, several fish samples from American Lake and one from Spanaway Lake were above new federal recommendations for protecting aquatic life.

Introduction

Background

Per- and polyfluoroalkyl substances (PFAS) are a large group of chemicals that include persistent, bioaccumulative, and toxic (PBT) compounds. In the early 2000s, one PFAS – perfluorooctane sulfonic acid (PFOS) – was reported as a widespread contaminant in wildlife across the globe (Giesy and Kannan 2001). Concern over the effects of PFAS on human health and its persistence in the environment led manufacturers to largely phase out the most bioaccumulative PFAS in the 2000s (PFOS) and 2010s (perfluorooctanoic acid (PFOA) and long-chain perfluoroalkyl acids (PFAAs)).

Washington State Department of Ecology (Ecology) identified PFOS as a chemical of concern when the State issued the PBT List in 2006 (WAC 173-333-310). The State also developed a chemical action plan for PFAS, outlining recommendations to address environmental exposure and reduce impacts on human health (Ecology 2022). The chemical action plan summarizes PFAS health effects, ecological toxicology, environmental occurrence, and exposure pathways. The Interstate Technology and Regulatory Council also provides detailed information on many aspects of PFAS in its technical and regulatory guidance (ITRC 2023).

In Washington State, PFAS was first detected in freshwater fish tissue in 2008 (Furl and Meredith 2010). Several Ecology studies since then have reported PFAS detections in fish tissue collected throughout the state (Johnson and Friese 2012; Mathieu and McCall 2017; Mathieu 2022). In every study, the dominant compound found in fillet tissue was PFOS.

Ecology's statewide surveys in 2008 and 2016 showed that fish PFAS concentrations were highest in urban lakes in Western Washington. Several urban lake fish fillet samples were above the Washington State Department of Health's (DOH's) levels of concern for human health for general and high consumer populations, which were provisional at the time. In response to those surveys, Ecology conducted a follow-up study at three Western Washington urban lakes to collect enough fish samples for a DOH consumption assessment (Mathieu 2022). Several species of fish collected from the three urban lakes had high enough PFOS concentrations to result in the first fish consumption advisory for PFOS in the state (WA DOH 2022).

These previous studies highlighted the need for additional PFAS testing throughout the state to document concentrations in a wide variety of water bodies and freshwater fish species. This 2023 study was carried out to help fill this data gap.

Study Design

In 2023, Ecology's PBT Monitoring Program collected freshwater fish tissue and surface water samples from ten Washington lakes for PFAS analysis (Figure 1). The goal of the study was to characterize the presence and concentrations of PFAS in fillet tissue of freshwater fish and make the data available for fish consumption guidance and advisories. A total of 324 fish were collected and analyzed as 75 composite samples and 13 individual samples. Three surface water samples were also collected from each lake to support our understanding of paired water PFAS conditions in the water bodies. This study was conducted under a quality assurance project plan (QAPP) (Mathieu and Foster 2023).

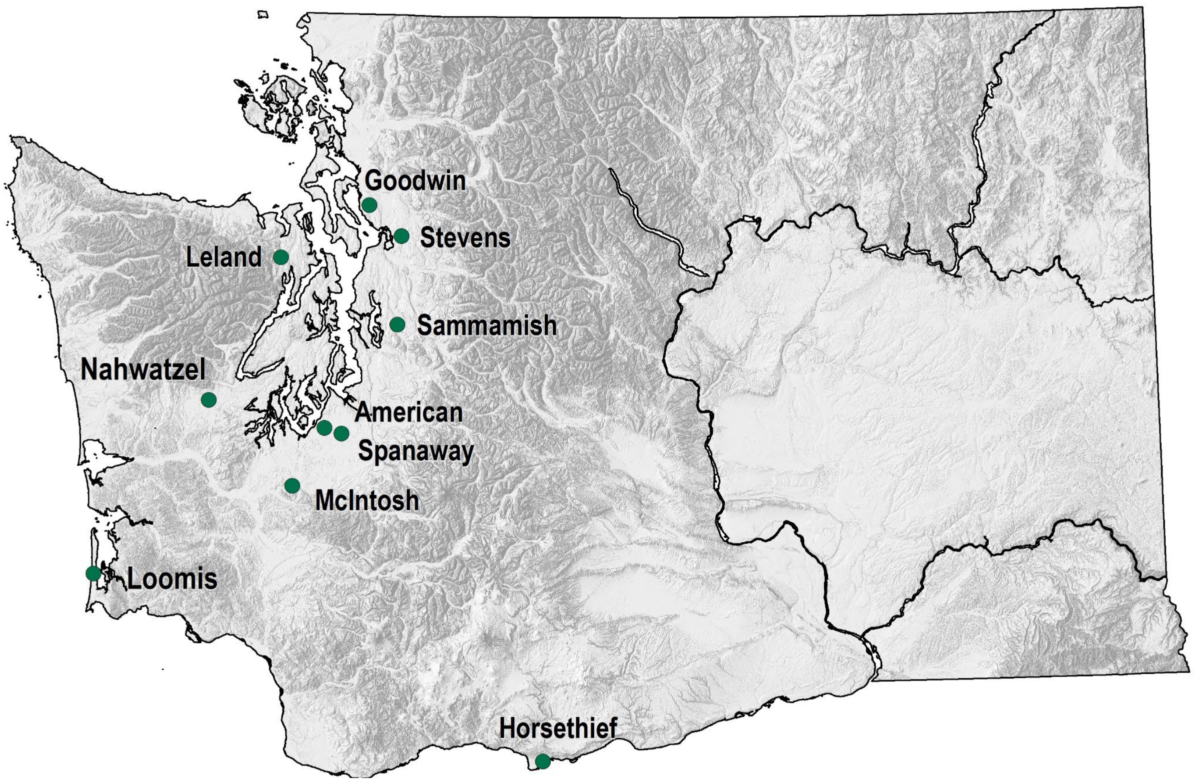

Figure 1. 2023 Study lake locations.

Lakes selected for this study included those with heavy local recreational angler presence (Sammamish and Stevens), areas with nearby drinking water detections of PFAS (American and Spanaway), and six exploratory PBT Monitoring lakes where fish were already being collected for a separate long-term monitoring study (Goodwin, Horsethief, Leland, Loomis, McIntosh, and Nahwatzel). The long-term monitoring sites were included to leverage existing efforts while filling data gaps on PFAS concentrations in fish from lakes across a range of physical characteristics and contamination potential. The PBT Monitoring lakes are located in mostly rural areas with varying degrees of development along their shorelines. Table 1 summarizes the study lake's physical characteristics, land uses, and potential PFAS pathways of interest.

Table 1. Study locations, physical characteristics, and land uses and types.

Lake	County	Drainage Basin (acres)	Surface Area (acres)	Lake Volume (acre-ft)	Maximum Depth (ft)	Land use/type
American	Pierce	16,300	1,100	60,000	90	urban/residential, military
Goodwin	Snohomish	3,300	560	13,000	50	residential, forested
Horsethief	Klickitat	—	92	—	—	recreation, grasslands
Leland	Jefferson	3,650	110	1,400	20	residential, forested, agriculture
Loomis	Pacific	922	170	830	9	residential, forested
McIntosh	Thurston	1,450	93	700	11	residential, forested,
Nahwatzel	Mason	3,970	270	4,600	25	residential, forested
Sammamish	King	62,700	4,900	283,900	105	urban/residential, forested
Spanaway	Pierce	10,880	280	4,600	28	urban/residential, military
Stevens	Snohomish	4,370	1,000	65,000	160	urban/residential, forested

PFAS = Per- and polyfluoroalkyl substances; land use and land type are defined in the Glossary.

Methods

Sample Collection

Fish Tissue

Fish Collection

Field crews collected freshwater fish samples from the ten lakes in September and October 2023. The primary collection method was electrofishing by boat. Field staff also used gill nets and angling to accommodate species of interest that prefer cooler waters at deeper depths (cutthroat trout, rainbow trout, and kokanee). All fish for this study were collected under required scientific research collection permits and through citizen angler donations that were collected following Washington State Fish and Wildlife (WDFW) fishing regulations. Field staff collected fish at Horsethief Lake with WDFW during a population survey, keeping any fish that fit the target size range and species for the study. All cutthroat trout samples from Lake Sammamish were donated by local citizen anglers.

Largemouth or smallmouth bass were collected from nine of the ten lakes. Nine additional species were collected, including black crappie, bluegill, brown bullhead, pumpkinseed, yellow perch, walleye, rainbow trout, cutthroat trout, and kokanee. Rainbow trout, cutthroat trout, and kokanee were three freshwater species targeted this year as they are popular with anglers but aren't well represented in PFAS data for Washington lakes. Lake Sammamish was the only water body where bass were not collected. Sampling efforts there focused on addressing angler concerns about PFAS concentrations in cutthroat trout following the PFOS fish consumption advisory for other freshwater species, which included bass (WA DOH 2022).

All fish caught were identified down to the species level. Non-target species were released, and target species were evaluated based on size and overall physical condition. Fish that met study requirements were processed in the field following standard operating procedures (Sandvik 2023a). After length and weight measurements, fish were double-wrapped individually in PFAS-free aluminum foil (dull-side in) with an ID tag, sealed in zip-top low-density polyethylene (LDPE) bags, stored on ice in the field, and then frozen to -20°C at Ecology headquarters until further processing.

Fish Tissue Processing

Individual fish were processed into 3 – 5 fish composite samples following standard operating procedures (Sandvik 2023b). Fish within composites were of similar size, where the smallest and largest fish lengths were within 75% of each other (USEPA 2000). Composite requirements were met for 67 of the 88 samples. Of the remaining 21 samples, 8 were composites of two fish, and thirteen were processed as individuals. Most of the single or two-fish samples resulted from:

- The fish didn't fit into other size-based samples for that species from the same water body (e.g., one rainbow trout at Lake Nahwatzel was too big to group into the other composites) or,
- There was a limited number of fish collected for that species at the water body (e.g., field crews caught only two largemouth bass at Horsethief Lake).

Seven cutthroat trout from Lake Stevens were processed as individuals because of uncertainties surrounding in-field species identification. Some of the fish resembled cutthroat trout, and some more strongly resembled rainbow trout, which are stocked at Lake Stevens. Project staff submitted fin clips to WDFW's deoxyribonucleic acid (DNA) laboratory in Olympia, WA, for species confirmation. Due to analysis hold-time constraints and to avoid a compositing error, the samples were processed as individuals while awaiting DNA results from WDFW.

Fish were processed by partially thawing individuals to remove slime and descale scaled species (trout, kokanee, bass, bluegill, pumpkinseed, crappie, perch, and walleye), leaving the skin intact and to remove slime and skin from scaleless species (brown bullhead). Where appropriate, staff collected scales prior to this step to submit for aging with WDFW.

Fish were then rinsed with cool tap water, and one or both fillets were removed with a scalpel or fillet knife. Fillets were cubed during removal, weighed to the nearest gram, and ground twice into a homogenate paste using a KitchenAid food mixer with grinding attachments. Equal-weight aliquots of each twice-ground homogenate were combined into a composite, then homogenized a third time using the KitchenAid food grinder and mixed in a pre-cleaned stainless-steel bowl to a consistent texture and color. Final composite sample homogenates were placed into the appropriate labeled sample containers and stored at -20°C until shipment to the laboratory. Archived samples were also stored at -20°C at Ecology's headquarters. All equipment coming into contact with fish samples was cleaned and decontaminated following the standard operating procedures (Friese 2021).

Fish carcasses were set aside after fillet removal to determine the sex of the fish and remove aging structures to submit for aging by WDFW biologists. Staff also collected fin clips from 32 cutthroat trout collected from Lake Stevens and Lake Sammamish. Clips were taken from the caudal fin of each fish using clean scissors, placed on blotter paper to dry, and then submitted to WDFW for DNA analysis.

Surface Water

Field crews collected three surface water samples from each of the ten study lakes during September and October 2023. Surface water samples were collected at three offshore locations away from potential shoreline sources of PFAS. Sampling points were designated in the QAPP (Mathieu and Foster 2023) and are presented in Appendix A.

The contract laboratory provided pre-cleaned 500 mL high-density polyethylene (HDPE) bottles for PFAS analysis. At sampling locations, PFAS sample bottles were triple-rinsed with ambient lake water prior to sample collection. Field staff used a “clean hands/dirty hands” approach, collecting surface water samples away from the boat and the motor at 15 – 30 cm below the surface using a stainless-steel telescopic pole.

In addition to PFAS, surface water samples were collected for analysis of three ancillary water parameters: total organic carbon (TOC), dissolved organic carbon (DOC), and total suspended solids (TSS). Ancillary water samples were collected using the same methods as the PFAS water samples, with the following exceptions. TOC sample bottles were pre-acidified and, therefore, not triple-rinsed prior to filling, and DOC samples were filtered in the field. Water temperature, conductivity, pH, dissolved oxygen, and oxygen reduction potential were measured in situ at 15 – 30 cm below the surface using a calibrated multi-parameter YSI sonde at each sample location.

All water samples were labeled, stored in LDPE zip-top bags, and stored on ice for transport. PFAS sample bottles were double-bagged. Field quality control samples – replicates and blanks – were collected alongside 10% of the samples. Field staff used laboratory-provided PFAS-free blank water to collect blank samples under field conditions. Sample IDs, sample coordinates, and water quality readings were recorded with all other field activities in a field notebook.

Laboratory Analysis

All PFAS samples were analyzed by SGS AXYS Analytical Services Ltd. in Sidney, B.C. Forty PFAS were measured in surface water and fish tissue samples following the EPA’s *2nd Draft Method 1633, Analysis of Per- and Polyfluoroalkyl Substances (PFAS) in Aqueous, Solid, Biosolids, and Tissue Samples by LC-MS/MS* (USEPA 2024a). Samples were analyzed using the second draft of the U.S. Environmental Protection Agency (EPA) method as that was the draft available and the laboratory held accreditation for at the time. The contract laboratory reported the PFAS results as anions.

Manchester Environmental Laboratory (MEL) in Port Orchard, WA, analyzed DOC and TOC in surface water samples using method SM5310B. Analytical Resources, LLC performed TSS analyses in surface water samples following SM 2540 D-97.

Data Processing and Analysis

PFAS data are presented in this report as individual analyte concentrations and total (T-) or summed PFAS values. T-PFAS values are calculated as the sum of 40 analytes for individual samples. Only detected PFAS results that were unqualified or qualified J were included in totals.

Results qualified as U, UJ, and NJ were assigned a value of zero in calculated T-PFAS sums. T-PFAS values were not entered into Ecology's EIM (Environmental Information Management System).

Spearman rank correlations were used to evaluate relationships between fish tissue PFAS concentrations and fish size and age, surface water PFAS concentrations and ancillary variables, and fish tissue PFAS concentrations with surface water PFAS concentrations. Correlations were only run on datasets with at least 5 data points. Non-detects were set to 0 for correlations. The section "Correlations" explains how data were grouped for each subset of relationships. All correlations were conducted in R.

Data Quality

MEL's data validation chemist reviewed and conducted an independent EPA Stage 4 data validation on all PFAS results from the contract laboratory. The data validation was conducted on data packages using manual review and verification of reported results following technical specifications and quality assurance/quality control requirements stated in:

- EPA Method 1633 Final, Analysis of Per- and Polyfluoroalkyl Substances (PFAS) in Aqueous, Solid, Biosolids, and Tissue Samples by LC-MS/MS, January 2024 (USEPA 2024a).
- SGS-AXYS Method MLA-110 Analytical Procedure for the Analysis of Per- and Polyfluoroalkyl Substances (PFAS) in Aqueous Samples, Solids, Tissues, AFFF products, Blood/Serums and Solvent Extracts by LC-MS/MS Revision 02, Version 13, September 2023.
- Quality Assurance Project Plan: Per- and Polyfluoroalkyl Substances in Freshwater Fish of Ten Lakes, 2023 (Mathieu and Foster 2023).
- National Functional Guidelines for Organic Superfund Methods Data Review (USEPA 2020).
- MEL Data Validation of EPA Method 1633 PFAS Analytical Data, SOP 770046, April 2024.

Fish Tissue Samples

Fish tissue samples were shipped to the laboratory on December 12, 2023. The holding time stated in the QAPP was six months held frozen at -20°C. The samples were received by the laboratory at the proper temperature and analyzed within the project-specific holding time.

The PFAS fish tissue data were deemed usable for this study, with the following exceptions. The data validator rejected all Perfluoro-3,6-dioxaheptanoate (NFDHA) results, as the method states that samples should be extracted immediately if NFDHA is an important analyte. NFDHA was not an analyte of interest for this project, and this rejection does not affect the project's objectives. Four sample results for N-methyl perfluorooctanesulfonamidoethanol (NMeFOSE) were also rejected due to low recoveries of extracted internal standards. This analyte was not detected in any of the other samples analyzed.

Reporting Limits

Results were reported down to the laboratory's contract-required detection limits or sample-specific detection limits, whichever was greater. The laboratory met method detection limits (MDLs) and limits of quantitation (LOQs) specified in the final Method EPA 1633. Detected results greater than the MDL but below the LOQ were qualified "J" as estimated values. All nondetected results below the LOQ were qualified as "UJ," indicating that the result was not detected at an estimated value.

Method Blanks

All method blank results met the measurement quality objectives (MQOs) of the QAPP (no analytes detected at or above half the LOQ). The data validator censored sample results based on method blank raw data; action levels of five times the detection in the method blank raw data were calculated and applied to sample results. Approximately four percent (152 out of 3,520) of sample results were qualified as non-detects at an estimated value (UJ) based on method blank contamination.

Analytes affected included 6:2 fluorotelomer sulfonate (6:2 FTS), N-ethyl perfluorooctanesulfonamidoethanol (NEtFOSE), N-methyl perfluorooctanesulfonamide (NMeFOSA), perfluorononanoate (PFNA), PFOA, PFOS, perfluorotetradecanoate (PFTeDA), perfluorotridecanoate (PFTrDA), and perfluoroundecanoate (PFUnA). All censored sample results were low (less than 1.0 ng/g) except for NEtFOSE. NEtFOSE results that were changed to UJ due to method blank contamination ranged from 1.16 ng/g to 3.16 ng/g.

Laboratory Control Samples

Ongoing precision and recovery (OPR) and low-level OPR samples met the final EPA Method 1633 acceptance limits, with the exception of low recoveries of 7:3 perfluorodecanoate (7:3 FTCA) in the equipment blank samples. Those results were not detected and qualified "UJ."

Matrix Spikes and Matrix Spike Duplicates

Matrix spikes and matrix spike duplicates met QAPP MQOs in almost all samples. Three samples were qualified as estimates for low recoveries (PFOS in two samples) and high recoveries (NEtFOSE; this sample was already qualified as NJ).

Laboratory Duplicates

All laboratory duplicate samples met QAPP MQOs for relative percent difference between the source sample and duplicate.

Extracted Internal Standards

Approximately two percent (69 out of 3,520) of sample results were qualified as estimates based on low surrogate recoveries (extracted internal standards). This affected PFTeDA and PFTrDA results primarily and, to a lesser extent, NEtFOSE and NMeFOSE. Additionally, two sample results were qualified as estimates due to high surrogate recoveries; both were N-methyl perfluorooctanesulfonamidoacetic acid (NMeFOSAA) results, and one was already qualified as NJ.

Compound Identification

Approximately one percent of samples (26 out of 3,520) were qualified as NJ, indicating that the analyte was tentatively identified, and the result value is an estimate. Analytes qualified as NJ included perfluorododecanoate (PFDoA), PFTeDA, NMeFOSAA, PFTrDA, PFDS, perfluoroheptanoate (PFHpA), and NEtFOSE. Results were qualified as NJ if chromatographic peaks met all qualitative criteria except for ion abundance ratios or an interference was observed at the expected retention time (NEtFOSE only).

Equipment Blanks

Four equipment blanks were collected to assess potential contamination in the fish collection and homogenization processes. Laboratory-provided blank water was used for blank rinses of aluminum foil, stainless steel utensils, and the grinding equipment used for homogenization. All equipment blanks met the QAPP MQO of no analyte present at or above half the LOQ. The data validator did not qualify any sample results based on equipment blanks.

Water Samples

Surface water samples were collected from September 13 through October 20, 2023, and stored at -20° C until being shipped in three shipments to the laboratory on October 7, November 1, and November 6, 2023. The laboratory received the samples in the proper temperature range and met holding times for extraction and analysis.

Analytical

All water sample results were deemed usable for this study. Quality control tests met MQOs outlined in the QAPP and in the Final Method 1633. No data were qualified based on laboratory control samples, method blanks, matrix spikes, laboratory duplicates, or internal extraction standards.

Based on mass-ion ratio outliers, 11 PFAS results were qualified as "NJ" to denote that the analyte was tentatively identified and the value is an estimate. These results were not included in sample totals; all were low concentrations (<1.0 ng/L), and their exclusion is not expected to affect the final results.

Sample results reported below the LOQ but above the MDL were qualified "J" to indicate an estimated value, or "UJ" if undetected.

Two TSS batches were analyzed outside of method holding times due to instrument issues. Associated samples were qualified "J" as estimates.

Field

Three surface water field replicates, and three field blanks were collected throughout the field season. No target PFAS were found in the field blanks at or above half the reporting limit. Relative percent differences (RPDs) between the source sample and field replicate sample were less than 20% for all PFAS analytes in the paired samples.

Three field replicate samples were collected for TSS, TOC, and DOC. One out of the three replicates for TSS had results substantially different than the source sample (>100% RPD). The associated sample was qualified "J" as an estimate, and this result should be used with caution.

Results and Discussion

Fish Tissue

A total of 324 individual freshwater fish were collected in fall 2023 from ten lakes, and fillets were analyzed as 75 composite samples and 13 individuals for PFAS. Summaries of detected fish tissue PFAS concentrations for each lake can be found in the following sections and in Appendix C. Fish biological data are provided in Appendix D. The common names, scientific names, and abbreviations of fish species collected for this project are included in Appendix E.

One or more PFAS were detected in 83 out of 88 fillet tissue samples (94%). Detected T-PFAS concentrations across all sites ranged from 0.11 ng/g to 204 ng/g, with a median of 4.2 ng/g and a mean of 27 ng/g. Out of 40 PFAS analytes, only 14 were detected in fish tissue. PFAS detected in fish tissue samples included PFSAs with carbon chain lengths of 6 – 10, PFCAs with carbon chain lengths of 9 – 14, and three precursors (perfluorooctane sulfonamide (PFOSA), NMeFOSAA, and NEtFOSE).

American Lake and Spanaway Lake

Figure 2 displays PFAS concentrations in American Lake and Spanaway Lake fish tissue samples, and Table 2 presents summary statistics of PFOS and T-PFAS values.

PFAS were present in all species and samples tested from American Lake and Spanaway Lake. American Lake had the highest PFAS concentrations of the ten lakes sampled. T-PFAS concentrations were 122 – 204 ng/g in smallmouth bass, the highest recorded in Washington state freshwater fish fillet tissue to date. Largemouth bass collected from American Lake contained T-PFAS concentrations of 58 – 146 ng/g, yellow perch contained 34 – 51 ng/g, and an individual rainbow trout sample contained 8.4 ng/g T-PFAS.

Largemouth bass from Spanaway Lake had the highest PFAS amounts among species collected there, with T-PFAS concentrations of 64 and 99 ng/g. A single smallmouth bass sample contained 74 ng/g T-PFAS. Composites of bluegills, pumpkinseed, and yellow perch contained 36, 29, and 24 ng/g, respectively.

PFOS was the dominant compound in all samples analyzed. In American Lake, PFOS made up 92% – 99% of the total PFAS concentration, while PFDA made up 1% – 3% of the total, and PFDoA and PFUnA made up 0% – 2%. PFHxS, PFHpS, PFNS, PFTeDA, PFDS, and PFTrDA were present in some samples but made up less than 1% of the total.

In Spanaway Lake, PFOS made up 93% – 96% of the T-PFAS in bass and yellow perch and 76% – 79% in bluegill and pumpkinseed. PFDA was the second-most dominant in the bass and perch samples, at 3% – 4% of the total, while NEtFOSE was the second most dominant in the bluegill and pumpkinseed (13% – 21%), followed by PFDA (3% – 5%). All other detected PFAS made up 2% or less of the total: PFDS, PFNA, PFNS, PFTrDA, and PFDoA.

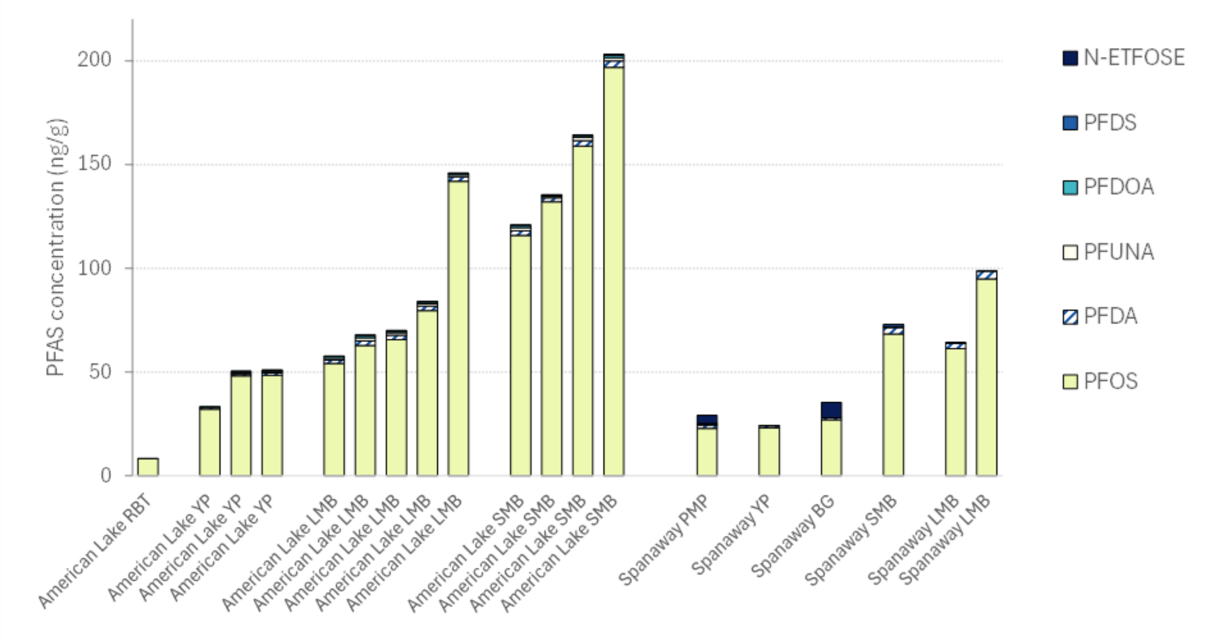

Figure 2. Detected PFAS concentrations in American Lake and Spanaway Lake fish.
RBT = rainbow trout; YP = yellow perch; LMB = largemouth bass; SMB = smallmouth bass; PMP = pumpkinseed; BG = bluegill; PFAS acronyms are presented in Appendix B. Only PFAS with detections greater than 1.0 ng/g in at least one sample are included in the figure.

Table 2. PFOS and T-PFAS concentration summaries of American Lake and Spanaway Lake fish.

Lake	Species	Number of Composites	PFOS Mean (ng/g)	PFOS Minimum–Maximum (ng/g)	T-PFAS Mean (ng/g)	T-PFAS Minimum–Maximum (ng/g)
American	largemouth bass	5	81	54–142	85	58–146
American	rainbow trout	1*	—	8.3	—	8.4
American	smallmouth bass	4	151	116–197	157	122–204
American	yellow perch	3	43	32–49	34–51	45
Spanaway	bluegill	1	—	27	—	36
Spanaway	largemouth bass	2**	78	61–95	82	64–99
Spanaway	pumpkinseed	1	—	23	—	29
Spanaway	smallmouth bass	1*	—	68	—	74
Spanaway	yellow perch	1	—	23	—	24

*individual fish analyzed; **one composite and one individual fish analyzed.

Lake Sammamish and Lake Stevens

Figure 3 displays PFAS concentrations in Lake Sammamish and Lake Stevens fish tissue samples, and Table 3 presents summary statistics of the PFOS and T-PFAS values.

All fish samples analyzed from Sammamish and Stevens contained PFAS. T-PFAS concentrations in Lake Sammamish cutthroat trout were relatively low (2.8 – 4.1 ng/g), with an average of 3.6 ng/g. Other species had previously been tested from the lake, and PFOS levels were high enough to warrant fish consumption advisories for those species (WA DOH 2022).

T-PFAS concentrations in Lake Stevens fish were highest in smallmouth bass (92 – 95 ng/g), followed by cutthroat trout (57 – 60 ng/g), largemouth bass (21 – 35 ng/g), and brown bullhead (6.2 – 14 ng/g). One kokanee was analyzed as an individual and had a T-PFAS concentration of 6.5 ng/g.

PFOS was the dominant compound across all samples, averaging 86% of the total PFAS concentration in Lake Sammamish samples. In Lake Sammamish cutthroat trout, PFDA made up 7% of the T-PFAS, and PFTeDA, PFTrDA, and PFDoA each contributed 5% or less.

In Lake Stevens fish, PFOS made up 70% – 90% of T-PFAS in cutthroat trout, kokanee, and bass and slightly less in brown bullhead (53% – 65%). PFDA was the second most dominant compound in all species other than brown bullhead (averaging 10%), followed by PFDoA and PFUnA (3%), and PFTrDA, PFDS, PFTeDA, and PFNA (2% or less). Two cutthroat trout samples contained trace amounts of NMeFOSAA, and one smallmouth bass sample contained trace amounts of PFOSA, both precursors contributing less than 0.01% of the total.

The Lake Stevens brown bullhead samples contained greater contributions of PFDoA (8% – 13%) and PFUnA (0% – 10%) and had contributions of PFDA, PFTeDA, and PFTrDA of around 6% – 8%. PFDS was present in the brown bullhead at 2% of the total in all samples.

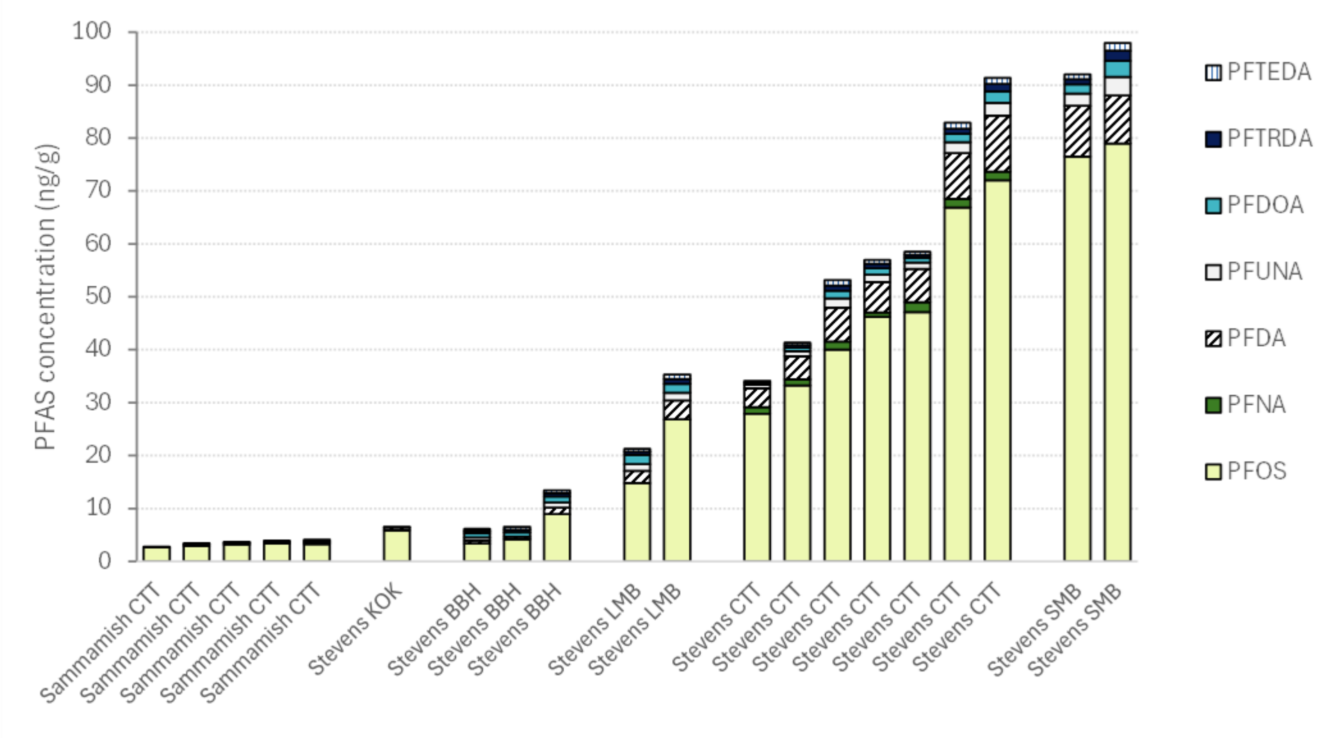

Figure 3. Detected PFAS concentrations in Lake Sammamish and Lake Stevens fish.

CTT = cutthroat trout; KOK = kokanee; LMB = largemouth bass; SMB = smallmouth bass; PFAS acronyms are presented in Appendix B. Only PFAS with detections greater than 1.0 ng/g in at least one sample are included in the figure.

Table 3. PFOS and T-PFAS concentration summaries of Lake Sammamish and Lake Stevens fish.

Lake	Species	Number of Composites	PFOS Mean (ng/g)	PFOS Minimum–Maximum (ng/g)	T-PFAS Mean (ng/g)	T-PFAS Minimum–Maximum (ng/g)
Sammamish	cutthroat trout	5	3.0	2.6–3.4	3.6	2.8–4.1
Stevens	brown bullhead	3	5.5	3.3–8.9	8.9	6.2–14
Stevens	kokanee	1*	—	5.9	—	6.5
Stevens	largemouth bass	2	21	15–27	28	21–35
Stevens	cutthroat trout	7*	48	28–72	60	34–92
Stevens	smallmouth bass	2**	78	76–79	95	92–99

*Individual fish analyzed.
**One composite and one individual fish were analyzed.

PBT Monitoring Lakes

Figures 4 and 5 display PFAS concentrations in the fish tissue samples collected from the PBT Monitoring lakes and Table 4 presents summary statistics of PFOS and T-PFAS concentrations.

All samples collected from Goodwin, Horsethief, Loomis, McIntosh, and Nahwatzel contained PFAS. In Leland Lake, PFAS was detected in 64% of samples.

Of the six PBT Monitoring sites, Lake Goodwin fish contained the highest T-PFAS concentrations. One largemouth bass composite from Lake Goodwin had a T-PFAS concentration of 19 ng/g. Smallmouth bass samples from the same lake were similar (14 – 15 ng/g), and yellow perch contained the lowest T-PFAS concentrations from the lake (3 – 5 ng/g).

Samples of black crappie and rainbow trout collected from Leland Lake contained T-PFAS concentrations of up to 7.7 and 10 ng/g, respectively. This was due to unusually high concentrations of NEtFOSE measured in the samples. Other species collected from Leland Lake (largemouth bass and bluegill) did not contain NEtFOSE, and their T-PFAS concentrations were lower than 1 ng/g. NEtFOSE was not detected in the surface water samples, and its source in the fish tissue is unknown. Samples of various species collected from the other PBT Monitoring lakes – Horsethief, Loomis, McIntosh, and Nahwatzel – all had T-PFAS concentrations of less than 5 ng/g.

The dominant PFAS across most samples was PFOS. Exceptions to this were bluegill from Leland Lake, where only PFTrDA was detected, and black crappie, where NEtFOSE was the dominant compound (92% – 96%). In Lake Nahwatzel largemouth bass, PFTrDA was the dominant compound (30% – 54%), followed by PFDoA, PFTeDA, PFUnA, and PFDA. PFOS was not detected in any of the Nahwatzel bass. In two of the rainbow trout samples from Nahwatzel, PFOS made up 79% – 87% of the total, with PFTrDA making up the rest, while the other two samples did not contain PFOS, only PFTrDA and PFTeDA.

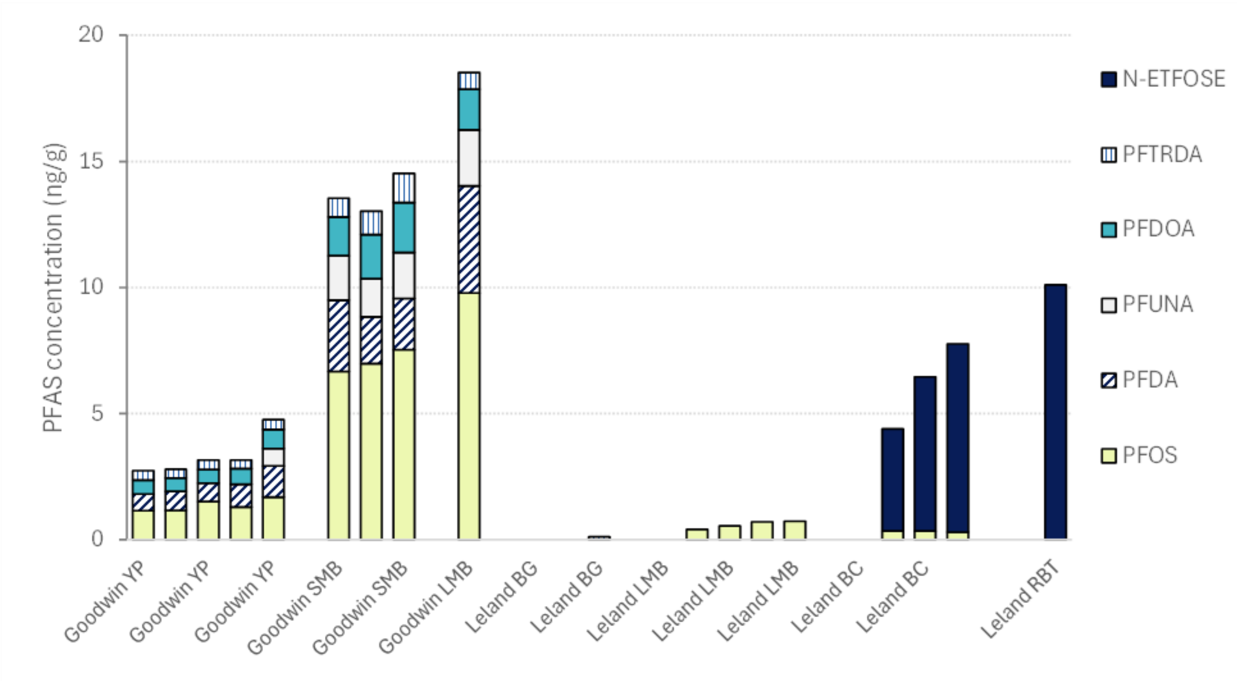

Figure 4. Detected PFAS concentrations in Lake Goodwin and Leland Lake.
YP = yellow perch; SMB = smallmouth bass; LMB = largemouth bass; BG = bluegill; BC = black crappie; RBT = rainbow trout; PFAS acronyms are presented in Appendix B. Only PFAS with detections greater than 1.0 ng/g in at least one sample are included in the figure.

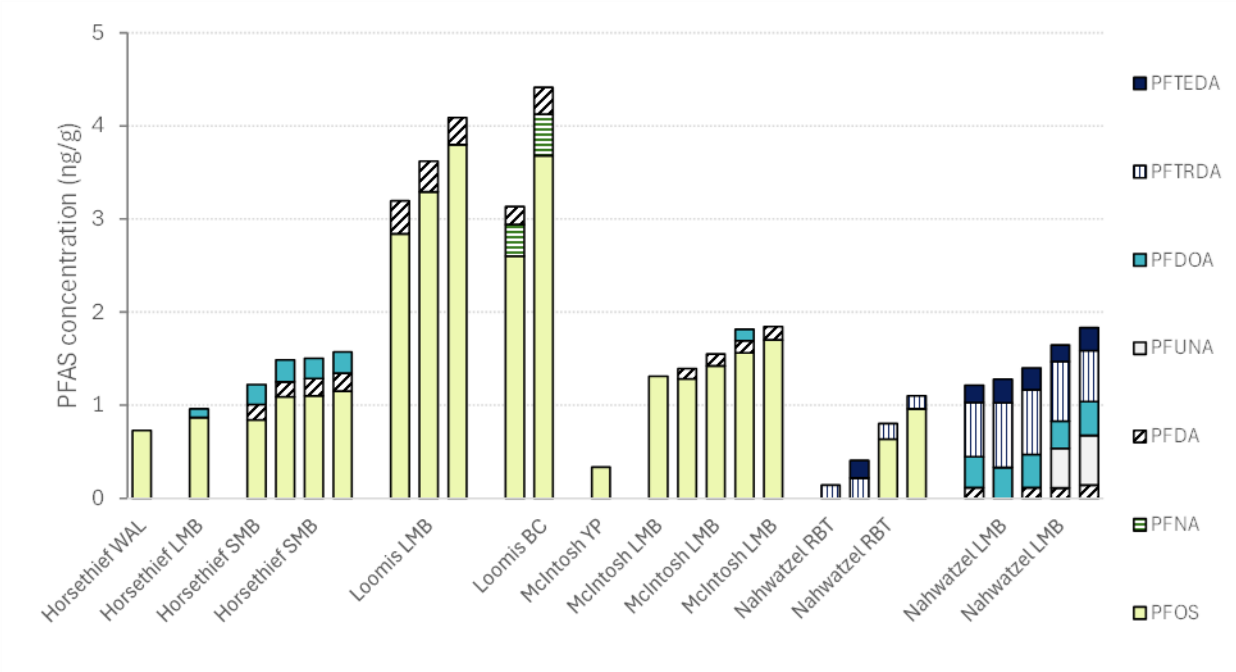

Figure 5. Detected PFAS concentrations in Horsethief, Loomis, McIntosh, and Nahwatzel Lakes.

WAL = walleye; SMB = smallmouth bass; LMB = largemouth bass; BC = black crappie; YP = yellow perch; RBT = rainbow trout; PFAS acronyms are presented in Appendix B.

Table 4. PFOS and T-PFAS concentration summaries of PBT Monitoring lakes fish.

Lake	Species	Number of Composites	PFOS Mean (ng/g)	PFOS Minimum–Maximum (ng/g)	T-PFAS Mean (ng/g)	T-PFAS Minimum–Maximum (ng/g)
Goodwin	largemouth bass	1	—	9.8	—	19
Goodwin	smallmouth bass	3	7.1	6.7–7.5	14	14–15
Goodwin	yellow perch	5	1.4	1.2–1.7	3.7	3.1–5.2
Horsethief	largemouth bass	1	—	0.9	—	1.0
Horsethief	smallmouth bass	4	1.0	0.8–1.1	1.4	1.2–1.6
Horsethief	walleye	1	—	0.7	—	0.7
Leland	black crappie	4	—	ND–0.3	—	ND–7.8
Leland	bluegill	3	—	ND	—	ND–0.1
Leland	largemouth bass	5	—	ND–0.7	—	ND–0.7
Leland	rainbow trout	2	—	ND	—	ND–10
Loomis	black crappie	2	3.1	2.6–3.7	3.8	3.1–4.4
Loomis	largemouth bass	3	3.3	2.8–3.8	3.6	3.2–4.1
McIntosh	largemouth bass	5	1.5	1.3–1.7	1.6	1.3–1.8
McIntosh	yellow perch	1	—	0.3	—	0.3
Nahwatzel	largemouth bass	5	—	ND	1.5	1.2–1.8
Nahwatzel	rainbow trout	4*	—	ND–1.0	0.6	0.1–1.1

ND = non-detect (analyte was not detected in sample).
*One sample was analyzed as an individual, and 3 samples were analyzed as composites.

Surface Water

A total of 30 surface water samples were collected at the same time as fish collections from the 10 lakes in fall 2023 for analysis of 40 PFAS analytes. Summaries of detected PFAS from the water bodies are presented in the following sections. Appendix B presents the full list of compounds analyzed.

Concentrations

Figure 6 presents average surface water T-PFAS concentrations for the study locations and their compound profiles. All lakes but Leland and Horsethief had surface waters with detectable levels of at least one PFAS. Average T-PFAS concentrations in lakes with detections ranged from 0.4 ng/L to 39.6 ng/L, with a median of 12.4 ng/L.

The highest T-PFAS concentrations were found in American Lake at 39.6 ng/L, followed by Spanaway (28.6 ng/L). Stevens and Goodwin – both of which have a mix of urban, suburban, and forested land surrounding them – contained average T-PFAS concentrations of 15 ng/L. The rest of the lakes had average T-PFAS concentrations of less than 10 ng/L: Sammamish (9.5 ng/L), Loomis (5.2 ng/L), McIntosh (0.7 ng/L), and Nahwatzel (0.4 ng/L). Only one compound – PFHpA – was detected in the surface waters of Lake Nahwatzel and only in one sample out of three.

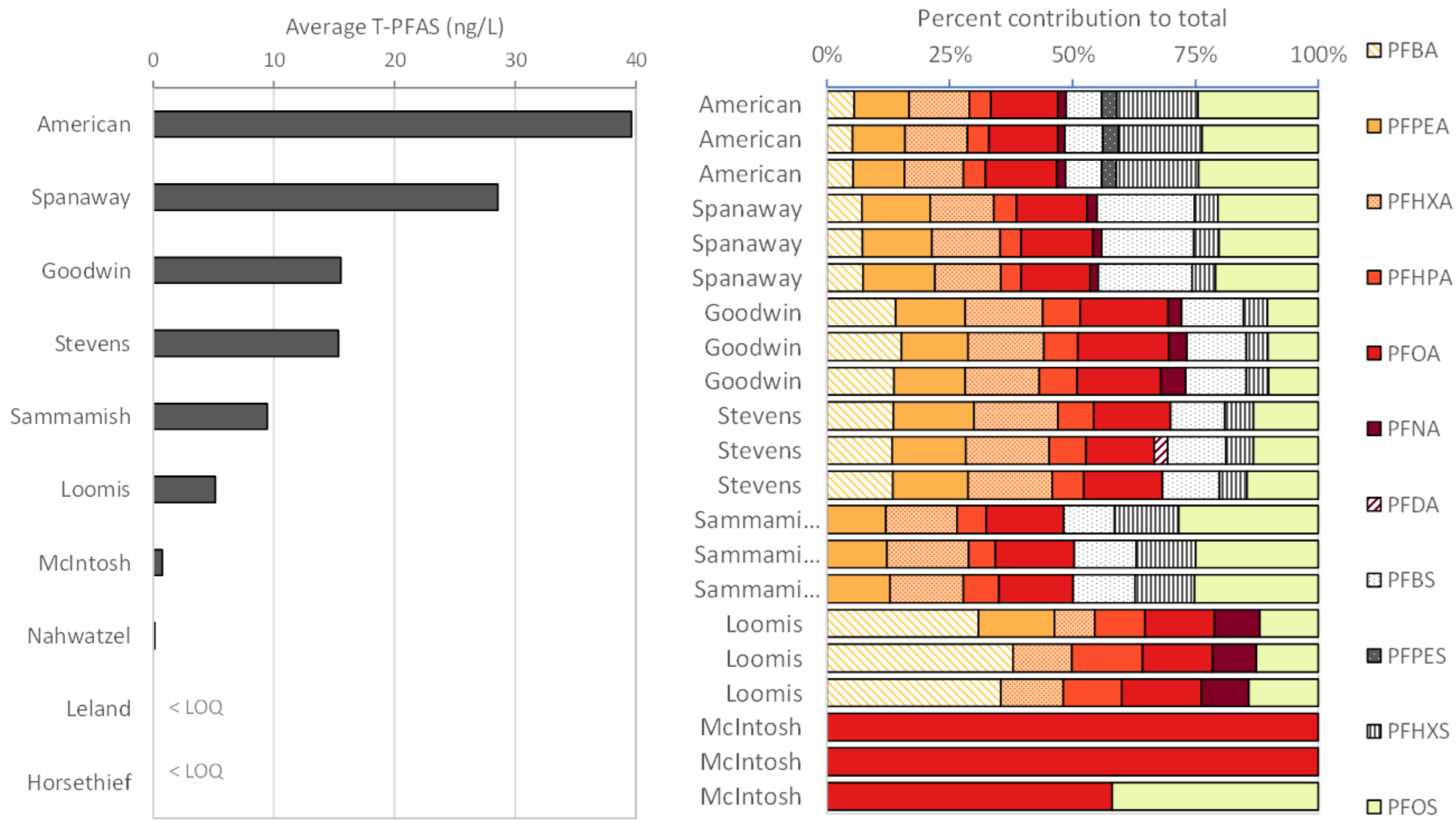

Figure 6. Average surface water total (T-) PFAS concentrations by lake (left) and detected compound profiles of individual samples (right).

Only lakes with detections in all three samples are shown on the right. PFAS acronyms are presented in Appendix B.

Out of 40 PFAS analyzed, only perfluoroalkyl acids with carbon chain lengths of 4 – 10 were detected in the surface water samples. Appendix B presents PFAS that were analyzed for but not detected. PFOA was found at the highest frequency in 70% of samples. PFOS, PFHpA, and perfluorohexanoate (PFHxA) were also frequently found in 60% – 63% of samples, and perfluoropentanoate (PFPeA), PFBA, perfluorobutane sulfonate (PFBS), and PFHxS were found in 50% – 53% of samples. PFNA was detected less frequently in 40% of samples. Perfluoropentane sulfonate (PFPeS) was detected only in the three samples from American Lake (10%), and perfluorodecanoate (PFDA) was detected in one sample from Lake Stevens.

Compound Profiles

On average, the PFAS that made up the highest contributions to T-PFAS (greater than 10%) in surface water included PFOA, PFOS, PFHxA, PFBA, and PFPeA. In the more urbanized lakes, PFBS contributed 12% on average to total concentrations and was undetected in the more remote lakes. PFHxS made up less than 10% on average across the samples but was more dominant in American Lake and Lake Sammamish. PFHxS and its precursors can be indicative of legacy aqueous film-forming foam (AFFF) applications (Houtz et al. 2013).

PFHpA was also present in contributions of less than 10% in most samples, except for larger contributions found in Loomis Lake waters. PFNA was present in about half of the lakes but in small amounts relative to other compounds (average of 4%). PFPeS and PFDA only contributed 3% of the total in the few samples in which they were detected.

In-lake Variability

All three surface water samples collected within a site were comparable to each other in both PFAS concentration and composition. Figure 7 shows the small variability across in-lake samples. For all lakes with T-PFAS concentrations greater than 1 ng/L, the relative standard deviation (RSD) across within-lake samples was between 1% and 10%. This supports using an average T-PFAS concentration and average compound contributions in surface waters for each lake, which are used in the following sections.

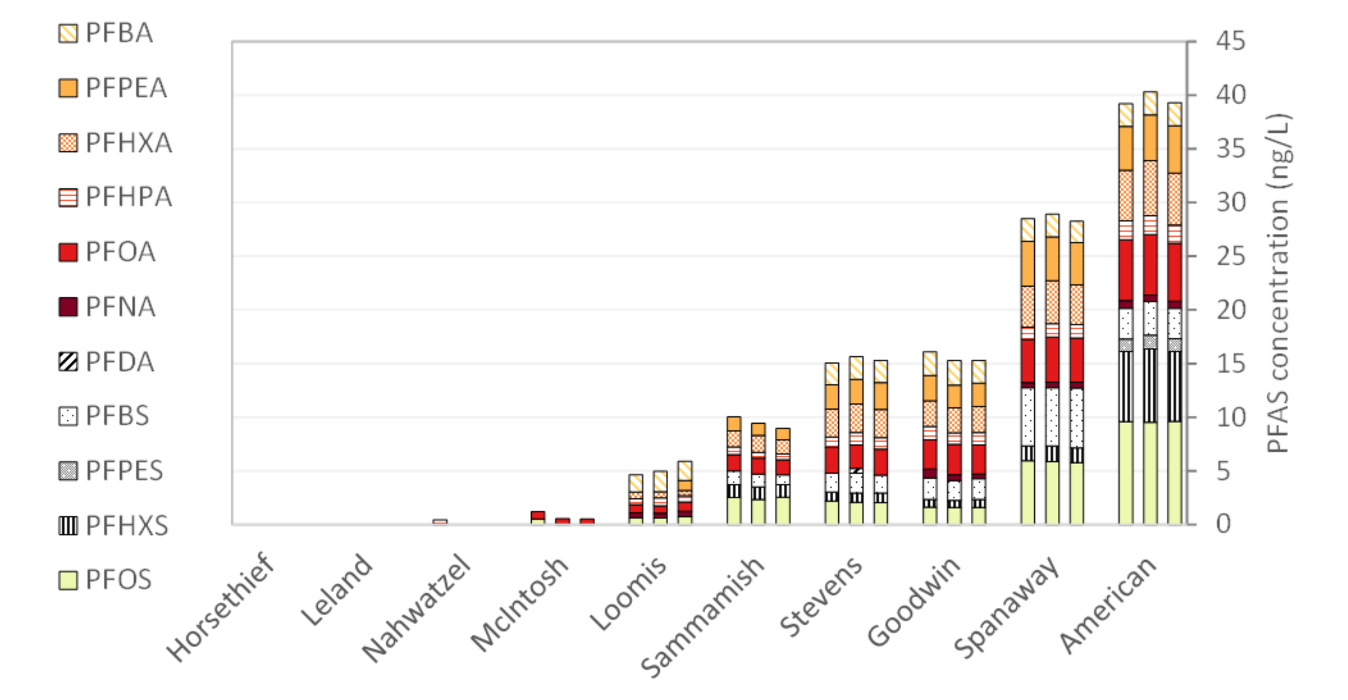

Figure 7. Detected PFAS concentrations for all surface water samples collected.

PFAS acronyms are presented in Appendix B.

Relationships between Fish Tissue and Water

Compound Profiles

PFAS composition profiles of the fish samples were dissimilar to those of paired surface water samples (Figures 8 and 9). Surface water PFAS profiles included a wide variety of PFAS and generally consisted of PFCAs with carbon chain lengths of 4 – 8 and PFSAs with 4, 6, and 8 carbons. In comparison, profiles of fish tissue were primarily made up of PFOS and PFCAs with 9 – 13 carbons. The exception to this pattern was Nahwatzel and Leland Lakes, where fish tissue concentrations were low and long-chain PFCAs (9 – 13 carbons) and non-PFAA precursors made up the majority of the total. This difference in the PFAS present in water versus which PFAS accumulate in fish tissue has been well documented in other studies (Goodrow et al. 2020); however, PFOS was commonly detected in both matrices in substantial amounts.

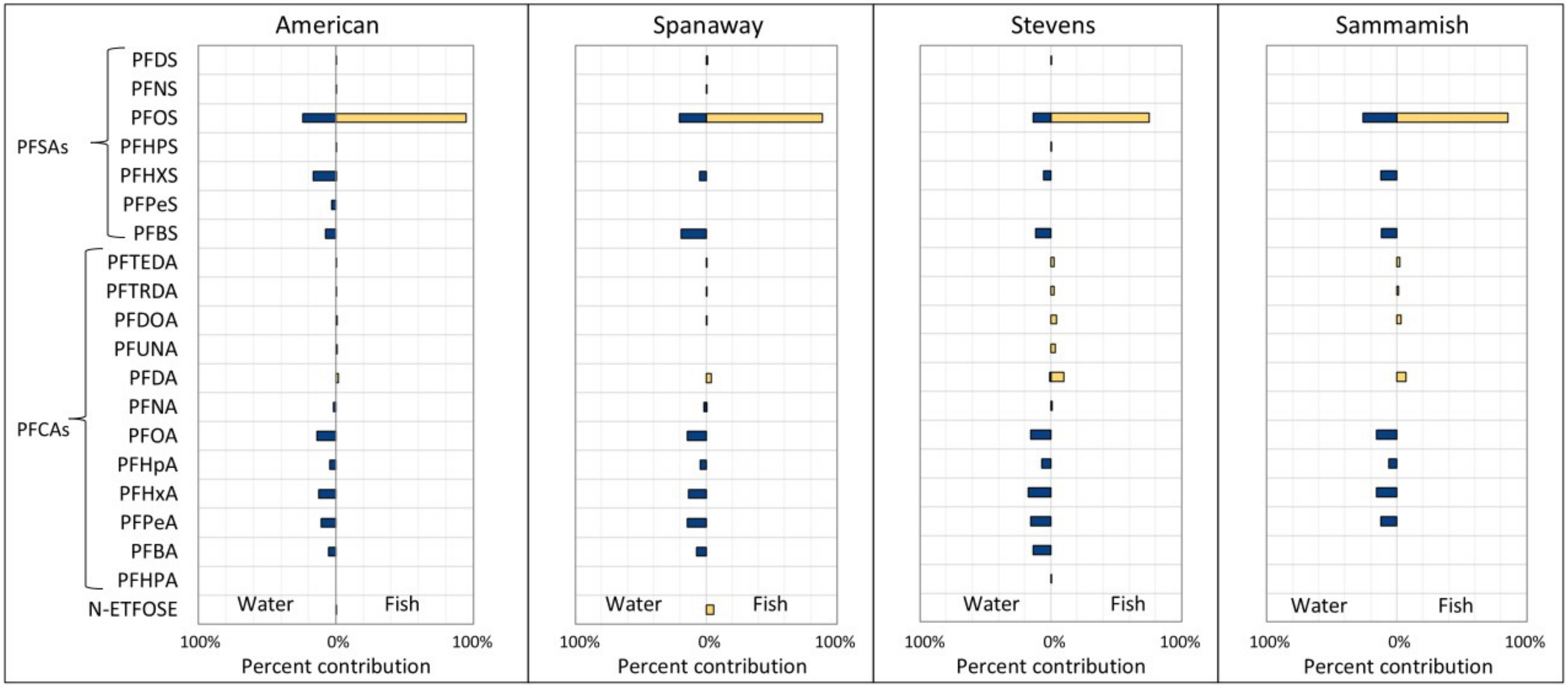

Figure 8. Average percent contribution profiles of PFAS in water (dark blue; left panels) and fish fillet tissue (light orange; right panels) of samples collected from American, Spanaway, Stevens, and Sammamish Lakes.

PFSA = perfluoroalkane sulfonates; PFCA = perfluoroalkyl carboxylates. PFAS acronyms are presented in Appendix B.

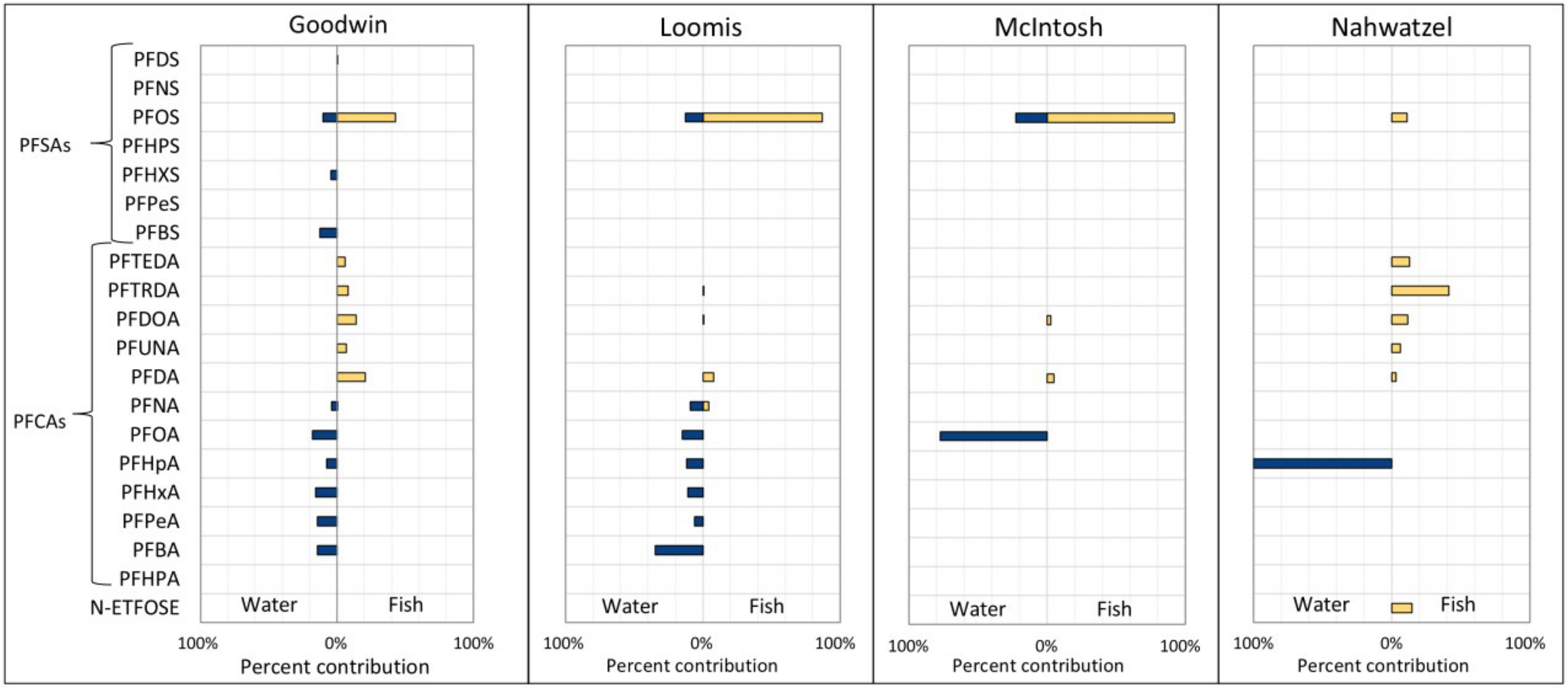

Figure 9. Average percent contribution profiles of PFAS in water (dark blue; left panels) and fish fillet tissue (light orange; right panels) of samples collected from Goodwin, Loomis, McIntosh, and Nahwatzel Lakes.

PFSA = perfluoroalkane sulfonates; PFCA = perfluoroalkyl carboxylates. PFAS acronyms are presented in Appendix B.

Fish PFAS and Ancillary Data Correlations

Our sample sizes for examining relationships between fish PFAS concentrations and fish size or age were limited. To control for differences attributed to water body-specific PFAS sources and species differences, only samples of the same species and site were used in a correlation.

PFOS and T-PFAS concentrations in largemouth bass collected from American Lake showed a significant positive correlation with fish length ($r_s(3) = .9$, $p = .035$ and $r_s(3) = .9$, $p = .035$, respectively) and fish weight ($r_s(3) = .9$, $p = .035$ and $r_s(3) = .9$, $p = .035$, respectively). No relationships between fish PFAS concentrations and size were observed for any other lake or species. Appendix F (Table F-1) lists the Spearman rank correlation coefficients for fillet PFOS and T-PFAS concentrations and ancillary data.

This lack of relationship between fish tissue PFAS concentrations and fish size has been demonstrated in other freshwater fish collected from North America (Gewurtz et al. 2014; Fair et al. 2019; Pickard et al. 2024). The positive correlation between PFAS concentrations and fish size among American Lake bass was unexpected. Additional sampling of bass with larger sample sizes would be needed to determine whether this relationship occurs in other water bodies.

Water PFAS and Ancillary Data

Correlations were run on average surface water PFAS concentrations at each lake with detections of at least one PFAS (n = 8) and paired average site ancillary water variables to examine associations among water parameters. No PFAS analytes detected in the surface waters were correlated with TSS, TOC, or DOC concentrations. In-situ measurements of pH, conductivity, temperature, and dissolved oxygen also showed no relationships with water PFAS concentrations. Correlation coefficients of surface water relationships are included in Appendix F, Table F-2.

Other studies have been mixed on associations between water PFAS concentrations and ancillary variables. Positive relationships have been demonstrated between PFAS and TSS or DOC in rivers and streams (Kali et al. 2025; Nguyen et al. 2017; Breitmeyer et al. 2023), but ancillary parameters were not found to affect water PFAS concentrations in other surface waters (Zhang et al. 2023; Ferreira de Silva et al. 2022). In many studies, location variables like population density and proximity to sources have the largest influence on water PFAS concentrations (Ferreira de Silva et al. 2022; Breitmeyer et al. 2023).

Water and Fish PFAS Concentrations

Relationships between fish and surface water PFAS were examined by correlations using average site fillet concentrations grouped by similar species and paired average site surface water concentrations. Figure 10 displays the data graphically.

Largemouth bass fillet PFOS and T-PFAS concentrations were highly correlated with average surface water PFOS and T-PFAS concentrations ($r_s(7) = .98$, $p < .001$ and $r_s(7) = .96$, $p < .001$, respectively). As surface water concentrations increased, so did fillet PFAS concentrations. The same positive correlation was observed for smallmouth bass fillet and surface water PFOS and T-PFAS concentrations ($r_s(4) = .93$, $p = .007$ and $r_s(4) = .81$, $p = .047$, respectively).

Fillet PFOS concentrations of small sunfish species grouped together (black crappie, bluegill, and pumpkinseed) also showed a positive correlation with surface water PFOS concentrations ($r_s(3) = .95$, $p = .013$). T-PFAS concentrations in the sunfish group showed a general increase with surface water T-PFAS, but the relationship was not significant ($r_s(3) = .79$, $p = .104$). The sample size for this species group was limited ($n = 5$).

Freshwater trout and salmon species – rainbow trout, cutthroat trout, and kokanee – did not show significant relationships between fish tissue and water for PFOS ($r_s(4) = .65$, $p = .156$) or T-PFAS ($r_s(4) = .72$, $p = .098$). Most of the trout and kokanee samples had relatively low PFAS concentrations (site averages were 1.5 – 8.4 ng/g T-PFAS), regardless of water PFAS concentrations.

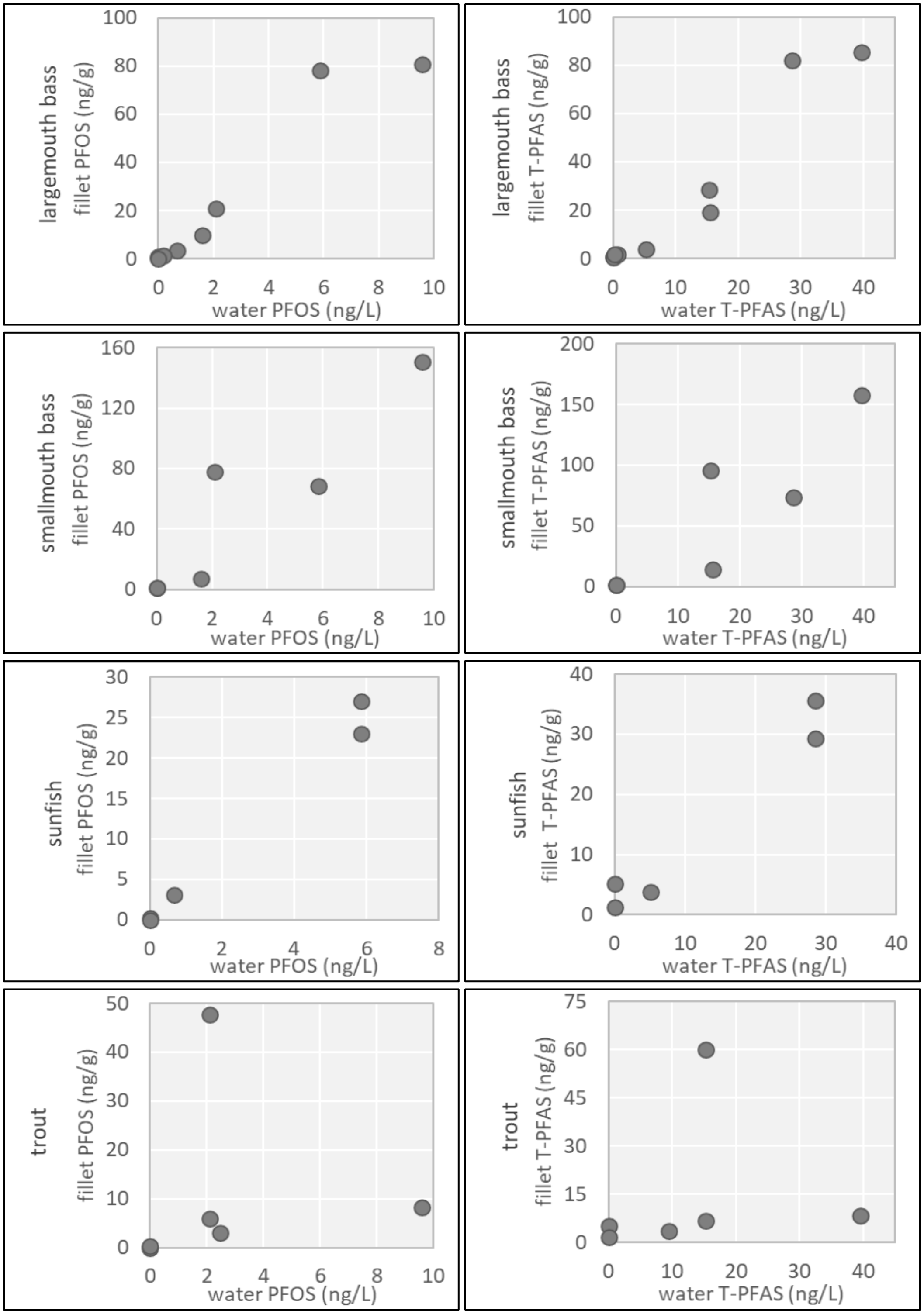

Figure 10. Average fillet tissue PFAS concentrations (ng/g) plotted against paired surface water PFAS concentrations (ng/L).

Left panels = PFOS; Right panels = T-PFAS.

The positive correlations between surface water and fish tissue PFAS concentrations suggest that location was a key factor affecting fish PFAS levels among the study lakes. Goodrow et al. (2020) also found significant and strong correlations between surface water and fish tissue PFAS concentrations collected from rivers and lakes in New Jersey, where the highest average fish PFOS concentrations were found in areas of direct sources. In an AFFF-impacted watershed within Massachusetts, fish tissue PFAS concentrations were also correlated with surface water PFAS concentrations, with levels in both matrices decreasing downgradient from the source zone (Pickard et al. 2024).

While proximity to point sources is often the key factor driving fish PFAS levels (Macorps et al. 2022; Pickard et al. 2024; Semerad et al. 2022), site-specific factors influencing PFAS concentrations in freshwater fish include trophic position, species differences, and diet (Semerad et al. 2022), though trophic position influence is inconsistent in the literature (Pickard et al. 2024). Neither trophic position nor diet were directly examined in this study, though species differences appeared to be important at some sites.

A relationship between water and fish PFAS concentrations was not observed for trout/salmon samples in this study. Most trout samples were low in PFAS even when water concentrations were high, suggesting a potential difference in how these species accumulate PFAS compared to the bass and smaller sunfish. However, the high concentrations of PFAS in cutthroat trout from Lake Stevens indicate that there is still potential for substantial accumulation in trout species. Additionally, lake trout in the Great Lakes have been found to contain more than twice as much PFOS as other freshwater species, including bass (Stahl et al. 2014). With rainbow trout, cutthroat trout, and kokanee being popular target angling species for eating, more testing of these species throughout the state should be included in future monitoring efforts.

Comparison to Other Findings

The following sections compare PFOS concentrations observed in this study to previously reported freshwater fish fillet data. PFOS is used instead of T-PFAS because of differing PFAS analytical suites among studies and is justified by the dominance of PFOS in fish tissue in all studies compared.

Comparison to Washington studies

Figure 11 displays a cumulative frequency distribution of all fillet PFOS concentrations from previous Ecology studies in Washington freshwater fish, with all species combined. PFOS concentrations in all species collected from the PBT Monitoring lakes and in cutthroat trout from Lake Sammamish fell within the lower range of previously reported PFOS levels in Washington state freshwater fish. Most of the samples collected from American, Spanaway, and Stevens were in the higher range of historical Washington fillet data. American Lake had the highest PFOS concentrations reported to date in Ecology studies of Washington state freshwater fish fillet tissues.

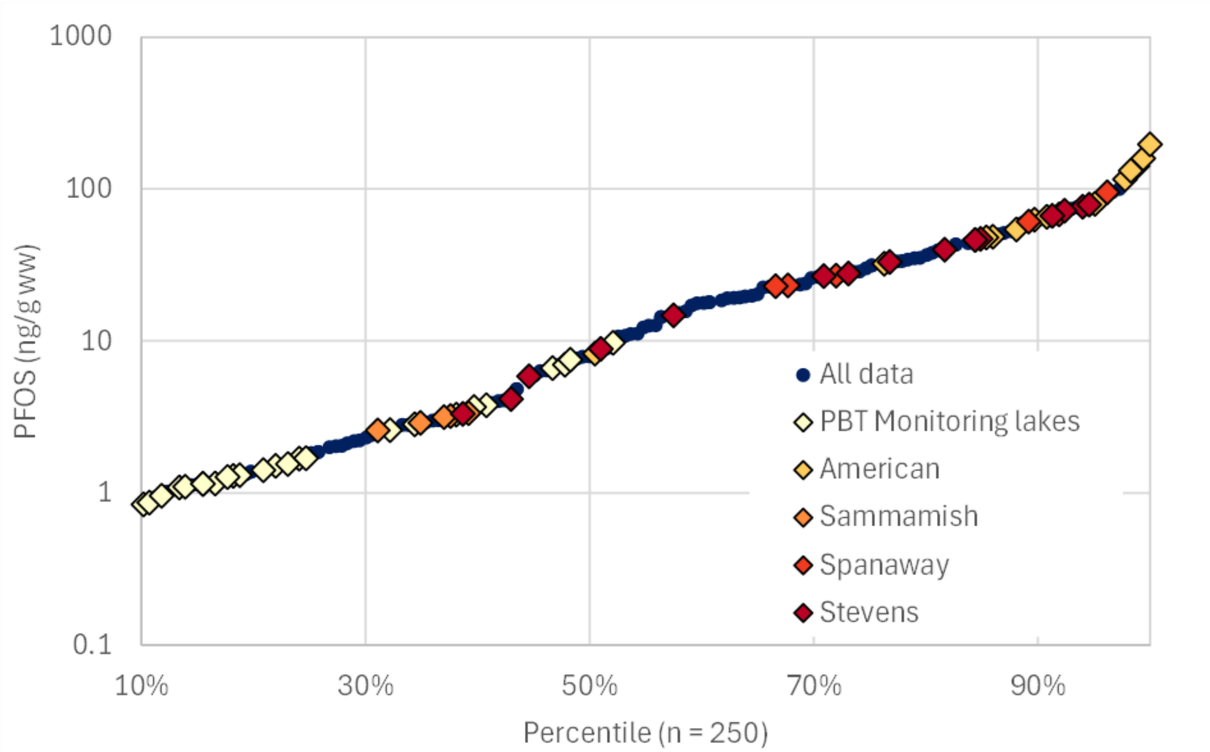

Figure 11. Cumulative frequency distribution of PFOS concentrations in freshwater fish fillet tissue collected in Washington State, 2008 – 2024.

"All data" in the graph refers to data from previous Ecology studies of PFOS in freshwater fish, accessed from Ecology's EIM database.

When compared on a species-specific basis, largemouth and smallmouth bass PFOS concentrations in the PBT Monitoring lakes were similar to concentrations in bass fillets collected from non-urban Washington water bodies in previous studies (Figure 12). Lake Stevens bass had comparable PFOS concentrations to what has been previously found in urban Washington lakes. In contrast, Spanaway and American bass PFOS levels were elevated compared to previous urban lake bass fillet concentrations.

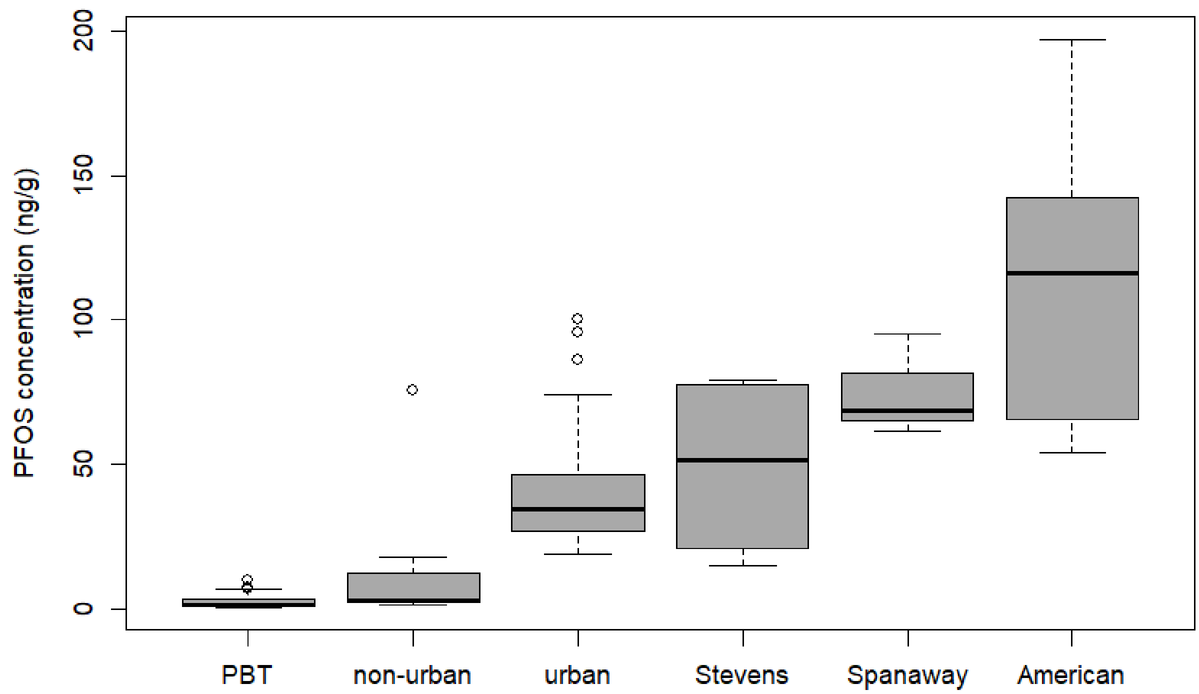

Figure 12. Boxplot of PFOS concentrations (ng/g) in largemouth bass and smallmouth bass fillet tissue reported from historical Washington state data ("non-urban" and "urban" lakes) and this study (PBT, Stevens, Spanaway, and American Lakes).

Figures 13 and 14 show PFOS concentration boxplots of yellow perch and trout/salmon species fillet tissue. For yellow perch samples, the PBT Monitoring lakes were well below historical urban fish PFOS levels, and American Lake perch was well above the urban lakes range.

PFOS concentrations in trout/salmon species collected from the PBT Monitoring lakes, Lake Sammamish, and American Lake were on the lower end of the historical data range of fillet PFOS levels. Lake Stevens cutthroat trout contained PFOS concentrations at the high end of the urban historical fillet data, with maximum values exceeding any previously reported trout species in Washington. It is unclear why the cutthroat trout in Lake Stevens were high compared to other samples in Washington state.

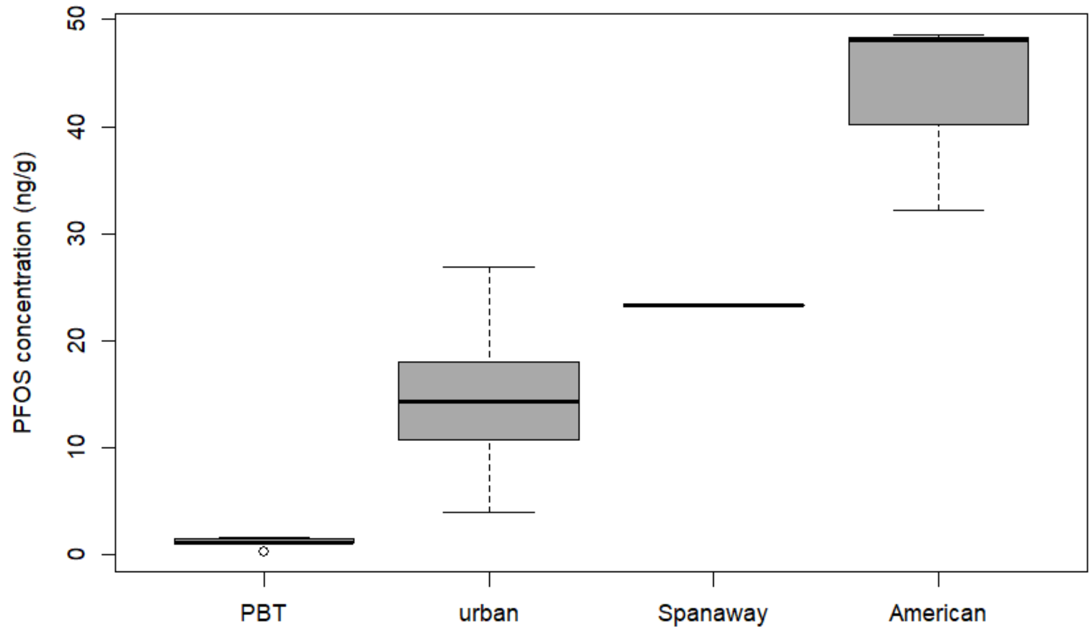

Figure 13. Boxplot of PFOS concentrations (ng/g) in yellow perch fillet tissue reported from historical Washington state data ("urban") and this study (PBT, Spanaway, and American Lakes).

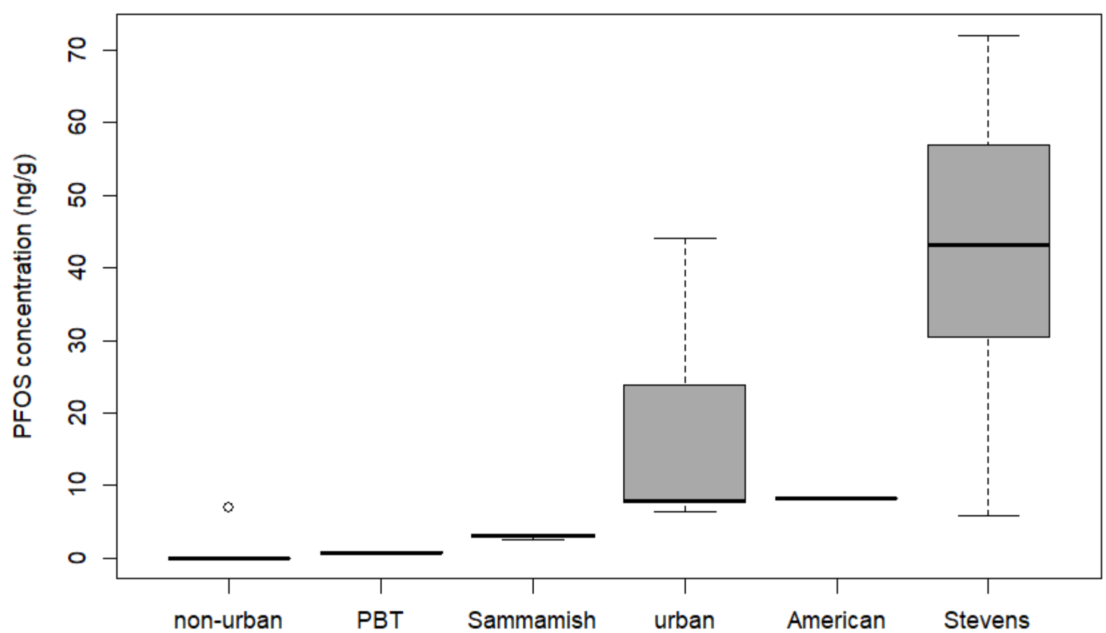

Figure 14. Boxplot of PFOS concentrations (ng/g) in trout and salmon species (rainbow trout, cutthroat trout, and kokanee) fillet tissue reported from historical Washington state data ("non-urban" and "urban" lakes) and this study (PBT, Sammamish, American, and Stevens Lakes).

Comparison to United States Freshwater Lakes

Data from this study fall within the range of PFOS concentrations observed in fillet tissue from multiple species of freshwater fish collected from lakes across the United States in 2022 (USEPA 2024b; Figure 15). The majority (87%) of samples collected across the U.S. contained PFOS concentrations below 10 ng/g (USEPA 2024b). Of the ten Washington lakes studied here, Horsethief, Leland, Loomis, McIntosh, Nahwatzel, and Sammamish fillet tissues all had concentrations of less than 10 ng/g and are comparable to the majority of freshwater fish surveyed in the U.S. by EPA.

Fish collected from American, Spanaway, and Stevens, as well as several samples from Goodwin, contained fillet PFOS concentrations above 10 ng/g and in the upper range of the U.S. fillet PFOS levels. Fourteen samples of bass and rainbow trout collected from American, Spanaway, and Stevens were in the 99th percentile of the U.S. freshwater fish fillet PFOS concentration dataset. PFOS concentrations in three American Lake bass samples (142 – 197 ng/g) were below only one sample in the U.S. dataset – the maximum PFOS concentration found – collected from a pond in Georgia (526 ng/g).

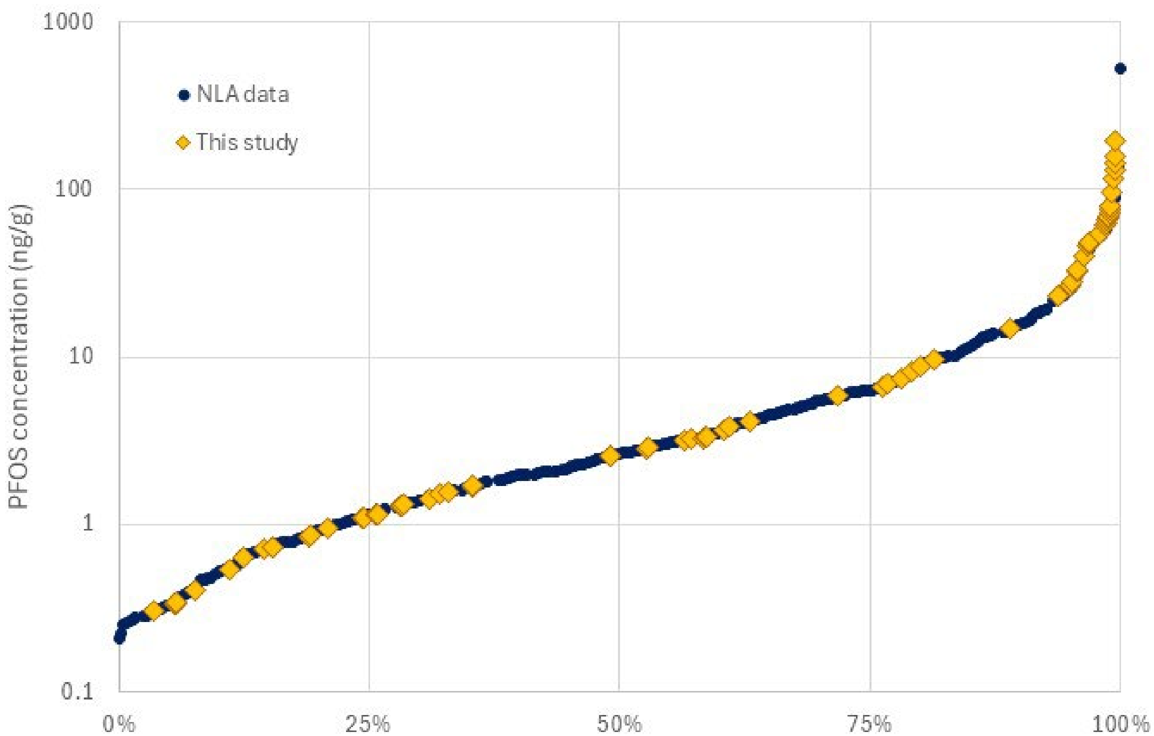

Figure 15. Cumulative frequency distribution of PFOS concentrations in freshwater fish fillet tissue collected by the EPA's 2022 National Lakes Assessment (NLA).
"NLA data" in the graph includes PFOS concentrations in freshwater fish fillets collected from lakes across the United States, as reported by USEPA (2024b). Non-detects were excluded from the graph. "This Study" data were not included in the percent rank calculations.

Ecological Relevance

Aquatic Life

PFAS concentrations of freshwater fillet tissue and surface water found in the ten lakes were below state aquatic life criteria. Washington's adopted aquatic life criteria for PFOA and PFOS in 2022 are based on the 2022 draft EPA recommendations for observed effects on the survival, growth, and reproduction of aquatic organisms (USEPA 2022a). Fillet tissue concentrations in the lakes were 1 – 3 orders of magnitude below the state's adopted PFOS aquatic life criteria for muscle tissue of 2,910 ng/g ww. Surface water samples were 3 – 7 orders of magnitude below the state's chronic and acute water column criteria for PFOA and PFOS.

In fall 2024, the EPA issued final recommended aquatic life criteria for PFOS (USEPA 2024c) and PFOA (USEPA 2024d), which were lower than the draft recommended criteria. Five bass samples from American Lake and one sample from Spanaway Lake contained fillet PFOS concentrations that were above the recommended EPA criteria for PFOS in freshwater muscle (87 ng/g ww). All surface water samples for this study were still well below the freshwater acute and chronic water column thresholds issued for PFOS and PFOA, as well as acute benchmarks for eight data-limited additional PFAS (USEPA 2024e).

Wildlife Consumers

The aquatic life criteria described above are not protective of wildlife that eat the fish. The EPA intends to review PFOS data and develop aquatic-dependent wildlife criteria in the future if appropriate (USEPA 2022b). While the U.S. does not currently have surface water or fish tissue PFAS thresholds protective of fish-eating wildlife, Canada has issued wildlife dietary guidelines for PFOS: 4.6 ng/g ww (mammals) and 8.2 ng/g ww (avian species) (ECCC 2018). Figure 16 compares samples collected during this study to the Canadian guidelines. Because of its persistence and bioaccumulative nature, PFOS has been reported to pose the highest ecological risk to aquatic systems (Condor et al. 2020).

Almost all fish analyzed from American, Stevens, and Spanaway contained PFOS concentrations above the Canadian guidelines for fish-consuming wildlife, suggesting ecological impacts from PFOS in these lakes. Only brown bullhead samples and one kokanee sample from Lake Stevens were below the guidelines. All other species analyzed from the three lakes exceeded it.

Smallmouth bass collected from Lake Goodwin were above mammalian diet guidelines but not avian. Only one sample from Goodwin – a largemouth bass composite –was above both mammalian and avian guidelines. Yellow perch sampled from the lake were below both thresholds.

Several lakes contained multiple species of fish with PFOS concentrations below the wildlife consumer guidelines: Horsethief, Leland, Loomis, McIntosh, Nahwatzel, and Sammamish. The levels of PFOS observed in fish collected from these lakes are below the expected levels of ecological impacts.

The Canadian wildlife consumer guidelines are based on whole-body PFOS concentrations, and the data from the lakes in comparison here represent fillet tissue concentrations. Fillet tissue concentrations are an underestimate of the true exposure to wildlife, as PFOS concentrations in the whole body are typically 2 – 3 times higher than fillet levels (Fair et al. 2019).

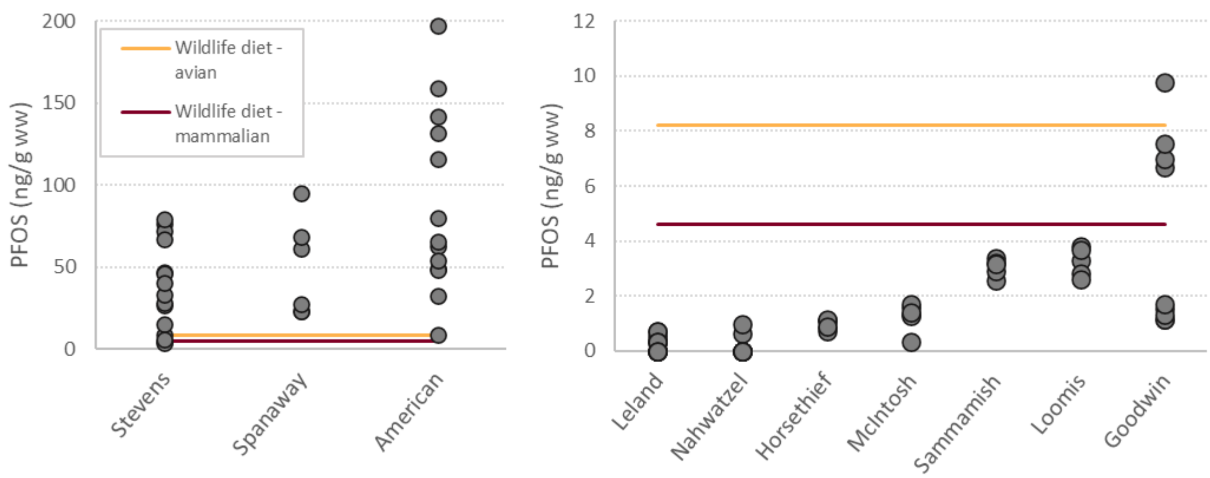

Figure 16. PFOS Concentrations in Multiple Freshwater Fish Species Fillet Samples Compared to Wildlife Consumer Guidelines.

Grey line = Environment and Climate Change Canada's whole body fish tissue federal guideline for avian wildlife diet; orange line = Environment and Climate Change Canada's whole body fish tissue federal guideline for mammalian wildlife diet.

Summary and Conclusions

In 2023, Ecology collected freshwater fish fillet tissue and surface water samples from ten Washington lakes for PFAS analysis. Results from this study help fill data gaps on PFAS concentrations in multiple species of freshwater fish sampled from a variety of water bodies, as well as paired surface water conditions. Data from this study support the following conclusions:

- Ninety-four percent (83 out of 88) of fish tissue samples contained at least one PFAS. Of the 40 PFAS analytes, only 14 were detected in fillet tissue. PFAS detected in fish tissue samples included PFSAs with carbon chain lengths of 6 – 10, PFCAs with carbon chain lengths of 9 – 14, and three precursors (PFOSA, NMeFOSAA, and NEtFOSE).
- T-PFAS concentrations were highest in American Lake fish fillet tissue samples (8.4 – 204 ng/g), followed by Spanaway (24 – 99 ng/g) and Stevens (6.2 – 99 ng/g), all of which had median and mean T-PFAS concentrations in fish above 10 ng/g. The lakes sampled as part of ongoing monitoring were generally from less developed watersheds and contained much lower PFAS concentrations. Of these, Goodwin had slightly elevated concentrations (T-PFAS above 10 ng/g) in bass samples, and several samples from Leland Lake had higher concentrations of NEtFOSE. All other fish samples from the PBT Monitoring lakes and cutthroat trout samples from Lake Sammamish contained T-PFAS concentrations of less than 5 ng/g.
- Overall, PFOS made up the majority of the T-PFAS burden in fillet tissues. PFOS concentrations in this study were within the range of previously reported freshwater fillet data in Washington State and lakes across the U.S. American Lake PFOS levels exceeded the fillet tissue range for Washington and were at the very high end of the U.S. fillet tissue PFOS range.
- Surface water samples from all lakes except Leland and Horsethief had detectable levels of at least one PFAS. Detected T-PFAS concentrations in surface water ranged from 0.4 ng/L (Lake Nahwatzel) to 39.6 ng/L (American Lake), with a median of 12.4 ng/L for all samples collected. Surface waters contained a wide variety of PFAS and primarily included PFCAs with carbon chain lengths of 4 – 8 and PFSAs with 4, 6, and 8 carbons.
- Fillet PFAS concentrations of bass and smaller sunfish species were correlated with surface water PFAS concentrations. Fillet concentrations increased as surface water concentrations increased. Trout species did not show the same relationship.
- All fillet samples analyzed from American, Stevens, and Spanaway Lakes, as well as several bass from Goodwin, contained PFOS levels that could harm wildlife consuming the fish. PFOS levels in fish from the other lakes were below these thresholds. PFAS concentrations in fish and surface water were not at levels that would indicate direct

harm to the fish themselves according to state thresholds, though several fish samples from American Lake and one from Spanaway Lake were above new federal recommendations for protecting aquatic life.

Recommendations

The results of this 2023 study support the following recommendations:

- Additional sampling of PFAS in freshwater fish tissue should occur throughout Washington to determine where fish PFAS concentrations may impact human or ecological health.
  - Sampling should focus on lakes near known or suspected point source areas and high environmental health disparities should be prioritized.
  - Future efforts should develop or expand collaboration with local anglers, fishing groups, and residents eating the fish.
- Relationships between fish tissue and surface water PFAS concentrations demonstrated by this study suggest that preliminary screening of surface water could help inform and prioritize water bodies for collections of bass and smaller sunfish species. Fish sampling efforts are time- and resource-intensive. Surface water samples would help direct resources to areas most likely to have impacted fish.
- Data from this study was submitted to the Washington State Department of Health to evaluate potential human health concerns. Toxicologists should assess whether fish consumption advisories should be issued based on this study's results.

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Glossary, Acronyms, and Abbreviations

Glossary

Land type: Description of physical characteristics of a specified land area (e.g., forested or grasslands).

Land use: Human activity or use for a specified land area (e.g., residential, industrial, or agricultural).

Parameter: Water quality constituent being measured (analyte). A physical, chemical, or biological property whose values determine environmental characteristics or behavior.

Point source: Sources of pollution that discharge at a specific location from pipes, outfalls, and conveyance channels to a surface water. Examples of point source discharges include municipal wastewater treatment plants, municipal stormwater systems, industrial wastewater treatment facilities, and construction sites where one or more acres of land are disturbed.

Stormwater: The portion of precipitation that does not naturally percolate into the ground or evaporate but instead runs off roads, pavement, and roofs during rainfall or snow melt. Stormwater can also come from hard or saturated grass surfaces such as lawns, pastures, and playfields, and from gravel roads and parking lots.

Watershed: A drainage area or basin in which all land and water areas drain or flow toward a central collector, such as a stream, river, or lake at a lower elevation.

Acronyms and Abbreviations

6:2 FTS	6:2 fluorotelomer sulfonate
7:3 FTCA	7:3 perfluorodecanoate
BC	black crappie
BBH	brown bullhead
BG	bluegill
CTT	cutthroat trout
DNA	deoxyribonucleic acid
DOC	dissolved organic carbon
DOH	Washington State Department of Health
Ecology	Washington State Department of Ecology
EIM	Environmental Information Management database
EPA	U.S. Environmental Protection Agency
KOK	kokanee

LDPE	low density polyethylene
LMB	largemouth bass
LOQ	limit of quantitation
MDL	method detection limit
MEL	Manchester Environmental Laboratory
MQO	measurement quality objective
NEtFOSE	perfluorooctanesulfonamidoethanol
NFDHA	perfluoro-3,6-dioxaheptanoate
NMeFOSA	N-methyl perfluorooctanesulfonamide
NMeFOSAA	N-methyl perfluorooctanesulfonamidoacetic acid
NMeFOSE	N-methyl perfluorooctanesulfonamidoethanol
OPR	ongoing precision and recovery
PBT	persistent, bioaccumulative, and toxic substance
PFAA	perfluoroalkyl acid
PFAS	per- and polyfluoroalkyl substance
PFBA	perfluorobutanoate
PFBS	perfluorobutane sulfonate
PFCA	perfluoroalkyl carboxylic acid
PFDA	perfluorodecanoate
PFDoA	perfluorododecanoate
PFHpA	perfluoroheptanoate
PFHxA	perfluorohexanoate
PFNA	perfluorononanoate
PFOA	perfluorooctanoate
PFOS	perfluorooctane sulfonate
PFPeA	perfluoropentanoate
PFPeS	perfluoropentane sulfonate
PFSA	perfluoroalkane sulfonate
PFTeDA	perfluorotetradecanoate
PFTrDA	perfluorotridecanoate
PFUnA	perfluoroundecanoate

PMP	pumpkinseed
RBT	rainbow trout
RPD	relative percent difference
QA	quality assurance
QAPP	quality assurance project plan
QC	quality control
RBT	rainbow trout
RSD	relative standard deviation
SMB	smallmouth bass
SOP	standard operating procedures
T-	total-
TOC	total organic carbon
TSS	total suspended solids
WAC	Washington Administrative Code
WAL	walleye
WDFW	Washington Department of Fish and Wildlife
WRIA	Water Resource Inventory Area
WWTP	Wastewater treatment plant
YP	yellow perch

Units of Measurement

°C	degrees centigrade
Cm	centimeter
ft	feet
ng/g	nanograms per gram (parts per billion)
ng/L	nanograms per liter (parts per trillion)
ww	wet weight

Appendices

Appendix A. Surface Water Sampling Locations

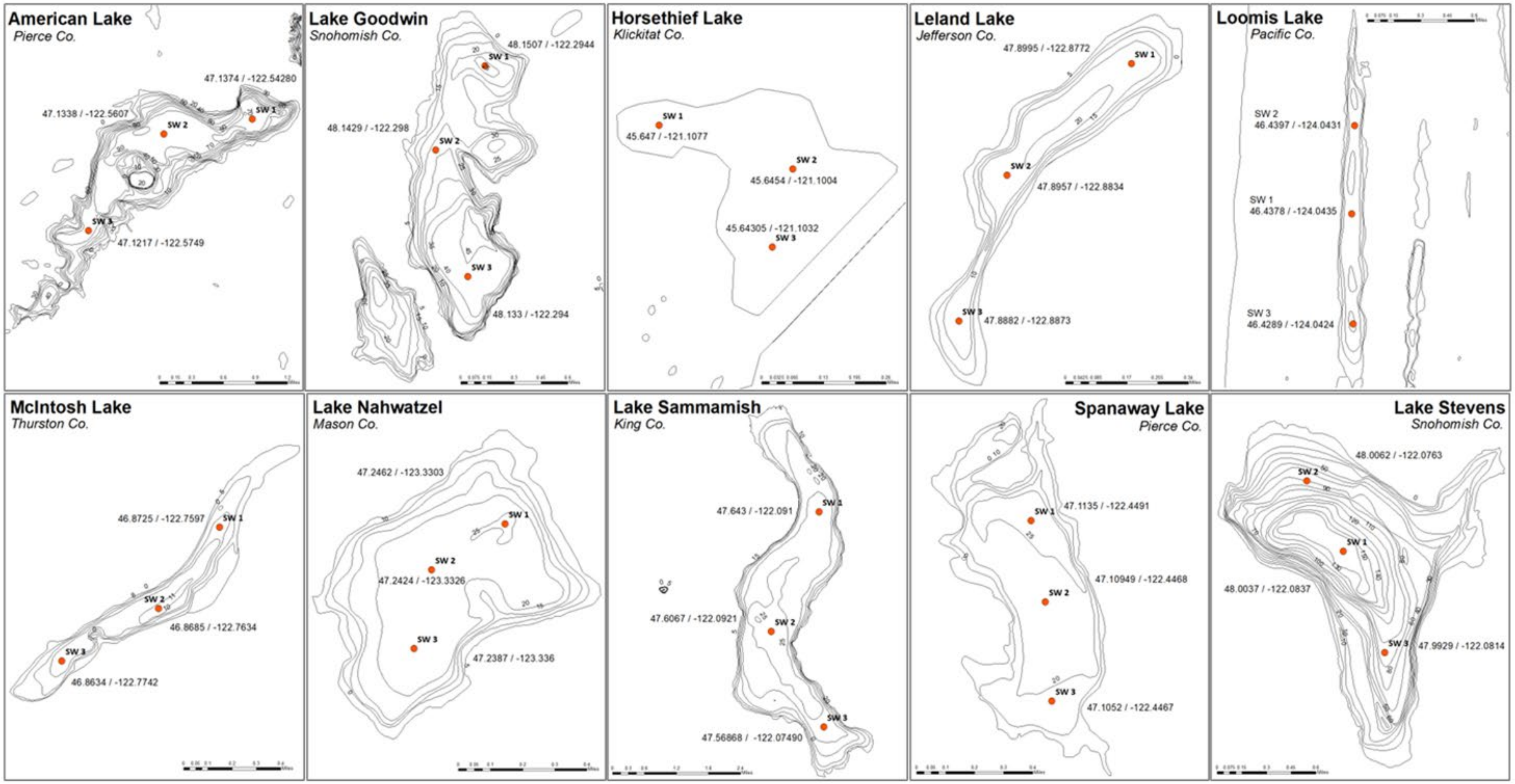

Figure A-1. Bathymetric maps of study locations with surface water sampling coordinates.

Appendix B. Target PFAS Analytes

Table B-1. PFAS analytes and their median reporting limits and detection limits for this study.

Analyte name	Abbreviated Analyte Name	CAS Number	Detected in Water Samples?	Water LOQ (ng/L)	Water DL (ng/L)	Detected in Fish Tissue Samples?	Fish Tissue LOQ (ng/g)	Fish Tissue DL (ng/g)
Perfluorobutanoate	PFBA	45048-62-2	Y	6.6	1.7	N	1.6	0.4
Perfluorohexanoate	PFHxA	92612-52-7	Y	1.7	0.4	N	0.4	0.1
Perfluoropentanoate	PFPeA	45167-47-3	Y	3.3	0.8	N	0.8	0.2
Perfluoroheptanoate	PFHpA	120885-29-2	Y	1.7	0.4	N	0.4	0.1
Perfluorooctanoate	PFOA	45285-51-6	Y	1.7	0.4	N	0.4	0.1
Perfluorononanoate	PFNA	72007-68-2	Y	1.7	0.4	Y	0.4	0.1
Perfluorodecanoate	PFDA	73829-36-4	Y	1.7	0.4	N	0.4	0.1
Perfluoroundecanoate	PFUnA	196859-54-8	N	1.7	0.4	Y	0.4	0.1
Perfluorododecanoate	PFDoA	171978-95-3	N	1.7	0.3	N	0.4	0.1
Perfluorotridecanoate	PFTrDA	862374-87-6	N	1.7	0.4	Y	0.4	0.1
Perfluorotetradecanoate	PFTeDA	365971-87-5	N	1.7	0.4	Y	0.4	0.1
Perfluorobutanesulfonate	PFBS	45187-15-3	Y	1.7	0.4	N	0.4	0.1
Perfluoropentane sulfonate	PFPeS	175905-36-9	Y	1.7	0.4	N	0.4	0.1
Perfluorohexane sulfonate	PFHxS	108427-53-8	Y	1.7	0.4	Y	0.4	0.1
Perfluoroheptane sulfonate	PFHpS	146689-46-5	N	1.7	0.4	Y	0.4	0.1
Perfluorooctane sulfonate	PFOS	45298-90-6	Y	1.7	0.4	Y	0.4	0.1
Perfluorononane sulfonate	PFNS	474511-07-4	N	1.7	0.4	Y	0.4	0.1

Analyte name	Abbreviated Analyte Name	CAS Number	Detected in Water Samples?	Water LOQ (ng/L)	Water DL (ng/L)	Detected in Fish Tissue Samples?	Fish Tissue LOQ (ng/g)	Fish Tissue DL (ng/g)
Perfluorodecane sulfonate	PFDS	126105-34-8	N	1.7	0.4	Y	0.4	0.1
Perfluorododecane sulfonate	PFDoS	343629-43-6	N	1.7	0.4	N	0.4	0.1
4:2 Fluorotelomer sulfonate	4:2 FTS	414911-30-1	N	6.6	1.7	N	1.6	0.4
6:2 Fluorotelomer sulfonate	6:2 FTS	425670-75-3	N	22.2	1.5	N	8.6	0.4
8:2 Fluorotelomer sulfonate	8:2 FTS	481071-78-7	N	6.6	1.4	N	1.6	0.3
Perfluorooctanesulfonamide	PFOSA	754-91-6	N	1.7	0.4	Y	0.4	0.1
N-methyl perfluorooctanesulfonamide	NMeFOSA	31506-32-8	N	1.9	0.4	N	0.5	0.1
N-ethyl perfluorooctanesulfonamide	NEtFOSA	4151-50-2	N	4.2	1.2	N	1.0	0.3
N-methyl perfluorooctanesulfonamidoacetic acid	NMeFOSAA	2355-31-9	N	1.7	0.4	Y	0.4	0.1
N-ethyl perfluorooctanesulfonamidoacetic acid	NEtFOSAA	2991-50-6	N	1.7	0.4	N	0.4	0.1
N-methyl perfluorooctanesulfonamidoethanol	NMeFOSE	24448-09-7	N	16.6	4.2	N	10.9	1.0
N-ethyl perfluorooctanesulfonamidoethanol	NEtFOSE	1691-99-2	N	12.5	4.2	Y	3.0	1.0
2,3,3,3-Tetrafluoro-2-(1,1,2,2,3,3,3-heptafluoropropoxy)propanoate	HFPO-DA	122499-17-6	N	6.3	1.7	N	1.5	0.4

Analyte name	Abbreviated Analyte Name	CAS Number	Detected in Water Samples?	Water LOQ (ng/L)	Water DL (ng/L)	Detected in Fish Tissue Samples?	Fish Tissue LOQ (ng/g)	Fish Tissue DL (ng/g)
Dodecafluoro-3H-4,8-dioxanonanoate	ADONA	2127366-90-7	N	6.6	1.7	N	1.6	0.4
Perfluoro-3-methoxypropanoate	PFMPA		N	3.3	0.8	N	0.8	0.2
Perfluoro-4-methoxybutanoate	PFMBA	1432017-36-1	N	1.7	0.4	N	0.4	0.1
Perfluoro-3,6-dioxaheptanoate	NFDHA	39187-41-2	N	3.3	0.8	N	1.8	0.2
9-chlorohexadecafluoro-3-oxanonane-1-sulfonate	9CL-PF3ONS	1621485-21-9	N	6.6	1.7	N	1.6	0.4
11-Chloroeicosafluoro-3-oxaundecane-1-sulfonate	11CL-PF3OUDS	2196242-82-5	N	6.6	1.7	N	1.6	0.4
Perfluoro(2-ethoxyethane)sulfonate	PFEESA	220689-13-4	N	1.7	0.4	N	0.4	0.1
3:3 perfluorohexanoate	3:3 FTCA	1169706-83-5	N	6.6	1.7	N	1.6	0.4
5:3 perfluoroctanoate	5:3 FTCA	1799325-94-2	N	41.6	10.4	N	10.0	2.5
7:3 perfluorodecanoate	7:3 FTCA	1799325-95-3	N	41.6	10.4	N	10.0	2.5

LOQ = limit of quantitation
DL = detection limit
Y = yes
N = no

Appendix C. Fish Tissue PFAS Summaries by Lake

Table C-1. American Lake PFAS summaries: perfluoroalkyl carboxylates.

Species	Statistic	PFDA	PFUnA	PFDoA	PFTrDA	PFTeDA
LMB	Min.-Max. (ng/g)	1.5–2.1	1.1–1.6	0.7–1.1	ND	ND–0.3
LMB	Median (ng/g)	2.0	1.2	0.8	—	—
LMB	Mean (ng/g)	1.9	1.2	0.8	—	—
LMB	Det. Freq.*	5/5	5/5	5/5	0/5	4/5
RBT	Min.-Max. (ng/g)	0.1	ND	ND	ND	ND
RBT	Median (ng/g)	—	—	—	—	—
RBT	Mean (ng/g)	—	—	—	—	—
RBT	Det. Freq.*	1/1	0/1	0/1	0/1	0/1
SMB	Min.-Max. (ng/g)	1.9–3.0	0.9–1.6	0.6–1.1	0.6–0.7	ND–0.6
SMB	Median (ng/g)	2.3	1.5	1.1	0.7	—
SMB	Mean (ng/g)	2.4	1.4	1.0	0.7	—
SMB	Det. Freq.*	4/4	4/4	4/4	4/4	2/4
YP	Min.-Max. (ng/g)	0.8–1.0	ND–0.7	0.4–0.6	ND	ND
YP	Median (ng/g)	1.0	—	0.5	—	—
YP	Mean (ng/g)	1.0	—	0.5	—	—
YP	Det. Freq.*	3/3	2/3	3/3	0/3	0/3

Det. Freq. = detection frequency (number of samples with detections/number of samples analyzed)
LMB = largemouth bass
ND = non-detect
RBT = rainbow trout
SMB = smallmouth bass
YP = yellow perch

Table C-2. American Lake PFAS summaries: perfluoroalkane sulfonates.

Species	Statistic	PFOS	PFHxS	PFHpS	PFNS	PFDS
LMB	Min.-Max. (ng/g)	54–142	ND	ND	ND	0.2–0.3
LMB	Median (ng/g)	66	—	—	—	0.2
LMB	Mean (ng/g)	81	—	—	—	0.2
LMB	Det. Freq.*	5/5	0/5	0/5	0/5	5/5
RBT	Min.-Max. (ng/g)	8.3	ND	ND	ND	ND
RBT	Median (ng/g)	—	—	—	—	—
RBT	Mean (ng/g)	—	—	—	—	—
RBT	Det. Freq.*	1/1	0/1	0/1	0/1	0/1
SMB	Min.-Max. (ng/g)	116–197	ND	ND	ND–0.1	0.2–0.4
SMB	Median (ng/g)	146	—	—	—	0.4
SMB	Mean (ng/g)	151	—	—	—	0.3
SMB	Det. Freq.*	4/4	0/4	0/4	1/4	4/4
YP	Min.-Max. (ng/g)	32–49	0.2–0.2	ND–0.1	ND	ND–0.2
YP	Median (ng/g)	48	0.2	—	—	—
YP	Mean (ng/g)	43	0.2	—	—	—
YP	Det. Freq.*	3/3	3/3	2/3	0/3	2/3

Det. Freq. = detection frequency (number of samples with detections/number of samples analyzed)
LMB = largemouth bass
ND = non-detect
RBT = rainbow trout
SMB = smallmouth bass
YP = yellow perch

Table C-3. Lake Goodwin PFAS summaries: perfluoroalkyl carboxylates.

Species	Statistic	PFNA	PFDA	PFUnA	PFDoA	PFTrDA	PFTeDA
LMB	Min.-Max. (ng/g)	ND	4.2	2.2	1.6	0.7	0.5
LMB	Median (ng/g)	—	—	—	—	—	—
LMB	Mean (ng/g)	—	—	—	—	—	—
LMB	Det. Freq.*	0/1	1/1	1/1	1/1	1/1	1/1
SMB	Min.-Max. (ng/g)	ND	1.9–2.8	1.5–1.8	1.5–2.0	0.7–1.2	ND–0.8
SMB	Median (ng/g)	—	2.0	1.8	1.8	0.9	—
SMB	Mean (ng/g)	—	2.2	1.7	1.8	0.9	—
SMB	Det. Freq.*	0/3	3/3	3/3	3/3	3/3	2/3
YP	Min.-Max. (ng/g)	ND–0.2	0.7–1.2	ND–0.7	0.5–0.8	0.3–0.4	ND–0.5
YP	Median (ng/g)	—	0.8	—	0.6	0.4	—
YP	Mean (ng/g)	—	0.9	—	0.6	0.4	—
YP	Det. Freq.*	1/5	5/5	1/5	5/5	5/5	4/5

Det. Freq. = detection frequency (number of samples with detections/number of samples analyzed);
LMB = largemouth bass; SMB = smallmouth bass; YP = yellow perch; ND = non-detect.

Table C-4. Lake Goodwin PFAS summaries: perfluoroalkane sulfonates.

Species	Statistic	PFOS	PFDS
LMB	Min.-Max. (ng/g)	9.8	0.1
LMB	Median (ng/g)	—	—
LMB	Mean (ng/g)	—	—
LMB	Det. Freq.*	1/1	1/1
SMB	Min.-Max. (ng/g)	6.7–7.5	0.1–2.0
SMB	Median (ng/g)	7	0.2
SMB	Mean (ng/g)	7	0.2
SMB	Det. Freq.*	3/3	3/3
YP	Min.-Max. (ng/g)	1.2–1.7	ND
YP	Median (ng/g)	1.3	—
YP	Mean (ng/g)	1.4	—
YP	Det. Freq.*	5/5	0/5

Det. Freq. = detection frequency (number of samples with detections/number of samples analyzed); LMB = largemouth bass; SMB = smallmouth bass; YP = yellow perch; ND = non-detect.

Table C-5. Horsethief Lake PFAS summaries: perfluoroalkyl acids.

Species	Statistic	PFDA	PFDoA	PFOS
LMB	Min.-Max. (ng/g)	ND	0.1	0.9
LMB	Median (ng/g)	—	—	—
LMB	Mean (ng/g)	—	—	—
LMB	Det. Freq.*	0/1	1/1	1/1
SMB	Min.-Max. (ng/g)	0.2–0.2	0.2–0.2	0.8–1.1
SMB	Median (ng/g)	0.2	0.2	1.1
SMB	Mean (ng/g)	0.2	0.2	1.0
SMB	Det. Freq.*	4/4	4/4	4/4
WAL	Min.-Max. (ng/g)	ND	ND	0.73
WAL	Median (ng/g)	—	—	—
WAL	Mean (ng/g)	—	—	—
WAL	Det. Freq.*	0/1	0/1	1/1

Det. Freq. = detection frequency (number of samples with detections/number of samples analyzed); LMB = largemouth bass; SMB = smallmouth bass; WAL = walleye; ND = non-detect.

Table C-6. Leland Lake PFAS summaries: perfluoroalkyl acids and NEtFOSE.

Species	Statistic	PFTrDA	PFOS	NEtFOSE
BC	Min.-Max. (ng/g)	ND	ND–0.3	ND–7.5
BC	Median (ng/g)	—	—	—
BC	Mean (ng/g)	—	—	—
BC	Det. Freq.*	0/4	3/4	3/4
BG	Min.-Max. (ng/g)	ND–0.11	ND	ND
BG	Median (ng/g)	—	—	—
BG	Mean (ng/g)	—	—	—
BG	Det. Freq.*	1/3	0/3	0/3
LMB	Min.-Max. (ng/g)	ND	ND–0.7	ND
LMB	Median (ng/g)	—	—	—
LMB	Mean (ng/g)	—	—	—
LMB	Det. Freq.*	0/5	4/5	0/5
RBT	Min.-Max. (ng/g)	ND	ND	ND–10
RBT	Median (ng/g)	—	—	—
RBT	Mean (ng/g)	—	—	—
RBT	Det. Freq.*	0/2	0/2	1/2

Det. Freq. = detection frequency (number of samples with detections/number of samples analyzed); BC = black crappie; BG = bluegill; LMB = largemouth bass; RBT = rainbow trout; ND = non-detect.

Table C-7. Loomis Lake PFAS summaries: perfluoroalkyl acids.

Species	Statistic	PFNA	PFDA	PFOS
BC	Min.-Max. (ng/g)	0.3–0.5	0.2–0.3	2.6–3.7
BC	Median (ng/g)	—	0.2	3.1
BC	Mean (ng/g)	—	0.2	3.1
BC	Det. Freq.*	2/2	2/2	2/2
LMB	Min.-Max. (ng/g)	ND	0.3–0.4	2.8–3.8
LMB	Median (ng/g)	—	0.3	3.3
LMB	Mean (ng/g)	—	0.3	3.3
LMB	Det. Freq.*	0/3	3/3	3/3

Det. Freq. = detection frequency (number of samples with detections/number of samples analyzed); BC = black crappie; LMB = largemouth bass; ND = non-detect.

Table C-8. McIntosh Lake PFAS summaries: perfluoroalkyl acids.

Species	Statistic	PFDA	PFDoA	PFOS
LMB	Min.-Max. (ng/g)	ND–0.1	ND–0.1	1.3–1.7
LMB	Median (ng/g)	—	—	1.4
LMB	Mean (ng/g)	—	—	1.5
LMB	Det. Freq.*	4/5	1/5	5/5
YP	Min.-Max. (ng/g)	ND	ND	0.30
YP	Median (ng/g)	—	—	—
YP	Mean (ng/g)	—	—	—
YP	Det. Freq.*	0/1	0/1	1/1

Det. Freq. = detection frequency (number of samples with detections/number of samples analyzed); LMB = largemouth bass; YP = yellow perch; ND = non-detect.

Table C-9. Lake Nahwatzel PFAS summaries: perfluoroalkyl acids.

Species	Statistic	PFDA	PFUnA	PFDoA	PFTrDA	PFTeDA	PFOS
LMB	Min.-Max. (ng/g)	ND–0.1	ND–0.5	0.3–0.4	0.6–0.7	0.2–0.3	ND
LMB	Median (ng/g)	—	—	0.3	0.6	0.2	—
LMB	Mean (ng/g)	—	—	0.3	0.6	0.2	—
LMB	Det. Freq.*	4/5	2/5	5/5	5/5	5/5	0/5
RBT	Min.-Max. (ng/g)	ND	ND	ND	0.1–0.2	ND–0.2	ND – 1.0
RBT	Median (ng/g)	—	—	—	0.2	—	—
RBT	Mean (ng/g)	—	—	—	0.2	—	—
RBT	Det. Freq.*	0/4	0/4	0/4	4/4	1/4	2/4

Det. Freq. = detection frequency (number of samples with detections/number of samples analyzed); LMB = largemouth bass; RBT = rainbow trout; ND = non-detect.

Table C-10. Lake Sammamish PFAS summaries: perfluoroalkyl acids.

Species	Statistic	PFDA	PFDoA	PFTrDA	PFTeDA	PFOS
CTT	Min.-Max. (ng/g)	0.2–0.3	ND–0.2	ND–0.2	ND–0.2	2.6–3.4
CTT	Median (ng/g)	0.3	—	—	—	3.2
CTT	Mean (ng/g)	0.3	—	—	—	3.0
CTT	Det. Freq.*	5/5	4/5	2/5	3/5	5/5

Det. Freq. = detection frequency (number of samples with detections/number of samples analyzed); CTT = cutthroat trout; ND = non-detect.

Table C-11. Spanaway Lake PFAS summaries: perfluoroalkyl carboxylates.

Species	Statistic	PFNA	PFDA	PFUnA	PFDoA	PFTrDA	PFTeDA
BG	Min.-Max. (ng/g)	0.1	1.0	ND	ND	ND	ND
BG	Median (ng/g)	—	—	—	—	—	—
BG	Mean (ng/g)	—	—	—	—	—	—
BG	Det. Freq.*	1/1	1/1	0/1	0/1	0/1	0/1
LMB	Min.-Max. (ng/g)	ND	2.4–3.6	ND	0.21–0.27	ND–0.14	ND
LMB	Median (ng/g)	—	3.0	—	0.2	—	—
LMB	Mean (ng/g)	—	3.0	—	0.2	—	—
LMB	Det. Freq.*	0/2	2/2	0/2	2/2	1/2	0/2
PMP	Min.-Max. (ng/g)	0.1	1.5	ND	0.1	ND	ND
PMP	Median (ng/g)	—	—	—	—	—	—
PMP	Mean (ng/g)	—	—	—	—	—	—
PMP	Det. Freq.*	1/1	1/1	0/1	1/1	0/1	0/1
SMB	Min.-Max. (ng/g)	ND	3.0	ND	0.4	0.3	0.2
SMB	Median (ng/g)	—	—	—	—	—	—
SMB	Mean (ng/g)	—	—	—	—	—	—
SMB	Det. Freq.*	0/1	1/1	0/1	1/1	1/1	1/1
YP	Min.-Max. (ng/g)	ND	0.8	ND	ND	ND	ND
YP	Median (ng/g)	—	—	—	—	—	—
YP	Mean (ng/g)	—	—	—	—	—	—
YP	Det. Freq.*	0/1	1/1	0/1	0/1	0/1	0/1

Det. Freq. = detection frequency (number of samples with detections/number of samples analyzed); BG = bluegill; LMB = largemouth bass; PMP = pumpkinseed; SMB = smallmouth bass; YP = yellow perch; ND = non-detect.

Table C-12. Spanaway Lake PFAS summaries: perfluoroalkane sulfonates and NEtFOSE.

Species	Statistic	PFOS	PFNS	PFDS	NEtFOSE
BG	Min.-Max. (ng/g)	27	ND	ND	7.4
BG	Median (ng/g)	—	—	—	—
BG	Mean (ng/g)	—	—	—	—
BG	Det. Freq.*	1/1	0/1	0/1	1/1
LMB	Min.-Max. (ng/g)	61–95	ND	ND–0.4	ND
LMB	Median (ng/g)	78	—	—	—
LMB	Mean (ng/g)	78	—	—	—
LMB	Det. Freq.*	2/2	0/2	1/2	0/2
PMP	Min.-Max. (ng/g)	23	ND	0.6	3.9
PMP	Median (ng/g)	—	—	—	—
PMP	Mean (ng/g)	—	—	—	—
PMP	Det. Freq.*	1/1	0/1	1/1	1/1
SMB	Min.-Max. (ng/g)	68	0.1	1.2	ND
SMB	Median (ng/g)	—	—	—	—
SMB	Mean (ng/g)	—	—	—	—
SMB	Det. Freq.*	1/1	1/1	1/1	0/1
YP	Min.-Max. (ng/g)	23	ND	0.2	ND
YP	Median (ng/g)	—	—	—	—
YP	Mean (ng/g)	—	—	—	—
YP	Det. Freq.*	1/1	0/1	1/1	0/1

Det. Freq. = detection frequency (number of samples with detections/number of samples analyzed); BG = bluegill; LMB = largemouth bass; PMP = pumpkinseed; SMB = smallmouth bass; YP = yellow perch; ND = non-detect.

Table C-13. Lake Stevens PFAS summaries: perfluoroalkyl carboxylates.

Species	Statistic	PFNA	PFDA	PFUnA	PFDoA	PFTrDA	PFTeDA
BBH	Min.-Max. (ng/g)	ND	0.4–1.2	ND–1.1	0.8–1.1	0.4–0.6	0.4–0.5
BBH	Median (ng/g)	—	0.6	—	0.9	0.5	0.5
BBH	Mean (ng/g)	—	0.7	—	0.9	0.5	0.5
BBH	Det. Freq.*	0/3	3/3	2/3	3/3	3/3	3/3
KOK	Min.-Max. (ng/g)	ND	0.5	ND	0.1	ND	ND
KOK	Median (ng/g)	—	—	—	—	—	—
KOK	Mean (ng/g)	—	—	—	—	—	—
KOK	Det. Freq.*	0/1	1/1	0/1	1/1	0/1	0/1
LMB	Min.-Max. (ng/g)	ND	2.3–3.6	1.3–1.5	1.7–1.7	0.6–0.9	0.5–0.8
LMB	Median (ng/g)	—	2.9	1.4	1.7	0.8	0.7
LMB	Mean (ng/g)	—	2.9	1.4	1.7	0.8	0.7
LMB	Det. Freq.*	0/2	2/2	2/2	2/2	2/2	2/2
RBT	Min.-Max. (ng/g)	0.8–1.9	3.6–11	0.6–2.4	0.4–2.2	ND–1.4	0.3–1.2
RBT	Median (ng/g)	1.5	6.3	1.4	1.2	—	0.7
RBT	Mean (ng/g)	1.4	6.5	1.5	1.2	—	0.8
RBT	Det. Freq.*	7/7	7/7	7/7	7/7	6/7	7/7
SMB	Min.-Max. (ng/g)	ND	9.1–9.6	2.3–3.5	1.8–3.1	1.0–1.9	0.9–1.5
SMB	Median (ng/g)	—	9.3	2.9	2.4	1.4	1.2
SMB	Mean (ng/g)	—	9.3	2.9	2.4	1.4	1.2
SMB	Det. Freq.*	0/2	2/2	2/2	2/2	2/2	2/2

Det. Freq. = detection frequency (number of samples with detections/number of samples analyzed); BBH = brown bullhead; KOK = kokanee; LMB = largemouth bass; RBT = rainbow trout; SMB = smallmouth bass; ND = non-detect.

Table C-14. Lake Stevens PFAS summary statistics: perfluoroalkane sulfonates and NMeFOSAA.

Species	Statistic	PFHpS	PFOS	PFDS	PFOSA	NMeFOSAA
BBH	Min.-Max. (ng/g)	ND	3.3–8.9	0.1–0.2	ND	ND
BBH	Median (ng/g)	—	4.2	0.2	—	—
BBH	Mean (ng/g)	—	5.5	0.2	—	—
BBH	Det. Freq.*	0/3	3/3	3/3	0/3	0/3
KOK	Min.-Max. (ng/g)	ND	5.9	ND	ND	ND
KOK	Median (ng/g)	—	—	—	—	—
KOK	Mean (ng/g)	—	—	—	—	—
KOK	Det. Freq.*	0/1	1/1	0/1	0/1	0/1
LMB	Min.-Max. (ng/g)	ND	15–27	0.1–0.2	ND	ND
LMB	Median (ng/g)	—	21	0.2	—	—
LMB	Mean (ng/g)	—	21	0.2	—	—
LMB	Det. Freq.*	0/2	2/2	2/2	0/2	0/2
CTT	Min.-Max. (ng/g)	ND–0.2	28–72	ND–0.3	ND	ND–0.1
CTT	Median (ng/g)	—	46	—	—	—
CTT	Mean (ng/g)	—	48	—	—	—
CTT	Det. Freq.*	4/7	7/7	5/7	0/7	2/7
SMB	Min.-Max. (ng/g)	ND	76–79	0.2–0.4	ND–0.3	ND
SMB	Median (ng/g)	—	78	0.3	—	—
SMB	Mean (ng/g)	—	78	0.3	—	—
SMB	Det. Freq.*	0/2	2/2	2/2	1/2	0/2

Det. Freq. = detection frequency (number of samples with detections/number of samples analyzed); BBH = brown bullhead; KOK = kokanee; LMB = largemouth bass; RBT = rainbow trout; SMB = smallmouth bass; ND = non-detect.

Appendix D. Ancillary fish data

Table D-1. Biological and composite data of fish samples collected for this study.

Sample ID	Site	Species	Collection Date	Number in Composite	Mean Total Length (mm)	Mean Total Weight (g)	Mean Age (years)
2311025-11	American Lake	largemouth bass	9/12/2023	5	218	126	2
2311025-12	American Lake	largemouth bass	9/12/2023	5	231	154	2
2311025-13	American Lake	largemouth bass	9/12/2023	5	245	180	2
2311025-14	American Lake	largemouth bass	9/12/2023	5	276	303	2
2311025-15	American Lake	largemouth bass	9/12/2023	2	425	1233	4
2311025-10	American Lake	rainbow trout	9/12/2023	1	319	402	2
2311025-16	American Lake	smallmouth bass	10/19/2023	5	377	718	3
2311025-17	American Lake	smallmouth bass	10/19/2023	4	429	1170	4
2311025-18	American Lake	smallmouth bass	10/19/2023	4	453	1331	6
2311025-19	American Lake	smallmouth bass	10/19/2023	3	481	1424	6
2311025-07	American Lake	yellow perch	9/12/2023	5	264	219	5
2311025-08	American Lake	yellow perch	9/12/2023	5	274	225	6
2311025-09	American Lake	yellow perch	9/12/2023	5	298	315	5

Sample ID	Site	Species	Collection Date	Number in Composite	Mean Total Length (mm)	Mean Total Weight (g)	Mean Age (years)
2311025-59	Lake Goodwin	largemouth bass	10/9/2023	3	263	290	2
2311025-51	Lake Goodwin	smallmouth bass	10/9/2023	5	182	84	1
2311025-52	Lake Goodwin	smallmouth bass	10/9/2023	3	216	140	2
2311025-53	Lake Goodwin	smallmouth bass	10/9/2023	3	261	237	2
2311025-54	Lake Goodwin	yellow perch	10/9/2023	5	150	41	1
2311025-55	Lake Goodwin	yellow perch	10/9/2023	5	158	44	1
2311025-56	Lake Goodwin	yellow perch	10/9/2023	5	168	53	1
2311025-57	Lake Goodwin	yellow perch	10/9/2023	5	173	57	1
2311025-58	Lake Goodwin	yellow perch	10/9/2023	5	185	71	1
2311025-50	Horsethief Lake	largemouth bass	10/4/2023	2	246	251	2
2311025-45	Horsethief Lake	smallmouth bass	10/4/2023	5	242	187	2
2311025-46	Horsethief Lake	smallmouth bass	10/4/2023	5	274	279	2
2311025-47	Horsethief Lake	smallmouth bass	10/4/2023	4	284	297	2
2311025-48	Horsethief Lake	smallmouth bass	10/4/2023	4	355	629	4

Sample ID	Site	Species	Collection Date	Number in Composite	Mean Total Length (mm)	Mean Total Weight (g)	Mean Age (years)
2311025-49	Horsethief Lake	walleye	10/4/2023	3	345	363	1
2311025-36	Leland Lake	black crappie	10/2/2023	5	173	70	2
2311025-37	Leland Lake	black crappie	10/2/2023	5	178	81	2
2311025-38	Leland Lake	black crappie	10/2/2023	4	197	106	2
2311025-39	Leland Lake	black crappie	10/2/2023	5	216	152	2
2311025-33	Leland Lake	bluegill	10/2/2023	5	163	89	2
2311025-34	Leland Lake	bluegill	10/2/2023	5	175	112	3
2311025-35	Leland Lake	bluegill	10/2/2023	4	189	142	3
2311025-28	Leland Lake	largemouth bass	10/2/2023	5	220	126	2
2311025-29	Leland Lake	largemouth bass	10/2/2023	5	244	182	2
2311025-30	Leland Lake	largemouth bass	10/2/2023	5	310	444	3
2311025-31	Leland Lake	largemouth bass	10/2/2023	5	397	972	6
2311025-32	Leland Lake	largemouth bass	10/2/2023	5	482	1631	7
2311025-40	Leland Lake	rainbow trout	10/2/2023	2	272	182	1

Sample ID	Site	Species	Collection Date	Number in Composite	Mean Total Length (mm)	Mean Total Weight (g)	Mean Age (years)
2311025-79	Leland Lake	rainbow trout	10/2/2023	3	336	454	2
2311025-77	Loomis Lake	black crappie	10/30/2023	4	281	363	5
2311025-78	Loomis Lake	black crappie	10/30/2023	3	305	461	6
2311025-74	Loomis Lake	largemouth bass	10/30/2023	3	279	326	2
2311025-75	Loomis Lake	largemouth bass	10/30/2023	3	314	455	3
2311025-76	Loomis Lake	largemouth bass	10/30/2023	2	438	1358	9
2311025-01	McIntosh Lake	largemouth bass	9/11/2023	5	221	135	2
2311025-02	McIntosh Lake	largemouth bass	9/11/2023	5	233	156	2
2311025-03	McIntosh Lake	largemouth bass	9/11/2023	5	250	183	3
2311025-04	McIntosh Lake	largemouth bass	9/11/2023	5	284	305	4
2311025-05	McIntosh Lake	largemouth bass	9/11/2023	5	400	905	7
2311025-06	McIntosh Lake	yellow perch	9/11/2023	4	191	76	4
2311025-20	Lake Nahwatzel	largemouth bass	9/13/2023	5	239	182	3
2311025-21	Lake Nahwatzel	largemouth bass	9/13/2023	5	258	224	3

Sample ID	Site	Species	Collection Date	Number in Composite	Mean Total Length (mm)	Mean Total Weight (g)	Mean Age (years)
2311025-22	Lake Nahwatzel	largemouth bass	9/13/2023	5	270	260	6
2311025-23	Lake Nahwatzel	largemouth bass	9/13/2023	5	283	299	6
2311025-24	Lake Nahwatzel	largemouth bass	9/13/2023	5	311	419	8
2311025-25	Lake Nahwatzel	rainbow trout	9/13/2023	3	311	324	2
2311025-26	Lake Nahwatzel	rainbow trout	9/13/2023	3	349	391	2
2311025-27	Lake Nahwatzel	rainbow trout	9/13/2023	2	371	511	2
2311025-82	Lake Nahwatzel	rainbow trout	9/13/2023	1	582	517	4
2311025-69	Lake Sammamish	cutthroat trout	10/9/2023	5	286	226	2
2311025-70	Lake Sammamish	cutthroat trout	10/9/2023	5	323	331	2
2311025-71	Lake Sammamish	cutthroat trout	10/9/2023	5	356	428	3
2311025-72	Lake Sammamish	cutthroat trout	10/9/2023	5	389	541	3
2311025-73	Lake Sammamish	cutthroat trout	10/9/2023	5	433	666	4
2311025-43	Spanaway Lake	bluegill	10/19/2023	4	154	73	2
2311025-44	Spanaway Lake	largemouth bass	10/19/2023	1	369	839	3

Sample ID	Site	Species	Collection Date	Number in Composite	Mean Total Length (mm)	Mean Total Weight (g)	Mean Age (years)
2311025-80	Spanaway Lake	largemouth bass	10/19/2023	2	246	218	2
2311025-42	Spanaway Lake	pumpkinseed	10/3/2023	2	166	109	2
2311025-83	Spanaway Lake	smallmouth bass	10/19/2023	1	409	996	4
2311025-41	Spanaway Lake	yellow perch	10/3/2023	5	266	257	2
2311025-60	Lake Stevens	brown bullhead	10/11/2023	3	272	245	2
2311025-61	Lake Stevens	brown bullhead	10/11/2023	3	289	306	2
2311025-62	Lake Stevens	brown bullhead	10/11/2023	3	379	819	4
2311025-66	Lake Stevens	cutthroat trout	10/11/2023	1	420	929	2
2311025-67	Lake Stevens	cutthroat trout	10/11/2023	1	426	825	2
2311025-84	Lake Stevens	cutthroat trout	10/11/2023	1	421	747	2
2311025-85	Lake Stevens	cutthroat trout	10/11/2023	1	417	942	2
2311025-86	Lake Stevens	cutthroat trout	10/11/2023	1	378	547	2
2311025-87	Lake Stevens	cutthroat trout	10/11/2023	1	380	569	2
2311025-88	Lake Stevens	cutthroat trout	10/11/2023	1	293	259	3

Sample ID	Site	Species	Collection Date	Number in Composite	Mean Total Length (mm)	Mean Total Weight (g)	Mean Age (years)
2311025-68	Lake Stevens	kokanee	10/11/2023	1	336	275	2
2311025-64	Lake Stevens	largemouth bass	10/11/2023	4	210	124	2
2311025-65	Lake Stevens	largemouth bass	10/11/2023	4	250	221	2
2311025-63	Lake Stevens	smallmouth bass	10/11/2023	1	273	283	2
2311025-81	Lake Stevens	smallmouth bass	10/11/2023	2	379	836	4

Appendix E. Fish Species

Table E-1. Fish species common names, scientific names, and abbreviations.

Common Name	Scientific Name	Species Code
Black crappie	*Pomoxis nigromaculatus*	BC
Bluegill	*Lepomis macrochirus*	BG
Brown bullhead	*Ameiurus nebulosus*	BBH
Cuthroat trout	*Oncorhynchus clarkii*	CTT
Kokanee	*Oncorhynchus nerka*	KOK
Largemouth bass	*Micropterus salmoides*	LMB
Pumpkinseed	*Lepomis gibbosus*	PMP
Rainbow trout	*Oncorhynchus mykiss*	RBT
Smallmouth bass	*Micropterus dolomieu*	SMB
Walleye	*Sander vitreus*	WAL
Yellow perch	*Perca flavescens*	YP

Appendix F. Correlations

Table F-1. Spearman rank correlation coefficients for fish PFOS and T-PFAS concentrations versus fish length, weight, and age.

Lake	n	Species	PFOS:Fish Length	PFOS:Fish Weight	PFOS:Fish Age	T-PFAS: Fish Length	T-PFAS: Fish Weight	T-PFAS: Fish Age
American	5	LMB	**0.90***	**0.90***	0.53	**0.90***	**0.90***	0.53
Goodwin	5	YP	0.40	0.40	n/a	0.70	0.70	n/a
Leland	5	LMB	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10
McIntosh	5	LMB	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10
Nahwatzel	5	LMB	—	—	—	0.80	0.80	0.72
Sammamish	5	CTT	0.60	0.60	0.60	0.70	0.70	0.70
Stevens	7	CTT	0.11	0.39	-0.20	0.11	0.39	-0.20

Note. Bold * indicates that the correlation coefficient is significant at $p < 0.05$.

Table F-2. Spearman rank correlation coefficients for surface water PFAS concentrations versus ancillary water variables.

Variable	PFBA	PFPEA	PFHXA	PFHPA	PFOA	PFNA	PFDA	PFBS	PFPES	PFHXS	PFOS	T-PFAS
TSS	-0.06	-0.07	-0.07	0.00	-0.03	0.10	-0.28	0.00	-0.28	-0.14	-0.03	-0.03
TOC	-0.02	-0.43	-0.43	-0.29	-0.33	-0.05	-0.08	-0.37	-0.58	-0.66	-0.52	-0.33
DOC	-0.15	-0.59	-0.59	-0.45	-0.52	-0.23	0.08	-0.59	-0.58	-0.83	-0.71	-0.52
pH	-0.29	-0.05	-0.05	-0.26	-0.05	-0.27	0.08	-0.10	0.41	0.17	0.10	-0.05
Cond.	0.22	0.44	0.44	0.45	0.43	0.34	-0.08	0.32	0.08	0.41	0.57	0.43
Temp.	0.02	0.14	0.14	0.12	0.10	0.05	-0.08	0.17	0.41	0.32	0.14	0.10
DO	-0.32	-0.11	-0.11	-0.36	-0.10	-0.43	0.25	-0.12	0.08	0.10	0.05	-0.10

Note. Bold * indicates that the correlation coefficient is significant at $p < 0.05$.