ADDENDUM 02

Characterization of Potential Adverse Health Effects Associated with Consuming Fish from Lake Worth

Tarrant County, Texas

2023

INTRODUCTION

This addendum report summarizes the per- and polyfluoroalkyl substances (PFAS) sampling results from fish collected in December 2020 and December 2022 from Lake Worth, Texas. The addendum report addresses public health implications of consuming contaminated fish with PFAS and suggests actions to protect humans from possible adverse health effects.

BACKGROUND

History of Lake Worth Fish Consumption Advisory

In August 1990, the United States Environmental Protection Agency (USEPA) placed Air Force Plant No. 4 (AFP4) on the USEPA National Priorities List because of contaminated groundwater (ATSDR 1998a). In 1999, the United States Geological Survey surveyed fish from Lake Worth and found widespread polychlorinated biphenyls (PCB) contamination (USGS 1999). In 2000, the Texas Department of Health (now the Texas Department of State Health Services, DSHS) issued Fish and Shellfish Consumption Advisory 18 (ADV-18) to protect people from consuming PCB-contaminated fish from Lake Worth (DSHS 2000).

In 2008, the DSHS expanded the 2000 fish survey to include additional sampling locations and contaminants. The 2000 results confirmed PCB contamination in catfish and smallmouth buffalo and identified aldrin, dieldrin, and polychlorinated dibenzo-para-dioxins and polychlorinated dibenzofurans (PCDDs/PCDFs) in channel catfish. Based on these results, DSHS rescinded ADV-18 and issued ADV-45. ADV-45 advised people not to consume blue catfish, channel catfish, and smallmouth buffalo from Lake Worth (DSHS 2010).

In 2016, DSHS conducted a follow-up fish survey in Lake Worth. Results of the 2016 survey indicated that the combination of PCBs and PCDDs/PCDFs in specific fish species, including blue catfish, common carp, flathead catfish, freshwater drum, smallmouth buffalo, striped bass, and white bass, exceeded DSHS guidelines for protection of human health (DSHS 2016). Based on these results, DSHS rescinded ADV-45 and issued ADV-60 (DSHS 2018). ADV-60 recommends:

- all people do not eat smallmouth buffalo
- women of childbearing age and children less than 12 years do not eat flathead catfish, and
- all people limit their consumption of blue catfish, common carp, flathead catfish, freshwater drum, striped bass, and white bass.

Per- and Polyfluoroalkyl Substances

Per- and polyfluoroalkyl substances (PFAS) are a group of environmental persistent and ubiquitous chemicals. Because their chemical structure produces an ability to repel both oil and water, these compounds have been widely used for several decades in many consumer products, including non-stick cookware, clothing, and cosmetics, and to produce various materials, including aqueous film forming foam (Barzne-Hanson 2017, Lindstrom 2011).

Evidence from both animal and human studies demonstrate associations between PFAS exposure and a variety of adverse health effects, including high cholesterol, adverse reproductive and developmental effects, altered liver enzymes, thyroid disorders, and pregnancy hypertension (USEPA 2021). Some PFAS chemicals have also been identified as possible human carcinogens (ATSDR 2020).

People are primarily exposed to PFAS through their diet, and fish and other seafood often contain high concentrations. Several studies have confirmed that fish intake is associated with elevated levels of multiple PFAS compounds in the US population (Holzer 2020, Fujii 2015). Although PFAS contamination in water bodies is pervasive and comes from a wide range of sources, water bodies located near military locations where aqueous film forming foam was frequently used may be at risk for contamination. Previous studies have observed high levels of PFAS in fish tissue collected adjacent to military sites with PFAS-contaminated soil and groundwater (Goodrow 2020).

In Texas, aqueous film forming foam was used at several former and active military bases throughout the state and has resulted in PFAS contamination in soil and groundwater (ATSDR 2020b). Some of these military facilities are located adjacent to water bodies. It is possible that historic use of aqueous film forming foam has also led to PFAS contamination in nearby surface water and may have contaminated fish in these water bodies.

Lake Worth, Texas

Lake Worth is a 3,489-acre impoundment of the West Fork Trinity River located within the city limits of Fort Worth, Texas in northwest Tarrant County. It was constructed in 1914 by the City of Fort Worth to provide a municipal water supply. The reservoir is bordered by the Fort Worth Nature Center and Refuge at the upstream end of the lake and residential and commercial properties surround most of the other parts of the lake. Two large industrial facilities are located adjacent to the south side of the reservoir: United States Air Station Joint Reserve Base–Fort Worth (NASFW) and AFP4. Past operations from NASFW and AFP4 have resulted in documented environmental contamination to Lake Worth. Additionally, the NASFW has identified PFAS in groundwater from former facility operations using aqueous film forming foam.

PURPOSE

The purpose of the 2020 and 2022 fish surveys was to 1) evaluate PFAS in fish from Lake Worth; 2) determine the public health implications of consuming PFAS-contaminated fish; and, 3) suggest actions to protect humans from possible adverse health effects of consuming contaminated fish.

METHODS

Fish Sampling and Preparation

For each sampling event, DSHS targeted a sample size of at least 60 fish samples based on power calculations using estimates from the New Jersey Department of Environmental Protection for safe amounts of specific PFAS compounds in fish for unlimited human consumption. DSHS determined 60 samples to be of adequate power (almost 100%) to detect differences between safe levels of PFAS and levels needing consumption advisories for each species of fish, should these differences truly exist (NJDEPP 2019).

DSHS aimed to collect at least 5 different fish species at each sampling location to represent distinct ecological groups, capture a wide geographical distribution, include fish that are of local recreational fishing value, and include fish that are commonly consumed. Fish species included, blue catfish, channel catfish, freshwater drum, largemouth bass, smallmouth buffalo, common carp, crappie species (spp.), and white bass. Among these fish species, catfish and bass are the most popular among anglers at from Lake Worth (TWPWD 2021).

Except for crappie, DSHS collected fish following standard operating procedures described in Texas Fish Consumption Advisory Program Standard Operating Procedures (DSHS 2016b). Texas Parks and Wildlife (TPWD) provided crappie spp to DSHS as part of their routine fish population sampling activities. TPWD collected crappie spp. using trap nets.

Sampling locations in 2020 and 2022 included those from the 2016 DSHS fish survey at Lake Worth (DSHS 2016), including Lake Worth Dam (site 1), near the NASFW (site 2), near Carswell Field Runway (site 3), near Meandering Creek Road (site 4), Woods Inlet (site 5), Live Oak Creek (site 6), near Woods Island (site 7), near Mosque Point (site 8), State Highway 199 Bridge (site 9) and West Fork Trinity River (site 10).

Figure 1. Fish sampling locations, Lake Worth, Texas in December 2020 and 2022.

Fish were stored on wet ice and processed at the TPWD Inland Fisheries office (Fort Worth, Texas) at the end of each day. DSHS following standard operating procedures from the DSHS Seafood and Aquatic Life Unit survey team standard operating procedures and EPA quality control/assurance manual (DSHS 2020, USEPA 2000a). All fish were weighed and measured, and two fish skin-off fillets were prepared. DSHS properly packaged and froze fish, and then hand-delivered the samples to the Geochemical and Environmental Research Group (GERG) Laboratory, Texas A&M University, College Station, Texas, for chemical analysis.

DSHS also removed sagittal otoliths from fish collected in 2020 for age estimation following otolith extraction procedures recommended by the Gulf States Marine Fisheries Commission and Texas Parks and Wildlife Department (GSMFC 2009, TPWD 2009). Fish age was not estimated in fish collected in 2022 because DSHS was not able to remove sagittal otoliths from fish.

PFAS

Twenty-eight analytes of PFAS compounds from the following seven groups of PFAS were evaluated:

- Perfluoroalkylcarboxilic acids (PFCAs)
- Perfluoroalkylsulfonates (PFASs)
- Perfluorooctanesulfonamides (PFOSAs)
- Telomer sulfonates
- Fluorotelomer carboxylic acids (FTCAs)
- Perfluorooctanesulfonamidoacetic acids
- Perfluoroether carboxylic acids (Gen X).

These seven categories of PFAS include 28 specific and common variations of PFAS analytes (Table 1). Among these compounds, perfluorohexanoic acid (PFHxA), a type of PFCA, and perfluorooctanesulfonic acid (PFOS), a type of PFAS, are both associated with aqueous film forming foam substances (Houtz 2013). Additionally, PFOS, PFHxA, perfluoro-n-nonanoic acid (PFNA), and perfluoro-n-octanoic acid (PFOA) have all been detected in other fish studies (NJDEPP 2018).

PFAS can be categorized by not only the terminal functional group, but also by its chain length. Short-chain PFAS include carboxylates with less than seven fluorinated carbon atoms (less than eight total carbons; PFHpA and shorter), and sulfonates with less than six carbons (PFBS). Long-chain compounds tend to bioaccumulate and be more toxic compared to shorter chain PFAS compounds. The solubility of PFAS compounds in water is inversely proportional to the length of the carbon chain (Conder 2008, Lau 2012, Prevedouros 2006). Both short- and long-chain types of PFAS were evaluated in fish collected from Lake Worth.

PFAS Analysis in Fish Samples

The GERG laboratory evaluated fish samples for PFAS using established methods (van Leeuwen 2009, Powley 2008). Briefly, the samples were stored frozen until homogenized and then frozen again until extraction. The samples and quality control samples were subsampled, weighed, spiked with surrogate standards, and extracted through dispersive solid phase extraction. The extracts were injected with standards and then analyzed using liquid chromatography tandem mass spectrometry. DSHS conducted quality assurance and quality control (QA/QC) on the analytical results following standard operating procedures and determined that data met QC/QC criteria as outlined in DSHS Seafood and Aquatic Life Unit survey team standard operating procedures and EPA quality control/assurance manual (DSHS 2020, USEPA 2000a).

Health-based Assessment Comparison (HAC) Values

If diverse species of fish are available, DSHS assumed that people eat a variety of species from a water body. Further, DSHS assumed that most fish species are mobile. In this analysis, DSHS combine data from different fish species and sample sites within Lake Worth to evaluate mean contaminant concentrations of PFAS in all samples. This approach intuitively reflects consumers' likely exposure over time to contaminants in fish from any water body but may not reflect the reality of exposure at a specific location within a water body or a single point in time.

DSHS evaluated PFAS in fish by comparing the mean concentration of a PFAS compound to its health-based assessment comparison (HAC) value for noncancer endpoints. HAC values are levels below which no adverse health effects are expected to occur following long-term and regular exposure. Chemical concentrations above HAC values do not necessarily mean there is a health concern, but rather suggests that further public health evaluation based on site-specific exposure conditions is needed. DSHS derived HAC values using reference doses (RfD) derived by the Texas Commission on Environmental Quality (TCEQ 2016) or other available health guidelines (Table 1). Health guidelines were not available for some PFAS compounds, including perfluoroundaconoic acid (PFUdA), perfluorononanesulfonic acid (PFNS), perfluoropentanesulfonic acid (PFPeS), perfluoroheptanoic acid (PFHpS) fluorotelomer carboxylic acids (FTCAs), perfluorooctancesulfonamidoacetic acids, and perfluoro ether carboxylic acids (such as Gen X). If detected, compounds without health guidelines were evaluated cumulatively as part of total PFAS.

Table 1. Per- and polyfluoroalkyl substances (PFAS) analytes (abbreviations) analyzed and available reference doses (RfD)	
Perfluoroalkylcarboxilic Acids (PFCAs)	RfD (mg/kg/day)
Perfluorotetradecanoic acid (PFTeDA)	1.2E-05
Perfluorotridecanoic acid (PFTrDA)	1.2E-05
Perfluorododecanoic acid (PFDoA)	1.2E-05
Perfluoroundaconoic acid (PFUdA)	NA
Perfluorodecanoic acid (PFDA)	1.5E-05
Perfluorononanoic acid (PFNA)	1.2E-05
Perfluorooctanoic acid (PFOA)	1.2E-05
Perfluoroheptanoic acid (PFHpA)	2.3E-05
Perfluorohexanoic acid (PFHxA)	3.8E-06
Perfluoropentanoic acid (PFPeA)	3.8E-06
Perfluorobutanoic acid (PFBA)	2.9E-03
Perfluoroalkylsulfonates (PFASs)	
Perfluorodecansulfonic acid (PFDS)	1.2E-05
Perfluorononanesulfonic acid (PFNS)	NA
Perfluorooctanesulfonic acid (PFOS)	2.3E-05
Perfluoroheptanesulfonic acid (PFHpS)	NA
Perfluorohexanesulfonic acid (PFHxS)	3.8E-06
Perfluoropentanesulfonic acid (PFPeS)	NA
Perfluorobutanesulfonic acid (PFBS)	1.4E-03
Perfluorooctanesulfonamides (PFOSAs)	
Perfluoro-1-octanesulfonamide (FOSA-1)	1.2E-05
Telomer Sulfonates	
Sodium 1H,1H,2H,2H-perfluorodecane sulfonate (8:2 FTS)	NA
Sodium 1H,1H,2H,2H-perfluorooctane sulfonate (6:2 FTS)	NA

Sodium 1H,1H,2H,2H-perfluorohexane sulfonate (4:2 FTS)	NA
Fluorotelomer carboxylic acids (FTCAs)	
2-Perfluorodecyl ethanoic acid (10:2 FTCA) FDEA	NA
2-Perfluorooctyl ethanoic acid (8:2 FTCA) FOEA	NA
2-Perfluorohexyl ethanoic acid (6:2 FTCA) FHEA	NA
Perfluorooctancesulfonamidoacetic Acids	
N-ethylperfluoro-1-octanesulfonamidoacetic acid (N-EtFOSAA)	NA
N-methylperfluoro-1-octanesulfonamidoacetic acid (N-MeFOSAA)	NA
Perfluoro ether carboxylic acids	
Hexafluoropropylene oxide dimer acid (GenX)	NA

Abbreviations: NA=not available; RfDs are from TCEQ (TCEQ 2016).

The HAC values were determined as follows:

$$HAC = \frac{RfD \times BW \ x \ RSC}{IR}$$

Where:

- HAC = Health-based assessment comparison value (ng/kg-day)
- RfD = Reference dose (ng/kg-day)
- BW = Body weight (kg)
- IR = Intake rate (kg/day)
- RSC = Relative source contribution (unitless)

DSHS used a relative source contribution of 1 for all HAC calculations assuming the majority of PFAS exposure is from fish consumption.

DSHS used standard exposure parameters for healthy adults, children (under 6 years) and subsistence fishers (Table 2) (USEPA 2000a). DSHS assumed an adult weighs 70 kilograms (kg) and consumes 30 grams (g) of fish per day and a child weighs 15 kg and consumes 15 g per day. DSHS assumed a meal size of 227 g (about 8 ounces) and 113 g (about 4 ounces) for an adult and child, respectively. Taken together, these assumptions equal about one meal of fish per week (or 4 meals per month) for both adults and children. This is a health protective exposure estimate which is consistent with a full and unrestricted use of the fish resource. Instead of estimating health risks for women of childbearing age, the health risks for children were applied to women of childbearing age.

Subsistence fishers are those that rely on fishing to provide for basic needs. Although DSHS does not consider subsistence fishers in their fish consumption advisories, this group was evaluated in the risk characterization because they might be at greater risk than other adults of exposure to contaminants in fish due to higher consumption rates. DSHS used a consumption rate of 142 g per day (g/day) and meal size of 227 g per meal (g/meal) for subsistence fishers (USEPA 2000a). Using these exposure parameters, DSHS estimated that a subsistence fisher would eat about 4.6 meals per week (or about 19 meals per month).

Table 2. Exposure parameters for target populations

Target Population	Body Weight (kg)	Intake Rate (g/day)	Meal Size (g/meal)
Adults	70	30	227
Children (less than 6 years)	15	15	113
Subsistence Fishers	70	142	227

Abbreviations: kg=kilogram; g/day=grams per day; g/meal=grams per meal

Hazard Quotients and Hazard Indices

To calculate noncancer health risks, DSHS calculated the hazard quotient (HQ). The HQ is the ratio of the estimated exposure to a chemical over the level at which no adverse health effect is expected. The HQ is derived by dividing the contaminant concentration detected in fish by the HAC. An HQ less than 1 means no adverse health effects are expected and an HQ greater than 1 means adverse health effects are possible.

The HQ was determined as follows:

$$HQ = \frac{C}{HAC}$$

Where:

- HQ = Hazard quotient (unitless)
- C = Mean concentration in fish (ng/kg wet)
- HAC = Health-based assessment comparison value (ng/kg)

DSHS calculated the hazard index (HI) to assess additive mixture toxicity. The HI is the sum of HQs for a group of chemicals that share a similar mode of action and target organ.

The HI was determined as follows:

$$HI = \sum HQ$$

Where:

- HI = Hazard index (unitless)
- HQ = Hazard quotient (unitless)

Because PFAS compounds have similar and overlapping modes of action and target organs and to consider PFAS without health guidelines, HIs were determined by combining the results of all PFAS substances detected (ATSDR 2021). DSHS also calculated HIs combining the mean concentrations of PFAS with other contaminants, including PCBs and PCDDs/PCDFs, detected in the 2016 Lake Worth fish survey (DSHS 2016). For this evaluation, DSHS assumed PCBs and PCDDs/PCDFs have similar modes of action and target organs as PFAS (ATSDR 1998b, ATSDR 2000).

The HI was determined as follows:

$$HI = \sum HQ$$

Where:

- HI = Hazard index (unitless)
- HQ = Hazard quotient (unitless)

Fish Consumption Advisory

Fish consumption advisories are not regulatory standards, but are recommendations intended to provide additional information to high-risk groups. DSHS develops risk-based fish consumption advisories following EPA guidance (USEPA 2020) and uses species-specific data on concentrations of individual contaminants to determine how often it is safe to eat a species of fish. A consumption advisory may be triggered when the HI is above 1 and if the calculated meals per month is below 4 (or below 1 meal per week). DSHC calculated the maximum number of recommended meals of fish per month (MpM) using standard exposure parameters (Table 2), health guidelines (such as TCEQ's RfDs) and the measured mean concentration of contaminant using the equation below:

$$MpM = \frac{RfD * BW * ED}{MS * C}$$

Where:

- MpM = Meals per month (meals/month)
- RfD = Reference dose (mg/kg-day)
- BW = Body weight (kg)
- ED = Exposure duration (30.44 days/month)
- MS = Meal size (kg/meal)
- C = Mean concentration in fish (ng/kg wet)

DSHS also determined meals per month from ingestion of fish contaminated with multiple substances (MpMmixture) using the equation below:

$$MpM(mixture) = \sum_{i=1} (\frac{RfD_i}{C_i}) * \frac{BW * ED}{MS}$$

Where:

- MpM = Meals per month (meals/month)
- RfD_i = Reference dose for chemical i (mg/kg-day)
- C_i = Mean concentration in fish for chemical i (ng/kg wet)
- BW = Body weight (kg)
- ED = Exposure duration (30.44 days/month)
- MS = Meal size (kg/meal)

Statistics

DSHS used a non-parametric analysis, Kendall's Tau, to determine significant correlations between average PFOS concentrations for each fish species and fish length, weight, and age, respectively, where $p > .05$ (Table 4, Figure A2).

RESULTS AND DISCUSSION

In 2020, DSHS collected fish samples from 10 sample sites across Lake Worth to provide spatial coverage of the study area, including Lake Worth Dam (site 1), near the NASFW (site 2), near Carswell Field Runway (site 3), near Meandering Creek Road (site 4), Woods Inlet (site 5), Live Oak Creek (site 6), near Woods Island (site 7), near Mosque Point (site 8), State Highway 199 Bridge (site 9) and West Fork Trinity River (site 10). In 2022 DSHS collected fish from locations that had the highest PFAS levels. These locations included: Lake Worth Dam (site 1), near the NASFW (site 2), Carswell Field Runway (site 3), Meandering Creek Road (site 4), Woods Inlet (site 5), near Mosque Point (site 8), and State Highway 199 Bridge (site 9).

Among the 2020 and 2022 sample events, DSHS collected a total of 109 fish of 8 different species (blue catfish, smallmouth buffalo, channel catfish, freshwater drum, largemouth bass, common carp, crappie spp, and white bass) from 10 different locations from Lake Worth (Table 3). In 2020, DSHS collected six blue catfish, 16 smallmouth buffalo, 10 channel catfish, 18 freshwater drum, and 10 largemouth bass (Table 3). In 2022, DSHS collected six common carp, 14 crappie spp, 7 freshwater drum, 11 largemouth bass, 7 smallmouth buffalo, and 4 white bass (Table 3).

Correlations between length and age for largemouth bass, channel catfish and blue catfish, respectively, were evaluated (Figure A1). PFOS levels in largemouth bass were positively correlated with fish length and weight, respectively (Table 4; Figure A2). Age was not correlated with PFOS levels in largemouth bass, blue catfish, and channel catfish.

Table 3. Location, type and number of fish collected from Lake Worth, Texas, December 2020 and 2022*

Species	2020 Fillets (n=60)	2022 Fillets (n=49)
Blue Catfish	6 (10)	NS
Channel Catfish	16 (27)	NS
Freshwater Drum	10 (17)	7 (14)
Largemouth Bass	18 (30)	11 (22)
Smallmouth buffalo	10 (17)	7 (14)
Common Carp	NS	6 (12)
Crappie spp	NS	14 (29)
White Bass	NS	4 (8)
Location		
Lake Worth Dam (site 1)	9 (15)	8 (16)
Naval Air Station (site 2)	7 (12)	5 (10)
Carswell Runway (site 3)	8 (13)	7 (14)
Meandering Creek (site 4)	9 (15)	9 (18)
Woods Inlet (site 5)	3 (5)	7 (14)
Live Oak Creek (site 6)	6 (10)	NS
Woods Island (site 7)	4 (7)	NS
Mosque Point (site 8)	4 (7)	7 (14)
State Highway Bridge 199 (site 9)	6 (10)	6 (12)

Table 3. Location, type and number of fish collected from Lake Worth, Texas, December 2020 and 2022*		
Species	2020 Fillets (n=60)	2022 Fillets (n=49)
West Fork Trinity River (site 10)	4 (7)	NS
Length (mm)		
Blue Catfish	640.3 (125.1)	NS
Smallmouth Buffalo	673.6 (51.5)	NS
Channel Catfish	504.8 (58.9)	NS
Freshwater Drum	495.5 (53.1)	505.0 (41.8)
Largemouth Bass	435.1 (39.7)	469.6 (51.9)
Common Carp	NS	606.3 (80.0)
Crappie spp	NS	281.7 (21.0)
White Bass	NS	303.0 (21.0)
Weight (g)		
Blue Catfish	3181.7 (1926.7)	NS
Smallmouth Buffalo	6359.5 (1474.3)	NS
Channel Catfish	1165.9 (501.3)	NS
Freshwater Drum	1771.1 (701.3)	1693.0 (458.8)
Largemouth Bass	1320.5 (488.9)	1617.2 (536.4)
Common Carp	NS	3269. 5 (1407.8)
Crappie spp	NS	329.6 (66.9)
White Bass	NS	342.3 (34.4)
Age (year)		
Blue Catfish	11.7 (2.9)	NS
Smallmouth Buffalo	NA	NA
Channel Catfish	6.3 (2.1)	NS
Freshwater Drum	NA	NA
Largemouth Bass	4.3 (1.1)	NA

Table 3. Location, type and number of fish collected from Lake Worth, Texas, December 2020 and 2022*		
Species	2020 Fillets (n=60)	2022 Fillets (n=49)
Common Carp	NS	NA
Crappie spp	NS	NA
White Bass	NS	NA

Notes: *Categorical variables are reported as n (percent) and continuous variables are reported as mean (standard deviation). Abbreviations: mm = millimeter; g = grams; NA = not analyzed; NS = not sampled.

Table 4. Correlation analysis of PFOS levels and length, weight, and age of fish			
	Tau	p value	n
Largemouth bass			
Length	**.29**	**.03**	29
Weight	**.31**	**.02**	29
Age	.21	.31	16
Channel catfish			
Length	-.03	.89	16
Weight	.02	.96	16
Age	.07	.71	16
Blue catfish			
Length	.47	.27	6
Weight	.47	.27	6
Age	.14	.7	6
Smallmouth buffalo			
Length	0	1	17
Weight	.09	.66	17
Freshwater drum			
Length	0	1	17
Weight	-.04	.84	17
Crappie spp			

Length	-.23	.25	14
Weight	-.14	.48	14
White bass			
Length	0	1	4
Weight	0	1	4

Notes: Kendall's Tau was used to determine statistically significant correlations (where 0 is not correlated and -1 and 1 are most correlated) between average PFOS concentrations for each fish species and fish length, weight, and age where $p < .05$. Bold values indicated statistically significant correlations.

PFAS Levels in Fish

The overall summary (including combined sampling results from 2020 and 2022 fish sampling events) of PFAS levels per fish species and location is provided in Table A1. PFAS was detected in all fish species and at all locations. Of the 28 PFAS analytes included in the survey, 21 were detected in at least one fish fillet (PFTeDA, PFTrDA, PFDoA, PFUdA, PFDA, PFNA, PFOA, PFHpS, PFPeA, PFBA, PFDS, PFNS, PFOS, PFHpS, PFHxS, PFHxA, PFPeS, PFBS, FOSA-1, 6:2FTS, and 8:2FTS).

Highest concentrations were measured in freshwater drum (50,841.9 ng/kg wet) and common carp (24,331.8 ng/kg wet) at the Carswell Field Runway (site 3). The lowest PFOS levels were detected in channel catfish (406.9 ng/kg and 557.7 ng/kg) at Woods Inlet and State Highway Bridge 199 (sites 5 and 9) and in blue catfish (881.1 ng/kg) at West Fork Trinity River (site 10) (Table A1). PFOS levels varied among species. Regardless of sample location, smallmouth buffalo, largemouth bass, and freshwater drum generally contained higher levels than channel catfish and blue catfish.

While PFOS was measured at the highest concentrations, there was variation of other PFAS analytes by sample location and species (Table A1). The longest chain PFAS compounds (greater than 9 carbons) were found in all fish species. Highest levels were measured in largemouth bass and freshwater drum at Lake Worth Dam (site 1) and Carswell Runway (site 3).

PFAS in Water and Sediment Samples

In 2020 one water sample was collected at Meandering Creek (site 4) and another at State Highway Bridge 199 Bridge (site 9). In 2022, seven additional water samples were collected at each fish sampling location, including Lake Worth Dam (site 1), Naval Air Station (site 2), Carswell Runway (site 3), Meandering Creek (site 4), Woods Inlet (site 5), Mosque Point (site 8), and State Highway Bridge 199 (site 9). All samples were analyzed for PFAS (Table 5). Ten PFAS compounds were detected in at least one of the water samples, including PFBA, PFPeA, PFHxA, PFHpA, PFOA, PFNA, PFBS, PFPeS, PFHxS, and PFOS. In 2022, PFOS and PFOA concentrations exceeded the EPA proposed maximum contaminant level of 4 nanograms per liter (ng/L) at the Meandering Creek (site 4) and Woods Inlet (site 5) (USEPA 2023).

Table 5. Detected PFAS (ng/L) in surface water, Lake Worth 2020 and 2022										
Site Location (sampling year)	PFBA	PFBS	PFHpA	PFHxA	PFHxS	PFOA	PFOS	PFPeA	PFNA	PFPeS
Lake Worth Dam - Site 1 (2022)	8.0	3.9	1.7	4.5	6.1	2.7	2.7	6.0	ND	ND
Naval Air Station - Site 2 (2022)	9.1	3.2	2.0	5.2	6.6	2.7	2.8	5.5	ND	ND
Carswell Runway - Site 3 (2022)	8.6	3.6	1.6	5.6	7.2	3.2	2.4	6.0	ND	ND
Meandering Creek - Site 4 (2022)	10.8	4.3	2.1	8.7	18.1	**4.7**	**4.9**	6.6	ND	ND
Meandering Creek - Site 4 (2020)	7.4	3.5	1.3	3.0	6.4	2.7	2.6	5.3	0.5	1.5
Woods Inlet - Site 5 (2022)	9.8	4.0	1.7	6.2	10.3	3.6	**4.5**	5.8	ND	ND
Mosque Point - Site 8 (2022)	8.2	2.8	1.5	3.7	4.1	2.3	1.6	5.0	ND	ND
State Highway Bridge 199 -Site 9 (2022)	8.1	3.0	1.2	2.5	1.7	1.6	0.8	4.8	ND	ND
State Highway Bridge 199 -Site 9 (2020)	7.4	1.8	0.9	1.5	0.9	1.5	0.9	3.5	0.5	ND

Abbreviations: ng/L=nanogram per liter; ND= not detected; PFAS= per- and polyfluoroalkyl substances; PFBA= perfluorobutanoic acid; PFPeA= perfluoropentanoic acid; PFHxA= perfluorohexanoic acid; PFOA= perfluorooctanoic acid; PFNA= perfluorononanoic acid; PFBS= perfluorobutanesulfonic acid; PFPeS= perfluoropentanesulfonic acid; PFHxS= perfluoropentanesulfonic acid; PFOS= perfluorooctanesulfonic acid; PFHpS=perfluoroheptanesulfonic acid; ND = not detected. Bold values indicated concentrations above the proposed maximum contaminant level.

In 2022, seven sediment samples were collected at each fish sampling location, including Lake Worth Dam (site 1), Naval Air Station (site 2), Carswell Runway (site 3), Meandering Creek (site 4), Woods Inlet (site 5), Mosque Point (site 8), and State Highway Bridge 199 (site 9) (Table 6). Ten PFAS compounds were detected in at least one of the sediment samples. These included: 6:2FTS, PFDA, PFHpA, PFHxA, PFHxS, PFNA, PFOA, PFOS, PFPeA, and PFUdA (Table 6). PFOS was detected most frequently and at the highest concentration compared to the other PFAS compounds. Most PFAS compounds were detected at Meandering Creek (site 4) and Woods Inlet (site 5). These sites are located adjacent to the naval air base and at the mouth of two creeks that feed into the lake. PFAS sources from the base and other inputs from urban creeks may contribute to these high concentrations.

Table 6. Detected PFAS (ng/kg) in sediment, Lake Worth, 2022										
Location	6:2FTS	PFDA	PFHpA	PFHxA	PFHxS	PFNA	PFOA	PFOS	PFPeA	PFUdA
Lake Worth Dam - Site 1 (2022)	1870.6	ND	ND	ND	ND	ND	ND	ND	ND	ND
Naval Air Station - Site 2 (2022)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Carswell Runway - Site 3 (2022)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Meandering Creek - Site 4 (2022)	ND	173.9	ND	ND	ND	ND	ND	2150.2	ND	ND
Woods Inlet - Site 5 (2022)	ND	75.7	123.8	91.2	124.7	120.4	170.4	714.5	74.5	115.1
Mosque Point - Site 8 (2022)	ND	ND	ND	ND	ND	ND	ND	230.8	ND	ND
State Highway Bridge 199 - Site 9 (2022)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

Abbreviations: ng/kg=nanogram per kilogram; ND= not detected; PFAS= per- and polyfluoroalkyl substances; 6:2FTS = sodium 1H,1H,2H,2H-perfluorooctane sulfonate; PFDA=perfluorodecanoic acid; PFHpA= perfluoroheptanoic acid; PFHxA= perfluorohexanoic acid; PFHxS= perfluorohexanesulfonic acid; PFNA= perfluorononanoic acid; PFOA= perfluorooctanoic acid; PFOS= perfluorooctanesulfonic acid; PFPeA= perfluoropentanoic acid; PFUdA= perfluoroudaconoic acid; ND = not detected.

Fish Consumption and Risk Assessment

DSHS evaluated the contribution of fish consumption on human exposure to PFAS by comparing the mean level (determine from the combined 2020 and 2022 sampling results) of a contaminant to its HAC value for noncancer endpoints. PFOS was detected at highest levels among the fish collected and average levels of PFOS were used to evaluate health risks. None of the other species of fish evaluated contained any PFAS substances with concentrations above HAC values. The average level of PFOS in freshwater drum was above the HAC value for subsistence fishers (HQ greater than 1) (Table 7).

Table 5. PFOS in fish and health assessment comparison (HAC) values and hazard quotients (HQ)

		Subsistence Fisher		Adult		Children/ Women of childbearing age *	
PFAS Type	Species	HAC (ng/kg)	HQ	HAC (ng/kg)	HQ	HAC (ng/kg)	HQ
PFOS	Blue catfish	11338	0.1	53666	0.02	23000	0.05
	Channel catfish	11338	0.1	53666	0.02	23000	0.06
	Common carp	11338	0.7	53666	0.2	23000	0.4
	Crappie spp	11338	0.5	53666	0.09	23000	0.2
	Freshwater drum	11338	**1.6**	53666	0.3	23000	0.8
	Largemouth bass	11338	1.0	53666	0.2	23000	0.5
	Smallmouth buffalo	11338	0.5	53666	0.09	23000	0.2
	White bass	11338	0.8	53666	0.2	23000	0.4

Notes: *Women of childbearing age and children less than 6 years. Bold value indicates an HQ above 1. Abbreviations: HAC=health assessment comparison; HQ=hazard quotient; ng/kg=nanogram per kilogram; PFAS= per- and polyfluoroalkyl substances; PFOS= perfluorooctanesulfonic acid.

DSHS calculated the number of 8-ounce meals of fish healthy adults, subsistence fishers, and children (women of childbearing age) could consume without significant risk of PFAS-related adverse effects (Table 8). DSHS estimated that adults could consume 3 to 42 meals per week (12 to 186 meals per month) of various fish contaminated with PFOS and not experience any adverse health effects. Similarly, women of childbearing age and children less than 6 years could safely consume 1 to 18 meals per week (5 to 79 meals per month) of various fish contaminated with PFOS. However, the estimated meals per week of freshwater drum (3 meals per week) and largemouth bass (4 meals per week) is less than what a subsistence fisher would expect to eat (5 meals per week).

Table 8. Estimated number of meals (per week and per month) for PFOS					
		Adult/Subsistence Fishers		Children/Pregnant Women*	
PFAS Type	Fish Species	Meals/Month	Meals/Week	Meals/Month	Meals/Week
PFOS	Blue catfish	183	42	79	18
	Channel catfish	163	37	70	16
	Common carp	26	6	11.4	3
	Crappie spp.	42	10	18.3	4
	Freshwater drum	12	3	5.3	1
	Largemouth bass	19	4	8.4	2
	Smallmouth buffalo	43	10	18.4	4
	White bass	25	6	10.7	2

Notes: *Women of childbearing age and children less than 6 years.
Abbreviation: PFOS= perfluorooctanesulfonic acid.

PFAS Mixture

DSHS evaluated how a potential additive mixture would affect the consumption results. DSHS assumed all detected PFAS have the same mode of action and target organ. The results show the HIs are below 1 for adults and children (women of childbearing age). The number of meals per month vary from 10 to 82 for adults and 4 to 35 for children (women of childbearing age) (Table 9).

The hazard index for subsistence fishers is above 1 for common carp, freshwater drum, largemouth bass, and white bass and the meals per month for these fish ranging from 10 to 18. Therefore, these fish contain total PFAS at levels that may cause adverse health effects for subsistence fishers who regularly eat these fish.

Table 9. Potential additive mixture for all PFAS, HI and meals per month					
	Subsistence Fishers	Adult	Children/ Pregnant Women*	Meals/Month Mixture	
Species	Hazard Index	Hazard Index	Hazard Index	Adult/ Subsistence Fisher	Children/ Pregnant Women*
Blue catfish	0.23	0.05	0.11	82	35
Channel catfish	0.24	0.05	0.12	80	35
Common carp	**1.11**	0.23	0.55	17	7
Crappie spp	0.72	0.15	0.36	26	11
Freshwater drum	**1.86**	0.39	0.92	10	4
Largemouth bass	**1.21**	0.25	0.59	16	7
Smallmouth buffalo	0.62	0.13	0.31	31	13
White bass	**1.04**	0.22	0.51	18	8

Notes: *Women of childbearing age and children less than 6 years. Bold value indicates hazard index above 1. Abbreviation: PFOS= perfluorooctanesulfonic acid. Abbreviations: PFAS= per- and polyfluoroalkyl substances; HI=hazard index.

The results from the 2016 fish survey from Lake Worth determined that consumption of multiple contaminants, PCBs and PCDDs/PCDFs, in fish (blue catfish, common carp, flathead catfish, freshwater drum, smallmouth buffalo, striped bass and white bass) increases the likelihood of noncancer health risks. Even though fish consumption advisories were not triggered for PFAS in the current evaluation, there is potential that it may affect consumption advisories when treated as a mixture with other chemicals. Therefore, DSHS calculated HIs and meals per week (and meals per month) and assumed that PFOS have a similar mode of action as PCBs and PCDDs/PCDFs that would produce an additive mixture toxic effect.

Table 10 shows that the cumulative effect of PFOS, PCBs and PCDDs/PCDFs contamination does not change the existing estimated meals per week for blue catfish, common carp, crappie spp., freshwater drum, smallmouth buffalo, and white bass from what was determined in 2016 for adults. While the meals per week for channel catfish and largemouth bass decreased slightly from 1.1 to 0.9 meals per week, the decrease is not enough to trigger a fish consumption advisory for these fish.

Table 10. Hazard quotient and meals per week for adult consumption of fish with combined contaminants				
	PCB and PCDD/PCDFs*		PCB and PCDD/PCDFs added with PFOS	
Contaminant/Species	Hazard Quotient	Meals per Week (adult)	Hazard Quotient	Meals per Week (adult)
Blue catfish				
PCBs	0.41	2.3	0.41	2.3
PCDDs/PCDFs	**1.10**	**0.8**	**1.10**	**0.8**
PFOS	NA	NA	0.02	42.2
Hazard Index (meals per week)	**1.51**	**0.6**	**1.53**	**0.6**
Channel catfish				
PCBs	0.43	2.2	0.43	2.2
PCDDs/PCDFs	0.44	2.1	0.44	2.1
PFOS	NA	NA	0.02	37.4
Hazard Index (meals per week)	0.87	1.1	0.89	1.0
Common carp				
PCBs	0.73	1.3	0.73	1.3
PCDDs/PCDFs	0.78	1.2	0.78	1.2
PFOS	NA	NA	0.15	6.1
Hazard Index (meals per week)	**1.51**	**0.6**	**1.66**	**0.6**
Crappie spp				
PCBs	0.12	7.9	0.12	7.9
PCDDs/PCDFs	0.09	10.1	0.09	10.1
PFOS	NA	NA	0.09	9.8
Hazard Index (meals per week)	0.21	4.4	0.30	3.0
Freshwater drum				
PCBs	0.26	3.6	0.26	3.6
PCDDs/PCDFs	**1.00**	**0.9**	**1.00**	**0.9**

Table 10. Hazard quotient and meals per week for adult consumption of fish with combined contaminants				
	PCB and PCDD/PCDFs*		PCB and PCDD/PCDFs added with PFOS	
Contaminant/Species	Hazard Quotient	Meals per Week (adult)	Hazard Quotient	Meals per Week (adult)
PFOS	NA	NA	0.33	2.8
Hazard Index (meals per week)	**1.26**	**0.7**	**1.58**	**0.7**
Largemouth bass				
PCBs	0.19	4.8	0.19	4.8
PCDDs/PCDFs	0.69	1.4	0.69	1.4
PFOS	NA	NA	0.21	4.5
Hazard Index (meals per week)	0.88	1.1	**1.09**	**0.9**
Smallmouth buffalo				
PCBs	**2.27**	**0.4**	**2.27**	**0.4**
PCDDs/PCDFs	**3.39**	**0.3**	**3.39**	**0.3**
PFOS	NA	NA	0.09	9.8
Hazard Index (meals per week)	**5.66**	**0.2**	**5.75**	**0.2**
White Bass				
PCBs	0.75	1.2	0.75	1.2
PCDDs/PCDFs	**1.09**	**0.8**	**1.09**	**0.8**
PFOS	NA	NA	0.16	5.7
Hazard Index (meals per week)	**1.84**	**0.5**	**2.00**	**0.5**

Notes: *The results from the 2016 fish survey from Lake Worth determined that consumption of multiple contaminants (DSHS 2016a). Bold values show HQ greater than 1 or meals per week less than 1. NA= not analyzed; PCB= polychlorinated biphenyls; PCDD/PCDF= polychlorinated dibenzo-para-dioxins and polychlorinated dibenzofurans; PFOS= perfluorooctanesulfonic acid.

Table 11 shows that the cumulative effect of PFOS, PCBs and PCDDs/PCDFs contamination does not change the existing estimated meals per week for blue catfish, common carp, crappie spp, freshwater drum, smallmouth buffalo, and white bass from what was determined in 2016 for women of childbearing age and children less than 6 years. While the meals per week for channel catfish and largemouth bass decreased slightly from 0.5 to 0.4 meals per week, respectively, the decrease is not enough to change the existing recommendations.

Table 11. Hazard quotient and meals per week women of childbearing age and children less than 6 years consumption of fish with combined contaminants

	PCB and PCDD/PCDFs*		PCB and PCDD/PCDFs added with PFOS and	
Contaminant/Species	Hazard Quotient	Meals per Week (child)	Hazard Quotient	Meals per Week (child)
Blue catfish				
PCBs	0.95	**1.0**	0.95	**1**
PCDDs/PCDFs	**2.57**	**0.4**	**2.57**	**0.4**
PFOS	NA	NA	0.05	18
Hazard Index (meals per week)	**3.52**	**0.3**	**3.57**	**0.3**
Channel catfish				
PCBs	1.00	**0.9**	1.00	**0.9**
PCDDs/PCDFs	**1.02**	**0.9**	**1.02**	**0.9**
PFOS	NA	NA	0.06	16
Hazard Index (meals per week)	**2.02**	**0.5**	**2.08**	**0.4**
Common Carp				
PCBs	**1.70**	**0.5**	**1.70**	**0.5**
PCDDs/PCDFs	**1.83**	**0.5**	**1.83**	**0.5**
PFOS	NA	NA	0.35	2.6
Hazard Index (meals per week)	**3.53**	**0.3**	**3.88**	**0.2**
Crappie spp				
PCBs	0.28	3.4	0.28	3.4
PCDDs/PCDFs	0.21	4.3	0.21	4.3
PFOS	NA	NA	0.22	4.2

Table 11. Hazard quotient and meals per week women of childbearing age and children less than 6 years consumption of fish with combined contaminants				
	PCB and PCDD/PCDFs*		PCB and PCDD/PCDFs added with PFOS and	
Contaminant/Species	Hazard Quotient	Meals per Week (child)	Hazard Quotient	Meals per Week (child)
Hazard Index (meals per week)	0.49	1.9	0.71	1.3
Freshwater drum				
PCBs	0.60	1.5	0.60	1.5
PCDDs/PCDFs	2.33	**0.4**	**2.33**	**0.4**
PFOS	NA	NA	0.77	1.2
Hazard Index (meals per week)	**2.93**	**0.3**	**3.70**	**0.3**
Largemouth bass				
PCBs	0.45	2.1	0.45	2.1
PCDDs/PCDFs	**1.60**	**0.6**	**1.60**	**0.6**
PFOS	NA	NA	0.48	1.9
Hazard Index (meals per week)	**2.05**	**0.5**	**2.53**	**0.4**
Smallmouth buffalo				
PCBs	**5.30**	**0.2**	**5.30**	**0.2**
PCDDs/PCDFs	**7.90**	**0.1**	**7.90**	**0.1**
PFOS	NA	NA	0.22	4.2
Hazard Index (meals per week)	**13.20**	**0.07**	**13.42**	**0.07**
White bass				
PCBs	**1.75**	**0.5**	**1.75**	**0.5**
PCDDs/PCDFs	**2.54**	**0.4**	**2.54**	**0.4**
PFOS	NA	NA	0.38	2.5
Hazard Index (meals per week)	**4.29**	**0.2**	**4.67**	**0.2**

Table 11. Hazard quotient and meals per week women of childbearing age and children less than 6 years consumption of fish with combined contaminants				
	PCB and PCDD/PCDFs*		PCB and PCDD/PCDFs added with PFOS and	
Contaminant/Species	Hazard Quotient	Meals per Week (child)	Hazard Quotient	Meals per Week (child)

Notes: Bold values show HQ greater than 1 or meals per week less than 1. NA=not analyzed; PCB= polychlorinated biphenyls; PCDD/PCDF= polychlorinated dibenzo-para-dioxins and polychlorinated dibenzofurans; PFOS= perfluorooctanesulfonic acid

CONCLUSIONS

This fish survey addresses the public health implications of consuming fish contaminated with PFAS from Lake Worth, Texas. Confidence in the conclusions from several species of fish is limited by the small sample size.

PFAS levels detected in fish, including blue catfish, channel catfish, common carp, crappie spp., freshwater drum, largemouth bass, smallmouth buffalo, and white bass do not exceed DSHS guidelines for protection of adults, women of childbearing age and children. Therefore, the consumption of PFAS in these fish species is not likely to cause noncancer risk to human health. However, the consumption of PFAS in freshwater drum and largemouth bass has the potential to cause health risk to subsistence fishers.

The results of the 2016 risk characterization from Lake Worth showed that regular and long-term consumption of blue catfish, freshwater drum, smallmouth buffalo, striped bass and white bass contaminated with PCBs and PCDDs/PCDFs may result in adverse noncancer health effects.

Based on 2016 results, DSHS made the following recommendations:

- All people should not consume smallmouth buffalo from Lake Worth.
- Women of childbearing age and children less than 6 years should not consume flathead catfish.
- Women of childbearing age and children less than 6 years may consume up to one four-ounce meal per month of blue catfish, common carp, freshwater drum, striped bass or white bass.
- Women of childbearing age and children less than 6 years may consume up to two four-ounce meals per month of channel catfish and largemouth bass.
- Adults and non-pregnant women may consume up to one eight-ounce meal per month of flathead catfish.

- Adults and non-pregnant women may consume up to two eight-ounce meals per month of blue catfish, common carp, striped bass or white bass.
- Adults and non-pregnant women may consume up to three eight-ounce meals per month of freshwater drum.

In the current risk characterization, the addition of PFOS to the existing fish contamination does not change the noncancer health risk conclusions. However, common carp, striped bass, white bass, and flathead catfish were not evaluated in the 2020 and 2022 evaluations.

RECOMMENDATIONS

1. DSHS continue the consumption advisory (ADV-60) presently in place for fish from Lake Worth until contaminants, such as PCBs and PCDDs/PCDFs, are shown to have decreased to levels that are unlikely to pose a risk to human health.
2. DSHS continue to regularly monitor fish from Lake Worth for the presence and concentrations of PCBs, PCDDs/PCDFs, and PFAS.
3. DSHS include this addendum to the 2016 Risk Characterization for Lake Worth.

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APPENDICES

Table A1. Mean concentrations of PFAS in fish fillets from Lake Worth, Texas 2020 and 2022.																						
Location	Fish Species (number sampled)	PFAS* type (ng/kg wet)																				
		PFBA	PFBS	PFDA	PFDoA	PFDS	PFHpA	PFHpS	PFHxA	PFHxS	PFNA	PFNS	PFOA	PFOS	PFPeA	PFPeS	PFTeDA	PFTrDA	PFUdA	62FTS	82FTS	FOSA1
Lake Worth Dam (Site 1)	Channel catfish (2)	36.5	ND	402.1	205.5	95.4	ND	ND	ND	16.4	35.1	ND	25.4	1436.6	ND	ND	46.3	45.7	267.5	ND	ND	ND
	Common carp (2)	ND	ND	893.4	629.9	536.4	ND	10.1	ND	80.2	70.0	17.0	10.0	6444.7	ND	ND	224.1	291.1	902.1	ND	ND	ND
	Freshwater drum (2)	24.0	ND	930.1	875.0	260.9	ND	ND	ND	ND	44.4	13.9	32.1	5785.3	ND	ND	208.7	250.9	1036.2	ND	ND	ND
	Largemouth bass (8)	27.9	21.2	826.6	362.5	251.9	5.0	2.5	2.4	17.6	21.7	23.5	48.7	10119.7	ND	ND	101.2	105.7	538.0	ND	ND	ND
	Smallmouth buffalo (2)	16.3	ND	427.0	376.7	254.9	ND	ND	ND	37.9	57.7	24.0	26.5	5714.4	ND	ND	147.8	235.6	498.1	ND	ND	ND
	White bass (1)	ND	ND	602.8	207.1	148.3	ND	35.3	ND	42.0	248.9	ND	ND	9013.5	ND	ND	90.0	95.8	292.4	ND	ND	ND
Naval Air Station (NAS) (Site 2)	Blue catfish (1)	50.6	ND	467.6	268.2	70.0	ND	ND	ND	ND	ND	ND	15.8	1857.5	ND	ND	86.6	80.9	392.5	ND	ND	ND
	Channel catfish (3)	56.5	ND	327.5	153.0	35.3	ND	ND	ND	13.9	67.5	ND	23.1	1112.3	8.8	ND	49.7	55.6	202.9	ND	ND	ND
	Common carp (1)	ND	ND	309.0	151.2	231.2	ND	ND	ND	111.4	29.8	ND	20.9	6500.0	ND	ND	97.8	117.9	239.5	ND	ND	ND
	Largemouth bass (3)	18.4	ND	693.6	315.5	375.6	ND	ND	ND	19.8	26.0	54.2	13.2	14209.4	ND	ND	129.6	164.5	405.1	ND	ND	ND
	Smallmouth buffalo (4)	26.0	ND	242.7	228.8	211.2	ND	10.2	ND	69.6	21.6	13.0	19.3	8290.0	ND	ND	89.4	95.2	295.8	ND	ND	ND

Carswell Field Runway (Site 3)	Channel catfish (2)	48.6	ND	194.6	110.0	42.5	ND	9.1	ND	201.9	32.3	ND	22.9	3986.3	12.1	ND	35.7	45.7	129.5	ND	ND	166.1
	Common carp (1)	ND	ND	###	911.3	###	ND	50.2	ND	119.5	59.2	87.3	21.3	24331.8	ND	ND	321.6	533.9	1201.1	ND	ND	ND
	Freshwater drum (5)	48.5	ND	765.1	590.0	240.0	ND	15.0	7.0	17.7	87.3	24.7	22.5	50841.9	7.4	ND	200.0	223.5	639.5	ND	73.6	ND
	Largemouth bass (3)	17.2	ND	589.6	254.8	304.8	ND	ND	5.5	16.4	26.1	46.3	13.2	14304.4	ND	ND	78.3	128.5	328.8	ND	ND	ND
	Smallmouth buffalo (2)	29.4	ND	256.8	303.8	167.4	ND	ND	ND	70.9	43.1	22.0	16.0	7349.3	ND	ND	170.0	156.4	315.9	ND	ND	ND
	White bass (2)	ND	ND	770.3	268.6	263.3	ND	31.3	ND	74.9	252.5	24.6	ND	9542.0	ND	ND	124.2	145.9	334.4	ND	ND	ND
Meandering Creek Road (Site 4)	Crappie spp (2)	ND	ND	383.3	148.6	155.7	ND	20.3	ND	335.7	152.9	ND	18.7	5971.7	8.5	8.3	64.9	60.3	229.5	ND	ND	ND
	Freshwater drum (4)	18.7	ND	593.5	571.7	139.4	ND	ND	ND	ND	69.2	9.6	14.5	4062.8	22.3	ND	255.1	263.8	570.5	92.9	ND	ND
	Largemouth bass (8)	35.9	ND	717.3	234.3	264.0	ND	4.6	ND	13.0	7.5	28.9	2.6	14235.3	ND	ND	78.6	96.0	388.4	ND	ND	ND
	Smallmouth buffalo (3)	29.9	ND	419.8	316.0	93.7	ND	ND	ND	23.1	58.2	ND	22.6	3962.6	ND	20.3	88.7	112.7	394.9	ND	ND	ND
	White bass (1)	ND	ND	426.9	150.7	189.0	ND	24.6	ND	31.6	150.8	17.9	ND	6541.7	ND	ND	83.8	99.1	197.3	ND	ND	ND
Woods Inlet (Site 5)	Channel catfish (1)	66.4	ND	182.0	97.8	31.0	ND	ND	ND	22.3	36.2	ND	21.4	984.7	ND	ND	47.4	64.4	123.4	ND	ND	ND
	Common carp (1)	ND	ND	571.6	450.2	151.4	ND	ND	ND	142.9	87.2	ND	33.6	3983.1	ND	ND	190.4	235.2	466.9	ND	ND	ND
	Crappie spp (4)	ND	ND	389.1	141.6	147.7	ND	24.8	ND	365.8	139.4	9.3	25.3	6062.2	ND	ND	76.2	60.9	229.2	ND	ND	ND

	Freshwater drum (1)	54.5	ND	436.9	711.2	47.8	ND	ND	ND	ND	64.5	ND	ND	2054.8	ND	ND	332.2	266.2	426.0	ND	ND	ND
	Largemouth bass (1)	ND	ND	374.1	301.4	120.6	ND	ND	ND	26.3	ND	ND	ND	9383.6	ND	ND	124.4	105.3	295.5	ND	ND	ND
	Smallmouth buffalo (2)	27.9	ND	372.8	273.6	105.8	ND	ND	ND	27.7	52.7	9.5	24.5	4614.4	ND	ND	124.5	107.7	338.3	ND	ND	ND
Live Oak Creek (Site 6)	Blue catfish (1)	47.0	ND	212.0	137.9	59.9	ND	ND	ND	ND	ND	ND	ND	885.5	ND	ND	47.7	48.9	211.2	ND	ND	ND
	Channel catfish (2)	68.7	ND	275.5	98.4	47.8	ND	ND	ND	ND	18.2	ND	ND	837.3	25.1	ND	43.4	50.6	179.7	ND	ND	ND
	Freshwater drum (1)	64.3	ND	688.5	185.8	116.5	ND	ND	ND	ND	ND	ND	31.4	5924.5	ND	ND	43.8	60.8	362.6	ND	ND	ND
	Largemouth bass (1)	34.5	ND	600.5	362.7	93.6	ND	ND	ND	ND	25.8	ND	ND	4140.0	ND	ND	135.6	105.8	345.2	ND	ND	ND
	Smallmouth buffalo (1)	63.7	ND	114.0	80.1	36.9	ND	ND	ND	ND	ND	ND	26.2	1081.1	39.9	ND	26.3	25.0	140.3	ND	ND	ND
Woods Island (Site 7)	Blue catfish (1)	72.1	ND	430.5	295.0	80.8	ND	ND	ND	ND	ND	ND	ND	1185.6	ND	ND	70.4	101.6	510.3	ND	ND	ND
	Channel catfish (2)	60.8	ND	253.2	100.1	32.6	ND	ND	ND	ND	10.1	ND	ND	482.3	ND	ND	27.1	41.3	182.7	549.9	ND	ND
	Smallmouth buffalo (1)	70.2	ND	208.3	138.0	88.7	ND	ND	ND	ND	19.8	ND	26.5	2290.4	ND	ND	42.1	44.6	228.4	ND	ND	ND
Mosque Point (Site 8)	Channel catfish (1)	71.6	ND	456.4	106.5	32.5	ND	ND	15.9	23.5	34.3	ND	ND	1566.6	ND	ND	18.2	33.9	198.9	ND	ND	ND
	Crappie spp (5)	ND	ND	339.0	114.3	123.6	ND	7.7	ND	144.2	107.2	ND	21.8	4233.9	ND	ND	58.2	48.9	186.6	ND	ND	ND
	Freshwater drum (2)	29.9	ND	501.7	389.2	52.2	ND	ND	ND	ND	71.3	ND	ND	2165.0	ND	ND	158.9	151.4	418.9	ND	ND	ND

	Largemouth bass (3)	47.7	ND	438.9	138.6	90.6	ND	ND	ND	ND	ND	ND	5.6	4711.7	ND	ND	28.9	29.2	226.2	ND	ND	ND
State Highway Bridge 199 (Site 9)	Channel catfish (3)	92.0	8.8	240.3	133.5	52.1	ND	ND	ND	ND	42.6	ND	7.8	624.4	ND	ND	75.5	55.0	139.1	ND	ND	ND
	Common carp (1)	ND	ND	141.7	207.3	57.2	ND	ND	ND	ND	22.3	ND	ND	1280.4	ND	ND	202.8	114.0	117.3	ND	ND	ND
	Crappie spp (3)	ND	ND	373.3	111.7	110.2	ND	6.1	ND	185.0	122.6	ND	21.5	4587.8	18.1	ND	70.4	53.4	203.1	ND	ND	ND
	Freshwater drum (1)	ND	ND	426.3	395.6	37.7	ND	ND	ND	ND	78.8	ND	22.2	1246.7	ND	ND	166.6	111.3	284.6	ND	ND	ND
	Largemouth bass (2)	86.1	ND	467.0	281.7	165.3	ND	17.4	ND	56.4	10.3	ND	18.5	6782.8	ND	ND	84.0	72.6	381.5	ND	ND	ND
	Smallmouth buffalo (2)	41.3	ND	97.1	127.8	49.7	ND	ND	ND	ND	ND	ND	ND	1144.9	ND	ND	75.1	64.7	119.5	174.0	ND	ND
West Fork Trinity River (Site 10)	Blue catfish (3)	54.3	ND	374.5	209.1	72.6	ND	ND	ND	ND	8.3	ND	ND	1044.1	ND	ND	63.9	94.8	325.7	ND	ND	ND
	Freshwater drum (1)	60.8	ND	562.0	309.8	144.7	ND	ND	ND	ND	26.8	ND	ND	4273.4	ND	ND	97.9	143.7	450.2	ND	ND	ND

*Abbreviations: PFAS = per- and polyfluoroalkyl substances; ND = not detected; PFBA = perfluorobutanoic acid; PFBS = perfluorobutanesulfonic acid; PFDA = perfluorodecanoic acid; PFDoA = perfluorododecanoic acid; PFDS = perfluorodecansulfonic acid; PFHpA = perfluoroheptanoic acid; PFHxS = perfluorohexanoic acid; PFNA = perfluorononanoic acid; PFOA = perfluorooctanoic acid; PFOS = perfluorooctanesulfonic acid; PFPeA = perfluoropentanoic acid; PFPeS = perfluoropentanesulfonic acid; PFTeDA = perfluorotetradecanoic acid; PFTrDA = perfluorotridecanoic acid; PFUdA = perfluoroundaconic acid; 62FTS = sodium 1H,1H,2H,2H-perfluorooctane sulfonate; 82FTS = sodium 1H,1H,2H,2H-perfluorodecane sulfonate; FOSA1 = perfluoro-1-octanesulfonamide.

Figure A1. Correlation of length and age for largemouth bass (n = 16), channel catfish (n = 16), and blue catfish (n = 6). mm = millimeter

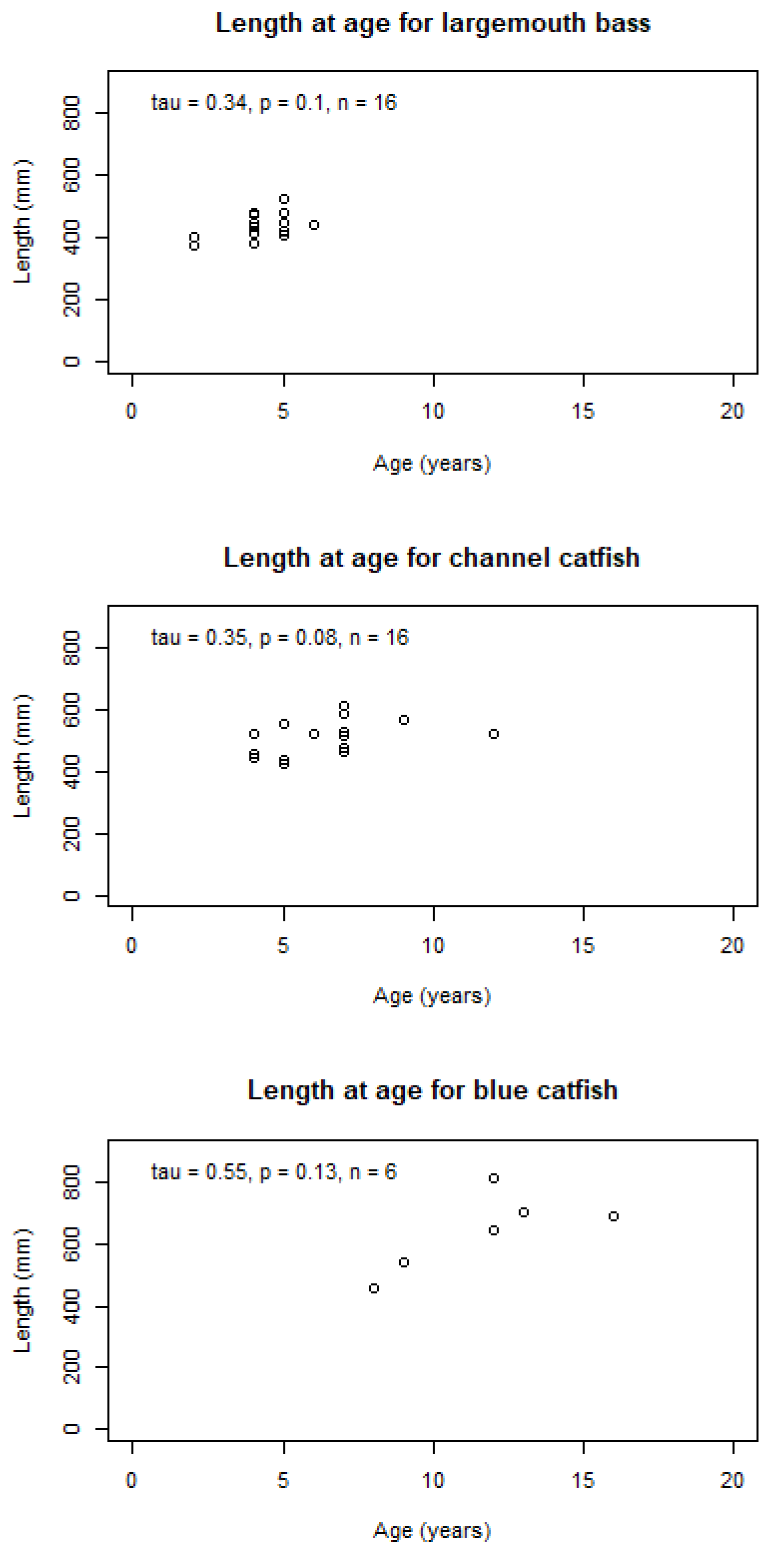
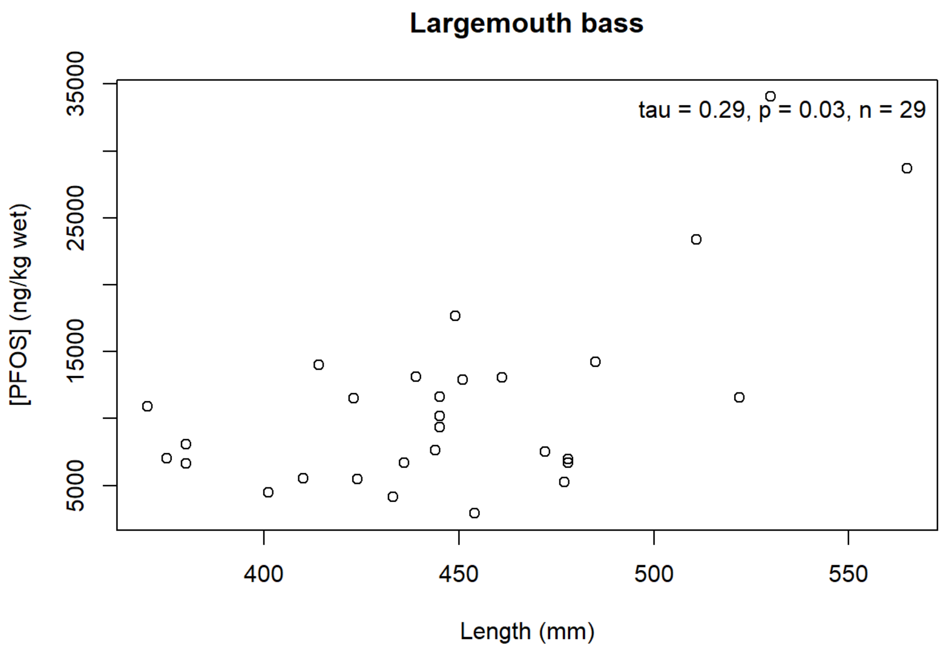
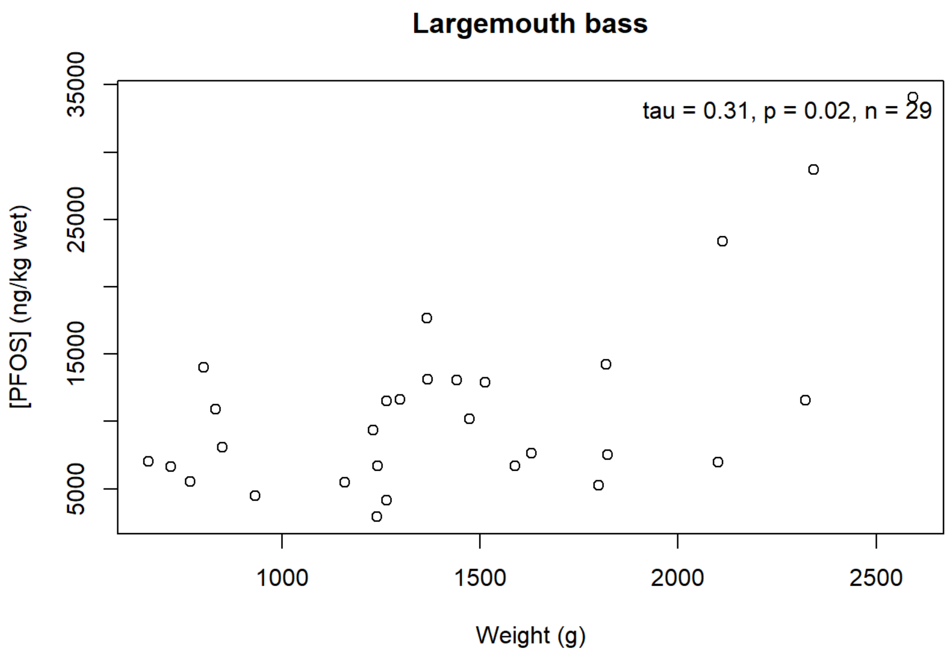
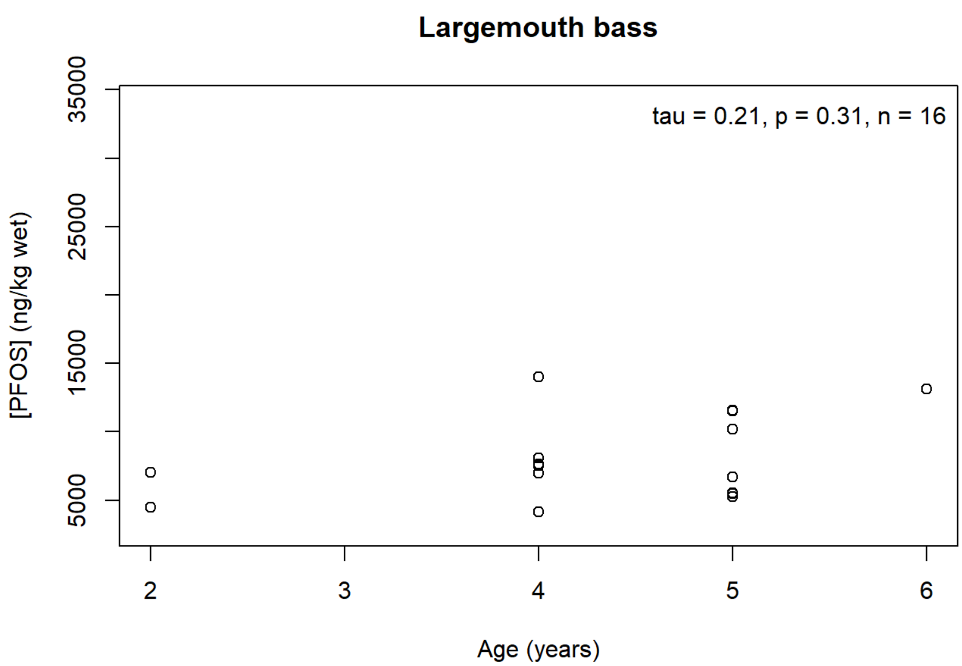
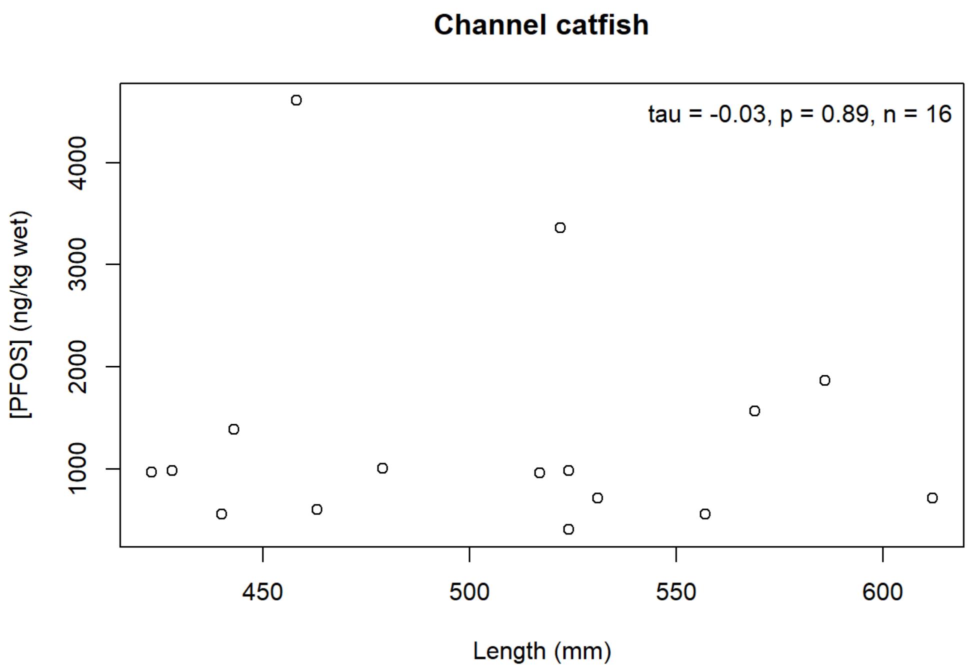


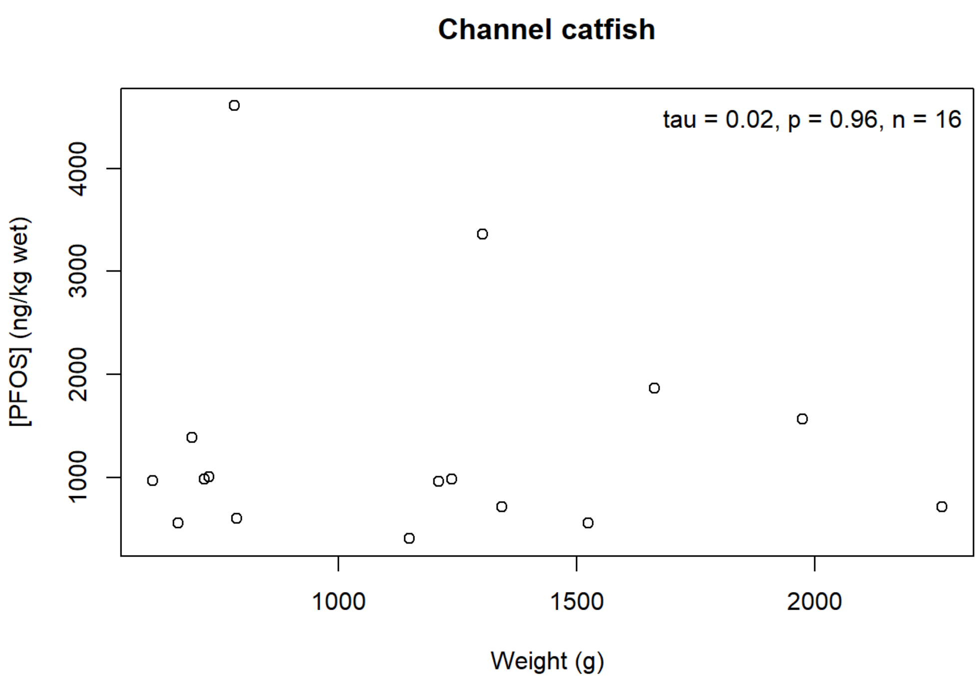
Figure A2. Correlation plots comparing PFOS concentrations (ng/kg wet) with length (mm), weight (g), and age (years), respectively, for each fish species. Age was not included for smallmouth buffalo, freshwater drum, crappie spp, common carp, or white bass. Correlations were analyzed using Kendall's Tau, where 0 is not correlated and -1 and 1 are most correlated. ng/kg = nanogram per kilogram; mm = millimeter.

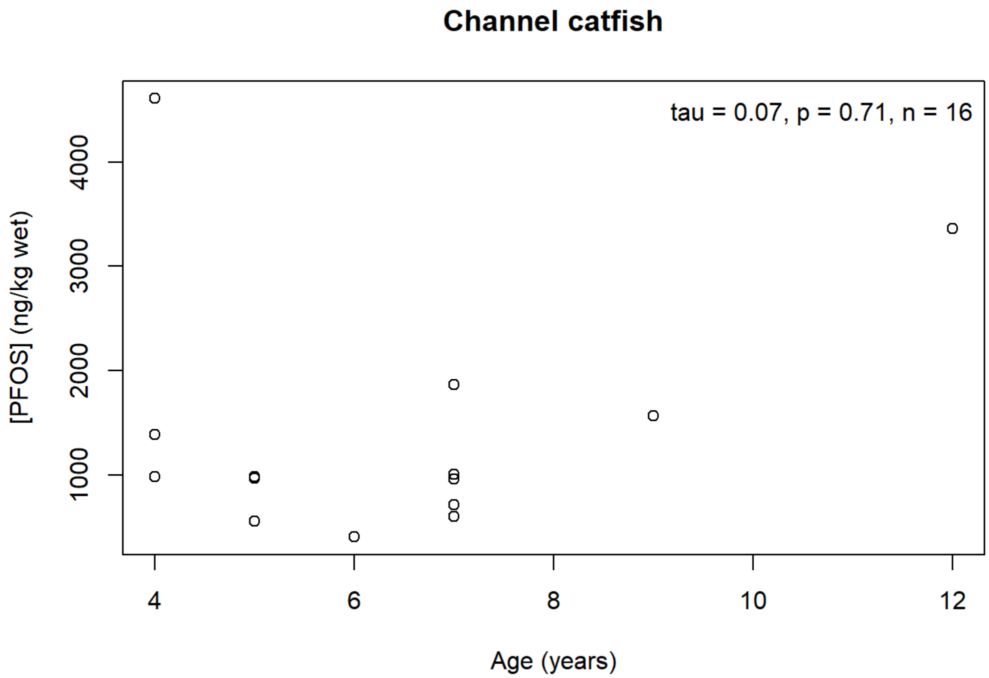


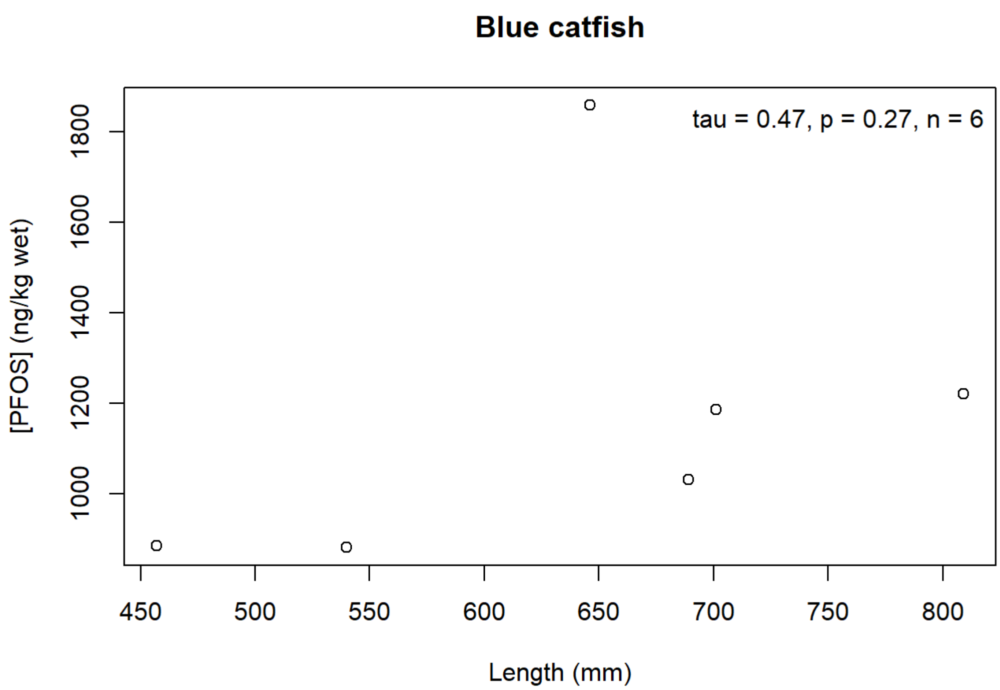

Largemouth bass
tau = 0.31, p = 0.02, n = 29
[PFOS] (ng/kg wet)
5000
15000
25000
35000
1000
1500
2000
2500
Weight (g)

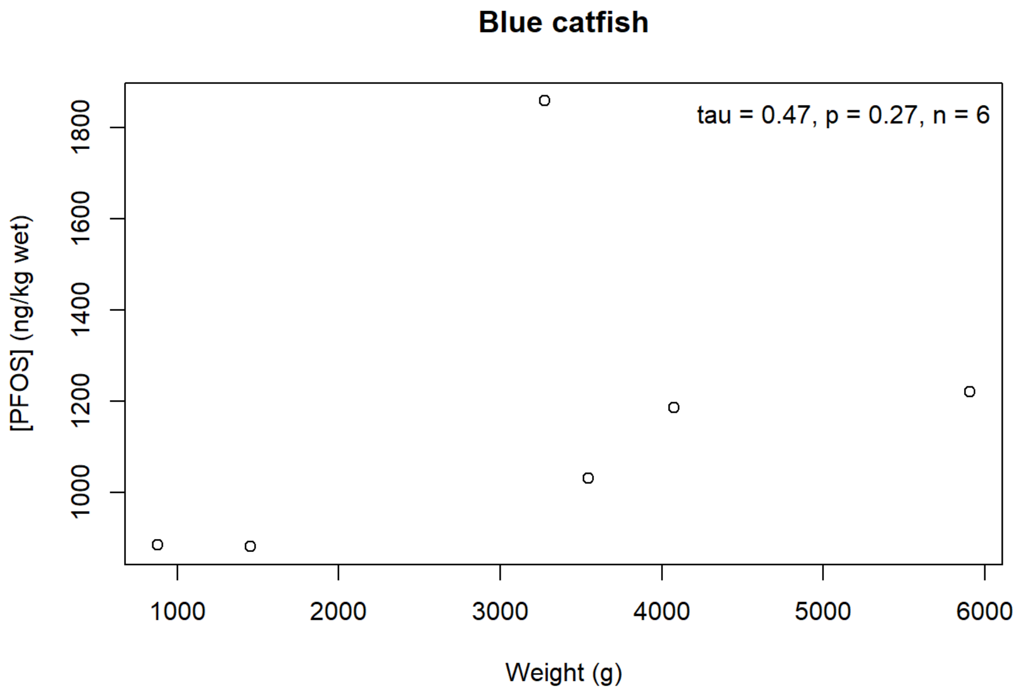

Largemouth bass
tau = 0.21, p = 0.31, n = 16
[PFOS] (ng/kg wet)
5000
15000
25000
35000
2
3
4
5
6
Age (years)

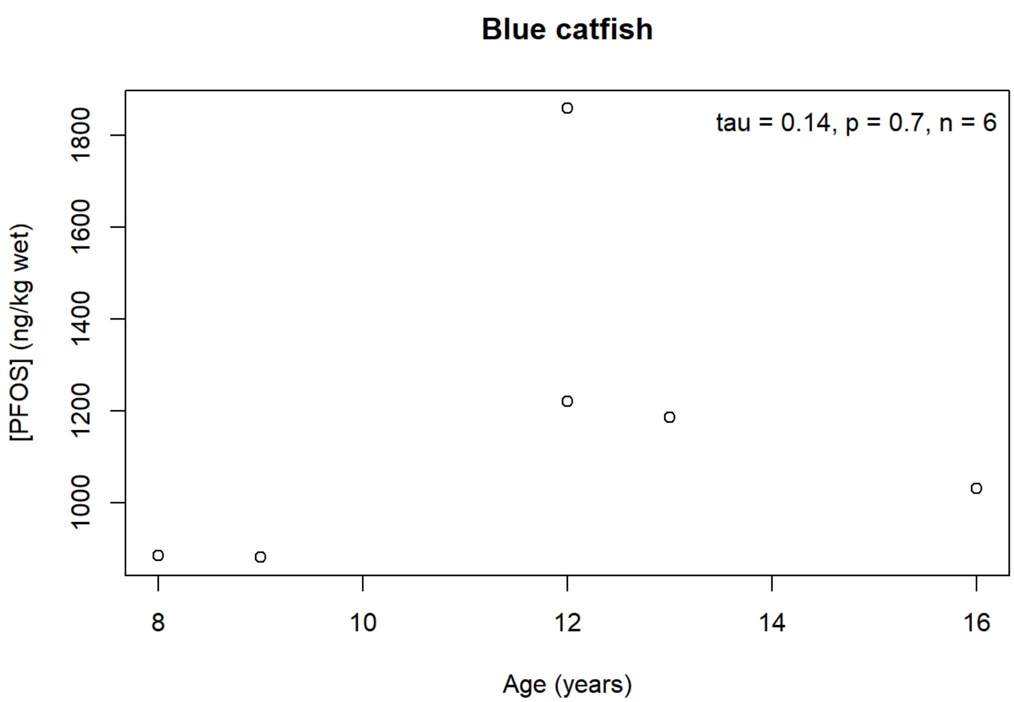

Channel catfish
tau = -0.03, p = 0.89, n = 16
[PFOS] (ng/kg wet)
1000
2000
3000
4000
450
500
550
600
Length (mm)

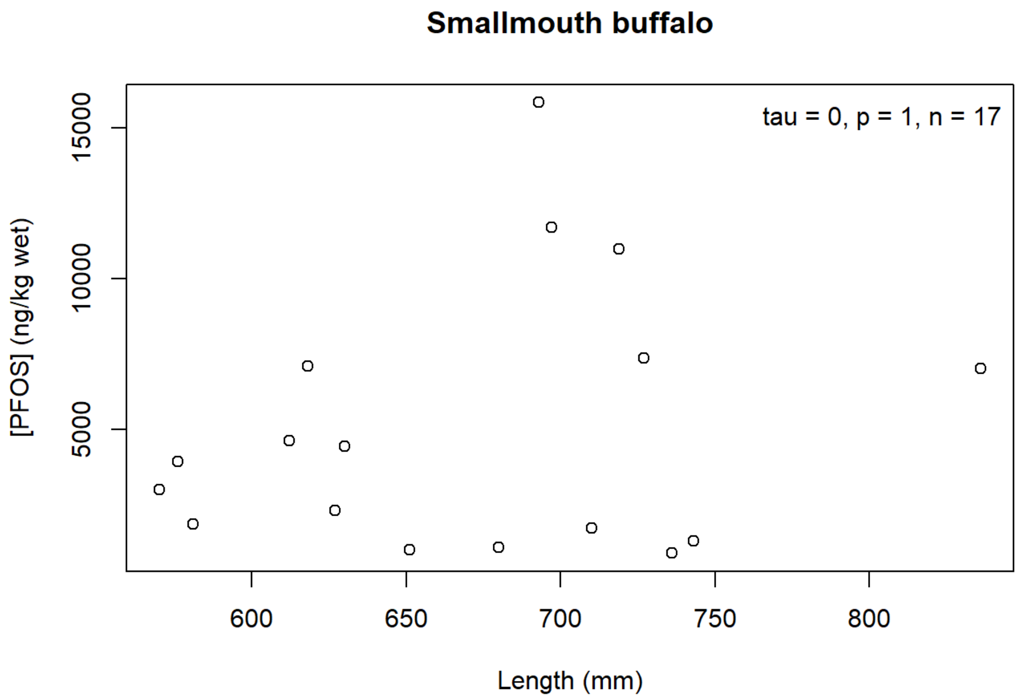

Channel catfish
tau = 0.02, p = 0.96, n = 16
[PFOS] (ng/kg wet)
1000
2000
3000
4000
1000
1500
2000
Weight (g)

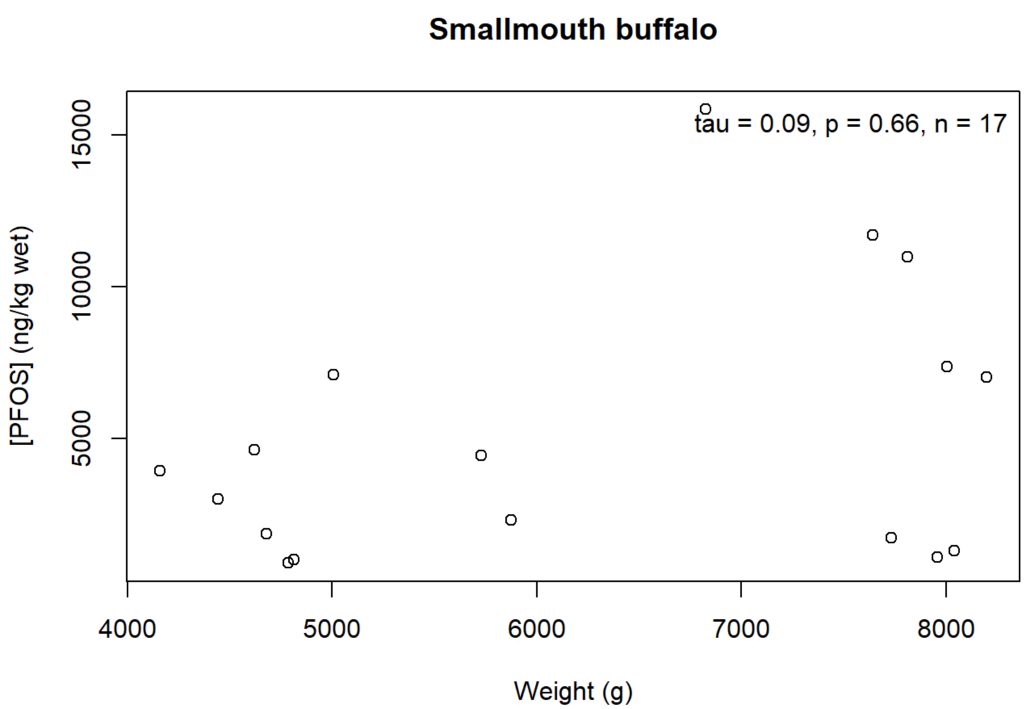

Channel catfish
tau = 0.07, p = 0.71, n = 16
[PFOS] (ng/kg wet)
1000
2000
3000
4000
4
6
8
10
12
Age (years)

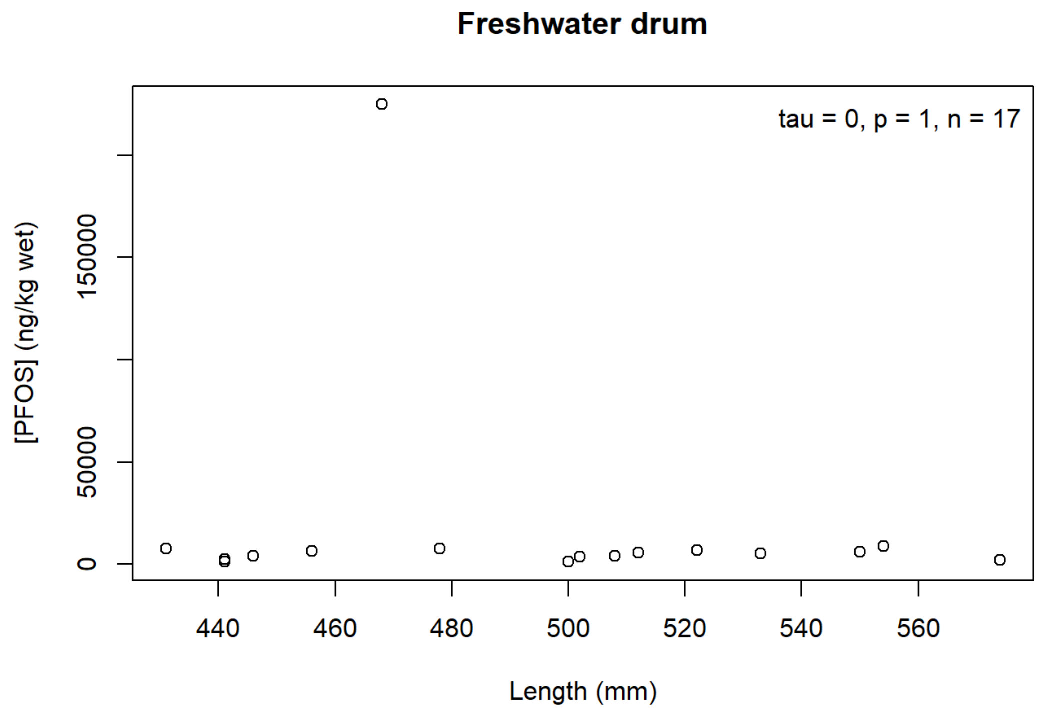

Blue catfish
tau = 0.47, p = 0.27, n = 6
[PFOS] (ng/kg wet)
1000
1200
1400
1600
1800
450
500
550
600
650
700
750
800
Length (mm)

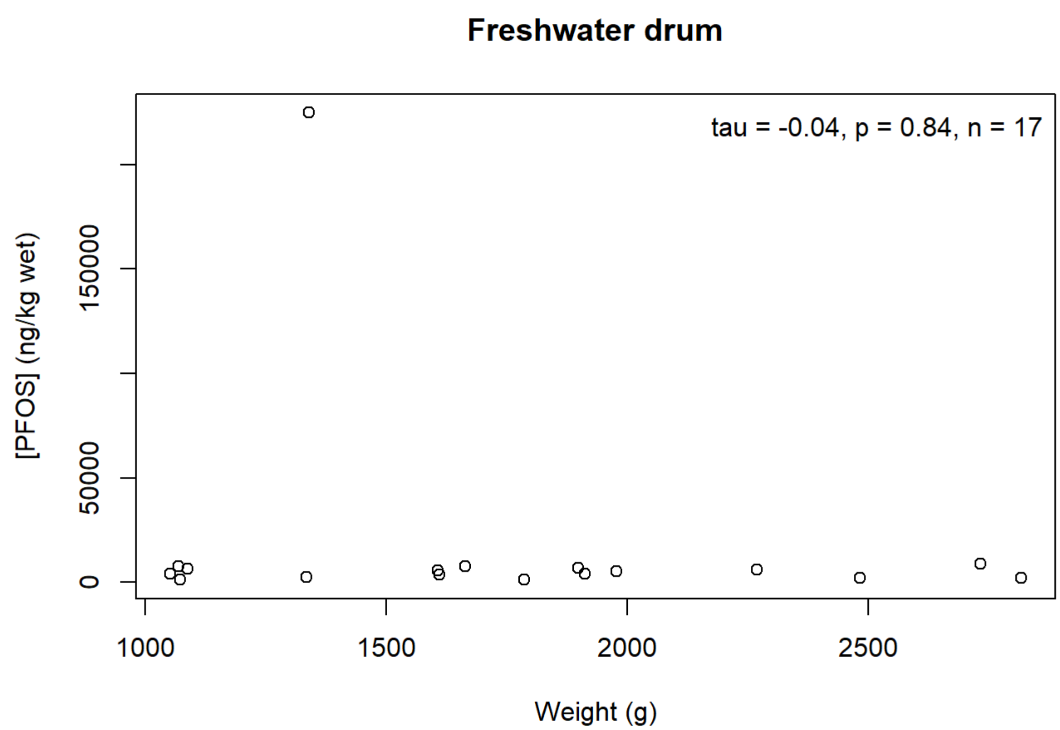

Blue catfish
tau = 0.47, p = 0.27, n = 6
[PFOS] (ng/kg wet)
1000
1200
1400
1600
1800
1000
2000
3000
4000
5000
6000
Weight (g)


Blue catfish
tau = 0.14, p = 0.7, n = 6
[PFOS] (ng/kg wet)
1000
1200
1400
1600
1800
8
10
12
14
16
Age (years)

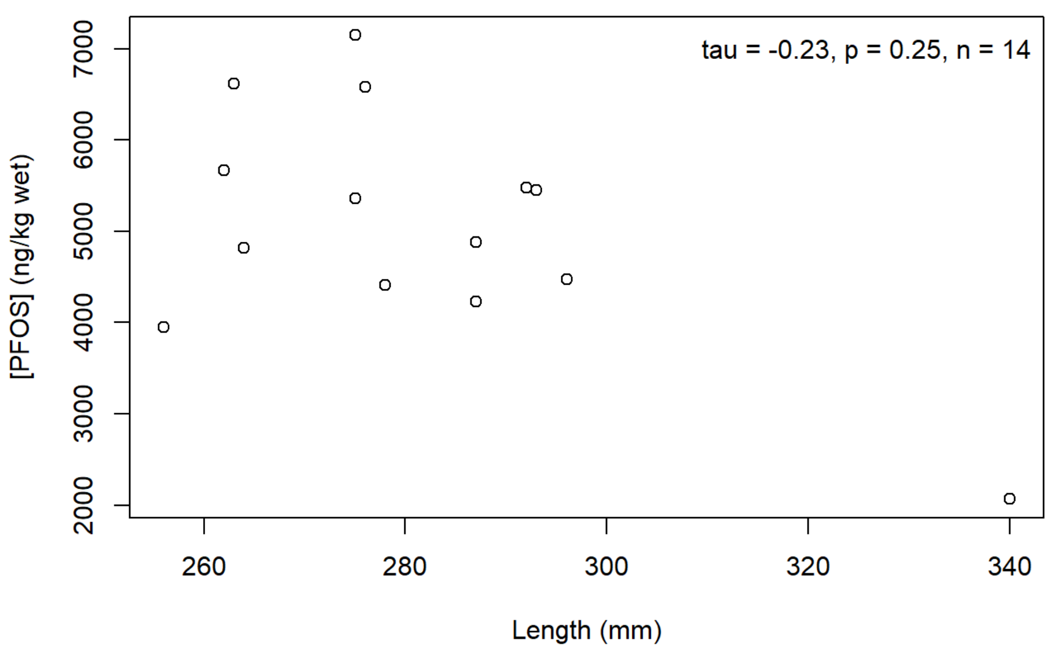

Smallmouth buffalo
tau = 0, p = 1, n = 17
[PFOS] (ng/kg wet)
5000
10000
15000
600
650
700
750
800
Length (mm)


Smallmouth buffalo
tau = 0.09, p = 0.66, n = 17
[PFOS] (ng/kg wet)
5000
10000
15000
4000
5000
6000
7000
8000
Weight (g)

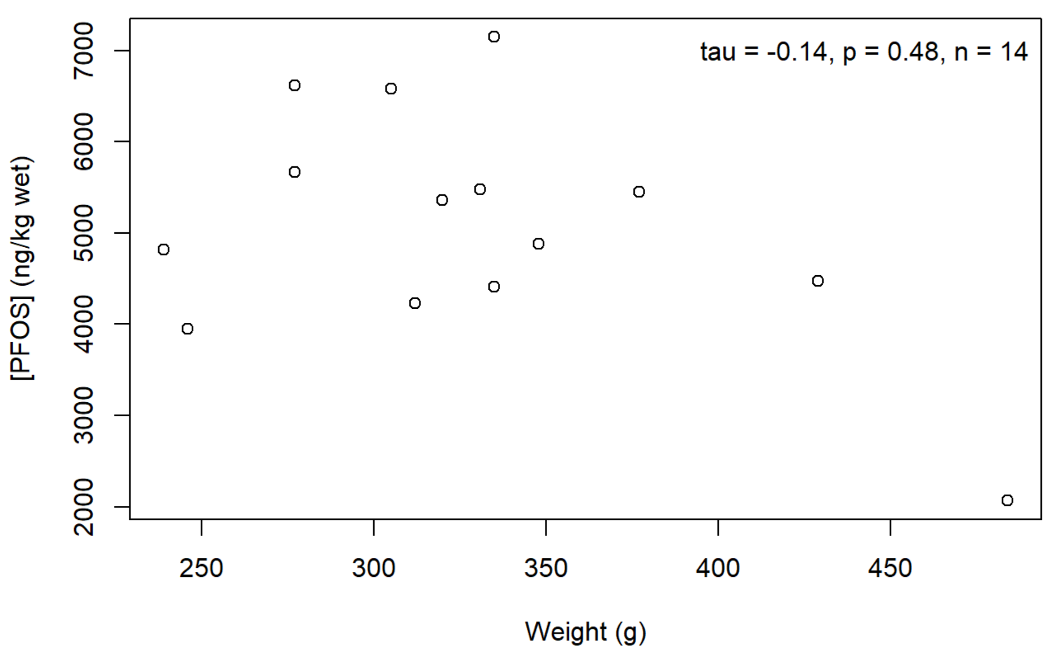

Freshwater drum
tau = 0, p = 1, n = 17
[PFOS] (ng/kg wet)
0
50000
150000
440
460
480
500
520
540
560
Length (mm)

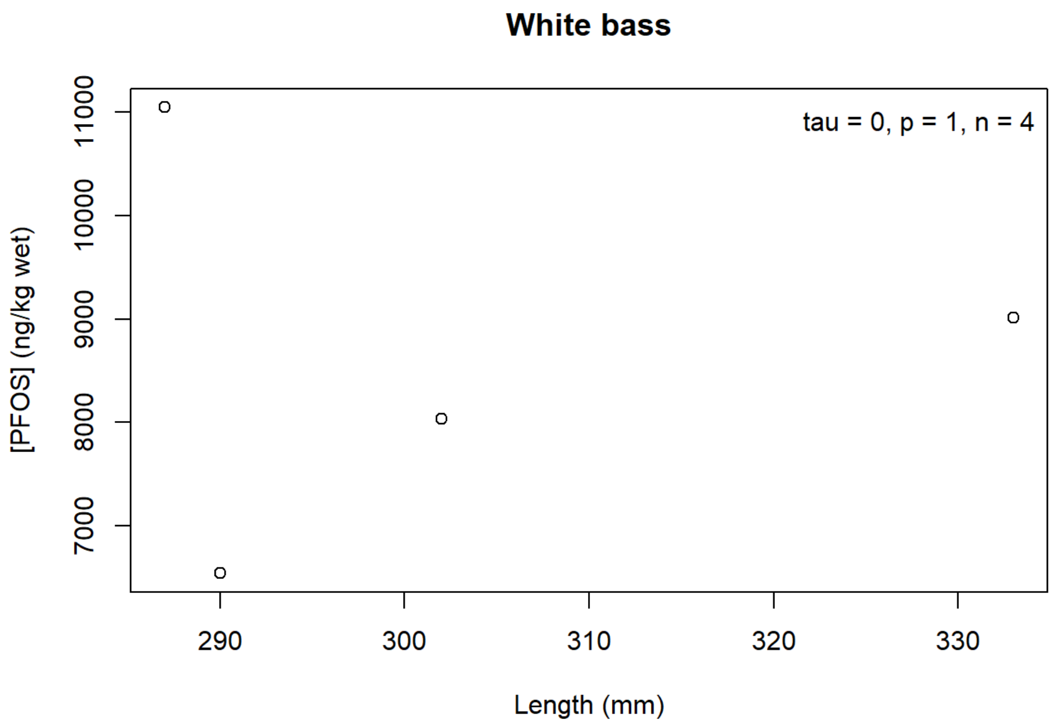

Freshwater drum
tau = -0.04, p = 0.84, n = 17
[PFOS] (ng/kg wet)
0
50000
150000
1000
1500
2000
2500
Weight (g)

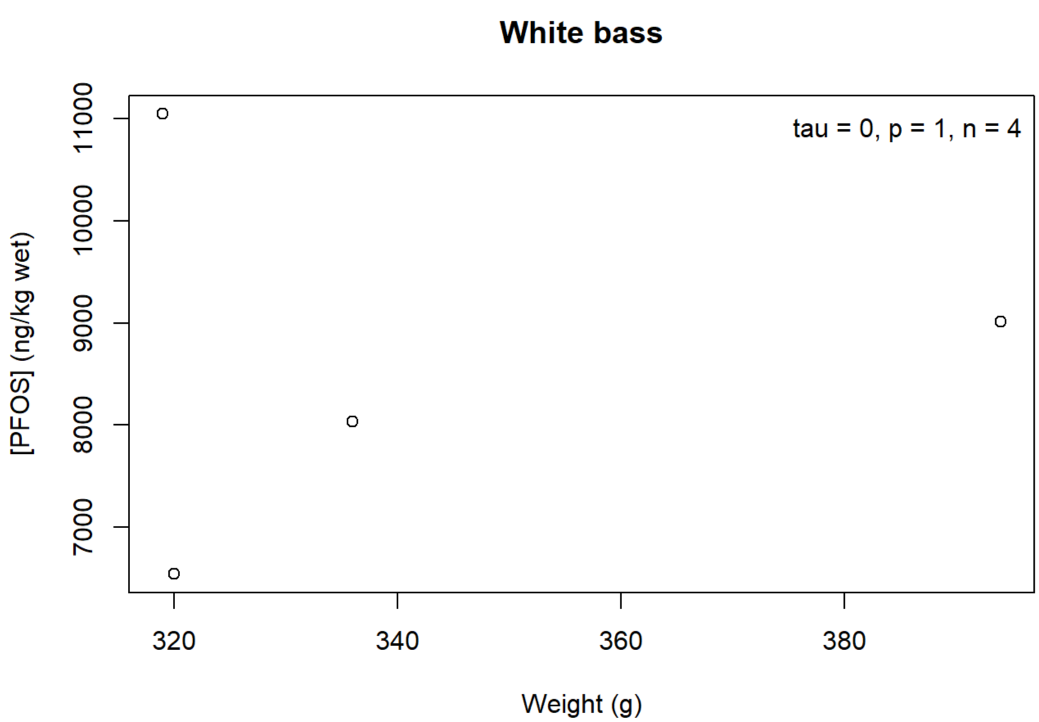
Crappie spp

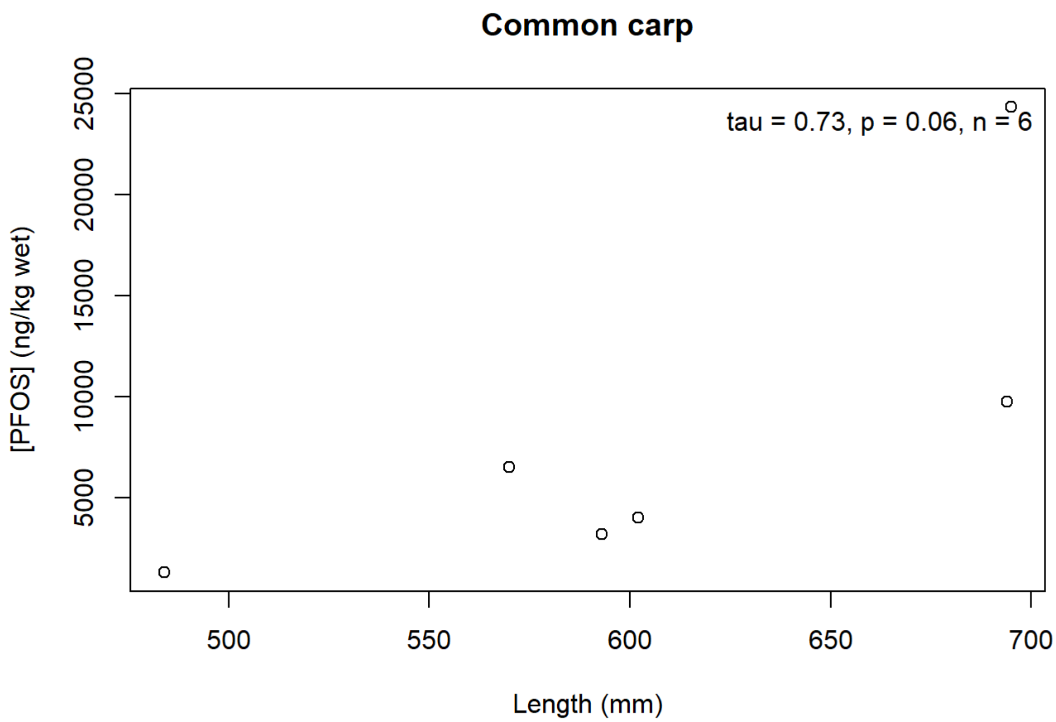


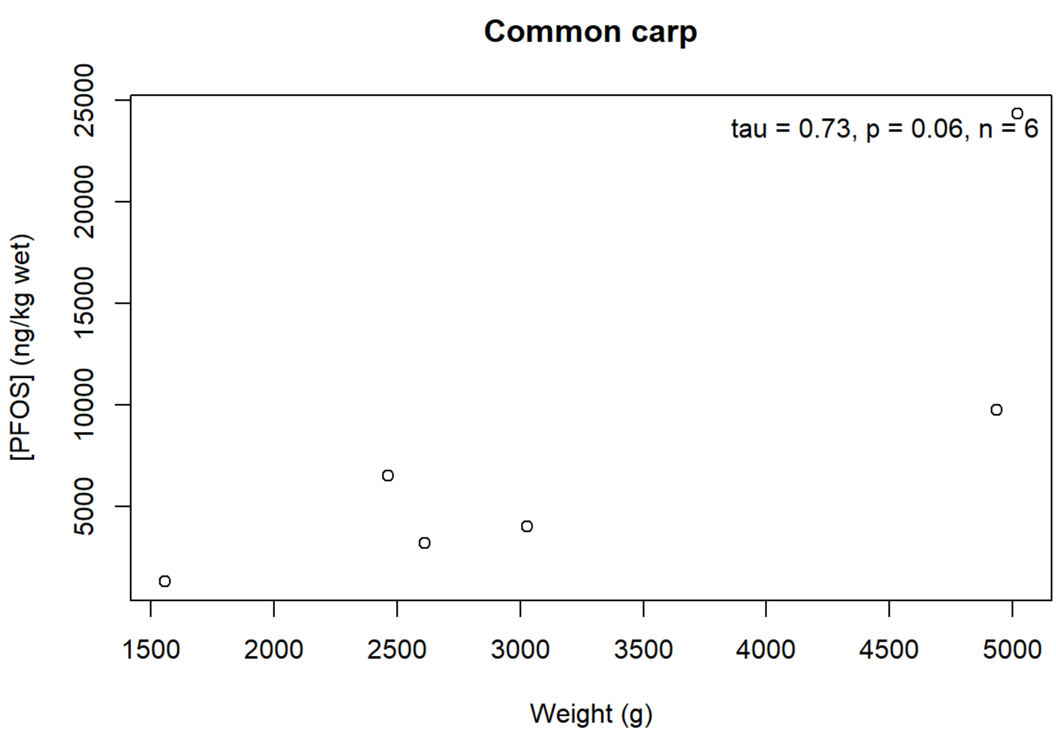
Crappie spp




White bass
tau = 0, p = 1, n = 4
[PFOS] (ng/kg wet)
7000
8000
9000
10000
11000
290
300
310
320
330
Length (mm)


White bass
tau = 0, p = 1, n = 4
[PFOS] (ng/kg wet)
7000
8000
9000
10000
11000
320
340
360
380
Weight (g)


Common carp
tau = 0.73, p = 0.06, n = 6
[PFOS] (ng/kg wet)
5000
10000
15000
20000
25000
500
550
600
650
700
Length (mm)


Common carp
tau = 0.73, p = 0.06, n = 6
[PFOS] (ng/kg wet)
5000
10000
15000
20000
25000
1500
2000
2500
3000
3500
4000
4500
5000
Weight (g)