3.5

SEDIMENT QUALITY IN THE FRASER RIVER BASIN

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Many pollutants entering the aquatic environment are extremely water insoluble and, as a result, readily bind to sediment particles in the water column. There is abundant evidence of environmental degradation in areas where water quality criteria are not exceeded, yet organisms in or near sediments are adversely affected (Chapman 1989; US EPA 1994). Contaminated sediments may be directly toxic to aquatic life (Swartz *et al.* 1985) or, through bioaccumulation and biomagnification, can cause long term chronic effects. As the Fraser River carries a relatively high sediment load (8–26 million tons/year) (Stewart and Tassone 1989), sediments make an ideal medium for the geographical and temporal characterization of contaminants in the basin.

Prior to the Fraser River Action Plan (FRAP), studies of contaminants associated with sediments in the Fraser Basin were relatively few and of limited geographical coverage. In 1990 and 1991, Derksen and Mitchell (Draft 1994) measured dioxins, furans and chlorophenolics in suspended sediments from Marguerite and Lillooet on the main stem of the Fraser River. Bed sediments from the upper Fraser River and Thompson sub-basin were measured for dioxins and furans in 1988 (Mah *et al.* 1989) and for a number of trace organics associated with pulp mill effluents from 1989 to 1991 (Dwernychuk 1990; Dwernychuk *et al.* 1991). In the Fraser estuary, trace organics and metals were measured in bed sediments between 1985 and 1992 (FREMP 1996).

FRAP sediment assessments were conducted between 1992 and 1996 in order to determine the current status of the basin and to establish a baseline of trace organic and metal concentrations in suspended and bed sediments, upstream and downstream of pulp mills and major cities. Contaminants associated with suspended sediments represent one route of exposure to organisms in the water column, whereas contami-

nants associated with bed sediments represent a route of exposure to benthic and bottom feeding organisms. The principal advantage of suspended sediment sampling is that it provides an integrated sample over a known period of time with a high degree of reproducibility (Sekela *et al.* 1994; 1995), whereas bed sediment sampling is a cost effective method for characterizing contaminant exposure over a longer period of time (weeks to years).

METHODS

Suspended sediments were sampled under varying flow conditions in three consecutive years between 1992 and 1994 (Sekela *et al.* 1995) and in the spring and fall of 1996 (Sylvestre *et al.* 1998a; 1998b). Bed sediments were sampled in three consecutive years between 1994 and 1996 (Brewer *et al.* 1998). Suspended sediments were sampled using continuous flow centrifuges; clarified water from the centrifuge was sampled using solid phase extraction. Ekman grabs were employed for bed sediment sampling. Sampling locations were chosen to coincide as much as possible with previous studies, as well as with those used in the FRAP resident fish health assessment study (Raymond *et al.* 1999) and the FRAP benthic community study (Reynoldson and Rosenberg 1999). Refer to Figure 1 for sampling locations for bed and suspended sediment sampling and to Table 1 for sample site descriptions and sample sizes.

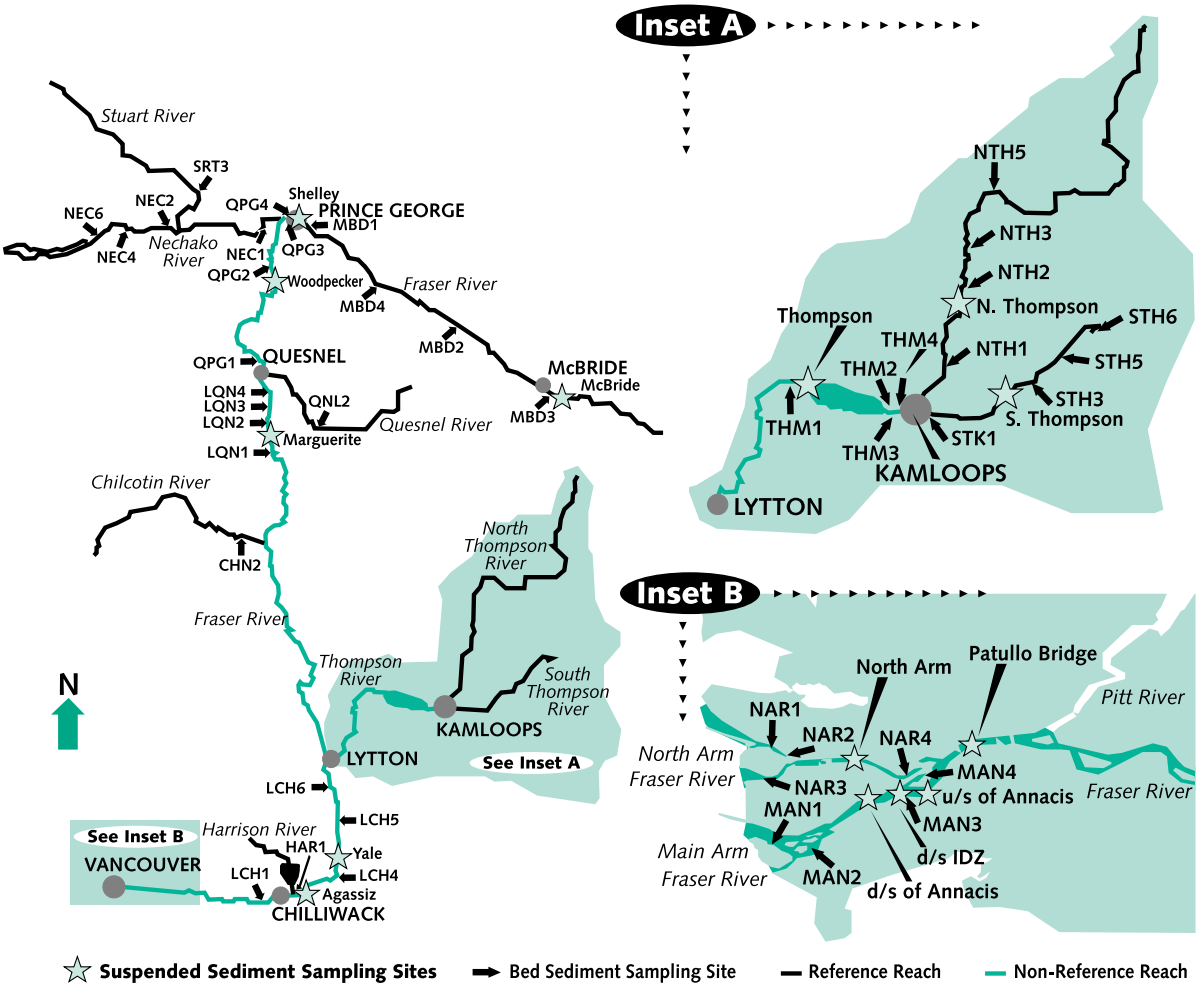

Figure 1. Fraser River Basin sediment sampling sites.

Table 1. Sediment sampling site/reach descriptions and sample sizes.

SAMPLE TYPE	REACH ID	GEOGRAPHICAL REGION	REACH DESCRIPTION	SITE/REACH TYPE	SAMPLE SIZE*
suspended	McBride	Upper Fraser	Fraser River 2 km upstream of McBride	reference	1
suspended	Shelley	Upper Fraser	Fraser River at Shelley	reference	4
suspended	Woodpecker	Upper Fraser	Fraser River at Woodpecker	non-reference	4
suspended	Marguerite	Upper Fraser	Fraser River at Marguerite ferry	non-reference	5
suspended	N. Thompson	Thompson sub-basin	N. Thompson River at McLure ferry	reference	3
suspended	S. Thompson	Thompson sub-basin	S. Thompson River 3 km upstream of McGreggor Creek at Lafarge Cement Plant	reference	1
suspended	Thompson	Thompson sub-basin	Thompson River at Steelhead Park near Savona	non-reference	4
suspended	Yale	Lower Fraser	Fraser River at Yale	non-reference	4
suspended	Agassiz	Lower Fraser	Fraser River at Agassiz Bridge	reference	1
suspended	Patullo Bridge	Lower Fraser	Fraser River Main Stem at Patullo Bridge	non-reference	1
suspended	Upstream of Annacis	Lower Fraser	Fraser River Main Arm at Alex Fraser Bridge upstream of Annacis STP	non-reference	1
suspended	Downstream of IDZ	Lower Fraser	Fraser River Main Arm immediately downstream of Annacis STP Initial Dilution Zone (IDZ)	non-reference	1
suspended	Downstream of Annacis	Lower Fraser	Fraser River Main Arm, 6 km downstream of Annacis STP	non-reference	1
suspended	North Arm	Lower Fraser	Fraser River North Arm at foot of Kerr Road	non-reference	1
bed	NEC	Upper Fraser	Nechako River	reference	4
bed	MBD	Upper Fraser	Fraser River from McBride to Prince George	reference	4
bed	QPG	Upper Fraser	Fraser River from Prince George to Quesnel	non-reference	4
bed	LQN	Upper Fraser	Fraser River from Quesnel to Lytton	non-reference	4
bed	SRT	Upper Fraser	Stuart River	reference	1
bed	CHN	Upper Fraser	Chilcotin River	reference	1
bed	QNL	Upper Fraser	Quesnel River	reference	1
bed	NTH	Thompson sub-basin	North Thompson River	reference	4
bed	THM	Thompson sub-basin	Thompson River	non-reference	4
bed	STH	Thompson sub-basin	South Thompson River	reference	3
bed	STK	Thompson sub-basin	South Thompson River at Kamloops	non-reference	1
bed	LCH	Lower Fraser	Fraser River from Lytton To Chilliwack	reference	4
bed	HAR	Lower Fraser	Harrison River	reference	1
bed	NAR	Lower Fraser	Fraser River North Arm	non-reference	4
bed	MAN	Lower Fraser	Fraser River Main Arm	non-reference	4

** sample size for suspended sediment samples denotes total number of samplings at each site from 1992–1996*
sample size for bed sediment samples denotes number of replicate samples collected per reach per year sampled

Sediments were sampled for several classes of contaminants associated with known sources (Table 2). Analysis of variance (ANOVA) was performed on bed sediment data to determine if significant differences exist between reaches. Organic parameter data were log transformed and analyzed by ANOVA followed by multiple comparison tests. If the assumptions for parametric tests were not satisfied, the data were analyzed by Kruskal-Wallis analysis of variance on ranks. Trace metals data were analyzed by analysis of covariance (ANCOVA), with the silt/clay fraction as the covariate. Principal components analysis (using the covariance matrix) was applied to per cent normalized data to identify geographical patterns within the data set.

Table 2. *Contaminants measured in suspended and bed sediments—sources and effects.*

CONTAMINANTS	MAJOR SOURCES	EFFECTS
Dioxins and furans	- pulp and paper mills using chlorine bleaching - incinerators - commercial chemicals (PCBs, pentachlorophenol, 2,4-D) - wood and fossil fuel combustion - sewage treatment plant effluents	- teratogenic - carcinogenic - acutely toxic - endocrine disrupting - bioaccumulative
Chlorophenolics	- pulp and paper mills using chlorine bleaching - wood treatment facilities/treated wood products - incinerators - chlorinated pesticides - sewage treatment plant effluents	- immunotoxic - fetotoxic - embryotoxic - fish tainting
Polycyclic Aromatic Hydrocarbons (PAHs)	- wood and fossil fuel combustion - creosote treated products - spills of petroleum products - slash burning - plant material - natural oil deposits	- carcinogenic - bioaccumulative
Chlorinated Pesticides	- agriculture - sewage treatment plant effluents - industrial effluents - global transport and deposition	- carcinogenic - endocrine disrupting - bioaccumulative
Polychlorinated Biphenyls (PCBs)	- transformers - lamp ballasts (pre-1980) - global transport and deposition - sewage treatment plant effluents - pulp and paper mill effluents	- immunotoxic - endocrine disrupting - bioaccumulative
Nonylphenol	- pulp and paper mills - textile processing and manufacturing - plastics manufacturing - leather processing - household cleaners - sewage treatment plant effluents	- acutely toxic - estrogenic - bioaccumulative
Trace Metals*	- mining and metallurgy - paints and dyes - electrical and electronic manufacturing - cleaning and duplicating - electroplating/finishing	- acutely toxic - endocrine disrupting - bioaccumulative

** some trace metals (e.g. iron, copper, zinc, manganese, selenium, cobalt, magnesuim) are required for normal biological function*

Insufficient replication did not allow for statistical analysis of the suspended sediment data. Organic parameter data for both bed and suspended sediments were normalized to one per cent organic carbon for the purposes of comparisons to guidelines, criteria and objectives. Toxicity equivalents (TEQs) for 2,3,7,8-tetrachlorodibenzo-para-dioxin (TCDD) (CEPA 1990) and PCBs (Ahlborg *et al.* 1994) were calculated with detection limits set at zero.

RESULTS AND DISCUSSION

Dioxins and Furans

Chlorinated dioxin and furan concentrations and 2,3,7,8-TCDD TEQs measured in suspended and bed sediments in the Fraser River Basin were generally elevated downstream of pulp mills and urban centres compared to reference sites. TEQs in suspended sediments were approximately double in the Fraser River Estuary, relative to the Agassiz reference site upstream of Vancouver, but similar to those in the Thompson River downstream of the pulp mill in Kamloops. TEQs in bed sediments were higher in the North Arm of the Fraser River in comparison to all other reaches in the basin, likely due to the large amounts of stormwater entering this reach of the river. No differences were found in dioxin concentrations measured in suspended sediments upstream and downstream of the Annacis Island Sewage Treatment Plant (STP), indicating that the STP is not likely a significant source of dioxins and furans to the Main Arm of the Fraser River.

Congener profiles in bed and suspended sediments were dominated by hepta- and octa-chlorinated dioxins and furans suggesting combustion and/or pentachlorophenol (PCP) sources. Since combustion and PCP source profiles are very similar, both are possible sources. However, the most pristine reference reaches (Chilcotin and Quesnel), which were least likely to have been affected by historical PCP use, exhibited a congener profile composed solely of dioxin congeners. Such a profile has not been associated with a PCP source (Czuczwa and Hites 1996). The South Thompson River site at Kamloops had a congener profile consistent with PCB contamination (Grundy *et al.* 1997). Dioxin and furan TEQs measured in bed sediments exceeded the interim federal sediment quality guideline of 0.25 pg/g TEQ at 29 of 44 bed sediment sites sampled from the basin, ranging from 0.002–8.75 pg/g TEQ, with the greatest exceedances occurring in the Thompson River and in the North Arm of the Fraser River (Table 3). The most toxic dioxin congener, 2,3,7,8-TCDD, exceeded these guidelines at three locations in the Fraser Basin: the Thompson River downstream of the pulp mill and in two sloughs in the North Arm of the Fraser River.

The exceedance of TEQ guidelines at reference locations, where non-point source combustion is a likely source of dioxins and furans, suggests that it may not be possible to meet the current interim federal guideline for 2,3,7,8-TCDD TEQ (CCME, Draft 1995). With the exception of the North Arm, TEQ concentrations in bed and suspended sediments were similar to those found in the Columbia River (Bortleson *et al.* 1994) and the northern rivers of Alberta (Crosley 1996a; 1996b; Pastershank and Muir 1995).

Dioxin and furan concentrations measured in suspended sediments from the upper Fraser and Thompson rivers varied seasonally, with higher concentrations in the winter base-flow period relative to the fall low-flow period. In the Fraser River, this concentration peak was attributed to a higher proportion of contaminated sediments in the river during base flow period when levels of natural erosion-derived suspended sediment are at their yearly lowest. In the Thompson River, this pattern was associated with inverse thermal stratification in Kamloops Lake during the limnological winter.

Temporally, concentrations in the upper Fraser River remained relatively constant between 1992 and 1996. A notable reduction in dioxin and furan concentrations was measured in the Thompson River at Savona in 1996 in comparison to 1993, when a failure in the effluent containment pond at the pulp mill in Kamloops resulted in a measured 2,3,7,8-TCDD TEQ of 7.6 pg/g at this site. However, the most dramatic reductions in dioxin and furan concentrations in suspended sediments occurred after the implementation of pulp mill

Table 3. Organic contaminants in bed sediments exceeding guidelines, criteria or objectives for the protection of aquatic life (1994–1996).

PARAMETER	NECHAKO RIVER	MCBRIDE TO PRINCE GEORGE	PRINCE GEORGE TO QUESNEL	QUESNEL TO LYTTON	STUART RIVER	CHILCOTIN RIVER	QUESNEL RIVER	NORTH THOMPSON RIVER	SOUTH THOMPSON RIVER	SOUTH THOMPSON RIVER AT KAMLOOPS	THOMPSON RIVER	LYTTON TO CHILLIWACK	HARRISON RIVER	MAIN ARM	NORTH ARM
Dioxins & Furans															
TEQs	F	F	F	F		F		F	F	F	F	F	F	F	F
2,3,7,8-TCDD											F				F
PAHs															
Naphthalene	P			P			P	P		P	P	P		P	P,O
Phenanthrene									F,P	F,P	F,P			F,P,O	F,P,O
Fluoranthene										F				F	F
Pyrene										F	F			F	F,O
Benz(a)anthracene									F					F,O	F,O
Chrysene										F	F			F	F
Benzo(a)pyrene										F,P	F			F,P,O	F
Dibenz(ah)anthracene														O	
PCBs															
Total PCBs				P						P					O
Aroclor 1254										P					
Aroclor 1260										P					P
Pesticides															
γ-HCH	F	F	F	F,P								F,P		F	F
β-HCH											P				
Total HCH			P	P											
Total Chlordane	P		P												
p,p'-DDE											F,P				
Total DDT					F,P									F,P	
Total DDT + metabolites					P						P			P	P

F indicates exceedence of Interim Federal Guideline (CCME, Draft 1995; Smith et al. 1996)
P indicates exceedence of Provincial Criteria (BC MELP 1995)
O indicates exceedence of Regional Objectives (Swain et al., Draft, 1996)

abatement measures consisting of the substitution of molecular chlorine with chlorine dioxide. Concentrations of 2,3,7,8-TCDD and 2,3,7,8-TCDF were approximately 95–99 per cent lower between 1992 and 1996, relative to those measured in 1990 prior to the initiation of chlorine dioxide substitution by the mills (Fig. 2). Similarly, concentrations of furans in bed sediments were approximately three orders of magnitude lower than those measured downstream of pulp mills in 1988 in the upper Fraser and Thompson rivers (Mah *et al.* 1989). Declines in TCDD and TCDF concentrations relative to pre-abatement levels were also observed in whitefish muscle tissue in the upper Fraser and Thompson basins (Raymond *et al.* 1999).

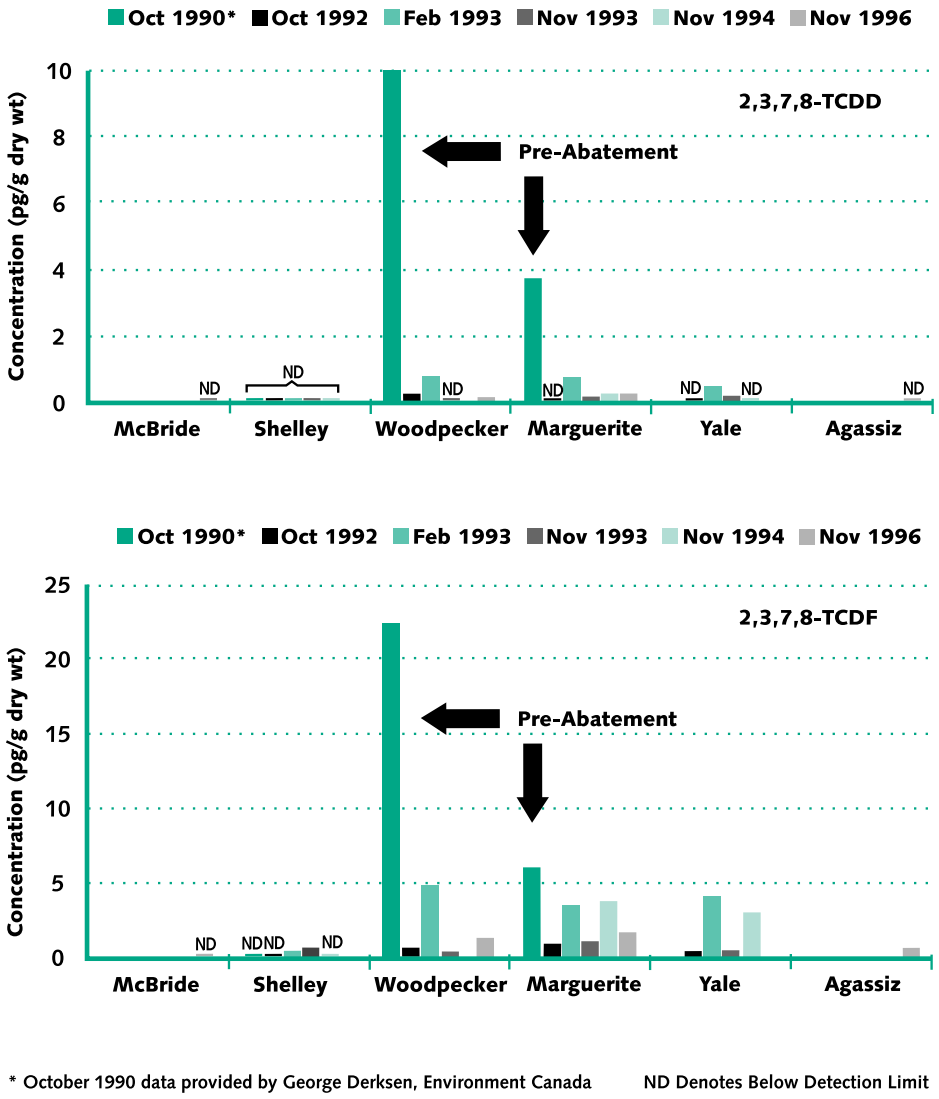

Figure 2. 2,3,7,8-TCDD and 2,3,7,8-TCDF in Fraser River suspended sediment (1990–1996).

Dioxin and furan partitioning to the suspended solid phase was highly variable and was strongly influenced by the sediment organic carbon (TOC) content. Log K_{ocs}, derived from field measurements, ranged between 4.3 to 8.4, and were generally in the range of published values (Mackay *et al.* 1992).

Chlorophenolics

Chlorophenolics measured in suspended and bed sediments were higher in concentration downstream of pulp mills relative to reference sites throughout the basin. Chloroguaiacols, chlorocatechols and chlorovanillins, all associated with pulp mill effluents, were found at higher concentrations than chlorophenols, traditionally associated with wood preservation. Generally, total chlorocatechols and chlorovanillins were higher in reaches downstream of pulp mills relative to reference reaches in the upper Fraser River, while total chloroguaiacols and chlorovanillins were elevated in the Thompson River downstream of the pulp mill at Kamloops.

All classes of chlorophenolics measured in bed sediments, including the chlorophenols, were elevated in the North Arm of the Fraser River relative to the Main Arm and the Lytton to Chilliwack reach upstream of the metropolitan Vancouver area. Total chlorophenolics measured in the Stuart River were similar to levels measured in the urbanized North Arm of the Fraser River, indicating that chlorophenolic sources possibly related to wood preservation may exist in this reach. The Annacis Island STP did not contribute substantially to the chlorophenolic concentrations measured in suspended sediments in the Main Arm of the lower Fraser River, as evidenced by similar concentrations measured upstream and downstream of the STP.

Concentrations of chlorophenolics measured in bed sediments from the Fraser River Basin were generally lower than those reported in the Columbia River (Bortleson *et al.* 1994), in the northern rivers in Alberta (Crosley 1996a) and in the Apalachicola-Chattahoochee-Flint River system in Florida (USGS NAWQA 1997). No sediment quality guidelines or criteria for the protection of aquatic life exist for chlorophenolics.

As was the case for dioxins and furans, chlorophenolic concentrations in suspended sediments varied seasonally with higher concentrations during the winter base-flow period relative to the fall low-flow period. Temporally, chlorophenolics measured in suspended sediments were detected in fewer numbers and at lower concentrations in 1996 relative to 1992–1994, indicating that the switch to 100 per cent chlorine dioxide substitution (implemented at all kraft mills in the basin between 1994 and 1996) was effective in reducing levels of these compounds. Pentachlorophenol measured in bed sediments was more than an order of magnitude lower than that detected in the North Arm of the Fraser River in 1987 (Swain and Walton 1988), prior to the deregistration of this compound as an antisapstain chemical in sawmills. Similarly, pulp mill related chlorophenolics have decreased from levels measured by Dwernychuk (1990) prior to the initiation of pulp mill abatement measures.

Generally, chlorophenolics were associated with the sediment phase in the range of 1–20 per cent in the Fraser River, whereas in the Thompson River <1 per cent were associated with this fraction. A lower suspended sediment concentration in the Thompson River (<5 mg/L) in comparison to that of the Fraser River (0.9–226 mg/L) is believed to account for the lower partitioning to sediments in the Thompson River. Log K_{ocs}, derived from field measurements, ranged between 2.8 to 7.0 and were generally higher than theoretical values (Karickhoff 1981), indicating that chlorophenolics are partitioning to the suspended solid phase in greater proportions than expected.

Resin and Fatty Acids

Resin acids measured in suspended and bed sediments were elevated downstream of pulp mills in the upper Fraser River, when compared to reference sites. The presence of five pulp mills and numerous sawmills in the Prince George to Quesnel reach of the Fraser River likely accounts for the observed elevated levels of these compounds. Resin acids in bed sediments were significantly higher ($p<0.05$) in the Fraser estuary than at reference sites upstream of the greater Vancouver area, likely due to numerous sources including wood processing industries, log boom storage and hog fuels. Chlorinated resin acids were detected only at sites located downstream of pulp mills. Dehydroabietic and abietic acids, both major components of pulp mill effluents (Fox 1977), comprised the greatest proportion of total resin acids. Total resin acids in suspended sediment from the Fraser Basin exceeded 100 µg/g, which is 10 times higher than the total resin acid concentration reported for suspended sediment from the upper Athabasca River (Crosley 1996b).

Total fatty acids in suspended sediments from the upper Fraser Basin were three to four times higher at sites downstream of pulp mills than at reference sites. In contrast, few differences were observed in total fatty acid concentrations measured in bed sediments throughout the Fraser Basin, and occasional upward deviations were attributed to local decomposition of organic matter. Palmitic acid comprised the largest proportion of the total fatty acids measured in both suspended and bed sediments. Fatty acid concentrations measured in the Fraser Basin were generally several fold higher than in bed sediments measured in the Columbia and Athabasca rivers (Bortleson *et al.* 1994; Crosley 1996b).

PAHs

Polycyclic aromatic hydrocarbons (PAHs) in suspended and bed sediments were higher downstream of urban centres relative to reference sites in both the Fraser River main stem and Thompson sub-basin. Total parent PAH concentrations in suspended sediments were approximately six times higher in the Fraser River Estuary relative to the Agassiz reference site. In bed sediments, total parent PAHs were twice as high in the heavily industrialized North Arm as in the Main Arm of the Fraser River, reflecting the large number of stormwater inputs to this reach. PAH source signatures (Yunker and Macdonald 1995) indicate that reference reaches were generally dominated by petroleum PAH sources, likely of natural origin, while non-reference reaches were characterized by petroleum and pyrogenic sources. Retene and other plant-derived PAHs in suspended sediments were elevated in the Fraser estuary where log boom storage, sawmill leachate and hog fuels are probable sources. In the fall of 1996, total parent PAHs measured immediately downstream of the Annacis Island STP initial dilution zone (IDZ) were over twice as high as those from upstream of the plant.

A number of PAHs measured in bed sediments exceeded federal and/or provincial sediment quality guidelines and criteria and/or draft regional objectives for the protection of aquatic life (Table 3). The relatively large number of exceedances in the Fraser estuary reaches and at the Thompson and South Thompson urban sites suggests that aquatic life may be affected by these contaminants in the more urbanized parts of the basin. Nevertheless, total parent PAHs, ranging from 7–1,000 ng/g, were several orders of magnitude lower than those measured in the northern rivers of Alberta (Crosley 1996a) and rivers in the Great Lakes Areas of Concern (Bolattino 1993).

PAH concentrations in suspended sediments varied seasonally in the Thompson River with higher concentrations in the winter base-flow period relative to the fall low-flow period (Fig. 3). Higher ratios of perylene to the remainder of the parent PAHs, measured throughout the Fraser River Basin during fall low flow, compared to winter base-flow, points to a mostly sedimentary PAH source in the fall season compared to a largely anthropogenic source in the winter season. PAH concentrations did not vary temporally in either bed or suspended sediment between 1992 and 1996. PAHs in bed sediments from the Fraser estuary were similar in concentration to those measured by Swain and Walton between 1989 and 1992 (Swain and Walton 1990; 1991; 1993).

Phase partitioning measurements indicated that, generally, <20 per cent of low molecular weight PAHs (LPAHs) and 20–80 per cent of high molecular weight PAHs (HPAHs) were found in the suspended solid phase. The high affinity of LPAHs for the water phase appears to increase their bioavailability, based on the predominance of LPAHs in peamouth chub muscle from the lower Fraser River (Raymond *et al.* 1999). Field estimates of log K_{ocs}, ranging between 3.0–7.3, were higher than published log K_{ocs} for LPAHs, but similar to published values for HPAHs (Mackay *et al.* 1992). Phase partitioning was influenced by site specific environmental factors such as the total organic carbon content of sediments and the suspended solids concentration.

Pesticides

Organochlorine pesticides measured in suspended and bed sediments were detected in trace levels (<10 ng/g) throughout the Fraser River Basin. Among those most commonly detected were DDT, DDE, HCB, α and γ HCH, chlordane, mirex and endosulphan sulphate. Similar levels of organochlorine pesticides were detected in rivers in the Great Lakes Areas of Concern (Bolattino 1993) and in river basins studied in the USA (Ott 1997; Stephens and Deacon 1997; Tate and Heiny 1997; Tornes *et al.* 1996; USGS NAWQA 1997). Both suspended and bed sediment data, in general, did not show a consistent pattern in pesticide concentrations between reference and non-reference sites in the upper Fraser and Thompson regions.

DDE in suspended sediments was detected in the Thompson River in concentrations four times higher than in the upper Fraser River. The same DDE pattern was observed by Raymond *et al.* (1999) in muscle from peamouth chub and mountain whitefish sampled in the same reaches. DDE+DDD/DDT metabolite ratios (Sanchez *et al.* 1993) indicated that in the upper Fraser reaches the DDT source may be more recent, perhaps originating from atmospheric deposition of globally transported pesticides. A less recent source was indicated for the Thompson reaches, where it may be linked to historical use in the region.

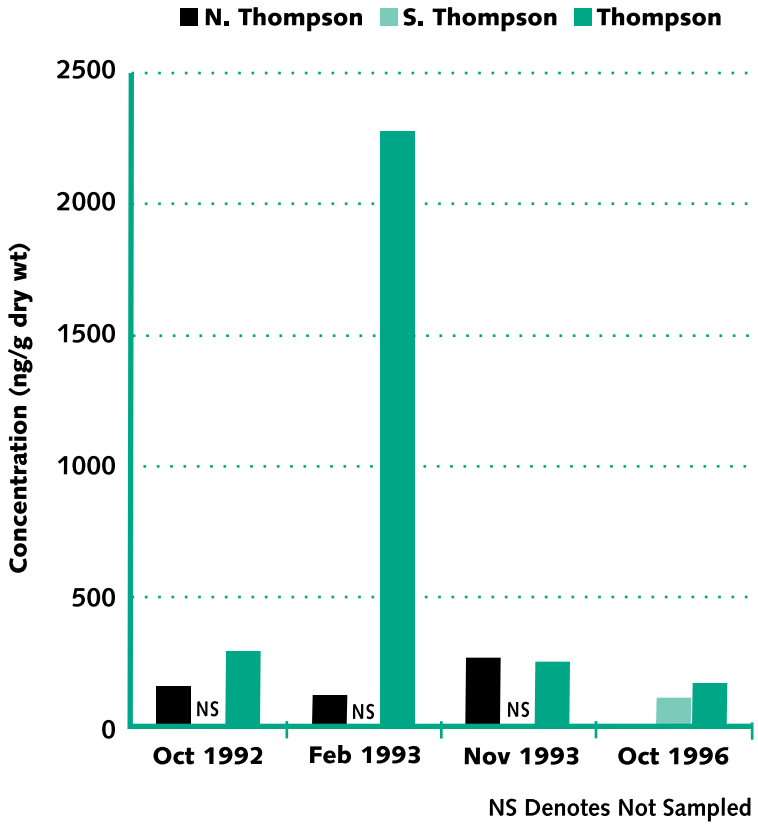

Figure 3. Total parent PAHs in North Thompson, South Thompson and Thompson River suspended sediment (1992–1996).

The highest levels of pesticides were generally detected in the lower Fraser River, with the exception of p,p'-DDT, measured in suspended sediments, which was approximately four times higher in concentration at the McBride and the South Thompson River reference sites than in the Fraser River Estuary. The Annacis Island STP did not contribute significantly to organochlorine pesticide concentrations in the Main Arm of the Fraser River. DDD and DDE concentrations measured in bed sediments from the North and Main Arms of the lower Fraser River were approximately an order of magnitude lower than those detected in 1989 by Swain and Walton (1990). A number of pesticides measured in bed sediments exceeded interim federal guidelines and/or provincial criteria for the protection of aquatic life (Table 3).

PCBs

Polychlorinated biphenyls (PCBs) measured in suspended and bed sediments were detected in trace levels in the upper Fraser and Thompson basins. Total PCB congeners in suspended sediments did not exceed 1.0 ng/g and generally did not differ between reference and non-reference sites. The suspended sediment data from the upper Fraser River did not indicate seasonal or temporal variability from 1992 to 1996. Two bed sediment sites had elevated total PCB concentrations exceeding provincial sediment quality criteria for the protection of aquatic life: a rural site on the Fraser River in the Quesnel to Lytton reach (26.4 ng/g) and an urban site on the South Thompson River in Kamloops (1,367.0 ng/g) (Table 3). Aroclors 1254 and 1260 also exceeded severe effects level criteria for the protection of aquatic life at the latter site which is affected by urban runoff.

Total PCBs measured in suspended sediments from the Fraser estuary were over 150 times higher than levels measured at the Agassiz reference site, upstream of the metropolitan Vancouver area, with the highest concentrations measured in the Main Arm of the Fraser River. Total PCB congeners were approximately 10 times higher, and TEQs were over 13 times higher in the Main Arm compared to the North Arm of the Fraser River. The presence of PCBs in sewage treatment plant effluent (Derksen, draft 1997) and elevated

concentrations of total PCBs downstream of the Annacis Island STP suggest that the STP may be a source of PCBs to the Main Arm of the Fraser River.

In contrast, bed sediments from the North Arm of the Fraser River had higher PCB concentrations than those of the Main Arm. Sediments from the North Arm of the Fraser River exceeded the provincial sediment quality criterion for the protection of aquatic life for Aroclor 1260 and the regional sediment quality objective for total PCB congeners (Table 3). The elevated levels of PCBs observed in the Fraser River Estuary likely reflect contributions from urban runoff. Peamouth chub liver, collected from the lower Fraser River, similarly had higher total PCB levels relative to the rest of the Fraser Basin (Raymond *et al.* 1999). PCB concentrations in bed sediments were four orders of magnitude lower than those in the Great Lakes Areas of Concern (Bolattino 1993) but generally similar to those measured in the northern rivers of Alberta (Crosley 1996a).

Nonylphenol

Total 4-nonylphenol measured in suspended and bed sediments was elevated at sites in or downstream of major cities in the Fraser River Basin. Total 4-nonylphenol in suspended sediments from Woodpecker and Marguerite was approximately double the concentration measured at the reference reach upstream of Prince George. Similarly, 4-nonylphenol was eight times higher in the Thompson River at Savona (56 ng/g) than in the South Thompson River upstream of Kamloops. However, the highest 4-nonylphenol levels were measured in the Main Arm of the Fraser River (mean=62 ng/g), downstream of the Annacis Island STP, where concentrations were double those measured at a location just upstream of the STP and approximately five times higher than at Agassiz. The detection of relatively high levels of 4-nonylphenol in suspended solids from STP effluent (GVRD, Draft 1996) and the elevated concentrations measured downstream of the plant suggest that the STP may be an important source of this compound to the Main Arm of the Fraser River.

With the exception of a single sample in the Stuart River reach, which had a 4-nonylphenol concentration of 570 ng/g, the highest 4-nonylphenol levels in bed sediments were measured in the North Arm of the Fraser River (7–64 ng/g). Concentrations in the heavily industrialized North Arm reach were three times higher than in the Lytton to Chilliwack reach upstream of metropolitan Vancouver. Concentrations in the North Arm of the Fraser River were approximately double those measured in the Main Arm of the Fraser River. However, levels in the North Arm were from 4–2,000 times lower than those measured in bottom sediments from heavily industrialized sites in the St. Lawrence River in Ontario (Bennie *et al*. 1996). Guidelines or criteria do not presently exist for 4-nonylphenol.

Total 4-nonylphenol partitioned to the suspended solid phase in the range of 0.8–9.3 per cent, indicating that this compound is largely found associated with the water phase. The calculated log K_{oc} was in the range of 4.7–5.7, which was higher than the theoretical log K_{oc} of 4.9 (Karickhoff 1981).

Metals

Elevated levels of copper, manganese and selenium were measured in suspended sediments from Savona relative to the South Thompson, upper Fraser and lower Fraser sites, while the highest levels of lead were measured at the McBride reference site, upstream of Prince George. Whereas natural sources are believed to contribute to the metal concentrations measured at McBride, metal enrichment from Kamloops City may account for the elevated levels measured at Savona. Trace metal concentrations in the lower Fraser River were similar to those found in the upper Fraser River, with the exception of arsenic. Arsenic concentrations were approximately double to those measured in the upper Fraser and Thompson rivers, likely due to contributions from wood preservation facilities in the lower Fraser River using copper arsenate-based wood preservatives.

In addition to arsenic, copper, zinc and lead measured in bed sediments were generally elevated in the Main and North Arms of the lower Fraser River relative to the upper Fraser River. However, concentrations measured in the Chilcotin and Quesnel reference reaches often exceeded those measured in the Fraser estuary.

These relatively high levels in the reference reaches are believed to originate from natural mineral deposits and historical mining activity (K. Andrews 1998, pers. comm.). Elevated levels of some metals measured in the Harrison River reach may be related to atmospheric deposition of trace metals from the greater Vancouver area (W. Belzer 1998, pers. comm.). As with suspended sediments, lead concentrations were highest in the McBride reference reach, indicating that these levels represent natural background concentrations for the basin. Lead concentrations in the lower Fraser River were similar to those measured at the same sites in 1990 and 1992 (Swain and Walton 1991; 1993) suggesting that levels of this metal may be leveling off after an initial sharp decrease associated with the banning of leaded gasoline in 1990.

Chromium, manganese, iron, nickel and copper exceeded provincial criteria (BC MELP 1995) at all sites in the Fraser Basin, indicating that these metals are naturally high in the sediments. Chromium also exceeded the draft sediment quality objective (<26 μg/g) for the Main Arm of the Fraser River (Swain *et al.,* draft 1996). Arsenic exceeded the provincial criterion of 6 μg/g in the Prince George to Quesnel reach, the Nechako, Stuart, Quesnel tributaries and the Fraser estuary. Zinc exceeded the provincial criterion of 120 μg/g in the North Arm of the Fraser River. Previous studies in the Fraser River Estuary have similarly reported metal concentrations exceeding provincial sediment quality criteria for many of the same metals measured in the present study (Swain and Walton 1990; 1991; 1993). In spite of these exceedences, most metals measured in the Fraser Basin were lower in concentration than levels found in the Columbia and Mississippi rivers (Bortleson *et al.* 1994; Garbarino, *et al.* 1995), the Great Lakes Areas of Concern (Bolattino 1993) and many rivers in the USA (Tornes *et al.* 1996; Ott 1997; USGS NAWQA 1997).

CONCLUSIONS

Dioxins, furans, chlorophenolics, resin and fatty acids, PAHs and 4-nonylphenol were measured in higher concentrations downstream of pulp mills and urban centres relative to reference locations throughout the Fraser River Basin. In contrast, organochlorine pesticides and PCBs were elevated relative to reference locations generally only in the urbanized lower Fraser estuary. The North Arm of the Fraser River generally had the highest levels of contaminants measured in bed sediments.

Urban runoff is the likely source of higher chlorinated dioxins, organochlorine pesticides, PCBs and PAHs, whereas pulp mills are the likely source of the lower chlorinated dioxins and furans, chlorophenolics and resin acids to the basin. The Annacis Island STP appears to be an important source of PCBs, PAHs and 4-nonylphenol to the Main Arm of the Fraser River. While metals were found to be naturally high in sediments throughout the Fraser Basin, elevated levels of some metals measured in urban areas may originate from anthropogenic sources. Seasonal fluctuations in contaminant concentrations in suspended sediment were measured for dioxins, furans, chlorophenolics and PAHs. Reductions in concentrations of dioxins, furans, chlorophenolics, pesticides and lead were noted relative to levels measured prior to 1991, due to regulations implemented in the 1980s and early 1990s. Dioxins, furans and HPAHs were generally associated with the suspended sediment phase, while chlorophenolics, LPAHs and 4-nonylphenol were found in higher proportions in the water phase. Exceedences of federal guidelines, provincial criteria and regional objectives for the protection of aquatic life in bed sediments were measured for dioxins and furans, PAHs, PCBs, pesticides and trace metals.

Geographically, urban areas such as the Fraser River Estuary and the Thompson River in and downstream of Kamloops were the most heavily impacted areas in the basin. The upper Fraser Basin was comparatively less impacted, although elevated levels of contaminants associated with pulp mills and municipal STPs were measured downstream of urban centres. On a larger scale, contaminants were generally similar or lower than those measured in other large river systems throughout North America, indicating that the basin is in a relatively good environmental state. Although the environmental quality of sediments from the basin is

considered to be generally good, the Thompson River and Fraser estuary should continue to be monitored to ensure that the environmental quality does not further degrade as a result of increasing stress from population growth.

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