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CONTAMINANTS IN LAKE SEDIMENTS AND FISH

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Lakes form an integral part of the Fraser River system. They are unique freshwater habitats that store large amounts of water and trap suspended sediments delivered by inflowing rivers. As integrators and collectors within their sub-basins, lakes provide an opportunity to study contaminant entry and transport within a river system on a watershed by watershed basis. For this purpose, we collected sediment cores from six lakes (Fig. 1; Table 1) and, from four of those, collected one species of fish. These lakes span basin-scale physiography including the Rocky Mountains, the Interior Plateau and the Coast Mountains. Some of the watersheds have seen little or no development (Moose, Chilko, Stuart, Harrison), whereas others have considerable industrial, municipal or agricultural activity (Kamloops, Nicola). The residence time ranges from eight weeks (Kamloops) to 17 years (Chilko) and all lakes are deep enough to be thermally stratified.

Lake sediments often contain a contaminant record of, for example, metals (Spliethoff and Hemond 1996; Von Gunten *et al.* 1997), organochlorines (Eisenreich *et al.* 1989; Muir *et al.* 1996; Oliver *et al.* 1989; Pearson *et al.* 1997; Sanders *et al.* 1994), polycyclic aromatic hydrocarbons (PAHs) (Christensen and Zhang 1993; Furlong *et al.* 1987; Vilanova *et al.* 1995; Wakeham *et al.* 1980) and other chemicals (Reiser *et al.* 1995). Indeed, sediments may provide the only means to reconstruct contaminant histories where monitoring is lacking. Although the literature gives many examples of lake sediment-core studies, these usually focus on an individual lake and a specific contaminant or source. Recently, northern Canadian lakes (Muir *et al.* 1996) and reservoirs in the United States (Van Metre *et al.* 1997) have been studied systematically to determine long-range transport of volatile contaminants over large scales. The Fraser River Action Plan

Table 1. Hydrographical and limnological characteristics of the lakes.

	MOOSE	STUART	CHILKO	KAMLOOPS	NICOLA	HARRISON
Area (km ²)	13.9	358	200	52.1	24.9	510
Volume (km ³)	0.73	9.3	23	3.70	0.57	80.5
Mean Depth (m)	52	26	137	71	23.5	158
Maximum Depth (m)	87	95	366	143	54.9	270
Bulk residence time (yr)	1.6	2.3	17	0.16	3.0	5.6
Discharge (km ³ /yr)	0.46	4.1	1.3	22	0.19	14.3
Watershed area (km ²)	1640	14600	2110	40386	2990	7870
Lake Yield (m/yr)	33	11.5	7.7	422	7.6	28
Watershed Yield (m/yr)	0.28	0.28	0.62	0.54	0.06	1.8
Lake Elevation (m)	1032	680	1172	336	627	10
References	2,3,4,6	2,3,4	2,3,4,5	1,2,3	2,3,4,5	2,3,4,7

1. Pharo and Carmack 1979

2. Provincial Maps giving bathymetry, areas, volumes and hypsometry

3. Water Survey of Canada. 1990a.

4. Water Survey of Canada. 1990b.

5. Provincial Lake file (Richard Dobrowski, pers. comm.)

6. Desloges and Gilbert 1995

7. Desloges and Gilbert 1991

offered the first opportunity to conduct a systematic survey of contaminant signals in dated cores from a number of lakes within the varied watersheds of this vast river basin.

Burbot (*Lota lota*) are freshwater cod with circumpolar distribution (Scott and Crossman 1973). In lakes and rivers, these predators typically occupy the top trophic position. In some areas of Canada, burbot are valued as a sport fish and the livers, in particular, are consumed by First Nations fishers. This species is therefore particularly appropriate for the study of persistent contaminants owing to the high trophic status, the lipid-rich livers which sequester hydrophobic organic contaminants, and the large existing database for comparison (Kidd *et al.* 1993; Kidd *et al.* 1995c; McCarthy *et al.* 1997; Muir *et al.* 1990; Muir *et al.* 1997). Unfortunately, burbot are not found in Chilko or Harrison lakes (McPhail *et al.* 1998), but are present in the remaining four lakes.

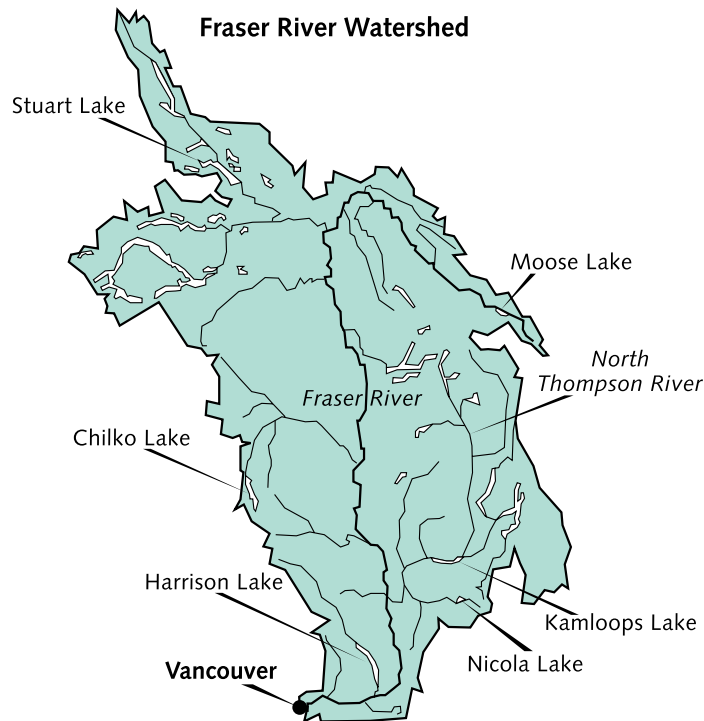


Figure 1. The Fraser drainage basin showing the locations of the six lakes.

Contaminants can enter lakes in at least two ways: (1) long-range atmospheric transport with deposition directly into the lake or onto the drainage basin and from there, through runoff, into the lake and (2) local, or regional, inputs of contaminants either through industrial or municipal effluent or via runoff from contaminated soils or surfaces. Contaminants that become strongly bound to particles may then be trapped in lakes where sediments tend to settle. Provided there is little sediment mixing or post-deposition mobil-

ity, sediments can provide a reliable history of contaminant burdens to the lake. Often, the source of the contaminant can be surmised either from the composition of classes of chemicals or from the date of contaminant appearance in a core compared to a known date of discharge.

For simplicity and brevity we present here only salient or representative features of the contaminant data in sediment cores and in burbot liver tissue. The sediment contaminant analyses include selected metals, hydrocarbons (PAHs and alkanes), organochlorine pesticides, polychlorinated biphenyls (PCBs) and chlorinated dioxins/furans (PCDD/Fs). Not all core sections have been analyzed for all contaminants; however, with the exception of dioxins and furans which were analyzed only for Kamloops Lake, measurements have been made for all of the contaminants on at least some core sections from each of the six lakes. The burbot liver analyses include organochlorine pesticides and metabolites, dominant toxaphene chlorobornanes, PCB congeners (both non-ortho and coplanar PCBs), total mercury (Hg) and methyl mercury.

The motive for the study was to assess whether long-range transport of airborne contaminants was a concern in the Fraser Basin. In that context, headwater systems above the influence of point sources should provide the best opportunity to isolate atmospherically derived contaminant signals and there was good evidence that such signals would be encountered (Donald *et al.* 1993; Gregor 1990). Sediment coring was used to determine the rates and recent history of contaminant input, whereas burbot liver was used to evaluate contaminant partitioning into biota and whether concentrations in fish approached guideline levels for human consumption or for the protection of wildlife dependent on fish.

METHODS

Cores were collected with a Kahl-Benthos gravity corer with a 10 cm acrylic tube (no catcher or cutter). Coring sites were generally situated in bathymetric depressions toward the centres of the lakes. All cores were sectioned within a few hours of collection by extruding the core upward incrementally. Sub-samples were stored frozen in cleaned glass (organic compounds) or plastic (metals, ^{210}Pb) containers. The cores collected for this study were dated using ^{210}Pb , ^{137}Cs measurements and by counting varves, where present. See Table 2 for calculated depth and mass accumulation rates based on these measures. The original data (dry-weight concentration vs. sediment depth) have then been converted to concentration versus time using these estimated rates (Table 2). Uncertainties in these rates should be borne in mind when considering the time assignments for sediment core slices or in assigning exact dates of entry of any given contaminant. Analytical methods and quality assurance protocols are fully described elsewhere (Macdonald *et al.* 1998; Macdonald and Paton 1997) and by the contract laboratories.

Table 2. Sedimentation rates at the core sites.

LAKE	LAT (N)	LONG (W)	DEPTH (m)	SED RATE g/cm ² /yr	95% CI g/cm ² /yr	SED RATE cm/yr	VARVES cm/yr	^{137}Cs cm/yr
Moose-1	52° 57.132	118° 54.395	80	0.33	0.27–0.44	0.31	0.35	— ²
Moose-2	52° 57.727	118° 56.225	74	0.20	0.18–0.24	0.214	0.26	—
Stuart-1	54° 39.669	124° 50.873	31	0.040	0.033–0.050	0.16	n/a ¹	—
Stuart-2	54° 31.010	124° 32.010	45	0.030	0.026–0.035	0.13	n/a	0.14
Chilko-1	51° 29.344	124° 12.054	153	0.064	0.050–0.089	0.14	n/a	—
Chilko-3	51° 26.650	124° 11.836	162	0.11? (slump)	—	—	0.22?	n/a
Kamloops-1	50° 46.669	120° 45.760	94	0.26	0.19–0.38	0.51	0.45	—
Kamloops-2	50° 44.808	120° 40.611	91	0.32	0.24–0.46	0.49	0.55	—
Nicola-1	50° 11.131	120° 29.899	50	0.090	0.071–0.12	0.38	n/a	0.35
Harrison-1	49° 34.519	121° 52.980	258	0.18	0.15–0.22	0.34	n/a	—

¹ Not applicable: varves were not observed

² — : not analyzed

Five large burbot (>50 cm total length) were collected by angling and trapping from Moose, Stuart, Kamloops and Nicola lakes. Livers were analyzed individually by contract laboratories. Detection limits varied between analytes and with sample mass, but averaged less than 1 ng/g wet weight. Analytical details are described fully in Shaw and Gray (in prep.).

INDIVIDUAL LAKE OBSERVATIONS

A summary of all the analytical and calculated results for contaminants in sediments and fish and the sedimentary fluxes of the contaminants are presented on the following pages in Tables 3, 4, 5, 6 and 7 to facilitate easier access, as each lake's results are discussed.

Table 3. Summary of metal data for sediment cores.

METAL $\mu\text{g/g}$	MOOSE	STUART	CHILKO	KAMLOOPS	NICOLA	HARRISON
Pb (background) ¹	31.0 \pm 2.1	15.5 \pm 0.86	13.2 \pm 2.8	26.3 \pm 2.6	8.4 \pm 0.6	17.1 \pm 1.2(8)
Pb (maximum) ²	38.1	22.3	20	37.5	11.3	26.5
Zn (background)	86.7 \pm 6.4	119 \pm 9	164 \pm 15	147 \pm 13	87.0 \pm 6.6	182 \pm 10
Zn (maximum)	130	136	188	173	103	213
Cu (background)	35.0 \pm 1.9	47.6 \pm 4.7	83.8 \pm 8.5	62.3 \pm 5.1	77.4 \pm 6.9	105 \pm 6
Cu (maximum)	50.3	65.9	92.6	69.9	89.8	124
Ni (background)	41.8 \pm 4.6	91 \pm 8	46.0 \pm 11.7	79.6 \pm 8.5	45.8 \pm 4.3	42.5 \pm 1.2
Ni (maximum)	134	117	63	89.9	52.9	59.5
Co (background)	17.9 \pm 1.2	17.0 \pm 0.7	27.7 \pm 3.5	30.0 \pm 2.5	19.3 \pm 1.7	28.2 \pm 1.4
Co (maximum)	32.2	22.3	32.3	35	22.5	29.5
Cr (background)	113 \pm 4	78.5 \pm 8.5	84.0 \pm 7.5	151 \pm 10	106 \pm 4	79.4 \pm 4.2
Cr (maximum)	140	102	102	169	132	110
Hg (background) ⁴	12.5 \pm 1.3	19.4 \pm 3.3	29.6 \pm 7.5	20 \pm 3	— ³	—
Hg (maximum) ⁴	24	158	42	52	—	—

¹ Background values were calculated as the average of the bottom 3-4 samples for the cores (\pm 1 sd).

² Bold numbers identify where a case can be made for significant contamination based on the metals profile in the core.

³ Not analyzed

⁴ ng/g

Table 4. Summary of maximum concentrations for organochlorine compounds in sediment cores.

COMPOUND ng/g	MOOSE	STUART	CHILKO	KAMLOOPS	NICOLA	HARRISON
# of samples	18	5	5	8	11	12
HCB	0.2	0.44	0.4	0.17	1.5	0.06
Total HCH	0.14	0.09	0.13	0.29	6.1	0.06
Heptachlor	<0.02–<0.1 ¹	<0.06–<0.17	<0.04–<0.43	<0.03–<0.73	<0.003–<0.38	<0.003–<0.07
Aldrin	<0.002–<0.01	<0.002–<0.01	<0.007–<0.09	<0.007–<0.09	0.14	<0.002–<0.02
Chlordane	0.01	0.07	0.02	<0.006–<0.33	3.1	0.06
Total DDT	1.73	1.25	0.32	1.95	323	8.7
Total Nonachlor	0.04	0.06	0.06	<0.006–<0.37	1.4	0.05
Mirex	0.007	0.008	0.01	<0.001–<0.08	0.25	0.06
Dieldrin	0.06	<0.06–<0.22	<0.05–<0.47	0.92	<0.06–<0.62	<0.02–<0.22
Endrin	<0.09–<1.3	<0.22–<0.8	<0.08–<2.1	2.6	<0.15–<1.2	<0.04–<0.53
Methoxychlor	<0.14–<1.7	<0.32–<1.0	<0.2–<4.2	<0.18–<7.9	<0.21–<2.6	<0.2–<0.94
Toxaphene	<0.12–<0.57	<0.46–<1.8	<0.04–<1.1	<0.2–<4.3	<0.13–<2.2	<0.08–<1.2
Total PCB	0.86	0.68	0.94	7.7	1.49	1.5

¹ The range of sample detection limits given where compounds were not detected.

Table 5. Summary of biological data for five burbot obtained from each lake and chemical analyses of their livers.

VARIABLE	KAMLOOPS	NICOLA	STUART	MOOSE ⁷
Biological Variables¹				
Age (years)	7 (5+–8+)	7 (6+–7+)	10 (9+–12+)	7 (5+–8+)
Fish Length (cm)	55 (47–61)	52 (48–58)	79 (70–96)	53 (40–63)
Fish Weight (g)	1248 (841–1634)	855 (580–1173)	2585 (1994–3586)	929 (352–1348)
Liver Wt (g)	135.2 (98.1–223.3)	24.0 (6.7–58.9)	69.2 (51.6–98.9)	21.4 (9.2–28.8)
HSI (%) ²	10.8 (7–14)	2.3 (1.2–5.0)	2.83 (1.5–4.3)	2.37 (2.1–2.6)
Percent Lipid	61 (52–71)	24.5 (5–56)	31.4 (13–62)	31.7 (22–36)
Summary Contaminant Concentrations^{3,4}				
Total PCBs (ng/g)	321.5 (250.9–407.9)	138.9 (91.7–251.3)	130.4 (74.2–203.1)	1912.5 (1198.8–3017.2)
Total Drins (ng/g)	7.0 (4.8–12.4)	1.8 (0.7–3.4)	2.0 (1.0–5.3)	5.2 (3.8–7.0)
Total Chlordane (ng/g)	28.2 (9.5–50.8)	16.5 (9.7–26.7)	27.9 (14.7–39.5)	95.8 (80.0–123.9)
Total HCH (ng/g)	20.1 (13.7–35.3)	3.4 (1.5–8.7)	7.2 (2.8–15.0)	3.1 (2.3–3.8)
Total DDT (ng/g)	289.8 (220.2–414.5)	974.3 (715.0–1563.5)	53.2 (24.5–102.6)	619.2 (415.4–904.4)
Ratio DDE/Total DDT	0.82 (0.74–1.0)	0.80 (0.76–0.83)	0.72 (0.64–0.80)	0.61 (0.56–0.65)
PCB-TCDD TEQs (pg/g) ⁵	13.6 (9.7–18.4)	4.4 (3.1–7.2)	6.6 (4.0–8.7)	25.1 (18.5–34.8)
Total Toxaphene (ng/g)	132.5 (94.0–210.0)	6.9 (1.6–39.0)	105.9 (56.0–180.0)	600.2 (470.0–720.0)
Methyl Mercury (µg/g)	0.01 (0.01–0.02)	0.03 (<0.05–0.07)	0.03 (0.02–0.09) ⁶	0.03 (0.02–0.08)
Total Mercury (µg/g)	<0.05	0.04 (<0.05–0.08)	0.04 (<0.05–0.10) ⁶	0.04 (<0.05–0.12)
Lipid-Normalized Concentrations³				
Total PCBs (ng/g lipid)	532 (363–755)	782 (163–2584)	517 (208–1562)	6140 (3329–13714)
Total Drins (ng/g lipid)	12 (8–19)	10 (6–15)	8 (7–9)	17 (14–21)
Total Chlordane (ng/g lipid)	47 (15–94)	93 (27–267)	111 (64–236)	307 (222–460)
Total HCH (ng/g lipid)	34 (19–68)	19 (15–32)	29 (21–77)	10 (9–10)
Total DDT (ng/g lipid)	480 (317–768)	5,496 (1277–18502)	211 (101–733)	1988 (1154–4111)
Total Toxaphene (ng/g lipid)	222 (149–404)	39 (8–390)	420 (290–786)	1927 (1306–3273)

¹. arithmetic means and range

². hepatosomatic index: liver weight/body weight *100

³. geometric means and range

⁴. non-detects set to 1/2 sample detection limit

⁵. toxic equivalent units calculated using dioxin-like PCB TEFs of Ahlborg et al. (1994)

⁶. due to QA problem, one analysis removed: n=4

⁷. summary does not include one aberrant individual

Table 6. Summary of hydrocarbon data for sediment cores.

COMPOUND ng/g	MOOSE	STUART	CHILKO	KAMLOOPS	NICOLA	HARRISON
Number of samples	18	5	5	8	11	12
Background Total PAH ¹	15 (est)	125 (est)	29 ± 8	35 (est)	46 ± 20	7 ± 2
Highest PAH ²	45	209	38	245	109	201
Background Total Alkane	1155 ± 320	7500 (est)	1600 ± 890	3800 (est)	11250 (est)	1790 ± 270
Highest Total Alkane ²	2053	8943	3170	19300	20600	4880

¹ Background values were calculated as the average of the bottom 3–4 samples for the cores (± 1 sd).

² Bold numbers identify where a case can be made for significant contamination based on the hydrocarbon profile in the core.

Table 7. Estimated contaminant fluxes to sediments for the six lakes.

METAL OR COMPOUND		MOOSE	STUART	CHILKO	KAMLOOPS	NICOLA	HARRISON
Pb ²	surface	0.8	0.05	<0.4	0.4	0.1	0.5
	maximum	2.3	0.3	<0.4	3.6	0.3	1.7
Zn ²	surface	12.5	0.2	<1.2	5.1	0.0	5.6
	maximum	14.3	0.5	<1.5	8.3	1.4	5.6
Cu ²	surface	5.0	0.03	<0.3	0.1	0.2	3.4
	maximum	5.0	0.5	<0.6	2.4	1.1	3.4
Hg ³	surface	1.8	0.2	0.0	0.0	n/a ¹	n/a
	maximum	3.8	5.6	<0.8	10.2	n/a	n/a
Total DDT ³	surface	0.13	<0.04	<0.06	<0.3	0.62	0.05
	maximum	0.6	0.05	0.02	0.6	29	1.6
Total HCH ³	surface	0.02	0.004	<0.02	<0.09	0.03	0.002
	maximum	0.05	0.004	0.01	0.09	0.54	0.01
Total PCB ³	surface	0.16	0.02	<0.6	<3	0.14	0.06
	maximum	0.28	0.03	0.06	2.5	0.13	0.27
Total PAH ³	surface	6.9	3.4	0.0	33	0.41	9.0
	maximum	9.9	3.4	0.6	67	5.7	34.9

¹ not available

² µg/cm²/yr

³ ng/cm²/yr

Moose Lake

This deep and relatively high elevation lake (1,000 m) receives most of its water from sub-alpine forest, permanent snow field, and glacial runoff from the uppermost portion of the Fraser River drainage in the Rocky Mountains. Ice covers the lake from December to mid-April in most years and the water remains fairly cool and turbid throughout the summer because of the glacial meltwater. Sediment trapping efficiency of the lake is probably high, due to both the residence time (greater than one year) and cool summer temperatures which would cause the influent river plume to plunge deep into the lake. Although remote from any settlement, a hydro power-line, a highway and a railway run along one side of the lake and the incoming river. Sedimentation rates determined by ²¹⁰Pb agree well with laminae counts (Table 2) and with previous work (Desloges 1995), leading to confidence both in the assigned dates and in the assumption that little or no mixing has occurred after deposition.

There is evidence of minor contamination by several heavy metals (Table 3; Pb, Zn, Cu, Ni, Co), the best example of which is Zn (Fig. 2). Some or all of the Pb contamination likely comes from highway automobile traffic (leaded gasoline used until the late 1970s) but the other contaminating metals must have another source, probably linked with the highway/railway corridor (e.g. road salt, highway construction). For these

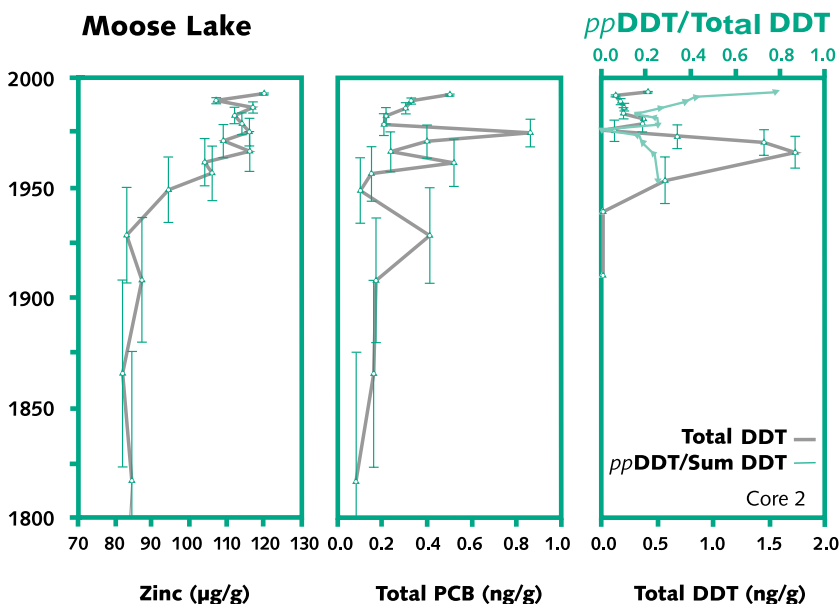


Figure 2. The concentration of Zn, Total PCBs, Total DDT and the *pp*DDT/total DDT ratio in Moose Lake sediments as a function of time. Error bars denote 95% confidence intervals.

sections of the core, DDD and DDE comprise 80 per cent of the Total DDT (sum of DDE, DDD and DDT), suggesting substantial weathering (Addison 1978). Sediment concentrations in the upper part of the core show that DDT fluxes markedly decreased after the 1960s. However, the surface sediment is elevated in Total DDT, 80 per cent of it composed of *pp*DDT, suggesting a recent input of relatively unweathered DDT.

Total PCB concentrations in the sediments are exceptionally low (<1 ng/g) compared with other remote lakes where observed values are an order of magnitude, or more, higher (Eisenreich *et al.* 1989; Muir *et al.* 1996; Sanders *et al.* 1994). These low values result in a noisy plot of Total PCB concentration as a function of time (Fig. 2), making it difficult to infer reliable long-term trends or to determine an accurate congener distribution. The low PCB concentrations in sediments may derive partly from a relatively rapid sedimentation rate (*i.e.*, dilution by inorganic particles) and partly from a hydrologic regime which causes some of the PCB (especially the more soluble, lighter components) either to volatilize or simply to pass through the lake (cf. Amituk Lake study in Barrie *et al.* 1997). The total PCB burden accumulated in these sediments since the 1940s, estimated at 20 ng/cm² (focus-correction would reduce this number), is, however, similar to inventories measured elsewhere in North America for lakes receiving PCBs via the atmosphere (Rapaport and Eisenreich 1988; Van Metre *et al.* 1997).

While Moose Lake sediments are relatively clean, the fish results are surprising (Table 5). Burbot livers contain elevated concentrations of PCB, total DDT and toxaphene. The levels of PCB were particularly high, averaging 1900 ng/g. This finding is similar to the results of Donald *et al.* (1993) who found that trout muscle tissue from Moose Lake contained the highest PCB levels of 14 continental divide lakes sampled. In several of the burbot collected in the FRAP study, PCB exceeds the 2000 ng/g wet weight human consumption guideline (BC MELP 1998). While the levels of DDT and toxaphene are below the 5000 ng/g wet weight US Food and Drug Administration legal limit for commercial food (US EPA 1989), Germany has recently established a legal tolerance level for toxaphene of 100 ng/g (de Geus *et al.* 1999). Both compounds averaged 600 ng/g of liver tissue in Moose Lake burbot.

metals, the contamination is first evident from about 1945–1950 for both cores. Hg also shows small, “noisy”, but detectable contamination in the upper layers of the sediment (after about 1950).

Pesticides are observed at very low levels in sediments (Table 4) with hexachlorocyclohexane (HCH), hexachlorobenzene (HCB) and dichlorodiphenyltrichloroethane (DDT) providing the clearest records for contamination. DDT enters the lake after about 1940 (Fig. 2) and peaks in the late '50s to mid '60s, consistent, within dating and sectioning resolution, with known aerial spraying of DDT in B.C. from 1946 to 1962 (Prebble 1975). For the deeper

On a lipid-weight basis, concentrations of organochlorines (OCs) in Moose Lake are among the highest measured in Canada (cf. Muir *et al.* 1997) although still lower than concentrations in lake trout from Lake Ontario (Kiriluk *et al.* 1995). It is interesting to note that the ratio of Total DDT to PCB is similar in fish from Stuart Lake, which would likely only receive DDT and PCB from the atmosphere (Fig. 3). This fact supports the hypothesis that the source of PCB in Moose is also atmospheric. In addition, the overall pattern of contamination by PCB, toxaphene and DDT in Moose Lake mirror data for top predator fish in other remote lakes receiving atmospheric contaminants (Muir *et al.* 1997; Nakata *et al.* 1995).

The DDE/Total DDT ratio in Moose Lake burbot was consistently less than 0.70 (Fig. 4) implying relatively unweathered contamination (Addison 1978; Sanchez *et al.* 1993). We infer from both the sediment and burbot results that a small amount of unweathered DDT has entered Moose Lake either directly from the atmosphere or in meltwater. The DDT

could have been recently delivered, but it is also plausible that it derives from older DDT that has been preserved undegraded in the snow and ice of the basin and released during a season of exceptional meltback. Total DDT concentrations exceeding drinking water guidelines (0.03 mg/L) have been found in a permanent snowfield layer deposited in the late 1980s in nearby Banff National Park. Most of this total DDT was composed of the parent-DDT congeners (Donald 1997, pers. comm.).

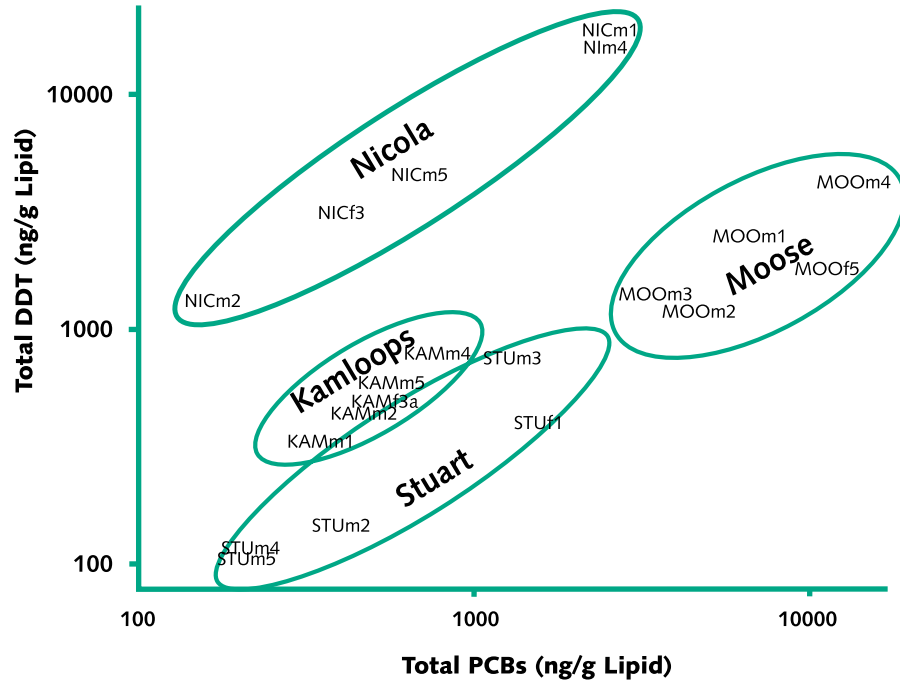


Figure 3. Lipid corrected Total DDT versus Total PCBs in burbot liver.

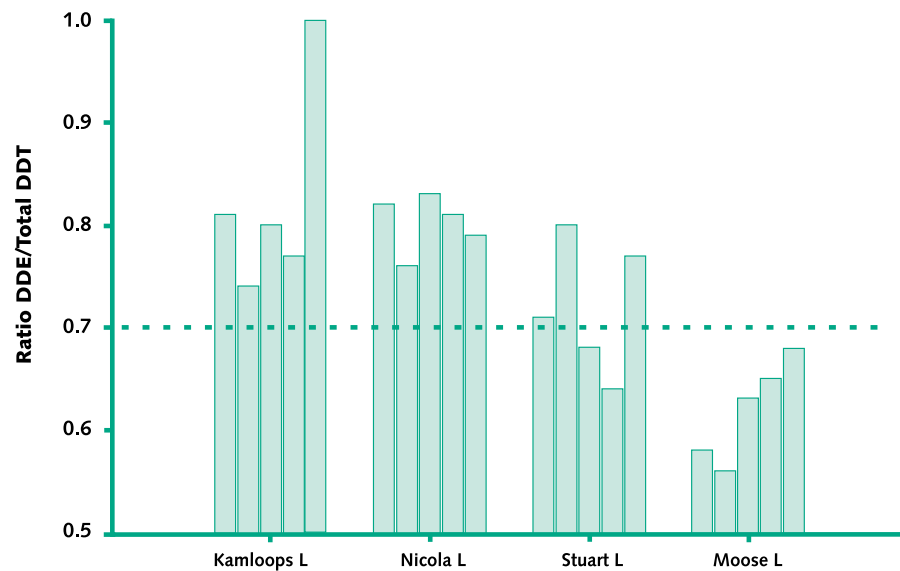


Figure 4. The ratio of DDE to Total DDT in burbot liver for the four lakes sampled for fish.

It is well known that biomagnification can produce extraordinarily high OC burdens in predatory fish from lakes (Kidd *et al.* 1995a; Kidd *et al.* 1995c; Kiriluk *et al.* 1995; Muir *et al.* 1997; Rasmussen *et al.* 1990). The PCB, toxaphene, DDT and chlordane data for burbot suggest that biomagnification must be at least partly implicated in Moose Lake. The OC data alone indicate that burbot are at the 4th to 5th trophic level and that the Moose Lake food web is longer than that of other lakes studied here or by Donald *et al.* (1993). What remains to be explained, however, is why the Total PCB/toxaphene ratio in Moose Lake burbot is consistently greater than three when in most remote lakes receiving only atmospheric contaminants this ratio is usually <1 (Muir *et al.* 1997), and why heavy congeners tend to dominate the PCB composition (Fig. 5). Where high Total PCB/toxaphene ratios have been observed elsewhere (Lake Laberge, Char Lake), local contamination by PCB was inferred—although not proven conclusively. The sediment record in Moose Lake appears to discount a local PCB spill and we must look elsewhere for an explanation. Perhaps unique physical and chemical processes are responsible for the transfer of these two contaminants to the lake and their apparent absence in sediments.

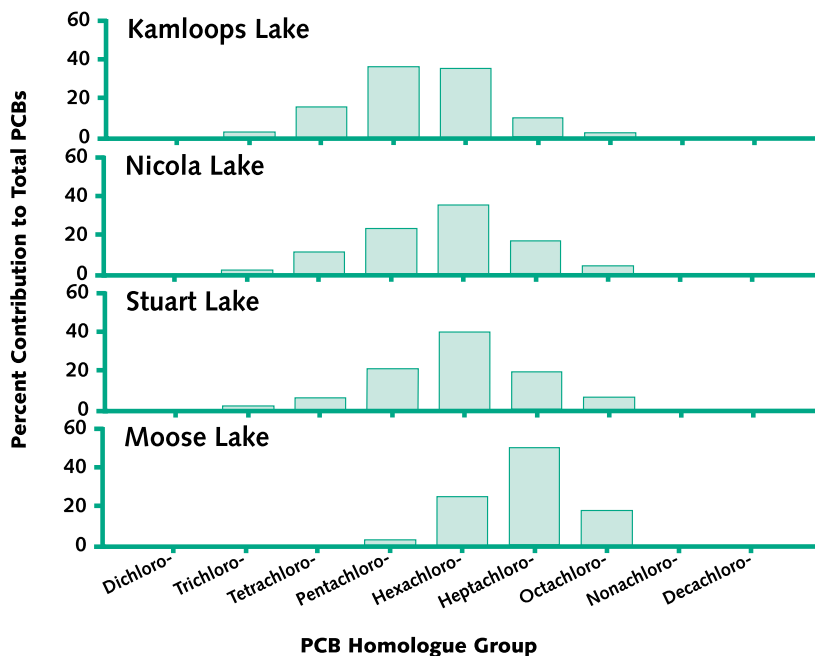


Figure 5. Patterns in PCB homologue groups in burbot liver for the four lakes sampled.

Due to its low Henry Law constant, toxaphene partitions strongly into water (Barrie *et al.* 1997). Therefore, we can expect the toxaphene concentrations in the lake to reflect concentrations in the incoming river modified by air-water exchange at the lake surface dependent on water temperature and the rate of mixing of deeper waters to the surface. In this scenario, the basin simply supplies cold, toxaphene-saturated water to the lake.

In contrast to toxaphene, PCBs, especially the heavier congeners, partition strongly to particles. Continuing with the rationale, the lighter congeners which are more volatile and less particle-attracted could be lost to the atmosphere during the annual cycle of partial snowfield melt and re-freezing while the heavier congeners become associated with suspended sediments in the runoff (Barrie *et al.* 1997; Gregor 1990). The loss of lighter PCBs (penta-, tetra-, tri-chlorinated biphenyls) from the congener profile in Moose Lake burbot (Fig. 5) could thus be explained. Certainly, the congener pattern to the right of CB136 (*i.e.*, PCBs with 6 or more chlorine substitutions) is very similar for all four lakes. This suggests a common, basin-scale (*i.e.*, atmospheric) source which has been altered in the case of Moose Lake by the partial loss of lighter components. In addition, both toxaphene and PCB concentrations in meltwater could be enhanced by sublimation of ice or snow, especially at higher altitudes or even by permanent snowfield and glacier ablation, releasing contaminants deposited at an earlier time when atmospheric deposition was greater.

These concentrating processes have to be more efficient with heavy PCBs than toxaphene to explain the higher ratio in burbot tissue. The lack of accumulation in sediments, particularly of PCBs, is also puzzling.

The hypothesis that physical and biological processes, rather than local contamination, lead to the OC patterns observed in Moose Lake burbot needs to be tested directly in comparative food-web studies.

Stuart Lake

This large and relatively shallow (mean depth 26 m) lake is the last in a chain of large lakes on the Nechako Plateau which together supply most of the flow to the Stuart River, which subsequently joins the Nechako River more than 60 km above its confluence with the Fraser at Prince George. The residence time of water in Stuart Lake is about 2.3 years and sediment input is very low, partly because most of the incoming rivers originate in large lakes and partly because local topography is not mountainous. As a result, the sedimentation rate is very low, and sediment composition is dominated by organic matter. The lake is usually ice-covered from mid-December to mid-April. Fort St. James (pop. ~5,000), by the lake near the outlet, has a lumber mill as do several smaller aboriginal communities in the basin. Treated sewage effluent is discharged to the river downstream of the lake. The Pinchi Fault, running along the northeast side of the lake, is known to contain abundant Hg mineralizations, some of which have been redistributed during glaciation (Plouffe 1995). The only known local contaminant source is a mercury mine and reduction plant, which operated during the 1940s and early 1970s, located near Pinchi Lake which drains into Stuart Lake (EVS 1996).

The background concentrations of PAH in lake sediments are relatively high in Stuart Lake (Table 6). High organic carbon content probably contributes to natural enrichment, and slow sedimentation rates imply a lack of diluting inorganic material as demonstrated by the relatively low and constant PAH fluxes (Table 7).

Most of the heavy metals in Stuart lake show no or only very slight trends with time. For example, there are minor enrichments of Pb observed between about 1940 to 1980 which can be attributed to the general use of leaded gasoline. An exception, however, is Hg which provides a very clear contaminant signal in the sediments (Fig. 6). Contaminant Hg entered the sediments in the 1940s and then decreased from 1950 to 1980 so that it has now returned almost to the original background. The appearance of Hg in Stuart Lake sediments coincides with the operation of the Hg mine near Pinchi Lake from 1940 to 1944, during which time the mine disposed of tailings into Pinchi Lake (EVS 1996). The mine reopened and operated from 1968 to 1975, but this later operation is not evident in the Stuart Lake sediment profiles, probably due to better environmental controls (EVS 1996). Integrating the contaminant Hg burden for the lake sediments at the two sites and prorating it for the sedimentary basin implies that as much as 100–200 kg of Hg entered the lake sediments during the war years—or about 0.01 per cent of the production.

Organochlorine determinations were made for only five core sections. These few data points reveal low sediment concentrations for pesticides and PCBs (Table 4), similar to observations from Moose Lake and consistent with long-range transport to the basin occurring predominantly after 1950. For example, the depth profile observed at S-1 (4 points; not shown) suggests that Total DDT was highest in the 1960s, in agreement with the documented use of DDT in aerial spraying (Prebble 1975), and consisted predominantly of weathered components (DDD, DDE). Deeper sections contain no detectable organochlorines, consistent with their age (mid-1930s or earlier).

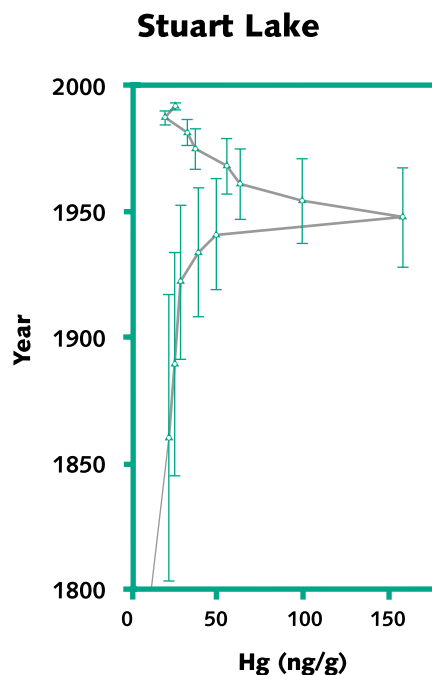


Figure 6. Hg in Stuart Lake sediments as a function of time (at S-1).

Burbot collected from Stuart Lake were longer (average 78 cm), heavier (average 2.3 kg) and older (average 9.3 years) than fish collected in the other three lakes. These factors have all been shown to correlate with higher concentrations of persistent OCs and Hg (Kidd *et al.* 1995b; Muir *et al.* 1997) and, therefore, fish from this lake might be expected to display relatively high pesticide and Hg levels. This was not the case, however, and concentrations of most OCs were in the lower end of the range of values measured at the other three lakes, particularly for DDT (Table 5). Organochlorine concentrations in burbot are entirely consistent with long-range atmospheric delivery to the lake watershed.

Despite gross Hg contamination of Pinchi Lake in the 1940s (Ableson and Gustavson 1979), and a fish advisory recommending limited consumption of lake trout from Pinchi Lake (Martin *et al.* 1995), there is no evidence of elevated Hg levels in burbot recently caught from Stuart Lake. This is not unexpected as Hg concentrations in sediments have declined to pre-1940 levels.

Chilko Lake

This remote and extremely deep (366 m) lake is nestled in the heavily glaciated Coast Range Mountains at over 1,100 m elevation. While the drainage basin is only 30 per cent larger than Moose Lake's, the water yield is 120 per cent larger. This is possibly due to lower evaporation/sublimation around Chilko as the annual precipitation in both areas is in the same range (600–1,200 mm [ESWG 1995]). Because the residence time is so long (17 yrs), the lake is probably a very effective sediment trap.

Unfortunately, the sediment core evidence suggests that the steep bathymetry exposes the profundal sediment basins to slumps of accumulated slope sediment which then disturb the stratigraphy. The lake is often very clear (Secchi depth ~40 m) in the early summer before glacier melting occurs and even then turbidity only affects the inlet area (Shortreed 1997, pers. comm.). The sedimentation rates were difficult to determine with precision due to disturbances in the sediment. Nevertheless, sediments show little evidence of metal trends with depth that could be interpreted as contamination. Similarly, there were only a few organochlorine compounds detected, and where they were detected, concentrations were uniformly low (Table 4). This suggests long-range atmospheric inputs only. Perhaps, in contrast to the situation in the Rockies, much of the annual contaminant deposition in the Coast Range drainage basin is not released in the annual summer melting, but is instead stored in snowfields and glaciers. Of course, Moose Lake had relatively low concentrations of OCs in its sediments in contrast to the high concentrations in burbot and, therefore, top predator fish (*e.g.* bull trout) should be sampled in Chilko Lake to see whether a similar condition exists there.

Kamloops Lake

Kamloops Lake is a riverine lake, situated downstream of the confluence of the North Thompson and South Thompson rivers, with the largest drainage basin (40,000 km²) of the six lakes and is not a headwater system. While its residence time is extremely short (8 weeks), Kamloops Lake is deep and the physical limnology is conducive to sediment trapping so that laminae are easily visible in cores (Pharo and Carmack 1979). The major sediment source is post-glacial lacustrine sediment banks along the lower reaches of the two rivers which become mobilized during high water and flows of the freshet (May–July). As there are many large lakes upstream in the drainage basin to trap sediments and their associated atmospherically derived contaminants, Kamloops Lake probably receives contaminants predominantly from the City of Kamloops. The lake does not freeze in most winters and continually cools with wind mixing to temperatures below 4°C (St. John *et al.* 1976).

While the largest industrial discharge today is the pulp mill (Hatfield Consultants 1995), in the past there was a small copper and rare-earth metal smelter (Bernard 1983) and a petroleum refinery. The municipal sewage treatment plant (serving 90,000 people) has been discharging a tertiary-treated effluent during the April to September period and has not been discharging during the fall/winter since the late 1970s. Two

railways, a hydro-power corridor, and the Trans-Canada Highway along the shore and the upstream rivers represent potential contaminant sources.

For most of the metals there is little evidence of sediment contamination. Pb may show slight enrichments after about 1950 similar to the other lakes and marine coastal regions of B.C. (*e.g.* see Macdonald *et al.* 1991) and Hg also shows a slight, but significant, enrichment in the upper portion of the sediment (Table 3) which could be related to use at the pulp mill as a slimicide (Waldichuk 1983).

Previous sampling in Kamloops Lake and experience elsewhere in B.C. led us to expect that polychlorinated dioxins and furans (PCDD/Fs) produced by pulp mills using chlorine bleach and/or pentachlorophenol (PCP) contaminated wood chips would be an important component of the OC burden in Kamloops Lake sediments (Macdonald *et al.* 1992; Trudel 1991; Mah *et al.* 1989). As anticipated, PCDD/Fs from pulp mill activities proved to be the dominant regional OC class, and a detailed analysis of their history and sources as recorded by the sediments is discussed in Macdonald *et al.* (1998).

Principal Component Analysis (PCA) of the OC data distinguished three major groups of PCDD/Fs: (I) lightly chlorinated compounds produced when chlorine was used to bleach pulp, (II) pulp mill digester-mediated condensation products of polychlorinated phenoxyphenol contaminants in polychlorophenates (polyCPs), and (III) highly chlorinated products of combustion and/or PCP contamination. In addition to the PCDD/Fs, a fourth group was identified consisting of most of the PCBs and possibly octachlorodibenzo-*p*-dioxin (OCDD) (Group IV). When the sediment core samples are plotted on a PCA biplot (Fig. 7) they

show that sediments were contaminated first by atmospheric inputs of low levels of PCB and higher chlorinated dioxins (Group IV). We infer that prior to the construction of the pulp mill, Kamloops Lake was similar to the other lakes in this study, receiving OCs primarily from the atmosphere. After construction of the mill, sediments were contaminated first by condensation products (a sign that chlorophenol-contaminated wood was used in the pulping process) and then by the pulp chlorination products (*e.g.* TCDD/F). The pulp mill stopped using CP-contaminated wood stock and phased out chlorine bleach with the result that recent sediments show a dramatic downturn in these compounds.

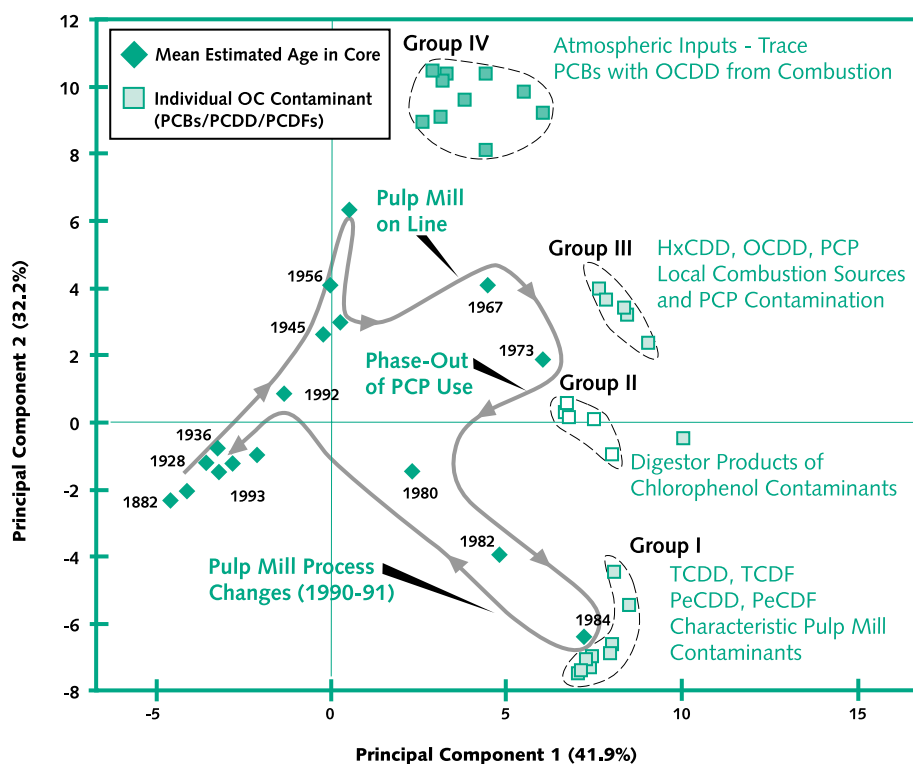


Figure 7. PCA biplot showing the association between the contaminants in sediment cores from Kamloops Lake and particular organochlorine chemical groups (PCDD/F, chlorophenolics and PCBs) and their relationship to major contaminant sources. Dates refer to ^{210}Pb estimates for core sections, which are linked in date order by the arrow line. The group designation and composition was determined from cluster analysis.

The predominant historical source of TEQ (dioxin toxicity equivalent units) to the lake sediments has been from TCDD/Fs produced when bleaching pulp with chlorine (Fig. 8; TEQs based on Toxic Equivalent Factors proposed by NATO[1988]). Although the production of these compounds was sharply curtailed in about 1990, they continue to be available for uptake in biota (Macdonald *et al.* 1998) and 2,3,7,8 TCDF was easily detected in peamouth chub and mountain whitefish sampled in 1994 (Raymond *et al.* 1999). Two other significant results emerged from the PCDD/F and PCB determinations: (1) the pulp chlorination process produced several PCBs (CBs 13, 15, 37) and (2) a secondary source of PCDD/Fs, witnessed as a pulse in the late 1940s to early 1950s, probably entered the sediments from lake-side treatment of power poles or railway ties with contaminated PCP (Fig. 9).

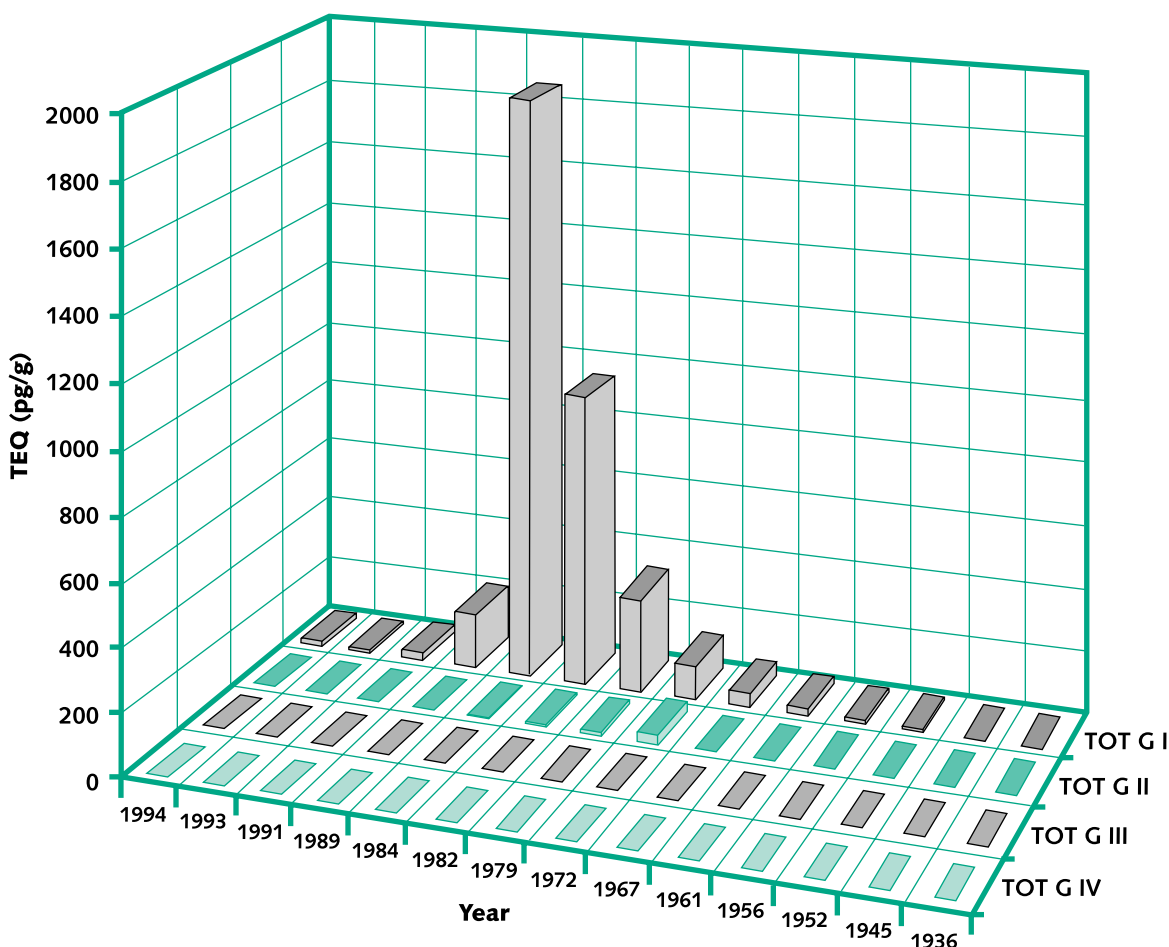


Figure 8. A plot of TEQ for the PCDD/F congener groups in Kamloops Lake sediments as a function of depth.

Other organochlorines, for example the pesticides, are found only at low or undetectable concentrations in sediments, comparable with the other lakes and consistent with large-scale atmospheric sources (Table 4). Dieldrin, endrin and DDT were detected in some of the core sections.

There is strong evidence of PAH contamination in Kamloops Lake where background concentrations of total PAH of 35 ng/g increase to 100–250 ng/g in the upper layers of the core (Table 6). Contaminant PAH could derive from a variety of sources including beehive burners, hogfuel burning, inputs of petroleum from the oil refinery and vehicles and from the use of various fuels including coal and oil. Entry of PAH into the lake could occur both in runoff and in atmospheric deposition.

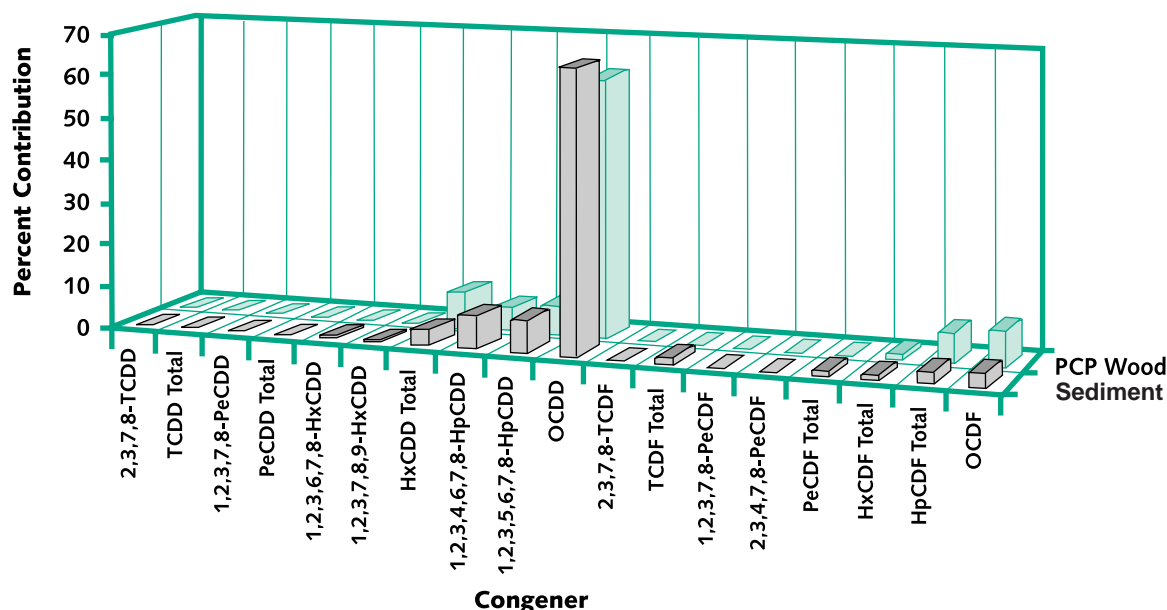


Figure 9. A comparison of the PCDD/F composition of the 20–25 cm sediment sample from Kamloops Lake with that of wood contaminated by PCP as reported in Van Oostdam and Ward (1995).

Despite the potential for local municipal, industrial and agricultural sources of contaminants to Kamloops Lake, concentrations of the measured organochlorines and Hg in burbot liver are not exceptional when compared to the other lakes. Burbot from Kamloops Lake were, however, unusual in having both a liver lipid content two to three times greater and hepatosomatic indices (HSI) which were three times greater than those found in fish from the other lakes (Table 5). Relatively elevated liver lipid content (though not HSI) was also found in peamouth chub in the vicinity of Kamloops Lake (Raymond *et al.* 1999), and has been attributed to the relatively high productivity of both the lake and Thompson River. However, liver enlargement and high lipid content are also common responses to contaminant exposure (Goede and Barton 1990; Oikari and Nakari 1982; Poels *et al.* 1980). Should these biological effects have been induced by toxic substances, then it likely involves contaminants other than those listed in Table 5, which show Kamloops burbot generally to be near the low end of concentration ranges.

Nicola Lake

Nicola is a warm, relatively shallow (mean depth 24 m), productive lake on the Thompson-Okanagan Plateau. Surrounding the lake are grasslands and hay fields used for cattle ranching, which grade into sub-alpine forest at the higher elevations. On the headwater streams entering Nicola Lake are other lakes which intercept the higher elevation inputs. There are no permanent snowfields or glaciers in the drainage basin, nor does the lake freeze over consistently in winter. Although the watershed population is sparse, atmospheric emissions from a major highway and the downstream City of Merritt (pop.~10,000), with its several sawmills, could contribute contaminants to the watershed.

With the exception of Pb, the sediments show little evidence of metal contamination. The minor Pb contamination (1–3 mg/g) could be supplied by local traffic which used leaded gasoline until the late 1970s.

Nicola Lake sediments exhibit gross contamination by DDT (Fig. 10) and minor contamination by chlor-dane and HCH (Table 4). At maximum concentration, the Total DDT in the sediments exceeds that of the other lakes by at least two orders of magnitude. The DDT is partly degraded, consisting of about 40 per cent DDT with the rest contributed by DDD and DDE. The dating shows that DDT entered the lake

during the late 1970s and mid 1980s—significantly later than the known use of DDT for aerial spraying (Prebble 1975) and the record of that spraying as found in Harrison Lake sediments (Fig. 11). Based on lake area, and assuming that accumulating sediments occupy half the lake, the inventory of Total DDT for Nicola Lake is roughly 50 kg. The amount and timing of DDT accumulation in the sediments suggests strongly that local applications have been heavy and that some applications may have occurred after the ban on its use in 1972.

The remarkable Total DDT concentrations in burbot liver (one sample contained 18,000 ng/g lipid, Table 5) suggest that some of the DDT released over a decade ago continues to be available for uptake in biota. The absence of corresponding high values of other organochlorines, specifically toxaphene which is actually lowest in Nicola Lake, leaves little doubt that these high Total DDT levels in burbot are produced by local contamination. Figure 3 also dramatizes the order of magnitude increase in the DDT/PCB ratio seen in Nicola Lake relative to the lakes receiving only atmospheric input. Comparison of the sediment and fish data with results from the other lakes suggests that over 90 per cent of the DDT in Nicola Lake must derive from local sources. This conclusion is supported by the large Total DDT inventory of 350 ng/cm², which is similar to that observed in Lake Ontario sediments, where DDT has entered from inflowing rivers (Wong *et al.* 1995), and much more than the 2.6–21.6 ng/cm² observed elsewhere in North America for atmospheric fallout (Rapaport and Eisenreich 1988). The prevalence of weathered products in fish (DDE/Total DDT >0.7, Fig. 4) and sediments ([DDD+DDE]/Total DDT >0.6) suggests that recycling of weathered DDT is occurring rather than recent input of fresh DDT.

It is surprising that the level of toxaphene is an order of magnitude lower than in the other lakes because some small lakes in the Nicola Lake drainage basin have been treated with toxaphene to kill undesired fish prior to stocking with trout (Stringer and McMynn 1960; Nordin 1997).

Harrison Lake

Harrison is a very deep (270 m) oligotrophic lake occupying a major valley in the Coast Range. It receives meltwater during summer from the extensive snowfields and glaciers and runoff from heavy rainfall at lower elevations during winter. While a significant portion of the sediment in the glacial runoff is trapped immediately upstream in Lillooet Lake (Gilbert 1973), sedimentation in Harrison remains substantial (Table 2). The lake, which is only 10 m above sea level, rarely freezes.

The drainage basin is relatively undeveloped, except for logging around the lake and some agriculture (north of Lillooet Lake). Atmospheric transport of contaminants from the urban and intensive agricultural areas of the lower Fraser Valley is likely (B. Thomson 1997, pers. comm.), and there has been a sawmill located at the outlet since the first settlement in the late 1800s.

Harrison Lake shows evidence of metal contamination by Pb and perhaps also Cr and Ni. Contamination by organochlorines is detectable, but at low concentrations consistent with an atmospheric source (Fig. 11). PAHs (Fig. 11) increase above background as early as 1890, reaching a maximum during the 1950s. Thereafter, levels decrease to the present time, although current surface concentrations still exceed those deep in the core. The source of the contaminant PAH is not clear and will require further detailed analysis of the

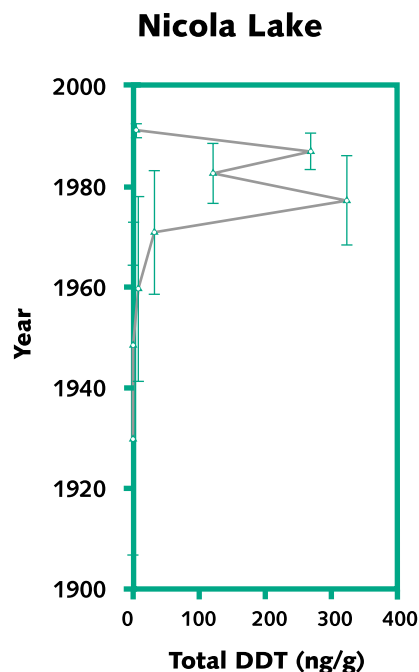


Figure 10. Total DDT concentration in Nicola Lake sediments as a function of time.

compound patterns. Likely sources include local slash and beehive burning as well as a larger-scale input from urban and industrial areas of the lower Fraser Valley. The substitution of coal by oil in the 1950s has been suggested as the reason why peak PAH fluxes are often observed in sediment horizons dating from that period (*e.g.* see Gschwend and Hites 1981; Macdonald and Creclius 1994).

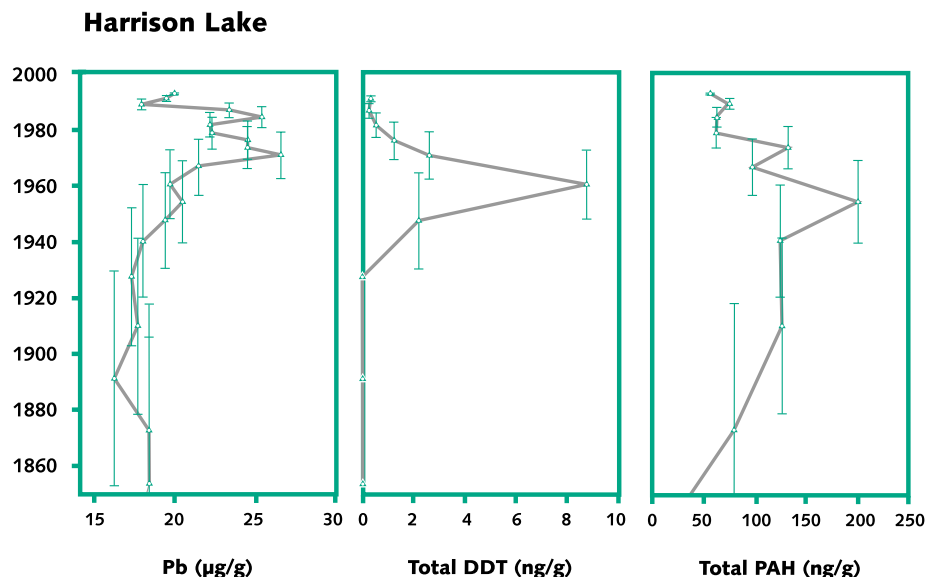


Figure 11. Pb, Total DDT and total PAH concentration in Harrison Lake sediments as a function of time.

SYNTHESIS

The data presented here suggest that four factors influence the contaminant concentrations observed in sediments and fish of lakes in the Fraser Basin: (1) long-range atmospheric transport of a variety of compounds (*e.g.* PCBs, OCDD, PAH, Pb, pesticides); (2) local contamination from activities within a lake's drainage (*e.g.* DDT, Hg, some metals, PAH, PCDD/Fs); (3) the physical setting of the lake (*e.g.* climate, drainage basin characteristics, lake hydrology); and (4) the food-web structure of the lake. The broad design of this reconnaissance study is not ideally suited to determining exactly how a given contaminant is delivered, altered during transport, and subsequently biomagnified and/or sequestered to sediments in each lake setting. Nevertheless, because we have measured a number of organochlorine contaminants in both sediments and the top-predator fish that concentrate them, we can infer how these factors interact and which may be most influential.

Metals

The surface layers of lake sediment reveal minor contamination as enrichments. Virtually all of the lake cores exhibit Pb contamination, usually after about 1950, as shown for Harrison Lake (Fig. 11). Compared to Kootenay Lake where local mining activities produced gross contamination (Macdonald *et al.* 1994; Rieberger 1992), the Pb enrichments are small (Table 3). Contamination is consistent with a widely distributed atmospheric source augmented by local emissions which can be ascribed predominantly to the once-common use of leaded gasoline. At their maximum (during the 1970s) these Pb fluxes (Table 7) fall within the deposition fluxes for "rural U.S. remote" (1.5 mg/cm²/yr) to "rural U.S. typical" (4 mg/cm²/yr) (Patterson and Settle 1987) and are less than those observed for the Strait of Georgia (6.4 ± 2.2 mg/cm²/yr) (Macdonald *et al.* 1991). Recently, Pb fluxes have been decreasing in response to the ban of leaded gasoline in the late 1970s. It is noteworthy that the largest Pb fluxes were observed in Kamloops, Moose and Harrison lakes, each of which has either a highway or a large urban centre as an obvious local source.

Of all the metals, Hg is of greatest concern due to its toxicity and potential to bioaccumulate. Stuart Lake, which received Hg contamination from a mine above it on Pinchi Lake, shows the clearest contaminant Hg signal, but Moose and Kamloops lakes also show minor Hg enrichments in recent sediments. Measurements of Hg in burbot liver, however, show no obvious biomagnification, suggesting methyl mercury production in these sediments is minimal.

Polycyclic Aromatic Hydrocarbons (PAHs) and Alkanes

PAHs in lake sediments derive from petrogenic (petroleum, diagenetic) or pyrogenic (combustion) sources which can, in principal, be distinguished by the pattern of PAH compounds (Yunker and Macdonald 1995). Note, however, that both petrogenic and combustion PAHs can be produced naturally or anthropogenically and the detailed pattern of PAH compounds must be examined to infer probable source. Parent PAHs (*i.e.* unsubstituted rings) tend to dominate the homologue series in the sediments collected from the six lakes implying that combustion is probably the most important PAH source (*e.g.* forest fires and burning of coal and oil). Kamloops, Harrison and Moose lakes show the clearest evidence of contaminant PAH (Table 7) and it is significant that these same lakes had the clearest Pb signal in their sediment. Both the Pb and PAH contamination can be explained by nearby sources (either a transport corridor or large urban centre). In particular, Kamloops Lake continues to receive a significant amount of contaminant PAH.

Alkane hydrocarbons often show marked enrichments toward the surface of sediment cores (Table 6) with prominent components of the alkane envelope being nC17 and the odd carbon alkanes between nC23 and nC33 (Yunker and Macdonald 1998). Although inputs of petroleum could enhance alkane concentrations in recent lake sediments, it is far more likely that the observed alkane enrichments derive naturally from lake algae (nC17) and terrestrial plant waxes (odd carbon nC23–nC33) (*cf.* Eglinton and Hamilton 1967; Meyers and Ishiwatari 1993). Therefore, the enrichment of alkanes in surface sediments of the lakes can be understood as predominantly an input of natural alkanes which are subsequently metabolized as the sediment ages. Kamloops Lake sediments have an additional alkane envelope between nC17 and nC23, possibly indicating petroleum input (Yunker and Macdonald 1998). However, a much more detailed analysis will be required to estimate the strength and pattern of this source.

Organochlorine Compounds

Most of the recent lake sediments (*i.e.* surface samples) exhibit a low background of OC contaminants. When compared with other locations reported in the literature (Table 8), the inventories and fluxes of PCB and DDT are consistent with a delivery by the atmosphere either globally or regionally, with the notable exceptions of DDT in Nicola Lake and PCB in Kamloops Lake. In both cases, local inputs are clearly responsible. DDT is often at a maximum in the 1960s sediment horizons reflecting use patterns in B.C. (Figs. 2, 10). Toxaphene was not detected in any sediment sample (detection limits varied from <0.2 to 2 ng/g), again consistent with low fluxes supported only by atmospheric deliveries (Pearson *et al.* 1997).

Table 8. Surface concentrations, fluxes and inventories for Total PCB and Total DDT for sites in North America receiving predominantly atmospheric organochlorines.

DATE	LOCATION	TOTAL PCB			TOTAL DDT		
		SURF. CONC ng/g	SURF. FLUX ng/cm ² /yr	INVENTORY ng/cm ²	SURF. CONC ng/g	SURF. FLUX ng/cm ² /yr	INVENTORY ng/cm ²
1993-1994	Fraser Lakes ¹	0.2–1.0	0.02–<3	<8–36	0–6.9	0.04–0.62	<2–350
1990	Arctic Lakes ²	2.4–39	0.01–0.43	1.9–18			
1981	Lake Ontario ³	250	12–18	500–600	50	1.9	250–500
1992	Wisconsin Lakes ⁴	2.6–89	0.19–0.76	1.3–8.8			
1986, 90	Lake Ontario ⁵	7–17.6	0.10–0.52	4.4–28			
Post 1980	Peat Cores, ⁶ Eastern NA		0.01–0.4	2.9–15.9		0.04–0.15	2.6–21.6
Post 1980	Lake Superior ⁷			0.1–8			10.4–27

References

¹ This study

² Muir *et al.* 1996

³ Eisenreich *et al.* 1989

⁴ Swackhamer and Armstrong 1986

⁵ Jeremiason *et al.* 1994

⁶ Rapaport and Eisenreich 1988

⁷ Eisenreich 1987

As observed elsewhere (Muir *et al.* 1997), three particular OCs are always found at high concentration in predator fish—toxaphene, PCB and DDT. Much of the lake-to-lake variation in fish OC concentration, therefore, probably derives from the physical and biological characteristics of each lake rather than variation in sources. In Moose Lake there must be an exceptionally strong partitioning into biota because neither sediment concentrations nor fluxes of PCBs, for example, are high relative to Kamloops Lake, downstream of an industrial city (~ 0.2 vs. ~ 3 ng/cm²/yr). This observation points to a more effective food chain bioconcentration process in Moose as opposed to the other lakes and we conclude, therefore, that Moose Lake is the most vulnerable of the lakes to long-range contaminants, either by virtue of its basin characteristics (seasonally frozen and alpine) or its food-web structure, or both. Out of a total of 17 lakes studied here and by Donald *et al.* (1993) for burbot and/or trout, the levels in Moose Lake are highest. The PCBs in Moose Lake burbot have not been linked to a local source and may simply reflect the accumulation of many years of atmospheric deposition in the snowfields which has not drained annually to the main valley-bottom river. Years of extreme meltback may subsequently transfer this “archived” PCB (and DDT) to the lake and river system. A similar process may be occurring in Chilko Lake but top predator fish were not obtained for study. The recent discovery that OC accumulation in snow in the Rocky and Coast mountains increases with elevation (Blais *et al.* 1998) also suggests that alpine lakes will receive a higher loading.

Not all OC contaminants come from distant points. A large amount of DDT entered Nicola Lake arriving during the 1980s from a local source, and weathered DDT compounds continue to be available for uptake in the lake’s biota. In a second example, PCDD/Fs and PCBs entered Kamloops Lake from a pulp mill between 1965 and 1990, but these have been dramatically reduced through process changes at the mill. Nevertheless, the levels of PCDD/Fs in peamouth chub and mountain whitefish from the Fraser Basin in 1994 were highest in the Thompson River sub-basin (Raymond *et al.* 1999) and burbot livers were twice as fat as those collected from the other lakes which can be an indicator of significant contaminant exposure.

CONCLUSIONS AND RECOMMENDATIONS

The continued presence of PCBs, toxaphene and DDT residues in fish long after the chemicals have been banned in Canada and the United States is a concern on two fronts. First, the detections indicate a potential problem to both wildlife and human consumers of these fish. Even the lowest burbot liver levels found in the Fraser Basin lakes exceed Canadian Tissue Residue Guidelines for the Protection of Wildlife Consumers of Aquatic Biota (0.79 pg TEQ/g for total PCB [values in Table 5 are based on Toxic Equivalent Factors from Ahlborg *et al.* 1994]; 6.3 ng/g for toxaphene; and 14.0 ng/g for DDT [Environment Canada 1999]). The only samples to come close to these guidelines are those from Nicola Lake for toxaphene, but they exceed the DDT guideline by the largest margin. The relevance of guidelines being exceeded in one tissue of one fish species needs to be considered. For one thing, as these compounds are lipophilic and burbot liver is lipid-rich in comparison to their muscle tissue, concentrations based on whole fish would be much lower. For another, the level of contamination in other fish species that are more likely to be eaten by other predator fish or osprey (which feed mostly on shallow water species like suckers) is not known.

The assessed potential health risk to human consumers of this species from these lakes can only be assessed if data are available on the consumption habits of people regularly eating burbot, especially the livers. The guidelines mentioned earlier are for food consumed regularly and are difficult to apply in this instance where consumption is sporadic or unknown.

The second issue addressed by this study is the trend in atmospheric loading of persistent organic chemicals and metals to the Fraser’s headwaters. In most cases, sediment cores indicate that loading of DDT and PCBs to the lakes has declined dramatically from peak loading rates in the 1970s. The data from Moose Lake (Fig. 2), on the other hand, suggest that they may now be increasing from the rates seen during the

1980s. Whether this is in response to releases from glacier and snowfield reservoirs of these chemicals or an increase in atmospheric deposition cannot be ascertained from this survey. (Unfortunately the detection limit for toxaphene in sediments was not low enough to obtain historical or present trends in its loading.) The loading of PAHs has declined as seen in the Harrison Lake core (Fig. 11) and their present sedimentary concentrations are well below guidelines. With respect to metal loading, lead, in particular, has declined in response to the introduction of unleaded gasoline. Loadings of other metals, while slightly elevated from their pristine rates, are not of concern.

Two studies are recommended:

- The data base on contaminants in top predator fish in B.C. lakes should be expanded to determine if there are other lakes, like Moose Lake, that exhibit inordinately high concentrations of PCB, toxaphene and DDT. Candidates for a survey should include a variety of lakes with differing hydrological conditions and a diversity of trophic structures. With a sufficient number of lakes, it should be possible to infer the particular lake and drainage basin characteristics that lead to high concentrations in top predators. This predictive capability can then be used to select remote lakes for future fish contaminant surveys.
- The importance of trophic structure versus contaminant loading characteristics to the level of contamination in the food web should be examined in Moose Lake, along with other selected lakes identified in the survey suggested above.

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