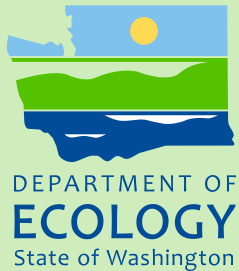




PBT Chemical Trends in Washington State Determined from Age-Dated Lake Sediment Cores

2011 Sampling Results



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Cover photo: Sediment core collected from Samish Lake.

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PBT Chemical Trends in Washington State Determined from Age-Dated Lake Sediment Cores

2011 Sampling Results

by

Callie Mathieu and Michael Friese

Environmental Assessment Program
Washington State Department of Ecology
Olympia, Washington 98504-7710

Waterbody Numbers:

Angle Lake WA-09-9010
Samish Lake WA-03-9160
Nahwatzel Lake WA-22-9060

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Abstract

This report summarizes results from the sixth year of an ongoing study to evaluate persistent, bioaccumulative, and toxic (PBT) chemical trends in Washington State through age-dated lake sediment cores. In 2011, sediment cores were collected from Angle, Samish, and Nahwatzel Lakes in western Washington and analyzed for mercury, lead, and polycyclic aromatic hydrocarbons (PAHs).

Mercury, lead, and PAHs were highest in urban Angle Lake, where levels rose during the first half of the 20th century and remained highly elevated between 1950 and 2000.

Mercury enrichment was modest at Samish Lake, with concentrations peaking around midcentury and leveling off between 1960 and 1990. Lead followed a pattern typical for that element, peaking in the mid-1970s. PAHs were at their maximum by 1920 and then declined linearly between 1920 and 2008.

Contaminant concentrations in the rural Nahwatzel Lake core were low and at background levels throughout the bottom 30 cm of the core. An increase in metals began around 10 cm and steadily increased through the top of the core. PAH levels in the top 10 cm of the core displayed an erratic pattern and were highly enriched at the peak.

Acknowledgements

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- Dale Norton for project guidance and reviewing the draft report.
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- Joan LeTourneau and Jean Maust for formatting and editing the final report.

Introduction

The threat of persistent, bioaccumulative, and toxic (PBT) chemicals in the environment prompted the Washington State Department of Ecology (Ecology) to create a strategy for PBT reduction in 2000 (Gallagher et al., 2000). Through the PBT initiative, chemical action plans (CAPs) are developed to evaluate uses and releases of PBTs in Washington State and make recommendations on actions to protect human health and the environment.

The first published CAP addressed mercury (Peele et al., 2003), followed by polybrominated diphenyl ethers (PBDEs) (Peele et al., 2006) and lead (Davies et al., 2009). A CAP for polycyclic aromatic hydrocarbons (PAHs) is currently drafted and in review (Davies, 2012). Detailed information on sources and effects of these chemicals can be found in the CAPs or through Ecology's website (www.ecy.wa.gov/programs/swfa/pbt/caps.html).

In 2006, Ecology's PBT Monitoring Program began collecting sediment cores from freshwater lakes to help track the occurrence and temporal trends of PBTs in Washington State. A single deep sediment core is collected from three lakes per year in order to construct historical deposition profiles. The first two years examined trends in mercury concentrations only (Coots, 2006). Lead and PAHs were added in 2008 (Meredith and Furl, 2008).

Results of sediment core samples from 2006-2010 are reported by Furl (2007 and 2008), Furl et al. (2009a), and Furl and Roberts (2010 and 2011). This report summarizes findings from 2011, the sixth year of sediment core sampling.

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Methods

Study Locations

Sediment cores were collected from Angle, Samish, and Nahwatzel Lakes in August 2011. Figure 1 displays the coring locations at each site. Sites were selected using criteria outlined in the Quality Assurance (QA) Project Plan (Coots, 2006). Consideration for site selections included achievement of statewide coverage, knowledge of lake depositional patterns, lake accessibility, and results from other studies such as Ecology’s Mercury Trends in Fish Tissue study (Seiders, 2006).

Angle Lake was chosen to evaluate PAH trends in a highly urbanized lake. Samish and Nahwatzel Lakes were selected because moderately high mercury levels in fish tissue have been reported in those lakes (Furl and Meredith, 2008a and Furl et al., 2009b). Table 1 and the following sections contain detailed information on the 2011 study lakes.

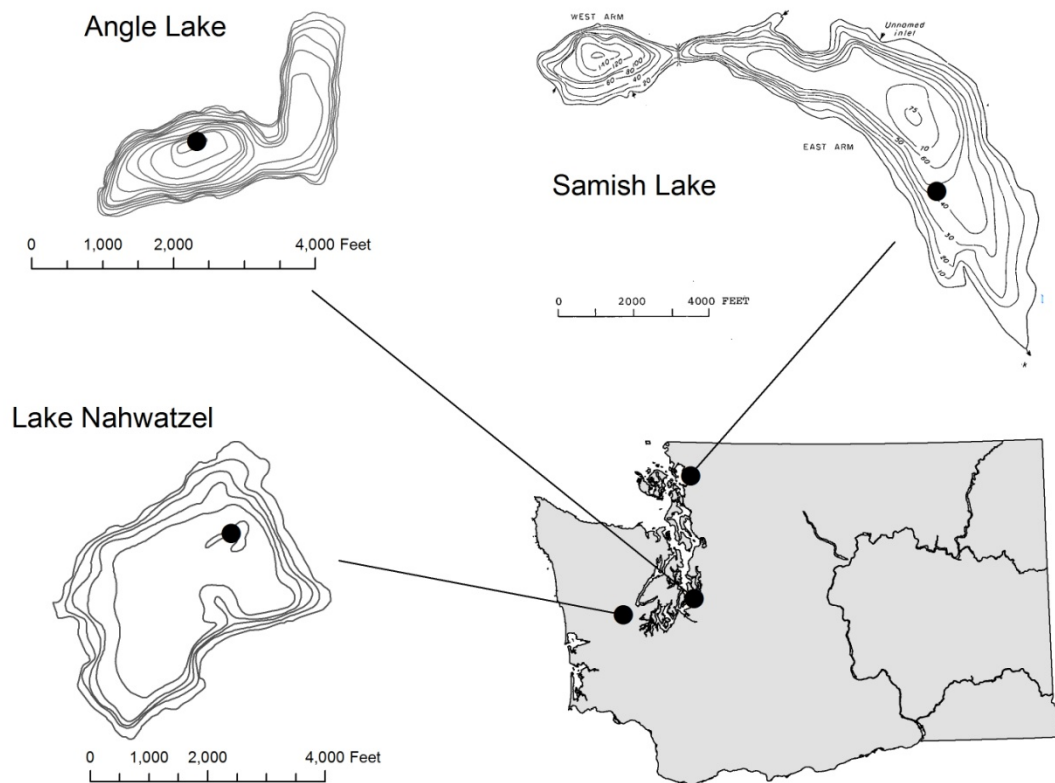


Figure 1. Sediment Coring Locations, 2011.

Coring locations for each lake are indicated by black circle.

Table 1. Geographical and Morphological Information for Study Lakes, 2011.

Lake	Angle	Samish (east arm)	Nahwatzel
Surface Area (acre)	100	680	270
Drainage Area (acre)	510	5,890	3,970
Volume (acre-ft)	2,600	24,000	4,600
Coring Site Depth (ft)	51	41	21
Maximum Depth (ft)	52	75	25
Mean Depth (ft)	25	31	17
DA:SA Ratio ¹	5.1	8.7	15
Precipitation (in) ²	38	52	94
Altitude (ft)	350	275	455
Coring Site Latitude/ Longitude (dd) ³	47.42797/ -122.28817	48.65985/ -122.38192	47.24501/ -123.33003
County	King	Whatcom	Mason

¹Drainage-area to surface-area ratio.

²1984-2010 average. Precipitation data provided by PRISM. www.prism.oregonstate.edu/

³Decimal degrees.

Angle Lake

Angle Lake lies in a heavily urbanized area of King County. Angle Lake is a glacially formed deep lake in an urban residential area (Dion et al., 1980). The watershed is small and mostly comprised of residential neighborhoods. A major interstate highway (I-5) is located a tenth of a mile from the southeastern shoreline, and an international airport lies less than a mile northwest of the lake.

There is no surface water inflow or outflow to the lake. The lake is fed by rainwater and groundwater. Outflow is primarily through groundwater seepage. When the lake overflows its banks, water drains through a sewer system installed in the late 1970s (Verhey and Mueller, 2001).

The geology of the drainage basin is comprised of glacial till and outwash deposits of sand and gravel with gravelly, sandy loam soils (Dion et al., 1980). Arents-Alderwood material (sandy loams that have been disturbed by urbanization) surround the lake with slopes of 6-15% (SSURGO database, accessed 05/2012). The risk of erosion for these soils is slight to moderate at this grade (WSDOT, 2003).

Samish Lake

Samish Lake is located southeast of Bellingham in Whatcom County. Samish Lake was formed when a glaciated valley was dammed by Northern slide deposits (Bortleson et al., 1974). Land cover is mostly forested with residential and commercial clearings. Lakeshore development is moderately dense with homes. An interstate highway (I-5) runs parallel along the northeast shore for almost 2 miles, within a quarter mile of the shoreline (Bortleson et al., 1974).

The main inflow is through Lake Creek on the western arm, with several ephemeral inflow streams entering from the surrounding mountainous terrain. The lake drains out to the south through Friday Creek.

Geology of the basin consists of a foundation of consolidated sedimentary rock with a thin upper layer of glacial drift (Bortleson et al., 1974). Surrounding sediments are made up of shallow and stony soils in higher elevations. Soils on the lower south slope are silt or stony silt loam (Bortleson et al., 1974).

Nahwatzel Lake

Nahwatzel Lake is a naturally formed lake in Mason County. Most of the shoreline is residentially developed, with the exception of the forested northwest shore. The majority of the watershed consists of privately owned commercial forest.

Outlet Creek flows into the lake on the northern shore and flows out on the western edge toward the Satsop River.

Geology of the surrounding basin consists of Vashon morainal deposits, with Vashon till deposits (fine grained) under most of the watershed (SSURGO database, accessed 05/2012). Sediments are comprised of gravelly sandy loam, with a 5-15% slope (SSURGO database, accessed 05/2012). Risk of erosion for these soils and slope is slight to moderate (WSDOT, 2003).

Field Methods

Ecology field crews collected sediment cores from deep, flat areas of the lakes using a Wildco stainless steel box corer containing a 13 cm x 13 cm x 50 cm acrylic liner. Collection efforts were guided by Ecology's Environmental Assessment Program's Standard Operating Procedure (SOP) for *Collection of Freshwater Sediment Core Samples Using a Box or KB Corer* (Furl and Meredith, 2008b). Cores were determined suitable for subsampling if the sediment-water interface was intact and the core was adequately deep (approximately 35-45 cm). Overlying water was siphoned off the top of the core, and 1 cm sections were removed using an extruding device.

Surface sediments for grain size analysis were collected at each coring location (within 3 meters) using a stainless steel Ponar grab. Sampling was conducted in accordance with the *Standard Operating Procedure for Freshwater Sediment Sampling* (Blakley, 2008). Sediment grabs were

kept if the sediment-water interface was preserved. Overlying water was removed with a siphon and the top 2 cm of the sediments collected using a stainless steel spoon.

The box corer, Ponar grab, and all equipment coming into contact with sediments were cleaned prior to sampling using the following procedure: Liquinox detergent and hot water wash, nitric acid rinse, de-ionized water rinse, and acetone rinse. The equipment was air dried and wrapped in foil until use in the field. The cleaning procedure was followed between lakes. If an initial core or grab proved unsuitable, the sampling equipment was washed with ambient lake water between samples.

Each core section and surface sediment grab sample was placed in a uniquely labeled 8-oz. I-Chem jar with a Teflon-lined lid. Samples were placed in plastic bags and put on ice in coolers for transport to Ecology headquarters. Core samples remained in coolers for no more than 48 hours before being frozen at Ecology headquarters at -20° C. Grab samples were stored at 4° C until undergoing grain-size analysis.

Sample Preparation and Analysis

Ecology staff processed sediment core samples at Ecology headquarters on a clean bench wrapped in aluminum foil. Two individual 1-cm horizons were homogenized until the sediments were uniform in color and texture. All chemical analyses were conducted on samples representing 2-cm slices of the sediment core. Because of low percent solids, two 1-cm slices had to be combined in order to achieve adequate sample size for chemical and radiochemical analyses. Sub-samples were taken from the sediment homogenate and placed in 4-oz. I-Chem jars with Teflon-lined lids for chemical analysis.

Table 2 provides information on sample preparation and analysis. A list of the 19 PAHs analyzed for this project is included in Appendix A. This list includes the 18 PAH compounds used to calculate Total-PAH sums for Ecology's proposed Sediment Quality Standard (SQS) (Michelsen, 2011), plus retene. Ecology's Manchester Environmental Laboratory (MEL) analyzed PAHs by GC/MS in selective ion monitoring mode, which measures a smaller set of compounds than a full scan but achieves a higher sensitivity and lower detection limits.

Table 2. Sample Preparation and Analysis.

Analyte	No. of samples	Method	Method citation	Laboratory
Mercury	45	CVAA	EPA 245.5	MEL
Lead	45	ICP-MS	EPA 200.8	MEL
PAHs	30	GC/MS SIM	EPA 8270	MEL
Total organic carbon	30	Acidification followed by CO ₂ measurement	PSEP-EPA, 1986	MEL
Grain size	3	Sieve and pipet	PSEP-EPA, 1986	CAS
²¹⁰ Pb	45	Gamma counting	EPA 901.1	Test America

CVAA: Cold vapor atomic absorption

ICP-MS: Inductively coupled plasma mass spectrometry

GC/MS SIM: Gas chromatography mass spectrometry in selective ion monitoring mode

CO₂: Carbon dioxide

EPA: Environmental Protection Agency

PSEP: Puget Sound Estuary Protocol

MEL: Manchester Environmental Laboratory

CAS: Columbia Analytical Services

Data Quality

MEL provided case narratives for analyses of mercury, lead, PAHs, Total organic carbon (TOC), and ²¹⁰Pb. All analyses were performed within method holding times. All instrument calibration checks were within acceptance limits with the exception of indeno(1,2,3-cd)pyrene, described below in the PAHs section. Results of quality control (QC) tests are described in the following sections. Appendix C includes detailed information on the chemical analyses performed for each core and their results.

Mercury and Lead

No mercury or lead was detected in the method blanks above reporting levels. Laboratory control samples (LCS) were within measurement quality objectives (MQOs). LCS recoveries averaged 93% (mercury) and 101% (lead). Average matrix spike recoveries were 126% (mercury) and 108% (lead).

One matrix spike recovery for mercury exceeded MQOs due to inhomogeneity of the sample. The relative percent difference (RPD) of laboratory duplicates for the sample was also outside of acceptance limits. The source sample (sample #1108056-16) was qualified “J” as an estimate. The third batch matrix spike duplicate recovery and RPD of duplicate samples exceeded MQOs, but the source sample was from a different project so no qualification was made.

The matrix spike and matrix spike duplicate recoveries for one lead sample were outside of MQOs. The level of lead in the source sample was too high for the standard spike amount. The RPD of the duplicate analysis for this sample exceeded acceptance limits, and the source sample was qualified “J” as an estimate (sample #1108056-20).

PAHs

QC tests for PAHs included method blanks, LCS, matrix spikes, matrix spike duplicates, standard reference materials (SRM), and laboratory duplicates. LCS recovery averages were 95% and SRM recoveries averaged 85%. Matrix spike and matrix spike duplicate recoveries averaged 93% and 91%. The average RPD of duplicate samples was 22%.

The following tests were outside of MQOs:

- Six target analytes were detected in one or more batch method blanks: 1-methylnaphthalene, 2-methylnaphthalene, acenaphthene, fluoranthene, naphthalene, and phenanthrene. All sample results were greater than three times the area counts in the associated method blank. Therefore, no qualifiers were added based on method blank data.
- Two LCS recoveries for anthracene were below MQOs (47% and 49%). All anthracene results were qualified “J” as estimates if detected or “UJ” if not detected.
- A single matrix spike duplicate recovery fell below MQO limits (49%) for anthracene. Anthracene results were already qualified.
- In laboratory duplicates, one RPD for benzo(ghi)perylene was above MQOs. RPDs for benzo(a)pyrene and retene were also outside of MQOs. The source samples were qualified “J” as an estimate for the respective compounds.
- SRM sample recoveries were low (below 65%) for acenaphthene, anthracene, fluorine, and pyrene. Dibenzo(a,h)anthracene recoveries were high, above 135%, probably due to interference from an isomer. No qualifications are made based on SRM recovery.
- A single high continuing calibration verification for indeno(1,2,3-cd)pyrene was outside of laboratory acceptance limits. As a result, samples #1108056-43 and 1108056-45 for indeno(1,2,3-cd)pyrene were qualified “J” as an estimate.

Total Organic Carbon

All QC tests for TOC analysis were within MQOs. Method blanks were below reporting limits. Duplicate samples averaged 5.5% RPD. SRM recoveries averaged 96%.

Lead-210

Low percent solids of sediment samples 1108056-03 through 1108056-12 (all from Lake Nahwatzel) resulted in insufficient volumes for ^{210}Pb analysis. These samples were re-analyzed using a smaller geometry and longer counting time.

QC tests for ^{210}Pb consisted of method blanks, duplicates, and LCS samples. No ^{210}Pb activity was detected in any of the method blanks above the reporting level. RPDs for duplicate samples were within MQOs.

Two out of four LCS recoveries exceeded MQOs, at 131% and 190%. Results for samples 1108056-03 through 1108056-12, and 1108056-17 through 1108056-30, were qualified “J” or “UJ” (if undetected) as estimates. The highest LCS, 190%, resulted from ^{210}Pb activity below the method detection limit (MDL). The low activity and high recovery of samples 1108056-03 through 1108056-12 are due to insufficient spike activity being used to produce a value above the MDL. The laboratory used lesser sample material and smaller filter geometry to match the low percent solids of the batch.

Data Processing

Sediment Calculations

The constant rate of supply (CRS) model was applied using ^{210}Pb measurements to estimate dates and varying sedimentation rates throughout the core (Appleby and Oldfield, 1978). The model uses the difference in supported and unsupported ^{210}Pb in sediment horizons. Supported ^{210}Pb is represented by the small amount of the precursor gas radon (^{222}Rn) that is captured in soils. Supported ^{210}Pb in the study cores was estimated as the average activity present at deep intervals where it appeared to no longer decline.

Unsupported ^{210}Pb represents atmospherically deposited ^{210}Pb resulting from the decay of ^{222}Rn that escapes in the atmosphere and is estimated by subtracting supported ^{210}Pb from total ^{210}Pb . Using the known half-life (22.3 years) of ^{210}Pb and the amount of the unsupported isotope, the rate of sedimentation and the date of formation can be calculated for approximately the last 150 years (Van Metre et al., 2004; Charles and Hites, 1987).

Sediment dry mass (g/cm^2) was calculated from percent solids data. An assumed sediment density of $2.7 \text{ g}/\text{cm}^3$ was used based on other Washington State coring studies (Paulson, 2004).

Mercury Flux Calculations

Contaminant flux rates ($\text{ug}/\text{m}^2/\text{yr}$) were calculated as the product of sediment mass accumulation rates and dry weight contaminant concentrations. Flux rate results are used to estimate net deposition to the lake. Flux rates normalize the variance involved with interpreting dry weight concentrations under varying sedimentation rates.

Enrichment Factors

Enrichment factors were calculated for the contaminants by dividing concentrations in the interval of interest by the baseline value. Baseline estimates were calculated by taking the average of the lowest contaminant values at the deepest core sections where concentrations were stable. The enrichment factor is a unitless value describing the amount concentrations have increased or decreased from the baseline.

Total PAH Calculations

A complete list of PAHs included in summed totals is presented in Appendix A. Summed values include only detected concentrations. Non-detected, or “U” flagged, values were set to zero for calculations. If no PAHs were detected in a sample, the highest detection limit represented the total; however, all 2011 samples contained at least one detected compound. Total values were qualified “J” if over 10% of individual compound results were qualified “J”.

Results and Discussion

The following sections discuss TOC, grain size, age-dating, sedimentation rates, mercury, lead, and PAHs in the sediment cores. Appendix B provides complete results of parameters analyzed.

Total Organic Carbon and Grain Size

Percent TOC in sediment core intervals ranged from 5.3%-20.4%. Average percent TOC values for Angle, Samish, and Nahwatzel Lakes were 16.1%, 5.9%, and 17.8%, respectively. TOC concentrations increased down the Angle Lake core. Concentrations varied little in the Samish and Nahwatzel cores. The Samish Lake core TOC values were much lower than the other two lakes.

The percent of fines (clay + silt) in surficial grab samples taken near the coring site were 34.6% (Angle), 84.6% (Samish), and 11.4% (Nahwatzel).

Age Dating

^{210}Pb activities throughout the three sediment cores are shown in Figure 2.

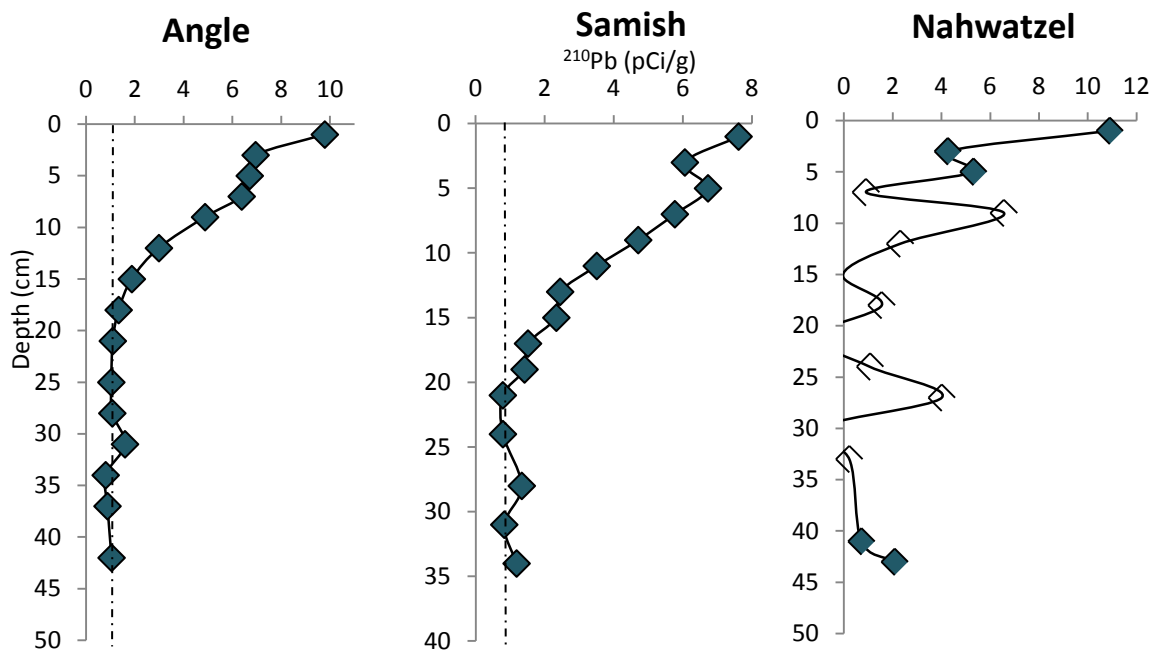


Figure 2. ^{210}Pb Activity Plotted Against Sediment Core Depth.

Unfilled markers indicate activity was not detected at level shown.

Dashed line represents supported ^{210}Pb .

A monotonic decline of ^{210}Pb activity was evident down the length of the core for Angle and Samish Lakes with the exception of one lower activity at the 2-4 cm interval of the Samish core. ^{210}Pb activities at Nahwatzel Lake were mostly undetected, and detected values displayed kinks at the top and bottom of the core.

Surficial sediments at Nahwatzel were mostly comprised of coarse-grained sand (89%), which has low adsorptive capacity for ^{210}Pb (Appleby and Oldfield, 1978). This, along with low percent solids of the sediment samples, may explain the limited detections of ^{210}Pb in the core. Due to the erratic and mostly undetected ^{210}Pb values, the CRS model could not be applied and no ages were assigned to the Nahwatzel core. Total lead could not be used for dating either, as peak values were observed in the top interval of the core.

Dates were calculated for Angle Lake using an estimated supported ^{210}Pb value of 1.08 pCi/g, derived from the average of the bottom six sediment core interval measurements. The Samish Lake core was dated using a supported ^{210}Pb value of 0.99 pCi/g (average of the bottom five measurements).

Yearly unsupported ^{210}Pb fluxes for Angle and Samish Lakes were 0.24 and 0.42 pCi/cm²/yr, respectively, which is within the 0.2-1 pCi/cm²/yr range proposed by Oldfield and Appleby (1984). Unsupported yearly ^{210}Pb fluxes determined from the CRS model are in good agreement with estimated fluxes calculated using atmospheric ^{210}Pb deposition data measured in Washington State (Nevissi, 1985). This indicates that little sediment focusing occurred at the coring sites, and therefore focus correcting factors were not applied to the cores.

Total lead concentration peaks occurred in the early-1970s at both Angle and Samish Lakes, adding confidence to the dates assigned by the CRS model. Total lead is often used as a secondary marker in dating cores, as maximum levels are typically seen in the 1970s, concurrent with peak leaded gasoline use. The estimated dates assigned to Samish Lake also agreed well with sediment core dates calculated from a previous study of the lake (Paulson, 2004).

Sedimentation Rates

Figure 3 displays sedimentation rates calculated for Angle and Samish Lakes.

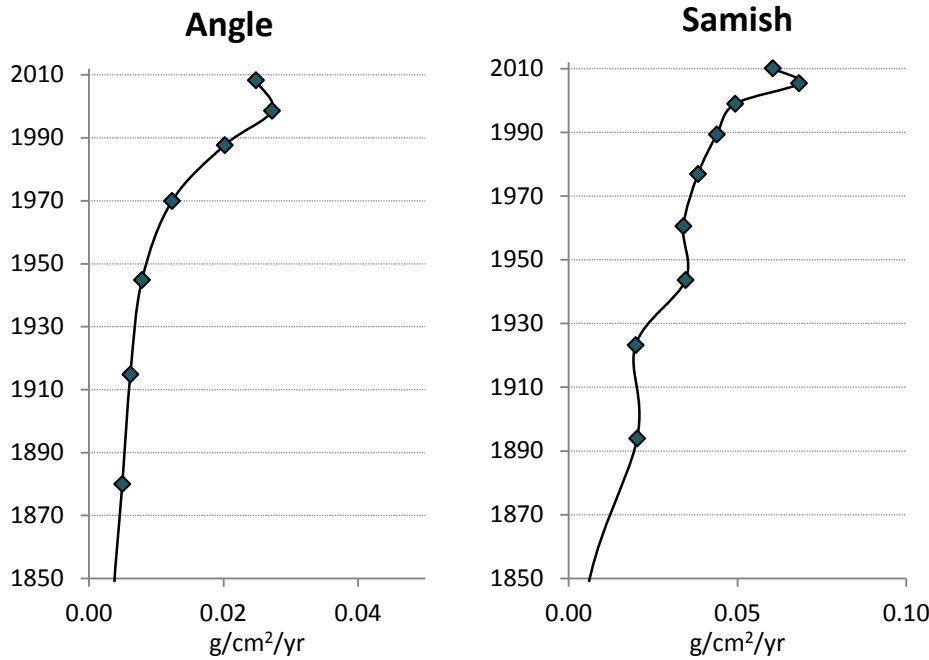


Figure 3. Estimated Sedimentation Rates for Angle and Samish Lakes.

Sedimentation rates ranged from 0.003-0.027 g/cm²/yr in the Angle Lake core and from 0.004-0.068 g/cm²/yr at Samish Lake.

In the Angle Lake core, sedimentation rates increased slowly from the late 1880s until the 1950s, where rates started increasing more rapidly until reaching the highest point in the late 1990s. A slight decrease in sedimentation occurs in the top-most sediment interval.

The Samish Lake core shows sedimentation rates increasing above background levels in the late 1800s. Sedimentation rates rose steadily throughout the 1900s until the maximum rate of 0.068 g/cm²/yr in 2005. A slight decline is seen in the top sediment layer.

Sedimentation rates at Angle and Samish Lakes were within the range of previously reported values from cores collected by Ecology between 2006-2011 (Figure 4). Angle Lake sedimentation rates were on the lower end but similar to the other lakes with no perennial surface water inflow/outflow and small drainage-area-to-surface-area ratios. Lakes with infrequent and lesser hydrological inputs typically have lower sedimentation rates.

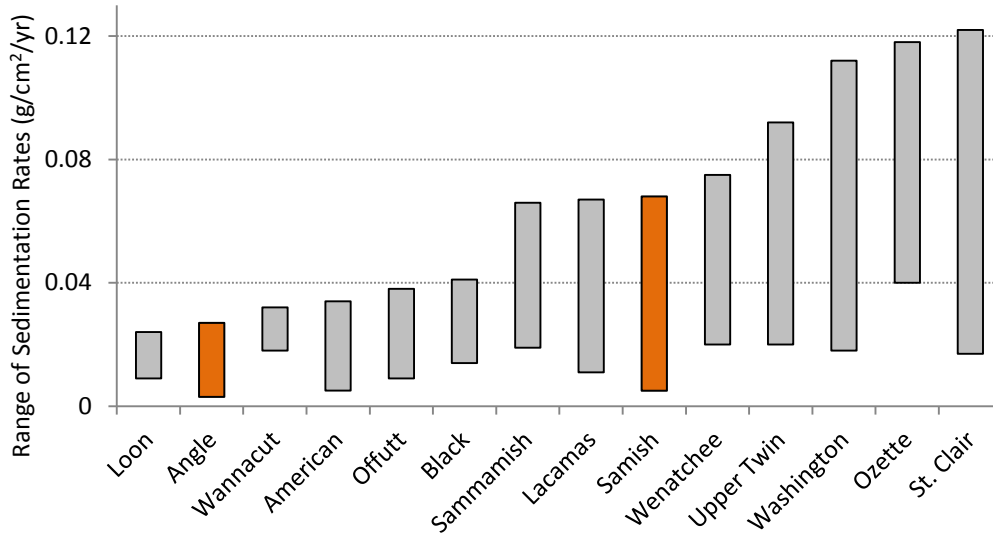


Figure 4. Sedimentation Rates (min – max) of Sediment Cores Collected between 2006-2011. *Orange bars denote 2011 study lakes.*

Contaminant Profiles

Mercury

Mercury concentrations and fluxes are presented in Figure 5. Table 3 summarizes mercury concentrations and enrichment factors.

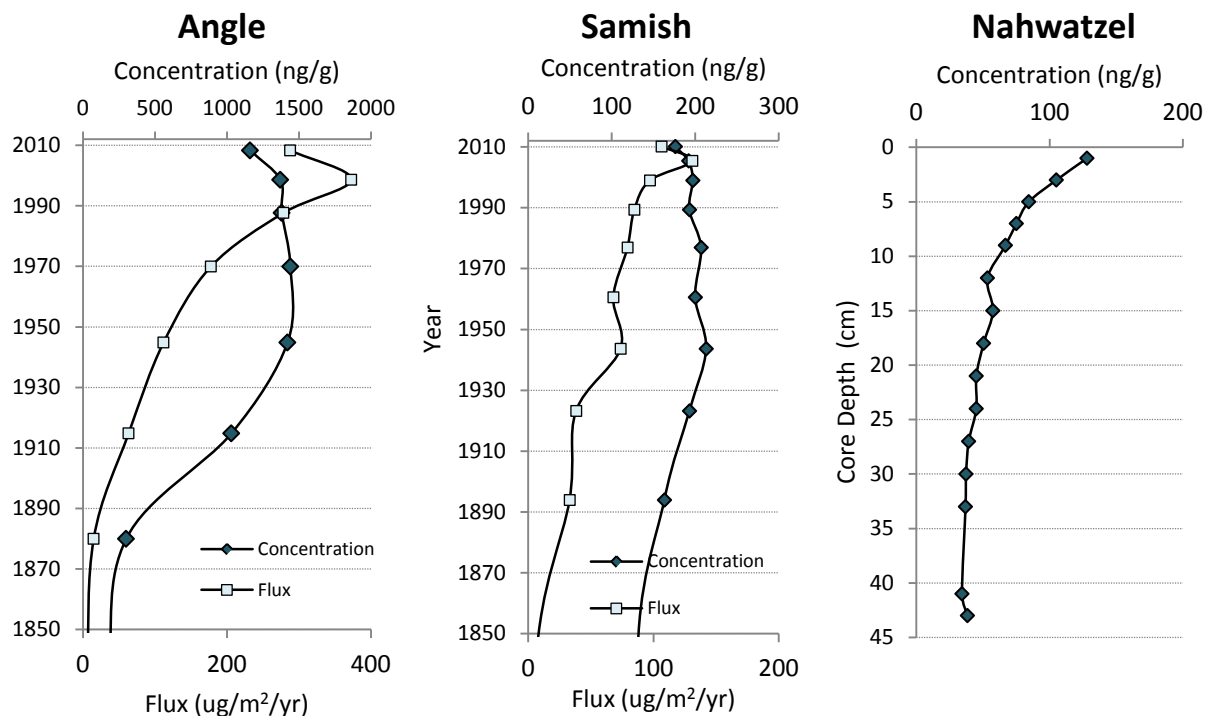


Figure 5. Mercury Concentrations (ng/g) and Fluxes (ug/m²/yr; Angle and Samish only) in Sediment Cores.

Note the differing y axes.

Mercury concentrations were highly elevated above baseline levels in the Angle Lake core throughout most of the 1900s. Levels rapidly increased over the first half of the 20th century, with the maximum concentration, 1440 ng/g (ppb), reached in 1970. Levels remained fairly constant over the second half of the century and showed a slight decrease in the top-sediment layer, though enrichment remained at 8.4. The modern mercury flux (2000-present) of Angle Lake was the highest of any core analyzed for this project since 2006. The peak mercury concentration was the second highest of maximums recorded over the last five years of the project, behind a mining-impact lake in northeastern Washington. The top sediment layer concentration (1160 ng/g) was well above Ecology's proposed SQS of 660 ng/g (Michelsen, 2011).

Mercury enrichment was modest in Samish Lake, with the peak at 1.4. Samish Lake mercury concentrations began increasing in the late 1800s, peaked around mid-century, and then leveled off between the 1960s and 1990s. Concentrations and fluxes decreased in recent sediments

(1998-present). The mercury flux profile closely resembles the sedimentation rate profile, due to low variation in mercury concentrations. Samish Lake flux rates were within the range of fluxes estimated for western Washington sediment cores collected between 2006-2010 (range = 3-378 ug/m²/yr).

Mercury concentrations remained near background levels throughout most of the Nahwatzel core. Enrichment started at around 9 cm and has steadily increased since then. Peak concentration and enrichment occurred in the top interval of the core at 128 ng/g and 3.4, respectively.

Table 3. Summary of Mercury Concentrations and Enrichment Results.

Lake	Range (ng/g)	Baseline (ng/g)	Peak Enrichment ¹	Modern Enrichment ²
Angle	101-1440	138	10.4 (1970)	8.4
Samish	131-213	149	1.4 (1943)	1.2
Nahwatzel	34.2-128	37	3.4	3.4

¹Date of peak enrichment in parentheses for Angle and Samish Lakes.

²Modern enrichment refers to the uppermost sediment core interval.

Lead

Lead concentration and flux profiles in the three sediment cores are shown in Figure 6. Summaries of lead concentrations and enrichment factors are provided in Table 4.

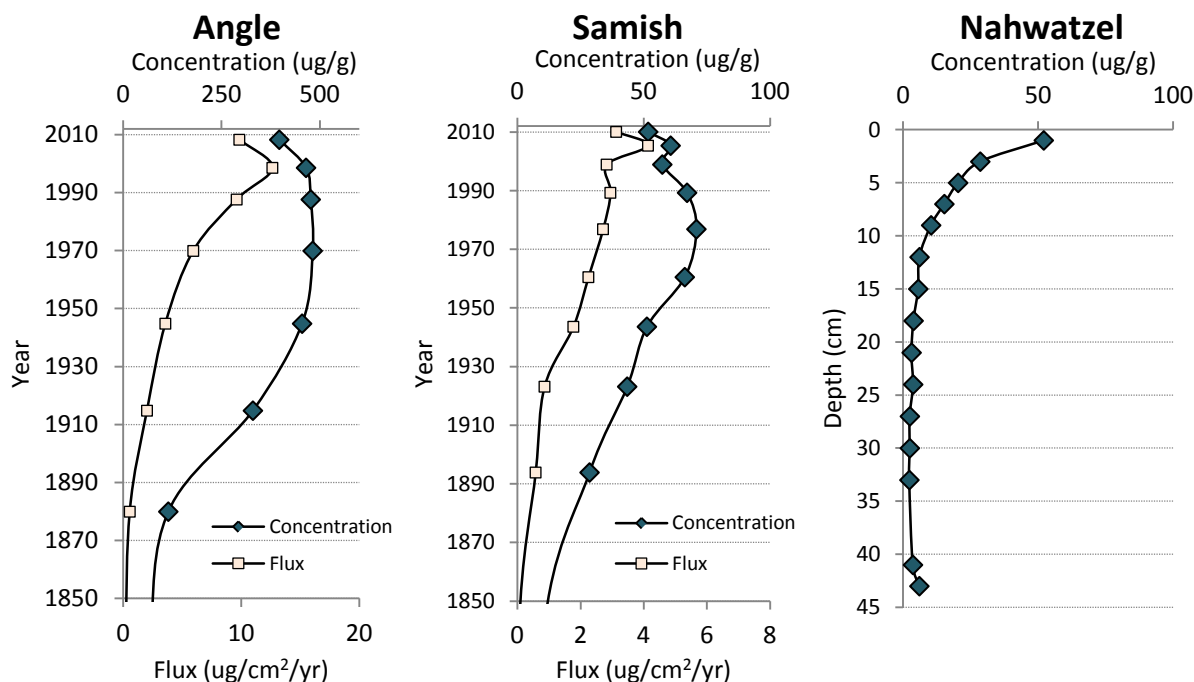


Figure 6. Lead Concentrations (ug/g) and fluxes (ug/cm²/yr; Angle and Samish only) in Sediment Cores.

Note the differing y axes.

The lead concentration and flux profile of Angle Lake was similar to that of mercury. After a steady increase over the first half of the 20th century, concentrations leveled off until around 1998, where they show a decline in the top sediment layer. The peak enrichment factor for lead was similar to that of mercury, at 10.0 in 1970. Above-baseline lead concentrations in the Angle Lake core are an order of magnitude higher than the other two lakes, and recent concentrations were higher than any other lake measured for this program from 2006 to 2011. Surficial sediments also exceeded Ecology's proposed SQS of 360 ug/g (ppm).

Samish Lake lead concentrations began increasing in the late 1800s and peaked in 1976. Concentrations have consistently declined since then, with the exception of a small increase around 2005. Enrichment factors for lead were much higher than that of mercury in Samish Lake. Peak enrichment occurred in 1976 at a factor of 9.0 and remained at 6.6 in modern sediments.

Lead concentrations at Nahwatzel Lake were low and near baseline concentrations throughout the bottom 30 cm of the core. An increase in lead levels began around 10 cm and steadily increased through the top of the core. Maximum concentrations occurred in the top-most layer of sediment, at 52 ug/g. Top sediments were highly enriched over baseline levels, at 13.1.

Table 4. Summary of Lead Concentrations and Enrichment Results.

Lake	Range (ug/g)	Baseline (ug/g)	Peak Enrichment ¹	Modern Enrichment ²
Angle	35.7-482	48	10.0 (1970)	8.2
Samish	6.54-70.9	7.8	9.0 (1976)	6.6
Nahwatzel	2.35-52.1	4.0	13.1	13.1

¹Date of peak enrichment in parentheses for Angle and Samish Lakes.

²Modern enrichment refers to the uppermost sediment core interval.

PAHs

Concentration and flux profiles of total PAHs in the three sediment cores are shown in Figure 7. For a list of all PAH compounds included in the total PAH sums, see Appendix A. Table 5 presents a summary of total PAH results and enrichment factors.

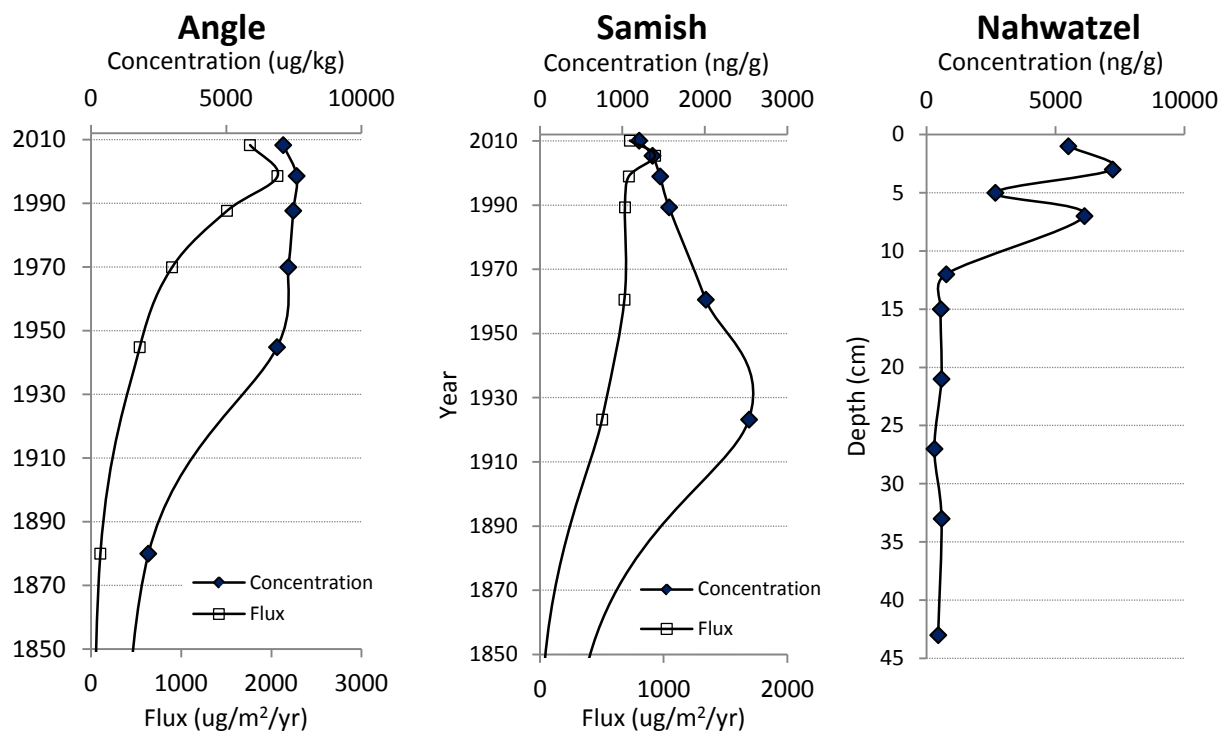


Figure 7. Total PAH Concentrations (ng/g) and Fluxes (ug/m²/yr) in Sediment Cores.

Note the differing y axes.

Total PAHs at Angle Lake were similar in profile to mercury and lead. Concentrations began increasing after the late 1800s and by 1945 were 6.4 times above baseline levels. Total PAHs remained mostly constant (around 7,500 ng/g) over the second half of the 1900s, with a slight decline in recent sediments to 7,110 ng/g. Modern enrichment remained at 6.6 in the top core interval. Concentrations throughout the core were highly elevated compared to other cores analyzed in Washington State for this project. However, surface sediment concentrations were well below the state's proposed SQS of 17,000 ng/g.

Samish Lake total PAHs were elevated over baseline levels and at their maximum (2,536 ng/g) by 1920. Since then levels have declined linearly. Modern enrichment was 5.8 times above the baseline level, down from 12.3 at peak enrichment.

Nahwatzel total PAH levels remained low until the top 10 cm of the core. PAH levels in the top of the core displayed an erratic pattern and were highly enriched, particularly at the peak (14.7 enrichment factor). Recent (top-layer) sediments contained PAH levels that were 11.2 times greater than baseline concentrations. The two spikes in total PAHs at 7 and 3 cm were driven by

pulses of high retene concentrations. Retene is formed by the combustion of softwood and could be indicative of forest fires or of wood burning for heat in the area (Ramdahl, 1983). It has also been suggested that retene could be formed by the breakdown of softwood resins (Hites et al., 1980).

Table 5. Summary of Total PAH Concentrations and Enrichment Results.

Lake	Range (ng/g)	Baseline (ng/g)	Peak Enrichment ¹	Modern Enrichment ²
Angle	946-7600	1080	7.0 (1998)	6.6
Samish	200-2540	206	12.3 (1923)	5.8
Nahwatzel	304-7210	492	14.7	11.2

¹Date of peak enrichment in parentheses for Angle and Samish Lakes.

²Modern enrichment refers to the uppermost sediment core interval.

Normalized PAHs

Figure 8 shows total PAH concentrations normalized to TOC. Normalization by organic carbon allows for direct comparison of PAH levels between lakes.

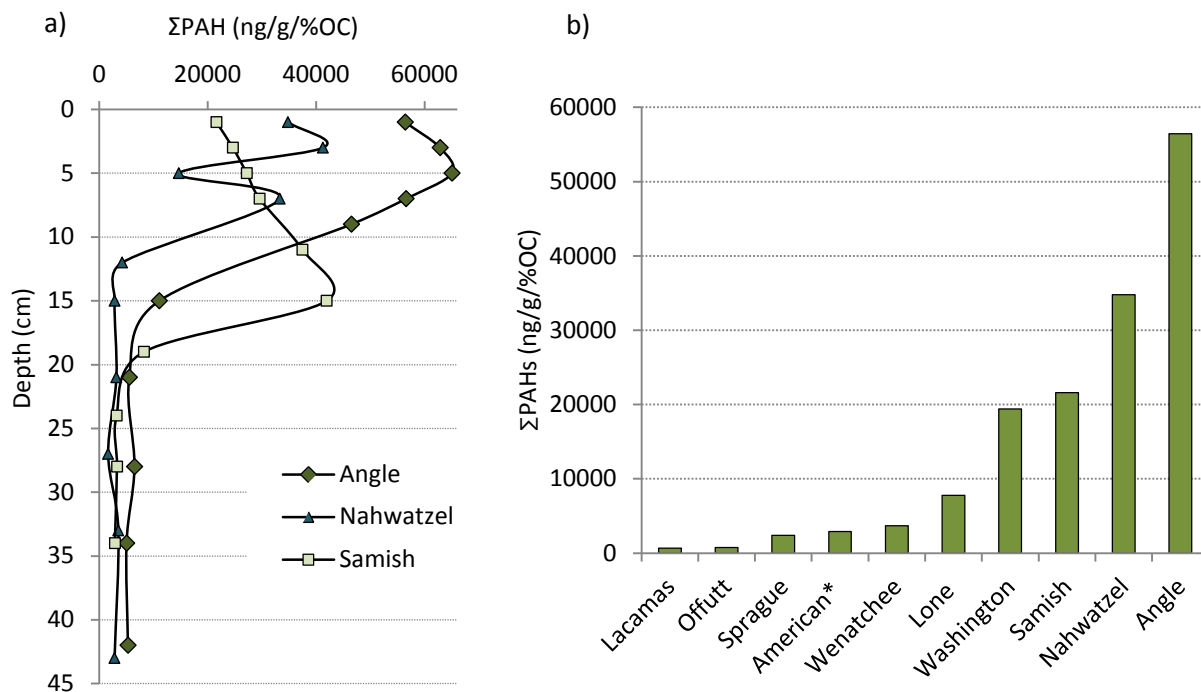


Figure 8. a) TOC-normalized PAH profiles in 2011 Sediment Cores; b) TOC-normalized PAHs in surficial (top) sediments (0-2 cm) of lakes analyzed from 2008 through 2011.

*The second sediment interval was used (2-3cm) at American Lake because no PAHs were detected in the top layer.

TOC-normalized PAH profiles (Figure 8a) were similar to non-normalized profiles for all three lakes due to the consistency of TOC levels throughout the cores. Samish Lake sediments had lower TOC values (5.9% average) and finer sediments than Angle and Nahwatzel Lakes (average TOC = 16% and 18%, respectively). Early (pre-industrial) sediments contained similar levels of normalized PAHs among the lakes. Samish Lake concentrations peaked earlier than maximums seen in the other two cores, but Angle Lake had the highest overall levels.

Normalized PAHs in surficial sediments (0-2 cm layer) (Figure 8b) of Angle Lake were the highest recorded among sediment cores analyzed by this study from 2008 to 2011. The 2011 Nahwatzel and Samish cores ranked second and third of TOC-normalized PAH contamination. High PAH concentrations of surficial sediments were reported by Van Metre et al. (2000) at Lake Ballinger (non-normalized PAH = 46,300 ng/g) which is located 25 miles north of Angle Lake, along the same major interstate highway.

Low and High Molecular Weight PAHs

Profiles of low and high molecular weight PAH sums are presented in Figure 9. Low molecular weight totals include PAH compounds containing less than four aromatic rings (LPAH) and high molecular weight totals include compounds with four or more aromatic rings (HPAH). The following compounds were used in the summing calculations:

- Total LPAH: naphthalene, acenaphthylene, acenaphthene, fluorene, anthracene, phenanthrene.
- Total HPAH: chrysene, benzo(a)anthracene, fluoranthene, pyrene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(ghi)perylene, indeno(1,2,3-cd)pyrene, dibenzo(a,h)anthracene.

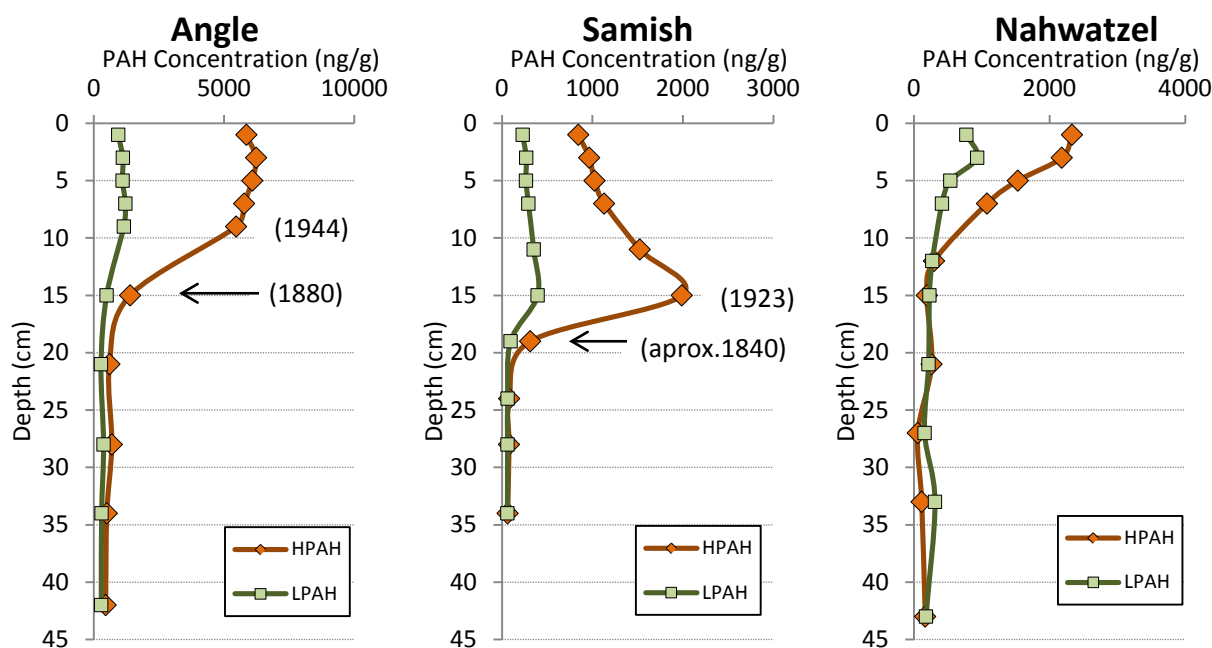


Figure 9. Total Low Molecular Weight and High Molecular Weight PAHs in Sediment Cores. *Y axis represents sediment core depth.*

All three sediment cores show an LPAH/HPAH ratio close to one in pre-industrial sediments. In the Angle and Samish Lake cores, HPAH increased over LPAH around the time of development and was highly elevated compared to LPAH by 1944 and 1923, respectively. HPAH was the dominant compound type in the top 10 cm of the Nahwatzel core. These high molecular weight PAH compounds are predominantly derived from combustion sources (Hites et al., 1980; Van Metre et al., 2000).

PAH Source Indicators

Parent PAH ratios were calculated to further investigate PAH sources in the sediment cores. The ratio of retene to the sum of retene plus chrysene [$\text{Ret}/(\text{Ret}+\text{Chy})$] provides an indication of PAH inputs from different pyrogenic (combustion) sources (Yan et al., 2005). A ratio of 0.15-0.5 indicates petroleum burning, the 0.3-0.45 range represents coal combustion, and 0.83-0.96 is indicative of softwood combustion sources (Yan et al., 2005). Figure 10 presents the $\text{Ret}/(\text{Ret}+\text{Chy})$ ratios in the 2011 sediment cores.

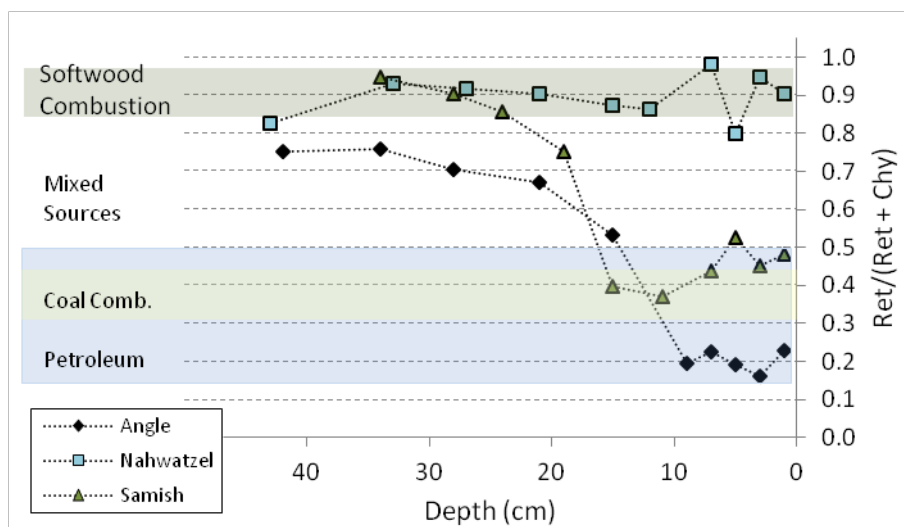


Figure 10. Ratios of Retene/(Retene + Chrysene) in Angle, Samish, and Nahwatzel Lake Cores.

Wood combustion appeared to be a predominant PAH source in earlier sediments of Samish, Nahwatzel, and to a lesser degree Angle Lake. In the Samish and Nahwatzel cores, retene ratios began decreasing around 15 cm from the top of the core, indicating a transition to petroleum and coal combustion inputs. Ratios fell into the petroleum/coal combustion range by 1923 at Samish Lake, and by 1944 Angle Lake ratios were completely in the petroleum combustion range. Nahwatzel Lake ratios show a consistent softwood combustion signature throughout the core.

Other ratios, using compounds of different molecular mass, indicate a mix of sources. A ratio using anthracene [anthracene/(anthracene+pyrene)] indicated pyrogenic petroleum (combustion) and petrogenic petroleum (e.g., motor oil runoff) were major sources throughout all three cores (Yunker et al., 2002). Whereas another ratio using indeno(1,2,3-cd)pyrene showed values normally seen for wood soot, wood combustion, and asphalt in the three cores (Yunker et al., 2002). Fluoranthene/fluoranthene + pyrene ratios indicated a consistent biomass/coal combustion signature in all three cores. All of these sources likely contribute to the PAH burden in the sediment cores. However, the retene ratio was the only one that varied throughout the depth of the cores, showing the change in PAH sources after industrialization.

The Angle Lake core provides a good example of PAH trends in a highly urbanized lake watershed. The rise of PAH levels throughout the first half of the 20th century mirrors the rapid development and transportation growth seen in the area during that timeframe. PAHs remained elevated throughout the second half of the century, as the nearby interstate highway and

international airport were expanding. Unlike all other sediment cores analyzed for this project, with the exception of urban Lake Washington, the Angle Lake PAH profile did not show declining levels in the second half of the century. Petroleum combustion sources from vehicle traffic appear to be a dominant source of the high PAH levels seen in this lake. Emissions from light-duty and heavy-duty gasoline vehicles have been found to be major sources of PAHs in the Puget Sound area (Roberts et al., 2011).

The above analysis does not take into account inputs from other potentially important sources, such as coal tar-based, creosote-treated wood and coal tar-based pavement sealcoats. Studies in Washington State have suggested that creosote-treated wood is a major contributor to environmental PAH levels in the state (Davies et al., 2012; Roberts et al., 2011). Other researchers have recently identified coal tar sealcoats as a major source of PAHs to lake sediments in the U.S. (Mahler et al., 2012 and references therein). However, in sediments where coal tar sealcoats are the primary source, concentrations are typically much higher than those seen in the cores analyzed for this study. Coal tar sealcoats are the dominant source where PAH concentrations are higher, but in lakes where sediment PAH levels are lower, combustion from vehicles is often the most important source (Van Metre and Mahler, 2010).

Conclusions

This report summarizes results from the sixth year of an ongoing study to evaluate historical contaminant trends in Washington State through age-dated sediment cores. In 2011, sediment cores were collected from Angle, Samish, and Nahwatzel Lakes and analyzed for mercury, lead, and PAHs. Angle Lake and Samish Lake sediments were dated using ^{210}Pb measurements and the constant rate of supply (CRS) model. No model could be used to estimate dates for Lake Nahwatzel sediments based on ^{210}Pb measurements.

Conclusions from this report are outlined below.

- Contaminant levels were highly elevated at Angle Lake. Maximum lead and PAH concentrations in the Angle Lake core were the highest recorded results since the beginning of this project, in 2006. Modern (2000-present) mercury fluxes were also higher than any other lake studied for this project.
- In the Angle Lake core, concentrations of all three contaminants increased above background levels over the first half of the 1990s, remained mostly constant throughout the last half of the 20th century, and decreased slightly in the top-most interval (approximately the last 10 years). Contaminant concentrations in modern sediments were 6.6-8.2 times greater than background levels.
- Mercury enrichment was modest at Samish Lake, with the peak concentration at 1.4 times above baseline levels. Mercury levels began increasing by the late 1800s, peaked around midcentury, and leveled off between the 1960s and 1990s. Mercury concentrations decreased in recent sediments (1998-2010).
- Lead concentrations at Samish Lake peaked in 1976 and consistently declined since then, with the exception of a small increase around 2005. Total PAHs reached their maximum by 1920 and then declined linearly between 1920 and the present.
- Mercury and lead concentrations at Nahwatzel Lake were low and at baseline levels throughout the bottom 30 cm of the core. An increase in mercury and lead began around 10 cm and steadily increased through the top of the core, with maximum concentrations observed in the top-most layer of sediment. PAH levels in the top of the core displayed an erratic pattern and were highly enriched, particularly at the peak (14.7 enrichment factor). Two spikes in total PAHs at 7 and 3 cm are driven by pulses of high retene concentrations, a by-product of softwood combustion or breakdown.
- Diagnostic ratios indicated that PAH sources for Angle and Samish Lakes included mostly softwood combustion in pre-1900s sediments, but turned to a mix of petroleum and biomass combustion sources by 1945 for Angle Lake and the 1920s for Samish. Softwood burning appeared to be the dominant source of PAHs at Nahwatzel Lake throughout the core record.

Recommendations

Results of this 2011 study support the following recommendations:

- Contaminants other than PAHs should be analyzed in future sediment cores to fill data gaps. Consider rotating analytes on a yearly basis to remain within budget constraints. For instance, analyze perfluorinated compounds in 2012, alternative flame retardants in 2013, etc. This will help to obtain information on trends in emerging contaminants in Washington State and support agency chemical action plans.
- Continue to target different land-use types in future site selections to gain data on a variety of potential PBT source pathways, including atmospheric deposition inputs and urban sources.
- Analyze ^{210}Pb activity in future sediment cores with alpha spectroscopy. This method requires significantly less dry sediment material and provides high resolution data.

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Appendices

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Appendix A. PAH Analyte List

Table A-1. PAHs Analyzed in 2011 Sediment Cores.

PAH Analyte List
1-Methylnaphthalene
2-Methylnaphthalene
Acenaphthene
Acenaphthylene
Anthracene
Benz[a]anthracene
Benzo(a)pyrene
Benzo(b)fluoranthene
Benzo(ghi)perylene
Benzo(k)fluoranthene
Chrysene
Dibenzo(a,h)anthracene
Fluoranthene
Fluorene
Indeno(1,2,3-cd)pyrene
Naphthalene
Phenanthrene
Pyrene
Retene

Appendix B. Sediment Core and Surface Sediment Data.

Table B-1. Angle Lake Sediment Core Results.

Section (cm intervals)	Midpoint (cm)	Analyte			
		Mercury (ng/g)	Lead (ug/g)	Total PAHs (ng/g)	TOC (%)
0-2	1	1160 J	397	7110	12.6
2-4	3	1370	465	7606	12.1
4-6	5	1380	477	7481	11.5
6-8	7	1440	482	7298	12.9
8-10	9	1420	455 J	6882	14.8
11-13	12	1030	330	-	-
14-16	15	299	115	2123	19.2
17-19	18	181	69.3	-	-
20-22	21	153	59.1	1057 J	19.1
24-26	25	161	52.4	-	-
27-29	28	160	52.6	1299 J	20.0
30-32	31	140	50.7	-	-
33-35	34	121	39.1	1026 J	20.4
36-38	37	131	47.5	-	-
41-43	42	101	35.7	946 J	17.9

J: The Analyte was positively identified. The associated result is an estimate.

Table B-2. Lake Samish Sediment Core results.

Section (cm intervals)	Midpoint (cm)	Analyte			
		Mercury (ng/g)	Lead (ug/g)	Total PAHs (ng/g)	TOC (%)
0-2	1	176	51.8	1203 J	5.57
2-4	3	192	60.7	1364 J	5.54
4-6	5	197	57.4	1457 J	5.36
6-8	7	193	67.2	1566	5.3
8-10	9	207	70.9	-	-
10-12	11	200	66.3	2011	5.37
12-14	13	213	51.3	-	-
14-16	15	193	43.5	2536	6.05
16-18	17	163	28.6	-	-
18-20	19	131	10.5	516 J	6.28
20-22	21	163	8.59	-	-
23-25	24	145	7.23	208 J	6.54
27-29	28	150	7.29	209 J	6.39
30-32	31	136	6.54	-	-
33-35	34	158	6.9	200 J	6.98

J: The analyte was positively identified. The associated result is an estimate.

Table B-3. Lake Nahwatzel Sediment Core Results.

Section (cm intervals)	Midpoint (cm)	Analyte			
		Mercury (ng/g)	Lead (ug/g)	Total PAHs (ng/g)	TOC (%)
0-2	1	128	52.1	5494	15.8
2-4	3	105	28.6	7214	17.5
4-6	5	84.3	20.4	2664	18.2
6-8	7	75	15.3	6119	18.4
8-10	9	66.8	10.4	-	-
11-13	12	53.3	6.10	762 J	18.2
14-16	15	57.4	5.65	549 J	19.6
17-19	18	50.4	3.91	-	-
20-22	21	44.9	3.17	576 J	18.5
23-25	24	44.9	3.75	-	-
26-28	27	39.2	2.52	304 J	19.1
29-31	30	37.2	2.51	-	-
32-34	33	36.8	2.35	581 J	16.7
40-42	41	34.2	3.67	-	-
42-44	43	38.3	6.04	449 J	16.2

J: The Analyte was positively identified. The associated result is an estimate.

Appendix C. Quality Assurance Data

Table C-1. Measurement Quality Objectives

Parameter	Surrogate % Recovery	SRM % Recovery	MS % Recovery	MSD RPD	Duplicate RPD	LCS % Recovery	Blank
Total Organic Carbon	---	75-125	---	---	< 20%	----	< LOQ
Grain Size	---	----	----	---	< 25%	----	---
Total Mercury	---	----	75-125	< 20%	---	85-115	< LOQ
Total Lead	---	----	75-125	< 20%	---	85-115	< LOQ
PAHs	2-Fluorobiphenyl– 30-115% Pyrene-D-10– 50-150% Terphenyl-D-14– 18-137%	65-135		<40%	< 40%	50-150	< LOQ
Lead ²¹⁰	---	----	---	---	<30%	80-120	< LOQ

SRM: Standard Reference Material

MS/MSD: Matrix Spike/ Matrix Spike Duplicate

RPD: Relative Percent Difference

LCS: Laboratory Control Sample

LOQ: Limit of Quantitation

Table C-2. Total Organic Carbon

Lab Method Blanks

Sample	Result (mg/kg dw)
B11IO58-BLK1	0.10 U
B11IO92-BLK1	0.10 U

U: The analyte was not detected at detection limit shown.

Lab Duplicate

Sample	Duplicate Result (ng/g dw)	Source Sample Result (ng/g dw)	RPD (%)
B11IO58-DUP1	0.84	0.75	11
B11IO58-DUP2	0.77	0.75	2
B11IO92-DUP1	12.4	12.6	2
B11IO92-DUP2	11.8	12.6	7

MS: Matrix Spike

MSD: Matrix Spike Duplicate

RPD: Relative Percent Difference

Reference Sample

Reference	Result (% Recovery)
B11IO58-SRM1	95
B11IO92-SRM1	97

Table C-3. Total Mercury

Lab Method Blanks

Sample	Result (ng/g dw)
B11IO29-BLK1	0.005 U
B11IO62-BLK1	0.005 U
B11IO69-BLK1	0.005 U

U: The analyte was not detected at detection limit shown.

Matrix Spikes

Sample	MS (% recovery)	MSD (% recovery)	RPD* (%)
B11IO29-MS1/MSD1	219	86	22
B11IO62-MS1/MSD2	80	80	0.2
B11IO69-MS1/MSD1	80	244	76

*RPD is calculated by laboratory based on recovered results.

MS: Matrix Spike

MSD: Matrix Spike Duplicate

RPD: Relative Percent Difference

Lab Control Samples

Sample	Result (% Recovery)
B11IO29-BS1	104
B11IO62-BS1	86
B11IO69-BS1	89

Table C-4. Total Lead

Lab Method Blanks

Sample	Result (ng/g dw)
B111O77-BLK1	0.05 U
B111106-BLK1	0.05 U
B111107-BLK1	0.05 U

U: The analyte was not detected at detection limit shown.

Matrix Spikes

Sample	MS (% recovery)	MSD (% recovery)	RPD*
B111O77-MS1/MSD1	148	-303	20
B111106-MS1/MSD1	77	103	8
B111107-MS1/MSD1	98	99	0.5

*RPD is calculated by laboratory based on recovered results.

MS: Matrix Spike

MSD: Matrix Spike Duplicate

RPD: Relative Percent Difference

Lab Control Samples

Sample	Result (% Recovery)
B111O77-LCS1	101
B111106-LCS1	101
B111107-LCS1	102

Standard Reference Materials

Reference	Result (% Recovery)
B111O77-SRM1	107
B111106-SRM1	101
B111107-SRM1	103

Table C-5. ²¹⁰Pb

Lab Method Blanks

Sample	Result (pCi/g)
MMQPH1AA	-0.205 U
MMQPP1AA	0.159 U
MMQPR1AA	0.048 U
MPP8E1AA	4.68 U

U: The analyte was not detected at detection limit shown.

Lab Duplicates

Sample	Original (pCi/g)	Duplicate (pCi/g)	RPD
1108056-03	5.55	5.07	9
1108056-16	9.07	10.50	15
1108056-31	6.98	8.25	17

Lab Control Samples

Sample	% Recovery
MMQPH1AC	118
MMQPP1AC	131
MMQPR1AC	117
MPP8E2AC	190

Table C-6. PAHs

Lab Method Blanks

Analyte	Sample No. B111070-BLK1		Sample No. B111076-BLK1	
	(ng/g dw)		(ng/g dw)	
1-Methylnaphthalene	1	U	0.165	J
2-Methylnaphthalene	0.157	J	0.352	J
Acenaphthene	2.5	U	0.184	J
Acenaphthylene	1	U	1	U
Anthracene	1	U	1	UJ
Benz[a]anthracene	1	U	1	U
Benzo(a)pyrene	2.5	U	2.5	U
Benzo(b)fluoranthene	2.5	U	2.5	U
Benzo(ghi)perylene	1	U	1	U
Benzo(k)fluoranthene	2.5	U	2.5	U
Chrysene	1	U	1	U
Dibenzo(a,h)anthracene	1	U	1	U
Fluoranthene	1	U	0.073	J
Fluorene	1	U	1	U
Indeno(1,2,3-cd)pyrene	1	U	1	U
Naphthalene	0.331	J	0.409	J
Phenanthrene	0.271	J	0.3155	J
Pyrene	2.5	U	2.5	U
Retene	5	U	5	U

U: The analyte was not detected at detection limit shown.

J: The analyte was positively identified. The associated result is an estimate.

UJ: undetected at level indicated; level is an estimate.

Lab Duplicates

Analyte	1108056-15		1108056-15 DUP		RPD (%)	1108056-42		1108056-42 DUP		RPD (%)
	(ng/g)		(ng/g)			(ng/g)		(ng/g)		
1-Methylnaphthalene	10.4		9.2		13	8.4		7.9		7
2-Methylnaphthalene	19.7		16.1		20	12.1		10.4		15
Acenaphthene	5.5	J	4.14	J	NC	2.4	J	2.9	J	NC
Acenaphthylene	9.2	U	10.0	U	NC	1.7	J	2.3		31
Anthracene	3.5	J	2.78	J	NC	1.4	J	1.4	J	NC
Benz[a]anthracene	5.1	J	3.9	J	NC	3.2		3.2		0.7
Benzo(a)pyrene	5.0	J	4.2	J	NC	5.7	U	4.2	J	NC
Benzo(b)fluoranthene	23.5		18.0	J	26	12.3		13.3		8
Benzo(ghi)perylene	20.6	J	13.7	J	41	14.4		15.4		6
Benzo(k)fluoranthene	8.4	J	6.2	J	NC	4.0	J	4.7	J	17
Chrysene	15.9		11.2		34	7.4		7.7		4
Dibenzo(a,h)anthracene	9.2	U	10.0	U	NC	1.4	J	1.5	J	6
Fluoranthene	40.9		30.6		29	13.3		13.5		2
Fluorene	25.1		21.2		17	8.6		7.2		17
Indeno(1,2,3-cd)pyrene	22.4		16.1		33	12.8		13.5		5
Naphthalene	46.5		39.2		17	23.6		18.7		23
Phenanthrene	97.2		76.9		23	25.2		21.1		18
Pyrene	24.1		14.6	J	NC	11.5		12.4		7
Retene	75.5		61.2		21	44.5	J	291	J	147

U: The analyte was not detected at detection limit shown.

J: The analyte was positively identified. The associated result is an estimate.

UU: Undetected at level indicated; level is an estimate.

NC: Not calculated. The laboratory only calculated RPDs when both results are confidently measured.

Matrix Spikes

Analyte	Sample No. 1108056-30			Sample No. 1108056-43		
	MS (%)	MSD (%)	RPD (%)	MS (%)	MSD (%)	RPD (%)
1-Methylnaphthalene	104	98	6	106	108	2
2-Methylnaphthalene	106	99	7	108	110	2
Acenaphthene	100	94	6	104	102	2
Acenaphthylene	96	90	6	100	103	3
Anthracene	51	49	4	53	54	2
Benz[a]anthracene	81	77	5	84	87	4
Benzo(a)pyrene	87	81	7	79	92	15
Benzo(b)fluoranthene	73	73	0	75	79	5
Benzo(ghi)perylene	88	83	6	85	94	10
Benzo(k)fluoranthene	100	94	6	102	106	4
Chrysene	94	87	8	101	107	6
Dibenzo(a,h)anthracene	93	89	4	89	96	8
Fluoranthene	79	76	4	89	87	2
Fluorene	105	93	12	100	101	1
Indeno(1,2,3-cd)pyrene	121	112	8	73	103	34
Naphthalene	109	93	16	106	104	2
Phenanthrene	96	75	25	95	99	4
Pyrene	80	77	4	93	91	2
Retene	95	97	2	121	101	18

Lab Control Samples

Analyte	B111070-BS1	B111076-BS1
	% Recovered	
1-Methylnaphthalene	93	107
2-Methylnaphthalene	99	108
Acenaphthene	89	98
Acenaphthylene	91	97
Anthracene	47	49
Benz[a]anthracene	83	86
Benzo(a)pyrene	91	94
Benzo(b)fluoranthene	85	81
Benzo(ghi)perylene	91	91
Benzo(k)fluoranthene	101	108
Chrysene	98	101
Dibenzo(a,h)anthracene	100	99
Fluoranthene	86	90
Fluorene	95	104
Indeno(1,2,3-cd)pyrene	92	99
Naphthalene	90	104
Phenanthrene	93	96
Pyrene	87	88
Retene	107	112

Lab Reference Samples

Analyte	B111070-SRM1	B111076-SRM1
	% Recovered	
1-Methylnaphthalene	103	111
2-Methylnaphthalene	97	109
Acenaphthene	43	47
Anthracene	32	37
Benz[a]anthracene	70	71
Benzo(a)pyrene	67	82
Benzo(b)fluoranthene	69	73
Benzo(ghi)perylene	95	95
Benzo(k)fluoranthene	83	84
Chrysene	101	111
Dibenzo(a,h)anthracene	142	193
Fluoranthene	68	71
Fluorene	39	40
Indeno(1,2,3-cd)pyrene	99	110
Naphthalene	102	117
Phenanthrene	94	106
Pyrene	65	70

Appendix D. Glossary, Acronyms, and Abbreviations

Glossary

²¹⁰Pb Activity: The number of nuclear transformations occurring in a given quantity of sediment per unit time (for instance picocuries per gram).

Anthropogenic: Human-caused.

Baseline: Average of pre-industrial contaminant concentrations.

Bioaccumulative pollutants: Pollutants that build up in the food chain.

Flux rate: Sediment accumulation rate times analyte concentration. Estimates net deposition to the coring site.

Horizon: Sediment interval measured in centimeters along a vertical gradient.

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

Pollution: Contamination or other alteration of the physical, chemical, or biological properties of any waters of the state. This includes change in temperature, taste, color, turbidity, or odor of the waters. It also includes discharge of any liquid, gaseous, solid, radioactive, or other substance into any waters of the state. This definition assumes that these changes will, or are likely to, create a nuisance or render such waters harmful, detrimental, or injurious to (1) public health, safety, or welfare, or (2) domestic, commercial, industrial, agricultural, recreational, or other legitimate beneficial uses, or (3) livestock, wild animals, birds, fish, or other aquatic life.

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

CRS	Constant rate of supply
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
Hg	Mercury
LCS	Laboratory control sample
MEL	Manchester Environmental Laboratory
MQO	Measurement Quality Objective
MS	Matrix spike
MSD	Matrix spike duplicate
PAH	Polycyclic aromatic hydrocarbon
Pb	Lead

PBT	Persistent, bioaccumulative, and toxic substance
QA	Quality Assurance
QC	Quality Control
Ra	Radium
Rn	Radon
RPD	Relative percent difference
SQS	Sediment Quality Standard
SRM	Standard reference materials
TOC	Total organic carbon
USGS	U.S. Geological Survey

Units of Measurement

g	gram, a unit of mass
kg	kilograms, a unit of mass equal to 1,000 grams.
km	kilometer, a unit of length equal to 1,000 meters.
m	meter
mg	milligrams
mg/Kg	milligrams per kilogram (parts per million)
ng/g	nanograms per gram (parts per billion)
pCi/g	picocuries per gram
ug/Kg	micrograms per kilogram (parts per billion)